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Letter

The microstructures and mechanical properties of cast Mg–Zn–Al–RE alloys

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ABSTRACT

The microstructures and mechanical properties of cast Mg–Zn–Al–RE alloys with 4 wt.% RE and variable Zn and Al contents were investigated. The results show that the alloys mainly consist of α-Mg, Al_2REZn_2, Al_4RE and τ-$Mg_{32}(Al,Zn)_{49}$ phases, and a little amount of the β-$Mg_{17}Al_{12}$ phase will also be formed with certain Zn and Al contents. When increasing the Zn or Al content, the distribution of the Al_2REZn_2 and Al_4RE phases will be changed from cluster to dispersed, and the content of τ-$Mg_{32}(Al,Zn)_{49}$ phase increased gradually. The distribution of the Al_2REZn_2 and Al_4RE phases, and the content of β- or τ-phase are critical to the mechanical properties of Mg–Zn–Al–RE alloys. The Mg–6Zn–5Al–4RE alloy with cluster Al_2REZn_2 phase and low content of β-phase, exhibits the optimal mechanical properties, and the ultimate tensile strength, yield strength and elongation are 242 MPa, 140 MPa and 6.4% at room temperature, respectively.

1. Introduction

Magnesium alloys, as one of the lightest structural metallic materials, have recently attained an increasing interest in weight reduction for the automotive industry because of their low density, high specific strength and stiffness, and good damping property. However, the low strength, poor formability and limited ductility at room temperature (RT) restrict its wider application [1,2]. Simultaneously, the range of applications for most magnesium alloys is limited by the low creep resistance and the obvious descending strength at elevated temperature, which makes it unsuitable for many of the component in automobile engines [3]. Until now, a series of heat resistant Mg–Al based alloys have been explored, such as AE, AJ, AS alloy systems, etc. It was reported that the AE44 alloy is being used in the engine cradle of Corvette by General Motors, and the engine block of all BMW cars is made from AJ62 alloy [4,5]. However, the high cost, low castability and/or poor recycling problem is still as a problem concerned [6].

The recent developments of heat resistance Mg alloys are mainly concentrated on the improvement of conventional Mg–Al based alloys by reducing the Al content to relatively low level and alloying with third element (Me), such as Si, rare earth (RE) and alkaline earth metals etc. [7]. The aims of these attempts are based on the idea of suppressing the formation of β-$Mg_{17}Al_{12}$ phase in alloys, combining with the formation of high thermal stability Mg–Me and Al–Me particles, thus the heat resistance of the alloys is improved [7,8]. Unfortunately, reducing Al content on the one hand will result in low strength, on the other hand, leads to the deterioration of castability [9]. Furthermore, the AE42 and AE44 alloys, which have low Al content, are only being used by die-casting to avoid the formation of massive Al–RE compounds. The Mg–Zn–Al (ZA) alloys, with more Zn content than Al, are regarded as a promising alloy to bridge the gap between AZ alloys and some heat resistant but costly alloys [10]. This alloy possesses excellent heat resistance, which is superior to the commercial AZ alloys, moreover it can be prepared by die-casting, without showing severe hot tearing and microporosity [10,11]. The results indicated that, in Mg–Zn–Al ternary alloys, as increasing the Zn content significantly with proper Zn/Al ratio, the β-$Mg_{17}Al_{12}$ phase will not be formed and the presence, instead, of the Mg–Zn–Al ternary phase [10,12]. However, this alloy has low ductility due to a large quantity of network eutectic phase distributing along the grain-boundaries. The recent progress mainly focuses on microstructure analysis of the ZA alloys and the relationship between compositions and heat tearing. The hot tearing on the die-cast ZA alloys is susceptible to the alloy composition, but it is difficult to obtain the acknowledged explanations [13]. The RE addition can refine and suppress the eutectic phase, as a result, improving the mechanical properties for the alloys, whereas there are still few reports about the phase composition, morphology and mechanical properties of the Mg–Zn–Al–RE alloys [14,15]. In our recent work, the Mg–6Zn–5Al–4RE alloy is mainly composed of Al_2REZn_2 phase, which has the similar morphology as the $Al_{11}RE_3$ phase in AE44 alloy, only a small amount of β-eutectic phase was found because of the high RE content. The alloy exhibits acceptable mechanical properties at RT and elevated temperature [16]. This paper is to present the influence of different combinations of

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Table 1
Chemical composition of the experimental alloys.

Alloy	Composition (mass %)							
	Zn	Al	Ce	La[a]	Nd[a]	Pr[a]	Mg	Total (RE)
ZAE654	5.364	4.994	2.079	1.092	0.822	0.229	Bal.	4.222
ZAE674	5.943	6.875	1.997	1.049	0.607	0.228	Bal.	3.881
ZAE854	8.014	4.772	2.379	1.250	0.723	0.272	Bal.	4.624
ZAE1054	10.146	4.987	1.956	1.027	0.594	0.223	Bal.	3.800

[a] Contents of La, Nd and Pr were calculated according to the compositions of mischmetal.

Zn and Al content on the microstructures as well as mechanical properties of the Mg–Zn–Al–RE alloys.

2. Experimental procedures

Three kinds of alloys with variable Zn and Al content were prepared from high purity Mg, Zn and Al, and Mg–22.7 wt.%RE master alloy under a flux protection in a graphite crucible and casting into a steel mould preheated to about 200 °C. The original nominal composition of RE was 51.46 Ce, 27.03 La, 5.88 Pr and 15.64 Nd (wt.%). The compositions of the ingots were analyzed by ARL4460 direct reading spectrometer, and the results are listed in Table 1. In order to delineate the grain-boundary, specimens selected at the corresponding position of the ingots were homogenized at 400 °C for 24 h and followed by water quenching. The microstructure was studied by Olympus GX71 optical microscopy. Phase analysis was detected by X-ray diffraction (XRD). Tensile testing was conducted on Instron-type testing machine with the constant strain rate of $5.56 \times 10^{-4}\,s^{-1}$ at RT and 150 °C. The heating-plus-holding time took 10 min to balance the temperature before tensile test at 150 °C. Fracture surface of the tensile samples was observed by scanning electron microscopy (SEM).

3. Results and discussion

Fig. 1 shows the XRD results of the as-cast alloys. As reported in previous investigation [16], the ZAE654 alloy consists of α-Mg, Al_2REZn_2 and Al_3RE phases, and a small quantity of β-$Mg_{17}Al_{12}$ eutectic phase. Compared to the ZAE654 alloy, it exhibits that, for the ZAE674 alloy, except for the formation of Al_2REZn_2 and Al_4RE phases, some new diffraction peaks which can be indexed as τ-$Mg_{32}(Al,Zn)_{49}$ phase can also be found in the alloy. The disappearance of β-$Mg_{17}Al_{12}$ phase in ZAE674 alloy may be attributed to the formation of Al_4RE phase consuming more Al atoms than that of Al_3RE phase formed in ZAE654 alloy. However, for the ZAE854 alloy, the phases have no evident change compared with the ZAE674 alloy. The increased Zn addition of ZAE1054 alloy only increases the content of secondary phase, especially the τ-phase, which can also be reflected from optical microscope observation (Fig. 2). It was reported that the phase compositions of Mg–Zn–Al alloy depend on the Zn/Al rate [11,12,17]. Whereas on the Mg–Zn–Al–RE alloy, the Al–RE and Al–RE–Zn phases will preferentially be formed, hence the content and the type of low temperature eutectic phase are determined by the surplus Zn and Al. The typical microstructures of the as-cast alloys are shown in Fig. 2. The microstructure is varied with different combinations of Zn and Al contents. In more detail, for the ZAE654 alloy, a small amount of lamellar β-eutectic phase can be found, and a large quantity of rod-like Al_2REZn_2 phase accumulates as cluster morphology. Compared with the ZAE654 alloy, the accumulative content of the rod-like phase in one cluster is decreased in ZAE674 alloy, but quantitative metallographic method indicates that all the alloys has similar total content of rod-like phase. The accumulative quantity of the rod-like phase further decreases in the ZAE854 alloy, and the τ-eutectic phase distributes as granular one. For the ZAE1054 alloy, which has the highest (Zn + Al) content, the rod-like phase becomes coarser and distributes by dispersed morphology, meanwhile a large quantity of coarse τ-phase forms. Fig. 3 shows the optical micrographs of the homogenized alloys. As shown in this figure, the rod-like phase in the all of examined alloys does not decompose due to high thermal stability, which would

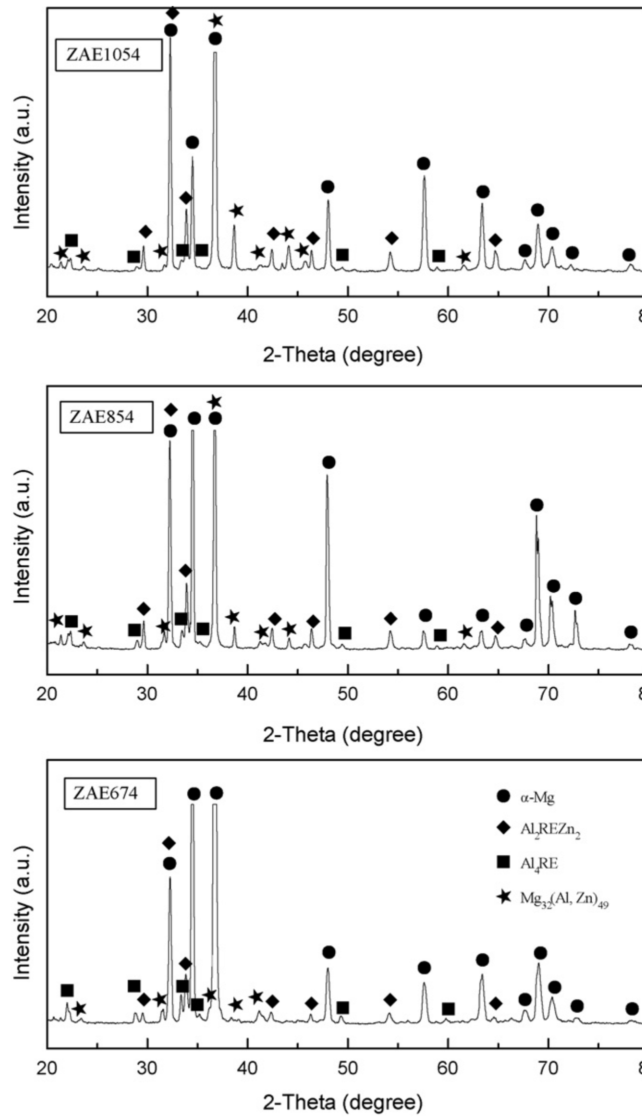

Fig. 1. X-ray diffraction pattern of the as-cast alloys.

provide a barrier to the sliding of the grain-boundary at elevated temperature.

The mechanical properties of the as-cast alloys at RT and 150 °C are listed in Table 2. It reveals that, the ZAE654 alloy exhibited optimal strength and ductility at RT and 150 °C. For comparison, some other Mg–Al based alloys developed for high temperature performance are presented in Table 3. It can be seen that, the mechanical properties of ZAE654 alloy at RT and 150 °C are higher than that of permanent-mold cast ACe44 and AE42 alloys, respectively, and the strength at RT is comparable to die-cast AE44 alloy. From the optical observation (Fig. 2), the distribution of rod-like Al_2REZn_2 phase in ZAE654 alloy is similar with the $Al_{11}Ce_3$ phase in ACe44 alloy, hence the improvement of the mechanical properties may be attributed to

Table 2
Tensile properties of the alloys tested at different temperatures.

Alloy	UTS (MPa)		YS (MPa)		Elongation (%)	
	RT	150 °C	RT	150 °C	RT	150 °C
ZAE654	242	125	140	89	6.4	9.1
ZAE674	168	112	93	70	3.2	5.4
ZAE854	174	120	95	86	3.1	4.3
ZAE1054	159	127	93	86	1.8	3.1

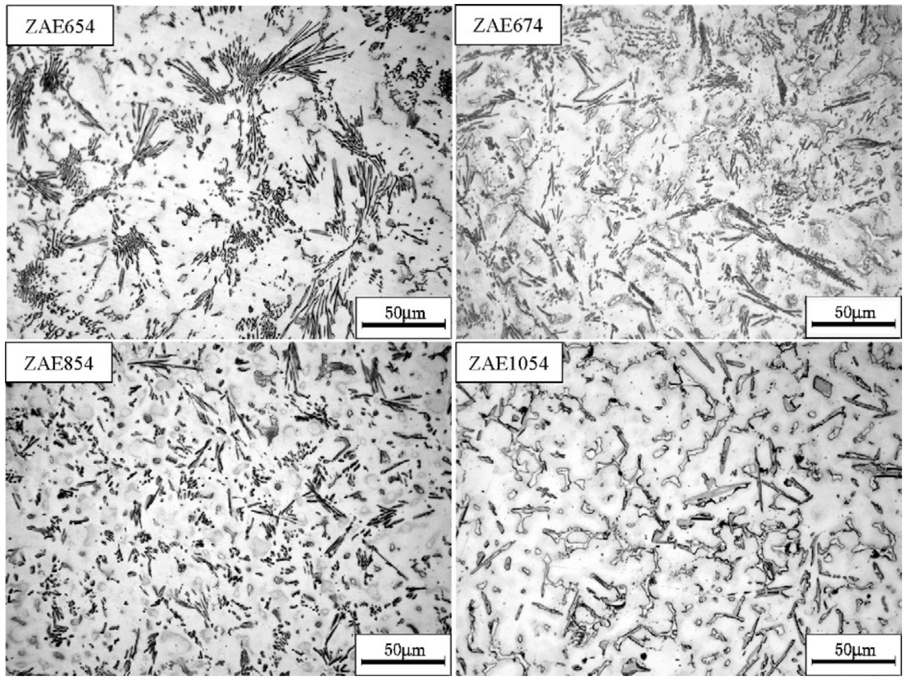

Fig. 2. Optical micrograph of the as-cast alloys.

the increased Zn and Al solutes in α-Mg matrix. Compared with the ZAE674 and ZAE854 alloys, which have the same solute content, it can be found that the ZAE854 alloy with more Zn content has higher thermal stability than that the ZAE674 alloy. It seems that the Zn element is better for the improvement of the thermal stability. In the present work, we consider that the mechanical properties of the Mg–Zn–Al–RE alloys are attributed to the following factors:

As can be seen from Fig. 3, the RE-containing phase in ZAE654 alloy mainly distributes at intragranular and triple grain-boundary, which plays an important role in strengthening the α-Mg matrix and hindering the sliding of the grain-boundary at elevated temperature [15]. However, with higher solute addition, the RE-containing phases become coarser and dispersive, which will lower the mechanical properties for the alloy. Furthermore, the more Zn or Al addition, the higher content of the Mg–Zn–Al eutectic phases will be formed, which would be distributed at grain-boundary by lamellar morphology, resulting in the decrease of ductility [22]. On the other hand, it is known that the Zn and Al elements are good strengtheners on the Mg–Zn–Al alloy systems [8]. The formation of RE-containing compound consumes large quantity of Zn and Al atoms, as a result, reducing the solute strengthening effect.

Fig. 4 shows the typical SEM fracture images of the ZAE1054 alloy tensile test at RT. Due to the *hcp* structure of α-Mg, failure of Mg based alloy is usually brittle through cleavage or quasi-cleavage

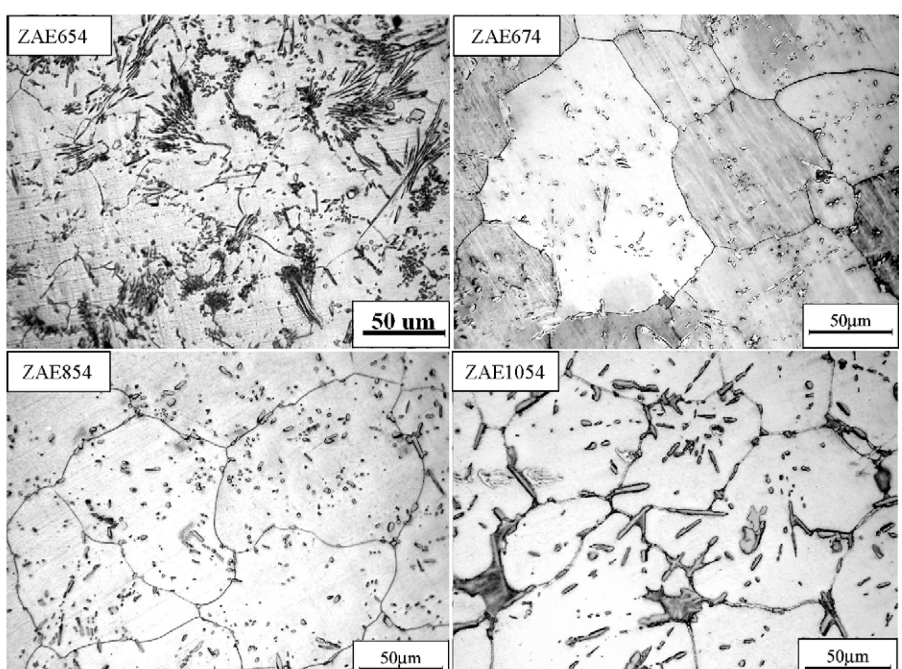

Fig. 3. Optical microstructure of the alloys homogenized at 400 °C for 24 h.

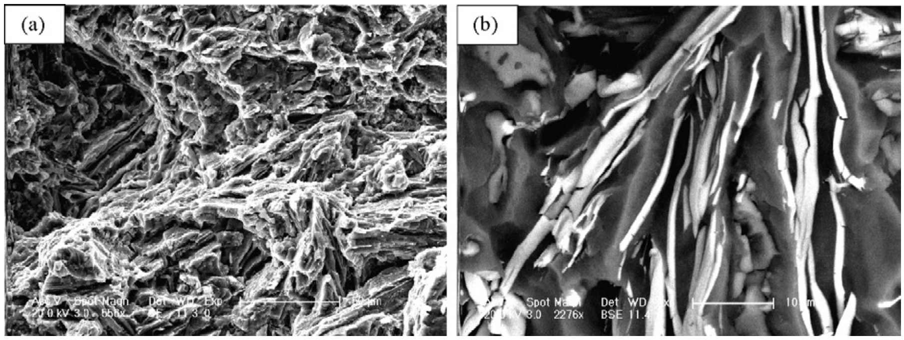

Fig. 4. SEM image of the ZAE1054 alloy tested at room temperature.

Table 3
Mechanical properties of some Mg–Al based alloys reported in Refs. [18–21].

Alloy	UTS (MPa)		YS (MPa)		Elongation (%)	
	RT	150 °C	RT	150 °C	RT	150 °C
AS41[b]	249	153	132	94	8.9	16.8
AE42[b]	240	160	135	100	12	22.0
AE42[a]	–	114	–	45	–	9.0
AE44[b]	247	145	140	110	11.0	25.0
ACe44[b]	250	147	141	109	10.0	25.0
ACe44[a]	100	–	55	–	2.0	–
AJ52[b]	202	164	145	108	4.0	13.6

[a] Permanent-mold casting.
[b] Die-casting.

[23]. From Fig. 4(a), no dimple is found, and the failure surface contains cleavage plane and steps, which is characteristic of cleavage fracture. The back-scatter observation indicates that a lot of cracks form on the rod-like phase and lamellar eutectic phase, which is attributed to the dislocation piles up, resulting in stress concentration (Fig. 4b). The cracks easily nucleate and propagate along these phases, thus lower mechanical properties of the alloy. The further improvement for the Mg–Zn–Al–RE alloys will concentrate on optimizing Zn, Al and RE content to prevent the formation of low temperature eutectic phase and controlling the morphology of the rod-like Al_2REZn_2 and Al_4RE phases.

4. Conclusions

1. The cast Mg–Zn–Al–RE alloy is mainly composed of α-Mg, Al_2REZn_2, Al_4RE and τ-$Mg_{32}(Al,Zn)_{49}$ phases, and the β-$Mg_{17}Al_{12}$ phase will also be formed when certain Zn and Al solutes added. The amount of τ-phase will increase with the increasing Zn or Al content.
2. The distribution of the RE-containing phase is related to the content of Zn or Al solute. The rod-like Al_2REZn_2 and Al_4RE phases become coarser due to more solute addition, and the morphology will be changed from cluster to dispersed one. The morphology of the rod-like phase and the content of low temperature eutectic phase play important role in the mechanical properties of the Mg–Zn–Al–RE alloy.
3. The Mg–6Zn–5Al–4RE alloy with cluster Al_2REZn_2 phase has optimal mechanical properties, whereas the Mg–10Zn–5Al–4RE alloy with dispersed rod-like Al_2REZn_2 and Al_4RE phases and high content of lamellar τ-$Mg_{32}(Al,Zn)_{49}$ phase has the lowest mechanical properties.

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