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Effect of rare earth additions on microstructure and mechanical properties of AZ91 magnesium alloys

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Abstract: In order to meet the demands of high temperature components in automobile, the microstructure and mechanical properties of several new die-casting AZ91-rare earth (RE) magnesium alloys were studied. The alloys were characterized by optical microscopy (OM), scan electron microscopy (SEM), energy dispersive X-ray spectrometry (EDX), tensile and creep tests. The results show that Ce addition has little effect on the mechanical properties of AZ91 alloy at high temperature, while Y and Nd addition play important role in the improvement of creep resistance. New alloys containing Y or Nd with excellent high temperature performance are selected to produce cylinder head cover of high power diesel engine of Red Flag car and oil pan of Besturn car. The new magnesium alloys with RE addition for die-casting have potential to produce power-train parts, and can greatly decrease weight.

Key words: magnesium alloy; rare earth; die-casting; high temperature; creep; microstructure

1 Introduction

The lightweight design is becoming more and more important in the vehicle design. The fuel consumption can reduce to 0.3−0.5 L per 100 km with 10% reduction in vehicle weight. One of the most important challenges is the application of innovative materials and technologies in the automobile lightweight design[1−2]. In comparison with traditional materials, magnesium alloys can offer several advantages, such as high level of weight reduction, high specific strength, good castability (especially in high pressure die-casting (HPDC)), good machinability, and reclamation[2−3]. There is an urge to save weight at the front axle, especially on front-wheel drive vehicles[4]. However, the high working temperature of power train components can cause serious problems for traditional magnesium alloy application[5]. AZ91 alloy cannot meet the demands of temperatures beyond 120 ˚C and high stress load[6]. On the other hand, it was reported that rare earth elements, such as Y, La, Nd or Ce, can improve the ambient and high temperature mechanical properties of magnesium alloys[7−10]. Therefore, in this work, AZ91 magnesium alloys with RE additions were studied in order to use them as automobile parts at 150 ˚C.

2 Experimental

2.1 Composition design

New alloys were developed and optimized specifically aiming at cylinder head cover and oil pan with complex geometries. AZ91 alloy was selected as base alloy due to its good castability. Rare earth including Ce, Y and Nd were selected as alloying elements in order to increase the high temperature creep resistance of AZ91 alloy. The low cost Mg-RE master alloys fabricated by electrolysis in Yinguang Magnesium Group, China, were used for rare earth addition. Table 1 shows the composition of the experimental alloys. These alloys were fabricated and their mechanical properties, castability, and creep resistance were investigated.

2.2 Alloy die-casting

Magnesium melts were prepared in a steel crucible with 20 kg capacity. The melt temperature did not exceed 780 ˚C, and the die-casting temperature was controlled at 650−660 ˚C. A 630 t cold-chamber die-

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Table 1 Composition of experimental alloys (mass fraction, %)

Alloy	Mg	Al	Zn	Ce	Y	Nd
1	Bal.	8.5−9.5	0.35−1.0	−	−	−
2	Bal.	8.5−9.5	0.35−1.0	0.5	−	−
3	Bal.	8.5−9.5	0.35−1.0	1.0	−	−
4	Bal.	8.5−9.5	0.35−1.0	1.5	−	−
5	Bal.	8.5−9.5	0.35−1.0	−	−	1.0
6	Bal.	8.5−9.5	0.35−1.0	−	1.0	−

casting machine was used to cast the melt into a four-cavity die including two tensile bars of 6 mm in diameter and 100 mm in gauge length, and two tensile creep bars of 10 mm in diameter and 100 mm in gauge length. For each alloy, at least 15 shots have been made.

2.3 Microstructure analysis and tensile creep test

The microstructures were analyzed using optical microscopy (OM), scan electron microscopy (SEM), and energy dispersive X-ray spectrometry (EDX).

Tensile creep tests were performed at 150 ˚C and 50 MPa by using RD_2-3 creep test machine. The test conditions were selected based on the requirements for cylinder head cover and oil pan. The temperature was measured in three locations (top, middle, and bottom of the gage length) of each specimen, and was controlled within ±1 ˚C. Tensile displacement was measured by two extensometers, and all time−strain−temperature data were recorded by a computer data acquisition system. At least three specimens were used for each test.

3 Results and discussion

3.1 Microstructure

Fig.1 shows the optical micrographs of AZ91 and selected alloys. The microstructure of AZ91 consists of fine *α*-Mg grains surrounded by eutectic particles (Fig.1(a)). From Figs.1(b)−(d), the grain size decreases with increasing the Ce content from 0.5% to 1.5% (mass fraction). When the Ce content is 1.5%, fine grain size is near to 10 μm. Therefore, Ce addition is demonstrated to be beneficial to refining the grain size of AZ91 alloy[11−12]. Nd or Y additions can also refine the grain size, but the effect is less obvious (Figs.1(e) and (f)).

3.2 Mechanical properties and creep behavior

The tensile mechanical properties at room temperature of the investigated alloys are shown in Fig.2(a). It can be seen that all the RE-containing alloys are stronger than AZ91 alloy. The ultimate tensile strength (UTS) and tensile yield strength (YS) of AZ91 is 220 MPa and 163 MPa, respectively. The UTS of the Ce-containing alloys are between 238 MPa and 275 MPa, and that of the alloys containing Nd and Y are 264 MPa and 272 MPa, respectively. The tensile yield strength of magnesium alloys with RE additions is between 172 and 187 MPa. Alloy 4 shows the highest strength due to its finest grain size near to 10 μm (Fig.1(d)).

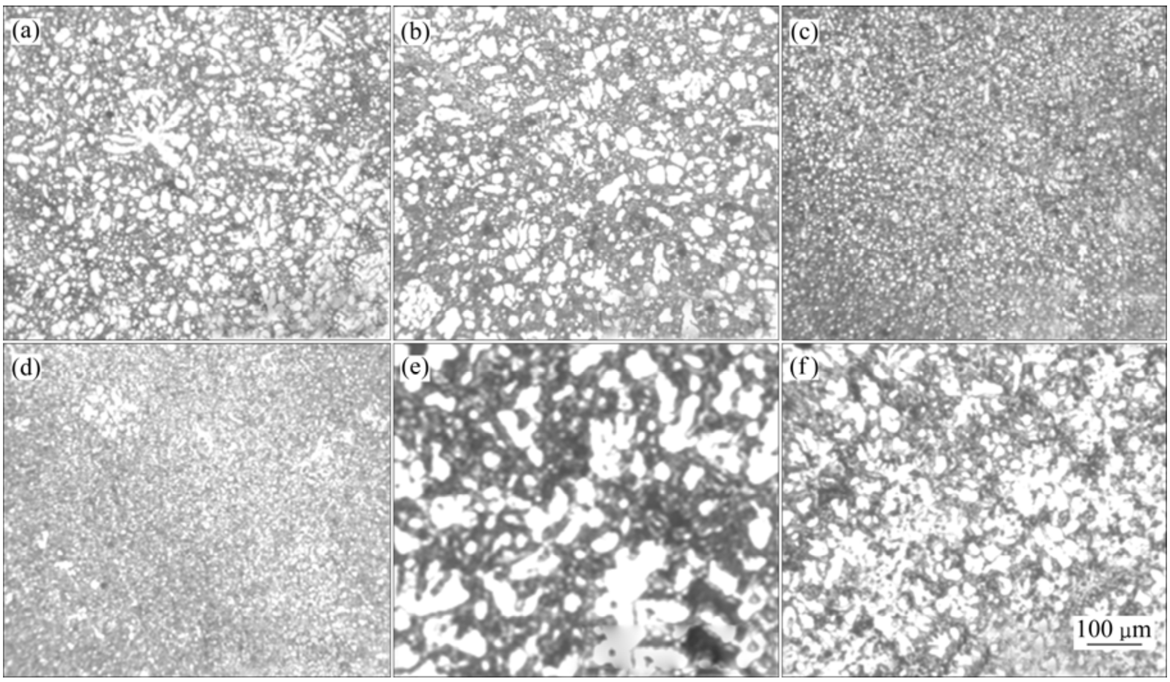

Fig.1 Microstructures of investigated alloys: (a) Alloy 1; (b) Alloy 2; (c) Alloy 3; (d) Alloy 4; (e) Alloy 5; (f) Alloy 6

Fig.2(b) shows the tensile creep curves of the investigated alloys tested at 150 ˚C and 50 MPa. The maximum creep extension of AZ91 alloy exceeds 3.5% (see curve 1 in Fig.2(b)). It was reported by many investigators that Ce addition in AZ91 alloy is beneficial to the creep resistance[13−14]. However, in this work, the Ce addition only slightly improves the creep resistance of the alloys and the maximum creep extension of the alloys with different Ce content is from about 0.5% to 2.5% (see curves 2−4 in Fig.2(b)). Alloy 5 and 6 exhibit much better performance in the creep test, and their maximum creep extensions are 0.14% and 0.11%, respectively (see curves 5−6 in Fig.2(b)).

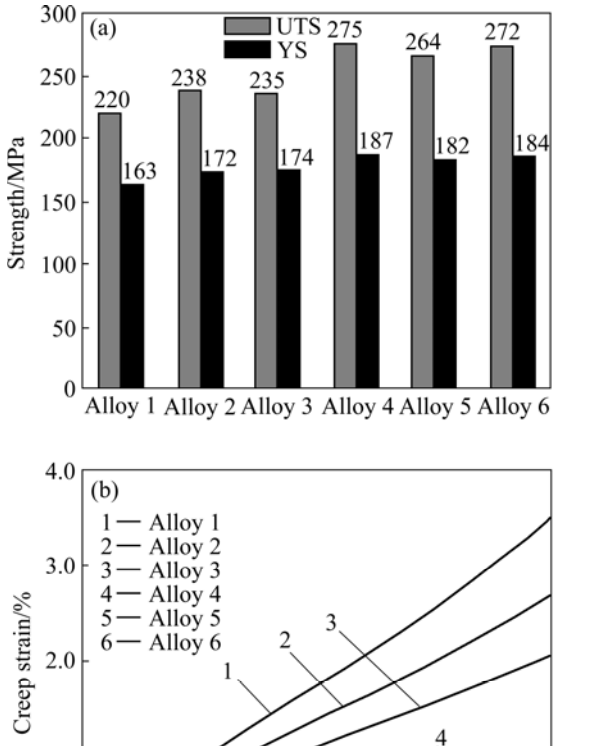

Fig.2 Tensile mechanical properties (a) and creep behavior (b) of AZ91 and five selected alloys

Fig.2(b) shows that Ce addition plays limited role in creep resistance. This may be caused by the following reasons. It can be seen that Ce addition forms $Al_{11}Ce_3$ in alloys 2−4 and the $Al_{11}Ce_3$ particles can refine the grain size significantly (Figs.1(b) and (d)). The finer grain size obviously increases the grain boundary area, hence increases the grain boundary slide during the creep test and decreases the creep resistance. Another reason is due to the thermal stability of $Al_{11}Ce_3$ phase[15−16]. The microstructures of alloy 2 before and after creep test are shown in Fig.3. Needle-like $Al_{11}Ce_3$ particles are observed in the microstructure before creep test as shown in Fig.3(a), while these particles disappear after creep test and only granular $Al_{11}Ce_3$ particles can be observed (Fig.3(b)). So, it can be concluded that the morphology of $Al_{11}Ce_3$ phase changes from needle-like to granular during creep test, although the melting point of $Al_{11}Ce_3$ is above 1 000 ˚C. Therefore, the limited improvement in creep resistance of the Ce-containing alloys is attributed to the morphology change of the strengthening phase and the fine grain size.

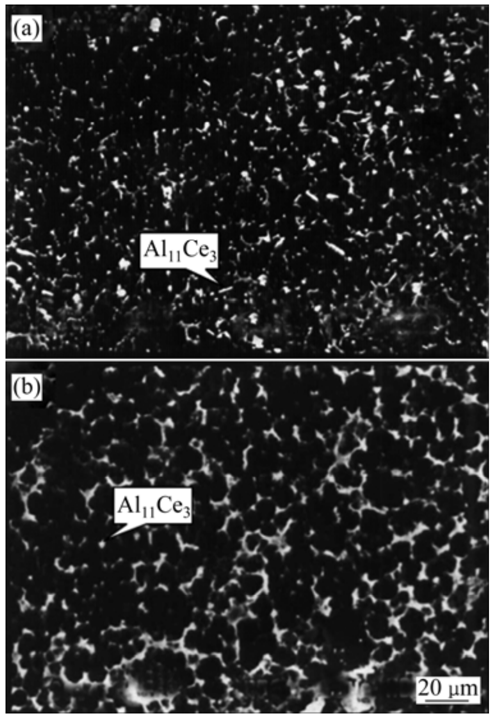

Fig.3 SEM microstructures of AZ91+0.5Ce alloy before (a) and after (b) creep tests

Fig.2(b) also shows that Nd or Y addition significantly improves the creep resistance of the investigated alloy. The morphology and EDX analysis of the secondary phase in alloy 6 are shown in Fig.4. Some fine particles are found to disperse inside the grains (Fig.4(a)). EDX analysis (Fig.4(b)) shows that these particles are most likely Al_2Y according to their molar ratio of Al to Y[8]. The secondary phase in alloy 5 is Al_2Nd which is similar to Al_2Y. The secondary phase inside the grains which can effectively block the dislocation slip within grains, combined with proper grain size, can greatly improve the creep resistance of alloy 5 and 6. However, the high price of pure Y and Nd restricts their extensive use in die-casting magnesium alloy. In this work, cheap Mg-Y and Mg-Nd master alloys fabricated by electrolysis were used to develop these new alloys. Considering the better creep resistance performance, the cost of the new alloys increased by RMB¥1 000−1 500 per ton is acceptable.

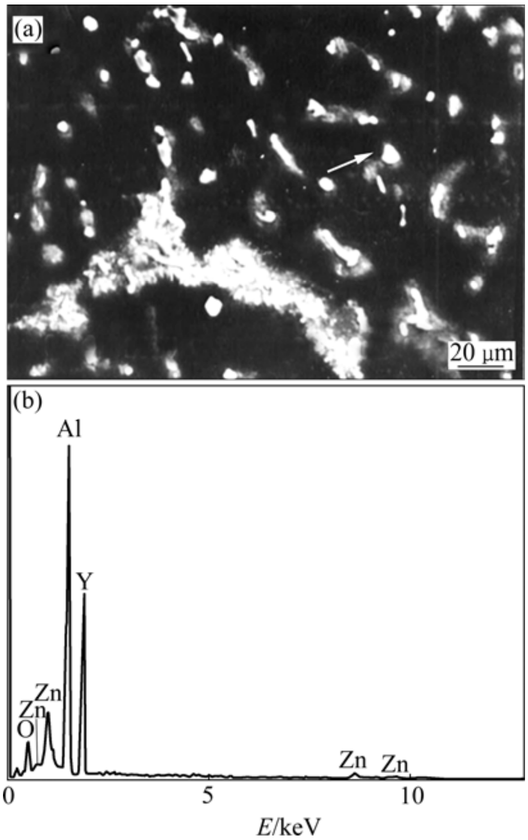

Fig.4 SEM microstructure (a) and EDX analysis result of secondary phase in alloy 6

3.3 Castability and production

Alloys 5 and 6 are used to produce cylinder head cover in "Red Flag" car in order to test their castability. The new alloys show better castability than AZ91 in die-casting process. Fifteen tons commercial ingots of alloys 5 and 6 are produced by using Mg-Y master alloy which is fabricated by electrolysis in Yinguang Magnesium Group, China. The ingots are used to produce cylinder head cover (Fig.5(a)) in diesel engine, which is designed by FAW (first automobile work). The working temperature of the cover is beyond 130 ˚C. The road tests show that the cylinder head cover produced by the new alloys can meet the working temperature demands. Now, the cylinder head cover is in the mass production. The oil pan of Besturn car (Fig.5(b)) produced by alloy 5 is another application of high temperature creep resistant die-casting Mg alloys. This oil pan is designed for a new generation passenger car engine of FAW and its working temperature is close to 150 ˚C. The road tests show that the oil pan produced by alloy 5 also meet the temperature demands.

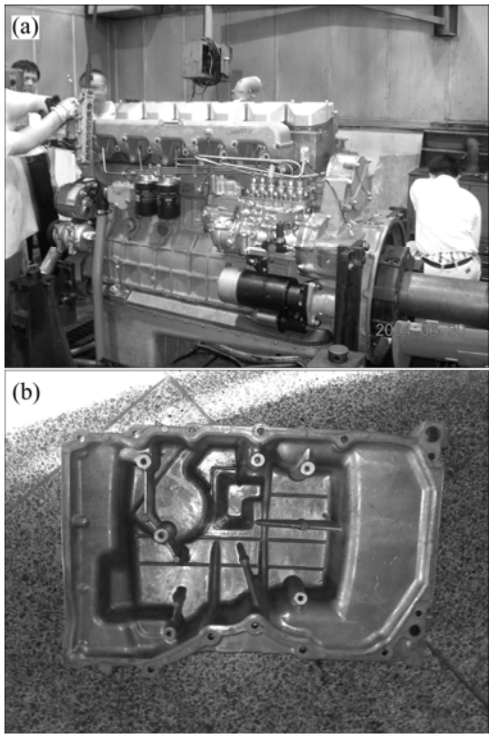

Fig.5 Application of high temperature creep resistant die-casting Mg alloys: (a) Cylinder head cover; (b) Oil pan

4 Conclusions

1) High temperature creep resistant die-casting magnesium alloys are successfully developed by adding rare earth into AZ91 alloy. The application of low cost Mg-RE master alloys fabricated by electrolysis can greatly decrease the cost of these new alloys, and open up a way to extend the use of Mg-RE alloys in die-casting.

2) Ce addition can decrease the grain size of the die-casting magnesium alloys, while Nd or Y addition has little effect on the grain size of the alloys. The morphology of $Al_{11}Ce_3$ strengthening phase in Ce-containing alloys changes from needle-like to granular during creep test at elevated temperature. The alloys with Nd or Y addition exhibit better creep resistance, and have potential to develop new creep resistant die-casting magnesium alloys for power-train components.

3) New high temperature creep resistant die-casting magnesium alloys are successfully used to produce cylinder head cover and oil pan. The new alloys can withstand the working temperature of 150 ˚C.

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