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Effects of rare earths on friction and wear characteristics of magnesium alloy AZ91D①

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Abstract: The influence of various rare-earth contents on the friction and wear characteristics of magnesium alloy AZ91D was studied. The results show that the wear resistance properties of rare-earth magnesium alloys are better than those of the matrix alloy under the testing conditions. Magnesium alloys undergo transition from mild wear to severe wear. The addition of rare earths refines the structure of alloys, improves the comprehensive behaviors of the magnesium alloys, increases the stability of oxidation films on worn surfaces, enhances the loading ability of rare-earth magnesium alloys, and delays the transition from mild wear to severe wear effectively.

Key words: rare earth; magnesium alloy; friction and wear
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1 INTRODUCTION

As the lightest metallic structural materials, magnesium alloy has low density, high specific strength and specific stiffness, good damping characteristic, excellent machinability and castability, etc. So more and more magnesium alloy products have been used in automobile, communication and aerospace industries[1-3]. At present time, the most commonly used magnesium alloy is AZ91D alloy. Despite the growing interest in magnesium alloys, very few data exist on their friction and wear behavior. While magnesium alloys would normally not be candidates for bearings, sliding seals or gears, there are certain situations in which they are subjected to sliding motion including automotive brakes, engine components(piston and cylinder bores). In addition, sliding wear is also an important consideration in material processing and assembly by rolling, extrusion, forging, etc. Therefore, it is essential to study the friction and wear behavior of magnesium alloys.

Rare earths(RE) are important alloying elements to magnesium alloys, which can improve many properties without affecting the electrical conductivity of the base alloys[4, 5]. The current work is designed to discuss the effects of rare earths on the friction and wear characteristics of magnesium alloy AZ91D.

2 EXPERIMENTAL

The basic chemical composition of the alloy in the experiment is 9% Al(mass fraction), 1% Zn, 0.2% Mn, and the balance is Mg. RE additions were made in the form of cerium rich misch metal. The addition amount of RE is 0.2%, 0.4%, 0.6%, 0.8%, 1.0%, respectively. Table 1 shows the mechanical properties of the AZ91D alloy with different addition amounts of RE.

Table1 Mechanical properties of magnesium alloys with or without rare earths

Materials	Hardness (HB)	Yield strength /MPa	Elongation /%
AZ91D	58	80	2.85
AZ91D+ 0.2% RE	61	84	2.89
AZ91D+ 0.4% RE	63	85	2.98
AZ91D+ 0.6% RE	66	88	3.14
AZ91D+ 0.8% RE	67	88	3.23
AZ91D+ 1.0% RE	69	91	3.44

Wear tests were conducted using a pin-on-disc type apparatus(MM-2000). In this system, the test sample(d 6 mm × 12 mm) was clamped in the holder and held against the rotating disc(70 mm in diameter and 10 mm in thickness). The disc was made of steel 5CrNiMo with hardness HRc= 55. The whole experiments were carried out under dry friction conditions at 25 ℃. The speed of the disc was 0.628 m/s. Range of loads was 20~ 110 N. The surface of the wear test samples was polished with 1000# SiC papers until the surface roughness R_a reached 0.3 μm. The disc and specimen were cleaned with acetone to remove any possible traces of grease and other sur-

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face contaminants. The wear results were taken from mass losses measured before and after the sliding tests to the nearest 0.1 mg using an analytical balance. Friction coefficients were calculated by dividing the mean friction force recorded during each experiment by the applied normal force. Worn surfaces and debris were examined under a scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDS).

3 RESULTS AND DISCUSSION

3.1 Influence of RE on microstructure of AZ91D alloy

Fig. 1 shows the microstructure of AZ91D alloy with or without RE. The addition amount of RE is 0.6%. It can be seen from the figure that the microstructure is refined obviously and gets more uniform and even by the addition of RE. This is also one of the most important benefits of RE on alloys[6-8]. The morphology of AZ91D alloy is composed of α-Mg matrix and irregular β-precipitation along grain boundaries ($Mg_{17}Al_{12}$) (Fig. 1(a)). After RE was added, a rod-like intermetallic phase —$Al_{11}RE_3$ phase was observed[9] and the volume of β-phase was somewhat decreased (Fig. 1(b)).

3.2 Influence of RE on wear characteristics of AZ91D alloy

Fig. 2 is the graph representing the friction coefficient of the alloys as a function of the applied load. It follows from the graph that the friction coefficients of the specimens with RE additions are lower than that of the alloy matrix and decrease with the increase in the addition amount of RE, indicating different wear behaviors between the specimens with and without RE. The friction coefficients are also reduced with increasing applied load and tend to be steady gradually. Load affects wear behavior by contact area and deformation. In the sliding process, the metal surface was in an elastic-plastic state and the real contacting area was not linearly related to the load, leading to the decrease of the friction coefficient with the increase of load[10].

The curves of the relationship between wear mass losses of alloys and load are shown in Fig. 3. It follows from the curves that the mass loss of both the matrix alloy as well as the alloy with RE additions increase with the increase in the applied load. It may be noted that the specimens with RE exhibit significantly lower wear rates than the base alloy specimens. The mass loss are reduced with the increase in REs content. It is clearly evident from the above mentioned curves that there exists a critical applied load, i. e. a transition phenomena at which there is a sudden increase in the wear rate of both materials with and without RE, implying that the magnesium alloys

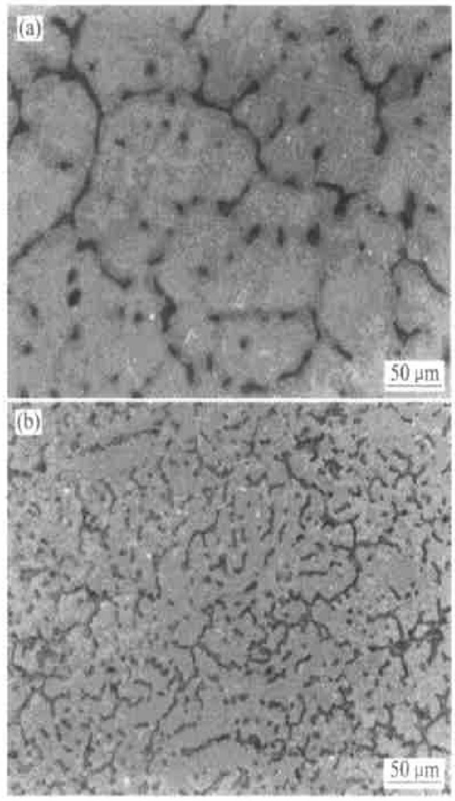

Fig. 1 Microstructures of magnesium alloys with or without rare earths
(a) —AZ91D; (b) —AZ91D+ 0.6% RE

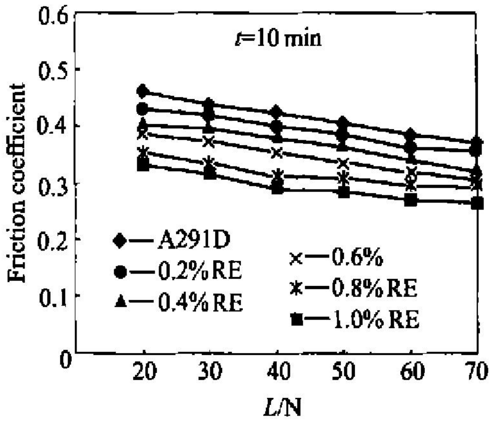

Fig. 2 Relation between friction coefficient and load (L)

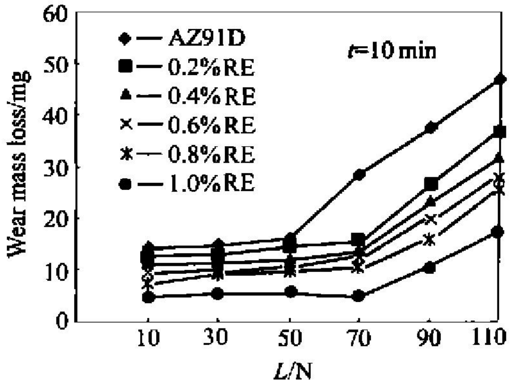

Fig. 3 Relation between wear mass loss and load (L)

undergo a transition from mild wear to severe wear. However, the transition load for the alloys with RE additions is about 20 N higher than that observed for the matrix alloy.

Fig. 4 indicates that the wear rates of the specimens with RE are also low at lower loads. Only fine scratches and shallow grooves can be seen from the morphology of the worn surface. The EDS analysis for Fig. 4(b) exhibits the presence of the main elements of O, Mg, Al, Zn, Fe (Table 2), implying that the surface layer consists of the oxides of these elements. The oxide layer not only acts as a lubricant, but also inhibits the direct contact between two tribo-couples, contributing to the reduction in the friction coefficient and the wear mass loss. Steady state wear conditions are maintained throughout the mild wear regime, at which the wear mechanism is referred as the oxidational wear. At high loads, the severe wear manifests itself by deep and wide grooves on the worn surface and also by a rapid rate of material removal in the form of generation of coarse metallic debris, which is more obvious for the matrix alloy. These are indications of the delamination wear. Table 3 is the EDS analysis for Fig. 4 (d). The content of the element O decreases greatly, but the amounts of Mg, Al, Zn are almost the same with those of the matrix alloy.

Table 2 EDX analysis on worn surface of tested alloy in Fig. 4(b)

Element	w/%	x/%
O	28.93	39.08
Mg	60.12	53.51
Al	7.61	5.91
Zn	1.57	0.52
Fe	1.77	0.68
Total	100	100

Table 3 EDX analysis on worn surface of tested alloy in Fig. 4(d)

Element	w/%	x/%
O	4.00	6.06
Mg	84.95	84.53
Al	10.07	9.05
Zn	0.94	0.35
Fe	0.04	0.02
Total	100	100

Generally speaking, however, the anti-wear property of the alloy with RE additives is much better than that of the matrix alloy under the same testing conditions. RE elements have strong affinity with the impurities such as O and S, which suppresses microporosities caused by these impurities. In melting process, RE elements can react with water and hydrogen existing in magnesium melt and form RE hydrides and oxides to degas hydrogen and decrease such defects as gas voids, pinholes, and porosities. So the casting quality is improved and crack initiation is decreased. Moreover, RE elements can also strengthen and purify grain boundaries. Hence, cracks are not apt to form at the grain boundaries[11].

In AZ91D alloy, the main strengthening phase is $Mg_{17}Al_{12}$, which has a low melting point of approximately 462 ℃ and poor thermal stability. $Mg_{17}Al_{12}$ phase can readily coarsen and soften when the temperature increases. In addition, $Mg_{17}Al_{12}$ has a cubic crystal structure incoherent with the hcp magnesium matrix, which leads to the fragility of Mg/$Mg_{17}Al_{12}$ interface. Additions of RE to AZ91D formed $Al_{11}RE_3$ precipitation in the alloy preferentially. $Al_{11}RE_3$ has much high melting point, along with the low diffusion speed of RE elements in magnesium at elevated temperature, makes $Al_{11}RE_3$ has high thermal stability. So sliding of grain boundaries and growth of cracks are effectively prevented at elevated temperature and high temperature properties are improved. The effects of RE on the wear behavior of the alloys are more obvious at high loads. The temperature of the worn surface would increase during the course of wear. So it is almost unavoidable for tribo-pairs to be oxidized in air, which plays an very important role in wear process. RE elements agglomerate at boundaries between the oxide layer and the matrix, which refines the structure and enhances the adherence and stability of the oxide layer. The wear resistance and the anti-delamination ability of the layer are increased and the load-bearing capacity of AZ91D alloy with RE additions is improved. The presence of RE, therefore, delays the transition from mild to severe wear effectively.

Fig. 5 provides the debris morphologies of specimens with or without RE additives. Cracks on the worn surface of magnesium alloys can be originated and propagate continuously by periodical alternating friction stresses and heat stresses. The oxide layers finally fracture and form into debris. Since the presence of RE can impede effectively the propagation of microcracks on the alloy surface, the debris of AZ91D with RE is much smaller than those of the matrix. The typical wear debris of the base alloy has a shiny metallic appearance and a plate-like shape. Debris in small size has slight effects on worn surface of the alloy and the tribo-surface state has little change. So the wear rate of magnesium alloys with RE additions can be steady for a long period. However, debris in large size can impair the tribo-surface of the base alloy severely, at which gorging and delamination wear get serious. Wear

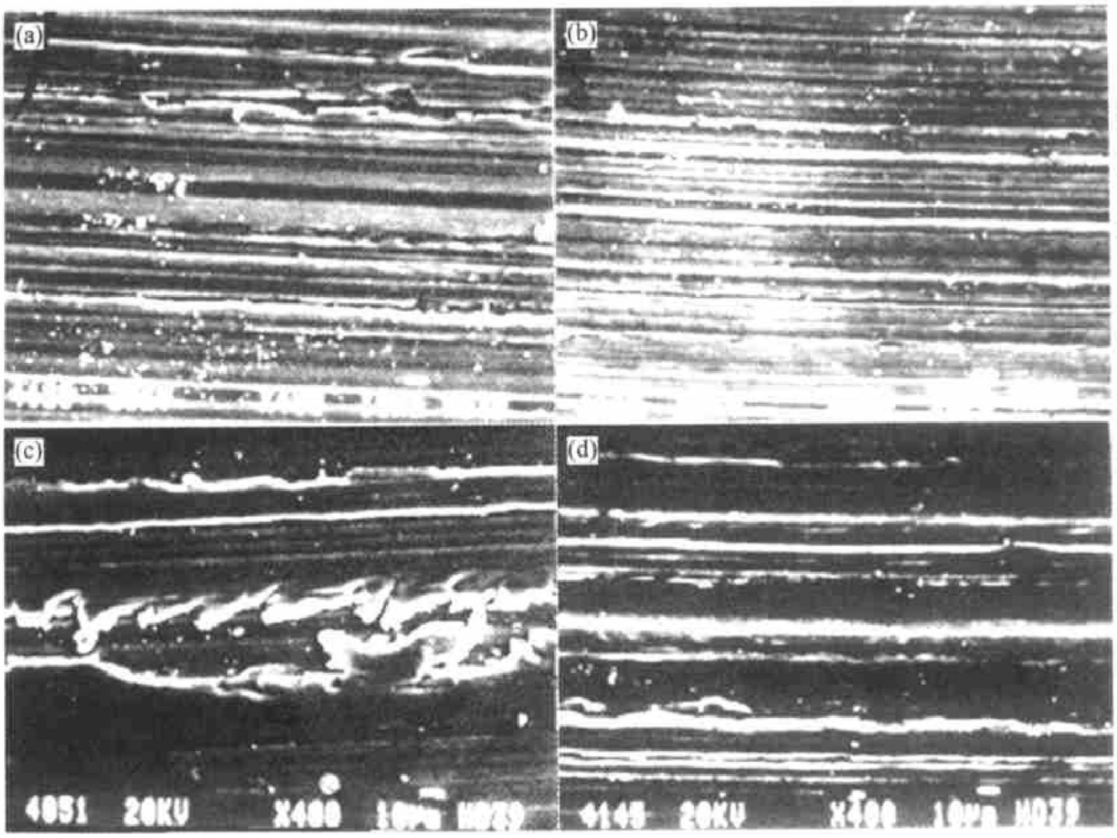

Fig. 4 Worn surface morphologies of magnesium alloy with or without RE
(a) —AZ91D(20 N); (b) —AZ91D+ 0.6% RE(30 N); (c) —AZ91D(90 N); (d) —AZ91D+ 0.6% RE(90 N)

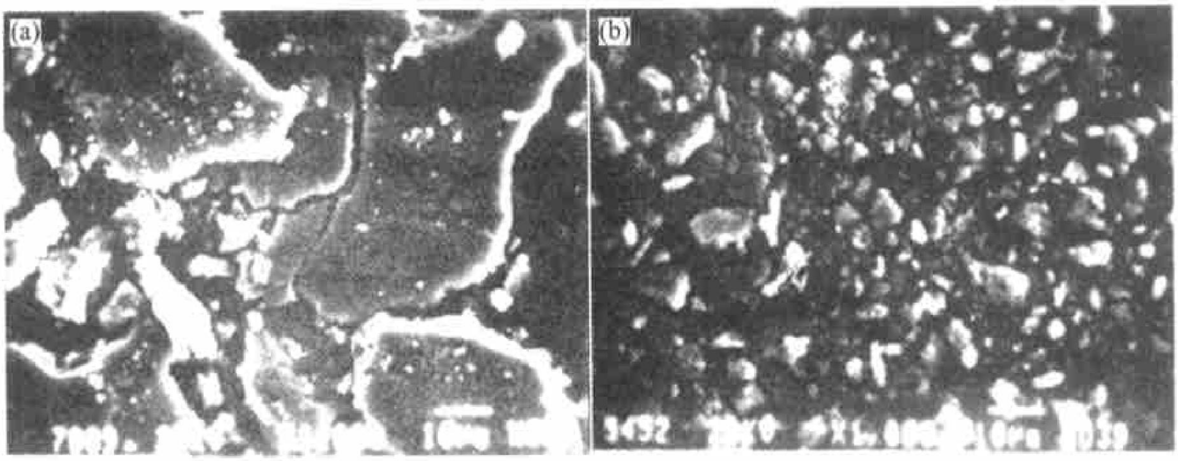

Fig. 5 Debris morphologies of magnesium alloys with or without RE(L= 50 N, t= 10 min)
(a) —AZ91D; (b) —AZ91D+ 0.6% RE

mass loss consequently increases rapidly with the increase in the applied loads.

4 CONCLUSIONS

1) The presence of RE improves the friction and wear behavior of AZ91D alloy. Under the testing conditions, the friction coefficients of the alloys with RE additions are lower than those of the base alloy. The wear resistance increases with the increase of RE content.

2) In the dry sliding process, magnesium alloys undergo transition from mild wear (oxidational wear) to severe wear (delamination wear) with the increase in applied load.

3) The addition of rare earths improves the comprehensive behaviors of the magnesium alloys, increases the stability of the oxidation layer on the worn surfaces, enhances the load-bearing capacity, and delays the transition from mild wear to severe wear effectively.

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