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Microstructures and wear properties of graphite and Al_2O_3 reinforced AZ91D-Ce_x composites

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Abstract: The magnesium matrix composites reinforced by graphite particles and Al_2O_3 short fibers were fabricated by squeeze-infiltration technique. The additions dispersed uniformly and no agglomeration and casting defect were observed. The microstructures and wear properties of the composites with different Ce contents of 0, 0.4%, 0.8% and 1.0%, respectively, were investigated. Especially, the effect of Ce on the properties was discussed. The results reveal that Ce enriches around the boundaries of graphite particles and forms Al_3Ce phase with Al. The addition of Ce refines the microstructures of the composites. With the increase of Ce content, the grain size becomes smaller and the wear resistance of the composite is improved. At low load, the composites have similar worn surface. At high load, the composite with 1.0% Ce has the best wear resistance due to the existence of Al_3Ce phase. The Al_3Ce phase improves the thermal stability of the matrix so the graphite particles can keep intact, which can still work as lubricant. At low load, the wear mechanism is abrasive wear and oxidation wear. At high load, the wear mechanism changes to delamination wear for all the composites.

Key words: magnesium matrix composite; graphite; Ce; wear property

1 Introduction

The density of magnesium is approximately two-thirds of that of aluminum and one-fifth of that of steel, which makes it attractive for applications where the mass reduction is critical[1]. However, Mg and its alloys were not used for high performance applications due to their low mechanical properties at room and elevated temperatures. The poor resistance to wear and corrosion is a serious impediment, preventing Mg alloys from being used as widely as Al alloys[2]. In the last two decades, many studies were done around Mg based metal matrix composites (MMCs). Particles, fibers or rare earth elements were used as additions to improve the wear properties of Mg alloys[3−5]. Most of the studies focus on SiC and TiC particles reinforced Mg MMCs, however, the investigation on self lubricating composite that uses graphite as addition is rather limited[6−12]. Recently, YANG et al[13] studied the graphite reinforced Mg MMCs and discussed the influence of different graphite content on mechanical properties. QI et al[14] investigated the formation of graphite film during the sliding process of Mg MMCs.

The purpose of this study is to investigate the feasibility of the fabrication of Mg MMCs reinforced by graphite and Ce using the squeeze-infiltration technique. The microstructure and wear resistance of the composite are discussed, especially the effect of the additions on the dry sliding wear behavior along with the changes of wear mechanism under different conditions.

2 Experimental

Mg-9Al-1Zn alloy (AZ91D) was chosen as matrix alloy. The addition of Ce was made in the form of cerium rich magnesium alloy. The mass fractions of Ce were 0.4%, 0.8% and 1.0%, respectively. The composite without Ce was made as compared material. The short fibers with a diameter of 8−12 μm and a length of 300−

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700 μm contained 98.9% Al_2O_3. The size of graphite particles was 100−150 μm. The contents of Al_2O_3 short fiber and graphite were kept constant with the volume fractions of 8% and 15%, respectively.

The process of fabricating the composites was composed of two steps. First, the graphite and Al_2O_3 short fibers were prepared into a preform. Second, the squeeze-infiltration technique was used to add molten AZ91D-Ce_x alloy into the preform. The pouring temperature was 680 ℃, the applied pressure was 55 MPa and was maintained for 60 s. The dimension of the composite was 105 mm in diameter and 20 mm in height. The microstructure was analyzed by Olympus PMG3 optical microscope (OM). The worn surface was analyzed by JSM-6700F scanning electron microscope (SEM) with an energy-dispersive X-ray spectrometer (EDS). Dry sliding wear tests were performed using a pin-on-disc type wear apparatus MM2000. In this system, the test specimen was *d*6 mm×12 mm, and the disc (*d*70 mm) was made of GCr15 steel with the hardness of HRC 55. The disc was kept rotating at a constant speed of 0.785 m/s, and slid a distance of 376.8 m. All the experiments were carried out at 25 ℃. The density of the sample was measured using the standard Archimedes method with distilled water. The mass changes before and after wear test were used to calculate the volume loss.

3 Results and discussion

3.1 Influence of Ce on microstructures of composites

The microstructures of the composites with different Ce contents are shown in Fig.1. It reveals that the added graphite particles and Al_2O_3 short fibers disperse uniformly in the composites and no agglomeration and casting defect are observed evidently. The graphite takes the form of block and the Al_2O_3 short fibers appear in round and needle shape. Compared with the composite without Ce, the grain size of the composite with Ce becomes smaller. It is because that in solidification, Ce is likely assembling along the grain boundaries and restrains grains from growing up. Fig.1(c) shows the backscattering SEM image of the composite, and some white phases that have needle shape are found around the boundaries of graphite. It is Al_3Ce phase confirmed by XRD analysis. The electronegativity of Ce makes Ce form Al_3Ce phase with Al in preference.

3.2 Influence of Ce on wear resistance of composites

The variations in wear loss with load of the composites with various Ce contents are shown in Fig.2. It reveals that the wear loss increases with increasing the test load for all composites. Under the given condition, the composite containing Ce shows better wear resistance

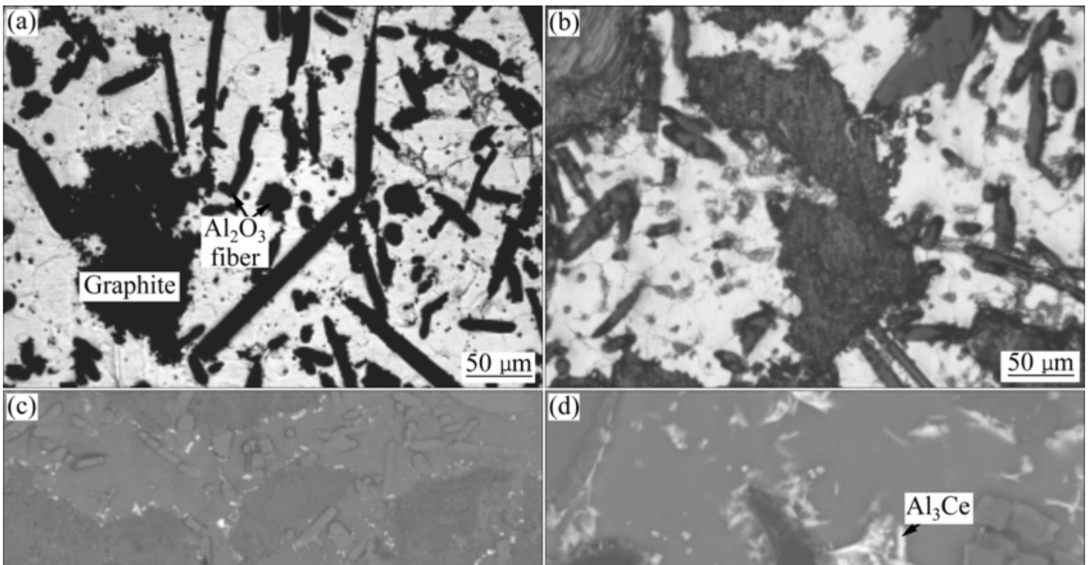

Fig.1 OM photos and backscattering SEM images of composites: (a) *w*(Ce)=0, OM; (b) *w*(Ce)=1.0%, OM; (c) *w*(Ce)=1.0%, SEM; (d) *w*(Ce)=1.0%, SEM

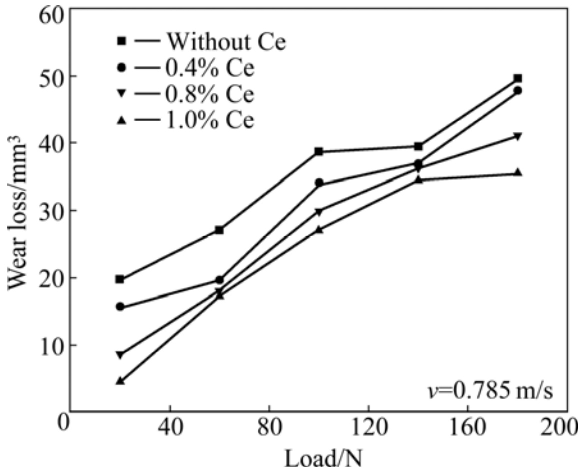

Fig.2 Variations of wear loss of composites with different loads

than the composite without Ce, and the composite with 1.0% Ce has the lowest wear loss. At load of 20 N, all the composites show low wear loss due to the presence of Al_2O_3 short fibers, which can keep intact and efficiently bear load. At load of 180 N, the wear loss of the composites without Ce and with 0.4% Ce increases sharply, but the composite with 1.0% Ce keeps the similar wear loss as that at load of 140 N. Compared with the composite without Ce, the composite with 1.0% Ce decreases by 76% and 29% in the wear loss at loads of 20 and 180 N, respectively. It implies that adding Ce delays the changes from mild wear to severe wear and still works effectively at high load.

3.3 Wear mechanism of composites

Fig.3 shows SEM images of worn surfaces of the composites at loads of 20 and 180 N. At load of 20 N, the worn surface of the composite without Ce has many parallel grooves, indicating that the wear mode is abrasive wear[15]. Around the parallel grooves, there are obvious oxidative area and powder debris, which implies the wear mechanism of oxidation wear. Although the composite with 1.0% Ce has similar worn surface with the composite without Ce at load of 20 N, the distance between grooves is narrower and the oxidative area is larger. This phenomenon indicates that the abrasive wear affects the composite with 1.0% Ce. The larger oxidative areas covering on the grooves can work as lubricant and makes the worn surface smooth. This worn surface corresponds to low wear loss of composite with 1.0% Ce at load of 20 N (Fig.2).

As increasing the test load, the worn surface deteriorates. At load of 180 N, the worn surface of the composite without Ce has metallic chips broken off and some cracks appear on the worn surface (Fig.3(c)). But the worn surface of the composite with 1.0% Ce is nearly intact and without obvious cracks. It is known that

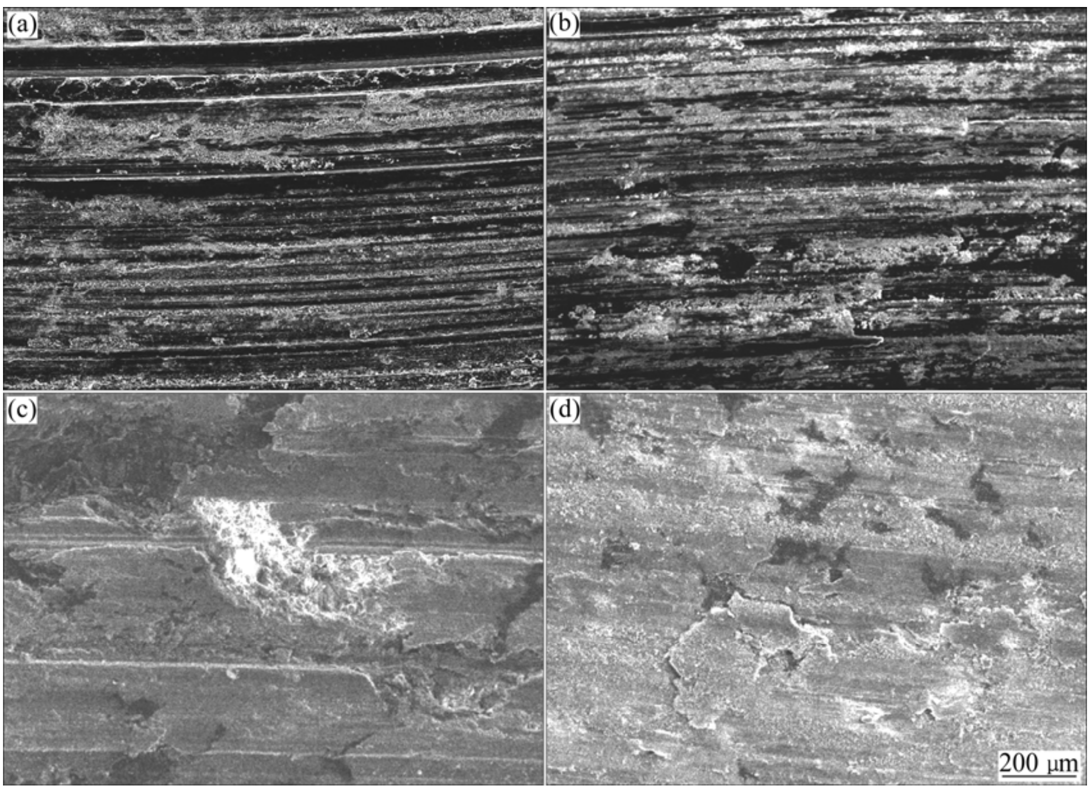

Fig.3 SEM images of worn surface of composites at different loads: (a) w(Ce)=0, 20 N; (b) w(Ce)=1.0%, 20 N; (c) w(Ce)=0%, 180 N; (d) w(Ce)=1.0%, 180 N

β-$Mg_{17}Al_{12}$ is the main strengthening phase in AZ91D alloy, which has a low melting point of approximately 462 ℃ and poor thermal stability[16]. After adding Ce to the matrix, Ce is in preference to form Al_3Ce with Al. Al_3Ce has high melting point and chemistry stabilization, along with low diffusion rate of Ce element in magnesium. So Al_3Ce exhibits high thermal stability. When the test load increases, the temperature between the friction pair increases rapidly. Al_3Ce phase as a part of the strengthening phase in AZ91D alloy gives high thermal stability to the matrix. At the same time, Al_3Ce can prevent the slide of grain boundaries and propagation of cracks effectively, improving the strength of the composite. So the graphite particles that act as lubricant in the matrix can keep intact, which decreases the effect of abrasive wear. Therefore, the composite with 1.0% Ce has better wear resistance at high load.

The optical photograph of lengthways profile of the composite (Fig.4(a)) shows that the plastic deformation occurs on the contact surface, and the grains next to the surface are elongated along the sliding direction. Some Al_2O_3 short fibers cannot bear the test load and break up, resulting in a decrease in the strength and consequently affecting the wear resistance of the composites. The plastic deformation and cracks make the worn surface easily peeled off as sliding continues, increasing the debris in flakes. However, after adding Ce into the composites, the plastic deformation becomes slight and the strength of the matrix is enhanced. So the wear loss of the composite with 1.0% Ce at load of 180 N is similar as that at load of 140 N.

When the test load increases, the surface temperature increases quickly along with softening phenomenon, the debris on the worn surface is easily pushed and extruded outside, and finally it accumulates at the edge of worn surface and has layers appearance. Because the small debris has less influence on wear process, the large debris deteriorates contact surface [17−18]. The composite without Ce has larger strip debris compared with the composite with 1.0% Ce (Fig.4(d)). The debris speeds up the changes from mild wear to severe wear[19]. Therefore, at low load the wear mechanism of the composites is abrasive wear and oxidation wear, at high load the wear mechanism changes to delamination wear for all the composites.

4 Conclusions

1) The graphite particles and Al_2O_3 short fibers reinforced AZ91D-Cex composites can be fabricated successfully by squeeze-infiltration technique. As increasing the Ce content, the size of grains becomes smaller. Rare earth phase that grows around the boundaries of graphite particles is proved to be Al_3Ce phase.

2) The wear resistance of the composites increases

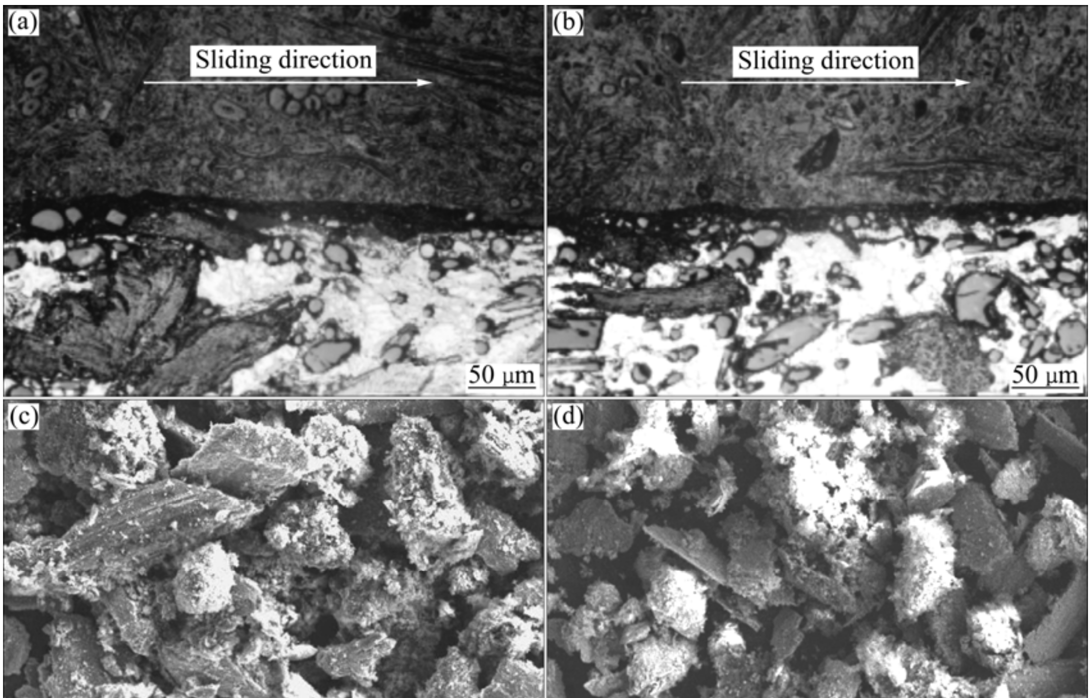

Fig.4 OM photographs of lengthways profile of composites at load of 180 N and SEM images of debris: (a) OM, w(Ce)=0; (b) OM, w(Ce)=1.0%; (c) SEM, w(Ce)=0; (d) SEM, w(Ce)=1.0%

with the Ce content increasing.

3) At low load, the wear mechanism is abrasive wear and oxidation wear; at high load, the wear mechanism changes to delamination wear for all the composites.

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