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Effect of particulate reinforcement on wear behavior of magnesium matrix composites

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Abstract: The friction and wear behavior of magnesium matrix composites reinforced with particulate Mg_2Si was characterized. The influence of Si, applied load and sliding rate on the wear behavior of Mg_2Si/AM60 magnesium matrix composites was studied. The results indicate that the particulate Mg_2Si can be synthesized by adding Si into magnesium alloy. The wear properties of AM60 magnesium alloy are significantly improved with Mg_2Si particles. The wear mass losses of AM60 magnesium alloy and Mg_2Si/AM60 magnesium matrix composites decrease with increase in applied load and sliding rate. The wear feature of the AM60 magnesium alloy is adhesion wear. The wear mechanism of Mg_2Si/AM60 magnesium matrix composites transforms from abrasive wear to adhesion wear with the increase of load.

Key words: magnesium alloy; Mg_2Si/AM60 composite; friction; wear; wear mechanism; abrasive wear; adhesion wear

1 Introduction

Among the light metals, Mg and its alloys have high potentials in automotive and aerospace industries due to their low densities and high specific strength [1,2]. However, its poor resistance to wear and corrosion is a serious impediment preventing them from being used as widely as Al alloys [3−6]. Recently, some researches have been done on magnesium matrix composites, which exhibit higher properties than single alloy [7−9].

The fabrication of magnesium matrix composites includes ex-situ method [8] and in-situ method [10−12]. Compared with the composites fabricated by ex-situ method, the in-situ synthesized composites exhibit some advantages, such as finer grains, clean interface and no contamination, good thermal stability and good compatibility with the matrix, which make it become an important development direction of fabrication magnesium matrix composites [10−12]. Mg_2Si was characterized by low density, high melting point, high hardness and strength and high elastic modulus, which becomes an ideal reinforcement particle of magnesium matrix composites. Recently, the investigation of magnesium matrix composites reinforced by Mg_2Si particles is more and more [13−15]. However, up to now, the study of wear characteristics on Mg_2Si/AM60 magnesium matrix composites is rarely reported. By means of in-situ synthesis, Mg_2Si/AM60 magnesium matrix composites are successfully fabricated and the friction wear properties are studied.

The main objectives of the present work are to study the microstructures of Mg_2Si/ AM60 magnesium matrix composites and to characterize the wear behavior of magnesium matrix composites reinforced Mg_2Si using apparatus M2000.

2 Experimental

The AM60 magnesium alloy used for this experiment was prepared. Melting was carried out in a steel crucible in the resistance furnace under flux cover. The crystallizing Si powder packed in aluminum foil was added into the molten with the bell-jar at 800 °C for 15 min. The molten was stirred for 5−10 min in order to make an ample dissolution and homogeneous diffusion of Si. The melt at 700 °C was poured into a permanent steel mold which was preheated to 200 °C to form ingot with 25 mm in diameter.

The wear tests were carried out using M−2000

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machine. The wear test specimens were cut from the middle of the ingot and the dimensions were 30 mm × 7 mm × 7 mm. The counter material used was 20Cr (HRC53). The tests were carried out at different loads (20, 30, 60 and 80 N). The sliding rates were 0.5 and 1.0 m/s. The tests were carried out at ambient temperature without any lubrication. The mass losses during the wear tests were calculated according to the differences in mass of the specimens measured before and after the tests using an electronic balance with sensitivity of 0.1 mg.

Metallographic specimens cut at the position that was 10 mm from the bottom of the ingot were polished through standard procedure and the microstructures of the composites were examined by OM and the worn surfaces of the composites were studied by FEI Quanta 200 scanning electron microscope (SEM). A 4% HNO_3-alcohol solution was used as the etchant of polishing samples. The phases in the composites were analyzed by X-ray diffraction (XRD) operated at 40 kV and 40 mA using Cu K_α radiation.

3 Results and discussion

3.1 Microstructures

The XRD analysis preformed on the AM60 magnesium alloy shown in Fig. 1(a) indicates that AM60 magnesium alloy consists of two phases, i.e., α-Mg matrix and β-$Mg_{17}Al_{12}$ phase. The XRD analysis preformed on the Mg_2Si/AM60 magnesium matrix composite shown in Fig. 1(b) confirms that the alloy consists of three phases, i.e., α-Mg matrix, β-$Mg_{17}Al_{12}$ phase and Mg_2Si phase.

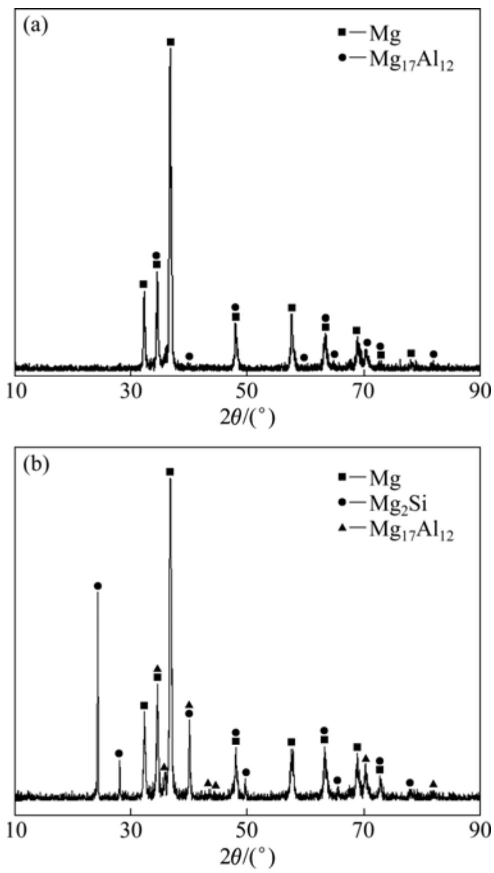

Fig. 1 XRD patterns for AM60 magnesium (a) and Mg_2Si/AM60 magnesium matrix composite (b)

The effects of Si on the microstructures of Mg_2Si/AM60 magnesium matrix composites are shown in Fig. 2. α-Mg and β-$Mg_{17}Al_{12}$ phases present in the AM60 magnesium alloy and the morphology is dendritic (Fig. 2(a)). Figures 2(b)−(d) show the microstructures of Mg_2Si/AM60 magnesium matrix composites. It is evident from Figs. 2(b)−(d) that the addition of Si has a remarkable effect on the microstructures. When 1.0% Si is added into AM60 magnesium alloy, a new Chinese script type Mg_2Si phase whose size is about 80 μm appears at the grain boundary. With the increase of Si addition, the Chinese script type Mg_2Si phase changes to block and the average size is 20 μm (Fig. 2(c)). When 5.0% Si is added into AM60 magnesium alloy, the Mg_2Si phase becomes coarse dendritic and its size is about 100 μm (Fig. 2(d)).

It can be seen from Fig. 2 that the Mg_2Si phase becomes coarse when the Si content is high. According to the theory of diffusion and phase transition, the coarsening rate of particles precipitated has related to the concentration of solute atoms. The higher the concentration of solutes atoms, the higher the coarsening rate of particles. Therefore, Mg_2Si phase could aggregate and grow with the increase of Si.

3.2 Wear property

The effects of loads on the wear mass losses of AM60 magnesium and Mg_2Si/AM60 magnesium matrix composites are presented in Fig. 3. It is clear from Fig. 3 that the wear mass losses of AM60 magnesium alloy and Mg_2Si/AM60 magnesium matrix composites increase with the increase of load. Figure 3 reveals that the wear mass loss of AM60 magnesium alloy is higher than that of Mg_2Si/AM60 magnesium matrix composites. And the wear mass loss decreases gradually with the increase of Si. The main strengthening phase of AM60 magnesium alloy is $Mg_{17}Al_{12}$ whose melting point is low (462 °C) and thermal stability is bad. $Mg_{17}Al_{12}$ will become soft at a high temperature caused by friction. Therefore, the wear property of AM60 magnesium alloy is low. However, the high thermal stability and high hardness particles Mg_2Si formed in AM60 magnesium alloy with addition Si, which can improve the wear property.

It also can be seen from Fig. 3 that the wear mass loss of AM60 magnesium alloy is similar to Mg_2Si/AM60 magnesium matrix composites at light loads (20 N and 30 N). However, the wear mass losses of AM60 magnesium alloy and Mg_2Si/AM60 magnesium

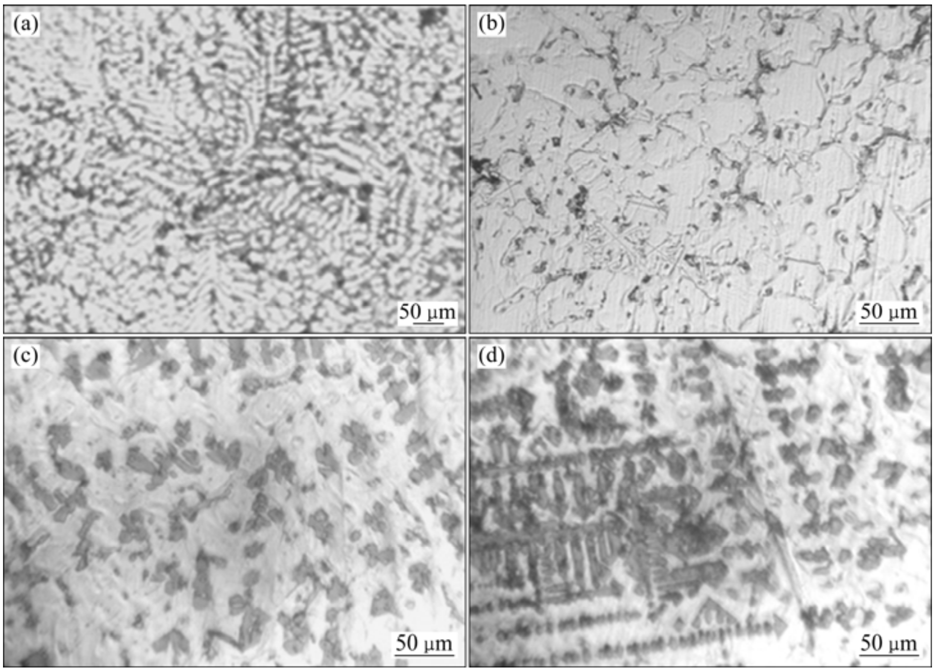

Fig. 2 Microstructures of Mg_2Si/AM60 magnesium matrix composites with different additions of Si: (a) 0; (b) 1.0%; (c) 3.0%; (d) 5.0%

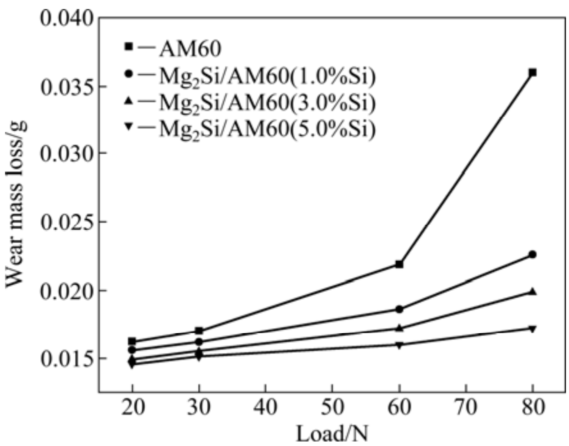

Fig. 3 Effects of load on wear mass loss

matrix composites are larger and larger at high loads (60 N and 80 N). The transformation from micro wear to dramatic wear appears when the load is 60 N for AM60 magnesium alloy. And the wear mass loss of AM60 magnesium alloy at 80 N is 2.25 times higher that at 20 N. This indicates that it is in the stage of drastic wear. However, the wear curve of Mg_2Si/AM60 magnesium matrix composites is flat when the load is smaller than 60 N and the wear mass loss of Mg_2Si/AM60 magnesium matrix composites is lower than that of AM60 magnesium alloy. The wear mass loss of Mg_2Si/AM60 magnesium matrix composites increases a little even though the load is 80 N, which illustrates that it still is in the stage of micro wear. It can be seen from Fig. 3 that the wear property of AM60 magnesium alloy improves with addition Si. The major reason is that the reinforced Mg_2Si particles whose hardness is much higher than that of the matrix magnesium alloy present in the alloy with addition of Si. The Mg_2Si phases can protect the soft matrix alloy and then induce the improvement of the wear property.

The effects of sliding rates on the wear mass losses of AM60 magnesium and Mg_2Si/AM60 magnesium matrix composites are shown in Fig. 4. Figure 4 shows that the wear mass loss of AM60 magnesium decreases with the increase of sliding rare. The phenomenon is caused by self-lubricating of AM60 magnesium under high temperatures. It can be seen from Fig. 4 that the wear mass loss of Mg_2Si/AM60 magnesium matrix composites (1.0%Si) at 1.0 m/s is lower than that at 0.5 m/s if the load is lower than 30 N. The major reason is that the friction temperature will increase at a high sliding rare when the load is low and then the oxide film which can restrict wear will be formed on the worn surface. Meanwhile, the reinforced particles Mg_2Si, which cannot be scaled off under the lower load, can undertake the major load. So the wear mass loss is low. In contrast, when the load is 60 N, the wear mass loss of Mg_2Si/AM60 magnesium matrix composites (1.0%Si) at 1.0 m/s is higher than that at 0.5 m/s. This is because that the friction temperature is very high at a high load and a high sliding rate and then the matrix alloy will become soft, which will induce the reinforced particles Mg_2Si to scale off easily and then cut the wear surface and form the long and deep ploughing on the worn surface.

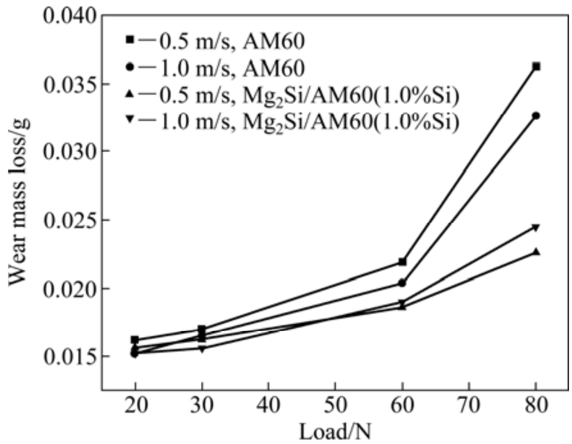

Fig. 4 Effects of sliding rate on wear mass loss

3.3 Worn surface morphology

Figure 5 illustrates the effects of loads on the worn surface morphology of AM60 magnesium alloy. It can be seen from Fig.5 that the worn surface is smooth and there is wear scar which is parallel to sliding direction. The wear scar forms obvious ploughing. The wear mass loss increases with the increase of load and the ploughing becomes wide and deep and there is metal peeling off. The results indicate that there is a deformation on the worn surface under the condition of pressure and friction heat because of the low hardness of AM60 magnesium alloy. Then the contact-points will be formed on the worn surface and become larger gradually, which will induce the spalling of matrix alloy. The observation of wear surface by SEM shows that the wear feature of the AM60 magnesium alloy is adhesion wear.

Figure 6 presents the effects of loads on the worn surface morphology of Mg_2Si/AM60 magnesium matrix composites with 1.0%Si. It can be seen from Fig. 6 that the worn surface is rougher and rougher with the increase of loads. The worn surface consists of discontinuous and narrow ploughing and there is a little wear debris on the worn surface when the load is 30 N (Fig. 6(a)). There is more obvious ploughing on the worn surface when the load is 60 N (Fig. 6(b)). However, the worn surface

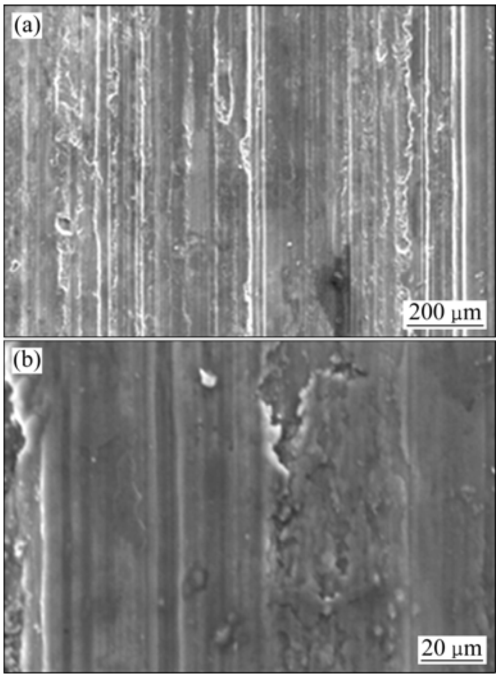

Fig. 5 Worn surface morphologies of AM60 magnesium alloy at different loads: (a) 60 N; (b) 80 N

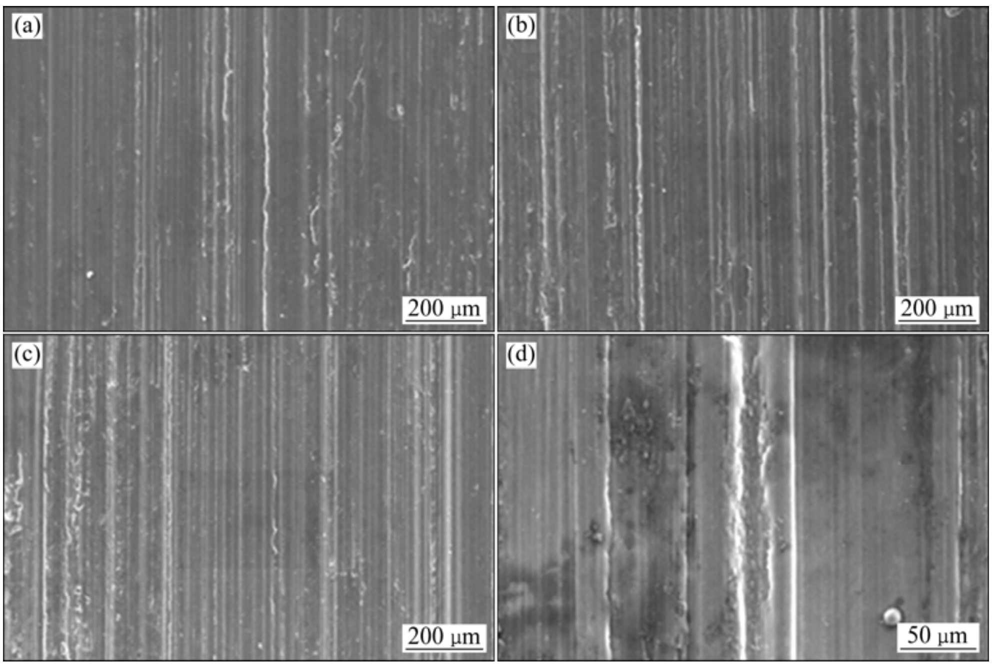

Fig. 6 Worn surface morphologies of Mg_2Si/AM60 magnesium matrix composites with 1.0%Si at different loads: (a) 30 N; (b) 60 N; (c,d) 80 N

morphology of Mg_2Si/AM60 magnesium matrix composites (Fig. 6(b)) is smoother than that of AM60 magnesium alloy (Fig. 5(a)). The reason is that the hard Mg_2Si phase of Mg_2Si/AM60 magnesium matrix composites can reduce the contact between magnesium alloy and 20Cr refined disc during wear process, which induces the reduction of the contact-point on the magnesium alloy matrix. Therefore, the worn surface of Mg_2Si/AM60 magnesium matrix composites is better and the wear mechanism of Mg_2Si/AM60 magnesium matrix composites is abrasive wear. When the load is 80 N, there is a lot of parallel, continuous and deep ploughing on the worn surface (Figs. 6(c) and (d)). Figure 6 indicates that the wear mass loss of Mg_2Si/AM60 magnesium matrix composites increases with the increase of load. The reinforced Mg_2Si particles cannot be scaled off and can restrict plough during wear when the load is low. However, the reinforced Mg_2Si particles will be scaled off from magnesium alloy matrix and cut wear surface when the load is high. So there is lots of ploughing on the worn surface. Therefore, the wear mechanism of Mg_2Si/AM60 magnesium matrix composites transforms from abrasive wear to adhesion wear with the increase of load.

Figure 7 shows the effects of Si content on the worn surface morphology of Mg_2Si/AM60 magnesium matrix composites. It is evident that the worn surface morphology consists of deep ploughing with 1.0%Si and there is some wear debris on the worn surface (Fig. 7(a)). With the increase of Si, the depth of the ploughing on the worn surface becomes shallower. There is a little ploughing on the worn surface when Si addition is 3.0% (Fig. 7(b)). The worn surface is smooth and the ploughing cannot be seen when Si content is 5.0% (Fig. 7(c)). The wear process is characterized by shallow delamination. The microstructures of Mg_2Si/AM60 magnesium matrix composites indicate that the reinforced Mg_2Si particles are more and more with the increase of Si content (Fig. 2). The previous researches [13−15] showed that the more the reinforced Mg_2Si particles are, the higher the hardness is. And the high hardness of Mg_2Si/AM60 magnesium matrix composites induces the improvement of the wear property. Meanwhile, the existence of Mg_2Si particles will reduce the friction interface and restrict the scaling of oxide layers. The reinforced Mg_2Si particle content is low and the morphology is fine Chinese script type if the Si content is low, and the hardness of the material is low, which cannot hider wear effectively. The reinforced Mg_2Si particle content is high and the morphology becomes block type and coarse dendritic with the increase of Si content, and the hardness of the material is high, which can restrict the wear effectively. Therefore, the wear properties of Mg_2Si/AM60 magnesium matrix composites increase with the increase of Si addition.

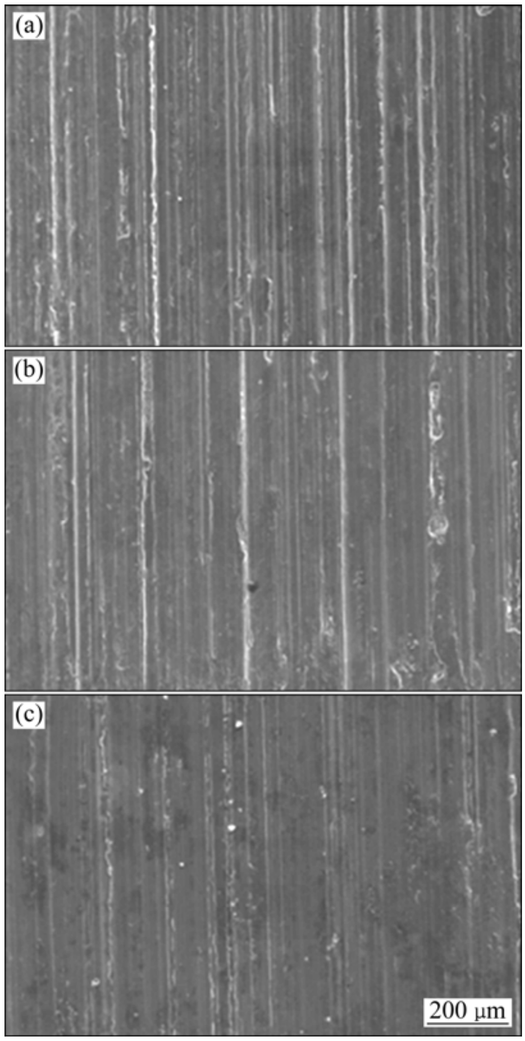

Fig. 7 Worn surface morphologies of Mg_2Si/AM60 magnesium matrix composites with different additions of Si: (a) 1.0%; (b) 3.0%; (c) 5.0%

4 Conclusions

1) The morphology of Mg_2Si particles is Chinese script type when 1.0%Si is added to AM60 magnesium alloy and the morphology of Mg_2Si particles becomes coarse dendritic when 5.0% Si is added to AM60 magnesium alloy.

2) The wear properties of Mg_2Si/AM60 magnesium matrix composites increase with the increase in Si content and decrease with the increase in applied load and sliding rate.

3) The wear mechanism of Mg_2Si/AM60 magnesium matrix composites transforms from abrasive wear to adhesion wear with the increase of load.

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增强颗粒对镁基复合材料磨损性能的影响

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摘 要：研究增强颗粒 Mg_2Si 对镁基复合材料摩擦磨损性能的影响，讨论 Si 加入量、载荷和滑动速度对 Mg_2Si/AM60 镁基复合材料磨损性能的影响。结果表明，向镁合金中加入合金元素 Si，可原位生成增强颗粒 Mg_2Si，增强颗粒 Mg_2Si 可明显提高 AM60 镁合金的磨损性能。随着载荷和滑动速度的增加，AM60 镁合金和 Mg_2Si/AM60 镁基复合材料的磨损量都增大。AM60 镁合金的磨损机制为粘着磨损。随着载荷的增大，Mg_2Si/AM60 镁基复合材料的磨损由磨粒磨损向粘着磨损转变。

关键词：镁合金；Mg_2Si/AM60 复合材料；摩擦；磨损；磨损机制；磨粒磨损；粘着磨损

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