Effects of silicon on mechanical properties of AM60 magnesium alloy

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Abstract: Silicon was added to improve the tensile, wear and creep behaviors of AM60 magnesium alloy in this study. The investigation has been undertaken by means of universal testing machine, HBE-3000A Brinell hardness tester, M-2000 friction-wear machine, DMA-Q800 creep machine, optical microscopy (OM) and scanning electron microscopy (SEM). The results indicate that the Chinese script type Mg_2Si particles are formed by adding Si into the AM60 magnesium alloy. The ultimate tensile strength and hardness of the AM60 magnesium alloy increases with the Si addition, and the ultimate tensile strength and hardness of the AM60+1.0wt.%Si alloy are increased by 12% and 19.8%, respectively in comparison with that of the AM60 magnesium alloy. The wear property and the high temperature creep property of the AM60 magnesium alloy are also improved with Si addition. The wear mechanisms of the AM60 and AM60+1.0wt.%Si alloys are adhesive wear and abrasion wear, respectively. While, the elongation of the AM60 magnesium alloy decreases with the addition of Si. The optimum Si addition content is 1.0wt.%.

Key words: magnesium alloy; tensile; wear; creep property
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In recent years, there has been an increasing growth of light-weight structural materials in the engineering applications where weight reduction is critical to improving performance. Magnesium and its alloys, owing to their attractive physical properties, are potential candidates for light-weight structural materials. However, Mg alloys are limited in high performance applications, such as in the aircraft and automotive industries due to their low mechanical properties.

Studies indicated that the addition of alloy elements to magnesium alloy could substantially improve the strength of the alloy [1-6]. The Si addition to magnesium alloy can increase the fluidity of the molten metal. The Mg_2Si formed by the addition of Si exhibits high melting temperature (1,087 ℃), low density (1,990 kg·m^{-3}), high elastic modulus (120 GPa) and low thermal expansion coefficient (7.5×10^{-6} k^{-1}) [5-6]. The main objectives of the present study are to study the effect of Si addition on mechanical properties of the AM60 magnesium alloy, and to characterize the tensile, sliding wear, and creep behaviors of the AM60 and AM60+$x$wt.%Si magnesium alloys (where x is the optimum Si addition content).

1 Experimental procedure

The commercial grade of AM60 magnesium alloy was used for

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this experiment. The alloy was melted in a steel crucible in a resistance furnace under flux cover. The crystallized Si powder was added into the melt with a bell-jar at 800 ℃ and the melt was held for 15 min. The amount of the crystallized Si powder addition was 0.5wt.%, 1.0wt.% and 1.5wt.%, respectively. Then the melt was stirred for 5 to10 min in order to make a sufficient dissolution and homogeneous diffusion of Si. The melt was poured at 700 ℃ into a permanent steel mold which was preheated to 200 ℃, to obtain ingot of 25 mm in diameter. The same condition was applied to make the specimen of the AM60 magnesium alloy without Si addition.

Metallographic specimens were cut at the position 10 mm from the bottom of the ingot and then mechanically ground, polished and etched with HNO_3-alcohol solution. Optical microscopy (OM) and scanning electron microscopy (SEM) were employed to analyze the microstructures. The tensile tests were carried out using a universal testing machine. Tensile test bars with the gauge dimension shown in Fig.1 were machined from the ingot. The Brinell hardness was measured using the HBE-3000A tester on hardness test specimens which were also cut at the position 10 mm from the bottom of the ingot. The wear tests were carried out using M-2000 machine. The wear test specimens were cut from the middle of the ingot and their dimension was 30 mm × 7 mm × 7 mm. The creep properties
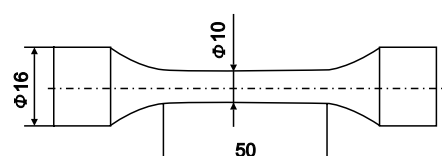

Fig. 1: Specimen for tensile test

were tested with the DMA-Q800 machine. The creep test specimens were also cut from the middle of the ingot and the dimension was 60 mm × 9 mm × 1 mm.

2 Results and discussion

2.1 Microstructures

Figure 2 shows the microstructures of the AM60 magnesium alloy with different Si additions. The as-cast AM60

magnesium alloy (without addition of Si) consists of primary α-Mg phase, eutectic magnesium phase and β-$Mg_{17}Al_{12}$ phase, as shown in (Fig. 2a), the morphology of the α-Mg phase is dendritic. A new Chinese script type Mg_2Si phase appears at the grain boundary with addition of 0.5wt.% Si (Fig. 2b). The amount of the Chinese script type Mg_2Si phase increases with increasing Si content, and the Mg_2Si phase becomes dendritic and massive with 1.5wt.% Si addition (Fig. 2d). It is obvious that the morphology of the primary α-Mg changes from dendritic into equiaxed with Si addition.
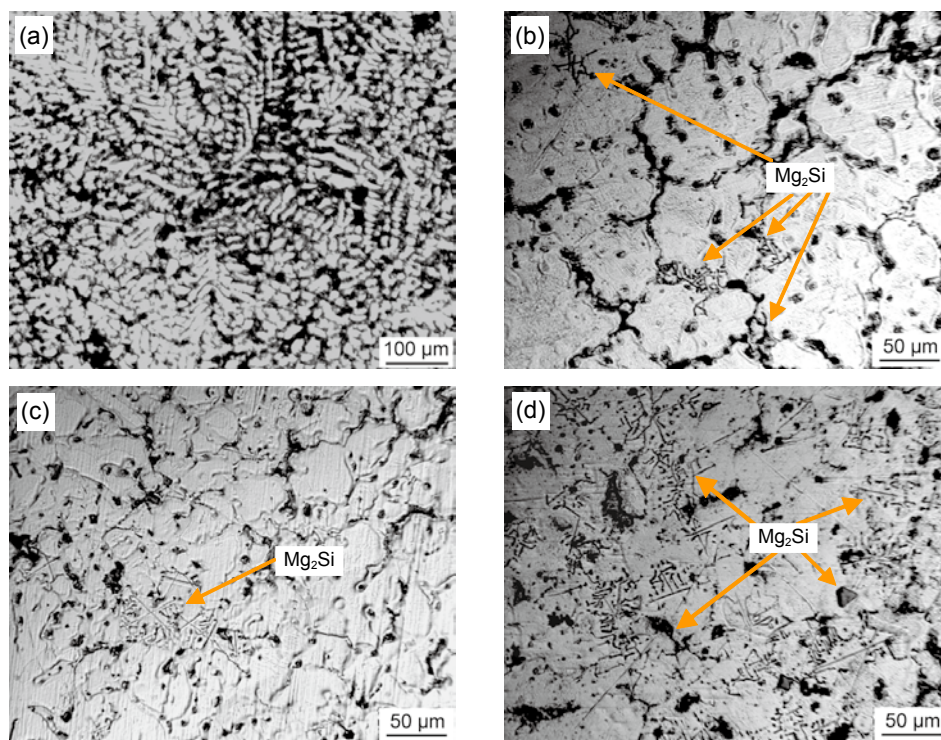

Fig.2: Microstructures of AM60 (a), AM60+0.5wt.%Si (b), AM60+1.0wt.%Si (c), AM60+1.5wt.%Si (d)

2.2 Tensile test results

Table 1 presents the tensile properties of AM60 magnesium alloys with different Si addition. The ultimate tensile strength and hardness of the AM60 magnesium alloy increase from 176.2 MPa and 45.9 HB to 197.5 MPa and 55.0 HB when Si addition increases from 0 to 1.0wt.%, representing 12% and 29.8% improvement, respectively. However, the ultimate tensile strength of the AM60 magnesium alloy decreases with excessive Si addition. It can be seen that the elongation of AM60 magnesium alloy decreases with addition of Si, while the hardness changes a little when the Si content increases from 0.5wt.% to 1.5wt.%.

Table 1: Tensile properties of AM60 magnesium alloys with different content of Si

Alloy	Ultimate tensile strength (MPa)	Elongation (%)	HB
AM60	176.2	7.38	45.9
AM60+0.5wt.%Si	182.5	5.55	53.8
AM60+1.0wt.%Si	197.5	4.83	55.0
AM60+1.5wt.%Si	183.0	3.42	56.0

The interface between the Mg matrix and the Mg_2Si phase is unlikely to be in a coherent state since lattice constants and structure of crystals are different from each other. Therefore, the strengthening mechanism can be illustrated as follows [6]:

(1) Enhanced dislocation density. Typical difference between thermal expansion coefficients of the AM60 magnesium alloy and the reinforcing Mg_2Si phase will cause a higher dislocation density in materials. The enhanced dislocation density acts as barrier to dislocation motion resulting in an increase in strength of the AM60.

(2) Load transfer. The stress will transfer from matrix to Mg_2Si phase during tensile process because the strength of Mg_2Si phase is higher than that of Mg matrix, leading to an increase in strength.

The reason for the elongation decrease of the AM60 alloy with Si addition is that the hard Mg_2Si phase with high melting point and brittleness is formed at the grain boundaries, and with its volume increase, the brittle Mg_2Si phase, segregates at the grain boundaries to reduce plasticity of the alloy.

Figure 3 shows SEM micrographs of fracture surfaces of the AM60 and the AM60+1.0wt.%Si alloys. It can be seen from
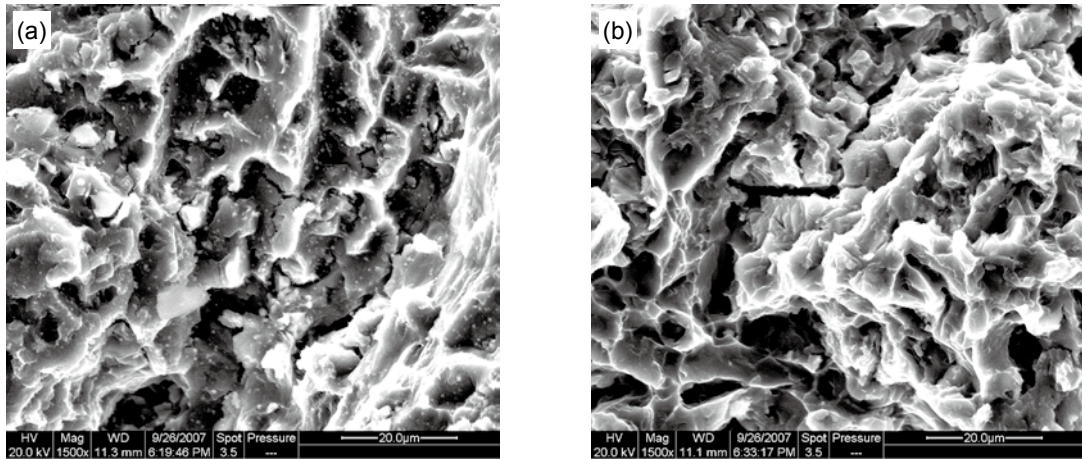
Fig. 3: SEM photos showing the fracture surfaces of AM60 (a) and AM60+1.0wt.%Si (b)

Fig. 3 that the fracture of both AM60 magnesium alloys is brittle cleavage fracture.

2.3 Wear test results

The wear test was carried out under the condition of 60 N load, wear rate of 1.0 m·s^{-1} and wear test duration of 5 min. According to the tensile test results, the optimum Si addition amount is 1.0wt.%. Therefore, the wear test and creep test were performed on the AM60 without Si and AM60+1.0wt.%Si alloys. Figure 4 presents the variation of wear weight loss as a function of the load for the AM60 and the AM60+1.0wt.%Si alloys. It is clear that the weight loss of both AM60 and AM60+1.0wt.%Si alloys increases with increasing the load. Figure 4 also reveals that the wear weight loss of the AM60 alloy is higher than that of the AM60+1.0wt.%Si alloy. The wear weight loss of the AM60 alloy and AM60+1.0wt.%Si alloy is similar at lower loading conditions (20 N and 30 N). However, the difference in weight loss between the two alloys becomes larger at higher loads (60 N and 80 N). The transformation from micro wear to dramatic wear appears when the load is 60 N for the AM60 magnesium alloy, and the wear weight loss of the AM60 magnesium alloy at 80 N load is 2.25 times higher than that at 20 N. However, as compared to the referenced AM60 magnesium alloy, the AM60+1.0wt.%Si alloy shows considerably flatter wear curve and lower weight loss especially when the load is smaller than 60 N. The wear
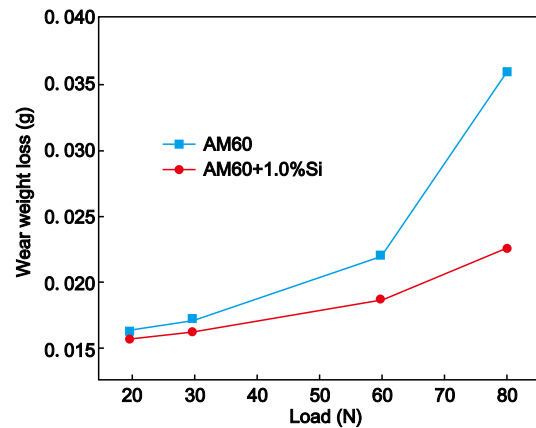

Fig. 4: Effect of load on wear weight loss

weight loss of the AM60+1.0wt.%Si alloy is still low even at the load of 80 N, which illustrates that it is still in the stage of micro wear. Figure 4 shows that the wear property of the AM60 magnesium alloy is improved with the addition of Si. The main reason is that the Chinese script type Mg$_2$Si phases with much higher hardness than that of the matrix magnesium alloy are present in the alloy from the Si addition. The Mg$_2$Si phases could protect the soft matrix alloy and then result in the improvement of wear property.

Figure 5 shows the morphologies of wear surface of the AM60 and the AM60+1.0wt.%Si alloys. The wear surface
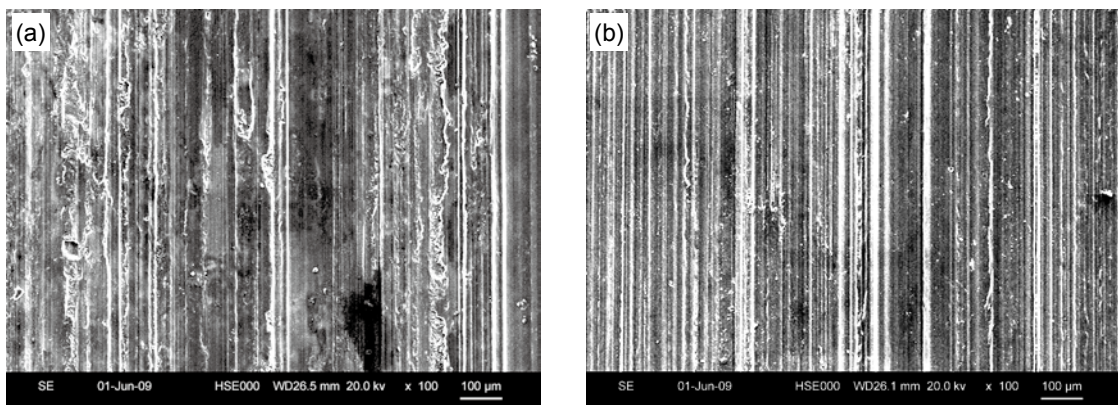

Fig. 5: Morphologies of wear surface AM60 (a) and AM60+1.0wt.%Si (b)

of the AM60 magnesium alloy is rough with unsmooth worn scar and obvious plough grooves (Fig. 5a). However, the wear surface of the AM60+1.0wt.%Si alloy is relatively smooth (Fig. 5b). The reason is that there was deformation on the wear surface under the condition of pressure and friction heat because of the lower hardness of the AM60 magnesium alloy. Then the sticky point would form on the wear surface and become larger gradually, which would induce the spalling of matrix alloy[7-8]. The observation of wear surface by SEM shows that the wear feature of the matrix AM60 alloy is adhesion wear. In contrast, the direct contact between the matrix alloy and grinding disc of the AM60+1.0wt.%Si alloy is reduced because of the presentation of hard particles Mg_2Si. The wear feature of the AM60+1.0wt.%Si alloy is abrasive wear.

2.4 Creep test results

The creep curves of the AM60 and AM60+1.0wt.%Si alloys at 250 ℃ and 40 MPa are illustrated in Fig. 6. It can be seen that both alloys have a short initial creep stage. The initial creep of the AM60 magnesium alloy is 0.84, higher than the value of 0.59 for the AM60+1.0wt.%Si alloy. The slope of creep curve decreases gradually, suggesting that creep rate decrease with time. Figure 6 indicates that the creep property of the AM60 magnesium alloy is improved with addition of Si.
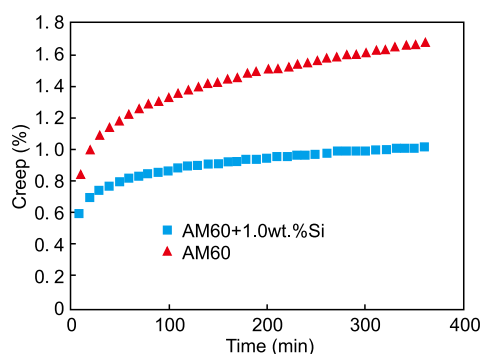

Fig. 6: Creep curve of alloys

Dislocation gliding and interface slipping are attributed to the dominant creep mechanism [9-10]. It can be seen from Fig. 6 that the creep property of the AM60+1.0wt.%Si alloy is better than that of the AM60 magnesium alloy. Mg_2Si is characterized by good thermal stability, high hardness and strength and high elastic modulus, which can hinder the interface slip and dislocation climb at high temperature by pinning the grain boundary and therefore improves the creep property of the alloy.

3 Conclusions

(1) The Chinese script type Mg_2Si phase is formed when Si is added into the AM60 magnesium alloy.

(2) The ultimate tensile strength and hardness of the AM60+$x$wt.%Si ($x = 0.5-1.5$) alloys are higher than those of the AM60 magnesium alloy. However, the elongation of the AM60 magnesium alloy without Si is higher. The optimum Si addition content is 1.0wt.%. The fracture of both AM60 magnesium alloy and AM60+1.0wt.%Si alloy is brittle fracture.

(3) The wear property of the AM60 magnesium alloy is improved with the Si addition. The wear feature of the matrix AM60 alloy is adhesion wear, while that of the AM60+1.0wt.%Si alloy is abrasive wear.

(4) The creep property of AM60 magnesium alloy at high temperature is improved with the addition of Si.

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