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Effects of Si on microstructure and mechanical properties of Mg-5Sn-2Sr alloy

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Key words: Magnesium alloy, Mg_2Si, Microstructure, Mechanical properties

Abstract

Phase constitution and microstructure of the Mg-5Sn-xSi-2Sr (x=0, 1, 2) alloys were analyzed by X-ray diffractometer, optical microscope and scanning electron microscope with an energy dispersive spectrometer. The tensile properties of the alloys were tested by electronic universal testing machine, and the fracture surfaces of the alloys were observed with scanning electron microscope. The results show that the microstructure of the Mg-5Sn-2Sr alloy consists of α-Mg, MgSnSr and Mg_2Sn phases. The addition of Si element can promote the formation of Mg_2Si phase on the grain boundary, and the content of Mg_2Si phase increases with increasing the Si element. Mg_2Si is a strengthening phase, which can effectively prevent grain boundary sliding and dislocation motion, and thus, the mechanical properties of the alloys were obviously enhanced. The mechanical properties of Mg-5Sn-2Si-2Sr alloy are better than other alloys, the tensile strength, yield strength, elongation and hardness are 147MPa, 110MPa, 5.0% and 47HB respectively.

1 Introduction

Magnesium alloys are the lightest structural alloys and have greatly potential applications in automotive, aerospace and other industries due to the unique combination of low density, high specific strength, superior damping capacity, good castability and excellent machineability[1,2]. However, the elevated temperature properties of magnesium alloys is poor, therefore, improving the elevated temperature properties has become a critical issue for its possible application in heat-resistant components[3,4]. Studies have shown that the Sn and Si elements are beneficial to improve heat resistance of magnesium alloys, which is attribute to the formation of the thermally stable Mg_2Sn and Mg_2Si phases[5]. Si is an effective alloying element for improving the high temperature properties of magnesium alloy since Si combines with Mg and forms the intermetallic compound Mg_2Si which exhibits high melting point, low density, high hardness and low thermal expansion coefficient[6]. Moreover, the intermetallic phase Mg_2Sn in Mg-Sn alloys has much higher melting point (770 ℃) than that of $Mg_{17}Al_{12}$ phase (462 ℃) in Mg-Al alloys. So, Mg-Sn-Si alloy is likely to have superior high-temperature resistance. But the mechanical properties of alloys will reduce due to the formation of the coarse dendrite-shape primary Mg_2Si in Mg-Si alloys with high Si content and the brittle chinese script eutectic Mg_2Si in Mg-Si alloys with low Si content[7]. It is widely known that the refinement of Mg_2Si phase is mainly responsible for improving the mechanical properties of alloys. Recent studies report that the Y addition can modify the morphology of Mg_2Si precipitates[8], but the price of rare earth is expensive, so the RE-containing Mg alloys don't have the market competition. Adding alkaline earth elements calcium and strontium can also refine the Mg_2Si phase and modify the morphology of Mg_2Si crystals[9-11]. The price of alkaline earth elements is cheaper than rare earth, thus, the Mg-Sn-Si alloys containing alkaline earth is one of the future development direction.

In recently years, the Mg-Sn based alloys has been a renewed interest globally in this alloy system as it has potential applications at elevated temperatures, including the Mg-Sn-Ca[3], Mg-Sn-Zn[4], Mg-Sn-Ce[12], Mg-Sn-Nd[13], Mg-Sn-Pb[14] and Mg-Sn-Y[15] alloys. Studies have shown the mechanical properties of Mg-(1-10)%Sn alloys and the mechanical properties of Mg-5%Sn alloy is better than other alloys[16]. Liu[17] also studies the effect of Sr on the microstructure and mechanical properties of as cast Mg-5wt.%Sn alloy at ambient and elevated temperatures, indicating that Sr can improve the thermal stability of Mg-Sn alloys. In this work, Si was added to Mg-5Sn-2Sr alloy for achieving more excellent mechanical property.

2 Experimental

The Mg-5Sn-xSi-2Sr (x=0, 1, 2) alloys were prepared using high purity Mg (99.9%), Sn (99.9%), and Mg-30%Si and Mg-30%Sr (mass fraction) master alloys according to the nominal composition in this study. The experimental alloys were melted in a crucible resistance furnace under $0.1\%N_2+0.15\%SF_6$ (volume fraction) atmosphere. The Mg-Si and Mg-Sr master alloys were added to the melt at 700℃, and the melt was mixed by artifical stirring for 1 min. After the melt was mixed completely, then held at 690℃ for 20 min and poured into a preheated permanent mould with a diameter of 120mm.

The phase constituent of the alloys was analyzed by using XRD-7000 type X-ray diffractometer (XRD). The samples were etched with the 3% (volume fraction) nitric acid alcohol solution, and then the microstructure analysis was carried out using an optical microscope (OM) and S-3400N type scanning electron microscope (SEM) with an energy dispersive spectrometer (EDS). The WDW-100 type electronic universal testing machine was employed to obtain the tensile properties of the alloys, the ultimate tensile strength (UTS), yield strength (YS) and elongation to failure were obtained based on the average of three tests. The tensile specimens shown in Fig.1 were fabricated by linear cutting from the casting. Furthermore, the fracture surfaces of the alloy samples with different compositions were observed by SEM. The hardness of alloys were tested by the brinell hardness tester.

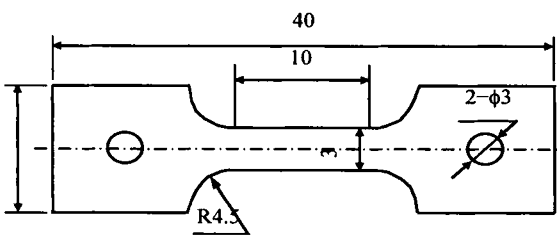

Fig.1 Morphology and size of the tensile tests samples (unit: mm)

3 Results and discussions

3.1 Microstructure analysis

Fig.2 shows the XRD patterns of the as-cast experimental alloys.

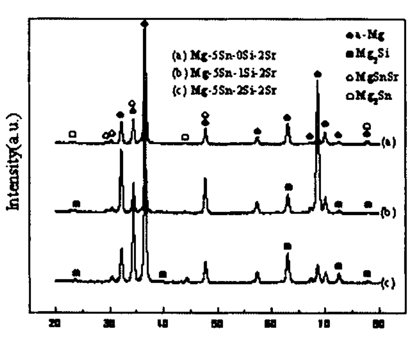

Fig.2 XRD patterns of as-cast experimental alloys

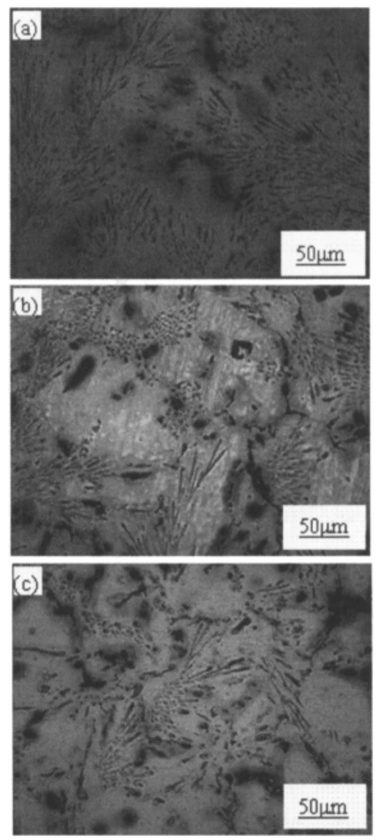

Fig.3 Optical images of the microstructures of the as-cast experimental alloys

(a) Mg-5Sn-0Si-2Sr; (b) Mg-5Sn-1Si-2Sr; (c) Mg-5Sn-2Si-2Sr

It is observed from Fig.2 (a) that the microstructure of the Mg-5Sn-2Sr consisted mainly of α-Mg, MgSnSr and Mg_2Sn phases. When adding Si to Mg-5Sn-2Sr alloy, new diffraction peaks were observed as labeled "■" in Fig.2 (b) and (c), the new diffraction peaks perfectly matched the characteristic peaks of Mg_2Si, and the Mg_2Si phase diffraction peak intensity increased with increasing Si content.

Fig.3 shows the optical microstructure of the investigated alloys in the as-cast condition. Fig.3 indicates that the experimental alloys are composed of α-Mg and secondary solidification phases (black and grey precipitates). The black phase with a blocky morphology was mainly gathered in the grain boundary areas and the volume and size of this phase grew up with the increasing Si additions. The grey phases with needle-like and particle-like morphologies were formed within the grain.

Fig.4 shows the SEM microstructure of the investigated alloys in the as-cast condition, and the EDS results of experimental alloys were shown in Table 1. Fig.4 (a) shows the microstructure of Mg-5Sn-0Si-2Sr alloy. According to XRD and EDS results, the phase with needle-like morphology is MgSnSr, and the blocky phase is Mg_2Sn whose typical morphology is shown in Fig.4 (a). Fig.4 (b) and (c) show the microstructure of Mg-5Sn-xSi-2Sr (x=1, 2) alloys, the particle-like (Fig.4 (b)) and feather-like phases (Fig.4 (c)) within grain are MgSnSr, and the Mg_2Sn and Mg_2Si phases are formed mainly along the grain boundaries. Since a maximum solid solubility of Si into Mg is only 0.003 at.% and Si atoms react with Mg atoms and are precipitated as an intermetallic compound of Mg_2Si[8]. In addition, the Mg_2Sn phase can be easily precipitated because of the high solubility limit of Sn in Mg (14.48 mass%) at 560 ℃ and its little solubility at ambient temperature[18].

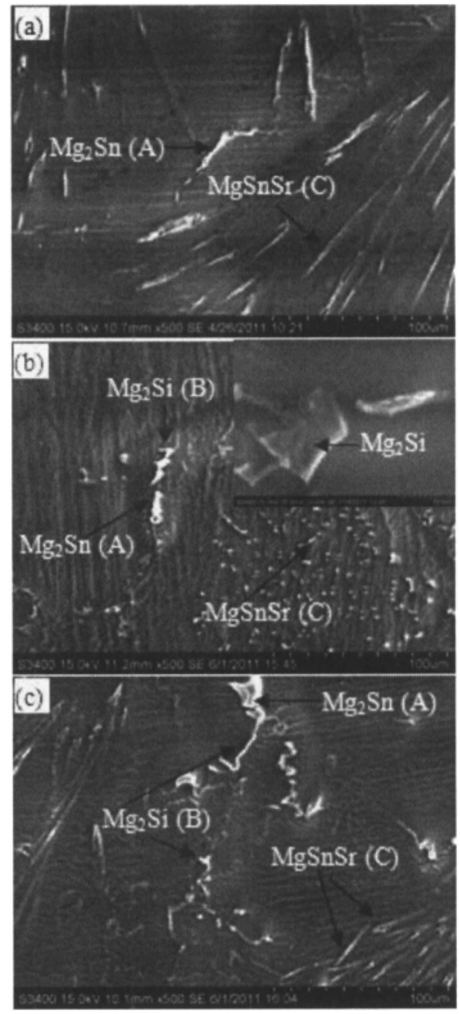

Fig.4 SEM images of the microstructures of the as-cast alloys (a) Mg-5Sn-0Si-2Sr; (b) Mg-5Sn-1Si-2Sr; (c) Mg-5Sn-2Si-2Sr

Table 1 EDS results of as-cast experimental alloys (molar fraction, %)

Element	Position in Fig.4(a)		Position in Fig.4(b)			Position in Fig.4(b)		
	A	B	A	B	C	A	B	C
Mg	74.05	67.28	68.35	69.39	88.25	70.80	70.26	71.46
Sn	25.95	22.62	28.05	6.49	9.24	27.97	7.99	16.51
Si			3.60	24.12		1.23	21.75	
Sr		10.10			7.51			12.03
Total	100	100	100	100	100	100	100	100

The results show that the microstructure of the Mg-5Sn-2Sr alloy consists of α-Mg, MgSnSr, Mg_2Sn phases. The addition of Si element can promote the formation of Mg_2Si phase on the grain boundary, and the content of Mg_2Si phase increases with increasing the Si element. The chinese script type Mg_2Si particle doesn't observed in the experimental alloys due to the addition of Sr element can refine the Mg_2Si phase[10].

3.2 Mechanical properties

The mechanical properties of experimental alloys are shown in Table 2. It can be seen that the ultimate tensile strength (UTS), yield strength (YS) and hardness increases with increasing the Si element. Adding the Si to Mg-5Sn-2Sr alloy can promote the mechanical properties. The Mg_2Si distributed along grain boundaries can effectively prevent grain boundary sliding and dislocation motion, so the tensile strength of alloy was obviously enhanced. The Mg_2Si exhibits a high hardness[8] of $4.5\times10^9 Nm^{-2}$, therefore it can promote the hardness of alloy. From the XRD and SEM results above, the volume fractions of Mg_2Si phase increases with increasing the Si element, therefore the mechanical properties of Mg-5Sn-2Si-2Sr alloy are better than Mg-5Sn-xSi-2Sr (x=0, 1) alloys.

Table 2 Mechanical properties of as-cast experimental alloys

Alloy	UTS/ MPa	YS/ MPa	Elongation/ %	Hardness/ HB
Mg-5Sn-0Si-2Sr	121	82	4.3	40
Mg-5Sn-1Si-2Sr	139	92	4.4	43
Mg-5Sn-2Si-2Sr	147	110	5.0	47

Fig.5 shows the SEM images of the tensile fracture surfaces for the experiment alloys. As shown in Fig.5, lots of cleavage planes and steps are present, some river patterns and minute lacerated ridges can also be observed in the local areas of the tensile fracture surfaces. It can be seen that the tensile fracture surfaces of experiment alloys have mixed characteristics of cleavage and quasi-cleavage fractures, which is the characteristic of brittle fracture. The fracture surfaces of Mg-5Sn-0Si-2Sr and Mg-5Sn-1Si-2Sr alloys exhibit relatively large cleavage-type facets (position A in Fig.5 (a) and (b)), while the fracture surfaces of Mg-5Sn-2Si-2Sr alloy are relatively small. Furthermore, some minute lacerated ridges and dimples can be seen from the fracture surfaces of the Mg-5Sn-2Si-2Sr alloy, therefore the Mg-5Sn-2Si-2Sr alloy exhibits better tensile strength and elongation.

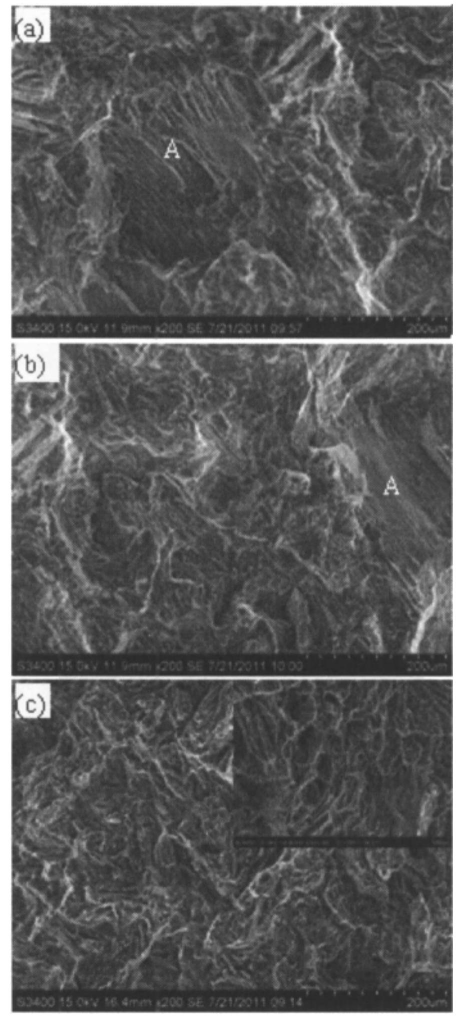

Fig.5 SEM images of tensile fractographs for as-cast alloys at room temperature

(a) Mg-5Sn-0Si-2Sr; (b) Mg-5Sn-1Si-2Sr; (c) Mg-5Sn-2Si-2Sr

4 Conclusions

(1) Mg-5Sn-2Sr alloy consists of α-Mg, MgSnSr, Mg_2Sn phases. The addition of Si element can promote the formation of Mg_2Si phase, and the volume fractions of Mg_2Si phase increases with increasing the Si element.

(2) Adding Si to Mg-5Sn-2Sr alloy can promote the mechanical properties because the Mg_2Si can effectively prevent grain boundary sliding and dislocation motion. The mechanical properties of Mg-5Sn-2Si-2Sr alloy are better than other alloys.

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