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Influence of Sb modification on microstructures and mechanical properties of Mg_2Si/AM60 composites

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Abstract: The refining effect and mechanism of Sb on Mg_2Si and the microstructure of the matrix were investigated. The results indicate that there are Mg_3Sb_2 particles in the composites with the addition of Sb, and Mg_3Sb_2 can promote the formation of fine polygonal type Mg_2Si by providing nucleation site. Meanwhile, the grain size of Sb modified alloy is finer than that of the matrix. The improved microstructure results in the improvement of mechanical properties. The ultimate tensile strength is increased by 12.2% with the addition of 0.8% Sb.

Key words: Mg_2Si; Sb modification; magnesium matrix composites; heterogeneous nucleation; mechanical property

1 Introduction

The composites prepared with in-situ reaction method are an important development direction of magnesium matrix composites. The reinforcement phase is produced in the matrix, which has many advantages such as small size, clean interface and no contamination, good thermal stability and good compatibility with the matrix[1]. There are reinforcement phases such as TiC[2], TiB_2[3], AlN[4] and Mg_2Si[1,5]. Especially, Mg_2Si is characterized by small density, high melting point, high hardness and strength and high elastic modulus, which becomes an ideal reinforcement phase of magnesium matrix composites. However, Chinese script type and plate-block Mg_2Si phases present in the matrix and dissever the matrix, which affect the mechanical properties of the matrix[6−12]. Therefore, the influences of Sb modification on the microstructure and mechanical properties of magnesium matrix composites Mg_2Si/AM60 were studied.

2 Experimental

The experimental materials were AM60 alloy and crystallizing Si. First, AM60 alloy was melted in electric resistance furnace protected by self-made covering agent and Ar to avoid oxidative combustion of Mg alloy. The crystallizing Si powders packed in aluminum foil were added into the melt with the bell-jar at 800 ˚C for 15 min. The melt was stirred for 5−10 min in order to make an ample dissolution and homogeneous diffusion of Si. After holding for 30 min, Sb was added into the melt at 700 ˚C for 5 min. Then the melt was poured into a steel mold.

Metallographic specimens from the same section were corroded by HNO_3-alcohol solution, whose microstructures were examined by OM and SEM. The Brielle hardness was measured by HBE−3000A. The tensile tests were carried out on an electric universal testing machine.

3 Results and discussion

3.1 Influence of Sb on microstructure of composites

Fig.1 shows the influence of Sb on the microstructure of composites. α-Mg, β-$Mg_{17}Al_{12}$ and Chinese script type Mg_2Si phases present in the composites without the addition of Sb. It is obvious that Chinese script type Mg_2Si is changed into particles with 0.4% Sb addition and the matrix structures are refined. The matrix structures are further refined with 0.8% Sb. As Sb addition is increased up to 1.2%, Mg_2Si begins to grow and is finer than that of un-modified composites.

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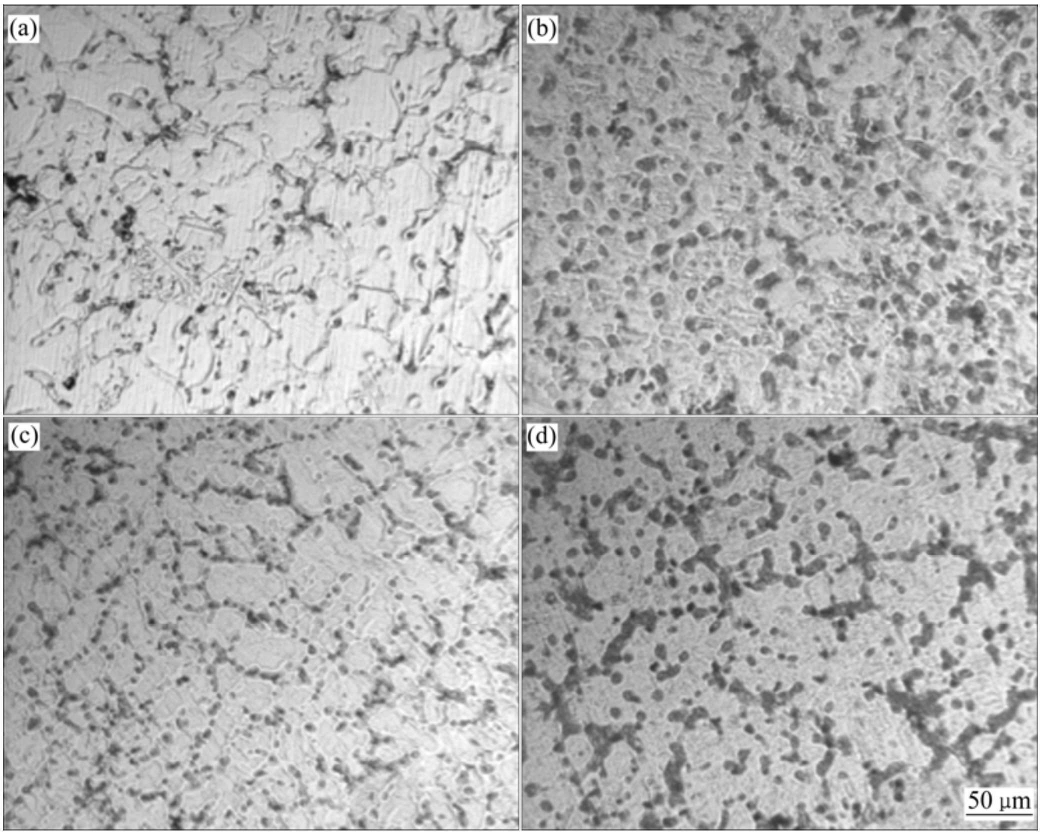

Fig.1 Effects of Sb on microstructures of composites: (a) w(Sb)=0; (b) w(Sb)=0.4%; (c) w(Sb)=0.8%; (d) w(Sb)=1.2%

3.2 Heterogeneous nucleation of Mg_2Si

The capability of heterogeneous nucleation depends on the interfacial energy between the nucleated substrate and crystalline phase. The factors of interfacial energy relate mainly to the lattice disregistry and electrostatic potential between the substrate and crystalline phase, chemical properties and morphology of substrate and so on[13−14]. TURNBULL and VONNDGUT pointed out that the factors promoting heterogeneous nucleation were determined by the lattice disregistry and a one-dimensional lattice model was supposed[15]. But BRAMFITT[16] found that the experimental results were different from the calculation ones with this one-dimensional lattice model. Therefore, a two-dimensional lattice model was put forward by him and the above problem was resolved. The two-dimensional lattice model was defined as:

$$\delta_{(hkl)_n}^{(hkl)_S}=\sum_{i=1}^{3}\frac{\left[\left|(d_{[uvw]_S^i}\cos\theta)-d_{[uvw]_n^i}\right|\Big/d_{[uvw]_n^i}\right]}{3}\times 100\% \tag{1}$$

where S is the lattice plane of substrate, n is the lattice plane of crystalline phase; $(hkl)_S$ is the low-index plane of substrate, $[uvw]_S$ is one direction of low-index plane on $(hkl)_S$; $(hkl)_n$ is the low-index plane of crystalline phase, $[uvw]_n$ is one direction of low-index plane on $(hkl)_n$; $d_{[uvw]_n}$ is the atomic distance in direction of $[uvw]_n$, $d_{[uvw]_S}$ is the atomic distance in direction of $[uvw]_S$; θ is the angle between $[uvw]_S$ and $[uvw]_n$.

Mg_2Si is a face-centered cubic structure with the lattice constants a=0.634 7 nm. Mg_3Sb_2 is a close-packed hexagonal structure with lattice constants a=0.457 0 nm and c=0.723 0 nm. According to Eq.(1), the parameters of lattice disregistry of Mg_2Si and Mg_3Sb_2 are listed in Table 1. The relationships of lattice disregistries among low-index planes (0001) of Mg_2Si and low-index planes

Table 1 Lattice disregistry parameters of Mg_3Sb_2 and Mg_2Si

Matching interface	$(hkl)_S$	$(hkl)_n$	$d_{[hkl]_S}$/nm	$d_{[hkl]_n}$/nm	θ/(°)
$(0001)_{Mg_3Sb_2}$ // $(100)_{Mg_2Si}$	$[\bar{1}2\bar{1}0]$	$[\bar{1}2\bar{1}0]$	0.457 0	0.634 7	0
	$[\bar{2}110]$	[011]	0.457 0	0.448 8	15
	$[\bar{1}010]$	[001]	0.791 5	0.634 7	0
$(0001)_{Mg_3Sb_2}$ // $(110)_{Mg_2Si}$	$[\bar{1}2\bar{1}0]$	[001]	0.457 0	0.634 7	0
	$[\bar{2}110]$	$[1\bar{1}1]$	0.457 0	1.099 3	5.26
	$[\bar{1}010]$	$[1\bar{1}0]$	0.791 5	0.448 8	0
$(0001)_{Mg_3Sb_2}$ // $(111)_{Mg_2Si}$	$[\bar{1}2\bar{1}0]$	$[\bar{1}10]$	0.457 0	0.448 8	0
	$[\bar{1}100]$	$[\bar{1}21]$	0.791 5	0.777 3	0
	$[\bar{2}110]$	[011]	0.457 0	0.448 8	0

(100), (110) and (111) of Mg_3Sb_2 are shown in Fig.2.

Substitute the data in Table 1 in Eq.(1), then

$$\delta^{(0001)_{Mg_3Sb_2}}_{(100)_{Mg_2Si}}=\{\frac{|0.457\,0-0.634\,7|}{0.634\,7}+\frac{|0.457\,0\times\cos 15^\circ-0.448\,8|}{0.448\,8}+\frac{|0.791\,5-0.634\,7|}{0.634\,7}\}/3\times 100\%=18.11\% \quad (2)$$

$$\delta^{(0001)_{Mg_3Sb_2}}_{(110)_{Mg_2Si}}=\{\frac{|0.457\,0-0.634\,7|}{0.634\,7}+\frac{|0.457\,0\times\cos 5.26^\circ-1.099\,3|}{1.099\,3}+\frac{|0.791\,5-0.448\,8|}{0.448\,8}\}/3\times 100\%=54.32\% \quad (3)$$

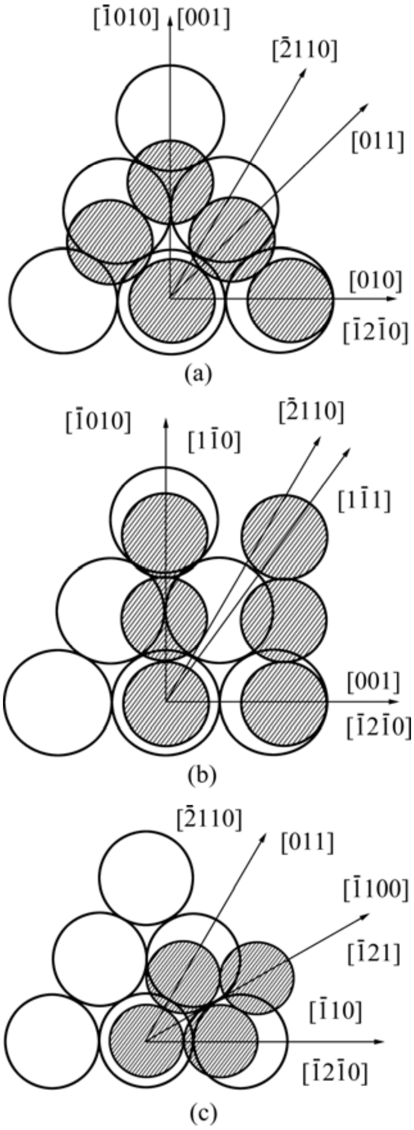

Fig.2 Relationships of lattice disregistries among low-index plane (0001) of Mg_3Sb_2 and low-index planes (100), (110) and (111) of Mg_2Si: (a) Mg_3Sb_2 (0001) and Mg_2Si (100); (b) Mg_3Sb_2 (0001) and Mg_2Si (110); (c) Mg_3Sb_2 (0001) and Mg_2Si (111)

$$\delta^{(0001)_{Mg_3Sb_2}}_{(111)_{Mg_2Si}}=\{\frac{|0.457\,0-0.448\,8|}{0.448\,8}+\frac{|0.791\,5-0.777\,3|}{0.777\,3}+\frac{|0.457\,0-0.448\,8|}{0.448\,8}\}/3\times 100\%=1.83\% \quad (4)$$

From Eqs.(2)−(4), the lattice disregistries between Mg_2Si (0001) and Mg_3Sb_2 (111) is 1.83% and less than 6%. So Mg_3Sb_2 can act as the heterogeneous nuclei of Mg_2Si. Fig.3(a) shows the SEM morphology of Mg_2Si particles in composites. Fig.3(b) shows the EDS spectrum of Mg_2Si core position, which contains the compounds of Mg, Si and Sb. It is inferred that Mg_3Sb_2 is nucleus core based on its atomic ratio.

Fig.1 shows that the grains can be refined by the addition of Sb. This phenomenon may be explained that the majority of Mg_3Sb_2 cores form during the solidification of alloy, and the Mg_2Si particles grow with Mg_3Sb_2 as the crystallization core. So a large number of finer Mg_2Si particles are obtained, which aggregate in front of solid-liquid interface so as to hinder the spread of atomic Al and obtain finer Mg_2Si particles and matrix. As shown in Fig.1, the modification effect becomes worse with 1.2% Sb. According to the theory of diffusion and phase transition, the coarsening rate of particles precipitated relates to the concentration of solute atoms. The higher the concentration of solutes atoms, the higher

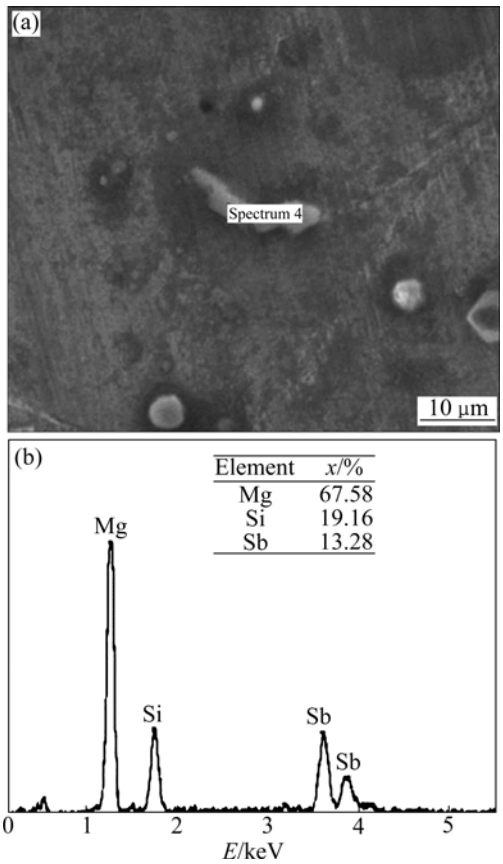

Fig.3 SEM morphology (a) and EDS spectrum (b) of Mg_2Si particles

the coarsening rate of particles. The Mg_3Sb_2 phase can aggregate and grow with increasing Sb content, and the heterogeneity of nuclear-point is reduced, which affects the nuclear-rate and makes Mg_2Si phase and the matrix enlarge. It is significant to affect Mg_2Si phase.

3.3 Effects of Sb on mechanical properties of composites

Fig.4 shows the effects of Sb on the mechanical properties of composites. The tensile strength of composites increases with increasing Sb content. The tensile strength is up to 221.6 MPa and improved by 12.2% when Sb content is 0.8%, compared with that of matrix. The tensile strength of composites decreases with further increasing Sb content, and the elongation rate of composites decreases with Sb content increasing.

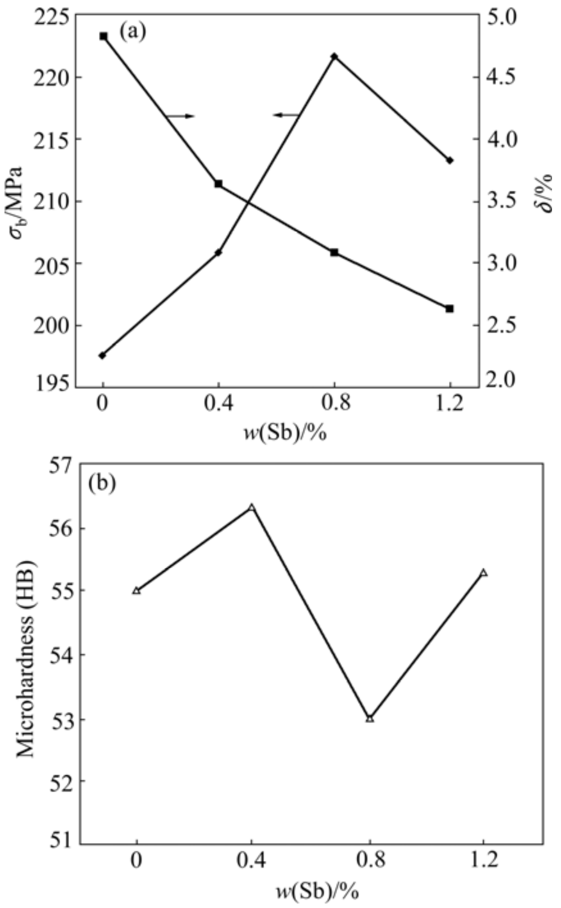

Fig.4 Effects of Sb on mechanical properties of composites

As shown in Fig.4(b), the hardness of composites changes little with increasing Sb content. The hardness of composites is HB 55 with no addition of Sb and HB 53−56.3 with the addition of Sb, which is mainly affected by the reinforcement of Mg_2Si. So the hardness has no change for the contents of Mg_2Si in composites maintain the original value even if Sb is introduced.

The mechanical properties of composites are improved with the addition of Sb. On one hand, Mg_2Si particles are refined and distributed at the matrix and grain boundaries, which increase the strength of composites for the pinning effect. On the other hand, the grains are refined by introducing Sb into composites. According to Hall-Petch formulation, the relationship between grain size and yield strength is expressed as follows.

$$\sigma_s = \sigma_0 + kD^{-1/2} \tag{5}$$

where σ_s is the yield strength, σ_0 and k are constant, and D is the grain size.

It is known from Eq.(5) that the yield strength increases with decreasing grain size. And decreasing the grain size means increasing grain boundaries, which can improve the mechanical properties of magnesium alloy because the grain boundaries can hinder the dislocation motion.

The reason why the elongation of composites decreases is that the melting point is high and the brittle hard-phase Mg_3Sb_2 forms at the grain boundaries with the addition of Sb, which increases the volume of brittle phase and makes Mg_2Si segregate at the grain boundaries to reduce the plasticity of Sb modified alloy.

4 Conclusions

1) The Chinese script type Mg_2Si present in the Mg_2Si/AM60 composite is changed into the finer particles with the addition of Sb. Meanwhile, the grain size of Sb modified alloy is finer than that of the matrix.

2) There is a new phase formed with the addition of Sb, which provides the nucleation core of Mg_2Si.

3) The proper introducing of Sb results in the improvement in mechanical properties.

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