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Effects of solution heat treatment on microstructure and mechanical properties of AZ61-0.7Si magnesium alloy

YANG Ming-bo(杨明波)[1], LIANG Xiao-feng(梁晓峰)[1], LI Hui(李　晖)[1], PAN Fu-sheng(潘复生)[2]

1. College of Materials Science and Engineering, Chongqing University of Technology, Chongqing 400050, China;
2. National Engineering Research Center for Magnesium Alloys, Chongqing University, Chongqing 400044, China

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Abstract: The effects of solution heat treatment on the microstructure and mechanical properties of AZ61-0.7Si magnesium alloy were investigated. The results indicate that the solution heat treatment can modify the Chinese script shaped Mg_2Si phases in the AZ61-0.7Si magnesium alloy. After being solutionized at 420 ˚C for 16−48 h, the morphology of the Mg_2Si phases in the AZ61-0.7Si alloy changes from the Chinese script shape to the short pole and block shapes. Accordingly, the tensile and creep properties of the AZ61-0.7Si alloy are improved. After being solutionized at 420 ˚C for 24 h and followed by aging treatment at 200 ˚C for 12 h, the heat-treated alloy exhibits relatively high tensile and creep properties than those of the as-cast alloy.

Key words: magnesium alloy; solution heat treatment; Mg_2Si phase; modification

1 Introduction

Magnesium alloys are the lightest structural alloys commercially available and have great potential for applications in automotive, aerospace and other industries. However, in recent years, improving the elevated temperature properties has become a critical issue for possible application of magnesium alloys in hot components. It has been shown that the Mg-Al-Si based alloys are thought as potential elevated temperature magnesium alloys[1−2], because the Mg_2Si formed by Si addition exhibits high melting point, high hardness, low density, high elastic modulus and low thermal expansion coefficient, and the Mg_2Si phase is very stable and can impede grain boundary sliding at elevated temperatures[3]. However, the Mg_2Si compound is prone to forming undesirable, coarse, Chinese script shape under the lower solidification rates, which would damage the mechanical properties. Therefore, the investigation about modification and refinement of the Mg_2Si phases in Mg-Al-Si based alloys has received much attention all over the world, and consequently many researches have been carried out. It has been reported that the Chinese script shaped Mg_2Si phases in Mg-Al-Si based alloys might be modified and refined by Sb[4−6], Ca and P additions[7−9]. However, some researches also found that Sb was not an effective modifier of the Mg_2Si phase[7]; Ca could result in cast defects such as a hot-crack[10]; and P could produce ignition and the amount of P addition was also difficult to control[4]. Therefore, further investigation on the modification of Chinese script shaped Mg_2Si phases needs to be considered.

Recent results indicate that the solution heat treatment could modify the Chinese script shaped Mg_2Si phase in the Mg-Al-Si based alloys[11−13]. For example, LU et al[11] found that the Mg_2Si particles in the Mg-6Al-*x*Si alloys tend to be spherodized during a solution heat treatment, and similar results were also reported by BARBAGALLO[12]. In spite of the above studies, the investigation about the effect of solution heat treatment on the microstructure and properties of the Mg-Al-Si based alloys is very scarce in the literature. In order to provide a theoretical guide for the properties improvement of the Mg-Al-Si based alloys by suitable heat treatment, the effect of solution heat treatment on the microstructure and mechanical properties of the

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Corresponding author: YANG Ming-bo; Tel: +86-23-68667455; E-mail: yangmingbo@cqut.edu.cn

AZ61-0.7Si magnesium alloy were investigated.

2 Experimental

The AZ61-0.7Si alloy was prepared by adding the following materials: commercial AM60 alloy, pure Al, pure Mg, pure Zn, and Al-30%Si master alloy. The experimental alloy was melted in a crucible resistance furnace and protected by a flux addition. After being treated by C_2Cl_6, the melt was held at 740 ˚C for 20 min and then poured into a permanent mould in order to obtain a casting. The tensile and creep specimens whose size has been reported in Ref.[13] were fabricated by spark cutting from the casting. The actual compositions (mass fraction, %) of the experimental alloy were given as follows: 92.37Mg, 5.92Al, 0.79Zn, 0.24Mn and 0.68Si.

In order to obtain the solution heat treatment temperature of the experimental alloy, the differential scanning calorimetry (DSC) was carried out using a NETZSCH STA 449C system. Samples of approximately 30 mg were heated in a flowing argon atmosphere from 30 to 700 ˚C for 5 min before being cooled down to 100 ˚C. The heating and cooling curves were recorded at a controlling speed of 15 ˚C/min. Based on the DSC results (Fig.1), the solutionized temperature of 420 ˚C was chosen for the experimental alloy. In a muffle furnace and under the condition of CO_2 atmosphere protection, the solution heat treatment of the experimental alloy was carried out at 420 ˚C for different holding times. Furthermore, the solutionized samples were aged at 180 ˚C and 200 ˚C for 0−24 h.

Both the as-cast and/or heat-treated samples were etched in an 8 % nitric acid distilled water solution, and then examined by an Olympus optical microscope and JEOL JSM-6460LV type scanning electron microscope (SEM) equipped with an Oxford energy dispersive spectrometer (EDS). The tensile properties of the as-cast and heat-treated experimental alloys at room temperature and 150 ˚C were determined from a stress—strain curve. The ultimate tensile strength (UTS), 0.2% yield strength

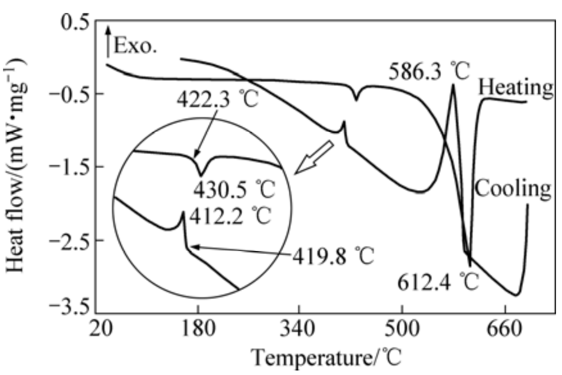

Fig.1 DSC curves of as-cast AZ61-0.7Si alloy

(YS) and elongation to failure were obtained based on the average of three tests. The constant-load tensile creep tests of the as-cast and heat-treated experimental alloys were performed at 150 ˚C and 50 MPa for 100 h. The total creep strain and minimum creep rates of the experimental alloys were measured from each elongation versus time curve.

3 Results and discussion

3.1 Microstructure

According to the previous investigations of the authors[14], the as-cast AZ61-0.7Si alloy is mainly composed of α-Mg, $M_{17}Al_{12}$ and Mg_2Si phases. Fig.2 shows the SEM image of the as-cast AZ61-0.7Si alloy. As shown in Fig.2, the Mg_2Si phases with Chinese script shape are clearly observed in the alloy, similar to the other Si-containing Mg-Al based alloys[2].

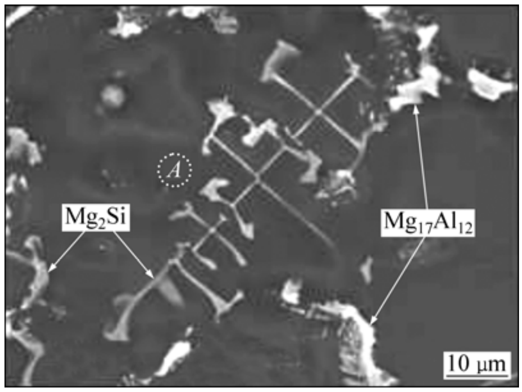

Fig.2 SEM image of as-cast AZ61-0.7Si alloy

Fig.3 shows the SEM images of the AZ61-0.7Si alloy solutionized at 420 ˚C for different times. As shown in Fig.3, after being solutionized at 420 ˚C, the $M_{17}Al_{12}$ phases in the AZ61-0.7Si alloy have dissolved into the matrix. However, the grey Mg_2Si phases and the white Al-Mn phases are clearly observed. Actually, this can be further confirmed by the EDS results of the matrixes near Mg_2Si phases in the as-cast and solutionized AZ61-0.7Si alloys (Table 1). It is found from Table 1 that little Si dissolves in the matrix after the solution heat treatment and Si is still in the form of the Mg_2Si. In addition, it is further found from Fig.3 that after being solutionized at 420 ˚C for 16−48 h the Chinese script shaped Mg_2Si phases in the AZ61-0.7Si alloy have became disconnected, and with increasing the solution treatment time from 16 to 48 h the morphology for parts of Mg_2Si phases gradually changes from initial Chinese script shape to the short pole and block shapes. The above results indicate that the solution heat treatment can modify the Chinese script shaped Mg_2Si phases in the AZ61-0.7Si alloy.

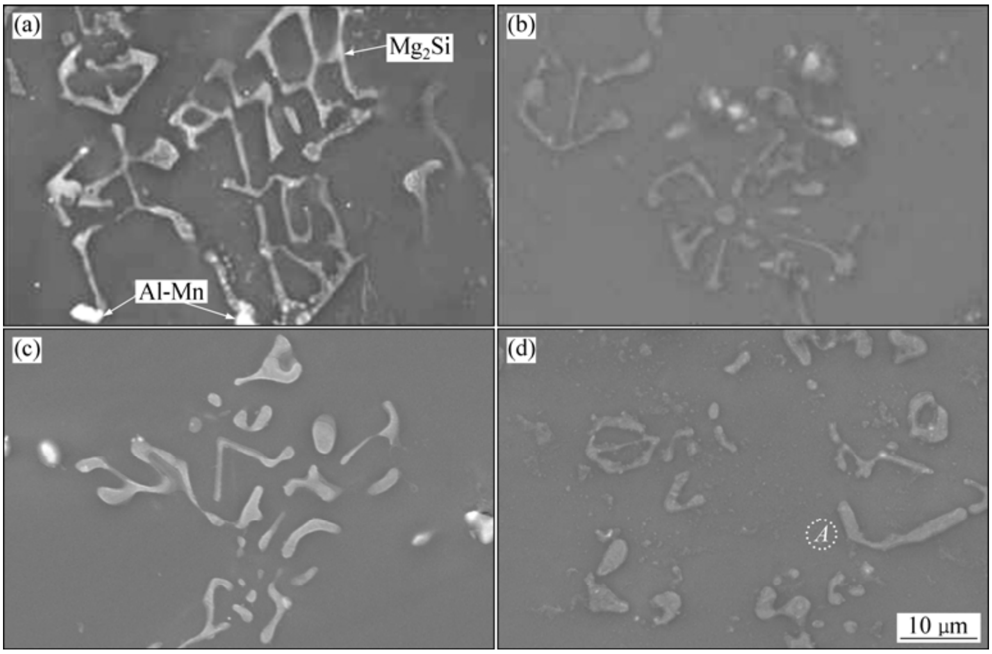

Fig.3 SEM images of AZ61-0.7Si alloy solutionized at 420 ˚C for different treatment times: (a) 8 h; (b) 16 h; (c) 24 h; (d) 48 h

Table 1 EDS results of matrix near Mg_2Si phase (molar fraction, %)

Position	Mg	Al	Zn	Si	Total
Point *A* in Fig.2	93.85	3.73	2.31	0.11	100
Point *A* in Fig.3(d)	91.47	4.62	3.78	0.13	100

3.2 Mechanical properties

Fig.4 shows the effect of the solutionizing time on the hardness of the AZ61-0.7Si alloy. In addition, the effect of the aging time on the hardness of the AZ61-0.7Si alloy solutionized at 420 ˚C for 24 h and followed by aging at 180 ˚C and 200 ˚C is also shown in Fig.4. According to Fig.4, the optimizing aging temperature and time for the AZ61-0.7Si alloy, 200 ˚C and 12 h, are chosen. Table 2 lists the tensile properties, including ultimate tensile strength (UTS), 0.2% yield strength (YS) and elongation, and creep properties of the AZ61-0.7Si alloy solutionized at 420 ˚C for 24 h and followed by aging treatment at 200 ˚C for 12 h. For comparison, the tensile and creep properties for the as-cast AZ61-0.7Si alloy are also listed in Table 2. It can be observed from Table 2 that the tensile and creep properties of the heat-treated alloy are higher than those of the as-cast alloy, indicating that the heat treatment can greatly improve the mechanical properties of the AZ61-0.7Si alloy. This situation is possibly related to the modification of the Mg_2Si phases during the solution heat treatment. It is well known that the presence of fine and uniform phases distributed along the grain boundaries in microstructure is easier to act as an effective straddle to the dislocation motion thus improving the properties of the engineering alloys[15]. Apparently, the coarse Chinese script shaped Mg_2Si phases in the as-cast AZ61-0.7Si alloy would give a detrimental effect on the mechanical properties of the alloy since the long cracks can easily nucleate along the interface between Chinese script shaped Mg_2Si particles and α-Mg matrix[8]. However, after solution heat treatment, the morphology of the Mg_2Si phase changes from the initial Chinese script shape to the short pole and block shapes, and then the extending trend of microcracks would decrease. Accordingly, after solution heat treatment and aging, the mechanical properties of the AZ61-0.7Si alloy are improved, especially the elongation.

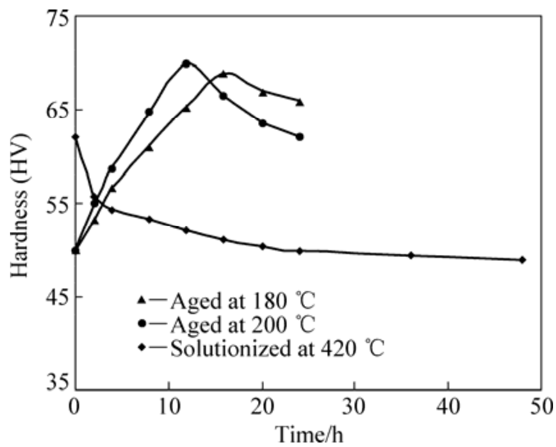

Fig.4 Effects of solutionizing and aging time on hardness of AZ61-0.7Si alloy

3.3 Discussion

The above results indicate that the solution heat

Table 2 Tensile and creep properties of AZ61-0.7Si alloy

State	Tensile property						Creep property	
	Room temperature			150 ˚C			150 ˚C and 50 MPa for 100 h	
	UTS/MPa	YS/MPa	Elongation/%	UTS/MPa	YS/MPa	Elongation/%	Total creep strain/%	Minimum creep rate/ $(10^{-3}\%\cdot h^{-1})$
As-cast	147	77	4	140	70	12	0.54	5.11
Heat-treated	175	99	5	170	94	16	0.48	4.63

treatment can modify the Chinese script shaped Mg_2Si phases in the AZ61-0.7Si alloy, leading to the improvement of mechanical properties. For the modification mechanism of the Mg_2Si phase during solution heat treatment, LU et al[11] thought that there always exist concaves and convexities on the Mg_2Si particles along the Mg_2Si/Mg interface, and these sites exist different stress level. Then during solution heat treatment, the interface tension makes the nearby Si atoms escape from the Mg_2Si lattice and move coincidently. At the same time, the Si atoms diffuse along the interfaces and enter the magnesium lattice in a new position to form Mg_2Si again, leading to the local decomposition and morphology changing of the Mg_2Si particles. As a result, the atom at the tip will move toward the middle; the concaves will become more sunken and convexities become smooth. It is supposed that the straight part of the particle keeps stable because the diffusion along the interface is homogeneous. Finally the linear particle will be broken near the concaves and the spheroidization of the sub-particles continues.

Although the above mentioned mechanism can easily explain the dissolving and breaking of the long branches of Chinese script shaped Mg_2Si phases, as shown in Fig.2, the Chinese script shaped Mg_2Si phase exhibits obvious dendrite character, whose dissolving and breaking could not be explained by the above mentioned view, especially before the Mg_2Si phases break to a long branches. It is well known that in the temperature and solute concentration fields fluctuation exists during solidification process, then the curvature fluctuation on the Mg_2Si phases surface should exist. Therefore, one possible explanation for the modification of Mg_2Si phases during solution heat treatment can be obtained by using Gibbs-Thomson formula. According to the Gibbs-Thomson formula[16], the Si concentration in the matrix corresponded to the site with larger curvature for Mg_2Si phase can be expressed as

$$C_\alpha(r) = C_\alpha(\infty)\exp\left(\frac{2\sigma V_B}{k_B T r}\right) \quad (1)$$

where $C_\alpha(r)$ is the Si concentration at the position with curvature radius r; $C_\alpha(\infty)$ is the Si concentration at flat interface; σ is the surface tension; V_B is the volume of Si atom; T is the temperature; k_B is a coefficient related to the shape. According to Eq.(1), the smaller the curvature radius is, the higher the Si concentration is. Considering that the curvature radii of different positions for an Chinese script shaped Mg_2Si phase might be different, then grads of Si concentration between these positions is formed. Therefore, during solution heat treatment, the Si atoms would diffuse from the position with large curvature and high Si concentration to flat interface with lower Si concentration, and then the balance of local Si concentration in these positions is broken. In order to keep the balance of Si concentration, these positions with larger curvature would be dissolved. Oppositely, in the α-Mg matrix corresponded to the flat interface, the Mg_2Si phases would form due to the supersaturation of Si concentration. As a result, these positions with larger curvature are broken, then the granule shaped Mg_2Si phases that have close curvature radii in different positions, would form. The process can be illustrated in Fig.5. As shown in Fig.5, the curvatures of these positions such as 'A' in Fig.5(a) are larger, then these position would be dissolved firstly (Fig.5(b)). Then, with the diffusion of Si atoms gradually, the Mg_2Si phase would be broken in these positions such as 'A' (Fig.5(c)). Finally, with prolonging the treatment time, the granule shaped Mg_2Si phases that have close curvature radii in different positions, would form (Fig.5(d)).

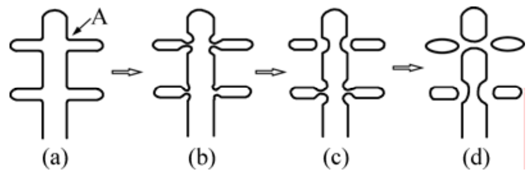

Fig.5 Sketch of dissolving and breaking process of Chinese script shaped Mg_2Si phase in larger curvature site

4 Conclusions

1) The solution heat treatment can modify the Chinese script shaped Mg_2Si phase in the AZ61-0.7Si magnesium alloy. After being solutionized at 420 ˚C for 16−48 h, the morphology of the Mg_2Si phase in the AZ61-0.7Si alloy changes from the initial Chinese script shape to the short pole and block shapes.

2) The effect of solution heat treatment on the morphology of the Mg_2Si phase can result in the improvement of the tensile and creep properties for the

AZ61-0.7Si magnesium alloy. After being solutionized at 420 ˚C for 24 h and followed by aging treatment at 200 ˚C for 12 h, the heat-treated alloy exhibits relatively high tensile and creep properties than those of the as-cast alloy.

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