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Effects of isothermal process parameters on semisolid microstructure of Mg−8%Al−1%Si alloy

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Abstract: A Mg−8%Al−1%Si alloy with semisolid microstructure was fabricated by isothermal heat treatment process. The effects of isothermal process parameters such as holding temperature and holding time on the microstructure of Mg−8%Al−1%Si alloy were investigated. The results show that a non-dendritic microstructure could be obtained by isothermal heat treatment. With increasing holding temperature from 560 to 575 °C or holding time from 5 to 30 min, the liquid volume fraction increases, the average size of *α*-Mg grains grows larger and globular tendency becomes more obvious. In addition, the Mg_2Si phase transforms from Chinese script shape to granule shape. The morphology modification mechanisium of Mg_2Si phase in Mg−8%Al−1%Si alloy during the semisolid isothermal heat treatment was also studied.

Key words: Mg−Al−Si alloy; semi-solid; microstructure; isothermal heat treatment; Mg_2Si phase

1 Introduction

Magnesium alloys are attractive candidates for automotive and aerospace applications because of their excellent properties [1,2]. For example, parts of the Mg−Al−Si series alloys, such as AS21 and AS41 alloys, have been successfully used in the drive system of automobile engines [3,4]. The Mg−Al−Si based alloy containing intermetallic compound Mg_2Si has high melting point, high hardness, high elastic modulus and low coefficient of thermal expansion (CET) [5−8]. Therefore, Mg_2Si can act as the very effective strengthening phase in magnesium alloys both at low and elevated temperatures.

However, Mg_2Si phase in the Mg−Al−Si based alloys is prone to forming undesirable coarse Chinese script shape, which can deteriorate the mechanical properties of the magnesium alloys [9,10]. In order to modify the Chinese script shaped Mg_2Si phases, many methods such as hot extrusion [11−13], rapid solidification [14], mechanical alloying [15] and micro-alloying (Ca, P, Sb and Sr) [16−20] have been studied. But these methods are too expensive and complex to be accepted by engineering community for general application [17,19,21].

Semisolid isothermal heat treatment is a novel method. Recent research found that the Chinese script shaped Mg_2Si phase in AS91 alloy could be modified to granule and/or polygon shapes by semisolid isothermal heat treatment [22,23]. Therefore, the semisolid isothermal heat treatment can be thought as a potential method for the modification of Chinese script shaped Mg_2Si phase in the Mg−Al−Si based magnesium alloys.

In the present work, the effects of isothermal process parameters on the microstructure of Mg−8%Al−1%Si alloys during isothermal heat treatment were investigated. The purpose was to develop a simplified method for the modification of Chinese script shaped Mg_2Si phase. It was expected that the preliminary results can be significant in promoting the fabrication of high quality Mg−Al−Si alloys.

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2 Experimental

The Mg−8%Al−1%Si alloy was prepared by adding the following materials: commercial pure Mg (purity > 99.9%), Al (purity >99.8%) and Si (purity >99.4%). The experimental alloy was melted in a resistance furnace and then poured into a permanent mould to produce the ingots. The actual chemical composition of the experimental alloy was determined by the ARL4460 Metals Analyzer and the result is listed in Table 1.

Table 1 Chemical composition of Mg−8%Al−1%Si alloy (mass fraction, %)

Al	Si	Zn	Sn	Mg
7.837	0.896	0.00641	0.00152	Bal.

Figure 1 shows the DSC curve of Mg−8%Al−1%Si alloy. According to Fig. 1, the semisolid isothermal temperatures of 560, 565, 570 and 575 °C were selected. Samples were cut from the initial as-cast alloy with dimensions of 12 mm×12 mm×14 mm, and put into resistance furnace at selected temperatures and held for 5, 10, 20 and 30 min, respectively, and then they were taken out for water quenching quickly.

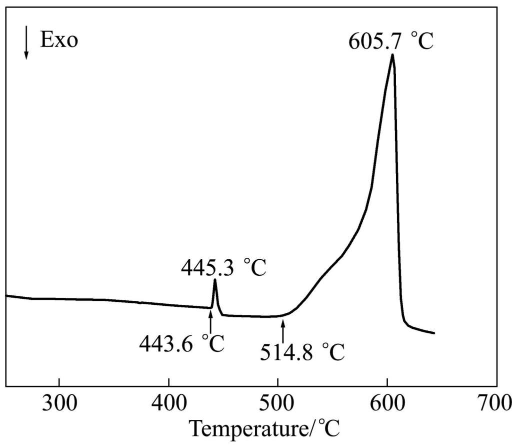

Fig. 1 DSC curve of as-cast Mg−8%Al−1%Si alloy

The samples (as-cast and semi-solid) were etched by 4% HNO_3 in alcohol. The microstructure and intermetallic phase analyses were investigated by OLYMPUS optical microscopy (OM). X-ray diffraction (XRD) (D/Max 2500PC Rigaku, Japan) was utilized for phase identification. The temperature of the eutectic reaction was measured using a differential scanning calorimeter (DSC) (PerkinElmer, USA) at a heating rate of 5 °C/min. The characteristics of microstructural evolution, such as liquid volume fraction and average grain size, were evaluated by image analysis system (Image-Pro plus).

3 Results and discussion

Figure 2 shows the XRD pattern and microstructure of the as-cast Mg−8%Al−1%Si alloy. The XRD result reveals that the main phases in the as-cast alloy are α-Mg, $Mg_{17}Al_{12}$ and Mg_2Si. It can be seen from Fig. 2(b) that the microstructure of the as-cast alloy is composed of α-Mg phase, $Mg_{17}Al_{12}$ phase and Chinese script shaped Mg_2Si phase. In general, the Mg_2Si phases in Mg−Al−Si based alloys are prone to forming coarse Chinese script shape at low solidification rate [9]. Therefore, under the permanent mould casting in this investigation, the Mg_2Si phase in Mg−8%Al−1%Si alloy exhibits coarse Chinese script morphology.

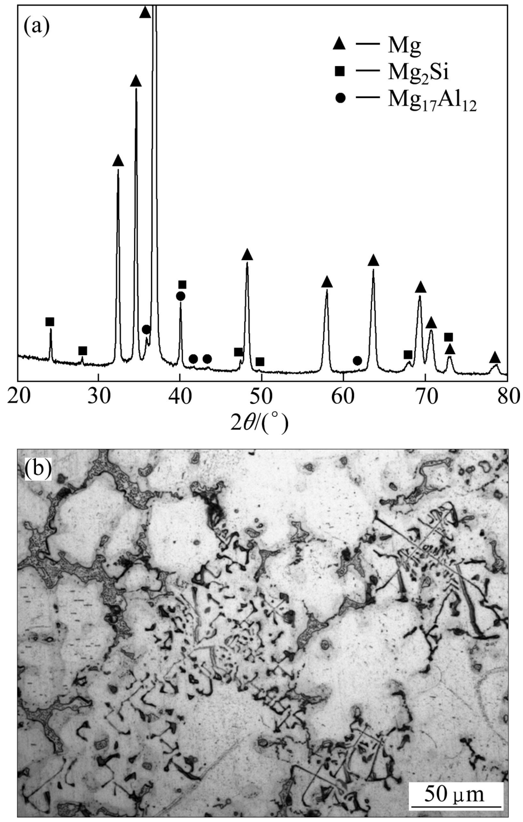

Fig. 2 XRD pattern (a) and OM image (b) of as-cast Mg−8%Al−1%Si alloy

Figures 3 and 4 show the semisolid microstructures of Mg−8%Al−1%Si alloy after being treated at different holding temperatures for 30 min and treated at 570 °C for different holding time. As seen in Fig.3, when the holding temperature is 560 °C, the liquid phases in Mg−8%Al−1%Si alloy distribute discontinuously, and the “liquid islands” are also found inside the α-Mg grains. With holding temperature increasing from 565 to 575 °C, the amount of liquid islands inside the α-Mg grains decreases, the amount of liquid phases distributed along α-Mg grain boundaries increases. Finally, the initial as-cast alloy ultimately evolves into non-dendritic microstructure.

By combining Figs.3 and 4, it is found that with the increase of holding temperature or time, the liquid volume fraction increases, the average size of α-Mg grains grows larger and the spheroidization of α-Mg grains becomes more and more obvious. The relation of holding temperature and time on the liquid volume fraction and the average size of α-Mg grains are shown in Fig. 5, which is done using the image analysis system. It is found from Fig. 5 that with the increase of holding temperature from 560 to 575 °C or holding time from 5 to 30 min, the liquid volume fraction increases and the average size of α-Mg grains increases, respectively. Then

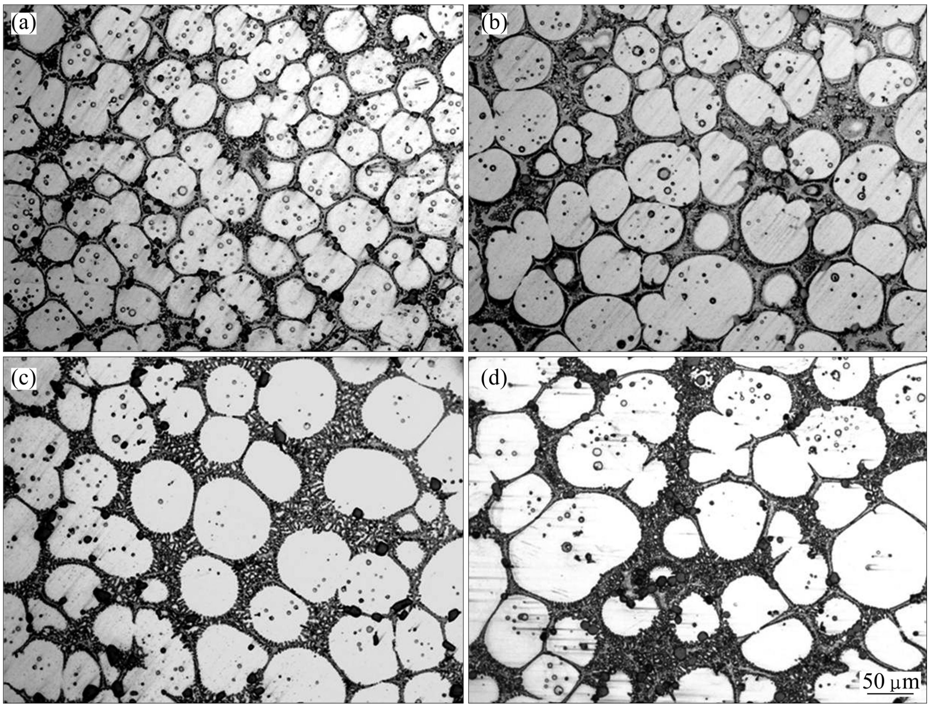

Fig. 3 OM images showing semisolid microstructures of Mg−8%Al−1%Si alloy held for 30 min at 560 °C (a), 565 °C (b), 570 °C (c) and 575 °C (d)

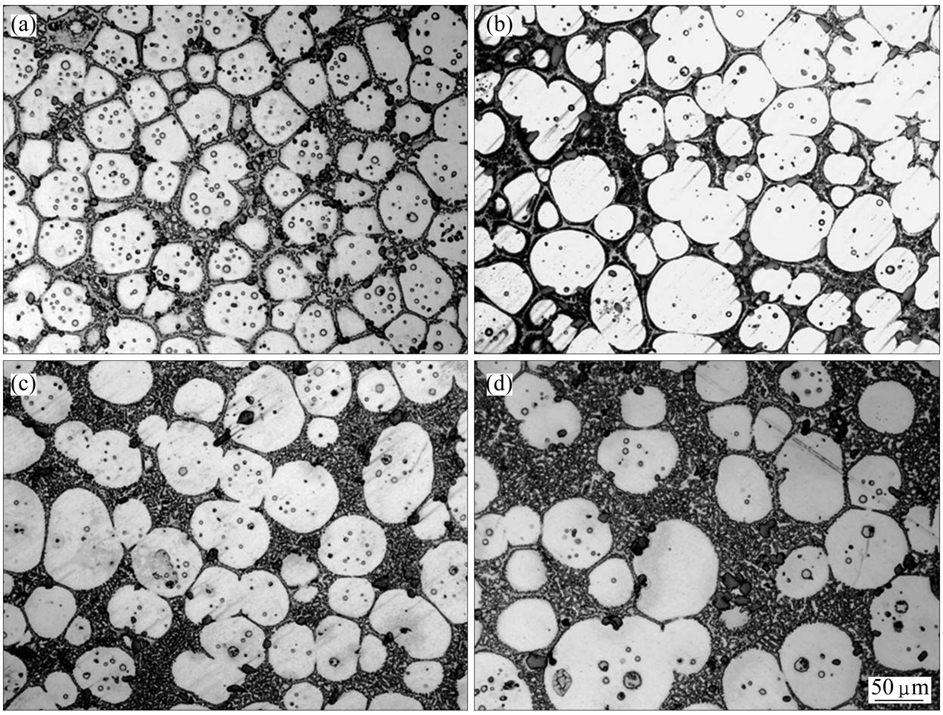

Fig. 4 OM images showing semisolid microstructures of Mg−8%Al−1%Si alloy held at 570 °C for 5 min (a), 10 min (b), 20 min (c) and 30 min (d)

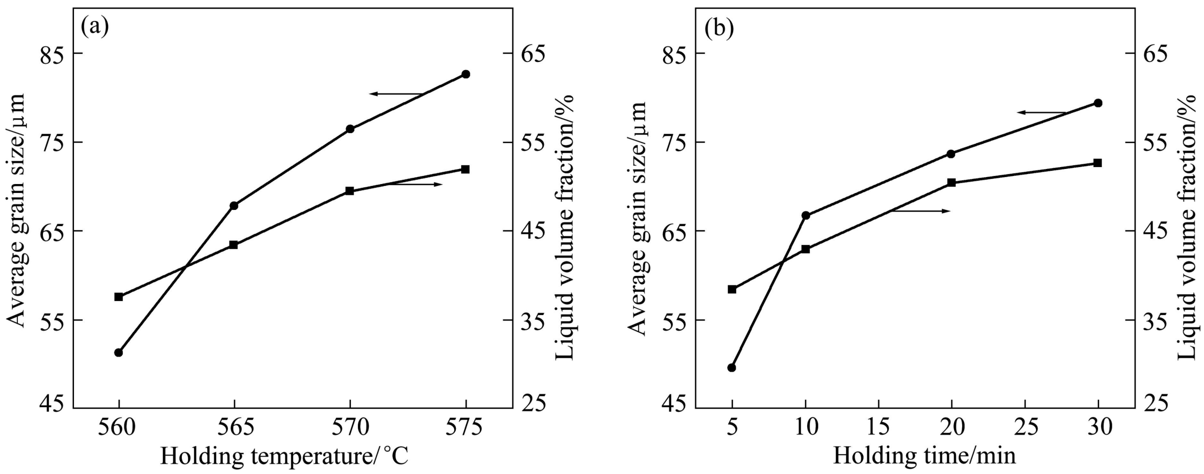

Fig. 5 Effects of holding temperature (a) and time (b) on liquid volume fraction and average size of α-Mg grains in semisolid Mg−8%Al−1%Si alloy

it is inferred that Mg−8%Al−1%Si alloy with non-dendritic microstructure can be fabricated by suitable semisolid isothermal heat treatment.

Figure 6 shows the morphology of Mg_2Si in Mg−8%Al−1%Si alloy after isothermal heat treatment. It is observed that the Mg_2Si phase in semisolid Mg−8%Al−1%Si alloy exhibits granule shapes, indicating that the semisolid isothermal heat treatment can modify the Chinese script shaped Mg_2Si phase in the as-cast Mg−8%Al−1%Si alloy.

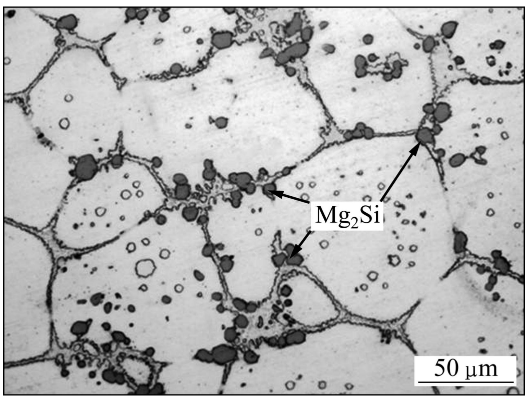

Fig. 6 OM image of Mg_2Si in Mg−8%Al−1%Si alloy after isothermal heat treatment

Since the melting temperature of Mg_2Si phase is 1085 °C [11], the modification of Chinese script shaped Mg_2Si phases can not be obtained in molten state during the semisolid isothermal heat treatment. There is curvature fluctuation on the surface of Mg_2Si phases because the fluctuation of the temperature and solute concentration exists during the solidification of the as-cast Mg−8%Al−1%Si alloy. Based on the above analysis, the modification mechanism of Chinese script shaped Mg_2Si phases can be explained by using the Gibbs-Thomson effect [24]. According to the Gibbs-Thomson formula, the Si concentration in the matrix corresponds to the site where the Mg_2Si phase has larger curvature, which can be expressed as [24]:

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

where $c_\alpha(r)$ is the Si concentration at the position with a curvature radius r; $c_\alpha(\infty)$ is the Si concentration at flat interface; V_B is the volume of Si atom; σ is the surface tension; k_B is the coefficient related to the shape and T is the temperature. Since the curvature radius of different positions for a Chinese script shaped Mg_2Si particle might be different, a concentration gradient of Si could be created between these positions. Therefore, during the semisolid isothermal heat treatment, the Si atoms would diffuse from the position where the curvature and Si concentration are respectively large and high to the flat interface where the Si concentration is lower, and then the balance of local Si concentration between these positions could be broken. Furthermore, in order to keep the balance of Si concentration, these positions with larger curvature could be dissolved. Oppositely, due to the supersaturation of Si concentration, the Mg_2Si phases could form in the α-Mg matrix corresponding to the flat interface. As a result, these positions with larger curvature could break, and then the granule shaped Mg_2Si phase would from, where different positions have close curvature radius. In spite of the above, the modification mechanism of Chinese script shaped Mg_2Si phases during semisolid isothermal heat treatment is not completely clear, and further investigation needs to be carried out.

4 Conclusions

1) It is possible to produce Mg−8%Al−1%Si alloy with non-dendritic microstructure by semisolid isothermal heat treatment.

2) With increasing holding temperature from 560 to 575 °C or holding time from 5 to 30 min, the liquid volume fraction increases, the average size of α-Mg grains grows and the globular tendency becomes more obvious.

3) The morphology of Mg_2Si phase transform from Chinese script shape to granule shape in Mg−8%Al−1%Si alloy during the semisolid isothermal heat treatment.

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等温热处理工艺参数对 Mg−8%Al−1%Si 合金半固态显微组织的影响

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摘 要：采用等温热处理工艺制备具有半固态显微组织的 Mg−8%Al−1%Si 合金，研究等温热处理工艺参数(等温温度和等温时间)对 Mg−8%Al−1%Si 合金显微组织的影响。结果表明：通过等温热处理工艺可以得到具有非枝晶组织的 Mg−8%Al−1%Si 合金。随着等温温度从 560 °C 升高至 575 °C 或等温时间从 5 min 延长至 30 min，半固态组织中的液相体积分数增加，α-Mg 晶粒尺寸变大并且其球化趋势明显。此外，在半固态组织中的共晶 Mg_2Si 相从汉字状转变成为颗粒状。研究等温热处理 Mg−8%Al−1%Si 合金中的共晶 Mg_2Si 相的形貌转变机制。

关键词：Mg−Al−Si 合金；半固态；显微组织；等温热处理；Mg_2Si 相

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