

## Effects of minor Sr addition on solidified structure and mechanical properties of Mg-Y-Cu alloy reinforced by long period ordered structure

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**Keywords:** Sr, Mg-Y-Cu alloy, solidified structure, mechanical properties, long period ordered structure

**Abstract.** Solidified structure and mechanical properties of Mg<sub>97</sub>Y<sub>2</sub>Cu<sub>1</sub> alloy reinforced by long period ordered structure with 0-0.3%wt Sr addition were investigated. The results indicate that the addition of Sr ranging from 0.1% to 0.2%, solidified structure of the alloy refines and homogenizes gradually. When the Sr addition increases to 0.3%, the alloy is over-modified. Mg<sub>17</sub>Sr<sub>2</sub> phase forms in the alloy with the addition of 0.2% and 0.3% Sr. With the increase of Sr addition, supercooling degree and mechanical properties of the alloy increases firstly, and then decreases. After adding 0.2% Sr to the alloy, the supercooling degree increases 6.7 °C in max. Mechanical properties of the alloy with 0.2% Sr addition is the best, the tensile strength and elongation of the alloy reach 215 MPa and 9.19%, which are increased by up to 24% and 58%, respectively, compared with the alloy without Sr addition.

### Introduction

Mg alloys offer numerous merits in physical, mechanical and casting properties, such as high specific strength and stiffness, good castability suitable for high pressure die casting, high damping capacity, good thermal and electric conductivity, which have a wide range in traffic, communication, electronics and aerospace fields [1, 2]. Mg alloys reinforced by long-period ordered structure are promising candidates for lightweight structural materials developed recently. As a new kind of reinforced phase in Mg alloys, the long-period ordered structure can improve mechanical properties greatly [3, 4]. Kawamura et al [5] found that Mg<sub>97</sub>Y<sub>2</sub>Cu<sub>1</sub> cast alloy has an 18R-type long period ordered structure that forms coherently with the  $\alpha$ -Mg matrix during casting.

The modification of microstructure is one of the most important, effective and simple methods for improving the mechanical properties of metallic materials. Sr has been proved to be an effective method for achieving a purposeful alteration of the microstructure of casting ingots, such as grain refinement. So far, Sr has been applied to refine grain of many Mg alloys. Alireza et al [6] found that Sr could reduce twinning and the dynamically recrystallized grain size of AZ31 alloy, also increase the surface cracking tendency during extrusion. Qiu et al [7] found that the 0.5% Sr addition could restrain the formation of  $\beta$ -Mg<sub>17</sub>Al<sub>12</sub> phase in Mg-6Zn-2Al-2Ca alloy. Yang et al [8] found that the addition of Sr could refine the grain size of Mg-9Li-3Al alloy and lead to the formation of the intermetallic compound. Peng et al [9] found that Sr could refine the microstructure of Mg-Nd-Zr alloy, and increase the volume fraction of the second phase. However, the refinement effect of Sr addition on solidified structure of Mg-Y-Cu alloy reinforced by long-period ordered structure is less researched. In this work, the effects of different Sr addition on solidified structure and mechanical properties of Mg<sub>97</sub>Y<sub>2</sub>Cu<sub>1</sub> alloy were studied.

## Experimental

Mg<sub>97</sub>Y<sub>2</sub>Cu<sub>1</sub> alloy was employed as the raw material for this study. Four alloys were prepared and their designed compositions are listed in Table 1. The experimental alloys were prepared from pure Mg, Mg-30Y and Mg-30Cu master alloys. Sr was added with the master alloy of Mg-25Sr. The alloy was first melted at 750 °C and held for 20 min under CO<sub>2</sub>+SF<sub>6</sub> mixture protection in an electrical resistance furnace using a mild steel crucible, and then the melt was poured into a graphite mold with a diameter of 25 mm, height of 80 mm and a wall-thickness of 5mm, which was preheated to the temperature of 180 °C. Effects of different Sr addition on solidified structure and mechanical properties of Mg<sub>97</sub>Y<sub>2</sub>Cu<sub>1</sub> alloy were studied. Samples of the experimental alloys were etched with a solution of 2%(volume fraction) nitric acid and ethyl alcohol, and then examined by an Olympos optical microscope and Quanta200 type scanning electron microscope (SEM) equipped with an Oxford energy dispersive spectrometer (EDS). Phases in the experimental alloys were analyzed by X-ray diffractometer (XRD). Samples of around 15 mg were heated in a flowing argon atmosphere from room temperature to 700 °C for 5 min before being cooled down to 100 °C. The cooling curves were recorded at a cooling speed of 10 °C/min.

Table 1 Nominal composition of experimental alloys

Alloy	w(Y)/%	w(Cu)/%	w(Sr)/%	w(Mg)/%
Mg <sub>97</sub> Y <sub>2</sub> Cu <sub>1</sub>	6.84	2.46	-	Bal.
Mg <sub>97</sub> Y <sub>2</sub> Cu <sub>1</sub> -0.1Sr	6.84	2.46	0.1	Bal.
Mg <sub>97</sub> Y <sub>2</sub> Cu <sub>1</sub> -0.2Sr	6.84	2.46	0.2	Bal.
Mg <sub>97</sub> Y <sub>2</sub> Cu <sub>1</sub> -0.3Sr	6.84	2.46	0.3	Bal.

## Results

Figure 1 and Figure 2 show morphology of primary phase and second phase of the alloy with different Sr addition. It can be seen that without modification of Sr, coarse equiaxed dendrite and continuous net-worked secondary phase can be normally observed in the alloy. The average grain size is about 300 μm and the distribution of the second phase is uneven. The addition of Sr ranging from 0.1% to 0.2%, primary grains of the alloy refine gradually. Second phase of the alloy becomes more uniform, and its volume fraction increases. When the addition of Sr is 0.2%, grain size of the alloy reaches about 100 μm, and morphology of second phase changes from continuously irregular strip-like shape to discontinuously irregular strip-like shape and fine granule-like shape. When the Sr addition increases to 0.3%, the alloy is over-modified. The above results indicate that Sr added to Mg<sub>97</sub>Y<sub>2</sub>Cu<sub>1</sub> alloy can refine and homogenize solidified structure of the alloy.

Figure 3 shows the X-ray diffraction (XRD) patterns of alloy with different Sr addition. It is shown that without or with the addition of 0.1% Sr in Mg<sub>97</sub>Y<sub>2</sub>Cu<sub>1</sub> alloy, there are primary α-Mg and Mg<sub>12</sub>Y<sub>1</sub>Cu<sub>1</sub> phase, furthermore a few of new Mg<sub>17</sub>Sr<sub>2</sub> phase forms in the alloy with the addition of 0.2% and 0.3% Sr.

Figure 4 shows the distribution of Sr element by surface scanning EDS analysis of the alloy with 0.2% Sr addition. It can be seen that that majority of Sr elements are distributed along the grain boundary in second phase, farthing of them are distributed in the matrix. It indicates that Sr distributing in front of the solid-liquid interface may inhibit the grain growth of the alloy.

Figure 5 shows the cooling curves of the different Sr-modified alloys. The peak temperature

was taken from the top of each peak. All these characteristic temperatures are summarized in Table 2. The crystallization temperature ( $T_L$ ) was taken by the extrapolation method from the rising point of the first exothermic peak. It can be found that after adding 0.1%-0.3%Sr,  $T_L$  of the alloy decreases. The supercooling degree  $\Delta T$  can be expressed as  $\Delta T = T_m - T_L$ , in which  $T_m$  is the melting temperature of the alloy. It is supposed that  $T_m$  is unchanged after adding Sr element. With the increase of Sr addition, the supercooling degree of the alloy increases firstly, and then decreases. After adding 0.2% Sr to the alloy, the supercooling degree increases 6.7 °C in max. It can also be found that  $T_U$ , the formation temperature of the  $Mg_{12}Y_1Cu_1$  phase, increases from 564 °C to 581 °C with 0.1% Sr addition. However,  $T_U$  decreases to 570 °C with 0.3% Sr addition.

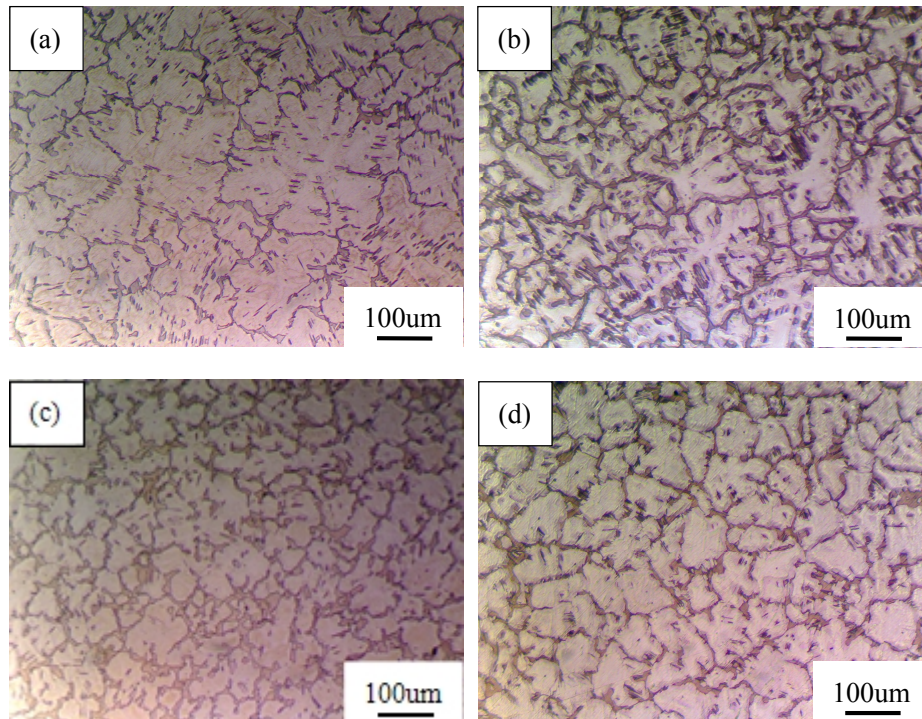


Figure 1 Morphology of primary phase of the alloy with different Sr addition  
(a) 0% Sr (b) 0.1% Sr (c) 0.2% Sr (d) 0.3% Sr

The effects of different Sr addition on mechanical properties of the alloy are shown in Fig.5. It is shown that with the increase of the addition of Sr, the mechanical properties of the alloy increases firstly, and then decreases. The mechanical properties of the alloy with 0.2% Sr addition is the best, the tensile strength and elongation of the alloy reach 215MPa and 9.19%, which are increased by up to 24% and 58%, respectively, compared with the alloy without Sr addition.

The fracture morphologies of the alloy without and with 0.2% Sr addition are shown in Fig.7. It is clear that without Sr addition treatment, the alloy exhibits the brittle batten feature, which is the typical quasi cleavage fracture. Comparatively, crystalline refining grain can restrain the cleavage fracture. There are many irregular distribution tear ridge in the fracture of sample with 0.2% Sr addition, the number of brittle batten decreases obviously and the number of dimple increases evidently, which is also quasi cleavage fracture.

## Discussion

It is well know that the nucleation and grain growth are the main influencing factors to determine the final grain size of the alloy. The effect of Sr addition on the  $\alpha$ -Mg phase of

Mg<sub>97</sub>Y<sub>2</sub>Cu<sub>1</sub> alloy can be explained on the basis of growth restriction factor (GRF) [10].

$$GRF = \sum_i m_i c_{0,i} (k_i - 1) \quad (1)$$

Where,  $m_i$  is the slope of the liquidus line in the binary phase diagram,  $c_{0,i}$  is the initial concentration of component  $i$ , and  $k_i$  is the equilibrium partition coefficient of component. In general, GRF represents the ability to inhibit grain growth. The greater the value of GRF is, the stronger its ability is to inhibit grain growth. It can be seen that the GRF value increases with Sr content. Accordingly, the grain growth is inhibited with the increase of Sr addition, realizing the goal of grain refinement. In addition, Sr, as the surface activity element, is similar to Ca with strong segregation ability in the melt. It forms the intensive constitutional undercooling in a diffusion layer ahead of the advancing solid/liquid interface, which also restricts grain growth and promotes nucleation.

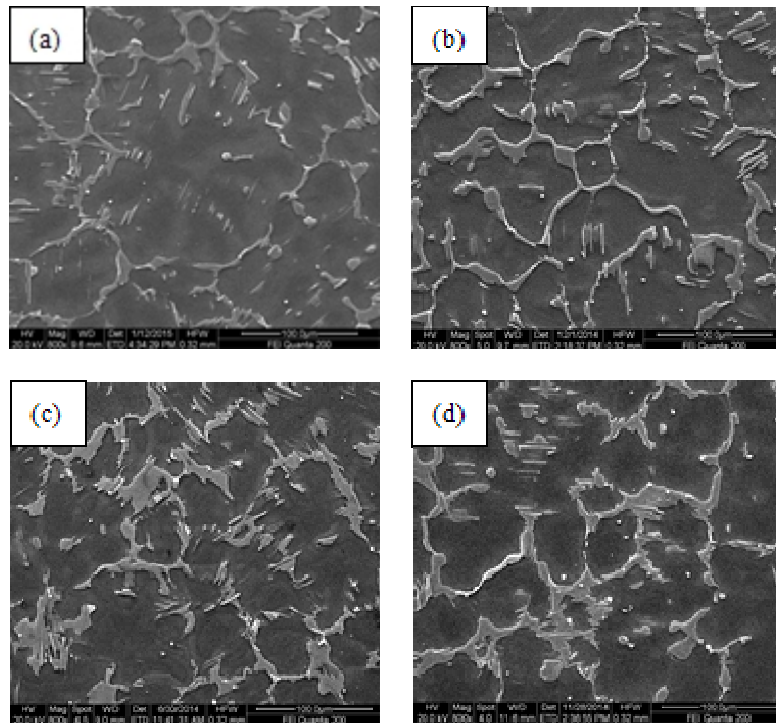


Figure 2 SEM images of the alloy with different Sr addition  
(a) 0% Sr (b) 0.1% Sr (c) 0.2% Sr (d) 0.3% Sr

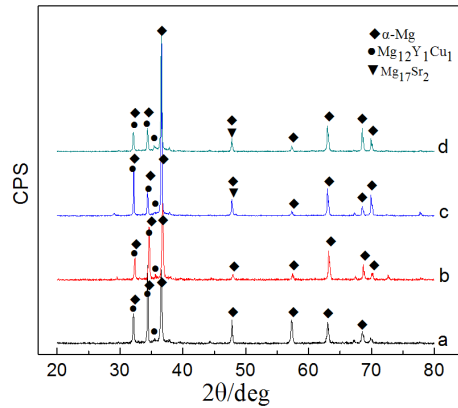


Figure 3 XRD patterns of the alloy with different Sr addition  
(a) 0% Sr (b) 0.1% Sr (c) 0.2% Sr (d) 0.3% Sr

During the solidification process, the added Sr increases the supercooling degree of the alloy.

According to the classical nucleation theory, the relationship between critical nucleation radius and supercooling degree is expressed as Eq.2 [11].

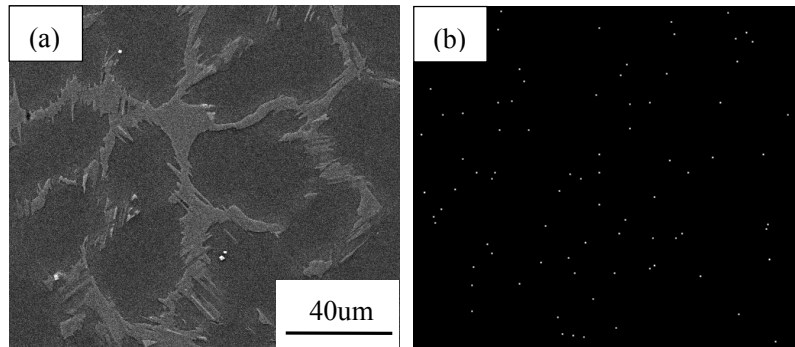


Figure 4 Distribution of Sr element in the alloy with 0.2% Sr addition

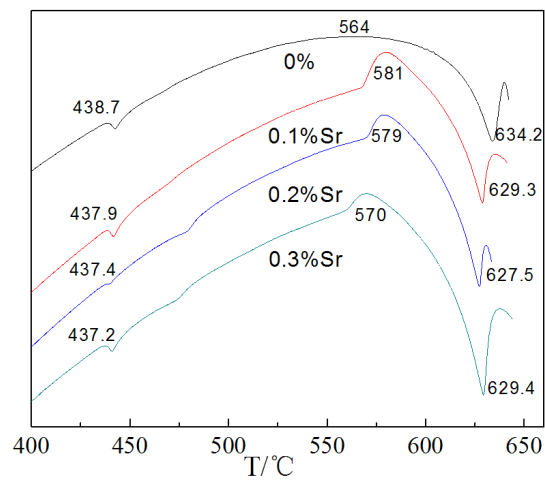


Figure 5 DSC cooling curves of the alloy modified with different Sr addition  
(a) 0% Sr (b) 0.1% Sr (c) 0.2% Sr (d) 0.3% Sr

Table 2 Characteristic temperature of experimental alloys in DSC cooling curves

Alloy	$T_E/^\circ\text{C}$	$T_U/^\circ\text{C}$	$T_L/^\circ\text{C}$	$\Delta T/^\circ\text{C}$
$\text{Mg}_{97}\text{Y}_2\text{Cu}_1$	438.7	564	634.2	0
$\text{Mg}_{97}\text{Y}_2\text{Cu}_1\text{-0.1Sr}$	437.9	581	629.3	4.9
$\text{Mg}_{97}\text{Y}_2\text{Cu}_1\text{-0.2Sr}$	437.4	579	627.5	6.7
$\text{Mg}_{97}\text{Y}_2\text{Cu}_1\text{-0.3Sr}$	437.2	570	629.4	4.8

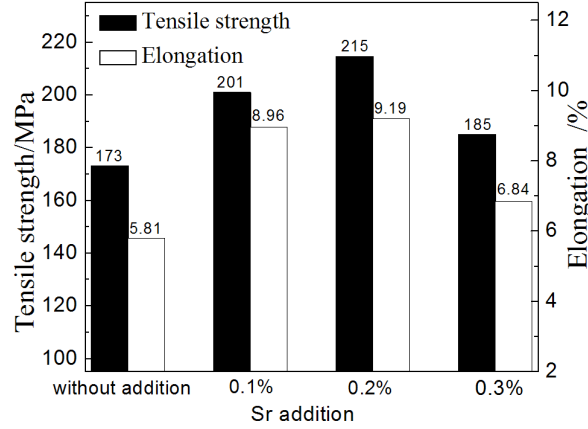


Figure 6 Effect of Sr addition on mechanical properties of the alloy

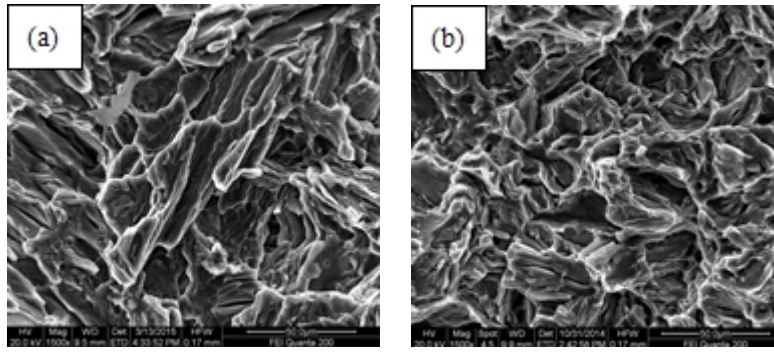


Figure 7 SEM images of fractographs of the alloy  
(a) 0% Sr (b) 0.2% Sr

$$r_k = \frac{2\sigma T_m}{L_m \cdot \Delta T} \quad (2)$$

Where,  $\sigma$  is embryos per unit area of surface energy,  $L_m$  is the crystal latent heat, in which parameters are all pre-determined. Under the given identical solidification condition (i.e cooling rate), the nucleation ratio mainly depends on the supercooling degree of the alloy. Generally, the higher the supercooling degree of the alloy is, the less the critical nucleation radius in the melt is. In this study, the increase of the supercooling degree induces the decrease of the critical nucleation radius in the alloy modified by Sr addition under the identical solidification condition. With increasing Sr addition from 0.1% to 0.2%, the supercooling degree increases, and the restriction on grain growth and the promotion on nucleation become more apparent. The grain size of  $\alpha$ -Mg matrix decreases from 300  $\mu\text{m}$  to 100  $\mu\text{m}$ . With 0.3% Sr addition, the supercooling degree of the alloy decreases, so grains of the alloy coarsen.

Second phase of the alloy is mainly formed on the grain boundary of  $\alpha$ -Mg matrix, so fine and uniform crystal is favorable to the morphology and distribution of second phase. After added more than 0.3% Sr, primary grains coarsen, so homogeneity of second phase decreases.

Grain boundary strengthening presented by the well-known hall-petch relation, is an established method of increasing the yield stress and is the main contributor to the improved mechanical properties. Grain refinement is an important factor to improve the mechanical properties of  $\text{Mg}_{97}\text{Y}_2\text{Cu}_1$  alloy in this experiment. When the addition of Sr is at 0~0.2%, with the increase of the addition of Sr, grain size of alloy decreases, so the tensile strength and elongation of the alloy increase. When the addition of Sr reaches 0.3%, the tensile strength and elongation of the alloy decrease because of grain coarsening. In addition, the morphology and distribution of second phase



also play an important factor to the improvement of mechanical properties of the alloy, because  $\text{Mg}_{97}\text{Y}_2\text{Cu}_1$  alloy is reinforced by long-period ordered structure. After added Sr treatment, second phase of the alloy becomes more uniform, its volume fraction increases, which is also beneficial to mechanical properties of the alloy.

## Conclusions

1) The addition of Sr ranging from 0.1% to 0.2%, solidified structure of the alloy refines and homogenizes gradually. When the Sr addition increases to 0.3%, the alloy is over-modified.  $\text{Mg}_{17}\text{Sr}_2$  phase forms in the alloy with additions of 0.2% and 0.3% Sr.

2) With the increase of Sr addition, supercooling degree and mechanical properties of the alloy increases firstly, and then decreases. After adding 0.2% Sr to the alloy, the supercooling degree increases 6.7 °C in max. Mechanical properties of the alloy with 0.2% Sr addition is the best, the tensile strength and elongation of the alloy reach 215 MPa and 9.19%, which are increased by up to 24% and 58%, respectively, compared with the alloy without Sr addition.

## Acknowledgements

This work was financially supported by the National Natural Science Foundation Project (51261026).

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