Grain-refinement strengthening effect of Y and Sm on magnesium alloy AZ81

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Abstract. The grain refinement mechanism and resulting grain-refinement strengthening effect of rare earth elements Y and Sm on magnesium alloy AZ81 have been investigated by means of microstructure analysis, tensile tests and theoretic calculation. The results show that the formation of high melting-point Al2Y and Al2Sm phases is observed in magnesium alloy AZ81 after 1.8 wt% Y and Sm addition. The phases act as the heterogeneous nucleation cores of α-Mg matrix, and refine the grain size. It leads to the effective grain-refinement strengthening and enhance the strength of the alloy.

1. Introduction

With the two increasingly serious worldwide problems energy crisis and environmental pollution, more and more attention has been paid to energy saving and environmental protection of automobiles and other means of transport. Using lightweight structural materials to reduce the weight of automobile body can not only reduce fuel consumption to achieve the purpose of energy saving, but also reduce exhaust emissions to meet the requirements of environmental protection [1]. Magnesium has a density of 1.74g/cm³, which is lower than that of aluminium and steel and is comparable to that of plastics. Therefore, as the lightest metal materials available in industry, magnesium alloys are more and more widely used in automobiles [2]. The weight of magnesium alloy has become one of the criteria for evaluating the performance of one automobile. The number of magnesium alloy parts has been used by major automotive companies in the world as a measure of whether their automotive products are technologically advanced or not [3,4].

AZ81 alloy is one of the typical representatives of Mg-Al-Zn (AZ) alloys and a widely used brand of magnesium alloys. It is a good combination in composition selection, which has not only good casting properties, but also good comprehensive mechanical properties. However, the mechanical properties of magnesium alloy AZ81 are not high at room temperature and are poor at high temperature, which limits its application in automobile parts [5,6]. The introduction of rare earth elements for grain-refinement strengthening has proved to be a very effective method to improve the mechanical properties of magnesium alloy AZ81 [7-10]. Y and Sm is an interesting combination of heavy and light rare earth elements, and a new type of high strength magnesium alloy with Y and Sm are developed [11-14]. In this paper, rare earth elements Y and Sm are introduced to magnesium alloy.
AZ81, the grain-refinement mechanism of Y and Sm is studied, and the related grain-refinement effect is evaluated.

2. Experimental
The design composition of AZ81 alloy was Mg-8.0Al-1.0Zn. The total addition of Y and Sm was 0 and 1.8wt%, and the mass ratio of Y and Sm was 2:1. Raw materials included pure aluminium, zinc and magnesium. Y and Sm were added in the form of master alloys Mg-25 wt%Y and Mg-25 wt%Sm. Before smelting, all raw materials should be dried to avoid bringing in moisture.

Alloy smelting was made by using an induction furnace and a corundum crucible. After the raw material melted, the alloy liquid was heated to 720 °C and then poured into a preheated metal mould. Melting and pouring process was protected with 1 vol.% SF₆ + 99 vol.% CO₂ gas mixture. After casting, the alloy ingot was divided into thin pieces and then treated by 420 °C/12 h solid solution and 220 °C/12 h aging.

Tensile specimens were machined. Tensile tests were carried out on Shimadzu AG-I 250 kN test equipment with a tensile rate of 1 mm/min. Metallographic samples were simultaneously prepared. The phase analysis was carried out by D8 Advance X-ray Diffraction (XRD). The microstructure was observed by Olympus optical microscope, and the grain size of the alloy was determined by the linear intercept method. The mechanism and the related strengthening effect of grain refinement were analyzed and calculated theoretically.

3. Results
3.1. Microstructure and mechanical properties
Figure 1 shows the microstructure morphologies of the two alloys after solution and aging treatment. It can be seen that the grain size of magnesium alloy AZ81 is large. The number of precipitate phase is small, and its distribution is uneven, as shown in Figure 1(a). After the addition of 1.8% rare earth elements Y and Sm, the microstructure of the alloy is improved, and the grain size is refined obviously. The number of discontinuous reticulated phase is reduced. The number of granular precipitate phases is increased, and its distribution is more uniform, as shown in Figure 1(b). It will have a beneficial effect on the mechanical properties, especially the strength of the alloy.

![Microstructure of the aged alloys](image)

Figure 1. Microstructure of the aged alloys

Figure 2 shows the XRD pattern of magnesium alloy AZ81 with 1.8% Y and Sm content. The results show that the addition of rare earth elements Y and Sm results in the formation of high melting-point phases Al₂Y and Al₂Sm in addition to α-Mg matrix and Mg₁₇Al₁₂ phase in the alloy.
The tensile mechanical properties of the two alloys treated by solution and ageing are shown in Table 1. It can be seen that the room temperature tensile strength and yield strength of the alloy are not high without rare earth elements, 203 MPa and 144 MPa, respectively. When the total content of Y and Sm is 1.8%, the tensile strength and yield strength of the alloy are increased significantly, reaching 236 MPa and 186 MPa, respectively. Meanwhile, the elongation of the alloy is also increased obviously. Therefore, the addition of 1.8% Y and Sm can not only improve the room temperature strength, but also improve the plasticity of magnesium alloy AZ81.

Table 1. Mechanical properties of the aged alloys

| Alloy             | Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) |
|-------------------|------------------------|----------------------|----------------|
| AZ81              | 203                    | 144                  | 4.5            |
| AZ81+1.8(Y+Sm)    | 236                    | 186                  | 8.0            |

3.2. Grain-refinement mechanism of Y and Sm

It is generally believed that an important condition for nucleation of new phases on the substrate is to satisfy the mismatch degree $\delta$ between low exponential crystal planes less than 15%. According to Bramfitt's two-dimensional lattice mismatch model, the formula for calculating mismatch degree $\delta$ is as follows [15]:

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

In the formula, $(hkl)$ is a low exponential crystal plane, $[uvw]$ is a low exponential crystal direction on $(hkl)$ crystal plane, $d_{[uvw]}$ is the atomic spacing along $[uvw]$ crystal direction, $s$ and $n$ represent the substrate and the new phase respectively, and $\theta$ is the angle between the substrate and the new phase orientations.

The lattice mismatch degree between $\text{Al}_2\text{Y}$ and $\alpha$-Mg has been calculated previously [16]. Now only the lattice mismatch degree between $\text{Al}_2\text{Sm}$ and $\alpha$-Mg is calculated. $\text{Al}_2\text{Sm}$ is a face-centered cubic structure with lattice constant $a=0.794$ nm [1,2]. Based on the lattice constants of $\alpha$-Mg ($a=0.321$ nm, $c=0.521$ nm) [1,2] and the formula (1), the lattice mismatch degree between the low exponential crystal planes (100), (110), (111) of $\text{Al}_2\text{Sm}$ and the base plane (0001) of $\alpha$-Mg can be calculated, as shown in Table 2.

Table 2. Calculation values of lattice mismatch degree $\delta$ between $\text{Al}_2\text{Sm}$ and $\alpha$-Mg

| Matching planes $[uvw]_s$ | $[uvw]_n$ | $d_{[uvw]_s}$/nm | $d_{[uvw]_n}$/nm | $\theta$(°) | $\delta$/% |
|---------------------------|-----------|------------------|------------------|-----------|----------|
| (100)$_{\text{Al}_2\text{Sm}}$(0001)$_{\text{Mg}}$ | [010]     | [1120]           | 0.794            | 0.642     | 0        |
|                           | [011]     | [0110]           | 1.123            | 1.284     | 15       | 11.56    |
|                           | [001]     | [1100]           | 1.588            | 1.668     | 0        |
From Table 2 and previous results [16], it can be seen that the lattice mismatch degrees of low index crystal planes between Al$_2$Y/Al$_2$Sm phase and α-Mg matrix (substrate) are less than 15%. Therefore, Al$_2$Y and Al$_2$Sm phases can be used as effective heterogeneous nucleation cores of α-Mg matrix, which can promote the nucleation of the alloy under low undercooling,2(122,258),(867,430)

3.3. Grain-refinement strengthening effect of Y and Sm

In general, the relationship between yield strength $\sigma_y$ and grain size $d$ of polycrystalline materials can be expressed by Hall-Petch formula as $^{[1,2]}$ 

$$\sigma_y = \sigma_0 + kd^{-1/2}$$  \hspace{1cm} (2)

The effect of rare earth elements Y and Sm on the grain-refinement strengthening of magnesium alloy AZ81 can be calculated by Hall-Petch formula. Assuming that the grain sizes of AZ81 and AZ81+1.8 (Y+Sm) alloys are $d_1$ and $d_2$, and the yield strengths are $\sigma_{y1}$ and $\sigma_{y2}$, respectively, it can be obtained from the formula (2) that

$$\sigma_{y1} = \sigma_0 + kd_1^{-1/2}$$  \hspace{1cm} (3)

$$\sigma_{y2} = \sigma_0 + kd_2^{-1/2}$$  \hspace{1cm} (4)

According to the above two formulas, it can be obtained as follows

$$\sigma_{y2} - \sigma_{y1} = k(d_2^{-1/2} - d_1^{-1/2})$$  \hspace{1cm} (5)

Combined with the above results of microstructure analysis (see Figure 1), the grain sizes $d_1=120$ µm and $d_2=40$ µm can be obtained by the linear intercept method. The $k$ value of commonly used magnesium alloys is 280-320 MPa·µm$^{1/2}$ $^{[1,2]}$, and here $k = 300$ MPa·µm$^{1/2}$. By substituting these data into formula (5), the contribution of grain-refinement strengthening by Y and Sm to the yield strength of magnesium alloy AZ81 can be calculated as

$$\sigma_{y2} - \sigma_{y1} = 300 \times (40^{-1/2} - 120^{-1/2}) = 20$$ MPa

Combined with the above tensile test results (see Table 1), after the addition of 1.8% Y and Sm, the yield strength of AZ81 alloy is increased by

$$186 - 144 = 42$$ MPa

Among which, the contribution of grain-refinement strengthening is 20 MPa, accounting for 47.6% of the total increase of yield strength. Therefore, grain-refinement strengthening is a very important strengthening mechanism for magnesium alloys, and its contribution to the strength of magnesium alloys should be paid enough attention.

4. Conclusions

Al$_2$Y and Al$_2$Sm phases with high melting-point can be formed by adding 1.8 wt% rare earth elements Y and Sm to magnesium alloy AZ81. The mismatch degree of low index crystal planes between them and α-Mg matrix is less than 15%. They can become effective heterogeneous nucleation cores of α-Mg matrix and refine the grain size of the alloy.

The addition of Y and Sm to magnesium alloy AZ81 results in an effective grain-refinement strengthening and improve the strength of the alloy. The theoretical calculation results show that the contribution of grain-refinement strengthening effect by Y and Sm to the yield strength of magnesium alloy AZ81 is 20 MPa, accounting for 47.6% of the total increase (42 MPa) of yield strength.
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References
[1] Ding W J 2007 Magnesium alloys science and technology (Beijing: Science Press) pp 1-399
[2] Chen Z H 2007 Heat resistant magnesium alloys (Beijing: Chemical Industry Press) pp1-534
[3] Peng Y H 2008 The application of magnesium alloy materials in auto industry Auto. Parts 20(2008)46
[4] Zhang C X, Chen P L, Chen H J, Shi A J and Guan S K 2008 Application and research progress of magnesium alloys in automobile industry Foundry Tech. 29(2008)531
[5] Wang X Q, Li Q A and Zhang X Y 2008 Effects of yttrium and neodymium on microstructure and mechanical properties of AZ81 magnesium alloy Rare Metal Mat. Eng. 37(2008)62
[6] Liu W J, Li Q A, Chen Z and Song X J 2013 Research progress on enhancing heat resistance of AZ81 alloy Hot Working Tech. 42(2013)11
[7] Wang H Y, Liu S F, Han H and Kang L G 2008 Progress of grain refinement and refining mechanism for magnesium alloys Foundry Tech. 29(2008)1734
[8] Liao H M, Long S Y, Xiao H Q and Zhu Z B 2008 Effect of Ce-rich mischmetal addition on microstructure and tensile properties of AZ81 alloy J. Chin. Soc. Rare Earths 26(2008)792
[9] Li M J and Ding Y T 2015 Effect of Gd and Sm on the microstructure and mechanical properties of AZ81 magnesium alloy Foundry 64(2015)105
[10] Li Q A, Chen X Y, Liu W J and Chen Z 2015 Effects of Sm and Nd on microstructure and properties of AZ81 magnesium alloy Chin. Rare Earths 36(2015)36
[11] Zhang Q, Li Q A, Jing X T and Zhang X Y 2010 Microstructure and mechanical properties of Mg-10Y-2.5Sm alloy J. Rare earths 28(2010)375
[12] Zhang Q, Chen J and Li Q A 2018 Strength stability of aging hardened Mg-10Y-1.5Sm alloy Rare Metal Mat. Eng. 47(2018)799
[13] Zhao Y, Wang Q D and Gao Y 2012. Effect of zinc addition on microstructure and mechanical properties of Mg-7Y-3Sm-0.5Zr alloy Trans. Nonferrous Met. Soc. China 22(2012)1924
[14] Lyu S Y, Li G D, Hu T, Zheng R X, Xiao W L and Ma C L 2018 A new cast Mg-Y-Sm-Zn-Zr alloy with high hardness Mater. Lett. 217(2018)79
[15] Bramfitt B L 1970 Effect of carbide and nitride additions on the heterogeneous nucleation behavior of liquid iron Metall. and Mater. Trans. B 1(1970)1987
[16] Li P and Wang Y 2015 Grain-refinement strengthening effect of Y on magnesium alloy AZ81 Chin. Rare Earths 36(2015)85