

Microstructure and segregation of magnesium alloy solidified under magnetostatic field^①

XU Guang-ming(许光明), BAO Weiping(包卫平), CUI Jian-zhong(崔建忠)
(The Key Laboratory of Electromagnetic Processing of Materials, Ministry of Education,
Northeastern University, Shenyang 110004, China)

Abstract: Magnesium alloys are materials with predominant performance, but its formability is needed to be improved. Increasing the content of soluble inside grain, the formability will be improved. The results show that when magnetostatic field is applied to the process of solidification of magnesium alloy, the grain is refined, and the soluble content inside grain increases, on the contrary the content of soluble decreases at grain boundary. Compared with the common solidification, when the magnesium alloy ZK60 is solidified under magnetostatic field, the content of calcium and zinc decrease respectively from 15.62%, 5.6% to 14.85%, 3.7% at grain boundary; the content of zinc increases from 0.68% to 0.91% inside grain. This will increase distortion inside matrix and more dislocation will supply slid deformation, as a result the formability will be improved.

Key words: magnesium alloy; magnetostatic field; segregation; alloying element

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1 INTRODUCTION

Nonferrous materials has displayed more and more important role in the 21st century. Among the nonferrous materials, magnesium alloy is the best one that is worth to be developed. Magnesium alloy is the lightest practical material in the nonferrous materials, but magnesium is a metal with a strong electronegativity. Its standard electric potential is -2.363 V, and its erosion resistance is not good. Because of the oxidization of magnesium alloy during its melting, formation and application, its advantage have not been best utilized, and its application is limited. As the development of the refining technology and advanced formation technology since 1990s, magnesium alloy was applied practically. It was widely used in not only aerospace but also automotive industry, electronic information industry and household fields^[1].

Magnesium alloy was firstly used in the aerospace field. Now it has been the first choice for the structural materials in automotive industry, as the automotive industry develops in the direction of light mass, saving energy, recovery, and preventing pollution.

Because of the special radar absorption characteristic, low density and high rigid, the magnesium alloy has been the hot material in the telecommunication industry.

China is a country with sufficient magnesium resource, and the output of original magnesium is only next to that of America in the world^[2,3]. The quanti-

ty demand of magnesium increased by 20% in the world recently. But the application of magnesium alloy in China is little, and most of original magnesium is used to export, which leads to the waste of magnesium resource. So, the urgent work for us is to develop technology of producing magnesium alloy, and to develop deformation industry to manufacture finishing product of magnesium alloy.

Recently, many studies about magnetostatic field on aluminum alloy^[4,5] have been done, but there is little on magnesium alloy. The studies on magnesium alloy mainly focus on grain refining^[6], effect of element on magnesium alloy^[7-10], and the effect of technology on the properties of magnesium alloy^[11-12]. The results of the study on aluminum alloy show that the solid solubility of the alloy elements in aluminum alloy is greatly increased, for example, the solid solubility of zinc in the aluminum alloy is increased from 4.3% to 5.1%, and the solid solubility of magnesium is increased from 1.13% to 1.9%, and the maximum is got at the magnetostatic field^[13]. Therefore it is worth to study the microstructure of magnesium alloy solidified in the magnetostatic field, and to build up the foundation of study on magnesium alloy.

2 EXPERIMENTAL

2.1 Device and materials

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Correspondence: XU Guang-ming, Associate professor, PhD; Tel: + 86-13304049003; E-mail: xu_gm@hotmail.com

The schematic sketch of experimental equipment is shown in Fig. 1. It is designed according to electromagnetic theory and experience^[14, 15]. The inner diameter of induction coil is 50 mm, the outer diameter is 150 mm, and the coil is made up with 8 layers of copper pipe. The coil is supplied by a special current source, which can supply both the direct current and the alternating current. Two ceramic pipes with different diameters were placed within the coil, and the gap space between two ceramic pipes is filled up with asbestos, also a resistance wire was placed in this gap to heat the magnesium alloy. The crucible for loading magnesium alloy is set up in the center of the inner ceramic pipe, where the biggest magnetic induction intensity appears.

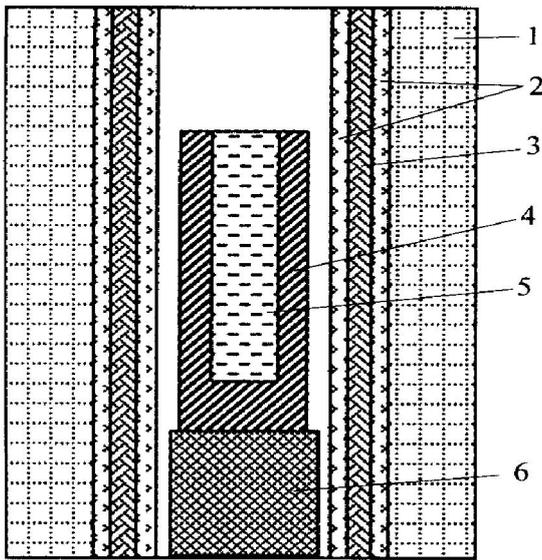


Fig. 1 Schematic sketch of process of solidification under electromagnetic field

- 1—Solenoid coil; 2—Ceramic tube;
- 3—Asbestos resistance wire; 4—Ceramic crucible;
- 5—Molten alloy; 6—Refractory brick

The magnesium alloy was firstly molten and refined, and the molten magnesium alloy was poured into the crucible; then the molten magnesium alloy was heated by the energy supplied by the resistance wire, and adjusted to a constant temperature, held at the temperature for some time. At last, the current of the resistance wire was turned off, and the current of coil was turned on. The molten magnesium alloy was cooled and solidified in the electromagnetic field, to ambient temperature by the cooling of the cooling water in the coil.

In order to research the effect of magnetic field on the microstructure of magnesium alloy, the same experiment was done without electromagnetic field. The magnesium alloy used in this experiment is ZK60, and its chemical constitution is as the following^[16]: $w(\text{Zn}) = 5.0\% - 7.0\%$, $w(\text{Zr}) = 0.3\% - 0.8\%$, $w(\text{Fe}, \text{Si}) < 0.01\%$, $w(\text{Cu}) < 0.03\%$, $w(\text{Ni}) < 0.005\%$, and balance magnesium.

The microstructure of magnesium alloy was observed with optical microscope, and the different microstructure of magnesium alloy was discovered.

2.2 Condition of electromagnetic field

In order to supply a uniform magnetic field for the solidification of magnesium alloy, there isn't any ferrous-magnetic material used in the equipment, and most of them are made of ceramic and brick, so the distribution of electromagnetic field won't be affected by the material of equipment. The current of coil is direct current, the current of coil is 170A, and the magnetic induction intensity is about 0.28T.

3 RESULTS AND ANALYSIS

During the experiment, the magnesium alloy was molten and refined firstly, then held at 650 °C for 30 min, at last the magnesium alloy was cooled and solidified under electromagnetic field. The sample of magnesium alloy was sawn into two parts along the central section, and the microstructure of the sample was gotten, as shown in Figs. 2 and 3.

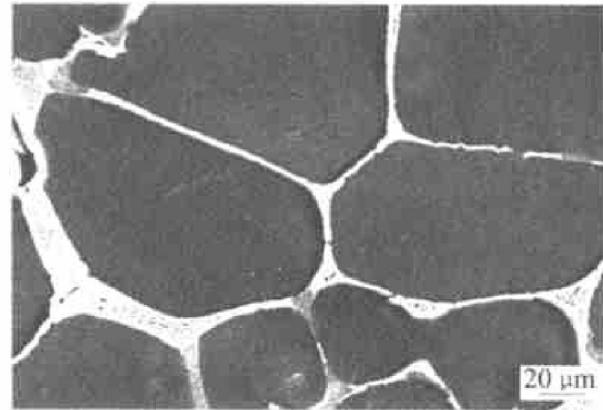


Fig. 2 Cast microstructure of ZK60 solidified without electromagnetic field

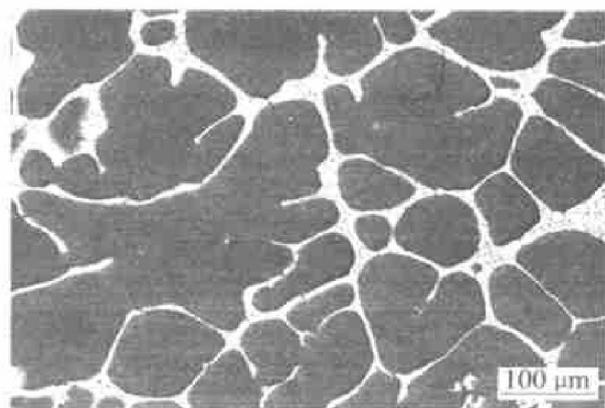


Fig. 3 Cast microstructure of ZK60 solidified in magnetostatic field

Fig. 2 is the cast microstructure of ZK60 solidified in common condition. From Fig. 2 we can see that the cast microstructure of ZK60 is composed of coarse grains when the magnesium alloy ZK60 solidified without electromagnetic field, and the grain boundary is composed of continuous and thick eutectic^[16].

Fig. 3 describes the cast microstructure of magnesium alloy ZK60 solidified in magnetostatic field. It can be found in Fig. 3 that when magnesium alloy solidifies in magnetostatic field, the microstructure is greatly changed and different from that in common cases, with the grain refined, the thickness of boundary eutectic decreasing, and the grain boundary becoming discontinuous. Also massive small eutectic appears near the grain boundary. All these will improve the mechanical property, especially increase the plasticity of magnesium alloy.

In order to investigate the reason why this phenomenon takes place, more research was done about the microstructure and the distribution of alloying element. The similar grain boundaries were selected to investigate the effect of magnetic field on the solid solubility.

In order to analyze the change of solid solubility of alloying element in magnesium under different conditions, energy disperse X-ray detector was used to scan the distribution of alloying element in magnesium alloy along the path described in Fig. 4.

Responding to the microstructure, the energy distribution along the paths shown in Fig. 4 are described in Fig. 5. From the energy distribution, it can be found that the grain boundary is greatly reduced when the magnesium alloy solidifies in magnetic field.

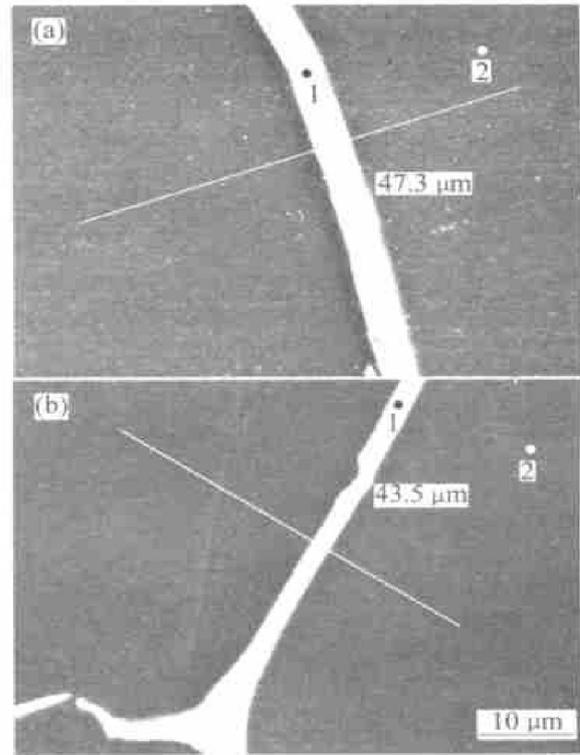


Fig. 4 Scan paths of alloying element in Mg alloy under different conditions
 (a) —Solidified without magnetic field;
 (b) —Solidified under magnetic field

Fig. 6 is the energy scanning at points 1 and 2 in Fig. 4(a), and the microstructure is obtained by solidifying without magnetic field. Fig. 7 is the energy scanning at points 1 and 2 in Fig. 4(b), whose microstructure is obtained by solidifying under magnetic field.

The energy scan at grain boundary and inside grain shows that the solute atoms content increases inside grains and decreases at the grain boundary under magnetic field. The scanned result is described in Table 1.

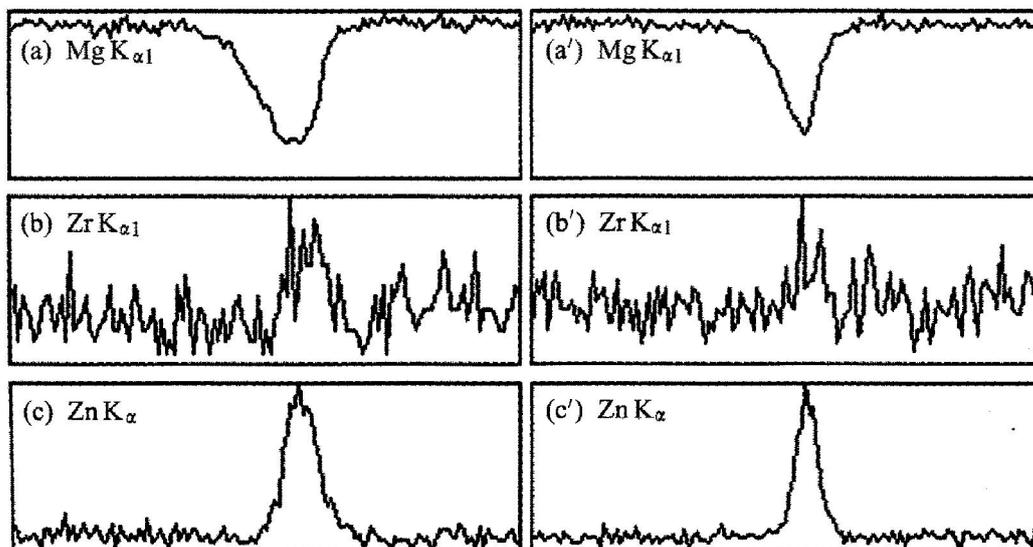


Fig. 5 EDS analysis with element line scanning in Mg alloy under different conditions
 (a), (b), (c) —Mg alloy solidified without magnetic field; (a'), (b'), (c') —Mg alloy solidified under magnetic field

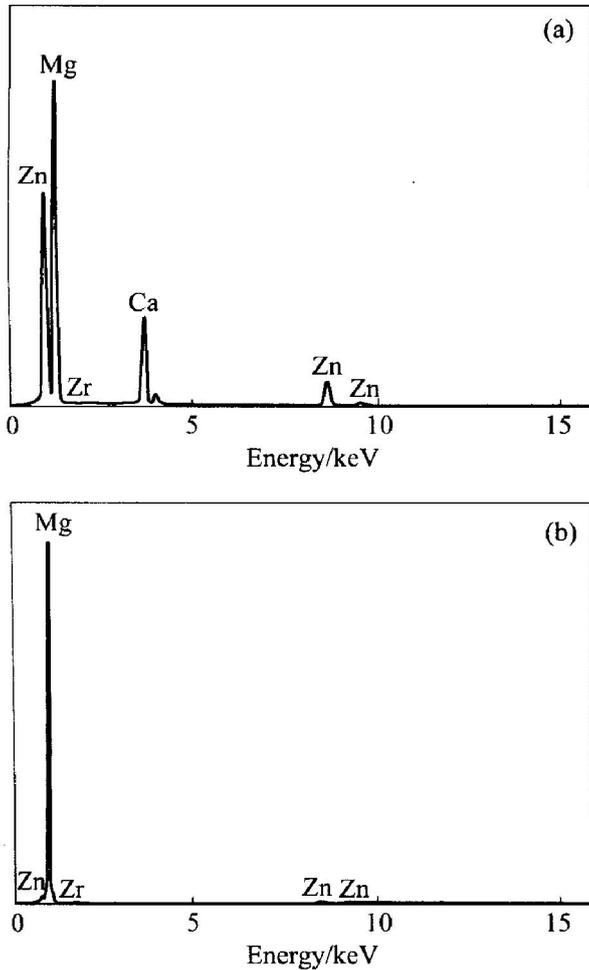


Fig. 6 Distribution of energy at points in microstructure solidified without magnetic field
 (a) —Energy distribution at point 1 of Fig. 4(a);
 (b) —Energy distribution at point 2 of Fig. 4(a)

Table 1 Element content at different points shown in Fig. 4(molar fraction, %)

Condition	Point	Mg	Zn	Zr	Ca
Common	1	71.22	15.62	0.3	5.6
	2	99.25	0.68	0.26	0
Magnetic field	1	76.11	14.85	0.29	3.7
	2	99.03	0.91	0.27	0

In the process of refining, some calcium is added to prevent the magnesium alloy from burning. Therefore, the calcium concentrates at the grain boundary. From chart 1, we can see that compared with the component of element in microstructure solidifies commonly, the solute element are reduced at grain boundary and raised inside grain. When magnesium alloy solidifies under magnetic field, at grain boundary, the content of zinc decreases from 15.62% to 14.85%, the content of calcium decreases from 5.6% to 3.7%, and the content of zirconium isn't changed. Inside grain, the content of zinc increases from 0.68% to 0.91%, and the contents of calcium and zirconium aren't changed.

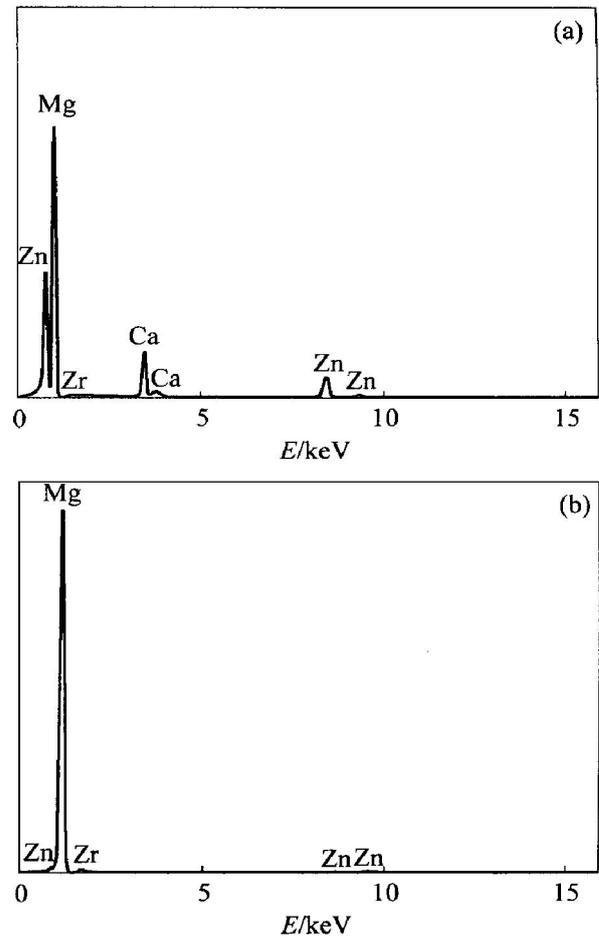


Fig. 7 Distribution of energy at points in microstructure solidified in magnetic field
 (a) —Energy distribution at point 1 of Fig. 4(b);
 (b) —Energy distribution at point 2 of Fig. 4(b)

The effect of magnetic field on magnesium alloy is just like that on aluminum. As a result of magnetic field, the solubility of solute element increases, the alloying element content increases inside grain, and decreases at grain boundary.

The reason that magnetic field raises the solubility of element can be analyzed with electromagnetic solidification. As we know that the soluble atoms are vibrating in the molten alloy, when magnetostatic field is applied to the molten alloy, the vibrating atoms is dragged by a force resulted from vibrating under magnetic field, which can be described by Fig. 8.

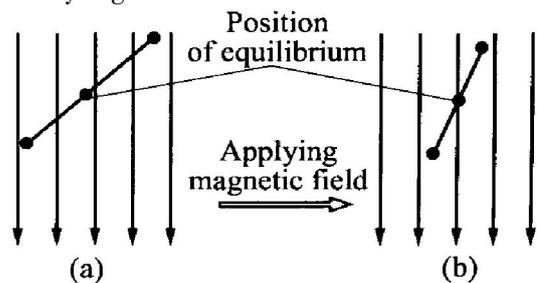


Fig. 8 Effect of magnetostatic field on vibration of atoms
 (a) —Common condition; (b) —Applied magnetic field

The force will make vibration normal to magnetic lines slowly, the amplitude of vibration decreases. Therefore, the soluble atoms loses some of its kinetic energy, and this kinetic energy will be changed into potential energy or other type of energy. The soluble atoms have to overcome more activation energy than ever to diffusion or go to another position.

During the solidification of magnesium alloy under magnetic field, the ability of the soluble atom to diffusion is limited, therefore much more soluble element atoms are anchored inside grain. As a result, less alloying element atoms are pulled to grain boundary, the content of element at boundary decreases, and the solute content increases inside grain.

5 CONCLUSIONS

1) As magnetostatic field applied to the process of solidification, the grain is greatly refined.

2) When magnesium alloy solidifies under magnetostatic field, the soluble content increases inside grain, and decreases at grain boundary.

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