Article ID: 1003 - 6326(2005)01 - 0072 - 05

Microstructures of AZ91D alloy solidified during electromagnetic stirring①

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Abstract: With the help of an electromagnetic stirring device self-made and alloy melt quenching technology, the effect of electromagnetic stirring parameters on the microstructures of semi-solid AZ91D alloy was mainly studied at the stirring frequency of 200 Hz. The experimental results show that when the stirring power rises, the primary α-Mg rosettes in the semi-solid melt will bear stronger man-made temperature fluctuation and the root remelting effect of the dendritic arms is promoted so that the spherical primary α-Mg grains become much more and rounder. If the stirring frequency is 200 Hz, the ideal semi-solid microstructure of AZ91D magnesium alloy can be obtained when the stirring power is increased to 6.0 kW. If the stirring frequency is 200 Hz and the stirring power is 6.0 kW, it is found that the lower cooling rate is favorable for the spherical primary α-Mg grains to be developed during the electromagnetic stirring stage. If the AZ91D magnesium alloy billet prepared during electromagnetic stirring at the stirring frequency of 200 Hz and the stirring power of 6.0 kW is reheated to the solidus and liquidus temperature region, the primary α-Mg grain's shape will get more spherical, so it is very advantageous to the semi-solid thixoforming process.

Key words: AZ91D magnesium alloy; semi-solid; electromagnetic stirring; microstructure
CLC number: TG 146.2 **Document code:** A

1 INTRODUCTION

A large number of aluminum alloy parts, such as engine block, engine head, air inlet pipe, and wheel, have been used in the cars for many years in order to reduce consumption of the fuel oil, air pollution and using cost. So the self-mass of cars continuously decreases, and it is called as the lightness campaign of cars. However, more attention has been paid to magnesium alloys recently in the automobile industry. It is expected that the aluminum alloy parts shall be replaced by magnesium alloy parts because the densities of various kinds of magnesium alloys are 1.75 - 1.85 mg/m^3 and approximately 64% of those of aluminum alloys, moreover, their specific strength is larger than that of aluminum alloys[1]. This motive has promoted the basic and applied researches about magnesium alloys. The semi-solid process of magnesium alloys is one of the important research fields and there are many theoretical and technological problems to be solved nowadays for developing more advanced and economical semi-solid process of magnesium alloys[2-9]. The mechanism of the microstructural transformation of magnesium alloys under different external field conditions is one of the most basic studies. ZHEN et al[10] and Kamado et al[11] studied the effect of mechanical stirring on the microstructure of semi-solid AZ91D magnesium alloy and found that it was favorable for the spherical process of primary α-Mg grains when the stirring rate increased and the stirring time prolonged. Hao et al studied the microstructural evolution of AZ91D magnesium alloy kept isothermally in the semi-solid region. They found that the primary α-Mg grains gradually changed to sphere shape at 570 ℃ with increasing time and evenly suspended in the liquid. They also found that the spherical process was faster and the primary α-Mg grains were a bit smaller in size when AZ91D magnesium alloy was modified before isothermally holding[12]. However, the reports on the microstructural evolution of magnesium alloys stirred by a rotational electromagnetic field have rarely been seen[13-15]. More researches should be done in this field so as to provide useful reference for preparation of the billet of semi-solid AZ91D magnesium alloy. Therefore, the effect of some rotational electromagnetic stirring parameters at the frequency of 200 Hz on the microstructures of AZ91D magne-

① **Foundation item:** Project(G2000067202) supported by the National Basic Research Program of China; Project(2002AA336080) supported by Hi-tech Research and Development Program of China; Project(50374012) supported by the National Natural Science Foundation of China

Received date: 2004 - 06 - 15; **Accepted date:** 2004 - 10 - 28

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sium alloy is studied.

2 EXPERIMENTAL

2.1 Experimental device

All experiments were conducted on the electromagnetic stirring equipment self-made, which is described in Fig. 1. It mainly consists of electromagnetic stirring system, heating system, stirring camber and stirring crucible. A rotational electromagnetic field is used in the stirring system. A cooling jacket is set up in the stirrer so as to protect the electromagnetic stirring system from overheat. A heating system, which uses electric resistance heater, is set up in the stirrer to melt the AZ91D magnesium alloy, and the heater temperature is controlled though the thermal couples in the heating system. But the real melt temperature is monitored by a thermal couple monitored under the stirring crucible. So the melt temperature may be controlled much exactly. The stirring crucible is made of high pure graphite and its inner diameter is 58 mm and its height is 60 mm. The stirring crucible is placed in the heating system and kept statically during stirring process. The stirring crucible is covered with a lid during heating and stirring process in case the AZ91D magnesium alloy melt catches fire, that is to say, the AZ91D magnesium alloy melt is wholly sealed in the stirring crucible during experiment.

2.2 Experimental method

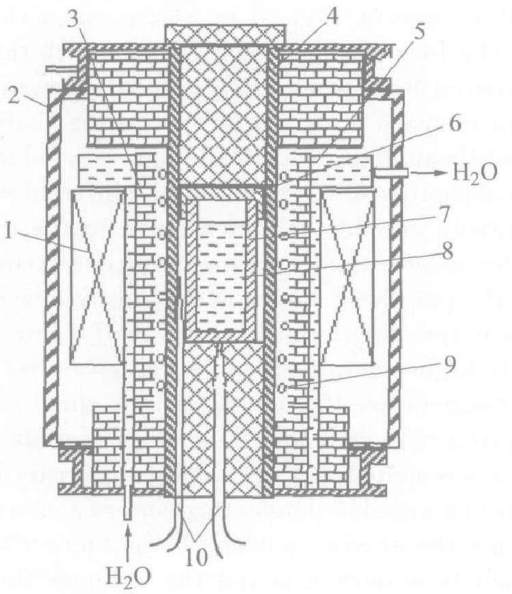

Fig. 1 Schematic diagram of electromagnetic stirring equipment
1 —Electromagnetic stirrer; 2 —Shell;
3 —Heat insulation layer; 4 —Corundum tube;
5 —Water cooling jacket; 6 —Crucible cover;
7 —Stirring crucible; 8 —Melt;
9 —Resistance coil; 10 —Thermal couple

The experimental metallic material was the commercial billet of AZ91D magnesium alloy. The compositions are listed in Table 1. The liquidus temperature and the solidus temperature of AZ91D are about 595 ℃ and 470 ℃, respectively.

Table 1 Compositions of AZ91D alloy used in this study (mass fraction, %)

Al	Zn	Mn	Be	Si
8.92	0.617	0.208 4	0.001 1	0.023

Fe	Cu	Ni	Mg
0.002 3	0.001 4	0.000 8	Balance

The purchased billet of AZ91D magnesium alloy, which was originally 60 mm in diameter and 800 mm in length, was machined to 55 mm in diameter and 55 mm in length. Then the machined billet was put into a graphitic stirring crucible and sheathed with a threaded graphite lid. The graphitic stirring crucible was then placed into the stirring chamber. After the stirring chamber was covered with a lid, the AZ91D magnesium alloy started to be heated and melted at 700 ℃. Then the melt was continuously cooled down and stirred simultaneously by a rotational electromagnetic field. The stirring was not stopped till the alloy melt was cooled to 580 ℃ in the semi-solid region. Then the graphitic stirring crucible filled with the semi-solid AZ91D melt was immediately thrown into water in order to avoid further structural evolution during the following cooling process. The stirring voltage can easily be set up from the electric source device so that the different stirring processes can be fulfilled.

The metallographic specimens were cut from the stirred billets at the given positions and roughly ground, finely polished and etched. The microstructures were observed and analyzed with an optical microscope of Neuphoto 21 type.

3 RESULTS AND DISCUSSION

3.1 Effect of stirring power on microstructures

Because it is very difficult to check the real stirring power of the stirrer, the nominal power, that is, the product of the stirring voltage and the stirring electric current, is used here. By adjusting the stirring voltage at a fixed frequency, an electromagnetic stirring field with different strength can be maintained and a different stirring power can exist in the AZ91D magnesium alloy melt. Fig. 2 shows the microstructures of semi-solid AZ91D magnesium alloy slurries quenched at 580 ℃, which are solidified at different stirring powers and the same frequency. The white phase in Fig. 2 is primary α-Mg.

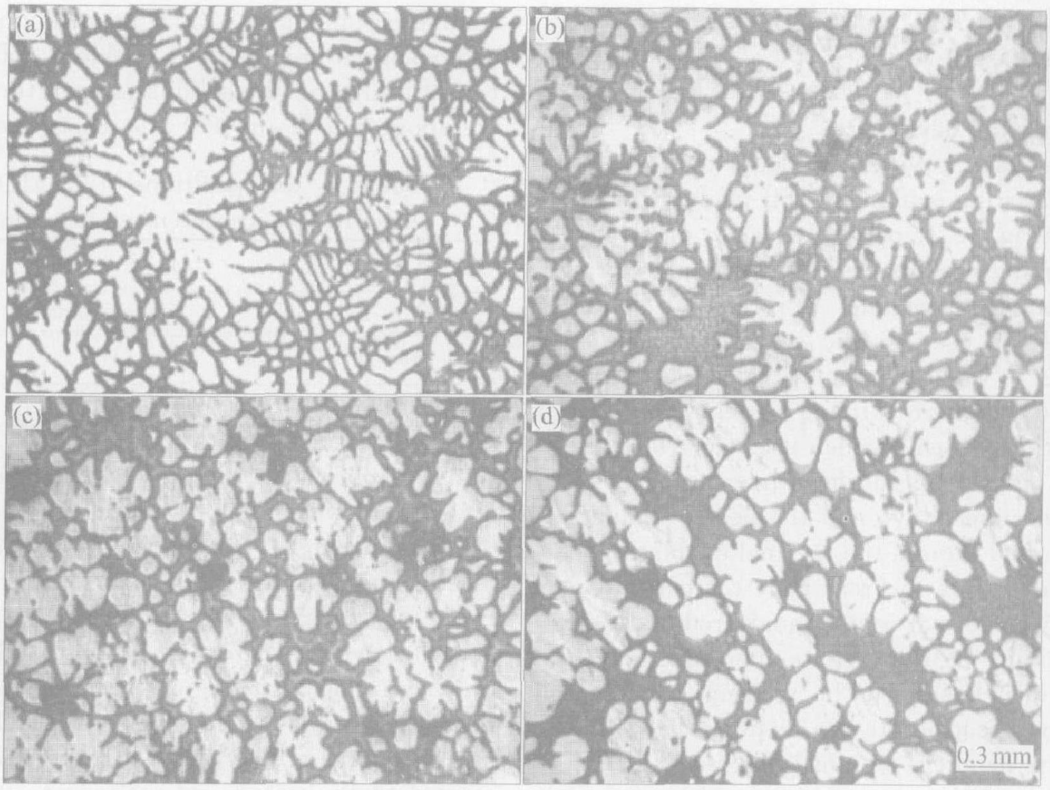

Fig. 2 Microstructures of semi-solid AZ91D quenched at 580 ℃ and stirred at frequency of 200 Hz and different powers
(a) —0 kW; (b) —1.5 kW; (c) —3.0 kW; (d) —6.0 kW

It can be seen from Fig. 2 that the electromagnetic stirring power has an important effect on the shape of primary α-Mg grains in semi-solid AZ91D magnesium alloy slurries. The microstructure of the as-cast billet solidified on conventional condition mainly consists of large dendritic primary α-Mg grains and inter-boundary intermetallic compounds of $Mg_{17}Al_{12}$ (β phase) and AlMn, as shown in Fig. 2(a). The primary α-Mg dendrites are usually large and have six secondary arms with 60° orientation and the secondary arms are obviously distinguished from the third arms. However, if being stirred at the nominal stirring power of 1.5 kW, the large primary α-Mg dendrites are changed to the equiaxed primary α-Mg grains and refined greatly. In addition, the third arms become lager and the difference between the secondary and the third arms becomes very small, as shown in Fig. 2(b). If the nominal stirring power is increased to 3 kW, the primary equiaxed α-Mg grains are further refined and the shape of the secondary arms is more like that of the third arms. Meanwhile, many spherical primary α-Mg grains appear in the solidified microstructures, as shown in Fig. 2(c). If the nominal stirring power is increased to 6 kW, the primary equiaxed α-Mg grains continue decreasing, the spherical primary α-Mg grains increase greatly, and it is more difficult to recognize the difference between the secondary and the third arms, as shown in Fig. 2(d).

It is favorable to the formation of spherical grains in the semi-solid microstructures of AZ91D magnesium alloy, if the stirring power is properly increased. This phenomenon may be related to the melt flow motion induced by electromagnetic stirring. The former experiments have shown that the melt stirred by a rotationally electromagnetic field is mainly turned horizontally around the shaft, but meanwhile an additional flow exists, by which the melt frequently moves up along the internal wall of the stirring crucible and then down to the center. So, the rosette-type primary dendrites frequently reach the periphery region with slightly lower temperature and then come to the melt center with slightly higher temperature, which gives rise to violent temperature fluctuation for the small rosette-type primary grains, and then many secondary arm roots are remelted and the spherical primary grains are formed greatly. Theoretical analysis also shows the lager the stirring power is, the more violently the melt flow motion is and the stronger the temperature fluctuation in the melt is. Then it is more possible for the secondary arm's roots to be remelted and there will be more spherical primary grains in the microstructures. Therefore, the root remelting of secondary arms is the main formation mechanism of the spherical primary grains during electromagnetic stirring process[16]. As to AZ91D magnesium alloy, when the stirring power increases, the flow of semi-solid melt should be more violent, and the rosette-type primary α-Mg grains will undergo much stronger temperature fluctuation. The fluctuation will make the secondary or third arms of rosette-type primary α-Mg grains remelt on their roots, and more and more spherical primary α-Mg grains will appear in the microstructures. While being stirred, the primary α-Mg grains collide and are rubbed with each other or with the liquid and conincidently ripen all the time so that the primary α-Mg grains gradually become spherical.

3.2 Effect of cooling rate on microstructures

When preparing semi-solid slurry or billet of AZ91D magnesium alloy stirred by electromagnetic field and cooled continuously, the cooling rate also has an important effect on the microstructures. Fig. 3 shows the microstructures of semi-solid AZ91D magnesium alloy formed in different cooling rate and stirred at 200 Hz and 6.0 kW. The melts of Fig. 3 (a) and (b) are cooled at 5 ℃/min and 9.4 ℃/min respectively. When the cooling rate is 9.4 ℃/min, the fine rosette-type primary α-Mg grains are dominative in the microstructures. However, When the cooling rate is reduced to 5 ℃/min, the semi-solid microstructures are changed obviously, consequently most of the rosette-type primary α-Mg grains disappear and the spherical primary α-Mg grains are increased largely. As a result, the smaller cooling rate is beneficial to getting the ideal semi-solid microstructures of AZ91D magnesium alloy.

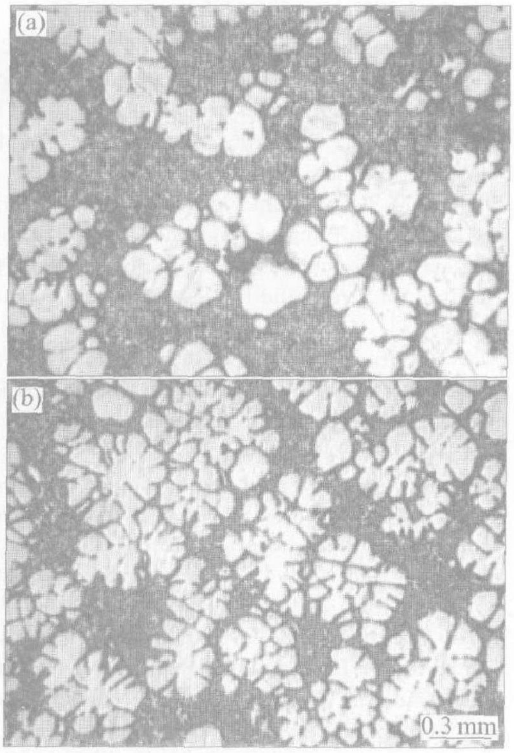

Fig. 3 Microstructures of semi-solid AZ91D alloy quenched at 580 ℃ and stirred at frequency of 200 Hz, power of 6.0 kW and different cooling rates
(a) —5 ℃/min; (b) —9.4 ℃/min

It is known from the above analysis that the root remelting of rosette arms is the main mechanism of microstructural transformation of semi-solid AZ91D magnesium alloy. So the fine rosette-type primary α-Mg grains are required to continuously undergo the micro temperature fluctuation. If the electromagnetic stirring time is prolonged, the fine rosette-type primary α-Mg grains will experience temperature fluctuation for a longer time and it is advantageous to the root remelting of rosette arms, so the primary α-Mg grains are more like sphere in shape and there are more spherical primary α-Mg grains. If the cooling rate is high, the stirring time will be shortened and the general number of temperature fluctuations undergone by the fine rosette-type primary α-Mg grains will decrease, too. So the number of root remelting of the rosette arms must fall down, the spherical primary α-Mg grains become less and the rosette-type primary α-Mg grains become more.

3.3 Effect of reheating process on microstructures

Fig. 4 shows the microstructures of AZ91D magnesium alloy, which is solidified at the cooling rate of 5 ℃/min and during electromagnetic stirring at 200 Hz and 6.0 kW, after being reheated to

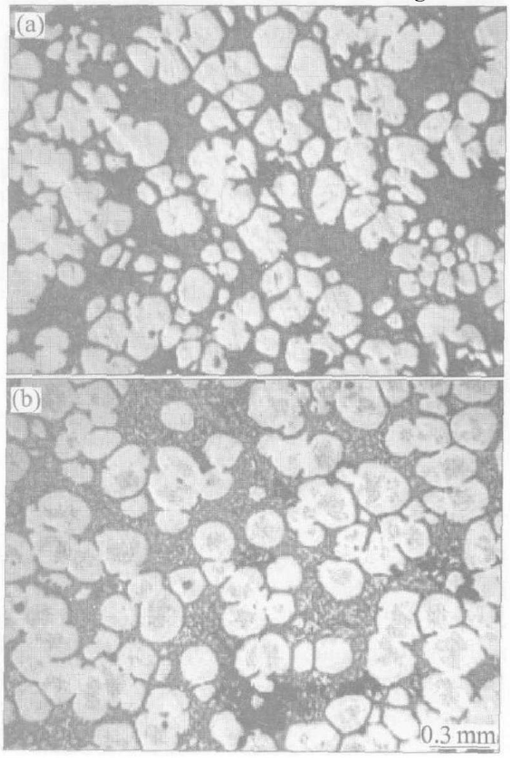

Fig. 4 Microstructures of as-cast and reheated semi-solid AZ91D alloy quenched at 580 ℃
(a) —As-cast;
(b) —Reheating temperature 580 ℃, soaking time 10 min

the semi-solid region. It can be seen from Fig. 4(a) that there are still some rosette-type primary α-Mg grains in the as-cast microstructures before reheating. However, after being reheated to the semi-solid region of 580 ℃ for a given time, the primary α-Mg grains in samples have varied greatly. After soaked for 5 min, the rosette-type arms in the origin microstructures have been melted away on their roots, and most of the rosette-type primary α-Mg grains have disappeared and given place to the spherical primary α-Mg grains. After soaked for 10 min, the spherical primary α-Mg grains are rounder and the original microstructures have wholly disappeared, as shown in Fig. 4(b). If the AZ91D magnesium alloy is solidified on conventional condition without electromagnetic stirring, the semi-solid reheating experiments show that compared with Fig. 2(a), which is the originally as-cast microstructure before reheated, though soaked for 10 min, the primary α-Mg grains are still dendritic as shown in Fig. 5. Even if soaked for 30 min, the primary α-Mg grains are still dendritic. Therefore, after the billet of AZ91D magnesium alloy prepared by electromagnetic stirring is reheated to the semi-solid region, the primary α-Mg grains will further be spheroidized and it is favorable for semi-solid thixoforming process.

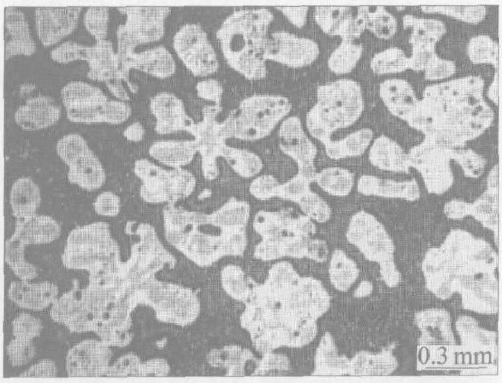

Fig. 5 Microstructures of semi-solid dendritic AZ91D alloy reheated at 580 ℃, soaked for 10 min and quenched in water

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(Edited by YANG Bing)