Modification of Primary Mg₂Si Crystals in Hypereutectic Mg-Si Alloy by Application Alternating Current

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The effect of application alternating current on the modification of primary Mg₂Si crystals in the hypereutectic Mg-4.8 mass%Si alloy has been investigated in the present study. The liquidus and eutectic temperatures of the Mg-4.8 mass%Si alloy are 761°C and 638°C, respectively. An alternating current of 60 A with frequency of 1 kHz was applied into the hypereutectic Mg-Si melt from different starting temperatures (770, 740, 700 and 670°C) till 630°C. The results show that primary Mg₂Si crystals could be refined effectively by application alternating current. The average sizes of primary Mg₂Si crystals were decreased to almost a half after being subjected to the alternating current. The starting temperature of the application alternating current is a very significant factor to determine the size uniformity of the primary Mg₂Si crystals, while it has no obvious effect on the average size of the primary Mg₂Si crystals. The refined primary Mg₂Si crystals have the lowest average size and the highest uniformity in sizes when the hypereutectic Mg-Si melt was treated by application alternating current from the starting temperature of 700°C. [doi:10.2320/matertrans.MRA2008235]

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1. Introduction

Magnesium alloys, the lightest metal structural materials, have been extensively paid attention to being applied in the automobile industry during the past two decades, in order to reduce fuel consumption and lower waste gas emission.¹⁻³⁾ Among the broad range of commercial magnesium alloys, the aluminum bearing magnesium alloys, such as AZ91D (Mg-9Al-0.8Zn) and AM60B (Mg-6Al-0.4Mn), take a dominating position of consumption for automobile applications.¹⁻⁵⁾ However, this group of magnesium alloys have poor creep resistance at temperatures above 125°C because the Mg₁₇Al₁₂ phase existed in the Mg-Al based alloys has poor thermal stability and its discontinuous precipitation can result in substantial grain boundary sliding at elevated temperatures.¹⁻⁵⁾ Therefore, the Mg-Al based alloys were limited to be applied in the powertrain components, such as engine blocks up to 200°C and engine pistons up to 300°C. Creep resistance is a major requirement for use of magnesium alloys in automobile powertrain components that are currently made of aluminium or cast iron.^{2,3)}

Up to now, many investigations have been carried out to improve the creep resistance for magnesium alloys. Several kinds of magnesium alloys have been developed with higher creep resistance.³⁻⁹⁾ Among these new alloys, the magnesium alloys containing Mg₂Si having excellent creep resistance have been paid attention extensively, since Mg₂Si compound exhibits a high melting temperature of 1085°C and high hardness of 4.5×10^9 Pa.^{3,8,9)} In particular, the hypereutectic Mg-Si alloys have high potential as structural materials for elevated temperature applications.³⁾ However, the hypereutectic Mg-Si alloys prepared by ordinary ingot metallurgy process have very low ductility and strength due to the large primary Mg₂Si crystal size and the brittle eutectic phase. It is well known that the refinement of microstructures is one of

the effective routes to improve mechanical properties for metal products. The die casting, which has been widely used to produce magnesium components, is not suitable for the hypereutectic Mg-Si alloys due to their high liquidus temperatures.³⁾ Some other advanced processing techniques such as hot extrusion,^{10,11)} rapid solidification,¹²⁾ and mechanical alloying¹³⁾ have been applied to produce alloys with fine Mg₂Si crystals uniformly dispersed in Mg-matrix. Compared with these techniques, the ingot metallurgy process is a more practical method, because it is commercially available at low production cost and can be accepted by the engineering community for general applications.

For the hypereutectic Mg-Si alloys prepared by ingot metallurgy process, their microstructures were traditionally refined by addition of refiners, such as rare earth element of yttrium,¹⁴⁾ compound containing boron of KBF₄.¹⁵⁾ However, the material composition becomes complex upon such addition, which makes the recycling of used materials difficult. Therefore, an alternative method for the development of hypereutectic Mg-Si alloys with refining microstructures and high strength is desired.

It has long been established that electromagnetic vibration can effectively refine the microstructures for a large range of metals prepared by the ingot metallurgy process.¹⁶⁻²⁷⁾ This route has an excellent advantage of making no change to the composition of the treated alloys. Many studies have been focused on the modification effect of electromagnetic vibration on the eutectic and primary Si crystals in the Al-Si alloys.²⁰⁻²³⁾ Unfortunately, few works have been performed on the modification of primary and eutectic Mg₂Si phase in the Mg-Si alloys treated by electromagnetic vibration.

In the present study, the modification effect of electromagnetic vibration induced by application alternating current on the primary Mg₂Si crystals in the hypereutectic Mg-Si alloys was investigated in order to develop an effective route to refine Mg₂Si crystals in the hypereutectic Mg-Si alloys.

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Fig. 1 The cooling curve of the prepared hypereutectic Mg-Si alloy cooled with furnace.

2. Experimental Procedure

Industrial pure Mg (99.9 mass% purity) and Si (99 mass% purity) were used as starting materials. Charges of about 3 kg with the nominal composition of Mg-5 mass%Si alloy were prepared as the experiment materials in the present study. The solidification characteristic of the prepared Mg-Si alloy was confirmed in order to designate experimental conditions. The prepared Mg-Si alloy of about 100 g was melt using MgO crucible with inner diameter of 30 mm and then was cooled in a furnace. A K-type thermocouple was inserted into the melt and the cooling curve was recorded using digital recorder (Keyence, GR-3500 type). The cooling curve is shown in Fig. 1. The primary Mg_2Si crystals began to precipitate from this Mg-Si melt from 761°C and the eutectic reaction occurred at about 638°C. Judged from Mg-Si binary alloy phase diagram,²⁸⁾ as shown in Fig. 2, the silicon content in the prepared Mg-Si alloy is approximately 4.8 mass% in the present study.

The samples treated by application alternating current were prepared as following. The hypereutectic Mg-Si alloy of about 25 g was melt at 800°C in a mild steel crucible using an electric resistance furnace under a protective flux cover (45 mass% MgCl_2 , 35 mass% KCl , 5 mass% CaF_2 , 15 mass% NaCl). The hypereutectic Mg-Si melt was manually stirred for 1 min using a magnesia rod for homogenization, and then was held for additional 10 min. Then, the slag was cleaned and the melt was poured into an Al_2O_3 tube which was preheated to 700°C using a small power self-made electric resistance furnace. This Al_2O_3 tube was held with clamp fixed on a bracket in advance, as shown in Fig. 3. The size of the Al_2O_3 tube is 21 mm in inner diameter, 25 mm in outer diameter and 70 mm in height.

After the melt was poured into the Al_2O_3 tube, a couple of tungsten electrodes (3 mm in diameter) were inserted into the melt quickly. The distance between the two tungsten electrodes was 12 mm. The tungsten electrodes were covered using Al_2O_3 pipe with size of 3 mm in inner diameter, 5 mm in outer diameter and 60 mm in height. The end part of the tungsten electrode with length of 5 mm was not covered to apply alternating current into the melt. The distance between

Fig. 2 The phase diagram of Mg-Si binary alloy.²⁸⁾

Fig. 3 Schematic view of the experimental apparatus.

the end of tungsten electrodes and the bottom of the Al_2O_3 tube was 10 mm. A K-type thermocouple was fixed on one of the two tungsten electrodes and the temperature of the melt was recorded automatically using digital recorder (Keyence, GR-3500 type). The temperature was begun to record from about 770°C. And then, the small power self-made electric resistance furnace was turned off and pulled off. The Al_2O_3 pipe filled with the hypereutectic Mg-Si melt was air-cooled. The alternating current of 60 A with frequency of 1 kHz was applied immediately when the melt was cooled to the designated temperature. The designated temperatures were 770, 740, 700 and 670°C in the present study, as shown in Fig. 2. The alternating current was turned off when the sample temperature was 630°C, at which the melt was fully solidified. For comparison, a sample without the application alternating current was prepared. Therefore, five samples were prepared in the present study.

The cylindrical ingots were cut longitudinally along the middle line parallel to the electrodes. Then, metallographic samples were cut at the position that was 20 mm from the bottom of the ingots. The samples for microstructure observation were prepared using a standard procedure with

Fig. 4 Observed area in the sample (unit: mm).

a final polishing with 0.05 μm alumina suspension. After that, the samples were etched with 3 vol% HF solution for 1 min. The etched samples were observed by a scanning electron microscope (SEM) (Keyence, VE-7800). The middle area between the two tungsten electrodes was selected as SEM observation area, as shown in Fig. 4. The size of the observed area was $15 \times 15 \text{ mm}^2$.

More than five pictures were taken for every sample from the observed area. In the present study, the length of primary trunk of the dendritic Mg_2Si crystal was measured as the size of Mg_2Si crystal. If the primary trunk directions were differentiated difficultly for some Mg_2Si crystals, the lengths along several directions for one crystal were measured and the longest length as its size. All Mg_2Si crystals existed in one picture taken from the observed area were measured. After that, Mg_2Si crystals in another picture were continuously measured till 200 primary Mg_2Si crystals for every sample were measured, then the 200 data of sizes were analyzed by statistical method to improve the veracity of judgment of modification effect of the application alternating current. The average value and standard deviation for the 200 primary Mg_2Si crystals were used to evaluate the modification effect of the application alternating current on the primary Mg_2Si crystal in the hypereutectic Mg-Si alloy.

3. Results

3.1 Cooling curves

The cooling histories for all samples were recorded and analyzed. It was found that the application alternating current has no obvious effect on the cooling history and eutectic temperature based on the cooling curves for all samples. The average cooling rates from 760 till 640°C and eutectic temperature for all samples are almost identical. They are about 1.9°C/s and 638°C , respectively. The cooling curves for the samples without treatment and treated by application alternating current from 700 till 630°C are illustrated in Fig. 5. In comparison with them, it was found that there was a slight rise of temperature after alternating current of 60 A was applied into the melt.

3.2 SEM observations of primary Mg_2Si phase

Figure 6 shows that SEM images of microstructures for the hypereutectic Mg-Si alloy without treatment. For this sample,

Fig. 5 Cooling curves for the samples without application alternating current treatment (a) and treated by application alternating current from 700 to 630°C (b).

its microstructure consists mainly of three constituents: primary Mg_2Si crystals, eutectic $\text{Mg}_2\text{Si} + \alpha\text{-Mg}$ phases and small amounts of $\alpha\text{-Mg}$ phase. For the primary Mg_2Si crystals, in addition to coarse dendritic morphologies, there are some Mg_2Si crystals with polygonal morphologies. For the $\alpha\text{-Mg}$ phase, there are two microstructural features could be observed in Fig. 6. One is that some primary Mg_2Si dendritic crystals are surrounded by a layer of $\alpha\text{-Mg}$ halos. The other is that some isolated island-shaped $\alpha\text{-Mg}$ phase could be observed. The $\alpha\text{-Mg}$ halos and isolated island-shaped $\alpha\text{-Mg}$ phases are surrounded by the eutectic structure of $\text{Mg}_2\text{Si} + \alpha\text{-Mg}$ phases.

Figure 7 shows that SEM images of microstructures for the hypereutectic Mg-Si alloy treated by application alternating current from different starting temperatures till 630°C . Likewise, the microstructures for these samples consists mainly of primary Mg_2Si crystals, eutectic $\text{Mg}_2\text{Si} + \alpha\text{-Mg}$ phases and small amounts of $\alpha\text{-Mg}$ phase. The isolated island-shaped $\alpha\text{-Mg}$ phase could also be observed in these four samples. Compared with the sample without treatment, the coarse dendritic primary Mg_2Si crystals could be hardly found and the primary Mg_2Si crystals were remarkably refined for these samples treated by application alternating current. However, it could be found that the refined primary Mg_2Si crystals agglomerated locally could be observed in the samples when the starting temperatures of the application

Fig. 6 Low magnification (a) and high magnification (b) SEM images of the hypereutectic Mg-Si alloy without application alternating current.

Fig. 7 SEM images of the hypereutectic Mg-Si alloy treated by application alternating current from different starting temperature ((a) 770°C, (b) 740°C, (c) 700°C, (d) 670°C till 630°C).

alternating current were 770 and 740°C. As a result, the refined primary Mg_2Si crystals distributed non-uniformly, as shown in Figs. 7(a) and 7(b). However, for the samples treated by application alternating current at the starting temperature of 700 and 670°C, the agglomeration of refined primary Mg_2Si crystals could hardly found and the refined Mg_2Si crystals distributed relatively uniformly, as shown in Figs. 7(c) and 7(d).

3.3 Statistical analysis results of the sizes of primary Mg_2Si crystals

For every sample, sizes of 200 primary Mg_2Si crystals

were measured. These 200 data were analyzed by statistical method. The statistical histogram of the primary Mg_2Si sizes are shown in Fig. 8 for the five samples prepared in the present study. In these figures, the size intervals for counting for the sample without treatment by application alternating current and for the samples treated by application alternating current at different temperature ranges are 100 μm and 50 μm , respectively. The results of statistical average size and standard deviation are listed in Table 1. Also, the total ratios of the numbers of coarse Mg_2Si crystals with sizes over than 400 μm to the 200 primary Mg_2Si crystals measured for all samples are listed.

Fig. 8 Statistical histogram of the primary Mg_2Si crystals size in the hypereutectic Mg-Si alloy without treatment (a) and treated by application alternating current from different starting temperature (b) 770°C, (c) 740°C, (d) 700°C, (e) 670°C till 630°C. The size intervals for counting in (a) and in (b) to (e) are 100 μm and 50 μm , respectively.

Table 1 Statistical results of the primary Mg_2Si size in the hypereutectic Mg-Si alloy treated by application alternating current in the different temperature ranges.

Sample No.	Temperature ranges of application alternating current	Statistical average size of primary Mg_2Si crystals (μm)	Standard deviation (μm)	Total ratio of the Mg_2Si crystals over than 400 μm
1	Without treatment	403	240.6	40.0%
2	770°C to 630°C	202	95.8	4.0%
3	740°C to 630°C	204	99.5	3.0%
4	700°C to 630°C	196	68.2	0%
5	670°C to 630°C	228	72.5	1.5%

For the sample without treatment, the sizes of primary Mg_2Si crystals distribute from $50\text{ }\mu\text{m}$ to about $1600\text{ }\mu\text{m}$ and mainly locate in the range of $100\text{ }\mu\text{m}$ to $700\text{ }\mu\text{m}$. Its statistical average size and standard deviation are $403\text{ }\mu\text{m}$ and $240.6\text{ }\mu\text{m}$, respectively. The ratio of the Mg_2Si crystals with sizes over than $1000\text{ }\mu\text{m}$ to the 200 crystals measured for this sample amounts to about 3%, which implies there existed some very coarse Mg_2Si crystals with complex dendritic morphologies (as shown in Fig. 6(b)) in the hypereutectic Mg-Si alloy without application alternating current.

For the samples treated by application alternating current from the starting temperatures of 770 and 740°C , the sizes of primary Mg_2Si crystals distribute from 50 to about $650\text{ }\mu\text{m}$ and mainly locate in the range of $50\text{ }\mu\text{m}$ to $400\text{ }\mu\text{m}$. The largest size was significantly refined from 1600 to $650\text{ }\mu\text{m}$ for these two samples. Their statistical average sizes and standard deviations are decreased to about $200\text{ }\mu\text{m}$ and $98\text{ }\mu\text{m}$, respectively. There are some primary Mg_2Si crystals with sizes over than $400\text{ }\mu\text{m}$ existed in these two samples and their total ratios to the 200 primary Mg_2Si crystals measured are about 4% and 3%, respectively. However, the total ratio of the Mg_2Si crystals with sizes over than $400\text{ }\mu\text{m}$ to the 200 primary Mg_2Si crystals measured amounts to about 40% for the sample without application alternating current.

When the starting temperatures of the application alternating current was decreased to 700°C , the large primary Mg_2Si crystals with sizes over than $400\text{ }\mu\text{m}$ could hardly found in the sample, as shown in Fig. 8(d). The sizes of primary Mg_2Si crystals mainly distribute from 50 to about $300\text{ }\mu\text{m}$ for this sample. Their statistical average sizes and standard deviations are decreased to $196\text{ }\mu\text{m}$ and $68.2\text{ }\mu\text{m}$, respectively. For the sample treated by application alternating current from the starting temperatures of 670°C , the sizes of primary Mg_2Si crystals mainly distribute from $100\text{ }\mu\text{m}$ to about $350\text{ }\mu\text{m}$. Their statistical average sizes and standard deviations are about $228\text{ }\mu\text{m}$ and $72.5\text{ }\mu\text{m}$, respectively. The total ratio of the primary Mg_2Si crystals with sizes over than $400\text{ }\mu\text{m}$ existed in this sample to the 200 primary Mg_2Si crystals measured is about 1.5%.

From the above results, it is known that primary Mg_2Si crystals could be refined due to the application alternating current for the hypereutectic Mg-Si melt. In particular, the coarse dendritic primary Mg_2Si crystals with size above $650\text{ }\mu\text{m}$ could be hardly found in the samples treated by application alternating current. The average sizes of primary Mg_2Si crystals were decreased almost half for the three samples treated from the starting temperature of 770 , 740 and 700°C . However, the standard deviations for the two samples treated from the higher starting temperature of 770 and 740°C are higher than that of sample treated from the starting temperature of 700°C . For the sample treated from the lower starting temperature of 670°C , its average size increased slightly but its standard deviation was low.

Based on the above results, a conclusion could be drawn that primary Mg_2Si crystals in the hypereutectic Mg-Si alloys could be refined effectively by application alternating current. The starting temperature of the application alternating current is a very significant factor to determine the size uniformity of primary Mg_2Si crystals, while it has no obvious effect on the average size primary Mg_2Si crystals. From the

viewpoint of modification effect, the optimal starting temperature is 700°C , at which primary Mg_2Si crystals have the lowest average size and the highest uniformity in sizes with the lowest standard deviation.

4. Discussion

4.1 Effect factors on the cooling history

Cooling history is an important factor to determine the microstructural evolution for a metal product. In order to realize the effect of the application alternating current on solidified structures of the hypereutectic Mg-Si alloy, it is essential to reckon the effect resulting from the differences in cooling rates after the alternating current was applied into the melt. When the alternating current, J with frequency 1 kHz is applied, an alternating magnetic field, B with the same frequency can be induced in the melt. This alternating magnetic field interacts with the electric current itself and induces an alternating electromagnetic vibration in the melt. Compared with the sample without alternating current treatment, the cooling histories for the samples treated by application alternating current could be influenced by another two factors. One factor is that joule heat generated in the sample will result in a decrease in cooling rate. The slight rise of temperature after application of alternating current (shown in Fig. 5(b)) should be the result of joule heat generation. The same phenomenon could not be found for the sample without application alternating current, as shown in Fig. 5(a). Another factor is the electromagnetic vibration, which can improve the transfer of heat to surrounding walls by forced convection, which will increase the cooling rate. It can be deduced that the effects of the above two factors on the cooling rate could counteract because the cooling rates were almost same for all samples. Therefore, the effect of cooling rate on the microstructures for the hypereutectic Mg-Si alloys could be excluded in the present study.

4.2 Microstructural evolution of hypereutectic Mg-Si alloys

According to the Mg-Si binary alloy phase diagram,²⁸⁾ as shown in Fig. 2, the Mg-4.8 mass% Si alloy is a typical hypereutectic alloy. If the cooling rate is sufficiently low, its solidification path is along a near equilibrium route. Consequently, its microstructure should consist of two constituents: primary Mg_2Si crystals and (Mg+ Mg_2Si) eutectic crystals. However, when the cooling rate is high, such as in the case of present experimental condition, solidification path is along a non-equilibrium route. After primary Mg_2Si crystals form, Mg will subsequently precipitate and grow as sub-primary crystals prior to the final eutectic reaction in the rest of the melt.²⁹⁾

In the present experimental conditions, the primary Mg_2Si crystals began to nucleate and grow in the hypereutectic Mg-Si melt after the temperature decreased to less than 761°C . In the studies performed by Ourfali *et al.*³⁰⁾ and Qin *et al.*³¹⁾ It was found that the morphologies of the primary Mg_2Si crystals would change from coarse equiaxed to dendritic with the cooling rate increasing to exceed a critical velocity. For the Mg_2Si crystal, its structure belongs to face centered cube (FCC) and its dendrite arm should grow along

the preferential [100] crystallographic directions.^{31,32} For the sample without alternating current treatment, the morphologies of the primary Mg_2Si crystals are mainly characterized by dendrites (shown in Fig. 6), which implies that the solidification cooling rate in the present study is above the critical velocity as reported by Ourfali *et al.*³⁰) and Qin *et al.*³¹) Moreover, based on the solidification theory,³³) it can be reasonably inferred that some new Mg_2Si crystals should nucleate from the melt during the growth of Mg_2Si crystals nucleated initially with the decrease of temperature. Compared with the precipitated Mg_2Si crystals at higher temperatures, these Mg_2Si crystals precipitated at lower temperatures can not grow into coarse dendritic morphologies due to no enough time before solidifying fully. Therefore, in addition to coarse Mg_2Si crystals with complex dendritic morphologies, there are also some polygonal Mg_2Si crystals in the hypereutectic Mg-Si alloys without alternating current treatment, as shown in Fig. 6.

As primary Mg_2Si crystals continuously grow, the liquid phase surrounding them becomes enriched with Mg due to the rejection of Mg solute atoms under the condition of high solidification cooling rate. When the local concentration of Mg solute is sufficient, the growth of Mg_2Si crystals will be limited and Mg will nucleate on the Mg_2Si facets and grow.²⁹) Consequently, Mg sub-primary crystals could be formed as halos surrounding Mg_2Si primary crystals. In addition to α -Mg halos, the isolated island shaped α -Mg phase could obviously observed in the present study, as shown in Figs. 6 and 7. It is difficult to explain clearly the formation of the isolated island shaped α -Mg phase. Based on the solidification theory,³³) it is possible that the real eutectic composition deviates the equilibrium eutectic composition under high solidification cooling rate. If the silicon concentration in the rest of Mg-Si melt is less than the real eutectic composition, the isolated island shaped α -Mg phase can form before the eutectic reaction occurs. Lastly, the Mg- Mg_2Si eutectic phases form in the rest of the melt. Consequently, under the present study, the microstructures consist of three consequents, as shown in Figs. 6 and 7.

4.3 Modification effect of the application alternating current

It is well known that when an alternating current with high frequency was applied into the melt, a vibrating electromagnetic body force could be induced in the liquid melt.^{24–27}) In the present study, when the alternating current was applied into the hypereutectic Mg-Si melt at high temperatures of 770°C and 740°C, it was interesting that obvious agglomerations of refined Mg_2Si crystals occurred in these two samples and the Mg_2Si crystals distributed non-uniformly, as shown in Figs. 7(a) and 7(b). In the Radjai's study,²⁰) the agglomeration of primary Si crystals in the hypereutectic Al-Si melt treated by electromagnetic vibration was found. The Si crystals refined to a specific size is a necessary condition for this phenomenon to occur, i.e. only the refined Si crystals with sizes less than the specific size agglomerate locally.²⁰)

Up to now, it is difficult to explain clearly why the agglomerations of Mg_2Si crystals occur after the hypereutectic Mg-Si melt was treated by application alternating current at the high temperatures. This phenomenon will be

Fig. 9 Theoretical mass fraction of the primary Mg_2Si crystals in Mg-4.8 mass%Si alloy versus solidified temperature under the condition of equilibrium solidification.

further investigated and reported. However, it is possible that the small sizes of Mg_2Si crystals precipitated in the initial stage of solidification should be responsible for the agglomeration of Mg_2Si crystals. In the initial stage of solidification, the mass fraction of the primary Mg_2Si crystals is low and the sizes should be small. These small Mg_2Si crystals should be easy to vibrate with the melt which was subjected to an electromagnetic vibration. Figure 9 shows the theoretical mass fraction of the primary Mg_2Si crystals precipitated from the hypereutectic Mg-4.8 mass%Si melt changes with the temperature under the equilibrium condition of solidification. For example, the theoretical mass fraction of the primary Mg_2Si crystals is only 2.6 mass% at the temperature of 740°C.

With the decrease in the solidified temperature to 700°C, the theoretical mass fraction of Mg_2Si crystals in the hypereutectic Mg-4.8 mass%Si melt increase to about 6.1 mass% from 2.6 mass% at the 740°C, as shown in Fig. 9. Also, some Mg_2Si crystals precipitated in the initial solidification stage should grow to coarse crystals with complex dendritic morphologies. Under these conditions, the oscillatory motion of Mg_2Si crystals will become difficult due to large sizes. Therefore, no obvious agglomerations of the Mg_2Si crystals were found in the samples treated by application alternating current from starting temperatures of 700 and 670°C.

Usually, it is widely accepted that the refinement of the structures caused by EMV attributes to the fragmentation by mechanical stress and by the re-melting of the primary solid phase due to constitutional undercooling.^{26,27}) For the latter, it is not necessary to think of the bonding among atoms. For the former, the present authors think that the dendritic Mg_2Si crystals were fragmented from some weak parts subjected to the EMV. In this case, a strong mechanical force would be required for breaking the dendritic Mg_2Si crystals because chemical bonding of an intermetallic compound is generally combination of covalent bond and metallic bond. Therefore, further investigation is required to clarify the detail of the refinement mechanism.

For the dendritic crystals, the weak parts should be the root regions where secondary dendrites grow from primary trunk of dendrites or third dendrites grow from the trunk

of secondary dendrites.³⁰⁾ These root regions will become smaller gradually because the melting point will decrease due to the enrichment of solutes rejected from the surfaces of the dendrites. These weak root regions were named as “shrinkage neck”.³³⁾ These broken Mg₂Si crystals with small sizes can also move with the melt. However, the oscillatory motion of the broken Mg₂Si crystals is difficult due to the high content of the Mg₂Si crystals in the melt and low temperatures, which can avoid the formation of agglomeration, resulting in distribution uniformly in the sample.

As for the agglomerations of the refined primary Mg₂Si crystals was concerned, it has been deeply discussed and reported in another study.³⁴⁾ After the refined primary Mg₂Si crystals agglomerated, the electrical conductivity at the regions containing Mg₂Si crystals would become low because the electrical conductivity of Mg₂Si crystal might be small than that of the melt.³²⁾ Therefore, the actual alternating current density passing through these regions should be less than that passing through the liquid melt. Consequently, the primary Mg₂Si crystals existed in the agglomerated regions could not be effectively broken. As for the sample treated from the starting temperature of 670°C, no enough time could be provided to effectively modify some primary dendritic Mg₂Si crystals before the melt was fully solidified. This might be the reason why the refined primary Mg₂Si crystals have the lowest average size and the highest size uniformity for the sample treated from the starting temperature of 700°C.

5. Conclusions

- (1) Application alternating current has no obvious effect on the cooling history and eutectic temperature during solidification for the hypereutectic Mg-Si alloys. Besides primary Mg₂Si crystals and eutectic Mg₂Si + α -Mg phases, its microstructures consist small amounts of α -Mg phase, including α -Mg halos and isolated island-shaped α -Mg phase. The α -Mg phase are surrounded by the eutectic structure of Mg₂Si + α -Mg phases.
- (2) Primary Mg₂Si crystals in the hypereutectic Mg-Si alloys could be refined effectively by application alternating current. The average sizes of primary Mg₂Si crystals were decreased to almost a half after being subjected to the alternating current.
- (3) The starting temperature of the application alternating current is a very significant factor to determine the size uniformity of the primary Mg₂Si crystals, while it has no obvious effect on the average size primary Mg₂Si crystals. The refined primary Mg₂Si crystals have the lowest average size and the highest size uniformity when the starting temperature was 700°C.

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