Effects of Operating Parameters on Modification of Primary Mg₂Si Crystals in Hypereutectic Mg-Si Alloy Treated by Imposition of Alternating Current

Jun Du^{1,2,*} and Kazuhiko Iwai¹

¹Department of Materials, Physics and Energy Engineering, Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan

²School of Materials Science and Engineering, South China University of Technology, Guangzhou 510640, P. R. China

An alternating current (AC) was imposed upon the hypereutectic Mg-Si melt during solidification to modify the primary Mg₂Si crystals in the fixed temperature range between 700 and 630°C. The effects of current intensity and frequency have been investigated in the present study. For every sample, 200 primary Mg₂Si crystals were measured and 200 data were then statistically analyzed. The average size and standard deviation were used to evaluate the modification effect, including the refinement and uniformity of sizes of the modified primary Mg₂Si crystals. The results show that both frequency and current intensity were significant to determine the modification effect. When the current intensity was fixed at 60 A, the average size increased and uniformity of sizes of the primary Mg₂Si crystals improved with the increase in the frequency to 2 kHz. However, in the case that the frequency was fixed at 1 kHz, the statistical average size increased and uniformity of sizes improved with the increase in the current intensity to 60 A. With the further increase in the current intensity to 90 A, the statistical average size and uniformity of sizes had no obvious changes. The average size drastically decreased and uniformity of sizes remarkably improved with the increase in the estimated electromagnetic force to a critical value of about 126 Nm⁻³, corresponding to the current intensity of 60 A and frequency of 1 kHz. However, the average size was constant if the electromagnetic force exceeded the critical value. [doi:10.2320/matertrans.MRA2008443]

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1. Introduction

Elevated temperature creep resistance is a very important property for magnesium alloys because they were thought as a promising candidate to be used to produce automobile components, which always work at high temperatures, such as engine blocks up to 200°C and engine pistons up to 300°C.^{1,2)} Many investigations have been carried out to improve the creep resistance of magnesium alloys and several new kinds of magnesium alloys have been developed with higher creep resistance.²⁻⁸⁾ Among these new alloys with high temperature creep resistance, the hypereutectic Mg-Si alloys have high potential as structural materials for elevated temperature applications.²⁾ 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.⁹⁾ Therefore, the refinement of the primary Mg₂Si crystals is very important to improve the mechanical properties of the hypereutectic Mg-Si alloys.

Some new advanced processing techniques such as hot extrusion,^{10,11)} rapid solidification¹²⁾ 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 compositions become complex upon such additions, 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.

Compared with the addition of refiners, the routes of the microstructures refinement caused by external energy fields have an excellent advantage of making no change to the composition of the treated alloys.¹⁶⁻¹⁹⁾ In particular, it has long been established that the electromagnetic vibration (EMV) can effectively refine the microstructures for a large range of metals prepared by the ingot metallurgy process.²⁰⁻²⁸⁾ For this route, the operating parameters of EMV were proved to be very important to determine the refining efficiency, including vibrating frequency,^{22,23,25-27)} current density,^{24,26,27)} magnetic flux density,^{26,27)} imposition timing, etc.^{24,28)}

For example, Mizutani *et al.*²²⁾ found that the vibration frequency near 1 kHz was most effective for the refinement of the primary silicon in the Al-17 mass%Si treated by EMV. Sugiura *et al.*²⁴⁾ found that there existed a threshold intensity of the electrical current for the microstructure refinement of the Sn-10 mass%Pb caused by EMV. The refining effect could be obtained only when EMV was imposed in the initial stage of the solidification. More recently, Li *et al.*²⁷⁾ reported that the effects of the operating parameters of EMV on the solidification behavior of AZ31 alloy and the best refining efficiency could be obtained under the condition of the optimum operating parameters.

In a word, EMV process has been demonstrated to be effective in producing refining microstructures for a large range of alloys. Unfortunately, few works have been performed on the modification of the primary and eutectic Mg₂Si phase in the primary Mg-Si alloys by EMV. The previous studies^{29,30)} performed by the present authors showed that the primary Mg₂Si crystals in a hypereutectic Mg-Si alloy could be effectively refined by a weak EMV which was induced in the melt by only imposing the

*Corresponding author, E-mail: tandujun@yahoo.com

alternating current (AC) of 60 A with high frequency of 1 kHz. The imposed temperature range of AC was proved to be a very significant factor to determine the size uniformity of the modified primary Mg_2Si crystals.³⁰⁾ In the present study, AC with different current intensities and frequencies were imposed upon a hypereutectic Mg-Si melt in a constant temperature range, to investigate the effects of the operating parameters on the modification of the primary Mg_2Si crystals.

2. Experimental Procedure

In the present study, the silicon content of the Mg-Si alloy used in this experiment was evaluated at approximately 4.8 mass%.²⁹⁾ Judged by the Mg-Si binary phase diagram,³¹⁾ the Mg-4.8 mass%Si alloy is a typical hypereutectic Mg-Si alloy. For this Mg-Si alloy, the primary Mg_2Si crystals begin to precipitate at about 761°C, and the Mg-Mg₂Si eutectic structures form at about 638°C.²⁹⁾

The preparation process of the samples treated by imposition of AC was simply depicted 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). Then, the melt was poured into an Al_2O_3 tube which was preheated to 700°C using a small in-house built electric resistance furnace. This Al_2O_3 tube was supported with a clamp fixed by a bracket in advance, as shown in Fig. 1. 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 AC into the melt. The distance between the end of tungsten electrodes and the bottom of the Al_2O_3 tube was 10 mm. A couple of K-type thermocouples was fixed on one

Fig. 1 Schematic view of the experimental apparatus.

Fig. 2 Observed area in the sample (unit: mm).

of the two tungsten electrodes and the temperature of the melt was recorded automatically using digital recorder (Keyence, GR-3500 type).

The small in-house built electric resistance furnace was turned off after the temperature of the melt decreased to about 770°C. And then, the brick (as shown in Fig. 1) was moved away and the small power self-made electric resistance furnace was pulled off. The hypereutectic Mg-Si melt filled in the Al_2O_3 pipe was air-cooled. In the present study, all samples were prepared by imposition of AC upon the hypereutectic Mg-Si melt in a constant temperature range between 700 and 630°C. For the Mg-4.8 mass%Si alloy, the theoretical mass fractions of primary Mg_2Si crystals were about 6.1 and 9.9 mass% at 700°C and eutectic temperature of 638°C, respectively.²⁹⁾ Two series of experiments were designed and performed. One series was that the current was set as constant 60 A and five different frequencies, i.e., 0.05, 0.1, 0.5, 1 and 2 kHz were selected. The other series was that the frequency was kept as 1 kHz and five current intensities were selected, i.e., 20, 40, 60, 80 and 90 A. For comparison, a sample without AC imposition was prepared. Therefore, ten samples were prepared in the present study.

The cylindrical ingots were cut longitudinally along the middle line parallel to the electrodes. The samples for microstructure observation were prepared using a standard procedure with 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. 2. The size of the observed area was $15 \times 15 \text{ mm}^2$.

To evaluate the modification effect of AC imposition, the sizes of the primary Mg_2Si crystals for all samples were measured from the SEM pictures, using the longest length of the primary trunk of the dendritic Mg_2Si crystals. All Mg_2Si crystals present in one SEM image area were measured. Mg_2Si crystals from other SEM images were also measured until 200 primary Mg_2Si crystals were obtained for every sample, and the 200 data were then analyzed using statistical methods. The average value and standard deviation were used to evaluate the effect of AC with different intensities and frequencies on the modification effect, including the refinement and uniformity of sizes of the modified primary Mg_2Si crystals.

Fig. 3 SEM image of the hypereutectic Mg-Si alloy without AC imposition.

3. Results

3.1 SEM observations of the primary Mg_2Si crystals

Figure 3 shows the SEM image of the hypereutectic Mg-Si alloy without AC imposition treatment. For this sample, it is obvious that the primary Mg_2Si crystals assume mainly the complex dendritic morphologies, like the crystals denoted by A and B. These two primary Mg_2Si crystals assume the long and coarse dendritic morphology with a unidirectional primary trunk and two perpendicular primary trunks, respectively. In addition, the primary Mg_2Si crystals with polygonal morphologies can also be observed, like the crystal denoted by C.

Figure 4 shows the SEM images of the hypereutectic Mg-Si alloy treated by imposition of AC with a constant current intensity of 60 A and different frequencies. For the sample treated by imposition of AC with low frequency of 0.05 kHz, many coarse and complex dendritic primary Mg_2Si crystals existed in this sample, as shown in Fig. 4(a). With the increase in the frequency to 0.1 kHz, the sizes of the primary Mg_2Si crystals were obviously refined and the number of the coarse dendritic primary Mg_2Si crystals decreased obviously. Compared in the Figs. 4(b), 4(c) and 4(d), it could be found that these trends continued with the increase in the frequency to 1 kHz. The coarse dendritic primary Mg_2Si crystals could hardly be found when the samples were treated by imposition of AC with high frequencies of 1 kHz and 2 kHz, as shown in Figs. 4(d) and 4(e).

Figure 5 shows the SEM images of the hypereutectic Mg-Si alloy treated by imposition of AC with a constant frequency of 1 kHz and different current intensities. To avoid repeating, the SEM image of the sample treated by imposition of AC with frequency of 1 kHz and current intensity of 60 A was omitted here, because it was shown in Fig. 4(d). Many coarse and complex dendritic primary Mg_2Si crystals could be observed in the sample treated by imposition of AC with the frequency of 1 kHz and the low current intensity of 20 A, as shown in Fig. 5(a). Compared in the Figs. 5(a) and 5(b) as well as Fig. 4(d), it could also be found that the sizes of the primary Mg_2Si crystals were obviously refined and the number of the coarse dendritic primary Mg_2Si crystals was decreased obviously with the

increase in the current intensity to 60 A. These trends were similar to the effect of frequency, as shown in the Figs. 4(b), 4(c) and 4(d). With the further increase in the current intensity to 80 or 90 A, the coarse dendritic primary Mg_2Si crystals could also hardly be found in these two samples, as shown in Figs. 5(c) and 5(d).

3.2 Statistical analysis results of the sizes of the primary Mg_2Si crystals

3.2.1 Statistical histograms

The statistical histograms of the sizes of 200 primary Mg_2Si crystals are shown in Figs. 6, 7 and 8 for all samples. Moreover, the ratio of the number of coarse Mg_2Si crystals with sizes over than 400 μm to the 200 primary Mg_2Si crystals measured for every sample is given in the figure, which is denoted by R , i.e. $R = (\text{number of primary } \text{Mg}_2\text{Si} \text{ crystals over than } 400 \mu\text{m})/200$. However, it should be noted that the obtained sizes of the Mg_2Si crystals might be the cross section of primary or secondary trunk of the coarse dendritic Mg_2Si crystals. The real sizes of dendritic Mg_2Si crystals should be measured in a three-dimensional space, but it is very difficult to carry out. Therefore, the effect of measurement method on the real sizes of primary crystals was omitted in the present study, but to aim at the relative change of primary crystals sizes after the AC imposition.

(1) Statistical histogram of the sample without AC imposition

Figure 6 shows the statistical histogram of the sizes of primary Mg_2Si crystals in the hypereutectic Mg-Si alloy without AC imposition. The size interval for counting in this figure was 100 μm . For this sample, the sizes of the primary Mg_2Si crystals distributed from 50 to 1600 μm . The ratio of the Mg_2Si crystals with sizes over than 1000 μm to the 200 crystals measured for this sample amounts to about 3%, which implies there existed some very long and coarse Mg_2Si crystals with complex dendritic morphologies (as shown in Fig. 3) in the hypereutectic Mg-Si alloy without AC imposition.

(2) Effect of frequency on statistical histograms

Figure 7 shows the statistical histograms of the sizes of primary Mg_2Si crystals in the hypereutectic Mg-Si alloy treated by imposition of AC with a constant current of 60 A and different frequencies. The size intervals for counting in these five figures were 50 μm . When the frequency was 0.05 kHz, the sizes of the primary Mg_2Si crystals in this sample distributed from 50 to 700 μm , as shown in Fig. 7(a). The ratio R for this sample was about 15%. However, the same ratio R for the sample without AC imposition was about 40%, as shown in Fig. 6. With the increase in the frequency to 0.1 kHz, the sizes of the primary Mg_2Si crystals in this sample also distributed from 50 to 700 μm , as shown in Fig. 7(b). However, the ratio R for this sample was further decreased to 6%. When the frequency was increased to 0.5 kHz, the distribution range of the Mg_2Si crystals sizes and the ratio R had no obvious change, as shown in Fig. 7(c). However, with the further increase in the frequency to 1 kHz, the distribution range of the Mg_2Si crystals sizes became narrow and the sizes located in the range from 50 to 400 μm , as shown in Fig. 7(d). Also, the ratio R for this sample was further decreased to 0%, which implies that no obvious

Fig. 4 SEM images of the hypereutectic Mg-Si alloy treated by imposition of AC with a constant current of 60 A and different frequencies of 0.05 (a), 0.1 (b), 0.5 (c), 1 (d) and 2 kHz (e).

coarse dendritic Mg_2Si crystals existed in this sample, as shown in Fig. 4(d). Compared with the histogram shown in Fig. 7(d), the Mg_2Si crystals sizes distributed in the same range from 50 to 400 μm although the frequency was further increased from 1 to 2 kHz, as shown in Fig. 7(e). However, it should be noted that the ratio of the Mg_2Si crystals with sizes in the range between 150 and 200 μm was much more than that of the other samples.

(3) Effect of current intensity on statistical histograms

Figure 8 shows the statistical histograms of the sizes of primary Mg_2Si crystals in the hypereutectic Mg-Si alloy treated by imposition of AC with a constant frequency of 1 kHz and different current intensities. The size intervals for

counting in these four figures were 50 μm . To avoid repeating, the statistical histogram of the sizes of primary Mg_2Si crystals in the sample treated by imposition of AC with frequency of 1 kHz and current intensity of 60 A is omitted here, because it is the same with Fig. 7(d) obtained from the same processing condition.

When the current was 20 A, the sizes of the primary Mg_2Si crystals in this sample distributed from 50 to 750 μm , as shown in Fig. 8(a). Compared with the sample without AC imposition, the ratio R for this sample was remarkably decreased from about 40% to 11%. With the increase in the current intensity to 40 A, the sizes distribution of the primary Mg_2Si crystals became narrow and the sizes located in the

Fig. 5 SEM images of the hypereutectic Mg-Si alloy treated by imposition of AC with a constant frequency of 1 kHz and different current intensities of 20 (a), 40 (b), 80 (c) and 90 A (d).

Fig. 6 Statistical histogram of the sizes of primary Mg_2Si crystals in the hypereutectic Mg-Si alloy without AC imposition.

range from 50 to 550 μm, as shown in Fig. 8(b). Furthermore, the ratio R for this sample was further decreased to 6.5%. When the current intensities were 60 A, 80 A and 90 A, it could be found that the distribution ranges of the Mg_2Si crystals sizes became narrower and the sizes located in the range from 50 to 400 μm for these three samples. Also, the ratios R were all further decreased to 0%, which implies no obvious coarse dendritic Mg_2Si crystals could be observed in these three samples, as shown in Fig. 4(d), Figs. 5(c) and 5(d). Furthermore, for the two samples when the current

intensities were 80 A and 90 A, the ratios of the Mg_2Si crystals with sizes in the range between 150 and 200 μm were much more than those of the other samples, as shown in Figs. 8(c) and 8(d).

3.2.2 Statistical average sizes and standard deviations

Figure 9 shows the effect of frequency on the statistical average size and standard deviation for the samples treated by imposition of AC when the current was fixed at 60 A. The obtained data for every frequency were listed in this figure. For the sample without AC imposition, its statistical average size and standard deviation were 403 μm and 241 μm, respectively. For the sample treated by imposition of AC with intensity of 60 A and low frequency of 0.05 kHz, the statistical average size and standard deviation for this sample were obviously decreased to 288 μm and 122 μm, respectively. With the further increase in the frequency to 0.1 kHz, the statistical average size and standard deviation were drastically decreased to 252 μm and 102 μm, respectively. After that, the statistical average size and standard deviation were both slowly decreased with the increase in the frequency. When the frequency was 2 kHz, the statistical average size and standard deviation for this sample were decreased to 176 μm and 62 μm, respectively. The low standard deviation implies high uniformity of sizes of the modified primary Mg_2Si crystals. Therefore, it could be known that the average sizes of the primary Mg_2Si crystals decreased, and meanwhile the uniformities of primary Mg_2Si crystals sizes improved with the increase in the frequency.

Fig. 7 Statistical histograms of the sizes of primary Mg_2Si crystals in the hypereutectic Mg-Si alloy treated by imposition of AC with a constant current intensity of 60 A and different frequencies of 0.05 (a), 0.1 (b), 0.5 (c), 1 (d) and 2 kHz (e).

Figure 10 shows the effect of current intensity on the statistical average size and standard deviation for the samples treated by imposition of AC when the frequency was fixed at 1 kHz. Likewise, the obtained data were listed in this figure. Compared with the sample without AC imposition, the statistical average size and standard deviation were drastically decreased to 257 μm and 118 μm even though the sample was treated by imposition of AC with low intensity of 20 A. With the increase in the current intensity, the statistical average size and standard deviation were gradually decreased. When the current intensity was 60 A, the statistical average size and standard deviation were decreased to 196 μm and 68 μm , respectively. After that, the further increase in the current intensity had no obvious effect on the statistical average size and standard deviation. When the current intensity was increased to 90 A, the statistical average size and standard deviation were 196 μm and 63 μm , respectively.

From the above results, it is known that the primary Mg_2Si crystals could be refined due to AC imposition upon the hypereutectic Mg-Si melt during solidification. The operating parameters of frequency and current intensity were both significant to determine the average size and uniformity of sizes for the primary Mg_2Si crystals when AC was imposed in the fixed temperature range between 700 and 630°C.

4. Discussion

In the present experimental conditions, the average cooling rates from 760 to 640°C were almost same for all samples and were about 1.9°C/s. The effect of cooling rate on the microstructures for the hypereutectic Mg-Si alloys could be excluded in the present study. The details about the effect of AC imposition on the cooling rate were discussed in the previous study.²⁹⁾ When the temperature was decreased to

Fig. 8 Statistical histograms of the sizes of primary Mg_2Si crystals in the hypereutectic Mg-Si alloy treated by imposition of AC with a constant frequency of 1 kHz and different current intensities of 20 (a), 40 (b), 80 (c) and 90 A (d).

Fig. 9 Effect of frequency on the statistical average size and standard deviation for the 200 particle sizes measured in the hypereutectic Mg-Si alloy treated by imposition of AC with a constant current intensity of 60 A.

Fig. 10 Effect of current intensity on the statistical average size and standard deviation for the 200 crystals sizes measured in the hypereutectic Mg-Si alloy treated by imposition of AC with a constant frequency of 1 kHz.

less than the liquidus temperature of 761°C , the primary Mg_2Si crystals began to nucleate and grow in the hypereutectic Mg-Si melt used in the present study.²⁹⁾ Under the present conditions, the primary Mg_2Si crystals grow into dendritic morphologies as dendritic growth manner, as shown in Fig. 3. The detailed discussions about the nucleation and growth of the primary Mg_2Si crystals had been carried out in the previous study.^{29,30)}

When an AC was imposed upon the hypereutectic Mg-Si melt, an alternating magnetic field with the same frequency could be induced in the melt.^{32,33)} Then, this alternating magnetic field interacted with the electric current itself and

then an electromagnetic vibration was induced in the melt. The electromagnetic force acting on the sample could be estimated. Firstly, the electrical current density, J in the sample is estimated using the assumption that the cross-section through which a current passes includes the electromagnetic skin layer of the melt between the electrodes.

$$J = \frac{I}{(h + 2\delta)(D + 2\delta)} [\text{Am}^{-2}] \quad (1)$$

where D is the diameter of the electrode, h is the depth of insertion of the electrodes in the melt, I is the imposed AC and δ is the electromagnetic skin layer defined as

Fig. 11 Effects of the operating parameters of frequency (a) and current intensity (b) on the theoretical electromagnetic force.

$$\delta = \sqrt{\frac{2}{\sigma\mu_0\omega}} \text{ [m]} \quad (2)$$

where μ_0 is the magnetic permeability, σ is the electrical conductivity of the liquid phase and ω is the angular frequency of AC. The calculated values of δ corresponding to the frequencies of 0.05, 0.1, 0.5, 1 and 2 kHz were 37.8, 26.8, 11.8, 8.7 and 7.1 mm, respectively.

The electromagnetic force F generated by the interaction between the imposed AC and its induced magnetic field B_{induced} can be estimated from Ampere's law

$$F = J \times B_{\text{induced}} \text{ [Nm}^{-3}] \quad (3)$$

where

$$B_{\text{induced}} = \frac{\mu_0 I}{2h + 2D + 8\delta} \quad (4)$$

However, it should be noticed that the real passing areas of current in the sample with the frequencies of 0.05 kHz, 0.1 kHz and 0.5 kHz were different from their corresponding calculated areas of $(h + 2\delta)(D + 2\delta)$. Therefore, the J and B_{induced} could not be estimated by eqs. (1) and (4) for the frequencies of 0.05, 0.1 and 0.5 kHz. When the frequencies were 0.05 and 0.1 kHz, the real passing area of AC should be the whole longitudinal section of the sample, which was about $21 \times 40 \text{ mm}^2$. Also, the real passing area of AC with the frequency of 0.5 kHz should be $21 \times (10 + h + \delta) \text{ mm}^2$. The J and B_{induced} should be estimated based on the real passing area of AC in the samples when the frequencies were 0.05, 0.1 and 0.5 kHz.

The magnitudes of the electromagnetic forces for all experimental conditions were theoretically estimated, which are shown in Fig. 11. Obviously, the electromagnetic forces are close related with the operating parameters, i.e. current intensity and frequency. The electromagnetic force was roughly proportional to the current intensity when the frequency was fixed at 1 kHz. However, as far as the effect of frequency was concerned, the electromagnetic forces were same when the frequencies were 0.05 and 0.1 kHz due to the same current passing area, i.e., the whole longitudinal section of the sample. After that, the electromagnetic force increased with the increase in the frequency.

When AC was imposed upon the melt, the electromagnetic force made the conductor to vibrate periodically, centering

on the equilibrium position according to its initial boundary condition. The experimental results showed that the primary Mg_2Si crystals could be modified by the weak EMV induced by AC imposition. The modification effect of the primary Mg_2Si crystals had a close relation with the operating parameters. Therefore, the modification effect should have close relation with the theoretical electromagnetic force since its magnitude was determined by the operating parameters, as shown in Fig. 11. Figure 12 shows the influence of the theoretical electromagnetic force on the average size and standard deviation of the primary Mg_2Si crystals. When the electromagnetic force was less than a critical value of about 126 Nm^{-3} corresponding to the current intensity of 60 A and frequency of 1 kHz, the statistical average size and the standard deviation drastically decreased with the increase in the electromagnetic force. However, the average size of the primary Mg_2Si crystals was constant when the electromagnetic force exceeded the critical value of 126 Nm^{-3} . Therefore, both the increase in the current intensity and frequency are useful ways to decrease the size of primary Mg_2Si under the critical condition in the present experimental condition.

When EMV is imposed upon the melt with a mushy zone, it was widely accepted that EMV contributes the fracture of the primary dendritic crystals resulting in the refinement of the solidified structure.^{21,27,28,33} In the present study, the AC was begun to apply into the Mg-4.8 mass%Si melt containing about 6.1 mass% of primary Mg_2Si crystals at 700°C .²⁹ The fragmentation of the primary Mg_2Si crystals caused by EMV was possibly responsible for the refinement caused by AC imposition, which has been discussed in the authors' previous studies.^{29,30} The coarse Mg_2Si crystals with complex dendritic morphologies should be broken at some weak parts caused by EMV. For the dendritic crystals, the weak parts should be the root regions where secondary dendrites grow from primary trunk of dendrites or tertiary dendrites grow from the trunk of secondary dendrites.³⁴ These weak root regions were named as "shrinkage neck".³⁴

After AC was imposed upon the hypereutectic melts containing primary Mg_2Si crystals, some coarse Mg_2Si crystals with complex dendritic morphology could be broken from the parts of "shrinkage necks" by the induced EMV into small crystals with polygonal morphology. As a result, the average size of the primary Mg_2Si crystals could be decreased.

Fig. 12 Effect of the electromagnetic force on the statistical average size (a) and standard deviation (b).

ed after the hypereutectic Mg-Si melt treated by imposition of AC. These small crystals with polygonal morphology could not be further broken by the weak EMV because no obvious weak parts existed in these crystals. Therefore, no obvious changes of the average size and standard deviation could be found with the increase in the electromagnetic force to exceed about 126 N m^{-3} , corresponded to the current intensity of 60 A and frequency of 1 kHz. Moreover, it should be noted that some new primary Mg_2Si crystals should nucleate and grow after the AC was applied into the hypereutectic Mg-4.8 mass%Si melt from 700°C . These new primary Mg_2Si crystals should grow into small particles with polygonal morphology due to no enough time to grow into coarse dendritic crystals before eutectic reaction occurs.²⁹⁾ It is possible that these small primary Mg_2Si crystals were smaller than those broken from coarse dendritic crystals by the EMF.

However, it should be noted that the average size of the primary Mg_2Si crystals was remarkably refined from 288 to $252 \mu\text{m}$ with the increase in the frequency from 0.05 to 0.1 kHz even though the estimated EMFs were almost same for these two frequencies. Modification of the primary Mg_2Si crystals should depend not only on intensity of the EMF but also on fluid motion and so on. Velocity distribution in the Al_2O_3 tube crucible depends on the frequency,²⁶⁾ and 0.05 kHz might be too low to induce the fluid motion. This might be one of the reasons why the grain sizes changed between 0.05 kHz and 0.1 kHz even though the EMF was the similar intensity. Further study should be needed about the effect of frequency on the modification of the primary Mg_2Si crystals.

5. Conclusions

- (1) The primary Mg_2Si crystals could be effectively refined for the hypereutectic Mg-Si melt during solidification by imposition of AC. The operating parameters of frequency and current intensity were both significant to determine the average size and uniformity of sizes for the primary Mg_2Si crystals.
- (2) When the current intensity was fixed at 60 A, the statistical average size increased and uniformity of sizes for the primary Mg_2Si crystals improved with the increase in the frequency to 2 kHz. However, in the case

that the frequency was fixed at 1 kHz, the statistical average size increased and uniformity of sizes improved with the increase in the current intensity to 60 A. With the further increase in the current intensity to 90 A, the statistical average size and uniformity of sizes had no obvious changes.

- (3) The average size of the modified primary Mg_2Si crystals drastically decreased with the increase in the estimated electromagnetic force to a critical value of about 126 N m^{-3} corresponding to the current intensity of 60 A and frequency of 1 kHz. However, the average size was constant if the electromagnetic force exceeded the critical value.

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