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The Effects of Electromagnetic Vibration on Macrosegregation in AZ80 Magnesium Alloy Billets

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The effects of electromagnetic vibration on macrosegregation in AZ80 magnesium alloy billets have been investigated experimentally. Comparing to conventional direct-chill casting, the enrichment for the alloying elements close to the billet surface is significantly reduced by the electromagnetic vibration. Increasing the stationary magnetic field, *i.e.*, increasing the intensity of the electromagnetic vibration results in uniform distributions of the metallic elements in the billet. The distribution of impurity iron has the same tendency with alloying element manganese with and without the electromagnetic vibration. The uniformity in the concentration profile of iron is higher than that for the alloying elements in the billet and increases with increasing the stationary magnetic field of the system used for generation of electromagnetic vibration.

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1. Introduction

In most direct-chill casting alloys, compositional homogeneity within casting is very difficult to attain, since solute redistribution is inevitable during alloy solidification. The macroscopic redistribution of alloy constituents during solidification was commonly called macrosegregation. With increasing the diameter the degree of the macrosegregation in the billet is aggravated. In direct-chill casting process, macrosegregation is formed within the mushy zone and is generally the result of interdendritic flow induced by shrinkage, geometry and gravity. This nonuniformity of alloy element distribution is more difficult to reduce subsequently by thermo-mechanical post-treatments and can lead to a nonuniform distribution of mechanical properties and contribute to cracking during extrusion or forging of wrought alloys or when an as-cast piece is severely loaded in service.[1,2] Under these circumstances, the ability to reduce the macrosegregation for direct-chill casting billet is crucial to get high quality wrought products.

Electromagnetic field has been widely used during the solidification of alloy to change the alloying element distribution. Yang *et al.* studied the segregation of copper and silicon in Al–Si–Cu alloy during electromagnetic centrifugal solidification and found that the electromagnetic force suppressed the accumulation of Cu in the outer area of the sample.[3] Nakada *et al.* investigated the stationary magnetic field on the modification of macroscopic segregations and porosities in continuously cast steel billets and found that the application of a higher magnetic flux density resulted in a decrease of the V-segregation and porosity in the billet.[4] Vives studied the effects of forced electromagnetic vibration on the solidification of aluminium alloys.[5–7] With the application of a stationary magnetic field (DC field) and an alternating magnetic field (AC field), the solidifying melts in the mold were forced vibrated by the Lorentz force, which resulted in the oscillatory melt flow in the mold and the refinement on the resulting grain structure. Based on this technique, electromagnetic vibration direct-chill casting has been developed in our laboratory.

The objective of this study is to compare the different response in macrosegregation for conventional direct-chill cast and electromagnetic vibration cast magnesium alloys. The alloy used in this paper is AZ80, which is a wrought magnesium alloy with a high alloying element content. Solutes distributions over the cross section of the large diameter 300 mm billets that cast by different processes are investigated, respectively.

2. Experimental Procedures

The composition for the AZ80 alloy used in this research is given in Table 1, where aluminum, zinc and manganese are the main alloying elements. The AZ80 alloy was prepared using commercial purity magnesium. The following alloying materials were added to the melt: commercial pure Al and Zn, $MnCl_2$-pills and Al–3%Be mother alloy. The melting was carried out in a laboratory electrical resistance furnace with an iron crucible containing approximately 130 kg of liquid magnesium and protected by $CO_2 + 0.5\%\ SF_6$ atmosphere. The melt was transferred to a semi-continuous casting machine at 923 K, about 50 K higher than the liquidus, and cast into billet with the diameter of 300 mm at the velocity of 80 mm/min.

The experimental apparatus for electromagnetic vibration is shown in Fig. 1. The billet mold is made of a stainless steel alloy, which was resistant to the magnetic field. The electromagnetic vibration was generated by the interaction of a stationary magnetic field and an alternating magnetic field. The stationary magnetic field was generated by supplying a 100-turn induction coil with direct current. A

Table 1 Chemical composition of AZ80 alloy (mass%).

Alloy AZ80								
Al	Zn	Mn	Si	Fe	Cu	Ni	Be	Mg
7.8	0.7	0.15	<0.01	<0.01	<0.03	<0.005	0.001	Bal.

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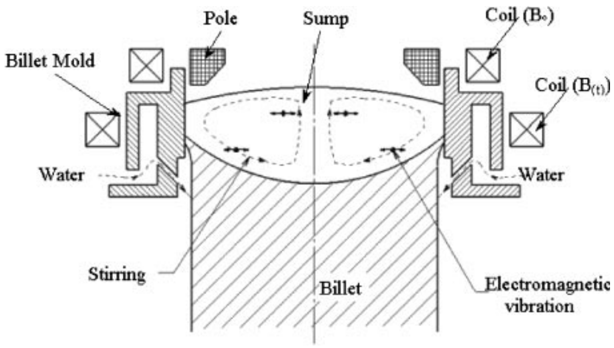


Fig. 1 Schematic diagram of semi-continuous casting of AZ80 billet under electromagnetic vibration.

ring shape pole was embedded in the coil to increase the intensity of the magnetic field. The alternating magnetic field was generated by another 100-turn coil, which was supplied by alternating current with a certain frequency. These two magnetic fields were nearly parallel to the axis of the billet. Under the effect of the alternating magnetic field, an induced current was generated in the melt. Thus by the interaction of the induced current and the applied magnetic fields forced convection and vibration were generated in the melt, respectively.[6)]

In the casting experiments, several AZ80 round billets of 300 mm in diameter were cast in a direct-chill casting installation built in our laboratory. In the conventional casting, the billets were cast while kept the casting parameters constant. In the electromagnetic vibration casting, the magnetic fields were applied at the onset of the casting while maintained the other casting parameters unchanged. The alternating magnetic field with the exciting frequency 30 Hz was held at 13000 A-turns and the stationary magnetic field was changed step-wise from 10000 A-turns to 15000 A-turns and then to 20000 A-turns. About 350 mm in length was cast in each condition of the stationary magnetic field.

Chemical composition was measured on samples that were cut in the horizontal section of the billet. A spark spectrum analyzer was used to measure the sample composition. Samples were ground to be mirror like and then washed with alcohol. Each sample was tested 5 times and the average was taken. The error of these measurements, taken as the standard deviation of measurements is always lower than 5%. Particles characterization of the AZ80 billet were carried out by scanning electron microscopy (SEM) on transverse section of the billet, polished using standard metallographic techniques.

3. Results

3.1 Appearance of AZ80 billets under different casting conditions

The billets that cast under different conditions are shown in Fig. 2. In conventional direct-chill casting, Fig. 2(a), the surface of the billet is bright. However, in the electromagnetic vibration casting, the melt is subjected to periodic Lorentz force, thus the value of the contact pressure between the melt and the mold exhibits periodic variation. During the casting, the air has more ability to react with the Mg melt, which results in the formation of oxidation film on the billet surface during the casting and makes the surface loss of brightness, Fig. 2(b).

A significant difference in appearance was also observed at the end of the billets when they were cast in different processes. In the conventional casting, due to the solidification contraction, surface wrinkling appears to spread from the billet center in radial direction and the shrinkage void is very large, as shown in Fig. 3(a). However, in the electromagnetic vibration casting, the melt solidifies under the effects of Lorentz force and a lot of vibrating ripples forms on the liquid surface until the melt solidifies completely. Contrary to the conventional casting, the shrinkage void under the electromagnetic vibration is very small, as shown in Fig. 3(b).

3.2 Distributions of the metallic elements in the billet

3.2.1 Main alloying elements

Macrosegregation is the one of the most important types of segregation that it is far more difficult to reduce subsequently by thermo-mechanical post-treatments. Several studies in the literature have examined macrosegregation profiles in the aluminium alloys.[8–11)] However, few literatures on segregation in magnesium alloy are available and no significant work has been undertaken so far. In our experiments, we investigated the macrosegregation in the AZ80 billets cast by different processes.

As aluminium, zinc and manganese are the main alloying elements in the AZ80 alloy, distributions of these elements in the billet greatly influence the properties of downstream forming. Figures 4(a)–(c) show the distributions of these three main alloying elements when the billet was cast in conventional process. Solute concentrations over the cross section of the billet are nonuniform: the metallic elements are highly enriched at the billet surface and their concentrations are significantly lower than the average value at the central part of the billet. From Fig. 4, it indicates that the three main alloying elements have the similar tendencies in the

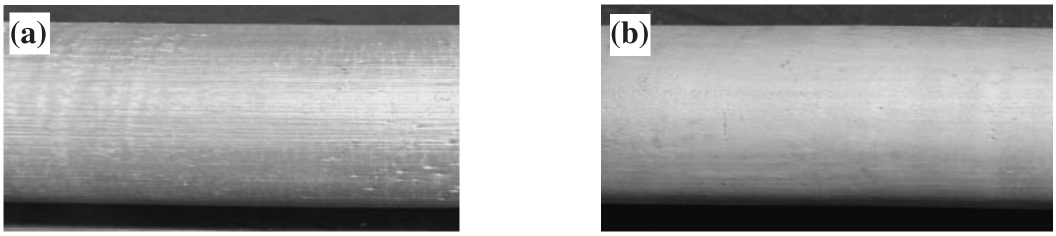


Fig. 2 AZ80 billets cast under different magnetic conditions (a) Conventional direct-chill casting (b) Electromagnetic vibration casting.

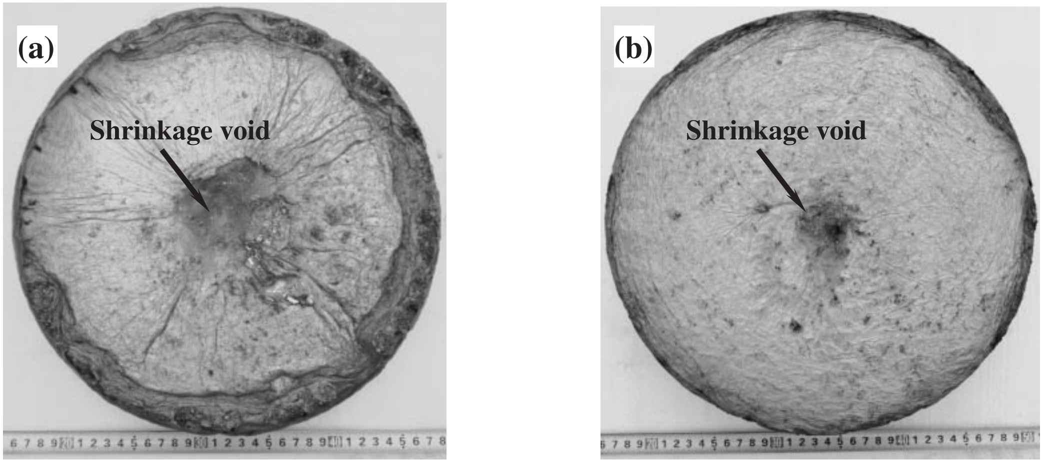


Fig. 3 Terminal billets of AZ80 alloys under different casting conditions (a) Conventional casting (b) Electromagnetic vibration casting.

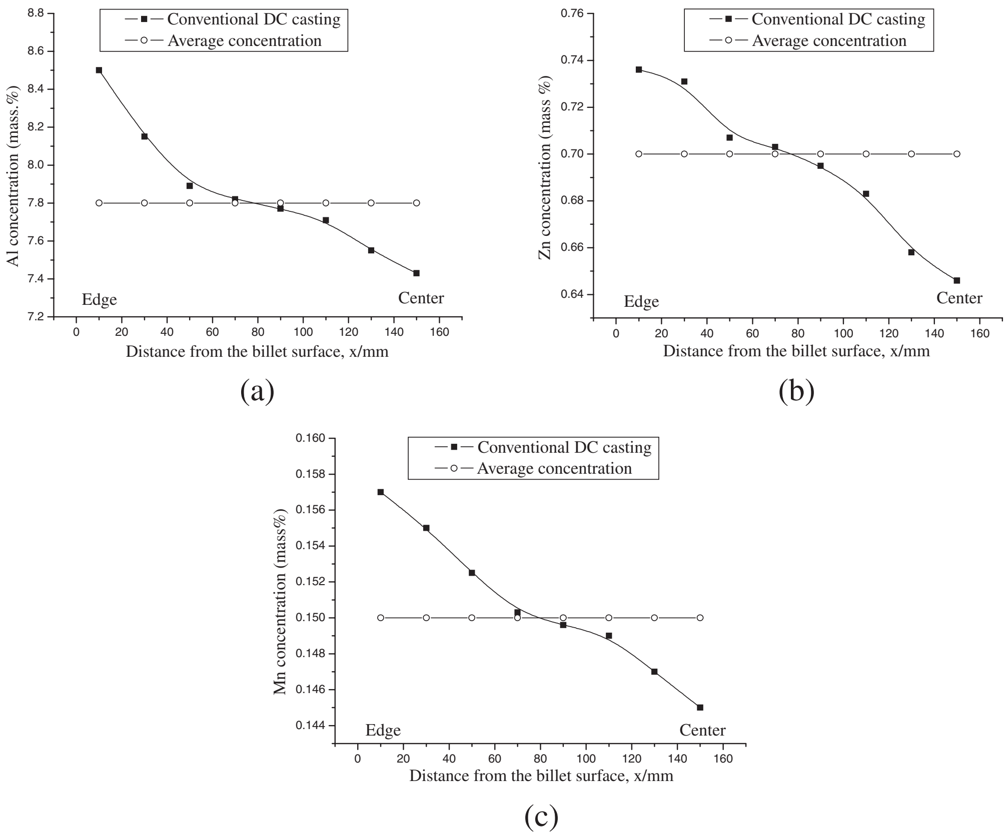


Fig. 4 Distributions of aluminum, zinc and manganese in the AZ80 billets under conventional casting conditions (a) aluminum (b) zinc (c) manganese.

distribution. These experimental results show that the phenomenon of macrosegregation in the aluminium alloys still exists in the magnesium alloy billet.

Under the effects of electromagnetic vibration, the distributions of the elements have been greatly changed. In our experiments, the intensity of the electromagnetic vibration was modulated by changing the values of the direct current in the coil. Figures 5(a)–(c) show distributions of aluminum, zinc and manganese under different intensities of the electromagnetic vibration, respectively. The electromagnetic vibration almost exerts a similar effect on each elements distribution in the solidified billet though their distribution features change to a large extent comparing to that in the conventional casting. As for aluminum, the concentration close to the billet surface is slightly decreased when the intensity of the stationary magnetic field (DC field) and the alternating magnetic field (AC field) were at 10000 A-turns and 13000 A-turns, respectively. With increasing the distance from the billet surface, its concentration profile shows a small decrease and then presents a sharp fall to the billet center. Keeping the alternating magnetic field constant and increasing the stationary magnetic field to 15000 A-turns,

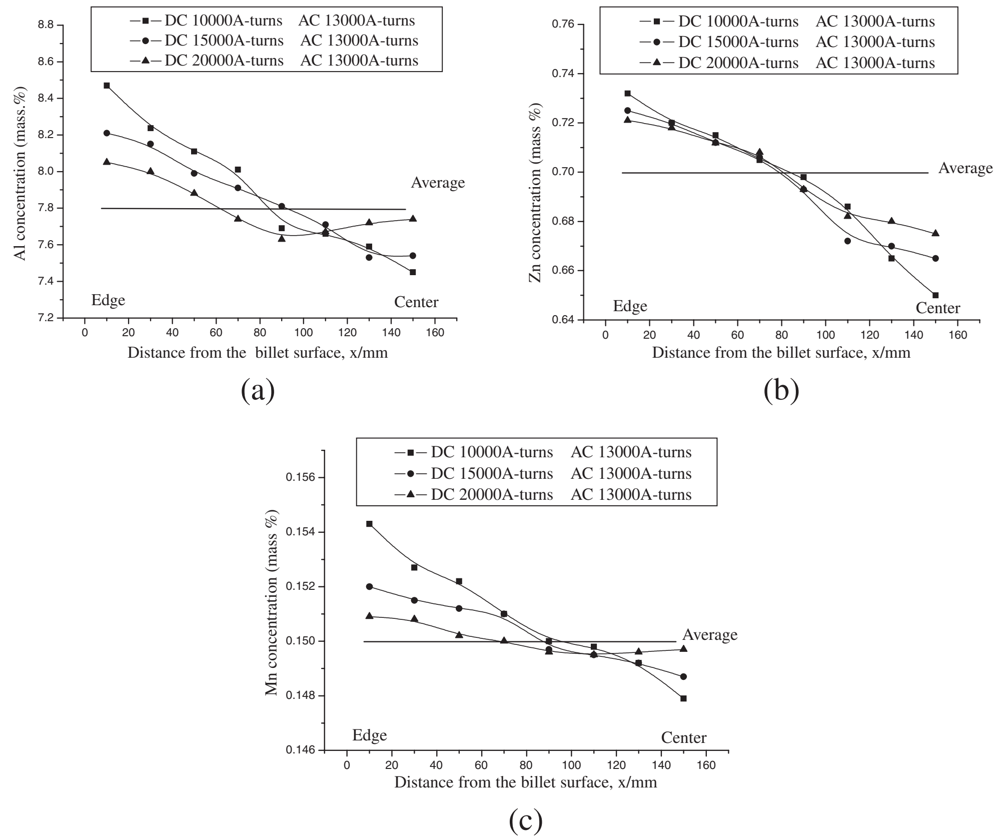


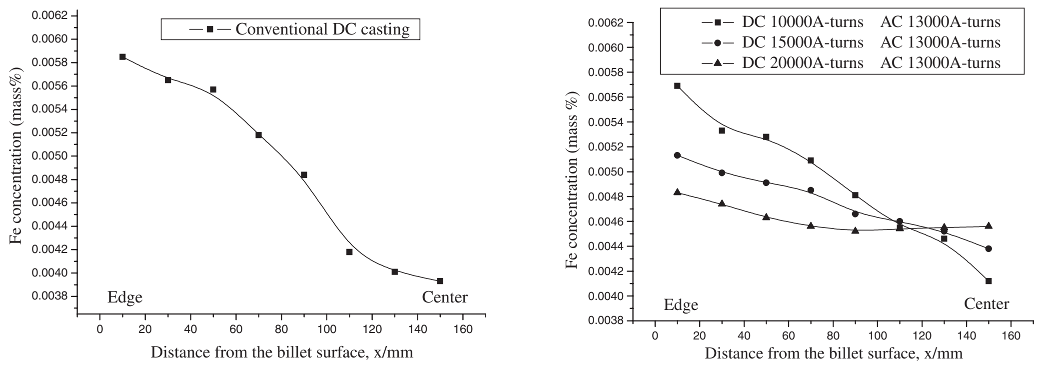
Fig. 5 Distributions of aluminum, zinc and manganese in the AZ80 billets under different electromagnetic vibration intensities (a) aluminum (b) zinc (c) manganese.

the phenomenon of the solute enrichment close to the billet surface is effectively suppressed. The concentration profile along the horizontal section of the billet is relatively uniform, though its concentration is still lower than the average value at the billet center. Further increasing the stationary magnetic field to 20000 A-turns, the concentration of aluminum at the billet edge is further decreased. The concentration profile in the billet is more uniform. An interesting phenomenon observed in experimental results is that aluminum concentration shows a slight increase at the billet center when the intensity of the stationary magnetic field is as high as 20000 A-turns. In the cases of zinc and manganese, we observed the similar trends as that for aluminum in corresponding electromagnetic vibration conditions. With increasing the stationary magnetic field, the concentrations for zinc and manganese are more uniform in the horizontal section of the billet. A slight increase in concentration was observed at the central part of the billet when the stationary magnetic field was high enough. However, the distribution for zinc in the billet is not as uniform as that for aluminum in the same electromagnetic vibration conditions in our casting experiments.

3.2.2 Impurity elements

Iron is one of the more harmful impurities in magnesium alloys in that it greatly reduces the corrosion resistance if present in even small amounts.[12] Concentration of iron in the magnesium alloy depends on the settling temperatures.[13] Although manganese is added into the magnesium alloys to remove iron, it still has some solubility in the magnesium alloy due to iron or steel containers used for melting magnesium and its alloys. However, there are few data available in the literatures on the iron distribution in the magnesium alloy billet under the magnetic fields. Even though the percentage of iron in magnesium alloy is very low, it is necessary to keep in mind the iron distribution in the AZ80 billets with and without the magnetic fields.

Figure 6(a) shows the distribution of iron in the horizontal section of the AZ80 billet cast in conventional process. Similar to the main alloying elements, iron is highly enriched close to the billet surface and depletes at the billet center. However, in the presence of the magnetic fields, the distribution of the iron significantly changes. Figure 6(b) shows the results obtained in the billet when it was cast under electromagnetic vibration conditions. With increasing the intensities of the electromagnetic vibration, the profile of iron concentration from the billet edge to the center tends to be more uniform. Comparing the segregations of iron with manganese, it should be noted that the distribution for iron in the billet shows a close relationship to that for manganese with and without magnetic fields. The iron concentration increases with the increase of the manganese concentration and vice versa. Comparing distributions of the iron with other alloy elements shows that the distribution of iron is more homogeneous than those of the other solute elements in the billet under the corresponding electromagnetic vibration conditions. The concentration of iron is almost constant over a wide range of distance from the billet surface when the intensity of the stationary magnetic field reaches its maximum power in our experiments.



(a) (b)

Fig. 6 Distributions of iron in the AZ80 billets under conventional and electromagnetic vibration conditions (a) conventional casting (b) electromagnetic vibration casting under different intensities.

4. Discussion

The macroscopic redistribution of alloy constituents during solidification is a defect, which occurs, in real metal processing systems. Macrosegregation in the aluminium alloy is generally attributed to the following mechanism: In direct-chill casting process, solute is rejected to the liquid during the solidification causing the liquid become richer in solutes. When the growing solid particles interlock with each other, solidification shrinkage-induced liquid flow drives the solute-rich liquid to the periphery of the billet through the interdendritic channels, which generally leads to macroscopic level compositional nonuniformity over the horizontal section of the billet.[14,15] As the solidification processes of most aluminium and magnesium alloys are all characterized by the formation of dendrites,[16] such macrosegregation in the aluminium and magnesium alloys are mainly caused by the flow behaviors of the interdendritic liquid-phase. This explains large-scale nonuniformity for the solutes in the AZ80 billet that is cast in conventional process.

In the electromagnetic vibration casting, a stationary magnetic field B_o and an alternating magnetic field $B_{(t)}$ are applied to the molten melt simultaneously.[5,6] These magnetic fields are nearly parallel to the vertical axis of the billet. Under the effects of the alternating magnetic field, according to the law of electromagnetic induction, an eddy current is induced in the molten melt, which is mainly concentrated in the regions close to the mold wall due to the skin effect.[17] Under the combined action of the B_o and $B_{(t)}$, a vibration is generated in the melt pool. The principle of electromagnetic vibration is shown in Fig. 7,[5] which is of dual origins: the $J \times B_{(t)}$ force consists of a time-independent component and an oscillatory component, while the interaction of induced current J and the stationary magnetic field B_o generates a vibrating force with the same frequency of the alternating magnetic field. It is the main part of the vibrating forces in the system. The electromagnetic vibration is mainly originated inside the electromagnetic skin depth area and owing to the medium elasticity, is propagated throughout the melt.

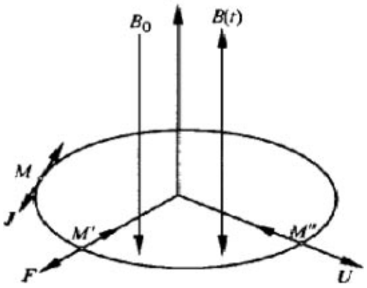


Fig. 7 Principle of production of electromagnetic vibration.

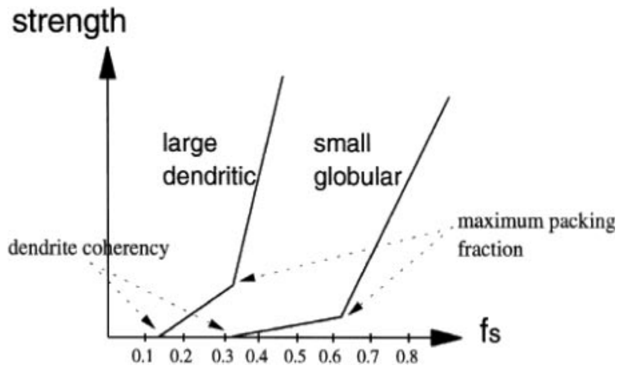
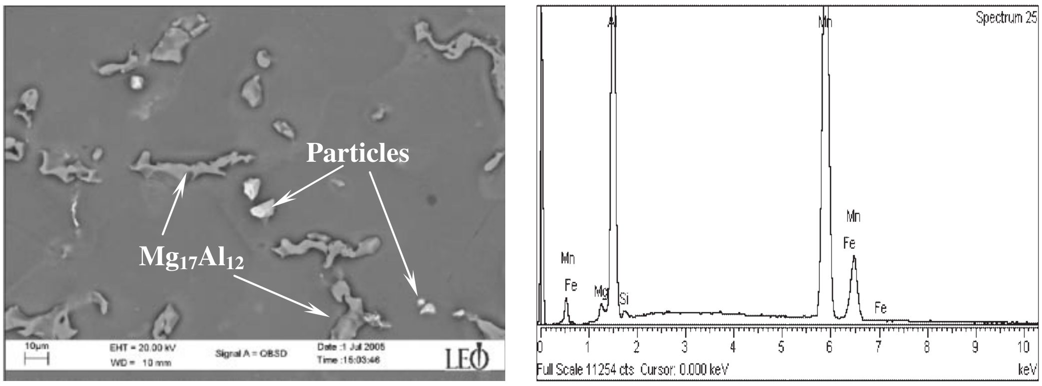


Fig. 8 Relation between the dendrite coherency and the grain shape.

The solidification of magnesium alloys, similar to the aluminum alloys, is generally characterized by the formation of dendrites. Dendrite coherency was defined as the solid fraction during solidification at which the dendrites started to impinge on each other and strength development begins. Dahle and Stjohn had shown in their paper that dendrite coherency was strongly related to the evolution of the microstructure during solidification.[18] Figure 8 summarizes the range of results they obtained for two extremes in microstructures: large dendritic grains and small globular grains. It was shown that the material generally did not have any shear strength before the dendrite coherency point, and that the formation of a coherent dendritic network was accompanied by an increase in strength. The point where the strength slope changed corresponded to maximum packing point. The dendrites coherency was strongly related to the



(a) (b)

Fig. 9 A typical Fe-rich particles in the AZ80 billet (a) Backscattered electron image of some Fe-rich particles and eutectic phase (b) EDX from Fe-rich particles.

evolution of the microstructures during the solidification. Alternation to solidification conditions that resulted in a refinement of the grain size or a more globular morphology postponed the dendrite coherency.

In the presence of electromagnetic vibration, the melt in the mold is solidified under conditions of vibrating magnetic fields and the grains in the billet are significantly refined. We had investigated the grain feature in another paper.[19] It reported that the electromagnetic vibration greatly refined the microstructures of the billet. Large dendritic grains disappeared although they were usually observed in conventional conditions. The billet exhibited fine-equiaxed grains, an effect ascribed to applied electromagnetic vibration. The authors believe that the changed shapes of the grains caused by the electromagnetic vibration postpone the dendrite coherency in the mushy zone. In conventional casting conditions interdendritic feeding is the main form of feeding operating to satisfy the shrinkage at the late stage in solidification,[18] which generally causes the solute enriched close to the periphery of the billet and occurrence of macrosegregation. However, in the presence of electromagnetic vibration, the dendrite coherency is postponed by the refined dendritic grains, that is to say, the time for the interdendritic feeding is reduced. The solute-rich liquid has not enough time to flow through the interdendritic channels before solidified. Thus the phenomenon of solute enriched at the billet surface is suppressed in our experiments.

In addition, in the absence of magnetic fields, the conditions for the grain growth are easily satisfied and the microstructures of the billet usually exhibit large dendritic grains. During the solidification contraction, these large irregularly dendritic grains that can interlock with each other produce the resistance to deformation, which generates stress and pressure gradient in the mushy zone. In the presence of magnetic fields, the melt is subjected to Lorentz force. Because of the big difference in electrical resistivity between the solid magnesium and liquid magnesium,[12] the current would rather transfer through the solidus phase and the dendritic network is subjected to larger Lorentz force than that for the interdendritic liquid. The network is forced vibrated intensely in the partial solidified melt. With the growth of dendritic network the vibrating dendrites can relieve the stress efficiently during the solidification and the stress is hard to accumulate in the mushy zone, that is to say, the melt has the improved ability to accommodate the large stress induced by solidification shrinkage. The driving force for back flow of the solute-rich liquid through the interdendritic channels is reduced, which may result in comparative uniform distribution of the alloying elements in the billet. Increasing the intensity of the electromagnetic vibration leads to larger oscillating amplitudes of the dendritic network in the mushy zone and more sufficient release of the stress, which in turn, causes the distribution of the alloying solutes more uniform throughout the billet.

As for iron, one of the main impurities in the magnesium alloy, its solid solubility in magnesium is very low with the result that most iron present forms intermetallic compounds.[20] Manganese is generally added into the magnesium alloy to reduce the corrosion rate by removing the presence of iron.[21] When iron is present in magnesium–aluminium alloy containing manganese, it usually exists as the Al–Mn–Fe intermetallic particles.[22] The electron backscatter diffraction technique was adopted for particles measurement in the billet. Figure 9 shows the backscattered image of some Fe-rich particles. They usually exist along the grain boundaries with the non-equilibrium phase $Mg_{17}Al_{12}$. EDX from the particles indicates that the particle is rich in Al, Mn, Fe and a little Si. Therefore, the iron exists as the intermetallic particles mainly containing aluminum and manganese in the billet.

This explains why iron and manganese have the similar tendency for distribution in the billet with and without the electromagnetic vibration. In the conventional casting iron and manganese are both highly enriched at the billet surface. In the presence of electromagnetic vibration, the concentration profiles for iron and manganese from the billet surface to the center are more uniform with increasing the stationary magnetic field of the vibrating system. The distribution of iron in the billet may be explained as follows: during the solidification, the Al–Mn–Fe intermetallic particles form in mushy zone. The convection flow in the mushy zone is effectively suppressed by the increased stationary magnetic field in the system of electromagnetic vibration. Thus the large-scale movement for the Fe–Mn–Al intermetallic particles is significantly restrained by the stationary magnetic fields. Moreover, in the presence of magnetic fields, these particles may be subjected to larger magnetic forces due to inclusion of iron. The movement for these particles in the mushy zone is harder than the other particles. Increasing the stationary magnetic intensity leads to larger intensity of vibration in the melt, which intensely restrains theirs movement and results in quite uniform distributions throughout the billet.

5. Conclusions

The electromagnetic vibration is applied to the direct-chill casting of AZ80 magnesium alloy billets experimentally. The macrosegregation of the alloying elements and the distribution of impurity iron in the billet with and without the electromagnetic vibration are investigated. The following conclusions can be drawn from this work.

In conventional direct-chill casting, the alloying elements of the AZ80 billet are enriched at the billet surface and depleted at the billet center. Their concentrations are inhomogeneous along the horizontal section of the billet. In the presence of electromagnetic vibration, the phenomenon of alloying elements enrichment at the billet surface is significantly suppressed by the imposed magnetic fields. Increasing the intensity of the electromagnetic vibration leads to more uniform distributions for the alloying elements in the billet. The impurity for iron exists as the intermetallic particles at the grain boundary and has the similar distribution tendency with manganese in the billet. In the presence of electromagnetic vibration, the distribution of the iron is more uniform than the alloying elements in the billet.

The mechanisms for the reduced macrosegregation in the billet are considered to be the postponement of the dendrite coherency and the release of accumulated stress in the mushy zone by the electromagnetic vibration. As for intermetallic particles inclusion of iron, the large-scale movement is considered to be significantly restrained in the mushy zone by the increased stationary magnetic field in the system of electromagnetic vibration.

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