Article ID: 1003－6326(2003)01－0158－04

Effect of electromagnetic field on macrosegregation of continuous casting 7075 alloy①

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Abstract: The effect of electromagnetic field on macrosegregation of continuous casting aluminum alloy was studied. 7075 aluminum alloy ingot with diameter of 200 mm was produced by electromagnetic casting. Magnitude of coil current was varied from 100 A to 600 A, and frequency from 10 Hz to 100 Hz. Variation of element content along the radius of ingot was examined by means of chemical analysis. The results show that electromagnetic casting process can effectively reduce the macrosegregation, and electromagnetic frequency has a great influence on element distribution along the radius of ingot. When frequency is 30 Hz, macrosegregation is eliminated completely.

Key words: electromagnetic field; continuous casting; macrosegregation; aluminum alloy
CLC number: TF 777; TG 113.12 **Document code:** A

1 INTRODUCTION

Macrosegregation is one of the most pronounced defects during continuous casting of aluminum alloys, which leads to large-scale inhomogeneity of alloying elements. As a typical Al-Zn-Mg-Cu alloy, 7075 alloy's as-cast structures present severe inverse segregation. Alloying elements is highly enriched at ingot surface to form a thick segregation zone, which, in turn, leads to a costly scalping operation in post-processing for reduction of segregation region, and the variation in composition over the cross section of the ingot greatly influences the microstructure and mechanical property of finished products. The application of electromagnetic casting(EMC) technique on improvement of products quality has attached great importance in recent years, and considerable developments have been achieved. Other than EMC[1] process, Vivès introduced a new electromagnetic casting technique[2,3], which mainly aimed at refinement of microstructure and elimination of casting defects. In this process, the coil surrounds the ingot mold; the constrained effect of electromagnetic force results in the formation of a convex surface meniscus, and reduces the height of contact line between the mold and the melt, which, in turn, reduces the primary cooling intensity. Electromagnetic forced convection carries the detached side branch into the melt, broadens the mushy zone, promotes the heterogeneous nucleation, decreases the height and the depth of the sump, and reduces the temperature gradient. All these effects result in a significant improvement of microstructures and surface quality. But comprehensive investigation in this field is still needed to be done. The purposes of the present article are to systematically study the effect of intensity and frequency of electromagnetic field on large-scale distribution of alloying elements in continuous casting process of 7075 alloy, discuss the mechanisms of elimination of macrosegregation by application of a magnetic field, achieve the optimized technique by which the macrosegregation can be inhibit to the best effect, and obtain the high quality products.

2 EXPERIMENTAL

Experimental equipment is schematically presented in Fig. 1. The inner diameter of the mold is 200 mm and a 50 turns coil is arranged outside the mold. In order to consider the influence of electromagnetic field on macrosegregation exclusively, throughout the process of experiment, conventional parameters were held constant as the following: a casting temperature at 720 ℃ and a casting speed at 60 mm/min. Firstly, under the frequency of 50 Hz, magnitude of coil current increased from 100 A to 600 A, so that the effect of magnetic field intensity on distribution of alloying elements could be evaluated. Secondly, magnitude of coil current was maintained at 400 A, frequency of alternating current was modulated in the range of 10－100 Hz, by which the effect of electromagnetic frequency was revealed.

① **Foundation item:** Project(G199906490501) supported by the National Key Fundamental Research and Development Program of China; Project(59974009) supported by the National Natural Science Foundation of China
Received date: 2001－08－14; **Accepted date:** 2002－09－02 **Correspondence:** CUI Jian-zhong, Professor

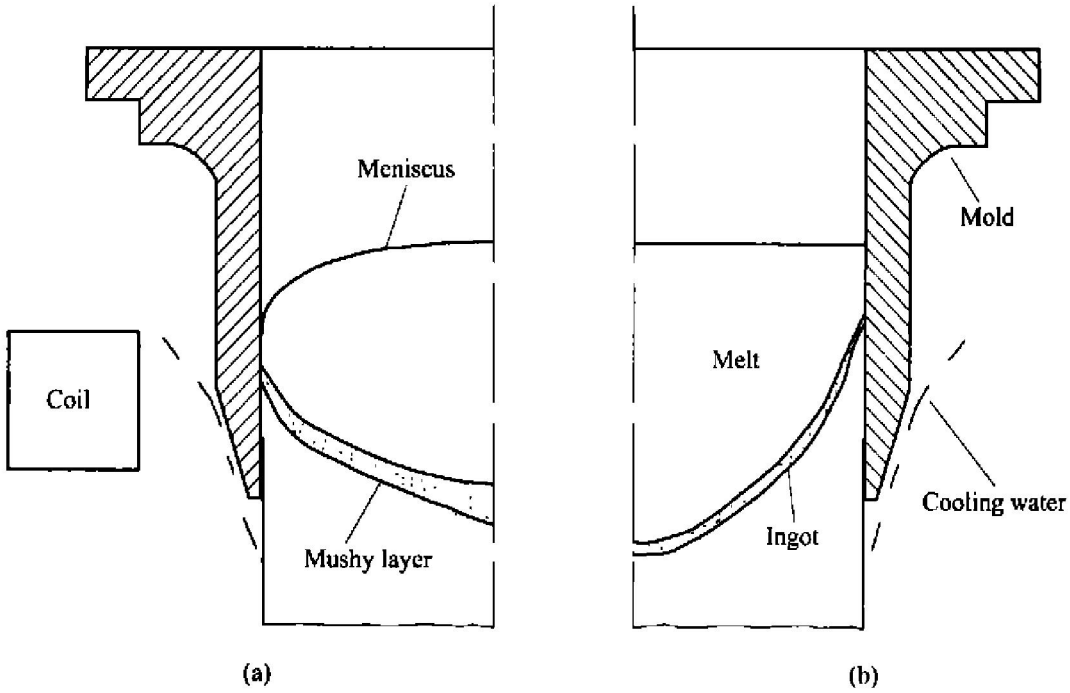

Fig. 1 Schematic illustration of casting process
(a) —electromagnetic casting; (b) —Absence of magnetic field

The chemical composition of 7075 alloy used in this experiment is shown in Table 1. The specimens were taken along the radius in cross-section of ingot, and variation of solute concentration with distance from ingot periphery was examined.

Table 1 Chemical composition of experimental 7075 alloy (mass fraction, %)

Zn	Mg	Cu	Cr	Mn	Al
5.70	2.30	1.43	0.20	0.20	Bal.

3 RESULTS AND DISCUSSION

3.1 Inverse segregation in continuous casting process

In the process of continuous casting of aluminum alloys, solidification shrinkage-induced flow drives the solute-rich liquid to the ingot surface, which leads to macroscopic level compositional nonuniformity over the cross section of ingot, and solute concentration at ingot surface is obviously higher than average value[4-8]. At the same time, initial solidified shell detaches from the mold because of shrinkage of ingot, and the existence of air gap greatly reduces the escape of heat[9]. The solidified shell is reheated by the melt, and metallostatic head force the interdendritic liquid to move through the shell to form the exudation layer, so the solute concentration at ingot surface is enriched further. The parameters, such as casting temperature, casting speed and cooling intensity, greatly affect the inverse segregation over the cross section of ingot, and solute distribution have close relationship with the shape of sump. Primary cooling intensity and the height of solidified shell mainly affect the solute concentration near ingot surface. Vicinity region near surface is depleted of alloying elements when surface exudation occurs[5, 7, 9]. Solute distribution in continuous casting process is caused by the combined effects of shrinkage induced flow and surface exudation.

The transportation of heat and mass occurs in the melt and the mushy layer, and the existence of the sump in continuous casting process leads to large-scale inhomogeneity of alloying elements over the cross section of ingot[6, 7, 9]. Fig. 2 shows the distribution of Zn element along the radius of ingot in the absence of electromagnetic field. Alloying element is highly enriched at ingot surface and greatly reduces surface quality. Solute concentration at center region of ingot is significant lower than average value, which is often ascribed to the sedimentation of floating dendrite fragments on the bottom of the sump[4, 7].

3.2 Effect of intensity of magnetic field on macrosegregation

Under the effect of the periodic current, the inductor generates a variable magnetic field in the melt, which, in turn, gives rise to an induced current, so the melt is subject to electromagnetic body force caused by the interaction of the eddy current and the magnetic field. The Lorentz force density is expressed as the following:

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} \quad (1)$$

The Lorentz force density consists of two parts[2]: the horizontal component is a potential forces balanced by

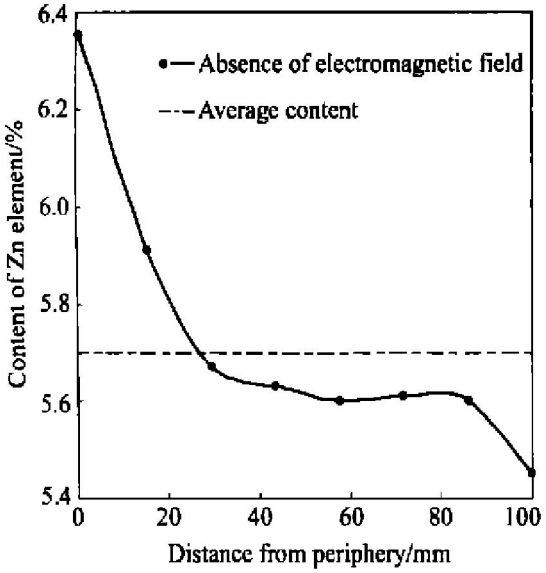

Fig. 2 Content of Zn element along radius of ingot in absence of electromagnetic field

static pressure of the melt, which results in the formation of a convex surface meniscus and can reduce the height of contact line between the melt and the mold, as a result, decrease the primary cooling intensity; the vertical component is a rotational force derived from the inclination of the magnetic field lines toward the axis of ingot symmetry, which results in a forced convection in the melt, so the ideal flow pattern in the melt will be achieved. When the overheated melt can be driven from center region of the melt to the periphery, the depth of sump decreases, the dendritic is remelted and detached, and it is carried away by convection from the shell to the inner region of the melt to promote the heterogeneous nucleation. All the effects which can effectively refine the microstructures and broaden the equiaxed zone, are helpful in elimination of inverse segregation of alloying elements[2, 7, 10, 11].

Fig. 3 shows the distribution of Zn element along the radius of ingot when intensity of coil current varies from 100 A to 600 A. In the presence of electromagnetic field, large-scale inhomogeneity of alloying elements is alleviated significantly. With the increase of current, forced convection in the melt is intensified accordingly; and with the increase of confined effect of horizontal component of Lorentz force, the height of contact line between the melt and mold be decreases, which, in turn, weakens the exudation effect, and solute concentration at ingot surface is pronouncedly decreased.

3.3 Effect of frequency on macrosegregation

As a principal parameter, frequency greatly influences distribution of magnetic flux density in conductive media. In the process of electromagnetic

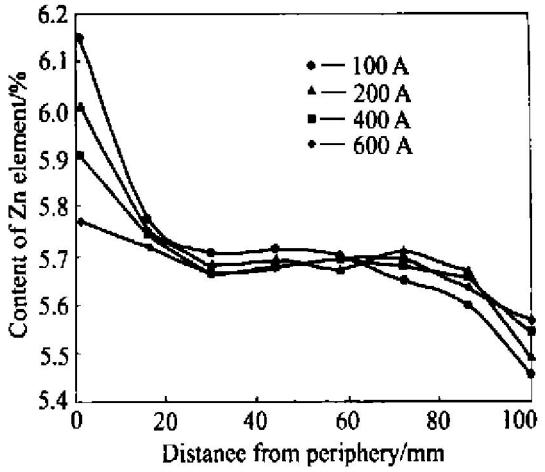

Fig. 3 Content of Zn element under different intensity of electromagnetic field

casting, flow pattern and temperature field of the melt can be modified by means of frequency modulation, and optimized conditions of solidification can be obtained. The characteristic length which specifies how the magnitude of magnetic field decreases as a function of distance into the liquid metal is the skin depth[12]:

$$\delta = \sqrt{\frac{1}{\sigma\mu\pi f}} \qquad (2)$$

where σ and μ are the conductivity and permeability, respectively, of the liquid metal and f is the frequency. When the operating frequency is relatively high(50 Hz or more), the skin depth is extremely small and the force density significantly concentrates near the surface of the metal. The rapid change in magnetic flux density across a small skin depth means a high gradient of force density which forms a stronger confined pressure, and the height of contact line between melt and mold decreased. But at the same time, stirring effect is also weakened. With the decrease of frequency, the magnetic field and induced currents are increased, and hence Lorentz force density is increased throughout the bulk of the liquid metal, so the rotational part becomes dominant and the forced convection is enhanced. With further decrease of frequency(less than 20 Hz), the magnetic flux density and phase angle is relatively uniform throughout the melt, and the rotational force is weakened again. Therefore, under a fixed magnetic intensity, the ideal flow pattern and temperature field can be obtained by application of a proper frequency of electromagnetic field.

Fig. 4 shows the distribution of Zn element along the radius under the different frequency of electromagnetic field, while the intensity is hold at 400 A. Being a primary parameter, the frequency greatly affects the distribution of Zn element. The large-scale inverse segregation and periphery segregation are drastically reduced at the

same time with the frequency of approximately 30 Hz. Fig. 5 shows the distribution of Cu element under the different frequency, which presents similar tendency with that of Zn element. Fig. 6 presents the distribution of Mg element under the frequency of 30 Hz in which the periphery segregation is reduced completely. The results show that with the frequency of 30 Hz, inverse segregation of alloying elements in the ingot with the diameter of 200 mm is inhibited to the best.

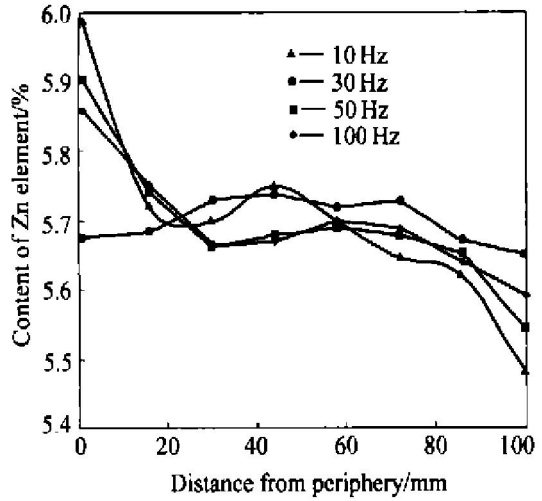

Fig. 4 Content of Zn element under different frequency of electromagnetic field

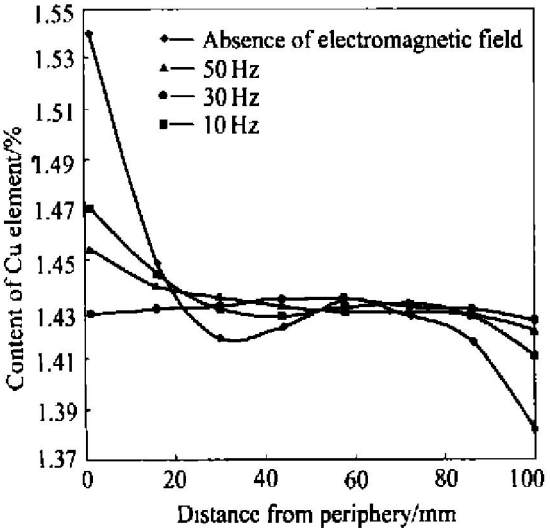

Fig. 5 Content of Cu element under different frequency of electromagnetic field

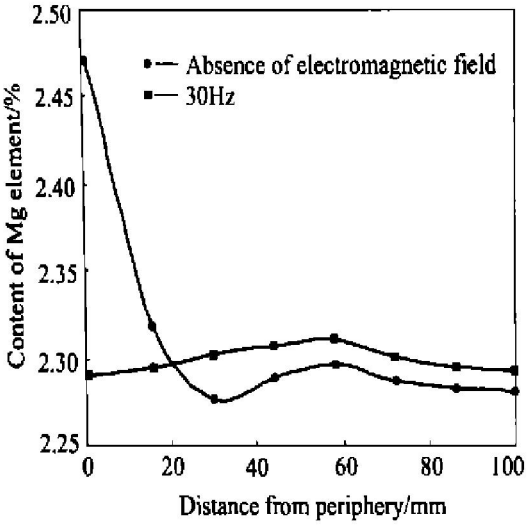

Fig. 6 Content of Mg element along radius of ingot

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(Edited by YANG Bing)