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DC casting of light alloys under magnetic fields

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Abstract: The working principle of LFEC(Low frequency electromagnetic casting) process developed in Northeastern University, China was introduced and the metallurgical results of LFEC were discussed according to the casting practices. The low frequency field around the mold produces Lorenz force, which can be divided into two parts: one is the potential force which will be balanced by a pressure gradient of the liquid and results in the formation of a convex surface meniscus and improves the surface quality; the other is the rotary force which stirs the liquid in the mold to refine the microstructures and homogenize the distribution of alloying elements. LFEC can refine microstructures remarkably, improve surface quality of the ingots, depress macrosegregation and eliminate cracks. Some new technologies, such as horizontal direct chill casting under low-frequency electromagnetic field (HLEC), DC casting of hollow billets under electromagnetic fields (HBEC), electromagnetic modifying of hypereutectic Al-Si alloys(EMM), air film casting under static magnetic field (AFCM), and multi-ingots casting under low-frequency magnetic field (MLFEC) were developed based on LFEC.

Key words: low frequency electromagnetic field; light alloy; DC casting; grain refinement

1 Introduction

As we know, China is the largest country in light metals and light alloys production. In 2008, 14 800 kt Al, 1 150 kt Al alloy wrought products and 630.7 kt Mg, 100 kt Mg alloy wrought products were produced, so that 1 200−1 300 kt Al alloys and 150 kt Mg alloy ingots were cast in China. Ingot casting is a large industry in China and important process for wrought product production because most of the defects, such as cavity and looses, impurity and inclusions, clacks and macrosegregation, can not be improved in following processing.

DC casting is widely used in ingots production of light alloys. Some new processes were developed to improve the metallurgical quality of the ingots, such as hot top casting, air slip casting[1], air film casting[2], LHC (low heat composite mold)[3] and ASM (Alcan sheet mold) for slab. Recently, some physical fields were applied in solidification and DC casting of alloys, such as magnetic field[4], electric current and ultrasonic field[5] to improve the metallurgical quality of ingots, in which magnetic field has been used in industrial production, because it is more effective and easy to control. EMC (electromagnetic casting) was developed by a Russian engineer in 1960s[6] and used in USA and Europe to cast ingots of some soft Al alloys, such as 1xxx, 3xxx and 5xxx system Al alloys.

In 1990, a new DC casting process—low frequency electromagnetic casting (LFEC) was developed in Key Lab for EPM, Northeastern University, China[7]. LFEC has been used in many factories to cast Al alloys and Mg alloys ingots with fine grains, low macrosegregation, better surface quality and free cracks. Based on LFEC many new DC casting processes were developed.

2 Principle of LFEC

Two theories are very important to understand LFEC. The first is Lorenz force produced by the interaction of magnetic field with induction current in electric objects. When a magnetic field is applied around the mold in DC casting, Lorenz force $\boldsymbol{F}$ can be written

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as[4]:

$$\boldsymbol{F}=\frac{1}{\mu}(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}-\frac{1}{2\mu}\nabla\boldsymbol{B}^2 \tag{1}$$

where the first item is the rotary force which is used to stir the liquid in the mold to refine the microstructures and improve the distribution of the alloying elements. The second item is the potential force which will be balanced by a pressure gradient of liquid and results in the formation of a convex surface meniscus to decrease the contact pressure and area of liquid alloy contacting with mold and improve the surface quality.

The second is the skin effect of the magnetic field and currents. The magnetic intensities in the mold when a magnetic field is applied with different frequencies are shown in Fig.1. We can see that the lower the frequency of the magnetic field, the higher the intensity in the mold, so that a low frequency magnetic field has a powerful implementation ability in liquid alloy.

The Lorenz force will produce a forced flow in the liquid alloy in the mold. The flow direction will change and the flow speed will increase compared with DC casting, as shown in Fig.2, which will make the alloying elements distribution uniform, increase the heat exchange between the liquid contacting with wall of the mold and change the temperature field in the mold markedly, as shown in Fig.3. The temperature of the liquid alloy is higher in DC casting than that in LFEC mostly. The alloy in the mold is liquid in most part in the DC casting. However, it becomes semisolid in most part in LFEC, which will increase grain nuclei and refine the microstructures.

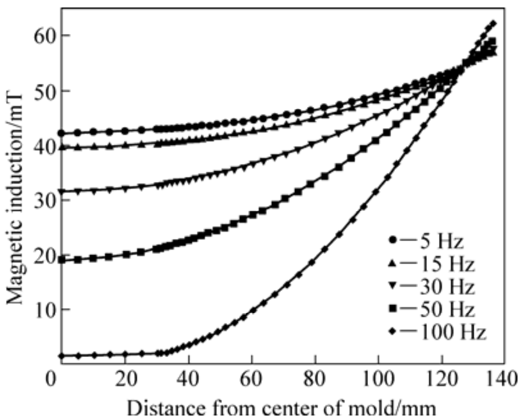

Fig.1 Magnetic induction in mold when magnetic field is applied with different frequencies

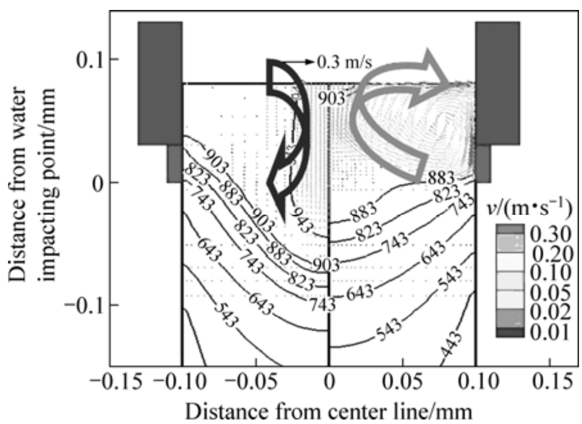

Fig.2 Flow fields of DC (left) and LFEC (right)

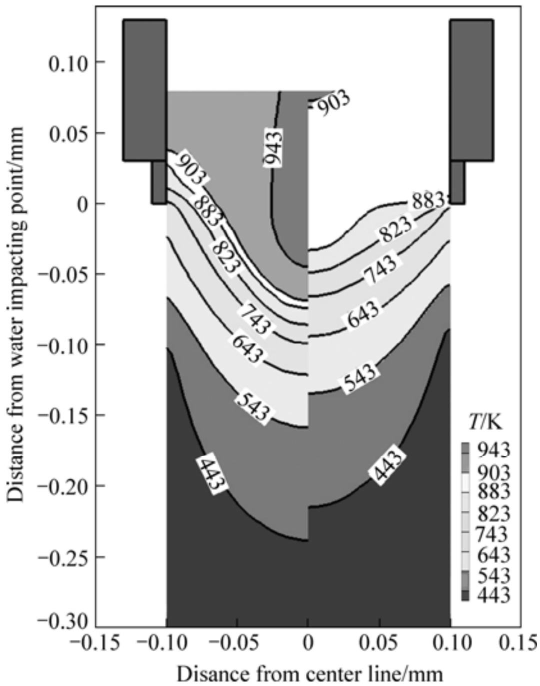

Fig.3 Temperature fields of DC (left) and LFEC (right)

3 Metallurgical results of LFEC

3.1 Grain refinement

Fig.4 shows the microstructures of 7050 alloy in edge and center of the *d*500 mm ingots by DC and LFEC cast. The dendritic grains with size more than 500 μm in DC casting change into fine equiaxed one with size less than 70 μm. This refining effect can be obtained in all system Al and Mg alloys.

3.2 Improvement of macrosegregation

Fig.5 shows the distribution of the alloying elements in *d*270 mm ingots of B96 alloy. The differences {(the content in the edge−the content in the center)/the analyzed content} of Zn, Mg and Cu content between edge and center of the ingots decrease from 10%, 34% and 40% in DC casting to 3%, 9% and 12.5% in LFEC casting. The improvement of macrosegregation will insure the homogeneity of the composition and the mechanical properties of the wrought products.

3.3 Improvement of surface quality

The surface quality of Mg alloys ingots is more difficult to control compared with Al alloys because

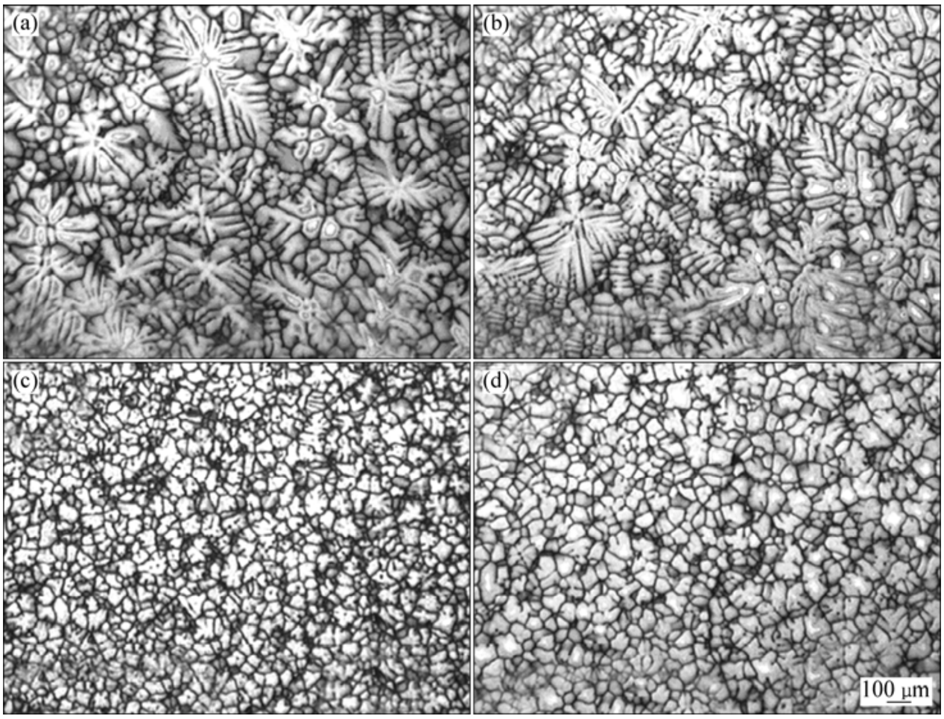

Fig.4 Microstructures of 7050 alloy cast by DC and LFEC: (a, b) DC; (c, d) LFEC; (a, c) edge; (b, d) center

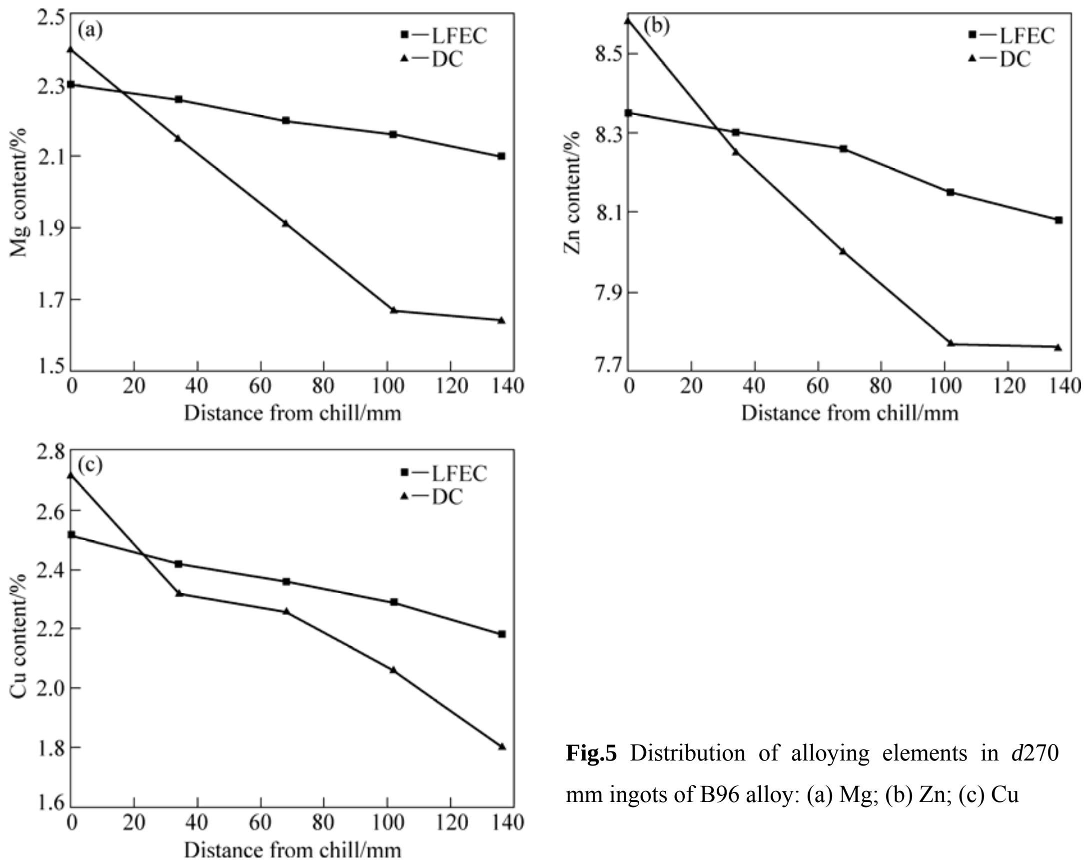

Fig.5 Distribution of alloying elements in *d*270 mm ingots of B96 alloy: (a) Mg; (b) Zn; (c) Cu

Mg alloy is easy to oxidize and burn and with low heat conductivity and high viscidity in liquid state. When Mg alloys are cast in LFEC, the surface, like Al alloy, without any defects can be obtained, so the cutting rate deceases greatly, as shown in Fig.6, which will increase the rate of the finished products.

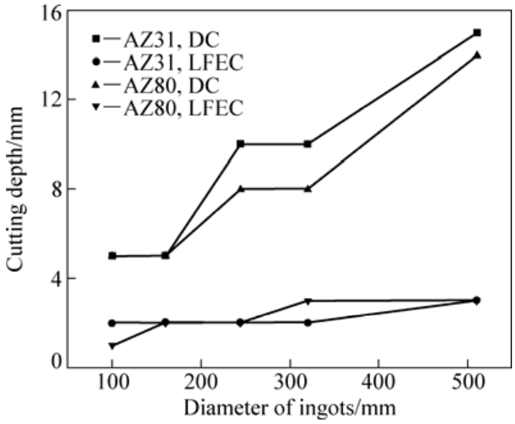

Fig.6 Cutting depth of Mg alloy ingots

3.4 Crack elimination[8]

Cracks are the serious defects in light alloy ingots which will result in the ingots scrapped or danger of safety. Cracks are easy to occur in the large size ingots with high alloying element content, such as 7000 and 2000 systems Al alloys, and ZK, WE systems Mg alloys.

The gradient of temperature, the sump depth, the stress and plastic deformation in the ingots will be reduced greatly in LFEC, which results in a decrease in the ratio of equivalent plastic strain to the fracture strain of the alloys. When the ratio is smaller than 1, no cracks take place. The comparison of the sump and the ratio of equivalent plastic strain to the fracture strain in the 7055 alloy ingots cast by DC and LFEC is shown in Fig.7 and Fig.8. Recently, this process was used in a Al manufacturing factory. 7050, 7150, 7085 and 7055 alloy billets with size of 0.36 m×1.0 m×2.0 m were cast without any cracks.

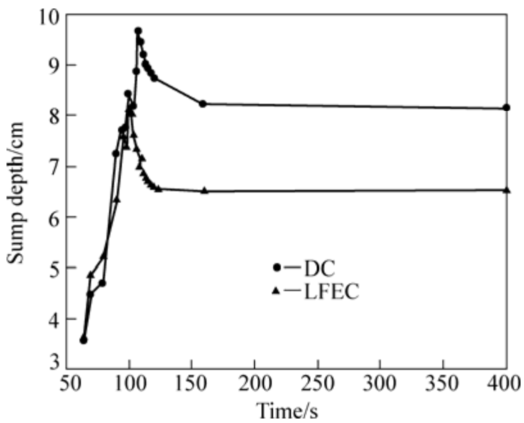

Fig.7 Sump depth of 7055 alloy billets cast by DC and LFEC

4 New developments in LFEC

4.1 Horizontal chill casting under low frequency electromagnetic field (HLEC)

The horizontal direct chill casting (HDCC) process has many advantages[9], such as lower investment,

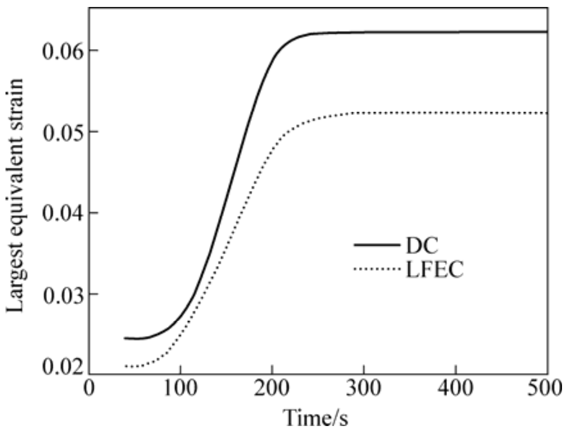

Fig.8 Largest equivalent strain in 7055 alloy billets of 200 mm×600 mm cast by DC and LFEC

higher flexibility. However, the largest problem in HDCC is that the gravity segregation will occur especially in the alloys with heavy elements, such as 2000 Al alloy with Cu and 7000 Al alloy with Zn. When a low frequency magnetic field is applied in HDCC, the gravity segregation can be improved much, as shown in Fig.9, so the limitation that HDCC can not cast the 2000 and 7000 Al alloys is broken through.

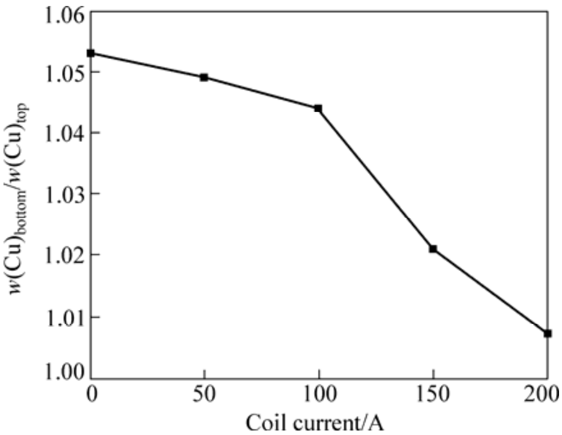

Fig.9 Ratio of Cu content in bottom to top of *d*100 mm 2024 alloy ingot cast

4.2 DC casting of hollow billets under electromagnetic fields (HBEC)

An out-phase electromagnetic field or a low frequency electromagnetic field has been applied in DC casting of hollow billets of 6061 Al alloys. The electromagnetic field produces a pushing force in the radial direction to the outside, which partially balances the static pressure of liquid metal, results in a reduction in the contact pressure between initial shell and the mold inner wall, and avoids "core holding" which is caused by the intense solidifying shrinkage. So a billet was obtained with high surface quality, fine globular grains and high mechanical property, as shown in Fig.10[10].

Fig.10 *d*350 mm×30 mm 6061 alloy hollow billets cast by HBEC

4.3 Electromagnetic modifying of hypereutectic Al-Si alloys(EMM)

Hypereutectic aluminum-silicon alloys are attractive materials for application in automotive industry. However, the mechanical properties are low for bulky primary Si and their macrosegregation. When a low frequency magnetic field is applied in DC casting of Al-20Si alloy, the average size of primary Si changes from 100 μm without a field to 25 μm with LFEC and its distribution becomes more homogenous, which results in the improvement in mechanical properties and wearing resistance[11].

4.4 Air film casting under static magnetic field (AFCM)

High surface quality is very important for extrusion products of 1000, 3000, 5000 and 6000 systems Al alloys because the ingots surface is not cut before extrusion in most manufacturers for increase in ratio of the finished products. Air slip casting is a good way to get high surface quality. However, it is more expensive. Air film casting (AFCM) is a new way with low cost. A static field was applied in air film casting to insure a steady meniscus and stabilize a small contact length of liquid alloy with mold wall. A glabrous surface like glass can be obtained by AFCM[12].

4.5 Multi-ingots casting under low-frequency magnetic field (MLFEC)

In industry, most manufacturers use multi-ingots casting process to increase productivity. The problem of application of a magnetic field in multi-ingots casting is the unwished electromagnetic interfere between coils. We determined the smallest distance by simulation and measurement, which has no effect on surface quality. Some shields are taken to shorten the distance between foils to increase the ingot number. This process was used in a factory to cast *d*120 mm×250 mm ingots of 6000 and 7000 systems Al alloys.

5 Conclusions

1) A new effective and economical process for light alloys DC casting (LFEC) was developed in Northeastern University, China, by which the microstructures can be refined remarkably, the surface quality can be improved, the macrosegregation can be reduced and the cracks can be eliminated.

2) In LFEC the powerful implementation ability of low frequency electromagnetic field makes the flow direction of the liquid alloy in the mold changes and the flow speed increases compared with DC casting, which results in an increase in pasty (semisolid) zone and decrease in sump depth.

3) Based on LFEC some new casting processes have been developed in Northeastern University also, such as HLEC, HBEC, EMM, and AFCM, which provide some new selections for ingots production with high metallurgical quality.

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