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Technological investigation of electromagnetic casting for double-ingot ①

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[Abstract] The double-ingot equipment of electromagnetic casting that consists of inductor, cooling water box, etc, was designed. The effects of inductor current and screen position on magnetic field distribution were investigated according to the measured results of series-connection inductor. From these results, the solidification front of melt should be controlled to the bottom of inductor. The key parameters such as casting speed, liquid column height and flow rate of cooling water are about 0.6 ~ 1.5 mm/s, 30 ~ 45 mm and 1.5 ~ 2.5 m^3/h, respectively. And the round double-ingot with a diameter of 240 mm and a length of 400 mm was cast.

[Key words] electromagnetic casting; double-ingots; forming experiment

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1 INTRODUCTION

The continuous casting of aluminum is the foundation of the electromagnetic casting (EMC), which began from the direct chill casting invented by Aloca Corporation and Vlw Corporation in 1935[1]. The principle of EMC was firstly described by Getselev and his co-workers in 1960[2]. And then, they cast the first EMC ingot in laboratory in 1966. Thereafter, the industry-scale ingots with diameter from 200 mm to 500 mm were cast in 1969. Subsequently, this method was spread to the former Czechoslovakia and other Eastern European countries. The principal advantage of the technology is that the aluminum is cast without contacting a physical mold depending on the electromagnetic forces, which excludes liquation build-ups and feather, and consequently, the surface finish of the ingot is usually smooth enough to be hot rolled without scalping operation. Because of the strong magnetic field, the structure and properties of the EMC ingot become much better. Since 1970's, occident has developed the technology in a big degree. The ingots of aluminum, copper, zinc, magnesium and their alloys were cast. At the same time, the new methods lying on different direction such as GE Levitation EMC and Horizontal EMC were implemented for casting ingots[3].

The EMC technology of round ingot was investigated at a limited extent in our country in 1980's[4]. During 7th Five-Year Plan, small square ingots of Al EMC with a cross-section gauge of 120 mm × 50 mm were cast by Dalian University of Technology and South-west Aluminum Processing Plant[5]. After 8th Five-Year Plan, some experiments were carried out on a pilot-scale caster at Dalian University of Technology. And in this laboratory, rectangular and round shape ingots made of different metals and alloys such as pure Al, 3004, 5182, 2024 and 6063, etc were cast. The cross-section gauge of the rectangular ingots was 520 mm × 130 mm and the diameter of the round ingots was 174 mm.

The industrialization of EMC technology depends on the steady parameters and high productivity. The multi-ingot technology has been used in business manufacture in Swiss and America. However, the EMC technology, especially the multi-ingot one is usually protected by the patent. So it is very difficult to find some publications in details on this aspect. This paper describes an investigation about the EMC double-ingot.

2 EXPERIMENTAL

2.1 Experimental equipment

Fig.1 is the view of the double-ingot experimental apparatus which consist of delivery system, casting control system, shaping and cooling system, melt furnace and power supply, etc. The shaping system composed of inductor, screen, cooling water box and bottom block is the main part of this equipment. The inductor and the primary part in the investigation, are executed by two single-turn induction coils in series. And the coils are made of copper plate with high electric conductivity. Especially, the vertical section of the inductor is bevel, its upper diameter is 300 mm, lower diameter is 260 mm, and the height is 40

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mm. Copper pipe is soldered to the outside of the inductor for cooling. The screen made of stainless steel is wedge-shaped, which can control the fluxion of the liquid metal and stabilize the column to assume an upright side. The bottom block made of aluminum alloy could load and chill the melt in the initial stage, whose diameter is 240 mm and height is 120 mm. In addition, the cooling water box is made from epoxy resin, which has well-proportioned coolant holes with a diameter of 2 mm. The medium-frequency electrical source at a power of 100 kW, at a frequency 2 500 Hz and at a current from 3 000 A to 6 000 A is applied to the inductor. The withdrawal system offers an alterable casting speed of 0 ~ 4 mm/s which can be adjusted by the STD5000 control machine.

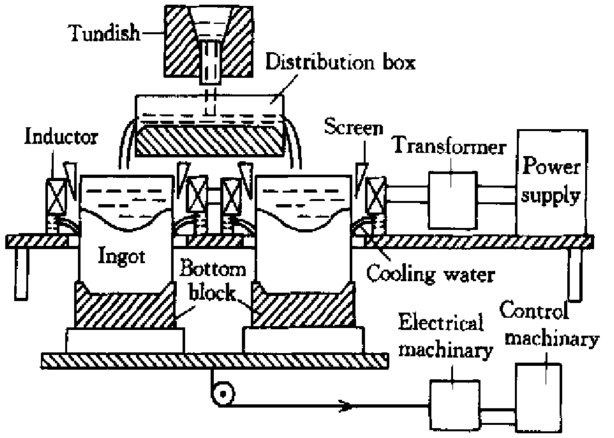

Fig.1 Schematic diagram of double-ingot EMC equipment

2.2 Measurement of magnetic field

During EMC process, it is necessary to get an electromagnetic force which can prevent the liquid metal from spilling and squeeze it to form a column. Therefore, it is important to know the distribution of magnetic field in the inductor for a technical experiment.

In this investigation, the radial and axial distribution of magnetic flux density in the twin inductor were measured and analyzed firstly. The results were compared with the magnetic field from single-inductor condition in order to find the position of the strongest magnetic field and decide the position of the solidification front. At the same time, the highest height of liquid metal which the magnetic field will support could be estimated.

The small coil method was used to measure the magnetic field in this investigation. The induced electro-motive force could be measured by the coil put in the inductor, and the magnetic flux density could be computed by following equation[6]:

$$B = E/4.44fNS \qquad (1)$$

where B is the magnetic flux density, E is the induced electro-motive force, f is the frequency (2 500 Hz), $N(=13)$ is the circle numbers of the coil, S is the effective area of the coil cross section (2.27×10^{-6} m^2).

The electromagnetic pressure could be expressed by the following equation[7]:

$$p = B^2/4\mu \qquad (2)$$

where μ is the magnetic permeability, and $\mu(\mathrm{Al}) = 4\pi \times 10^{-7}$ H/m.

The location of the measuring points along the radial direction in horizontal cross section is shown in Fig.2. Where, point 1 is the point on the external surface of the ingot whose distance from the inductor is 10 mm. And then, point 11 is the center of the ingot. Spaces between adjacent measuring points are 2, 4, 4, 4, 6, 10, 10, 15, 25, 40 mm, respectively. The position of $z = 0$ stands for the bottom level of the inductor for every run, and d is the depth that the screen being interposed between the inductor and the melt.

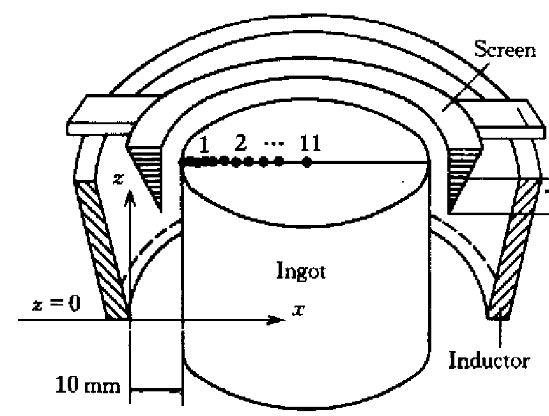

Fig.2 Positions of measuring points

2.3 EMC technology for double-ingot

After obtaining the distribution of the magnetic field, the solidification front and the height of the liquid column, the shaping experiment for a double-ingot could be done. Just like the single-ingot, the technique procedures are: melt → adjusting the positions of inductor, screen, water jacket and bottom block → operating cooling system → turning on power supply → casting → in steady stage, keeping in withdrawal speed, casting rate and solidification rate with rational value to have steady liquid column height and solidification front until the end of the casting.

3 RESULTS AND DISCUSSION

3.1 Radial distribution of magnetic field

The distribution of magnetic flux density from inductor to the center of ingot is shown in Fig.3. Five horizontal cross-sections with $z = -6, 0, 6, 24, 42$ mm are measured, and the inductor current is 4800 A. As shown in Fig.3, the broken line without data mark represents the radial distribution of the sin-

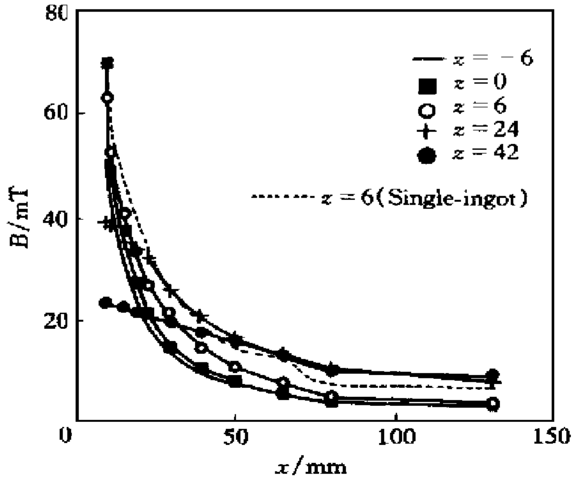

Fig.3 Distribution of magnetic field along radial direction
(4800 A, without screen)

gle-ingot at $z = 6$ mm which is the strongest section of magnetic field.

As also shown in Fig.3, the variation of magnetic field intensity along the radial direction obeys the exponential distribution, and it gradual changes in the center. Furthermore, the magnetic field intensity reduces with increasing z, which means that there is a weaker magnetic field near the top of the liquid column. At the section of $z = 0$, the variation of magnetic field is remarkable.

3.2 Axial distribution of magnetic field

As shown in Fig.4, the magnetic field intensity has different peak value for different points with z changing from -6 mm to 42 mm. The variation of magnetic field gradually changes over a definite height. For point 1, which is close to the inductor, the strongest magnetic field is discovered at the position of $z = 0$. B gradually reduces with increasing z,

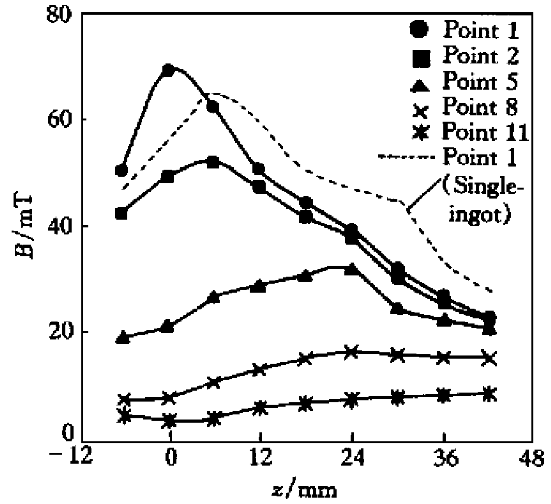

Fig.4 Distribution of magnetic field along axial direction
(4800 A, without screen)

which is helpful for the equilibrium between electromagnetic pressure and hydrostatic pressure. Therefore, the solidification front should correspond with the bottom of the inductor to assume an upright side of liquid column. The equilibrium condition of interface is as following: $\rho gh = p$, from which the height (h) of metal that the inductor can support is about 42 mm[8]. In Fig.4, the dotted line without data mark describes the distribution of magnetic field along the axial direction for a single-ingot, and B gets the biggest value at $z = 6$ mm, it is smaller than that of the double-ingot in some sort.

3.3 Effect of inductor current

The effect of various inductor currents is shown in Fig.5. The influence of the inductor currents on the magnetic field is very distinct just like the condition of the single-ingot. The magnetic flux density increases by 7 mT with the current increasing by 400 A.

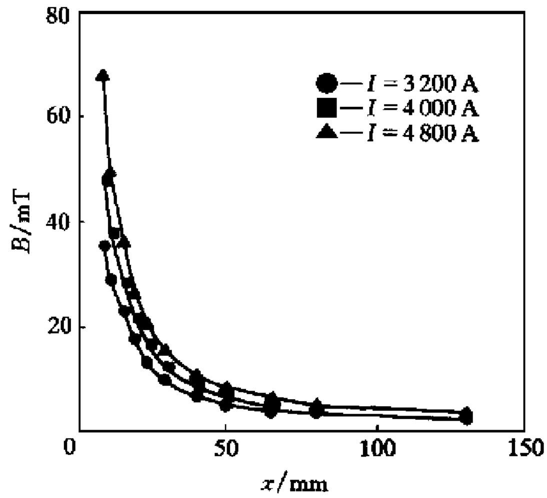

Fig.5 Effect of inductor current on magnetic field
($z = 0$, without screen)

3.4 Effect of screen

In single-ingot EMC process, the magnetic field is modified by the presence of the stainless steel screen, which can control the fluxion of the liquid metal and stabilize the column. Fig.6 shows that the screen weakens the magnetic field on liquid column top and at solidification front. On the other hand, it has little influence on the magnetic field in the middle part of ingot. That means, the screen is helpful to form an upright side of column. here of $d = 0$ means the condition without screen.

As above mentioned, the distribution of magnetic field along the radial and axial direction, the effect of the inductor currents and the screen on the magnetic flux density is same as the condition of the single-ingot. Therefore, it is very possible to cast an EMC double-ingot referring to the technical parameters of the single-ingot.

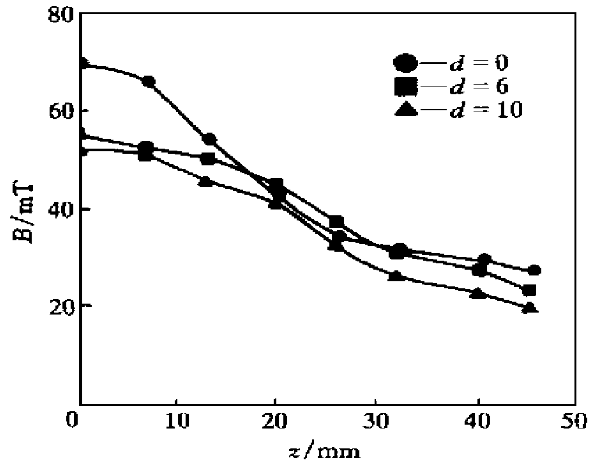

Fig.6 Effect of screen on magnetic field (I = 4800 A, point 1)

3.5 Shaping experiment

EMC is a complicated continuous process being influenced by electromagnetic field, temperature field and flow field, etc. Thus, its technical parameters including flow rate of cooling water, height of liquid metal and casting speed, etc need a rational matching. For the double-ingot condition, the interactional twin-inductor requires more well-proportioned cooling water and better control of melt flow. The shaping experiments for double-ingot were done in this research depending on the experience of single-ingot.

When pouring temperature was 730 ℃, casting speed was 0.8 mm/s and total flow rate of quench water was 1.6 m^3/h, the experiment failed. The reason of leakage is that the depth of screen inserted at 5 mm led to the stronger magnetic field on the top of the ingot, which makes the liquid column not to have an upright side. At the same time, the cooling water is not well-proportioned.

By improving the cooling water box, increasing the depth of screen interposed by 10 mm and keeping the experimental condition at pouring temperature being 720 ℃ and the cooling water flow rate being 2.5 m^3/h, a double-ingot with a height of 150 mm was cast as shown in Fig.7(a). However, the continuous withdrawal was not successful because the bad distribution of melt flow resulted in visible difference of liquid height in each coil. Furthermore, the stronger water coolant leads to the lower liquid column solidifying quickly, that is why the withdrawal process could not enter the steady stage.

After horizontal adjusting plate was put under the distribution box, the cubage of the tundish was enlarged and the flow rate of cooling water was kept at 2 m^3/h, casting speed at 1 mm/s and pouring temperature at 710 ℃, the double-ingot with a height about 200 mm was produced, as shown in Fig.7(b). The failing reason of this run is that the length of the distribution was so long that the melt flow had stronger strike to the liquid column and led to breakout during the steady stage. In addition, the two coils of the inductor influences each other, the magnetic flux density in one coil will increase obviously if the melt leaks in another coil, and the liquid column will shrink with increasing electromagnetic pressure. As shown in Fig.7(b), the ingot at right had a trapezia vertical-section.

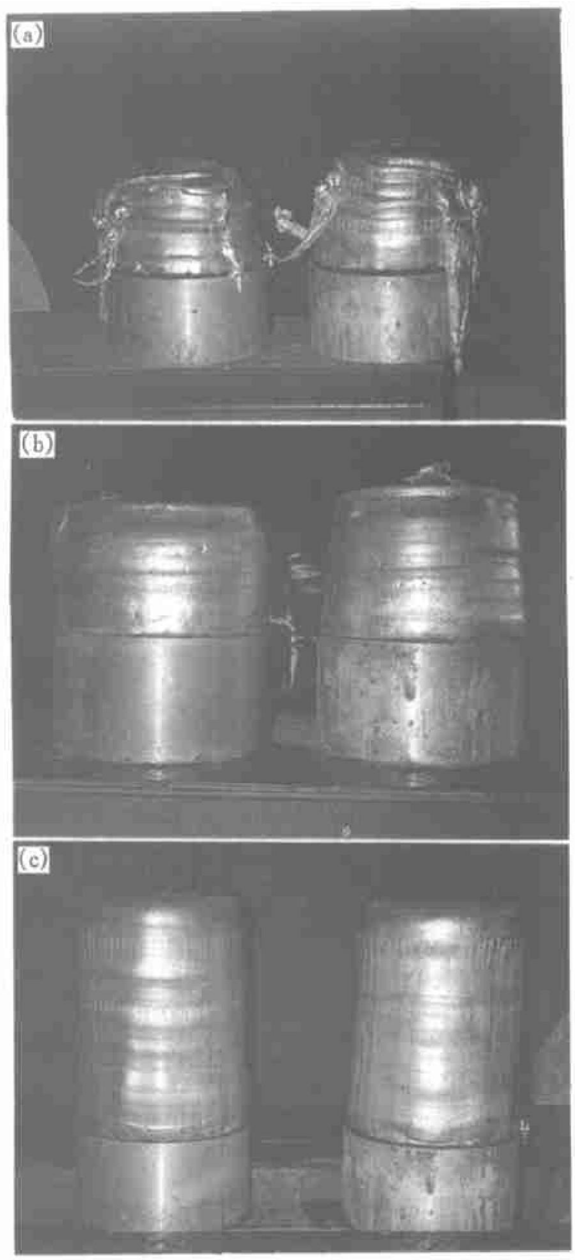

Fig.7 Photographs of double-ingot EMC

After contrasting the results of each run above mentioned, improving on the structure of distribution box, the technological condition was confirmed: pouring temperature being 720 ℃, screen inserted depth being 10 mm, liquid column height being 32 ~ 35 mm, cooling water flow rate being 2 m^3/h, casting

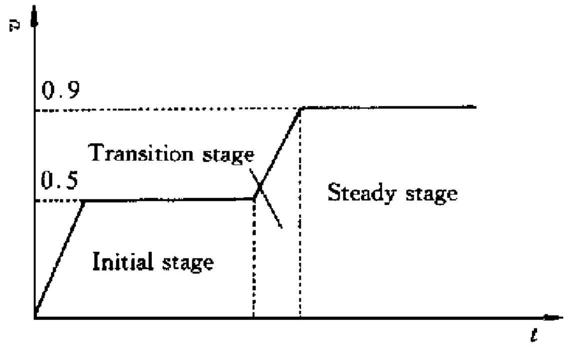

Fig.8 Relationship between casting speed and time

speed being 0.9 mm/s in steady stage and inductor current of 5 000 A. The curve in Fig.8 showed the casting speed as a function of time during this withdrawal process.

4 CONCLUSIONS

1) The strongest magnetic field appears at the position of $z = 0$, and the solidification front should be controlled at this position during withdrawal process.

2) The bigger the inductor current, the stronger the magnetic field. The magnetic flux density increases by 7 mT with the current increasing by 400 A.

3) The interaction of the double-ingot is obvious. The electromagnetic pressure will remarkably enhance in one coil when the liquid metal leaks in another coil.

4) When pouring temperature ranges from 710 ℃ to 730 ℃, casting speed ranges from 0.6 mm/s to 1.5 mm/s, depth of screen ranges from 10 mm to 15 mm, liquid column ranges from 30 mm to 45 mm, flow rate of cooling water ranges from 1.5 m^3/h to 2.5 m^3/h and inductor current ranges from 4800 A to 5 200 A, the double-ingot with smooth surface can be cast successfully.

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