CONTROL OF FORMABILITY OF EMC LIQUID METAL COLUMN①

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ABSTRACT Based on the measurement of the liquid metal column shape and magnetic field, the influences of liquid column height and inductor current as well as screen position on electro-magnetic casting (EMC) ingot shape were investigated. The magnetic field overlap phenomenon in inductor corner was demonstrated, the optimum control parameters were determined as follows: (1) h_z = 30~ 45 mm; (2) I_d = 4 400~ 4 800 A; and (3) h_s = 12~ 18 mm.

Key word electro-magnetic casting liquid column height electro-magnetic forming

1 INTRODUCTION

EMC (electro-magnetic casting) is a kind of continuous casting technique without mould, the forming of liquid metal is controlled by electromagnetic pressure. The principle of EMC is shown in Fig. 1[1]. EMC ingot's surface is very smooth, its inner structure has the advantages of homogeneity in structure and meticulousness in shape, thus it possesses higher mechanical properties, especially, rolling property. As a result, the technique is widely used in Europe and America, and also being paid great attention to in China[2, 3]. Owing to EMC process being affected by electromagnetic field, fluid field and temperature field and so on, simultaneously, the stable control of liquid column shape is extremely important. Vives and Rico[4] conducted experimental work on the electro-magnetic force and flow on liquid column. Sakane, Li and Evans[5] presented a mathematic model to describe the shape of the liquid column and the metal flow. Furui *et al*[6] studied the influences of the screen material, screen position and the current on the liquid column shape, Zhu Xiaoying[2] analyzed formability column of EMC little slab ingot. However, the research about the forming control parameters and the shaping characteristics of liquid column is less known for big ingot, especially, the ingot's corner shape.

In this paper, the shape of the liquid column of aluminum alloy ingot and magnetic field distribution in inductor are measured experimentally, the affections of liquid column height and inductor current as well as screen position on EMC mouldability and stability are investigated. The magnetic field overlap phenomenon in inductor corner is also analyzed, moreover, the optimum control parameters are presented.

2 EXPERIMENTAL

2.1 *Experimental Device*

EMC experimental device is shown in Fig. 2, which is composed of intermediate frequency power supply, inductor, melting and pouring system, water cooling system and casting machine. The inductor is a single-turn coil made from copper plate, the screen is made from thin stainless steel, it acts upon restraining liquid metal fluid and forming the stable liquid column. The power is 100 kW and the frequency is 2 500 Hz. Thebottom mould is made from heat-

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Fig. 1 Schematic diagram of EMC

Fig. 2 Device of EMC

resistant brick whose density is 0.4 g/cm^3, and the ingot's section is 520 mm × 130 mm.

2.2 *The Measurement of Liquid Column Shape*

The shape of liquid column is measured by the metal burning method, i.e. inserting a foil into the molten aluminum bath, the contact part with liquid aluminum is burnt away, then the liquid column shape can be copied.

2.3 *The Measurement of Magnetic Field*

The magnetic field is measured by a small coil. Based on the principle of electro-magnetic induction, the coil's electro-motive force can be measured and magnetic field strength can be calculated as follows:

$$B = E/(4.44fNS)$$

where B —magnetic induction strength, T; E —induction electro-motive force of the little coil, V; f —frequency, Hz; N —the little coil's circle; S —coil's section. In this experiment, $f = 2\,400$ Hz, $N = 10$, and $S = 3.14 \times 10^{-6}$ m^2. The measuring probe is shown in Fig. 3.

3 RESULTS AND DISCUSSION

3.1 *The Liquid Column Shape Parameter*

EMC has severe requirements on semi-suspending liquid column as follows: (1) suitable height; (2) vertical sides and (3) stable surface. In order to characterize the formability of the liquid column quantitatively, the shape parameter S_a is defined as

$$S_a = S_e/Dh_z$$

where h_z is the height of the liquid column; and D is the distance between the transition point from curve to horizontal line on the top of liquid column and the vertical line along the liquid column's side; S_e is the area of the liquid column within the box with h_z and D as its sides. It is clear that the closer to unity the S_a is, the better the liquid column shape will be, see Fig. 4.

Fig. 3 Measuring probe

Fig. 4 Definition of shape parameter S_a

3. 2 *The Choice of Liquid Column Height*

Fig. 5 shows the measured liquid column shape when h_z is 20, 30, 40, 45 and 50 mm respectively. The correspondingly calculated shape parameters are shown in Table 1. It is clear that the lower the liquid column is, the smaller the liquid column width and the lesser the shape parameter will be. This is available when liquid metal static pressure is lower. However, when the liquid column is very high (h_z = 50 mm), as a result of that the liquid metal's static pressure is higher than the electro-magnetic force, the liquid column sides incline, so the shape parameter reduces (S_a = 0.824 only).

Experimental results expressed that the liquid column sides are nearly vertical and the shape parameters are relatively higher when h_z = 30~45 mm , especially, S_a reaches the biggest value 0.869 at h_z = 40 mm. According to the experimental results, the good liquid column formability can be obtained when the height is controlled in the range of 30~ 45 mm. It agrees with the earlier research results of EMC technical parameters[7].

3. 3 *The Determination of Inductor Current*

The inductor current decides the magnetic field and electromagnetic pressure, therefore, decides the forming and stability of liquid column. Fig. 6 indicates the shape of the liquid column when inductor current I_d is 4 000, 4 400, 4 800 and 5 200 A resparately under the condition of h_z = 40 mm, the calculating values of the shape parameter S_a are shown in Table 2. It can be seen from Fig. 6 that the top of liquid column shrinks with the increasing of inductor current obviously. The suitable shapes, whose shape parameter is S_a = 0.834 and S_a = 0.861

Table 1 Affection of h_z on shape parameter S_a

h_z / mm	20	30	40	45	50
S_a	0.832	0.863	0.869	0.858	0.824

Fig. 5 Shape of liquid column when h_z = 20, 30, 40, 45, 50 mm respectively

1 — h_z = 20 mm; 2 — h_z = 30 mm;
3 — h_z = 40 mm; 4 — h_z = 45 mm;
5 — h_z = 50 mm

Fig. 6 Liquid column shape

1 — I_d = 4 000 A; 2 —4 400 A;
3 —4 800 A; 4 —5 200 A

Table 2 Affection of I_d on shape parameter S_a

I_d / A	4000	4400	4800	5200
S_a	0.805	0.834	0.861	0.765

respectively, are obtained when I_d = 4 400 A and 4 800 A.

Fig. 7 also shows the influence of inductor current upon the liquid column shape when the quantity of liquid metal aluminum is certain. The relation among I_d, S_a and h_z is shown in Table 3. The results demonstrate that not only the liquid column height will rise and the width will reduce, but also the shape parameters will increase with the inductor current. For example, when current changes from 3 600 A to 5 600 A, both of the shape parameter S_a and the liquid column height h_z increase from 0.825, 33 mm to 0.882, 43 mm correspondingly, that is to say, the bigger the inductor current is, the higher the shape parameter will be. This result agrees well with the research work of EMC little slab ingot[2].

Fig. 7 Affection of inductor current on the liquid column shape

1 — I_d = 3 600 A; 2 — I_d = 4 000 A; 3 — I_d = 4 800 A; 5 — I_d = 5 200 A; 6 — I_d = 5 600 A

However, the electro-magnetic stirring action will result in liquid metal flow intensely if the current surpasses 4 800 A, and the shape of liquid column becomes extremely unstable. Especially, the defects of slag inclusion will produce as soon as the oxide film on the liquid column surface is destroyed.

Above research results show that the inductor current should be controlled in the range of I_d = 4 400~ 4 800 A.

Table 3 The relation among I_d, h_z and S_a

I_d / A	3 600	4 000	4 400	4 800	5 200	5 600
S_a	0.825	0.838	0.853	0.861	0.865	0.882
h_z / mm	33	36	38.5	40	41.5	43

3.4 *The Choice of Screen Position*

The screen acts on reducing the top magnetic field and restraining molten fluid caused by the electro-magnetic stirring for forming a stable liquid column. The distance h_s between the screen bottom and the centre of inductor is defined as screen position. The liquid column shapes when h_s = 6, 12, 18 mm and ∞ respectively are shown in Fig. 8. The relation among h_s, S_a and h_z is listed in Table 4.

Fig. 8 Affection of screen position on liquid column shape

(a) —photograph; (b) —schematic diagram

1 — h_s = 6 mm; 2 — h_s = 12 mm; 3 — h_s = 18 mm; 4 — h_s = ∞

It can be seen that the liquid column inclines when the screen position is low, because the screen reduces the magnetic field and electromagnetic force greatly. However, the liquid column's side is vertical approximately at h_s = 12 mm and the shape parameter S_a reaches its biggest value 0.861. When $h_s = 18$ mm, the top shape becomes more circlular relatively than $h_s = 12$ mm, because the electromagnetic pressure increases slightly, but the change is not pronounced. When no screen, that is to say $h_s = \infty$, it can be seen that the liquid column's width reduces largely, the height of liquid column increases considerably, and the liquid column's shape becomes a taper, its S_a is only 0.785. Moreover, the liquid column's fluctuation caused by molten flow can be observed during experiment obviously. Therefore it is available to use screen for the forming and stabilizing of liquid column.

Table 4 The affection of h_s on shape parameter S_a

h_s / mm	6	12	18	∞
S_a	0.834	0.861	0.843	0.785
h_z / mm	39	40	41.5	44.5

The experiment results show that the affection of screen position changing from 12 mm to 18 mm on the shape of liquid column is not remarkable, it is because of using an arc inductor.

According to the above results the screen position should be controlled in the range of $h_s = 12 \sim 18$ mm.

3.5 *The Control of Liquid Column Corner Shape*

Fig. 9 shows the photographs of EMC ingot and the section shape, the section size is 520 mm × 130 mm. It expresses the big circular corner defect in ingot's corner that is not favorable for rolling process.

For the purpose of seeking the producing reason, the magnetic induction distribution is measured in ingot's corner and shown in Fig. 10. The magnetic induction at the center of wide and narrow side as well as the corner is $B_a = 59$ mT, $B_b = 54$ mT and $B_0 = 108$ mT respectively, i.e. $B_0 \approx B_a + B_b$, that is to say, there is an obvious magnetic induction overlap phenomenon in ingot's corner. Because of the big electromagnetic force, the corner's liquid column is compelled to condense and the big circular corner defect is

Fig. 9 Photographs of EMC ingot and section shape

(a) —EMC ingot; (b) —sectioin shape

Fig. 10 Magnetic induction of ingot's corner

produced after solidification.

In order to balance the magnetic induction distribution and eliminate the defect, a new type of inductor with four kinds of corner shape is designed employing the method of adjusting the gap between inductor and ingot as shown in Fig. 11, and the casting experiment is carried out. The obtained ingot section shape is shown in Fig. 11 also, from which it can be seen that the nearly vertical corner shape is gotten at position 4. It also indicates that the corner's inductor structure is reasonable.

Fig. 11 **Inductor and ingot corner shape**

4 CONCLUSIONS

(1) The optimum liquid column height is $h_z = 30 \sim 45$ mm;

(2) The reasonable inductor current is $I_d = 4400 \sim 4800$ A;

(3) The screen position should be controlled in range of $h_s = 12 \sim 18$ mm;

(4) The main reason causing the circular corner defect is the magnetic induction overlap in ingot's corner, and it can be eliminated by adjusting the gap between inductor and ingot.

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