SOME CHARACTERISTICS OF LIQUID METAL MENISCUS IN ELECTROMAGNETIC FIELD[①]

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ABSTRACT Some factors affecting the shape, the surface flow and the stability of meniscus of melt were investigated. Experimental results showed that under certain conditions the height and profile of melt meniscus can be changed by adjusting the weight of liquid metal column and an ideal shape of melt meniscus with vertical side can be obtained. A decrease in diameter and an increase in height of meniscus also can be achieved by increasing the induction power. The insertion of screen apparently improved the meniscus shape, resulting in a better shape with a near vertical periphery and a flat top, restrained the surface flow, and therefore made the meniscus be stable. A restraint magnetic field almost eliminated the surface flow but gave no effect on the meniscus shape.

Key words liquid metal meniscus electromagnetic cast unidirectional solidification

1 INTRODUCTION

Electromagnetic cast (EMC) is a mouldless cast technique using an electromagnetic force to replace a mould to balance the hydraulic pressure of liqud metal column. In this process, the most important factors that decide the process are stability, constant height and vertical periphery of meniscus of melt. If meniscus is too high to be balanced with electromagnetic pressure, or the surface flow caused by electromagnetic stirring is strong enough to cause a swing of meniscus, the process may fail or produce a bad effect on surface quality[1]. A vertical periphery is very important in electromagnetic cast process; it decides the quality of solidified ingots and the uniforminity in cross section. In addtion, the flow caused by electromagnetic force would break the growing crystals into pieces[2, 3], which is harmful to unidirectional crystal growth. The purpose of this study is to explore the factors which affect the meniscus shape, stability and surface flow, and to find the ways by which the surface flow can be eliminated and the meniscus shape can also be improved.

2 EXPERIMENTAL METHODS

2.1 *The Methods of Changing Meniscus Shape and Surface Flow*

Aluminum with 99.7% purity, as shown in Fig. 1, was put into an induction coil on a bottom substrate, and a high frequency current was supplied to the coil. During heating the aluminium was melted, possessing a column-like profile under the action of the electromagetic force. Changing the supplied power, we can change the electromagnetic pressure, and therefore change the meniscus shape. Inserting a screen in, we can change the distribution of magnetic field, resulting in an improvement of meniscus shape and its surface flow. By adjusting the liquid metal weight, the balance between hydraulic pres-

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sure of melt and electromagnetic pressure can be changed, and the meniscus shape will be changed too. By adding a restraint magnetic field on the meniscus, the surface flow might be eliminated.

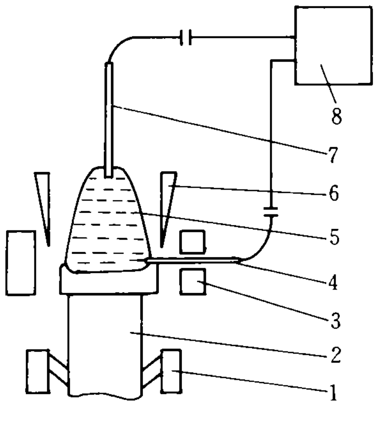

Fig. 1 The scheme of electromagnetic containment

1—cooler; 2—bottom substrate; 3—induction coil; 4—thermocouple; 5—meniscus of melt; 6—system of screen and restraint; 7—thermo couple; 8—recorder

2. 2 *Measurements*

A 1. 5 mm diameter ceramic bar was insert into the molten metal along the axis; its submerged length was measured as the height of meniscus. The meniscus shapes were fixed by suddenly increasing the supply of cooling water under the electromagnetic pressure, thus the features of surface flow and stability of meniscus were carefully observed. A 0. 3 mm diameter NiCr-NiSi thermocouples were used to measure the temperature.

3 RESULTS AND DISCUSSION

3. 1 *The Relationship Between Height and Shape of Meniscus*

In experiment, one end of d 25 mm diameter aluminum bar was put into the induction coil and melted, then a meniscus was built up. By moving up the bar slowly, more metal was melted and the height of meniscus was increased. It was found from the experiment that the meniscus height affected apparently the shape and stability of meniscus. As shown in Fig. 2, with the increase of meniscus height, the meniscus profile changed from cone-shaped through column to cucurbitaceous shape. Meniscuses with cone and column shapes were more stable than that with cucurbitaceous shape. In latter case, the meniscus presented an apparent swing and more easily collapsed. The features of surface flow showed no apparent difference in different shapes. The temperature measurement in the meniscus showed that the melt superheat was about 10～15 ℃ in the cone, about 30 ℃ in the column and up to 40 ℃ in the cucurbitaceous meniscus zone. It was seen from the results mentioned above that although the meniscus was stable in cone, its periphery was not vertical, and therefore the cross section of solidified ingot was no longer constant, and, the ingot surface quality could not be guaranteed while the S/L interface of ingot fluctuated. In addition, the low superheat in conical meniscus zone was unable to establish an enough temperature gradient G_L ahead of the S/L interface to help a column crystal to grow. On the other hand the degree of superheat and temperature gradient were larger in the cucurbitaceous meniscus zone, but the meniscus was too high in this situation, which was less stable and caused a larger hydraulic pressure at the S/L interface, therefore it was very easy to collapse. In electromagnetic cast, the most important requisite is to keep the meniscus from collapse, so the cucurbitaceous meniscus is considered to be undesirable. By comparison, the column meniscus is more satisfactory for the requirements of stability and temperature gradient. Especially, if the process causes some fluctuations, the column meniscus can keep the cross section of solidified ingot to be constant and make the product in good quality.

The reason about variations of meniscus shape shown in Fig. 2 is due to the change of the balance between the hydraulic and electro-

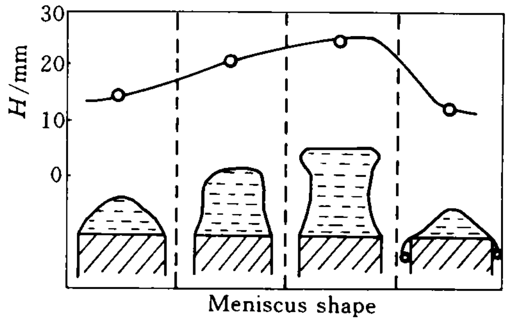

Fig. 2 The relationship between meniscus height H and meniscus shape

magnetic pressure on the meniscus surface. In electromagnetic cast process an essential relation is that at any level of height h there exists an equation:

$$\rho g h = |\boldsymbol{J}_\theta \times \boldsymbol{B}_z|$$ [4]

where ρ is the density of liquid metal; $\boldsymbol{B}_z$ is the axial component of $\boldsymbol{B}$ on the meniscus surface at any level of height. That is, the hydraulic pressure equals to the elecrtromagnetic pressure at any location on the meniscus surface. The equation implies that if the distribution of magnetic flux density B is unchangeable, the hydraulic pressure at any height level is increased with the increase of meniscus height, so that the previous balance between the hydraulic and electromagnetic pressure no longer exists. In order to establish a new balance, the cross section and the magnetic flux of the meniscus have to be augmented, so as to induce a larger current density $\boldsymbol{J}_\theta$ on the meniscus periphery; in addition, at different heights, the $\boldsymbol{B}$ produced by the inductor current and its component $\boldsymbol{B}_z$ are different. At a higher level, there appear more scattered and weaker $\boldsymbol{B}$ and $\boldsymbol{B}_z$ which act on the meniscus periphery, thus, a larger cross section is needed for crossing by a larger magnetic flux that induces a larger $\boldsymbol{J}_\theta$ and a larger electromagnetic pressure $|\boldsymbol{J}_\theta \times \boldsymbol{B}_z|$ (even though $\boldsymbol{B}_z$ is less) to balance the increased hydraulic pressure $\rho h g$ (because of the increase of h). That is, with the increase of meniscus height H the cross section of meniscus increases, and the increase rate of cross section on the upper part is much larger. This is the reason why the meniscus shape varies from cone through column to cucurbitaceous shape with the increase of meniscus height. At the meantime, the induced heat increases with the variation of meniscus from cone through column to cucurbitaceous shape, which causes the degree of superheat and temperature gradient G_L to increase.

3.2 *The Effects of Magnetic Flux Density **B** and Screen on the Dimension of Meniscus*

In the electromagnetic cast, it is expected that the electromagnetic pressure is not only to contain the molten metal but also to control the diameters of ingots by changing the magnetic flux density. A general relation between $\boldsymbol{B}$ and power P is $P = \boldsymbol{k} \cdot B^2$. Our experiments showed that the meniscus height could be adjusted by changing power P, as shown in Fig. 3. Since the B can be controlled by the power P, the meniscus height H will increase with the increase of power P (also B increase). That is, with a constant weight of molten metal, the ingot diameter can reduce by raising P (also means raising B). The relation was similar in the case of using screen. The only difference was that the meniscus height was lower while P was kept at the same value(B also the same). By comparing the two charts in Fig. 3, this was evident. This result pointed out that the expected diameter could be obtained by adjusting the inductor power P (i.e. adjusting B).

Following is some discussion about the relationship in Fig. 3. It is known that increasing the power results in increase of current I in the induction coil, and because of the relation $B = \boldsymbol{k} \cdot \boldsymbol{I}$, the magnetic flux density B increases also. Equation $P_m = \frac{B^2}{2u_0}$ [5] implies that the largest electromagnetic pressure P_m is decided by the B. If power P increases, then the B increases, and finally the P_m increases. In order to maintain balance between the P_m and the P_0 that is decided by $P_0 = \rho H g$ (where H is the meniscus height), the only way is to increase the height of the meniscus of melt by diminishing its diameter. With the insertion of screen, a reverse current is induced in the screen. This current also establishes a magnetic field which is reverse in direction to original field. As a result of cancellation, the real $\boldsymbol{B}$ decreases, therefore the electromagnetic pressure $P_m = \frac{B^2}{2u_0}$ also decreases. Finally the meniscus reduces its height H by augmenting its cross section to balance the reduced electromagnetic pressure.

3.3 *The Actions of Screen and Restraint Magnetic Field on Restraining Surface Flow and Stabilizing Meniscus*

The shape, the stability and the surface flow of melt meniscus were carefully observed under different conditions, for example, without screen, with screen, and with both screen and restraint magnetic field. The results are shown in Fig. 4. Without screen, the meniscus shape was just like a cone, and the surface flow was quite strong, resulting in the meniscus unstable, and often breaking the oxide film, so that the containment failed. When the screen was inserted in, the meniscus shape nearly became a column which had an approximately vertical periphery and a flat top surface, and the surface flow was reduced apparently, and the meniscus was quite stable. When a screen and a restraint magnetic field whose magnetic field lines were cut by the flowing molten metal were added simultaneously, the meniscus profile was still a column just as in the case with a single screen, but the surface flow almost disappeared and the menisucs was very quiet and steady. This is just what we expected. Fig. 5 is the photographs of fixed meniscuses obtained by quenching under electromagnetic pressure. So far, in our experiments an ideal meniscus was obtained, which was stable, no surface flow, and had an approximately vertical periphery and flat top surface. It made future continuous cast to be possible.

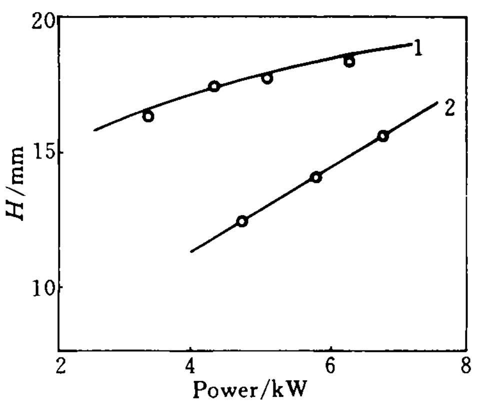

Fig. 3 The relationship between meniscus height and power

1—without screen; —with screen

While a screen is inserted in, a current is induced in the screen which is reverse to the current of coil in direction. The two reverse currents produce two reverse magnetic fields. The results of cancellation makes the magnetic flux density $\boldsymbol{B}$ to be weaker, therefore, the $\boldsymbol{B}_z$ is weaker too. In order to balance the present hydraulic pressure, the electromagnetic pressure $P = |\boldsymbol{J}_\theta \times \boldsymbol{B}_z|$ is not allowed to be reduced, although the $\boldsymbol{B}_z$ has been reduced. In this condition, the melt meniscus augments its cross-section and makes its periphery more vertical, thus the magnetic flux which crosses the cross section is increased. The increased magnetic flux induces a larger current density $\boldsymbol{J}_\theta$, so the electromagnetic pressure $P = |\boldsymbol{J}_\theta \times \boldsymbol{B}_z|$ is not reduced enough and can still balance the hydraulic pressure . Another force which

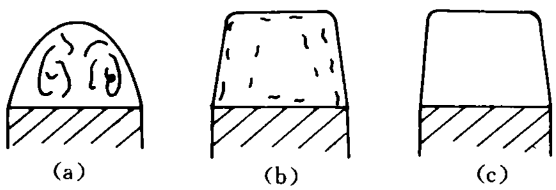

Fig. 4 The effect of screen and restraint magnetic field on meniscus shape and surface flow

(a)—without screen; (b)—with screen; (c)—with screen and restraint magnetic field

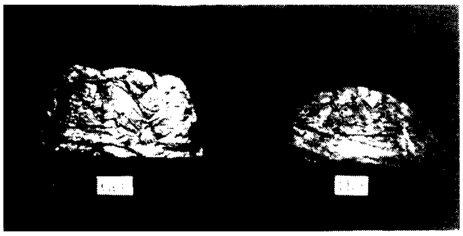

Fig. 5 Photographs of meniscus shapes fixed by quenching
(a)—with screen; (b)—without screen

causes the surface flow is $F = J_\theta \times B_r$. Inserting a screen in implies to lengthen the induction coil along the axis, therefore the scatter of magnetic field is apparently reduced. In this situation, the radial component B_r is very small, so the stirring force F is significantly reduced and the surface flow is reduced too.

When a restraint magnetic field exists, a force named Lorentz force acts on the flowing conductive liquid metal as if a viscosity which is usually called "magnetic viscosity" were added in the fluid. This "viscosity" can be measured with $M = BL\sqrt{\frac{\sigma}{\rho v}}$ [6]. In our experiments it was found that when the amplitude of restraint magnetic field B was in the range of 0.12~0.22 T, this viscosity stopped the fluid flow. However, because of no interference between restraint magnetic field and high frequency magnetic field which was just used to contain the liquid metal, the restraint magnetic field gave no effect on the meniscus shape.

4 CONCLUSIONS

(1) Meniscus shape with a near vertical side can be obtained by adjusting the weight of molten metal.

(2) With a screen or without a screen, increasing current in induction coil can increase meniscus height of melt and reduce its diameter. This is an important means to control the ingot diameter in electromagnetic cast.

(3) The insertion of a screen apparently improved the meniscus shape, so that an ideal stable meniscus with a near vertical periphery, a flat top surface, and less surface flow was obtained.

(4) When the amplitude of an existing restraint magnetic field was over 0.12 T, the surface flow was apparently reduced or even eliminated. The restraint magnetic field increased the stability of meniscus and gave no effect on the meniscus shape.

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