LATERAL STABILITY OF ALTERNATIVE HORIZONTAL LEVITATION ELECTROMAGNETIC CONTINUOUS CASTING OF ALUMINIUM SHEET①

Deng Kang†, Shen Min†† and Ren Zhongming†

† *College of Materials Science and Engineering, Shanghai University, Shanghai 200072, P. R. China*

†† *Shanghai Institute of Applied Mathematics and Mechanics, Shanghai University, Shanghai 200072, P. R. China*

ABSTRACT The lateral stability of alternative horizontal levitation electromagnetic continuous casting process of aluminium sheet was analyzed by correlating the lateral electromagnetic force on the aluminium sheet to the lateral position disturbance of the sheet which was set between the side blocks. The results show that when a small disturbance occurs to the lateral position of the sheet, the unbalanced lateral force caused by disturbance will make it greater. Therefore, the lateral position of the sheet is an unstable balanced position, which explains the observation of instability in experiment. Based on the analyses, an explanation for the formation of rod after the appearance of the instability in the casting process of aluminium sheet was given.

Key words stability horizontal continuous casting electromagnetic casting aluminium sheet

1 INTRODUCTION

Alternative electromagnetic continuous casting is a highlighted new technique. In this technique the electromagnetic force produced by the interaction between the electromagnetic field and the induced eddy current in the molten metal can levitate and constrain the metal into certain shape[2-6] or partly compensate the hydrodynamic pressure acting on the mold and realizes the soft contact between the metal and the mold[7, 8]. This technique plays an important role in high speed and near net shape casting with high ingot surface quality. Also, the accompanying stirring effect of the interaction can refine the grains and avoid shrinkage[9].

The alternative horizontal levitation electromagnetic continuous casting of aluminium sheet which was put forward several years ago takes the obvious advantages of no contact with the mold and horizontal shaping[4]. But, it brings about the problem of stability in continuous casting process. In the experiment of horizontal electromagnetic continuous casting of aluminium sheet, it was observed that the continuous casting process can be maintained only under very critical condition and very small disturbance can result in its collapse. Ref. [3] made some investigations on the characteristics of both the vertical and lateral forces acting on the aluminium sheet, but did not relate the experiment results to the stability. The numerical computation in Ref. [8, 10] just emphasized the maximization of levitation force. Ref. [10] only made the qualitative analysis on the stability of the vertical position disturbance of the aluminium sheet and concluded that the process was self-stable which could not explain the instability in experimental observation. As the disturbance is arbitrary, it is necessary to consider the lateral position disturbance.

In present paper, the stability of lateral position disturbance of the aluminium sheet was in-

① Received Dec. 29, 1997; accepted Feb. 29, 1998

vestigated by both the theoretical computation with finite element method and the analysis on the experimental results in Ref. [3]. The results show that the balanced position of aluminium sheet is an unstable one. Hence, any small lateral disturbance occuring in the position of the sheet will result in an unbalanced force which tends to make it larger and finally the continuous casting collapses. The research also explains the reason why rod shaped ingot is often cast after the happening of instability.

2 MODEL OF ELECTROMAGNETIC FIELD

The apparatus of alternative horizontal levitation electromagnetic continuous casting of aluminium sheet was introduced in Ref. [3]. To make an analysis on the stability of above horizontal alternative electromagnetic continuous casting process, the electromagnetic field of the apparatus disturbance appearing must be calculated. Therefore, the mathematical model for the electromagnetic field should be set up first. Here, the assumptions adopted in Ref. [10] is still valid and the mathematical model is written as follows.

The Maxwell' s equation system of the steady electromagnetic field is

$$\nabla\times\dot{\boldsymbol{E}} = -jw\dot{\boldsymbol{B}} \quad \text{(Farady's law)} \quad (1)$$

$$\nabla\times\dot{\boldsymbol{H}} = \dot{\boldsymbol{J}} \quad \text{(Ampere's law)} \quad (2)$$

$$\nabla\cdot\dot{\boldsymbol{B}} = \boldsymbol{O} \quad \text{(Magnetic flux law continuity)} \quad (3)$$

$$\dot{\boldsymbol{J}} = \sigma\dot{\boldsymbol{E}} \quad \text{(Ohm's law)} \quad (4)$$

$$\dot{\boldsymbol{B}} = \mu\dot{\boldsymbol{H}} \quad \text{(Magnetic constitutive property)} \quad (5)$$

where top marks represent complex variables. A magnetic vector potential is introduced as

$$\dot{\boldsymbol{B}} = \nabla\dot{\boldsymbol{A}} \quad (6)$$

and specify

$$\nabla\cdot\dot{\boldsymbol{A}} = 0 \quad (7)$$

Then, following eqn. is obtained.

$$\dot{\boldsymbol{E}} = -j\omega\dot{\boldsymbol{A}} + \nabla\dot{\varphi} \quad (8)$$

where $\dot{\varphi}$ is a complex scaler electrical potential. If the permeability of media is constant, eqn. 2 becomes

$$\frac{1}{\mu}\nabla^2\dot{\boldsymbol{A}} = -\dot{\boldsymbol{J}} \quad (9)$$

According to the assumptions in Ref. [10], simplification can be made to eqns. 8, 9 and following eqn. can be derived

$$\frac{1}{\mu}\nabla^2\dot{A}_Z - j\omega\sigma\dot{A}_Z = -\dot{J}_Z \quad (10)$$

and boundary conditions are

$$\begin{cases}\Gamma_1: \dot{A}_Z = \dot{A}_0 \\ \Gamma_2: \dfrac{\partial\dot{A}_Z}{\partial n} = \mu\dot{H}_t\end{cases} \quad (11)$$

where $\dot{A}_Z$ or $\dot{J}_Z$ are Z-component of $\dot{\boldsymbol{A}}$ or $\dot{\boldsymbol{J}}$, respectively, $\dot{A}_0$ is the known value of $\dot{A}_Z$ at the boundary Γ_1, and $\dot{H}_t$ is the known value of tangential component of magnetic intensity at the boundary Γ_2. Due to the lateral disturbance occurring to a position of the sheet, the electromagnetic field is not a symmetry one. Therefore, the entire field should be taken as calculating region. Here, the finite element method is used to solve the eqn. 10 with respect to the first kind boundary condition in eqn. 11. The other related variables are calculated from the solution of $\dot{A}_Z$ by following eqns.

$$\dot{\boldsymbol{J}} = -j\omega\sigma\dot{A}_Z\boldsymbol{k} \quad \text{(Induced eddy current)} \quad (12)$$

$$\dot{\boldsymbol{B}} = \frac{\partial\dot{A}_Z}{\partial y}\boldsymbol{i} - \frac{\partial\dot{A}_Z}{\partial x}\boldsymbol{j} \quad \text{(Magnetic flux density)} \quad (13)$$

$$\boldsymbol{F} = \mathrm{Re}\left(\frac{\dot{\boldsymbol{J}}\times\dot{\boldsymbol{B}}^*}{2}\right) \quad \text{(Electromagnetic force)} \quad (14)$$

$$\boldsymbol{p}_m = \frac{\dot{\boldsymbol{B}}\times\dot{\boldsymbol{B}}^*}{4\mu} \quad \text{(Electromagnetic pressure)} \quad (15)$$

where mark * represents the conjugated complex variable.

3 STABILITY ANALYSES

It is obvious that the electromagnetic continuous casting of aluminium sheet can be realized only when the summation of the hydrodynamic pressure and the mass of sheet is balanced by the vertical component of total electromagnetic force and also the lateral component of the total force must be zero or self-balanced. Otherwise, it will become unstable and collapse. In previous work, only the first aspect of the problem was investigated[8, 10]. This paper emphasized the stability problem caused by the unbalanced lateral component of the electromagnetic force.

If the aluminium sheet is always kept strictly at the center between the side blocks, the total lateral force is zero. But in practice, there are always some disturbances which cause it deviate from the central position. If the unbalanced forces caused by these disturbances make the sheet to restore its original balanced central position, the process is stable and the continuous casting of aluminium sheet can be realized. Otherwise, the tendency of disturbance will be amplified by the unbalanced force and the continuous casting collapses.

Now the problem is whether the unbalanced forces make the disturbance greater. To get the answer the unbalanced lateral component of electromagnetic force acting on the aluminium sheet must be calculated under different value of the lateral displacement of the sheet. Here, it is done numerically by finite element method as above mentioned and by calculation from the experimental results in Ref. [3].

According to eqns. 12~14, the X and Y components of total electromagnetic force are calculated from the solution of $\dot{A}_Z$ by following eqns.

$$f_X = \mathrm{Re}\left[-j\omega\sigma\int_{-h}^{h}\int_{-w+\Delta l}^{w+\Delta l}\dot{A}_Z\cdot\frac{\partial\dot{A}_Z^*}{\partial x}\mathrm{d}x\,\mathrm{d}y\right] \tag{16}$$

$$f_Y = \mathrm{Re}\left[-j\omega\sigma\int_{-h}^{h}\int_{-w+\Delta l}^{w+\Delta l}\dot{A}_Z\cdot\frac{\partial\dot{A}_Z^*}{\partial y}\mathrm{d}x\,\mathrm{d}y\right] \tag{17}$$

where h and w are half thickness and half width of aluminium sheet respectively, and Δl is the lateral displacement of the sheet caused by disturbance (see Fig. 1). Then, the stability criteria with respect to lateral disturbance for the alternative horizontal levitation electromagnetic continuous casting of aluminium sheet can be expressed as: For any small disturbance Δl, if $f_X < 0$ when $\Delta l > 0$ and $f_X > 0$ when $\Delta l < 0$, the continuous casting process is laterally stable, otherwise, it is unstable.

In Ref. [3], the experimental results of lateral force acting on a segment of aluminium at different lateral position were provided. The total lateral force acting on aluminium sheet can be calculated by the integration of the measured lateral force F acting on the segment over the lateral space occupied by the sheet under the assumption of neglecting the mutual induction between the segments' induced eddy currents, that is,

$$\begin{aligned} f_X &= \frac{h_L}{h_w}\int_{-w+\Delta l}^{w+\Delta l}F\,\mathrm{d}x = \frac{h_L}{h_w}\left[\int_{-w+\Delta l}^{0}F\,\mathrm{d}x + \int_{0}^{w+\Delta l}F\,\mathrm{d}x\right] \\ &= \frac{h_L}{h_w}\left[-\int_{0}^{w-\Delta l}F\,\mathrm{d}x + \int_{0}^{w+\Delta l}F\,\mathrm{d}x\right] \\ &= \frac{h_L}{h_w}\int_{w-\Delta l}^{w+\Delta l}F\,\mathrm{d}x \end{aligned} \tag{18}$$

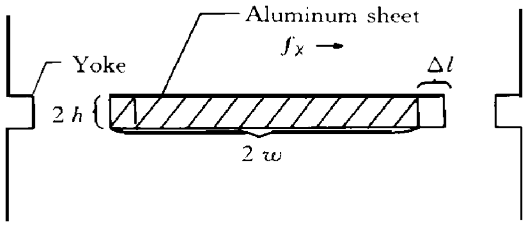

Fig. 1 Definition of geometry parameters and positive direction of total lateral force

For different width of aluminium sheet, Fig. 2 shows the correlation between the total lateral force f_X acting on the aluminium sheet and the lateral disturbance Δl which is computed from both the finite element computational results by eqn. 16 and the experiment results in Ref. [3] by eqn. 18 for the case of 1.7 A coil current. It can be seen from Fig. 2 that $f > 0$ is always the case for $\Delta l > 0$ and $f < 0$ for $\Delta l < 0$. Then, according to above lateral stability criteria, the continuous casting of aluminium sheet is unstable. Therefore, from the view of lateral disturbance stability, the continuous casting process can only be maintained under the condition of no disturbance which is impossible for practical application. It is necessary to improve the structure of apparatus to achieve lateral stability to apply the technique. The results in Fig. 2 also show that the smaller the width of aluminium sheet is, the smaller the unbalanced lateral force is, and then, the more stable the casting process is. But smaller width will result in smaller levitation force. If the levitation should be maintained, the shape of the ingot will be changed to reach a balance between the stability and levitation. This is the reason why rod shape ingot is often obtained if the levitation is continued after lateral instability. The analyses of the entire process of this instability and the determination of final ingot shape should consider the interaction between electromagnetic field and the flow of the molten metal with free-surface.

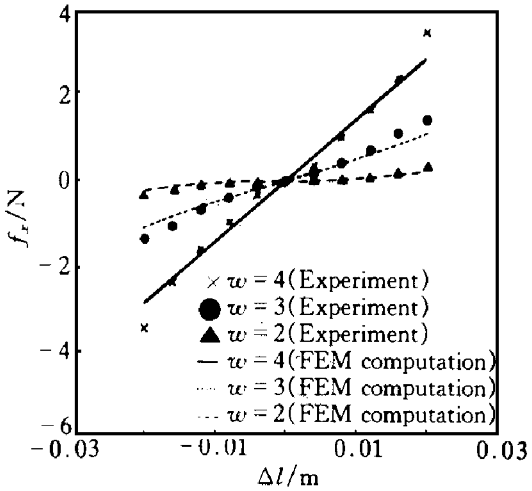

Fig. 2 Correlation between total lateral force and lateral disturbance for different width of aluminium sheet

4 CONCLUSION

The results show that the continuous casting process is laterally unstable. Besides which, they can also partly explain the reason why the apparatus has the tendency of casting rod shape ingot after instability. The analyses of entire process of instability needs to consider the interaction between electromagnetic field and flow of molten metal with free surface. What the most important is the structure of the apparatus should be improved to prevent the instability and realized the no mold continuous casting of aluminium sheet.

SYMBOLS

B —Magnetic flux density; ***H*** —Intensity of magnetic field; ***E*** —Intensity of electrical field; ***J*** —Current density; ***A*** —Vector magnetic potential; ω —Angular frequency; j —$\sqrt{-1}$; ***i*** —Unit vector in X direction; ***j*** —Unit vector in Y direction; ***k*** —Unit vector in Z direction; ***f*** —Electromagnetic force; $\boldsymbol{p}_m$ —Electromagnetic pressure; h_w —Width of aluminium segment in experiment; h_t —Thickness of aluminium sheet; σ —Conductivity; μ —Permeability; Δl —Lateral disturbance displacement; h —Half thickness of aluminium sheet; w —Half width of aluminium sheet; ***F*** —The measured lateral force on aluminium segment in experiment.

REFERENCES

1 Sakane J *et al*. Metall Trans, 1988, 9B(3): 397.
2 Ren Z M *et al*. Journal of Dalian Univ of Tech, (in Chinese), 1994, 34(5): 556.
3 Ren Z M *et al*. The Chinese Journal of Nonferrous Metals, (in Chinese), 1994, 4(4): 78.
4 Ren Z M *et al*. The Chinese Journal of Nonferrous Metals, (in Chinese), 1993, 3(2): 93.
5 Ren Z M *et al*. The Chinese Journal of Nonferrous Metals, (in Chinese), 1996, 6(1): 108.
6 Ren Z M *et al*. Acta Metallurgical Sinica, (in Chinese), 1996, 36(4): 462.
7 Ren Z M *et al*. Journal of Dalian Univ of Tech, (in Chinese), 1991, 31(4): 419.
8 Ren Z M *et al*. Journal of Dalian Univ of Tech, (in Chinese), 1992, 32(1): 121.
9 Asai S. Tesu to Hagane, 1989, 75(1): 32.
10 Zhu S J *et al*. Trans Nonferrous Met Soc China, 1996, 6(4): 42.

(Edited by Huang Jinsong)