Confining of Molten Metal by Imposition of D.C. Magnetic Field and D.C. Electric Current

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A new method of confining a molten metal by imposing D.C. magnetic field and D.C. electric current has been proposed. The confinement of a molten metal was demonstrated by a model experiment using a molten gallium with low melting temperature. By using of newly proposed plural pairs of electrodes, the molten metal could be confined under rather weak magnetic field of 0.5 T. The electric current required for confining a molten metal has been theoretically predicted. It has been found that the theoretical prediction agrees well with experimental data. The model experiment demonstrated that the method proposed in this study is promising for industrial applications.

KEY WORDS: galvanizing process; cold crucible; stable confinement of molten metal; magnetic field and electric current; electromagnetic processing of material.

1. Introduction

In metals processing, the confining of a molten metal without use of mechanical equipment is of great interest. For example, in a conventional galvanizing process, a strip of steel is dipped into a zinc bath and pulled out upward by use of a sink roll equipped in the bath for changing the moving direction of the strip, where the surface quality of the strip are retarded due to scratches caused by direct contact between the roll and the strip. Furthermore, in the conventional galvanizing process, rather large amount of a molten metal is held in a bath so that quickly change of its metal composition is not easy. In addition, the maintenance and replacement of the rolls are required so often since they are easily eroded in the bath. To solve the problems mentioned above, a new galvanizing process was proposed, where the bath capacity can be reduced, the sink roll is replaced by a magnetic confinement using a high magnetic field, and the strip is inserted into a hole equipped on the bottom wall of the bath.

On the other hand, in a cold crucible process where such chemically active metals or metals with a high melting temperature, as titanium and zirconium can be melted and levitated by magnetic pressure, the control of ejecting rate of molten metals has strongly been desired not only for atomizing the molten metals as the particles with uniform size, but also for precision casting. Hitherto, alternating and traveling magnetic fields have been used for confining a molten metal and controlling its flow in a channel. Those, however, inevitably bring hydrodynamic unstable phenomenon and the stable confining of a molten metal has not been available.

In a process confining a molten metal by simultaneous imposition of D.C. magnetic field and D.C. electric current, large electric current is required for reducing the intensity of the magnetic field. In this case, however, the electric current, tends to converge at a pin point on electrodes, which leads to an unstable state in hydrodynamics aspect. Especially, for confining a molten metal with a high static pressure, such condition as high magnetic field and low electric current is essential not only for preventing the pin point convergence of electric current, but also for reducing operating cost.

In this study, is order to solve the unstable state we have proposed a new method which will lead a new process for confining a molten metal. The method enables to stably confine a molten metal under the condition of a low intensity of magnetic field and a high value of electric current, i.e., reasonable operating cost. The usefulness of the method has been demonstrated by a model experiment using a molten metal.

2. Experimental

2.1. The Case Using a Pair of Electrodes

An experimental apparatus is schematically shown in Fig. 1, where magnetic field and electric current are imposed perpendicular to each other in a plane perpendicular to a molten metal flow. The electric current was controlled by an electric power supply and an electric resistance set in a series circuit. Molten gallium of which an depth with 26 mm had initially been held, was fed to a copper channel with rectangular shape by lifting a stopper. To observe the behavior of the molten metal flow in the bore of a super
conducting magnet, a part of the channel was made by a transparent acrylic plastic. The magnetic field imposed on molten gallium was 4 or 2 T.

In the case of 4 T, electric voltages of 2, 3, 4, 5, 6 and 7 were imposed. The pictures of the front edge behavior of the molten metal taken at elapsed time of 0, 1, 2, 5, 10 and 15 s are shown in Fig. 2, where the front edge is so illustrated by a white line as to make its position clear. Here the elapsed time of 0 s is defined as the moment when the molten metal contacts with the copper electrodes. When an electric voltage of 2 V was imposed, the electric current was 0.7 A and the molten gallium could not be confined. When an electric voltage of 7 V was imposed, the current was 2.10 A and the front edge oscillated backward and forward.

When the electric voltage between 3 V and 6 V, the molten gallium was stably confined. In the cases of 3 V and 4 V, the static pressure imposed on the molten metal was slightly larger than that induced by the Lorentz force so that the molten gallium was confined with a convex front shape toward the flow direction. In the case of 5 V, the front shape was nearly flat. On the other hand, when 6 V was imposed, the molten gallium was suppressed backward for a few seconds and then stably confined. In this case, the static pressure induced by the Lorentz force was slightly larger than that of the molten metal so that it was confined with a concave front shape toward the flow direction.

In the case of 2 T, the electric voltages of 4, 6, 8, 10 and 12 were imposed. The pictures of the front edge behavior taken at 0, 1, 2, 3, 5, 8, 10 and 15 s, are shown in Fig. 3, where the front edge is illustrated by a white line as was done in Fig. 2. When 4 V was imposed, the electric current was 1.17 A and the molten gallium was not confined. When 6 V, the electric current was 0.70 A and the molten gallium was stably confined. In the cases of 8 V and 10 V, the front of the molten gallium was finely oscillated though it sometime was stably confined. This oscillation behavior in the short time interval was often observed at 8 V over the period between 5.53 s and 6.78 s in Fig. 3. Such oscillation of molten gallium, namely intermittent contact between molten metal and electrodes, however, was never observed at 4 T. This reason can be explained as braking effect, namely the magnetic viscosity under the imposition of 2 T, is weaker than that under 4 T.

The observed results mentioned above are given in Table 1 listed by imposed magnetic field and electric current, where stably confined and unconfined conditions are indicated by the marks of ◯ and ×, respectively. Here, the...
shaded region indicates an anticipated stable confinement. From these experimental results, it is understood that magnetic field and electric voltage must be so adequately selected in a narrow range as to confine a molten metal when using a pair of electrodes.

Before experiments, the two type of molten metal confinement was imaged. One is the type where a molten metal is confined at the edge of electrodes as shown in Fig. 4(a). The other is the type where the molten metal enters between two electrodes to be confined as shown in Fig. 4(b). In the experiment, however, only the former type shown in Fig. 4(a) was seen and the latter type given in Fig. 4(b) was never observed. This reason can be explained as follows: once a molten metal contacts with an electrode, electric current reaches at the maximum value which is determined by imposed electric voltage and resistance, and never changes with increasing in the contacting area between molten metal and electrode. That is, the electric current is not limited by the electric resistance in the circuit, but by the electric current capacity of an electric power supply. Thus, for confinement of a molten metal with a high static pressure, a large amount of electric current is necessary. In such a case, a large amount of electric current converge at the edge point of electrodes. This electric convergency leads to cause a molten metal unstable, namely, such intermittent contact between molten metal and electrodes accompanying sparks, which brings serious damage on electrodes.

2.2. The Case Using Plural Pairs of Electrodes

The experimental apparatus having five pairs of electrodes is schematically shown in Fig. 5. Each electric resistance was connected with each electrode in series and set parallel in the total electric circuit. Under the assumption that a molten metal would be confined at the 3rd pair of electrodes, the distributions of electric current and electromagnetic force are schematically illustrated in Fig. 6. Under on imposed magnetic field, the total electric current, $I_{\text{total}}$, can be determined to induce the total Lorentz force, $F_{\text{total}}$, which is needed for confining a molten metal. Let us divide $I_{\text{total}}$ into the three currents of $I_1$, $I_2$ and $I_3$, which are imposed on each pair of electrodes, and denote the generated Lorentz forces as $F_1$, $F_2$ and $F_3$, respectively. Thus, the total Lorentz force should be equal to the sum of $F_1$, $F_2$ and $F_3$, that is, $F_{\text{total}}=F_1+F_2+F_3$. In this way, by separating an electrode into plural pairs of electrodes, the amount of the electric current passing through each pair of electrodes can be reduced.

Under the imposition of such magnetic fields as 4, 2, 1
and 0.5 T, experiments similar to the previous case with a pair of electrodes, were carried out by changing electric voltage. Under the imposed magnetic field of 4 T, the imposed electric voltage was changed from 1 to 6 V. The front edge behaviors of a molten metal, which were observed at each time when the metal began to contact with each pair of electrodes, and those at the elapsed times at 5, 10 and 20 s after the confinement, are shown in Fig. 7, where the front edge is illustrated by a white line as was done in Figs. 2 and 3. The molten gallium was stably confined at the 3rd pair of electrodes with total applied electric current of 1.20 A under 1 V, at the 2nd pair with 1.22 A under 2 V, at the first pair with 1.03 A under 3 V and 1.33 A under 4 V. In the cases of the impositions of 5 and 6 V, the front edge oscillated at the first pair of electrodes, at which electric currents were 1.69 A and 1.85 A, respectively, although the stable confinement was observed sometimes.

In the case of imposed magnetic field of 2 T, the imposed electric voltage was changed from 1 to 7 V. The molten gallium was not confined at 1 V. When 2 V was imposed, the molten gallium was stably confined at the 4th pair of electrodes with the total electric current of 2.69 A. In the cases of 4, 5 and 6 V, the molten gallium was stably confined at the 3rd, 2nd and 2nd pairs of electrodes, with electric currents of 3.35 A, 2.72 A and 3.12 A, respectively. In the case of 7 V, the front edge of molten gallium oscillated and could oscillate.
not be confined stably.

In the case of imposed magnetic field of 1 T, the imposed electric voltage was changed from 4 to 12 V. When 4 V was imposed, the molten gallium was not confined. In the cases of 6, 8 and 10 V, it was stably confined at the 4th, 3rd and 2nd pairs of electrodes, with total electric currents of 6.32 A, 6.39 A and 5.39 A, respectively. In the case of 12 V, the front edge of a molten gallium rippled at the 1st pair of electrodes and could not be confined stably.

In the case of imposed magnetic field of 0.5 T, the imposed electric voltage was changed from 10 to 14 V. The front edge behavior, which was going to contact with electrodes and its views at the elapsed time of 5, 10 and 20 s after reaching to the stable state of confinement, are shown in Fig. 8, where the front edge is illustrated by a white line as was done in the previous figures. When 10 V was imposed, the molten gallium was not confined. In the cases of 12 and 14 V, it was stably confined at the 5th and 3rd pairs of electrodes, with electric currents of 15.7 A and 11.2 A, respectively.

When a large electric current was imposed under a high electric voltage, the unstable behavior like intermittent contact between molten metal and electrode was observed even for in the case adopting plural pairs of electrodes. This unstable behavior is similar to that observed for the case adopting a pair of electrodes. Under a same intensity of magnetic field, the total current required for confining of a molten metal should be same, since the Lorentz Force is given in \( F = J \times B \). However, in the practical experiment, the total current was slightly different at a same imposed electric voltages. This comes from the following two reasons. One is that the imposed magnetic field was a little bit different at each electrode. The other is that an extra electric current is needed to suppress the hydrodynamic pressure accompanied with the molten metal flow, which is caused by heterogeneous distribution of electromagnetic force.

The experimental results are given in Table 2 listed by imposed magnetic field and electric current, where the marks of \( \bigcirc \) and \( \times \) indicate the stably confined and unconfined conditions, respectively. In addition, the shaded area shows the anticipated stable confinement. The range of electric voltage for the stable confinement is larger in Table 2 then that for a pair of electrodes in Table 1 except only the case where unstable phenomenon appeared under 5 and 6 V at 4 T. The unstable phenomenon seen for the case of the five pairs of electrodes could be caused by an asperity between electrodes and acryle wall surface of the channel, namely caused by the apparatus used.

Even in the case where a large Lorentz force is required to confine a molten metal having a high static pressure, the molten metal will be confined by dividing electric currents with plural pairs of electrodes. Consequently, convergency of electric current in current pass can be prevented by adopting plural pairs of electrodes to result in that a molten metal can be more stably confined. Furthermore, the technique of the plural pairs of electrodes enables to reduce the intensity of magnetic field without increasing the amount of electric current. This implies that the process for confining a molten metal and controlling its flow can be designed in more reasonable cost in the comparison with the process using one pair of electrodes. Furthermore, precise control of a molten metal flow would be possible by changing electric resistances connecting with each pair of electrode along the channel of molten metal, in such a way that the smaller value of resistance is set at the upper region of flow and inversely the larger one at the down stream.

### Table 2. Experimental result in the case with five pairs of electrodes.

| Imposed voltage | Order of electrode | Elapsed time |
|-----------------|--------------------|--------------|
|                 | first | second | third | fourth | fifth | 5s | 10s | 20s |
| 10 V            | Copper electrodes | Molten metal | Total current(A) 13.8 |
| 12 V            |       |        |       |        |       |     |     |     |
| 14 V            |       |        |       |        |       |     |     |     |

Fig. 8. Molten metal behavior observed in a channel with five pairs of electrodes under 0.5 T.

### 3. Discussion

The coordinate axes used for theoretical analysis are...
shown in Figs. 1 and 5. Let us denote the x, y and z axes to the directions of flow, width and depth of a channel, respectively. In this system, a static pressure \( P \) and Lorentz force \( f = \mathbf{J} \times \mathbf{B} \) act in the x-direction. \(^3\) On a volume element of molten metal with \( Ax \), \( Ay \) and \( Az \) set in a flow, the force balance in the x-direction is written as Eq. (1).

\[
(P_x - P_{x+Ax}) Ay Az + (J \times B)_x Ax Ay Az = 0 \quad \text{..........}(1)
\]

Dividing Eq. (1) by \( Ay Az \) from Eq. (1) and integrating the resulted equation in the x-direction under the conditions of \( P_x = \rho gh \) at \( x = 0 \) and \( P_x = 0 \) at \( x = L \), yield Eq. (2).

\[
\rho gh - (J \cdot B)_x L = 0 \quad \text{..................................}(2)
\]

where \( J_n \) is the electric current density in the y-direction and \( B_z \) the magnetic field density in the z-direction. By using the relation of \( I_x = J_n L d \), Eq. (2) yields Eq. (3).

\[
\rho gh d = (I_x B_z) \quad \text{..................................}(3)
\]

The left hand term in Eq. (3) which can be determined from experimental conditions, is indicated by \( k = \rho gh d \).

Then, Eq. (3) is reduced to Eq. (4).

\[
I_x = k / B_z \quad \text{..................................}(4)
\]

That is, the electric current for confining a molten metal is proportional to \( 1 / B_z \). The proportional constant of \( k \) in Eq. (4) is calculated as \( k = 6.21 \text{ AT} \) by substituting experimental conditions of the channel height \( d = 4 \times 10^{-3} \text{ m} \), the holding height \( h = 26 \times 10^{-3} \text{ m} \), and density of molten gallium \( \rho = 6.090 \text{ kg/m}^3 \).

**Figure 9** shows the theoretically estimated relation between the electric current \( I_x \) and the inverse of magnetic flux density, \( 1 / B \). In the figure, the experimental results obtained in the both cases with one and five pairs of electrodes are also plotted. The total electric current in the cases with one and five pairs of electrodes are nearly same at \( 1 / B = 0.5 \) and the theoretical prediction given by Eq. (4) agrees well with the experimental data. It is seen in Fig. 9 that the experimental values of electric current are more deviated from the theoretical prediction with decreasing the magnetic field. This reason could be explained as follows; under an imposed magnetic field when a molten metal can not be confined at an arbitrary pair of electrodes, it will contact with the next pair of electrodes and can be confined if the electric current is enough at the next pair of electrodes. This stepwise contact of the molten metal with electrodes brings a stepwise increase in the total current to confine the molten metal. When a low intensity of magnetic field is imposed, the electric current at each pair of electrodes for confining the molten metal have to be larger in the comparison with the case of a higher intensity of magnetic field. Thus the increment of electric current passing the next pair of electrodes have to be larger in the case with low magnetic field. Thus, in the process to confine the molten metal with using plural pairs of electrodes, the electrical current does not change continuously, but stepwise. Namely, this leads to a difficulty in continuously adjusting the electric current as the theoretical prediction.

4. Conclusion

On the basis of the idea that the plural pairs of electrodes, which are set parallel to each other and connected in series to electric resistance, can provide a more stable confinement of a molten metal, a model experiment using a molten gallium was conducted. The following results have been obtained.

1. The plural pairs of electrodes is useful for electromagnetic confinement of the molten metal.
2. The use of the plural pairs of electrodes is effective even under the condition with smaller magnetic flux density and higher electric current.
3. The electromagnetic confinement process of molten metal using the plural pairs of electrodes can control its flow with more reasonable cost in comparison with the case using a pair of electrodes.

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**Nomenclature**

- \( B \): Magnetic flux density (T)
- \( d \): Width of a channel (m)
- \( g \): Gravity of acceleration (m/s²)
- \( h \): Height of molten metal (m)
- \( I \): Electric current (A)
- \( J \): Electric current density (A/m²)
- \( k \): Constant (AT)
- \( L \): Length of channel (m)
- \( P \): Static pressure of molten metal (Pa)
- \( \rho \): Density of molten metal (kg/m³)

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