Level Meter for the Electromagnetic Continuous Casting of Steel Billet

Goohwa KIM, Hoyoung KIM, Kijang OH, Joonpyo PARK, Heetae JEONG and Eui-Wan LEE

Research Institute of Industrial Science and Technology (RIST), PO Box 135, Pohang, 790-600, Korea. E-mail: goohk@rist.re.kr
1) Department of Physics, Kyungpook National University, Deagu, Korea.

(Received on July 22, 2002; accepted in final form on September 19, 2002)

A level measuring system has been investigated to work with the electromagnetic continuous casting of steel billet, based on the principle of electromagnetic induction. The basic idea of the development is the distinction of the magnetic field measured in the mold into the effect of the applied one and the effect of the level variation. Several candidates of induction type magnetic probes were devised and examined. It was seen that the so-called global sensor was the proper one from the viewpoint of sensing range, resolution of the signal, and robustness to the external perturbation. The level of the melt was successfully calculated from the sensor output by employing the reference voltage for the set current in the power supply as a measure of the applied magnetic field. The use of the global sensor associated with the electronic device and the program showed that the resolution of the measurement was within ±0.2 mm, the dynamic range of sensing the level was 0–300 mm below the top of the mold under the electromagnetic field at 20 kHz. In its application to commercial scale electromagnetic continuous casting at a billet caster of POSCO works, it worked well with the existing control device in supplying the molten steel to the mold. Particularly, its accuracy and promptness was sufficient to control the level at the initial stage of casting.

KEY WORDS: electromagnetic continuous casting; metal; level measuring system; electromagnetic induction.

1. Introduction

In continuous casting of steel, the control of the melt level in the mold greatly affects the product quality and the casting operation itself. When the level is unstable, this not only results in a deterioration of product quality, but also leads to breakouts in the strand, which, if severe, may cause the casting work to stop. Therefore, in order to cast strands of sound quality and to run a stable casting operation, it is imperative to measure and control the melt level.

Various methods to measure the level of molten metal have been devised and applied to continuous casting process. Particularly, methods of using thermocouples and gamma rays have been used since the initial effort of continuous casting. In the 1980’s, a method based on electromagnetic induction was devised to enhance measurement accuracy and since then has been applied frequently in continuous casting.

Electromagnetic continuous casting (EMC) technology prevents the occurrence of casting defects on the surface and subsurface of cast pieces by using an alternating magnetic field to form a thin, uniform early-solidified shell. This is achieved by the electromagnetic force and Joule heat at the meniscus in the mold. EMC uses an inductor coil to generate the electromagnetic field in the mold, which causes a strong alternating magnetic field near the molten metal level. Therefore, it is not easy to employ existing level meters because either they interfere with the inductor coil spatially or the magnetic field near the level greatly affects the signal of the electromagnetic measuring sensor. Until now, reported methods of level measurement in EMC have been based on measuring the variations in the electric output load of the power supply connected to the inductor coil, i.e., the resonant frequency measurement method and the inductance measurement method. Although these methods provide excellent sensitivity in the region occupied by the inductor coil, they may be insensitive in areas outside of the coil region. On the other hand, for EMC using a pulsative alternating magnetic field, a level measurement method synchronized to the magnetic field has been devised and used. This method measures molten metal level only in the instant when power is not supplied to the inductor coil, using the existing eddy current sensor.

The objective of this study is to develop a level meter with a wide dynamic range for EMC application. The basic idea of the development is the distinction of the magnetic field measured in the mold between the effect of the applied one by the inductor coil and the effect of the level variation. Two kinds of induction type magnetic probes were devised and examined to characterize the effect of the arrangement and the measuring component of the magnetic field. Several parameters to represent the applied magnetic field by the inductor coil have been investigated to find an invariable parameter with respect to the variation of the melt level. The optimal sensor and the associated electronic devices were
appropriate for application to commercial electromagnetic continuous casting of steel billet at POSCO works.

2. Theoretical Background

Figure 1 shows the principle of the measurement of molten metal level using electromagnetic induction, which is comprised of an inductor coil, a conductor, and a magnetic sensor of induction coil type. The inductor coil, where alternating current is supplied from a power supply, generates a magnetic field \( B_0 \), and an electromotive force \( e \) described in the Eq. (1), which is generated in a conductor existing in the region affected by this magnetic field. This electromotive force forms an induced current \( I \) circuit, where the magnitude of the induced current is proportional to the electrical conductivity of the conductor by Ohm’s law.

\[
e = -\frac{d}{dt} \int_S B_0 \cdot \text{n} \, ds \quad \text{..............(1)}
\]

In Eq. (1), \( S \) is the area of the induced current circuit. The generated induced current flows in an opposite direction to the coil current as implied by the negative sign of the Eq. (1). Therefore, the direction of induced magnetic field \( B_i \) generated by the induced current \( I \) is also opposite to the applied magnetic field \( B_0 \), as indicated in Fig. 1.

Since the azimuthal component of the induced magnetic field is zero, there exist the components of radial direction \( B_{ir} \) and axial direction \( B_{iz} \), and they can be expressed as in the Eqs. (2)–(4).\(^{17}\)

\[
B_{ir} = B_0 \hat{r} + B_{iz} \hat{z} \quad \text{..................(2)}
\]

\[
B_{ir} = \mu_0 I \frac{2z}{r \sqrt{(a+r)^2+z^2}} \left[ -K(m)+\frac{a^2+r^2+z^2}{(a-r)^2+z^2} E(m) \right] \quad \text{..............(3)}
\]

\[
B_{iz} = \mu_0 I \frac{2z}{r \sqrt{(a+r)^2+z^2}} \left[ K(m)+\frac{a^2+r^2+z^2}{(a-r)^2+z^2} E(m) \right] \quad \text{..............(4)}
\]

In the above equation, \( \mu_0 \) is the magnetic permeability in vacuum, \( a \) is the radius in the current loop, \( r \) is the radial distance from the axis of the inductor coil, \( z \) is the axial distance from the surface of the conductor, and \( K(m) \) and \( E(m) \) are complete elliptical integrals of the first and second kind, respectively, for the coefficient \( m \) defined in the Eq. (5).

\[
m = 4ar \left[ (a+r)^2+z^2 \right]^{-1} \quad \text{...................(5)}
\]

Therefore, when the axial distance between the inductor coil and the conductor is changed for the given applied magnetic field, the induced current varies according to the Eq. (1) and the induced magnetic field also varies according to the Eqs. (3) and (4).

The induction coil type magnetic sensor, installed near the conductor and inductor coil as shown in Fig. 1, will measure the change of applied magnetic field and of induced magnetic field as voltage at the point where the sensor is located. The sensor output can be expressed by

\[
V = -\frac{d}{dt} \int_S (B_i + B_0) \cdot \text{n} \, ds \quad \text{..............(6)}
\]

where, the integration is conducted at the area of the induction coil type magnetic sensor. When the relative location between the inductor coil and the sensor are fixed and the coil current is constant, the applied magnetic field determined by the current passing the inductor coil (inductor coil current) is invariable, and the sensor output just includes the variation of the induced magnetic field. A proper calibration between the measured voltage and the level can give the location of the molten metal level. The conventional eddy current level sensor is based on this principle.

However, in the EMC process the current of the inductor coil is a variable quantity due to two reasons. One is the adjust to the intensity of the electromagnetic field and the other is the use of load-resonant power supply. When the level is changed, the sensor output includes both variations of the applied magnetic field and the induced magnetic field. Therefore, the level can be calculated only if the variation of the applied magnetic field can be eliminated from the measured value. In this work, an invariable quantity has been chosen among parameters of the power supply and employed as a measure of the applied magnetic field to extract the level information from the measured voltage of the induction type level sensor.

3. Experiments

The EMC mold is made of copper in a form of a square tubular shape. The inductor coil is about 85 mm in height and has been installed so that its center is positioned about 130 mm below the top of the mold. A load-resonant type of power supply with an electric capacity of 200 kW at 20 kHz was used to supply power to the inductor coil. The output parameters of power supply, for example voltage, current and frequency, were measured and analyzed to determine invariable quantities for the level variation. The inductor coil current was measured by the current monitor (Model-1423C, PEARSON ELECTRONICS, INC.). During the experiments, the geometry of the coil located after the capacitor box was fixed to maintain the inductance and coil resistance at the same values.

Two types of magnetic sensors were investigated to determine an appropriate configuration. The first one, labeled

---

**Fig. 1.** Schematic figure of the electromagnetic induction principle for the level sensor.
‘local sensor’, was devised to measure a local magnetic field at the mold periphery, and the other one, labeled ‘global sensor’, to measure an integrated value of the magnetic field within an area encompassed by the sensor. The local sensor was constructed by winding 0.5 mm diameter copper wire 80 times on a 5 mm diameter, 10 mm length ceramic rod. With the local sensor, the parallel and perpendicular components of the magnetic field to the mold axis were measured. The global sensor was constructed by winding 2 times with 5 mm copper wire, and it measured the parallel component of the magnetic field to the mold axis. With these two sensors, the effects of the sensor shape, the installation position, and the measuring components of the magnetic field were examined.

For the experiment and calibration, metal blocks called ‘cold charges’ were machined to simulate the molten metal and their temperature was maintained at constant value by water-cooling method. The cold charges of tin and stainless steel were used to demonstrate the variation of electric conductivity, which may occur from the temperature change of the molten metal.

An electronic device was fabricated to extract the melt level from the measured sensor signal. It included a band-pass filter, AC to DC converter, analog to digital converter, etc. For the application to the commercial billet caster, its output signal was modulated to the existing controller regulating the amount of the melt supply to the mold.

4. Results and Discussion

4.1. Characteristics of Level Sensors

4.1.1. Local Sensor and Global Sensor

The local sensor has been installed at the top of the mold and its axis was aligned to the measuring component of the magnetic field. Both components of perpendicular \( B_y \) and parallel \( B_x \) to the mold axis were measured. Figure 2 shows a typical result to the inductor coil current 1 000 A with the cold charge of stainless steel. In this paper, we defined the level as the position in the mold of the top surface of the cold charge from the top surface of the mold. When the output of a sensor shows one to one correspondence to the level, it basically can be employed as a level meter. Furthermore, large variations in sensor output to the level variation and big S/N ratio would be crucial for its performance. In Fig. 2, we can see the one to one correspondence in the range of 0–300 mm for both the perpendicular and parallel components. However, the signal variation was not large enough against the level variation in the range of 0–60 mm for the perpendicular component, and in the range of 100–300 mm for the parallel component. Moreover, since the local sensor measured the local magnetic field, its output was seen to be too sensitive to structures around the mold and to the arrangement of the sensor.

Figure 3 shows a typical output of the global sensor with the same condition of Fig. 2, like 1 000 A of the inductor coil current and the cold charge of stainless steel. Position A and B indicate the locations of the sensor at the top of the mold and just above the inductor coil, respectively. Both cases show one to one correspondence in the range of 0–300 mm. In case A, variations of the output were large in the whole range of 0–300 mm compared to case B.

Meanwhile, even though the structure around the mold was changed during the experiments, it was observed that the trend of the output signal remained quite stable. Based on these observations, the global sensor installed at the top of the mold was chosen as the level sensor for EMC.

4.1.2. Effect of the Electric Property

Since the electrical conductivity of the charge is related to the induced current as described in the theoretical background, it may affect the sensor output. Particularly, since the temperature variation of the melt in the mold results in the change of the electric conductivity of the melt, the measured level would be shifted according to the variation of the melt temperature.

In order to ascertain the effect of the electric conductivity and skin depth, three kinds of cold charges were examined: tin block, stainless steel block, and a 2.5 mm thick stainless steel shell. Typical outputs of the global sensor for each case were compared in Fig. 4, where the coil current was 1 000 A, and the gain of the electronic device was modulated to have its maximum value below 5 V. When the cold charge level was located far from the inductor coil (over 400 mm below the mold top), the sensor could not recognize it. This output merely indicates the effect of the applied magnetic field and thus, the values were identical for all three charges. Above this level, the output shows the effect of the electric properties of the charges. Since the electrical conductivity of tin \((7.8 \times 10^6 \text{ S/m})\) is larger than that
of stainless steel (1.4×10⁶ S/m) at room temperature, the induced magnetic field of tin is bigger than that of stainless steel and eventually its sensor output is smaller by 16% at the level of 100 mm. In case of shell and block of stainless steel, the amount of the induced magnetic field of the block was larger than that of the shell because the thickness of the shell was smaller than the so-called skin depth of the stainless steel (about 3 mm at room temperature). Therefore, the sensor output for the stainless steel shell was highest among the three. From these observations, the level meter should be calibrated for the real melt in order to be applied to the casting operation and particularly, the effect of the temperature variation of the melt may also be considered in the calibration.

4.2. Construction and Application of Level Meter

4.2.1. Output Parameters of the Power Supply

In case of the load-resonant type power supply, the electric parameters of the inductor coil such as voltage, current, and frequency vary with the changes of the melt level, as typically shown in Fig. 5. This was observed in the following way: the coil current was set without the charge inside the mold, and then the charge was inserted into the mold up to 0 mm level and moved down without any control of the power supply. The set values were 530 A, 410 V, and 18.62 kHz. When the charge top was located at the top of the mold, the measurement was 584 A, 428 V, and 19.85 kHz. As the charge top moved down, all the values decreased to those of the initially set values, which was expected because the utmost of low level is identical to the mold without the charge. The important fact is the change of the current according to the level variation. It means that the level variation results in the change of the applied magnetic field, as described in the theoretical background, and that the measurement of the level sensor should be corrected to exclude the effect of the variation of the applied magnetic field originated from the level change. In this experiment, several parameters of the power supply, such as the currents and the voltages of an inverter and a DC power supply part, were examined. From these examined parameters, a “reference voltage” to set the current of the inductor coil, which is a voltage in the DC part of the power supply to control the inverter’s output current, was found invariable regardless of variations in the level, as shown in Fig. 6. Therefore, this voltage of the power supply has been employed to represent the applied magnetic field in the process of level conversion from the sensor output.

4.2.2. Level Conversion from the Sensor Output

Figure 7 has illustrated the relation of the level and the sensor output with various inductor coil currents that were set in an empty mold. Figure 4 shows the global sensor output for various cold charges. Figure 5 shows the electric parameters of the inductor coil according to the charge level. Figure 6 shows the level dependence of the sensor output, the inductor coil current, and the reference voltage for set current. Figure 7 shows the global sensor outputs versus the charge level for various coil currents.
tions showed that the following equation was proper to describe the relation between the level \((L)\) and the sensor output \((V)\).

\[
V = A - (A - B)e^{-kL}\text{........................(7)}
\]

In this equation, \(A\) is the sensor output when the level is located far enough from the inductor coil and sensor, \(B\) is the sensor output value when the level is at the top of the mold \((L = 0)\), and \(D\) and \(k\) are coefficients representing the configuration and location of the sensor. Since \(A\) and \(B\) have linear dependence upon a reference voltage for the set current, the level can be converted from the sensor output by employing the reference voltage.

4.2.3. Application to EMC

An electronic module to calculate the level was composed and the above coefficients were evaluated and put into the program. The output of this module was modulated to the existing controller regulating the amount of the melt supply to the mold in order to apply the electromagnetic casting of steel billet at POSCO works. Figure 8 shows a result of the level measurement by dipping the stainless strip (1 mm thick and 10 mm wide) during the casting experiment. It shows a difference between the actual molten steel level \((L_{\text{steel}})\) and the value \((L_{\text{meas}})\) estimated from Eq. (7). The difference originated from the electrical conductivity between the molten steel and stainless steel of cold charge. To correct the level calculated from the Eq. (7) with the actual level, the linear interpolation in the level range of 50 to 150 mm was conducted and the program adopted.

Figure 9 shows a typical example of level measurement showing the initial 60 s of electromagnetic continuous casting. In this casting, a set level of molten steel was 100 mm below the top of the mold and the dummy bar was installed at 210 mm below the top of the mold. It indicates that the developed level meter was working well enough at the starting period of the casting. The minute fluctuation seen after 20 s was the effect of the mold oscillation since the inductor coil and the mold were joined together. The level drop at 20 s indicates a slip of the dummy bar occurred at this time and the level fluctuated instantaneously. The inserted figure in Fig. 9 is the trend of molten steel level during whole period of casting, which showed that the level was accurately measured when accounting for the variation of inductor coil current. The resolution of the level meter was \(\pm 0.2\) mm, but the level was adjusted to a tolerance of \(\pm 4\) mm by the accuracy of level controller.

5. Conclusion

The level meter of the molten metal was devised to apply the electromagnetic continuous casting of steel billet based on the principle of electromagnetic induction. The use of cold charges to simulate the molten metal was effective in devising the level sensor and in analyzing the experimental results. The difference between the cold charge and the molten metal has been corrected with the actual values. The so-called global sensor was found to be better than the local sensor in considering dynamic range, S/N ratio, and stability to the external perturbation. The level of the melt was successfully calculated from the sensor output by employing the reference voltage for the set current in the power supply as a measure of the applied magnetic field. The use of the global sensor associated with the electronic device and the program showed that the resolution of the measurement was within \(\pm 0.2\) mm, the dynamic range of sensing the level was 0–300 mm below the top of the mold under the electromagnetic field at 20 kHz. In its application to commercial scale continuous casting at a billet caster of POSCO works, it worked well with the existing control device in supplying the molten steel to the mold. Particularly, its accuracy and promptness was adequate to control the level at the initial stage of casting.

REFERENCES

1) S. Kumar, I. V. Samarasekera and J. K. Brimacombe: Iron Steelmaker, 24 (1997), No. 6, 53.
2) K. Kawakami, T. Kitagawa and Y. Hiratani: Tetsu-to-Hagané, 67 (1981), 1190.
3) K. Kawakami: Tetsu-to-Hagané, 74 (1988), 1204.
4) T. Yamada, S. Ando and Y. Kawase: US-Patent 4647854, (1987).
5) I. Sumi, K. Sassa and S. Asai: Tetsu-to-Hagané, 78 (1992), 447.
6) T. Li, S. Nagaya, K. Sassa and S. Asai: Metall. Mater. Trans. B, 26B (1995), 353.
7) S. Itoyama, H. Tozawa, T. Mochida and K. Kurokawa: ISIJ Int., 38 (1998), 461.
8) H. Nakata, M. Kokita and K. Ebina: Tetsu-to-Hagané, 80 (1994), 711.
9) S. Furuhashi, M. Yoshida and T. Tanaka: Tetsu-to-Hagané, 84
10) T. Toh, E. Takeuchi, M. Hojo, H. Kawai and S. Matsumura: *ISIJ Int.*, 37 (1997), 1112.

11) K. Ayata, K. Miyazawa, H. Uesugi, E. Takeuchi, H. Yamana and N. Beesho: *CAMP-ISIJ*, 10 (1997), 828.

12) J. P. Park, H. Jeong, D. J. Sim and H. Kim: *J. Korea Inst. Met. Mater.*, 36 (1998), 1598.

13) H. Kim, J. P. Park, H. Jeong and J. Kim: *ISIJ Int.*, 42 (2002), 171.

14) P. G. Friedmann, F. N. Patris and A. W. Tomalesky: US-Patent 4446562, (1984).

15) Japanese Patent Laid-open Publication No. Heisei 6-122056, (1994).

16) H. Shimakage et al.: *CAMP-ISIJ*, 13 (2000), 814.

17) J. D. Jackson: Classical Electrodynamics, 2nd Ed., John Wiley & Sons Publication, New York, (1975), 177.