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DEVELOPMENT OF IMMERSION TYPE MOLTEN STEEL LEVELMETER

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ABSTRACT

Molten steel level information of ladle is very important for process control in steelmaking process. At secondary refining process , measuring lance and snokel have to keep constant thier depth from molten steel surface. But, there is much slag on the molten steel surface. Besides, not only the thickness of slag is varied with refining condition, but also molten steel level is largely affected by firebrick errosion. Then, optical measuring method and/or by human eyes cannot detect true molten steel surface, but slag surface. This slag thickness is 300mm at maximum, then huge diameter eddy current sensor will be needed if that type sensor is applied. In addition to, cooling system is necessary because the molten steel and slag temperature is very high. This is not practically. To solve this problem, immersion type levelmeter is developed. This sensor is made up from primary and secondary cylindrical coils. High frequency current is applied to primary coil. Electro-motive force from secondary coil is measured,which is varied with molten steel level. This complete set is installed within stainless steel long capsule and attached to top of lance. This sensor is immersed into molten steel bath of ladle or tundish with protection of expendable paper sleeve.

1.INTRODUCTION

Pig iron made from ore through blast furnace. This material is very hard but fragily, because it includes much impurities such as carbon,sillicon,etc. In order to remove such impurities, oxygen gas jet is added to molten pig iron in LD converter. Then, pig iron is changed to moletn steel by oxidization of impurities in this refining process. After that, molten steel are solidified through ingot casting or continuous casting process. Recentry, some secondary refining processes are applied between LD converter and casting process, in order to adjust the composition and to compensate the temperature of molten steel in ladle. These secondary refining processes are classfied into some types. One is the type which has degassing (remove Hydrogen, Nitrogen,etc), composition adjustment and heating functions , such as RH (RH Type vacuum degassing equipment). Another type has not degassing function but others are same as before, for example LF(Ladle furnace), CAS(Composition adjustment by sealed Argon bubbling Type secondary refining process) ,etc.

Like this, secondary refining process is very important part in steelmaking process for decision of products quality. Because, there are last stage of composition adjusting and temperature compensating. Therefore, temperature measurment and composition analysis is very important. Among them, it is very important whether measured value is typical of ladle or not,as same as accuracy of measured value. Ladle of used in our works is about 4 meters tall and it's diameter is about 3 meters. Therefore, temperature and composition of molten steel is slightly different according to it's position in ladle.This is the reason why we think much of the depth of measuring point in ladle. In RH and CAS, degassing and/or composition adjustment are carried out with snokel immersing into molten steel bath. In RH (shown in Figure 1), if position of snokel from molten steel surface is upper than set point value, then slag or mixture of slag and steel come into degassing vessel. Then exhaust dact is clogged by suctioned slag and we have to stop the

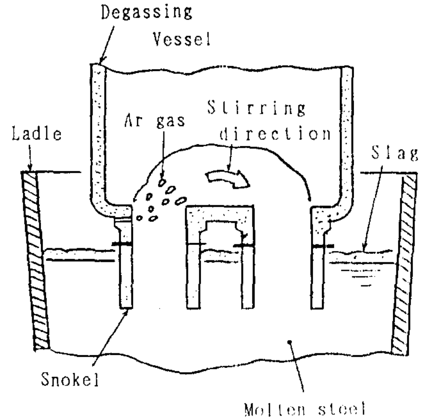

Figure 1.Outline of molten steel circulation at RH

operation. Besides, molten steel of ladle is contaminate by impurities from slag disintegration. In CAS, these troubles are same as above.

True molten steel level is varied with firebrick errosion. For example, level changes by firebrick errosion is about 200mm. On the other hand, slag volume is changed by operation conditions, then slag thickness is changed from 50mm to 300mm. So, slag surface position range comes about 500mm. By optical measuring method and/or human eyes, we can detect slag surface position, not true molten steel surface.

2. MEASURING PLINCIPLE

(1). Comparison with other methods

Conventional methods of non-contact type distance measurement are ultrasonic type, optical reflection type, eddy current type or electromagnetic induction type. Environment temperature avobe the slag or molten steel is very high and besides, it is differect with position and changed quickly. Ultrasonic type is not suitable for this measurement because of it's measured value is strongly affected with medium temperature.

Eddy current type is adquately for dusty environment, but large diameter sensor is needed for long range of about 500mm. Compared with other methods(Table 1), immersion type levelmeter has many advantages as follows.

a. Measuring range is variable by changing coil length.
b. Good accuracy.
c. Economical cost.
d. Robustness because of heatproof design and no movable part.
e. Wide application is expected because of small diameter.

Table 1. Comparison with other method

Type	Immersion	Eddy current	Optical
Range	○	△	×
Accuracy	○	○	×
Continuous measurement	×	○	○
Cost	○	△	○
Robustness	○	△	×
Dimension	Small	Large	Not so small
Composition	Simple	Cooling system needed	Complex

(2). Principle of Immersion Type Levelmeter [2]

This levelmeter is consist of two parts. One is signal processing unit, another is sensor head. Signal processing unit excites primary coil with AC current and, detectes the signal from secondary coil. Sensor head is made of primary, secondary coil, bobbin and within stainless protect tube. Material of coil is sort of copper and nickel alloy, then, the coil is able to use for high temperature of 1200℃ without cooling.

In order to simulate the output signal of secondary coil, simple model is introduced as shown in Figure 2.

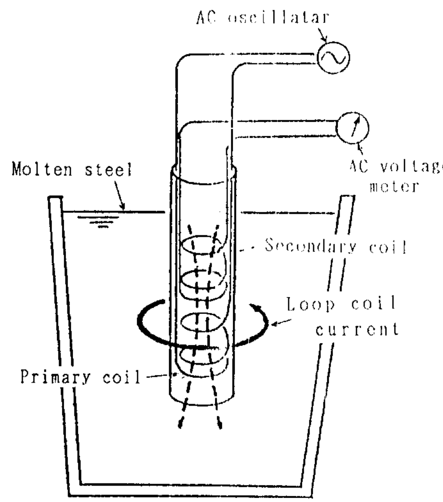

Figure 2. Principle of level detecion

We suppose that there is imaginary one turn coil corresponding to molten steel level. This imaginary coil is named loop coil. Primary coil exciting with AC current, magnetic flux ϕ_0 is generated from coil. This magnetic flux and loop coil cross each other, and following voltage is induced in loop coil.

$$E = \frac{d}{dt}(\phi_0) \quad [V]$$
$$= \frac{d}{dt}(B_0 S) \quad [V]$$
$$= \frac{d}{dt}\left(\frac{\mu_0 \pi r^2 N I}{L}\right) \quad [V] \qquad (1)$$

where, B_0 : density of magnetic flux by primary coil
S : cross sectional area of primary coil
r : radius of primary coil
μ_0: magnetic permeability
N : turn of primary coil
I : primary coil current
L : primary coil length

By this induced voltage E, current I which is proportionally to conductivity of loop coil is generated in loop coil. Direction of magnetic field by this current is opposite to the direction of magnetic field by primary coil. Therefore, magnetic flux of primary coil is changed by loop coil current.

a. Output signal from secondary coil in model

To simplify the model, we assume followings.

*1. Conductivity of molten steel is infinity.

*2. All other materials are insulators except for molten steel, primary coil and secondary coil.

And difinitions are as follows.

*1. Primary and secondary coil length is L

*2. Turn of primary and secondary coil are N and M

*3. Exciting current of primary coil is $I_0 \exp\{i\omega t\}$.

*4. Magnetic flux of primary coil is ϕ_c.

In the secondary coil is open and without molten steel, voltage of secondary coil will be calculated as follows.

$$e_2 = -\frac{d}{dt}\phi$$

$$= -\frac{i\omega\pi_0 r_c^2 NM}{L} I_0 e^{i\omega t} \qquad (2)$$

where, ω : $2\pi f$

f : frequency of exite current

r_c : radius of primary and secondary coil

i : $\sqrt{-1}$

b. In the case of with molten steel around the sensor

In the coils are immersed into molten steel, magnetic flux is shown in next equation.

$$\phi_c + \phi_L = 0 \qquad (3)$$

: ϕ_L is magnetic flux by loop coil current.

: r_L is average radius of loop coil current in molten steel

: ϕ is the magnetic flux acrossing to secondary coil.

Considering the molten steel level ℓ, the ϕ is followings.

$$\phi = \phi_c + \left(\frac{r_c}{r_L}\right)^2 \phi_L \cdot \frac{\ell}{L} \qquad (4)$$

: is variable from 0 to L.

Then, secondary coil voltage is ;

$$e_2 = -\frac{d}{dt}(\phi)$$

$$= -\frac{d}{dt}\left\{\phi_c + \frac{\ell}{L}\left(\frac{r_c}{r_L}\right)^2 \phi_L\right\} \qquad (5)$$

$$= -\frac{i\omega\mu_0\pi r_c^2 NM}{L}\left\{1 - \frac{\ell}{L}\left(\frac{r_c}{r_L}\right)^2\right\} I_0 e^{i\omega t} \qquad (6)$$

In equation (6), second term shows the effect of molten steel level.

When $(r_c/r_L)^2$ is close to 1, output signal e_2 shows maximum change and we can expect the S/N ratio rise up. In the second term (concerned in molten steel) of equation (6), we have to compensate r_L according to temperature because of assumption conductivity of molten steel is infinity.

3. BASIC APPROACH

Developement procedure is as follows.

(1) Fundamental Experiments

At laboratory, relation among the material, size and turn of coil, frequency and output were studied at cold condition.

(2) Experiment by molten Alminium

Using electric induction furnace and molten Alminium, hot model experiment was carried out.

(3) Application for molten steel

At CAS refining process, measuring system was installed and applied for operation.

(1) Fundamental Experiment

a. Relation between frequency and output

It is well known that output signal shows the maximum value for the characteristic frequency. Table 2 shows the material and size of sample used in fundamental experiments.

Table 2. Material and size of each sample

	JIS symbol	Size[mm]
Al	ADC12	ϕ50×t3.0
SUS	SUS304TP	ϕ60×t8.7
SS	STS38	ϕ60×t8.7

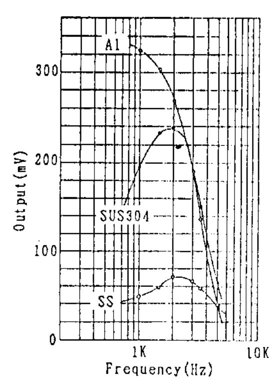

Figure 3. Ralation between output and frequency

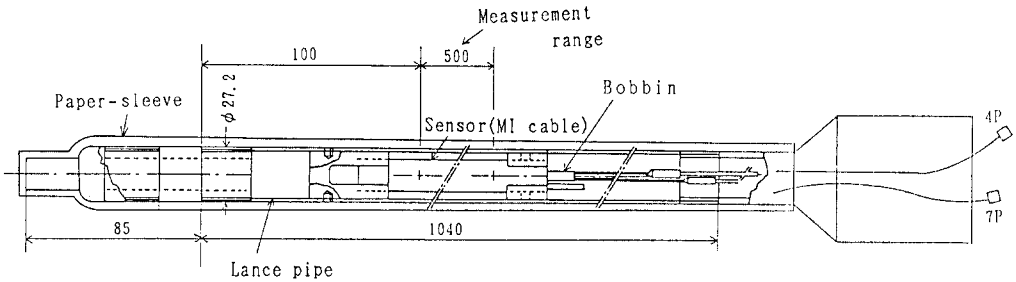

Figure 4. Cross section of Immersion Type Levelmeter

Experimental results are shown in Figure 3. Output means the change of output signal when each sample (pipe) inserts 300mm into sensor head. SUS304TP is similar to molten steel in point of magnetic permeability and conductivity in these samples. Then, the frequency of 2 KHz is applied for this levelmeter.

b. Size effect of materials

In order to simulate the diffrence of average radius of loop coil(molten steel), some diffrent diameter Alminium pipes are applied for this experiment and relation to output signal is studied. Experimental results are shown in Figure 5. The output signal change at 300mm insertion and ratio of average radius of loop coil are shown in Table 3. Good agreement with S/S(Al) and r_L/r_L(Al), it is confirmed that equation(6) is properly.

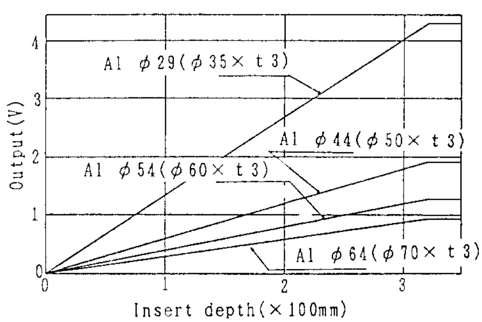

Figure 5. Relation between output and diameter of pipes

Table 3. Output signal and average radius

	Output =S[V]	r_L [mm]	$R=(1/r_L)^2$	S/S(A)	R/R(A)
φ29(A)	4.0	32	9.766	1.0	1.0
φ44(B)	1.8	47	4.527	0.45	0.46
φ54(C)	1.2	57	3.078	0.30	0.32

c. Effect of Electromagnetic parameter

Output signal is largely influenced with electro and magnetic parameter of measured materials. Because that absolute value of loop coil current is changed with electrical conductivity and magnetic permeability.

In this experiment, three kinds of metal pipes are applied. Electrical conductivity and magnetic permeability μ_s of each sample are shown in Table 4. Figure 6 is the results of experiment. According to

Table 4. Conductivity and magnetic permeability

	Conductivity(σ)	μ_s
ADC12	0.125	1
SUS304TP	0.0143	1.002
STS38	0.0714	750

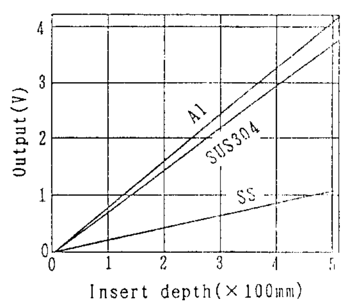

Figure 6. Relation between output and materials

electromagnetic parameter of materials, penetration depth of loop coil current is varied. Penetration depth is in proportion to $(1/\mu_s\sigma)^{1/n}$ and then effective loop coil radius is function of this term. Table 5 shows ratio of $(1/\mu_s\sigma)^{1/4}$. Output of STS38 (SS) is about 0.22 of ADC12(Al). It's ratio from Figure 6 agrees with $(1/\mu_s\sigma)^{1/4}$ very much. On the other hand, ratio of SUS304TP and ACD12 from Figure 6 is quite diffrent from Table 5. But, thickness of SUS304TP and ADC12 is different such as 8.7mm and

3.0mm. Difference of output between ADC12 and SUS304TP can be explained by compensation of diameter such as

$$\sqrt{\frac{d(SUS)}{d(Al)}} = \sqrt{\frac{8.7}{3.0}} = 1.7$$

Table 5. Comparison of coeficient

	d= $(1/\mu_s\sigma)^{1/4}$	d/d(Al)
ADC12	1.682	1.0
SUS304TP	2.891	1.719
STS38	0.3696	0.220

(2) Experiment by molten Alminium

We can merely get the chance of experiment using molten steel at works. Then, off-line test at hot condition by molten Alminium is executed before ladle test. Experimental conditions are as follows.

a. Material : Alminium[JIS A1100(Al-0.12C)]
b. Temperature : 700 ℃
c. Immersed depth : 115 mm
d. Sensor gain : 1～5 V / 0～500 mm
e. *Sensor protection tube : Paper sleeve*
(applying expendable type Temperaturemeasuring probe.)

Recording chart is shown in Figure 7. Read out data from chart is about 116 mm and it means good accuracy.

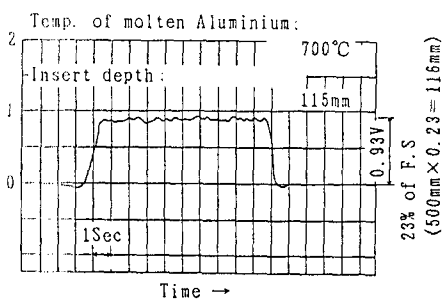

Figure 7. Output signal by molten Aluminium

(3) Application for molten steel

Hot condition experiment using steel is carried out at Ladle Furnace(LF). The sensor head is installed within temperature measuring lance. Experiment conditions are as follows.

a. Steel grade : Carbon steel
b. Temperature : about 1550 ℃
c. Immersed depth : 5 levels(50, 150, 250, 350 and 450mm)
d. Sensor gain : As same as the experiment by molten Alminium.
e. Sensor protection tube : As same as the experiment by molten Alminium

Table 6 shows main specifications of this immersion type levelmeter. Upper limit of operation temperature is about 1200℃ without cooling and protection tube. But if paper sleeve protection is apllied, this sensor can used in molten steel over 1700℃ during 20 seconds.

Table 6. Specification of immersion type levelmeter

Length of levelmeter	1265 mm
Outside diameter	φ27.2
Upper limit temperature	1200 ℃
Measurement range	500 mm
accuracy (At off-line test)	±2 mm
Excite frequency	2 KHz
Output signal	4～20 mA

Figure 8 shows the recording chart of level and temperature of molten steel of ladle at 450mm immersed depth. Figure 9 is the results of by changing immersed depth. Essentially, output signal have to be in proportion to immersed depth. But, actual data shows the tendency of saturating and fluctuation is rather large. Recording chart of level from figure 8 includes large ripple. This ripple is caused by molten steel splushing because of humidity of paper sleeve.

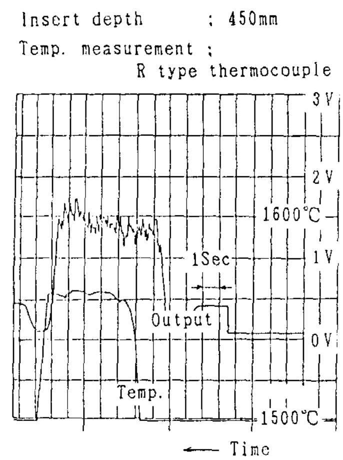

Figure 8. Output signal by molten steel
(Paper sleeve)

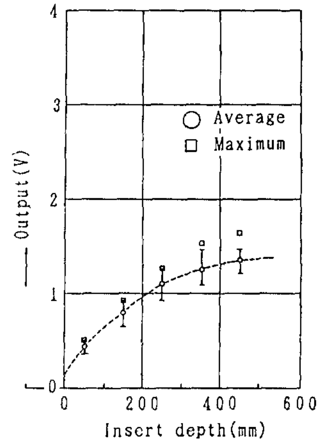

Figure 9. Test results by molten steel (Paper sleeve)

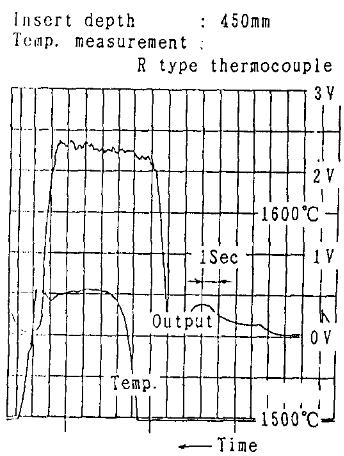

Figure 10. Output signal by non-splush type probe

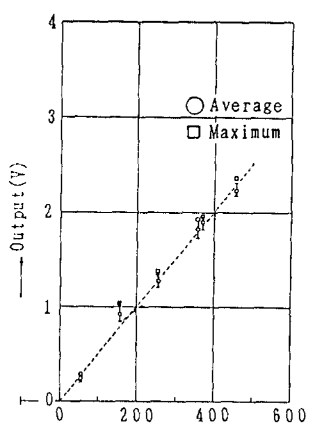

Figure 11. Test results by non-splush probe

Splushing breaks the loop coil partly, then effective thickness of loop coil is changed. To minimize this ripple, non-splush type paper sleeve is applied for protection tube. Figure 10 shows the output signal waveform by non-splush type. The ripple decreases and waveform becomes stable and smooth. After that, accuracy, linearity and repeatability are improved very much. These results are shown in Figure 11.

(4) Operation at CAS

After many experiments as mentioned above, this levelmeter system is installed and operated at CAS process. Figure 12 shows the schematic diagram of application at CAS. Sensor head is included within temperature and sampling lance. This lance is operated by motor and it's position is detected by pulse generator. Absolute position of true molten steel surface is calculated from lance position and sensor signal by signal processing unit. This system is useful for CAS operation.

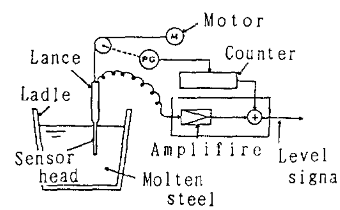

Figure 12. Application for CAS

4. CONCLUSION

Immersion type levelmeter for molten steel is developed succeessfully. It's features are as follows;

(1) Measuring range is very wide, for example 500 mm.
(2) Accuracy is less than 10 mm.
(3) It's operation is able to use over 1700℃ high temperature.
(4) Small diameter(ϕ16) is available.

Wide applications are expected such as follows.

a. Molten iron level at main trough or runner in blast furnace.
b. Molten iron level in torpedo car
c. Molten steel level at LD converter by sub-lance.
d. Molten steel at Tundish in continuous casting.

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