Eddy current method for steel billet mould level control

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Abstract. The relevant issue of metal level control in a mould of continuous casting machine (CCM) is improving the measurement accuracy when adding slag powders in a mould. The main disadvantage of the widely used radiometric metal level control devices (MLCDs) is the dependence of the output signal on the amount of slag in a mould. Eddy current (EC) sensor for metal level control is not sensitive to the slag. It detects metal level indirectly by temperature of copper mould wall, which is in contact with liquid metal. As a consequence, eddy current MLCD speed of response is limited to the time constant of thermal transient processes in a mould wall, which is insufficient to modern steel industry. This paper deals with a mould CCM metal level control method by means of the EC sensor based on signal detection from the liquid metal through a copper mould wall. The direct method provides required signal speed of response of eddy current MLCD in the case of steel casting with the slag.

1. Introduction
Continuous casting of steel is widely used in steel industries. Liquid metal from a ladle pours into mould. The working part of the mould is a bottomless copper vessel of rectangular or round cross-section, where liquid metal is continuously fed from the ladle. Metal partly solidifies in the water-cooled mould and, at the same time, withdrawals to the secondary cooling zone where the billet finally solidifies. Metal quality and capacity CCM are related to the metal level stability. A level decrease causes appearance of subsurface defects such as discontinuities, and a level increase leads to non-metallic inclusions and slag entrapments [1]. The level instability can lead to harming of solidified billet shell and its breakout. Thus, MLCD should meet the high requirements for accuracy and speed of response [2].

Eddy current and radiometric non-destructive methods are mostly used for metal level determination. The radiometric MLCD is characterized by simple and reliable design and high speed of response. Nevertheless, its output signal depends not only on liquid metal level in a mould, but also on amount of slag. Slag as a powder is added to the steel meniscus where it flows down into the gap between mould and solidified billet shell. The slag layer provides lubrication between primary solidified shell and a copper wall mould [3]. The amount of slag affects the level of measurement result, which is reflected in the accuracy of the MLCD and billet quality. The eddy current method does not have this drawback, because slag is a non-conductive material, so eddy currents do not induce in it.

The issue of eddy current method is that control of the metal level in a billet-casting machine with cross-section to 200 mm is possible only when the sensor is placed on the side as shown in figure 1.
The way the sensor is situated, metal level control can be carried out only through a copper wall of 15-20 mm, which screens the electromagnetic excitation field.

One more condition that makes metal level control with EC sensor difficult is heating a copper wall with liquid metal to a temperature of 150°C on the outer surface [4]. In this way, the liquid metal with the electrical conductivity $\sigma = 0.75$ MS/m is screened by the copper wall with a gradient of the electrical conductivity $\sigma$ from 58 to 40 MS/m due to heating. The fact that the wall heating is related to the metal level is used for the metal level determination [5,6], but speed of response of this method is limited to the time constant of thermal transient processes in a copper wall. The time constant is insufficient to provide the required speed of response [2]. It is necessary to control the pouring of the mould by the signal from the metal, not by the temperature in the wall. The problem has not been solved before, despite the relevance and commercial demand.

2. Methods
The steel level determination by the signal from the liquid metal involves dealing a number of problems. The first problem is to detect a low signal from the metal against the signal from the copper wall heat and the sensor drift. The wall heat signal is 20-50 times greater than the liquid metal signal in the excitation frequency range $f$ of 40 to 100 Hz. The second problem is to provide a self-calibration of the EC sensor. It is needed because of the variety of shapes and sizes of a mould and other casting factors.

The self-calibrating problem has been solved by using an arrayed EC sensor. The arrayed EC sensor consists of one elongated excitation coil and receiver coils arranged in a row. The advantage of such configuration is the fact that the calibration dependence “voltage – steel level” is not required since the output signal of the sensor is a distribution of receiver coil signals along the sensor length. The signal distribution is shown in figure 2.

When the metal meniscus moves, the distribution moves along with it. The level determination is limited to measuring the position of the feature point on the signal distribution. The main informative parameter is the relative offset of the feature point, and an absolute signal value no longer plays a defining role. The arrayed EC sensor has all the properties of the conventional one in terms of approaches to reduce the effect of interfering factors [7]. For the direct steel level control method it is necessary to use several approaches for reducing the effect of interfering factors.

Figure 1. EC sensor placed on a mould: 1 – copper walls, 2 – liquid metal, 3 – EC sensor, 4 – mould body, 5 - cooling jacket.
A surface arrayed EC sensor is selected as a universal one to the testing object form. According to Ansys Electromagnetic simulation results, it has been determined the best ratio between the width of excitation coil and the excitation frequency. The model geometry of EC sensor embedded into the mould with the cross-section of 180×180 mm and wall thickness of 15 mm is shown in figure 3(a). Figure 3(b) shows the simulated temperature distribution in a mould volume due to the liquid metal pouring.

Figure 2. The distribution of receiver coils signals along an arrayed EC sensor.

Figure 3. (a) The model of the arrayed EC sensor on the mould: 1 – copper mould, 2 – liquid metal, 3 – excitation coil, 4 – receiver coils. (b) Temperature distribution in the mould volume.
As Ansys simulation shows, amplitude ratio of 1:15 in favor to the wall heat signal is achieved at the excitation frequency of up to 100 Hz and the width of excitation coil of 100 mm. This ratio can provide to reduce the effect of interfering factors. It depends on the shape of signal plot in the complex plane.

Figure 4(a) shows the EC sensor signal plot in the complex plane from changing of level metal Z with the wall heating influence at the excitation frequency of 40 Hz. The voltage in the receiver coils for cold empty mould corresponds to zero in the complex plane. The verification of the finite element model has been carried out as part of an industrial experiment while a mould pouring with the liquid steel. As the experiment shows (figure 4(b)), the EC sensor signals plots from the metal level Z are too curvilinear to use approaches to reduce the effect of interfering factors in the complex plane.

In order to detect the signal from the metal level against the signal from the copper wall heat it has been decided to apply techniques for the spectral analysis. The liquid metal surface is unstable. There are always the surface oscillations with amplitude of a few mm. The oscillations lead to the changing of voltage in the receiver coils placed near to the steel meniscus, but there are no oscillations in the remote coils. The liquid metal is very fluid, the meniscus oscillations occur with a period less than 1 s. This differs from the receiver voltage changing caused by the moving of the wall temperature distribution. As the simulation results have shown, the metal level changing with a period less than 1 s does not lead to significant heat of the mould wall because of the inertia of the thermal transient processes. Therefore, the separating of the metal signal and heat signal is performed in the frequency domain: a signal at a frequency more than 2 Hz is a signal from the meniscus oscillations. The metal level is determined by the coordinate of the signal distribution maximum obtained by means of the arrayed EC sensor.

The efficiency of proposed method is proved by the industrial experiment. During the experiment, output responses of EC and radiometric sensor are compared. The radiometric sensor response is accepted as a true one. The comparison criteria is the time needed for the appearance of the EC output signal to become an equal to the radiometric sensor output on the intervals of rapid changing of the metal level. Figure 5 shows that the speed response of EC sensor and radiometric sensor are equal on the intervals of rapid steel level changing.
3. Results and Discussion

The control method of the metal level in a CCM mould based on the detection EC signal from the meniscus oscillation meets the requirements of the response MLCD speed. The proposed method allows reducing the effect of the wall heat through the detection useful information in the frequency domain and increasing the response speed of EC sensor. At the same time, a number of potentially interfering factors have not been considered in the present research. Among these is the electromagnetic stirring of the liquid phase of continuously cast billet. The electromagnetic stirring is usually used for high-quality steel casting in order to improve quality of billet surface and subsurface zone. The approaches for reducing the electromagnetic stirring effect on the EC sensor are described in [8]. These approaches are not effective for direct steel level control because the signal from metal is low. The copper wall of the mould and other conductive elements, placed near the EC sensor can oscillate. This is another interfering factor for direct level control method because these oscillations can result in the signal changing similar to the signal from the metal surface oscillations.

According to the experiment results, there are time intervals of less than 1 s without the metal surface oscillations in the EC signal. The nature of this effect has not been studied yet, therefore, one should use the indirect level control method based on the wall temperature measurement at these intervals.

4. Conclusion

The EC sensor for direct metal level control in a mould has been developed as a result of the experiment and numerical simulation. The method based on the analysis of receiver coils signals in the frequency domain has been proposed for detection information about the meniscus level in a mould. The spectrum component that equals to the frequency of steel meniscus oscillations is determined as a useful signal. Then the metal level is calculated by the coordinate of the signal distribution maximum obtained by means of the arrayed EC sensor. The efficiency of proposed method is proved by the industrial experiment. The study concludes that there is range of issues for further research to improve and develop the proposed method.

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