Measuring and Controlling System of Mold Flux Thickness for Continuous Casting of Slabs

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ABSTRACT

For continuous casting, it is well known that mold flux provides crucial functions such as insulation for liquid steel, lubrication and heat transfer for solidified shell in the mold. This means being able to measure and control mold flux thickness is in high demand for no break-out operation and high surface quality of slabs. In this paper, a newly developed measuring and controlling system using laser sensors and combined with optical cameras for constant target thickness of mold flux has been introduced. For plant trials, two horizontally swinging systems were installed over the 2,000mm wide mold. Thanks to the independently moving systems, the flux feeding speed was controlled to account for the different mold flux consumption ratio for each side of the mold. The consumption amount of mold flux has been calculated and evaluated using the embedded algorithm with real time base for various casting conditions such as casting width and speed.

Keywords: Continuous casting, Mold flux, Thickness measurement, Automatic feeding

INTRODUCTION

For the continuous casting, mold flux provides several key roles such as lubrication for solidified steel, insulation for meniscus, absorption of inclusions and control of heat transfer from solidified shell to the mold plate for breakout-free operation and high surface quality of slabs (Fig. 1). For these purposes, molten steel in the mold has to be covered by constant thickness of mold slag and powder. However, during casting, mold flux thickness varies since the flux consumption rate is changing with casting speed, casting width, steel grade and liquid steel temperature.

Mold flux consumption rate is one of the most representative parameters among flux’s physical properties because it could affect the safe casting operation and the quality of products. But, it is not easy to measure and quantify the rate. In addition, for slab casting, the consumption rate for each half side of the mold may be different due to asymmetric steel flow in the mold. In which case, the mold powder feeding rate should be adjusted for each side of the mold. Specifically, a side of mold with hotter meniscus would consume more mold flux than the other side, so more powder should be fed to compensate it.

For the beginning and closing stages of continuous casting, the mold powder feeding rate should also be adjusted from the normal casting period. At the beginning stage of casting, the feeding rate should be higher to rapidly obtain the target thickness of mold flux. On the contrary, at the closing stage of casting, mold flux thickness should be reduced, otherwise too much unmelted powder remains on the tail of the slab which could disturb sound solidification of the tail strand.
In order to maintain the constant mold flux thickness during whole casting stage, flux thickness should be measured and feeding rate should be controlled for each casting variables. Also it is essential to measure and control mold flux thickness independently for both sides of the mold to cope with different flux consumption caused by asymmetric steel flow in the mold.

Figure 1. Functions of mold flux for continuous casting.

CONCEPT DESIGN

The new multi-crystal design by SMS Concast has been developed to measure both the real position of steel meniscus and the thickness of mold powder with a single instrument using radiometric solution. However, this instrument should be installed under the mold cover and near the copper mold. It is useful for billet or bloom casters.\(^1\)

The Radio-Frequency(RF) sensor has also been developed to continuously measure both the liquid steel level and mold flux power layer thickness on the basis of a physical resonance phenomenon of the electromagnetic waves in semi closed cavity. However, two radio antennas need to be installed on the copper mold as a transmitter and receiver of signal, so revision of mold is unavoidable.\(^2\)

Ergolines has developed the system using a laser scanner and a camera; a blue laser line is projected on the mold flux surface and recorded by a camera. The system is integrated directly into the powder diffuser, combining automated mold powder feeding with a non-invasive installation and the plant trial was successfully carried out.\(^3\) However, this system was developed for billet casting, so the detecting area is not wide enough for slab casting. Also, the system was installed on the mold cover using a magnetic fastener so that it could make only a thin laser line on the surface of mold flux.

Three different types of systems seem suitable for billet or bloom casters. However, for the slab caster which has a wide mold and an electromagnetic current level sensor, a new concept is necessary for measuring mold flux thickness. Fig. 2 shows continuous casting facilities including a tundish, a tundish car, a sliding gate system, a SEN (Submerged Entry Nozzle), a mold, a mold cover, an ECLM (Electromagnetic Current Level Meter) and a mold flux feeder for slabs. As shown in Fig. 2, the space between the tundish bottom and the mold cover is very narrow (\(\leq 250\)mm), so sensor size should be considered.

Fig. 3 shows the close view of mold and mold flux surface. When mold flux is burning by heat from molten steel, red flames and dust are always generated so that sensor protectable housing is necessary for protection. In the middle of the mold, a SEN is located so that the radiation heat from the SEN and flame near the SEN should be considered when designing the instrument. In addition, the ECLM’s location at the right side of mold should be taken into account.

Figure 2. Continuous casting facilities near the tundish and casting mold
Figure 3. Mold flux feeding and its flame

Fig. 4 shows schematic diagrams of the mold size and mold flux thickness profile from each view. Mold size is 1,000~2,000mmW x 250mmH (Fig 4 (a)). A single feeding tube for mold flux moves horizontally to cover whole mold flux’s top surface. This feeding tube moves between the tundish bottom and mold top as shown in Fig. 2 and Fig. 3. As shown in Fig.4 (c), mold flux thickness is different on each side of mold due to asymmetric flow in the mold, so making measuring sensor necessary for both sides of the mold. In order to measure the surface profile of mold flux for wide mold, a scanning facility is essential to cover the whole surface of mold flux. Also, sensors should be installed above the mold and mold flux to measure the mold flux thickness.

Various sensing systems were reviewed and tested to select the optimum sensor for detecting the mold flux surface. Sensors and their performances such as near-infrared laser scanner, structured light scanner, ToF 3D camera, line laser+3D camera, and line laser + pinhole camera are introduced in Table 1.
A lab scale test was carried out using the near-infrared scanner. The resolution of the scanner was very high, but the size was too big and heavy to install in the small space over the casting mold. A structured laser type sensor was tested at the pilot continuous caster after the lab scale test. Detecting mold flux was possible when the flux powder was not burned. However, there was some difficulty in detecting the surface of mold flux because of the red flames generated when the flux was burning. 3D camera using ToF (Time of Flight) concept has an advantage in terms of a wider detection area of 400mm, but this area is still not wide enough to detect the 1,000mm width of a half mold. It has a resolution problem as well.

The laser-line triangulation method combined with a camera was tested using lab scale equipment. Fig. 5 shows the test equipment and test result using this combination of a 3D camera and a line laser. For scanning the surface of the mold flux top surface, a set of a moving table and a tray containing flux powder was used. A green and a blue line laser were tested to compare performances. The out-power of laser was 200mW. The wave length of the blue line laser was 445nm. For the green laser it was 550nm. When mold flux was burning, serious noise was detected for the green laser while any noise was not found for the blue line laser. This is because the wave length of the green laser is very close to that of the red flame, 625~740nm. Although the combination of a blue line laser and a 3D camera showed excellent resolution even for burning flux and an image processor was imbedded in the 3D camera, the size of the camera is not small enough to install in the narrow space of 250mm between a tundish and a mold.
A pinhole camera lighter than a 3D camera was tested in combination with a blue line laser. A 2D camera was also tested to compare the performance with the pinhole camera. For displaying and monitoring, a separate image processor was used. Fig. 6 shows the test result. The resolution is high enough to detect burning mold flux surface using both the pinhole camera and the 2D camera. Thanks to the image processor, a 2D surface profile is able to be converted to a 3D image. The temperature above the burning mold flux is around 400°C. The pinhole camera has the advantage of enduring this high temperature.

By the result of a series of reviews and lab scale experiments, the combination of a blue line laser and pinhole camera was selected as the sensor unit. This sensor unit needs housing for protection from the hot and dusty environment caused by burning mold flux powder over the molten steel in the mold. The sensor housing containing a camera and a laser should swing horizontally and scan to detect the position of whole surface of mold flux.

![Image](Figure 6. Lab scale test using the combination of a pinhole camera and a blue line laser.)

Based on this design concept, the mold flux feeder and its profile measuring system was drawn. As shown in Fig. 7 (a), the measuring system is composed of dual sensor arms, moving systems, a control panel and HMI for operation. The sensor arms, moving system and control panel are installed on the mold flux feeder while a computer including HMI is set up in the casting operation room. The feeding and measuring systems are remotely and automatically controlled using the HMI. Fig. 7(b) shows the layout of a mold flux feeder, a profile measuring system and the casting machines.

![Image](Figure 7. Schematic view of the mold flux feeder and profile measuring system)

The sensor arms including sensor housing are rotating and moving forward/backward using servo-motors. The rotation frequency of the feeding screw in the feeding tube is linked and controlled with the flux thickness data measured by the sensors. The feeder tube swings horizontally at the almost same height of the thickness sensors. To avoid the collision of the sensor unit with the moving feeder tube, each sensor unit is scheduled to swing on the opposite side of the feeder tube with the help of the PLC (Programmable Logic Controller) logic for moving system. For example, when the feeder tube is moving on the left side of mold, only the right side sensor arm is reacting to measure the mold flux thickness.
Fig. 8 describes the sensor arm and its moving system. It is composed of a sensor housing, sensor arm, a moving system including a guide actuator, a swing axis, a gear box and a motor. A pinhole camera, a dual laser and a proximity sensor are set up in the housing. The housing is cooled by air blowing. Air curtains are attached at the bottom outlet of the housing to protect the lens and laser sensor from the hot dust. A proximity sensor is needed to prevent the collision with the SEN and ECLM.

![Sensor arm and its moving system](image)

**Figure 8.** Measuring sensor housing and its moving system.

Fig. 9 shows the dual laser applied for this measuring system. Both the profile data of mold flux near the SEN and the narrow face corner of the mold are important. Even though sensors are protected by the housing and cooling air, coming close to the hot SEN is so risky that a minimum 100mm distance is required to endure the radiation heat from the SEN. In order to measure the profile of mold flux near both the SEN and narrow face of the mold, two lasers are needed.

In addition, one of the lasers should be inclined because a vertically installed laser cannot reach close enough to the SEN as shown in Fig. 9, so it is not recommended. However, this inclined laser cannot detect the mold flux near the narrow face mold because of the disturbance from mold top. The surface of mold flux locates below the top of the mold plate by around 50–100mm. A dead zone was formed around 100mm due to the disturbance of the mold top.

![Measuring range using the single laser sensor and a camera](image)

**Figure 9.** Measuring range using the single laser sensor and a camera.

A vertical laser is added to resolve this problem. Fig. 9 and Fig. 10 explain how the dual lasers can reduce the dead zone. When laser No.1 arrives at position ①, thickness starts to be measured because the camera can see the laser line for the first time as shown in Fig. 9. Soon laser No. 2 arrives at position ② and the camera detects laser No.2 so that the thickness data displays together with laser No. 1 line which has already arrived at position ③. In this way, the dead zone could be reduced dramatically to less than 10mm.
Fig. 11 describes how to convert the measured surface of mold flux to infer the thickness. In order to measure the surface position more precisely, a groove at the wide side of the mold plate is selected as a base line. The distance from the groove to the surface of mold flux detected using the sensor unit is “b”. “a” is the distance from the groove of the mold plate to the meniscus of molten steel. The height of molten steel is always uniform with the help of the ECLM. The thickness of mold flux “c” is “a-b”. So the thickness of mold flux is defined as that of whole mold flux including slag, sintered and powder layers.

**Figures 10 and 11**

**EXPERIMENTS and RESULTS**

Several off-line experiments and plant trials have been carried out after making the measuring system and assembling them to the mold flux feeder. Before the plant trial, the mold flux thickness measuring system was calibrated using precisely machined standard samples made of steel. Fig. 12 shows the assembled sensors and a wooden mock-up mold for pre-test. Calibration was conducted using the mock-up mold and the steel samples.
As shown in Fig. 13, four different thickness samples - 5mm, 10mm, 15mm and 20mm - were used. They are located on the specific position of a 10mm thick base steel plate in the mock-up mold as shown in Fig. 13 (a). Fig. 13 (b) shows the results after scanning and measuring the height of samples using the measuring system. Error range is analyzed as 0.2~0.8mm, under 1mm. These results are quite acceptable to apply for measuring the mold flux thickness.

The mold flux thickness data are transmitted to a PLC program for controlling the rotation frequency of feeding screw. Feeding rate of mold flux is controlled with the screw's rotating frequency. A simple test was conducted to calibrate the feeding rate. Fig. 14 indicates the relationship between the feeding screw frequency and feeding rate. Feeding rate linearly increases with increasing screw frequency. The equation is induced to $y = 0.102 x - 0.0493$ with $y =$ feeding rate, $x = $ screw frequency. This equation is very accurate with $R^2=0.9993$. Using this equation the feeding amount and consumption rate of mold flux can be obtained.
After successful lab and pre-tests, several plant trials were implemented for the slab continuous casting machine. Fig. 15 shows a photograph taken above the casing mold. At the right side of the mold, a sensor unit is moving from the narrow face to the SEN. Two blue laser lines are detecting the surface of mold flux. The right side sensor unit has to be stopped near the ECLM to avoid the collision with the help of the proximity sensor. On the left side of mold, the feeding tube is moving and feeding mold flux powder.

Fig. 16 shows the variation of mold flux thickness during casting. At the initial stage of casting, mold flux was manually fed so that the flux thickness was lower than the target thickness (60mm) by 20mm. After automatic flux thickness measuring and flux feeding had started, flux powder was fed with maximum feeding rate to rapidly fill up to the target thickness. Thanks to the control system, target thicknesses for both sides were satisfied. The variation was less than 10mm ($\pm$ 5mm) for whole casting period except the initial stage of manual feeding.
Fig. 17 shows the mold flux feeding time and feeding rate. As shown in Fig 17 (a), at the front casting period, the feeding rate for the left side of mold was higher than the right side. As the casting width begins to change in the middle of the casting period, the feeding rate begins to change as well, converging to almost the same rate for both sides of the mold. Towards the end of the casting period, the feeding rate showed opposite trend. The right side feeding rate was higher than the left side of the mold. This result was caused by asymmetric flow of molten steel in the mold. When the molten steel flows to the left side more rapidly than right side, the meniscus would be hotter so that the viscosity of mold slag is changed to be lower. By the effect of lower viscosity of flux, infiltration of flux into the gap between steel shell and mold plate increases. Consequently, higher feeding rate is necessary to fill up the mold flux thickness for the left side of mold. This result is schematically explained in Fig. 4.

With the help of the model equation and the PLC program, feeding time required for one cycle of each side of the mold was controlled and recorded so that the feeding amount of mold flux for each cycle was calculated. If the casting weight of slab was known, mold flux consumption rate was calculated as shown in Fig. 17 (b). The consumption rate decreased with narrow casting width.

![Figure 17](image)

CONCLUSIONS

An automatic mold flux thickness measuring and controlling system has been developed and tested for slab continuous casting. The system was composed of a sensor unit, two horizontally swinging arms, a control panel and HMI. A blue line laser and a combined optical camera adapted to measure the thickness of mold flux in the mold. To scan the top surface of mold flux, two horizontally moving arms attached with the sensor units were applied for the 2,000mm wide mold.
Thanks to the independently controllable moving and sensing systems, mold flux thicknesses for each side of the mold were detected as different when asymmetric flow was generated in the mold. Feeding rate was successfully controlled using the automated system so that uniform thickness of mold flux was maintained during the whole casting period in spite of varying casting conditions such as casting width, casting speed and molten steel temperature. With the help of the system, mold flux consuming rate was calculated for various casting conditions and mold flux physical properties.

REFERENCES