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A study on electromagnetic transducers for the continuous casting process

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ABSTRACT

Purpose: One of the areas in the continuous casting process that has not been definitively instrumented is a method for reliably locating the part of a continuously cast strand that remains liquid for a period after the outer portion has solidified. Therefore, this paper is focused on the measurement of the solidification point made by a through transmission technique based on the relationship between ultrasonic speed and measured temperature using an EMAT sensor.

Design/methodology/approach: An EMAT (Electro Magnetic Acoustic Transducer) has been designed and fabricated with an elongated spiral coil and a permanent magnetic core. Al75×75mm and 75×100mm simulators with 2, 4, 8, 16 and 32 mm holes were produced and demonstrated that the location of the final solidification point during the continuous casting process can be monitored using a 1.0 MHz frequency.

Findings: The solidification point in a continuous casting bloom could be detected through a series of tests with the use of a fabricated probe and the amplitude extent of ultrasonic wave decreases as the hole diameter of the simulators increases. Furthermore, through a test of lift-off effect it was found that the extent of amplitude decreases as lift-off increases, thus one of the most important factors for a field application.

Research limitations/implications: As cutting speed and cutting length can be predicted from a miniaturization of the sensor and construction of an on-line system for a field installation, a considerable amount of time and energy can be saved by reducing mistake ratio and curtailing unnecessary processes.

Originality/value: The measured ultrasonic waves allow for prediction of the casting speed necessary to correctly locate the liquid core and thereby maximize the benefits of soft reduction and the productivity of the machine.

Keywords: Analysis and modeling; Continuous casting process; Electromagnetic transducers; Solidification point; Measured temperature

1. Introduction

For slab molding in steel works, molten steel in aligned ladles is generally poured through a tundish into a mold. As various sensors and control units are connected to the mold and lower tundish roll, the continuous casting process is controlled automatically. In this process, the solidification point has a major effect on the quality of products. However, usually the solidification point will be predicted based on inaccurate results calculated from a computer simulation. The early stage of research using an EMAT sensor has been concentrated not only on detecting defects, but also as a fundamental study on the ultrasonic duplex of each mode. Studies on defect-detection in welds have been carried out by NIST (National Institute of Standards and Technology), etc. IZFP and the Rockwell

International Science Center (RISC) [1] have developed studies on ultrasonic duplex and defect-detection in long tubes. In addition, at Iowa State University and Osaka University an EMAT sensor was applied to measure residual stresses and plastic anisotropy [2-5]. In comparison with a piezoelectric transducer, an EMAT sensor can transfer electromagnetic energy to mechanical vibration energy. However, it is hard to get the S/N (Signal/Noise) ratio to a level equivalent to the piezoelectric transducer since it has low conversion efficiency. Also, technology was developed in order to measure process speed and the damper of ultrasonic waves. Using sound resonance defined by the relationship between ultrasonic waves in a testing unit and its thickness, equipment was developed to considerably cover most downsides of the EMAT, namely, low conversion efficiency and S/N ratio [6-10]. Furthermore, in the U.S., Japan and Europe studies on the use of ultrasonic testing on materials with high temperatures are in progress. Nippon Steel, Mitsubishi and Hitachi are especially interested in the development of a defect-inspection system of steel material at the temperature of 1000°C. Also, Kawasaki Steel Corp. has been conducting a series of experiments to verify that the EMMA (Electro Magnetic Metal Acoustics) system can detect the solidification point in the continuous casting process [11]. In order to achieve this objective, experiments under various conditions in the steel mill have been carried out using an EMAT in order to locate the exact position of the fluid core. In addition, the measurement of slab thickness and the detection of solidification point were verified utilizing a rivet method, in other words, inserting some rivets into molten slabs. However, waveform derived from the EMMA system signal was found only when rivets were in solid form. The need for an increased signal and noise reduction was due to the low S/N ratio of the EMAT. Recently, BHP, in order to predict the cut length of bloom and enhance productivity, has conducted a series of experiments with a 400×630mm bloom utilizing an EMMA system developed in Sweden [12]. The system was installed at the withdrawal roll (where the bloom is completely solidified) for prediction of torch cutting speed and for comparison with results as predicted by a computer simulation. It was concluded that the system could detect the solidification point, and was useful for on-line control, but it was unknown whether it was a success or not.

Therefore, this paper is focused on the measurement of the solidification point made by a through transmission technique based on the relationship between ultrasonic speed and measured temperature using an EMAT sensor. Also, the possibilities for practical application were reviewed by constructing a reproduction of the system for laboratory experiment.

2. The principle of EMAT sensor

The principle of EMAT has been constantly studied and developed since 1931. Strength is generated from inside an electric conductor by the application of a magnetic field and current induction [13-14]. The conductor is a continuous casting slab, and the surface layer is vibrated at ultrasonic frequency by generating force into the slab. It is used to induce equivalent surface current force on the surface layer of the slab.

Ultrasonic waves such as the Rayleigh Wave, longitudinal wave and transverse wave selected for use in the slab can be generated by changing not only the configuration of the current force, but also the type, size and location of the electromagnet and current coil in a coil. Receiving waves can be detected as the electromagnet ultrasonic wave operates like a transmitter as explained above. Movement of the ultrasonic wave on the surface layer generates current inducing electromotive force in the coil of the receiver under the magnetic field. Coil electromotive force depends on an ultrasonic wave formed under the receiver. As the speed of the ultrasonic wave depends on the temperature, the time it takes for the ultrasonic force to move from the transmitter to the receiver is a function of the temperature scope inside the metal. Use of an EMAT sensor in measuring the average temperature is possible by measuring this transmission time. Shear wave is the most suitable method in detecting the solidification point and measuring the average temperature in the continuous casting process since it does not pass through solid or liquid. Significantly, this signal is distinctive in that it is not transmitted in the transition zone of a molten metal between solid and liquid (called the mush zone) if the liquid has no viscosity [15]. Since there are possibilities that a probe can be damaged at high temperatures, accurate design and production should be required. There are two ways to control this. The first way is to circulate cooling water to allow it to cool down through compulsion. The second way is to utilize tungsten, molybdenum and platinum coils in an electromagnet core with a high curie point. In this study, the first method was employed using a probe to measure the inner temperature in a real condition, and a composite study, when necessary, was applied by introducing the second method.

The EMAT sensor is composed of an Elongated Spiral (ES) forming an eddy current and a permanent magnetic core generating a static magnetic field. ES coils of the sensor which were employed to measure solidification points, measure 0.08mm, 0.2mm and 0.45mm respectively. Probes for receiving and transmitting were placed together in one unit and included 4 permanent magnets measuring 5 ×5 ×10mm. Each coil was employed with magnetic cores measuring 0.08mm and 0.45mm wound around it forty three times. Considering the structure of the furnace and electromagnetic acoustic code, a probe was produced for transmission to perform from one side and receiving from the other; thus, a through transmission method. As EMAT transmits a high frequency signal to an elongated spiral coil, which then delivers an electromagnetic wave to a simulator, it can generate ultrasonic wave even when it is not in contact with the simulator. However, it can enhance its signal when the two are in close contact at a maximum extent.

To perform an EMAT sensor, a gated amplifier for giving burst-type force to the eddy current-generating coil and a receiver for filtering and amplification of signal received are required. A RAM1000 from RITEC Corp. was employed as a receiving apparatus and a gated amplifier. A RAM1000 can provide strong force and sufficient frequency to the EMAT by tentatively adjusting the size and time of burst. Furthermore, it can considerably heighten the S/N signal since it receives signal in a super heterodyne method. In order to identify whether the solidification point can be detected using an EMAT sensor, the Al 75 ×75mm and 75 ×100mm simulators were machined with 2mm, 4mm, 8mm, 16mm and 32mm holes in diameter respectively. Fig.1. shows the simulators produced.

To verify the operation of the EMAT sensor, fix two micrometers of a detection sensor on the center of both sides of the EMAT for measuring directivity. For accurate fixing, make marks on the probe and simulators in advance, and then store the verified signal in the memory of a digital oscilloscope by operating all the duplex units for electromagnetic acoustic waves. Next, transmit the reaching time, amplitude and measured result of signal frequency stored in the oscilloscope to a PC and plot the stored result. The EMAT was tested under various conditions through a full range of frequencies.

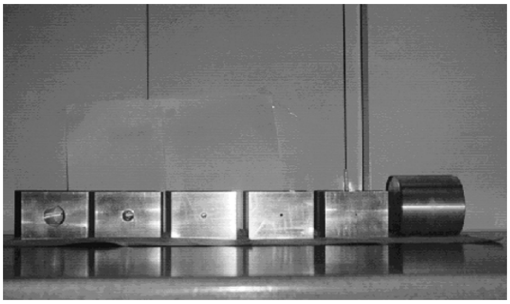

Fig. 1. Photograph of a specimen used for experiment

3. Results and discussion

In this experiment, the EMAT generates ultrasonic waves by oscillating between 2MHz and 0.2MHz with an interval of 0.2MHz. Fig.2. shows that it generates ultrasonic wave by using a high frequency of 1MHz and acquires an ultrasonic wave signal by passing through the Al 75 ×100mm simulator. The first high frequency signal (A) is high frequency noise received by the EMAT, and the second signal (B) is the ultrasonic wave which is the signal received when passing through the simulator. (C) and (D) are the round signals reflected from the surface of the Al simulator. The performance of the EMAT depends on which coil thickness is selected. If a coil of a suitable thickness is selected with consideration of electric resistance and sensitivity etc., the electric signal (high frequency pulse) can be easily transmitted into a dynamic signal (ultrasonic wave) and vice versa. In most cases, the elongated spiral coil for transmission is thicker than that for receiving in an EMAT.

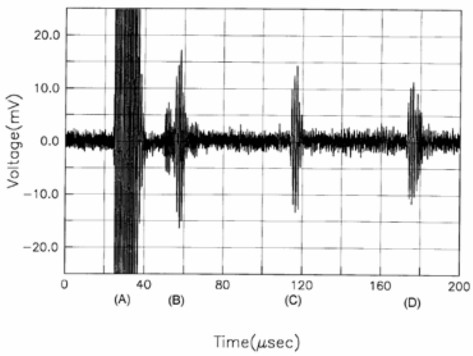

Fig. 2. Change of voltage versus time

The simulator is a fundamental part of the ultrasonic wave-generating equipment employed by the EMAT sensor. That is, the extent of ultrasonic wave generation depends upon the characteristics of the simulator (thickness, quality, electromagnetic). In this respect, a test of the lift-off effect is necessary in calculating the generation of ultrasonic waves. Fig. from 3 to 4 show the experimental results of lift-off effect using 1.0MHz; sender fixed & receiver lift-off and receiver fixed & sender lift-off.

Fig.3. displays the result by passing 1.0MHz frequency through a simulator while transmitting set fixing and receiver lift-off. It can be recognized that the amplitude goes down as the lift-off effect goes up. The experimental result under a condition of receiver fixing and transmitting set lift-off by using a frequency of 1.0MHz is represented in Fig.4. According to Fig.4., electric interaction is high as lift-off is low, whereas electromagnetic interaction considerably decreases in a high sphere of lift-off, which leads amplitude to decrease. This signifies that electromagnetic interaction decreases in a high sphere of lift-off. Therefore, it is very important to note that the EMAT sensor is useful for measuring things such as lift-off. (I still can’t determine the true meaning of this sentence).

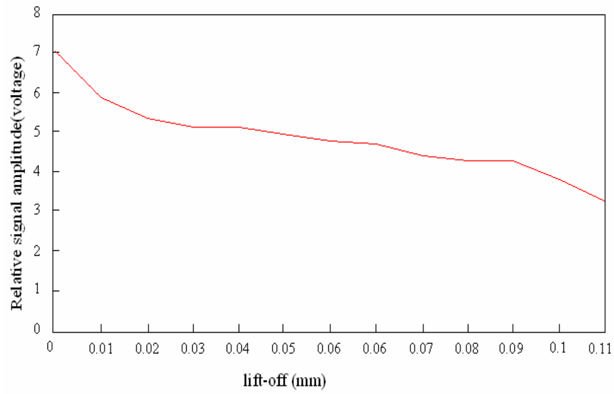

Fig. 3. Signal amplitude of sender fixed and receiver lift-off for 1MHz

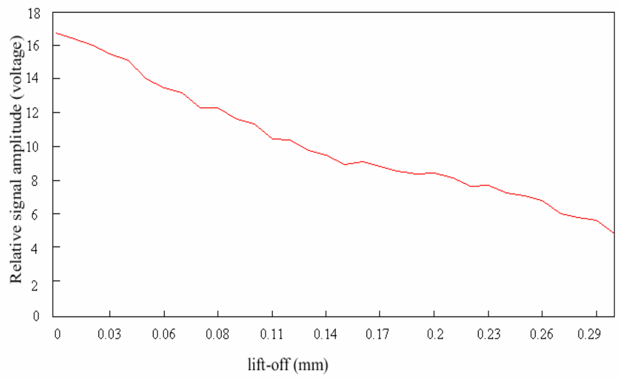

Fig. 4. Signal amplitude of receiver fixed andsender lift-off for 1MHz

4. Conclusions

The development and procedure for detecting the solidification point in a continuous casting process with an EMAT sensor was presented. Considering the structure of the continuous casting process and the required electromagnetic wave mode, a Lorentz-force probe was developed using an elongated spiral coil and permanent magnetic core for transmission on one side and receiving on the other side in a through transmission method. In order to study the logicality of technique development for solidification point detection in a continuous casting bloom, Al75×75mm and 75 ×100mm simulators with 2, 4, 8, 16 and 32mm holes in diameter were produced to measure the change of ultrasonic wave signal with a 1.0MHz frequency. It was found that amplitude extent decreases as the hole diameter of the simulators increases. Furthermore, through a test of lift-off effect it was found that the extent of amplitude decreases as lift-off increases, thus one of the most important factors for a field application.

In conclusion, it was identified that the solidification point in a continuous casting bloom could be detected through a series of tests with the use of a fabricated probe. As cutting speed and cutting length can be predicted from a miniaturization of the sensor and construction of an on-line system for a field installation, a considerable amount of time and energy can be saved by reducing mistake ratio and curtailing unnecessary processes.

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