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Quality control for the continuous casting process using electromagnetic transducers

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ABSTRACT

Purpose: The continuous casting process is controlled automatically because various sensors and control units are connected to the mold and lower tundish roll. The solidification point in the process has a major factor on the quality of products, but the point has been predicted depending on the inaccurate calculated results from a computer simulation until now. Therefore, the objective of this paper is to develop the EMAT sensors for the measurement of the solidification point made by a through transmission technique based on the relationship between ultrasonic speed and measured temperature.

Design/methodology/approach: 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 to measure 0.08mm, 0.2mm and 0.45mm as solidification points were employed respectively. Probes for receiving and transmitting which included 4 permanent magnets measuring 5 ×5 ×10mm, were placed together in one unit. Each coil was used to magnetic cores measuring 0.08mm and 0.45mm wound around it forty three times. The AI 75 ×75mm and 75 ×100mm simulators to identify whether the solidification point can be detected using an EMAT sensor, were machined with 2mm, 4mm, 8mm, 16mm and 32mm holes in diameter respectively.

Findings: The electromagnetic interaction decreases in a high sphere of lift-off. Solidification point in a continuous casting processing 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, the sensor developed is useful for measuring things such as lift-off.

Research limitations/implications: A considerable amount of time and energy for miniaturization of the sensor and construction of an on-line system for a field installation should be saved by reducing mistake ratio and curtailing unnecessary processes.

Originality/value: The solidification point in a continuous casting processing could be detected through a series of tests with the use of the developed EMAT sensor.

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

1. Introduction

In the steel industry, a lot of techniques and skilled operations are required to manufacture high-quality products, promote safe operation and maintain the efficiency of equipment. Molten steel in aligned ladles for slab molding in steel works is generally poured through a tundish into a mold. The continuous casting process is controlled automatically because various sensors and control units are connected to the mold and lower tundish roll. Even if the solidification point in this process has a major effect on the quality of products, the solidification point has been predicted depending on the inaccurate calculated results from a computer simulation. The early studies on applications of an EMAT sensor have been concentrated detecting defects as a fundamental study on the ultrasonic duplex of each mode. Not only NIST (National Institute of Standards and Technology) and IZFP have carried out defect-detection in welds, but also the Rockwell International Science Center (RISC) [11] has developed studies on ultrasonic duplex and defect-detection in long tubes. Furthermore, an EMAT sensor at Iowa State University and Osaka University was applied to measure residual stresses and plastic anisotropy [9,10,17,20]. The sensor in comparison with a piezoelectric transducer can transfer electromagnetic energy to mechanical vibration energy. Therefore, it is quite difficult to get the S/N (Signal/Noise) ratio to equivalent level of the the piezoelectric transducer since it has low conversion efficiency. Also, 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 has developed to considerably cover most downsides of the EMAT, namely, low conversion efficiency and S/N ratio [1,2,3,4,15,16,18,19,22,24,26]. Recently studies on the use of ultrasonic testing on materials with high temperatures in the U.S., Japan and Europe have been in progress. Regarding the continuous casting process, not only 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, but 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 [12]. The experiments under various conditions in the steel mill to achieve this objective have been carried out using an EMAT to locate the exact position of the fluid core [7,8,13,14,21,25,27]. In addition, the measurement of slab thickness and the detection of solidification point were verified utilizing a rivet method. However, waveform derived from the EMMA system signal was found only when rivets were in solid form, but an increased signal and noise reduction was required because of the low S/N ratio of the EMAT. BHP 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.[1] The system employed was installed at the withdrawal roll (where the bloom is completely solidified) to predict torch cutting speed and for comparison with results as predicted by a computer simulation. The system could be detected the solidification point, and was useful for on-line control.

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

2. Structure of EMAT sensor

Since 1931, the theory and applications of EMAT ensor have been constantly studied. Strength is generated from inside an electric conductor by the application of a magnetic field and current induction. The conductor is a continuous casting slab, and the surface layer is vibrated at ultrasonic frequency by generating force into the slab to induce equivalent surface current force on the surface layer of the slab [6,23].

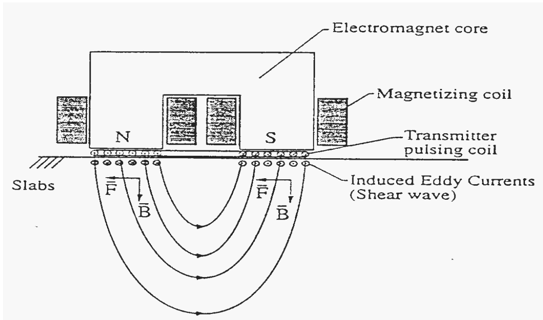


Fig. 1. Basic principle of EMAT echo sensor

Generated surface current and magnetic fields create electromagnetic force on the surface layer of the slab. Force is reflected and generates waves through the slab as shown in Figure 1. The EMAT compounds the magnetic field B with the eddy current *i* into the formation of the Lorentz force F.

$$F = i \times B$$

Ultrasonic waves such as the Rayleigh Wave, longitudinal wave and transverse wave selected for use in the slab can be generated by changing the configuration of the current force, 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 as a transmitter. 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. Because the speed of the ultrasonic wave depends on the temperature, it takes for the ultrasonic force to move from the transmitter to the receiver as a function of the temperature scope inside the metal. An EMAT sensor employed in measuring the average temperature is also 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 whether it does pass through solid or liquid. Significantly, this signal is distinctive so 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 [28]. Since there are possibilities that a probe can be damaged at high temperatures, accurate design and production should be required. To solve this problem, circulation of cooling water to allow it to cool down through compulsion, or utilization of tungsten, molybdenum and platinum coils in an electromagnet core with a high curie point schould be selected. In this study, the first method was employed using a probe to measure the inner temperature in a real condition, but 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 to measure 0.08mm, 0.2mm and 0.45mm solidification points, were respectively employed. Probes for receiving and transmitting which included 4 permanent magnets measuring 5 ×5 ×10mm, were placed together in one unit. Each coil was used to magnetic cores measuring 0.08mm and 0.45mm wound around it forty three times. A probe considering the structure of the furnace and electromagnetic acoustic code was produced for transmission to perform from one side and receiving from the other; thus, a through transmission method. When 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 if 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.

3. Performance test for 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 to perform an EMAT sensor are required. A RAM1000 from RITEC employed as a receiving apparatus and a gated amplifier, 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. The AI 75 ×75mm and 75 ×100mm simulators to identify whether the solidification point can be detected using an EMAT sensor, were machined with 2mm, 4mm, 8mm, 16mm and 32mm holes in diameter respectively. Figure 2. shows the simulators produced.

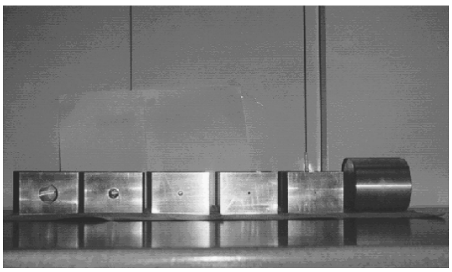


Fig. 2. Photograph of a specimen used for experiment

Two micrometers of a detection sensor on the center of both sides of the EMAT for measuring directivity to verify the operation of the EMAT sensor was fixed. 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. After that, 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.

4. Results and discussion

4.1. Performance test of EMAT

The EMAT in this experiment, generates ultrasonic waves by oscillating between 2MHz and 0.2MHz with an interval of 0.2MHz. Figure 3. represents 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 that 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.

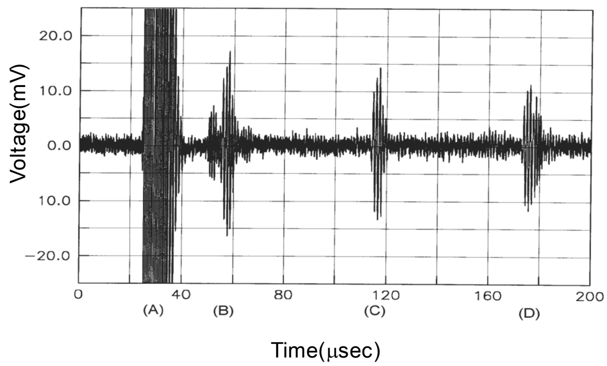


Fig. 3. Change of voltage versus time

4.2. The test on effects of lift-off

The simulator as a fundamental part of the ultrasonic wave-generating equipment was employed by the EMAT sensor. 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 very important to calculate the generation of ultrasonic waves. Figures from 4 to 5 show the experimental results of lift-off effect using

1.0MHz; sender fixed & receiver lift-off and receiver fixed & sender lift-off.

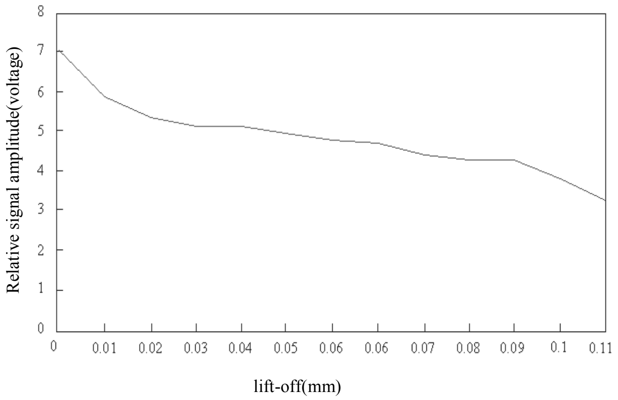


Fig. 4. Signal amplitude of sender fixed and receiver lift-off for 1MHz

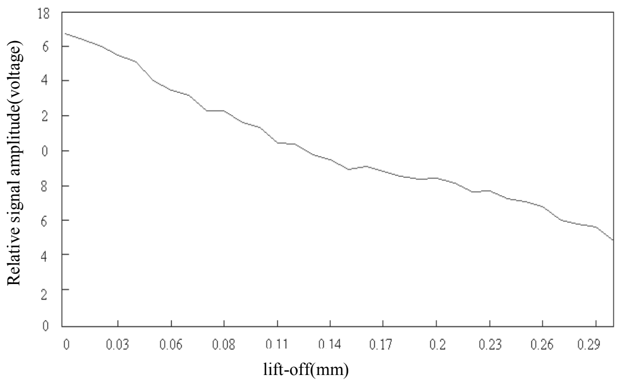


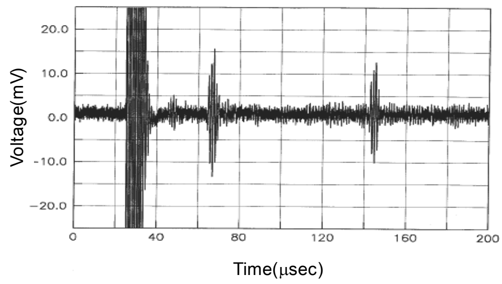
Fig. 5. Signal amplitude of receiver fixed and sender lift-off for 1MHz

Figure 4. shows 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 Figure 5. According to Figure 5, 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.

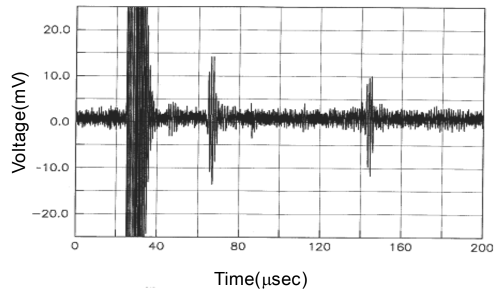
4.3. Measurement of ultrasonic wave signal according to change of hole size

Figure 6. plots ultrasonic waves, represented by the signal received, as they pass through simulator holes of 2, 4, 8, 16 and 32mm in diameter respectively. The signal is recorded as a voltage, which is the ratio of the signal received to that transmitted. Figure 6a. shows an ultrasonic wave generated by using a high frequency of 1MHz in a 2mm hole diameter. The value of amplitude of the hole measured with an ultrasonic wave signal passing through a simulator was 15.6830. The ultrasonic

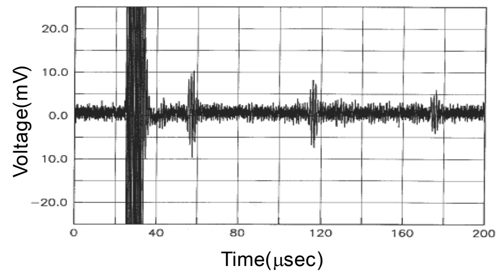
a) 2mm hole diameter



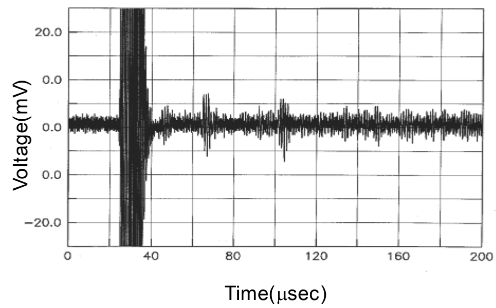
b) 4mm hole diameter



c) 8mm hole diameter



d) 16mm hole diameter



e) 32mm hole diameter

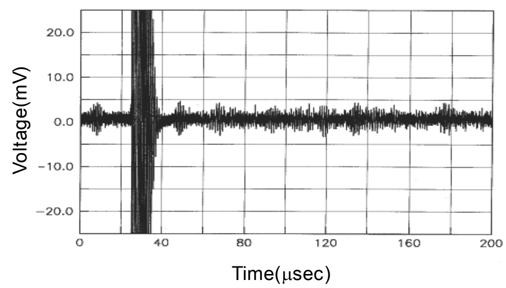


Fig. 6. Ultrasonic wave response according to a change of hole size

wave generated using a high frequency of 1MHz in a 4mm hole diameter was represented in Figure 6b. The result for an ultrasonic wave generated using a high frequency of 1MHz in an 8mm hole diameter was shown in Figure 6c. It was shown that amplitude decreased and the waveform and shape of the receiving force remained unchanged. Figure 6d. presents ultrasonic wave generated using a high frequency of 1MHz through a simulator with a 16mm diameter. The received signal of the same frequency through a 32mm hole diameter was shown in Figure 6e. Using all diameters indicated in Figure 6., the relationship between the received signal amplitude and hole diameter is shown in Figure 7. We observed that the amplitude value of the hole measured with an ultrasonic wave signal passing through a simulator decreased as the hole diameter increased. It can be concluded from Figs. 6-7 that when the hole diameter increases, not only does the measured ultrasonic wave signal decrease from 15.6830 to 1.0312, but also the waveform and shape of the pulse received are identical.

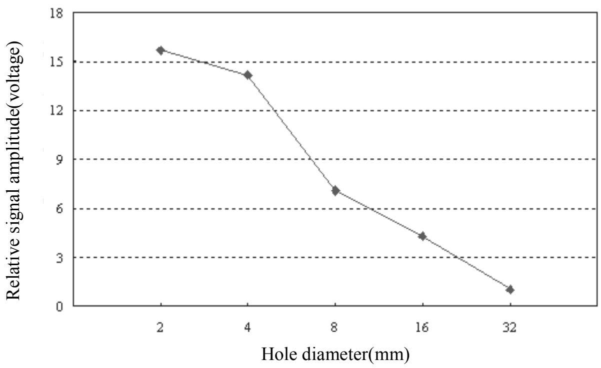


Fig. **7.** Relation between the signal amplitude and hole diameter

4.4. Measurement of ultrasonic wave signal according to change of frequency

Relative signal amplitude were measured as a function of frequency, simulator size and viscous fluid independently, and represented in Figures 8-19.

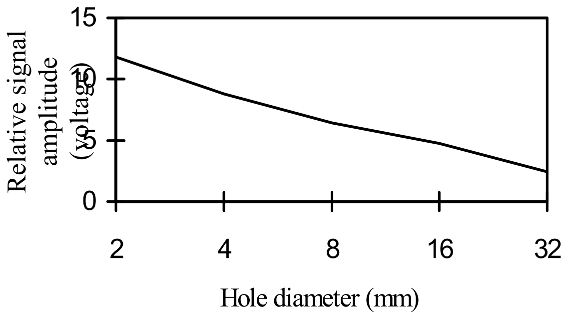


Fig. 8. Relationship between signal amplitude and 75 × 75 mm simulator for air and 0.6 MHz frequency

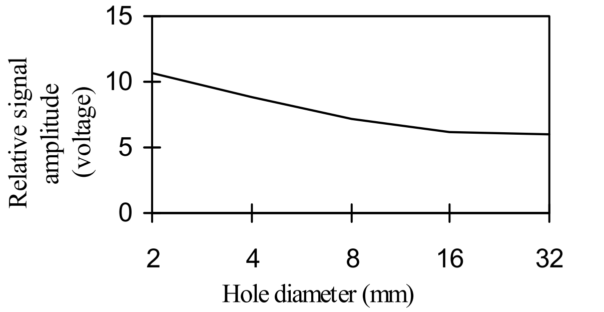


Fig. 9. Relationship between signal amplitude and 75 × 75 mm simulator for air and 1 MHz frequency

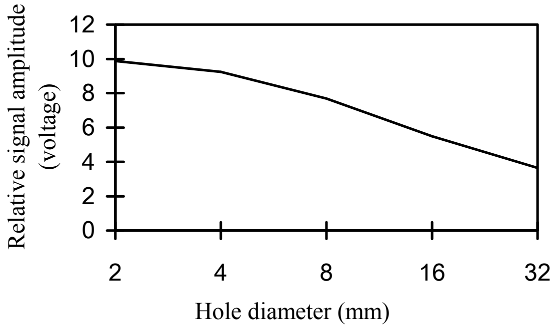


Fig. 10. Relationship between signal amplitude and 75 × 100 mm simulator for air and 0.6 MHz frequency

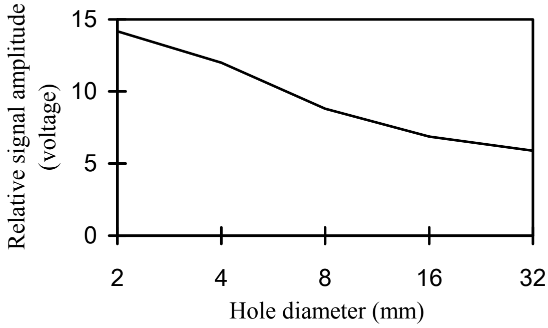


Fig. 11. Relationship between signal amplitude and 75 × 100 mm simulator for air and 1 MHz frequency

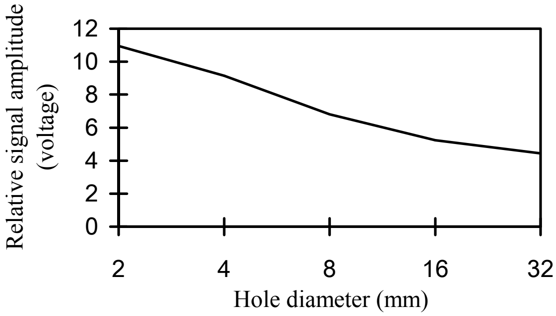


Fig. 12. Relationship between signal amplitude and 75 × 75mm simulator for water and 0.6 MHz frequency

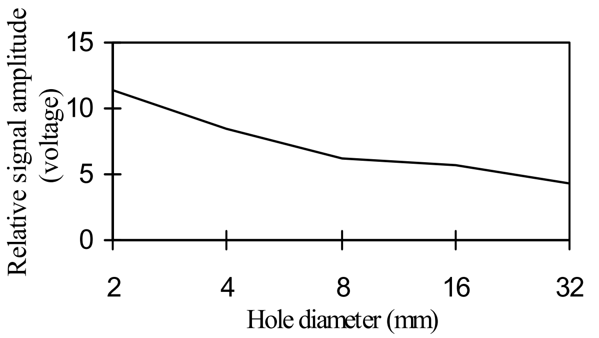


Fig. 13. Relationship between signal amplitude and 75 × 75mm simulator for water and 1 MHz frequency

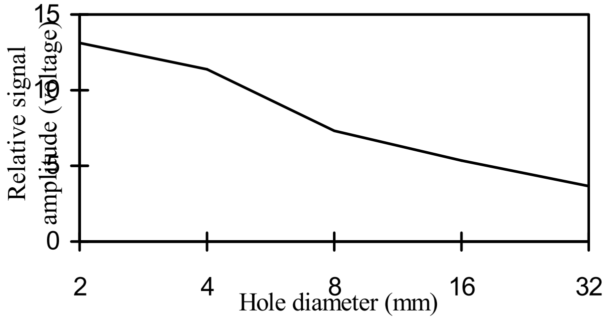


Fig. 14. Relationship between signal amplitude and 75 × 100mm simulator for water and 0.6 MHz frequency

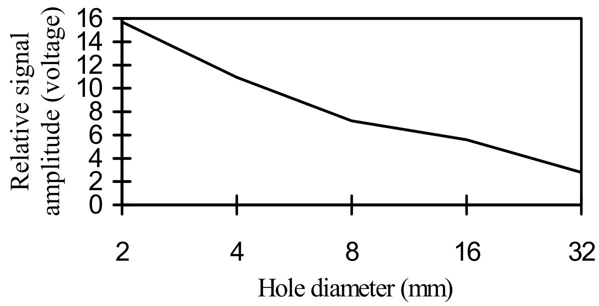


Fig. 15. Relationship between signal amplitude and 75 × 100mm simulator for water and 1 MHz frequency

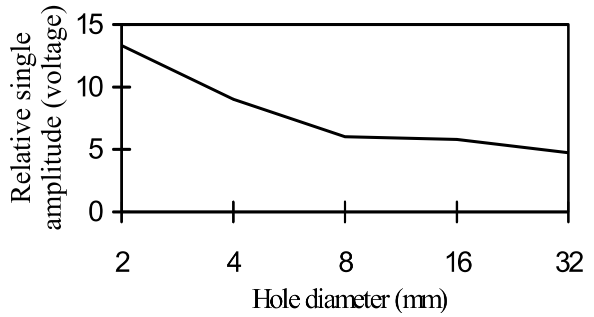


Fig. 16. Relationship between signal amplitude and 75 × 75mm simulator for viscous fluid and 0.6 MHz frequency

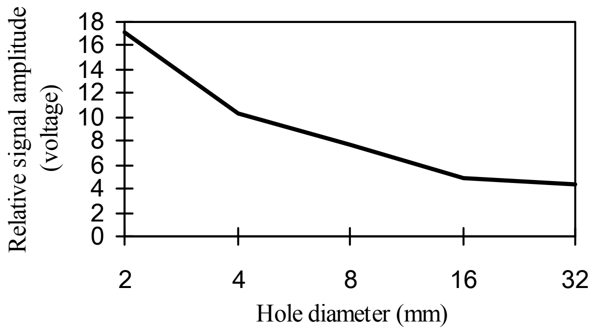


Fig. 17. Relationship between signal amplitude and 75 × 75mm simulator for viscous fluid and 1 MHz frequency

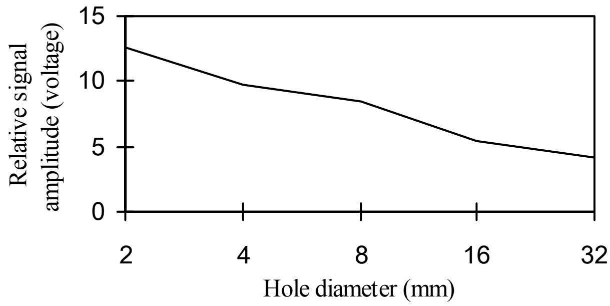


Fig. 18. Relationship between signal amplitude and 75 × 100mm simulator for viscous fluid and 0.6 MHz frequency

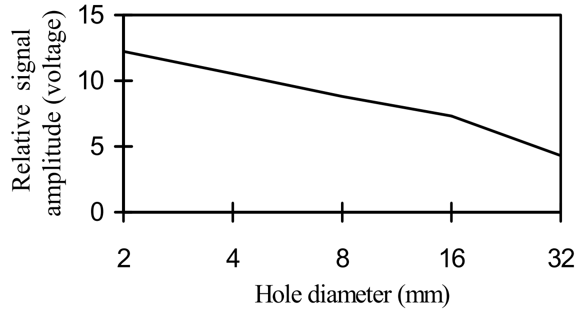


Fig. 19. Relationship between signal amplitude and 75 ×100mm imulator for viscous fluid and 0.6 MHz frequency

It can be seen from Figs. 8-17 that this relationship has been shown to decrease value of the relative signal amplitude as the hole diameter increased. However, frequency and viscus fluid wern't affected by the relative signal amplitude because there was no difference of viscosity.

5. Conclusions

Using an EMAT sensor developed, a new technique for detecting the solidification point in a continuous casting process was represented. Based on 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. Al75×75mm and 75 ×100mm simulators with 2, 4, 8, 16 and 32mm holes in diameter to study the logicality of technique development for solidification point detection in a continuous casting bloom, were produced to measure the change of ultrasonic wave signal with a 1.0MHz frequency. The amplitude extent decreases as the hole diameter of the simulators increases. Furthermore, it was found that the extent of amplitude decreases as lift-off increases through a test of lift-off effect as one of the most important factors for a field application.

It was also 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 hole diameter and frequency 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.

Acknowledgements

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