Journal of Physics: Conference Series **520** (2014) 012011 doi:10.1088/1742-6596/520/1/012011

High Sensitivity EMAT System using Chirp Pulse Compression and Its Application to Crater End Detection in Continuous Casting

Y Iizuka[1] and Y Awajiya[2]

Steel Research Laboratory, JFE Steel Corporation
[1]1-1, Minamiwatarida-cho, Kawasaki-ku, Kawasaki, 210-0855, Japan
[2]1, Kawasaki-cho, Chuo-ku, Chiba, 260-0835, Japan

Email: y-iizuka@jfe-steel.co.jp

Abstract. A high sensitivity EMAT system using chirp pulse compression technique was developed. The system uses a high power gated amplifier having 2kVpp output to transmit chirp waves. Pulse compression of the received signals are performed digitally in a PC after amplification and analog-to-digital conversion. A 20dB improvement of the signal-to-noise ratio was achieved by chirp pulse compression and synchronous averaging. A new surface cooling technique was also developed to improve the signal amplitude of the bulk shear wave with hot steel, and its effectiveness was demonstrated. An actual plant test of crater end detection by the developed EMAT system was conducted at a continuous caster, and clear detection by non-contact EMATs was achieved.

1. Introduction

In the steel industry, non-contact ultrasonic testing methods have been expected as in-line nondestructive evaluation techniques for hot processes. Crater end detection in continuous casting is one example of this need. It is required in order to improve casting productivity and slab internal quality. Electromagnetic acoustic transducer (EMAT) techniques had been tried previously [1,2,3], but due to the low sensitivity of conventional EMAT techniques, liftoff had been limited to less than 2mm. Since a touch roll is used to maintain this narrow liftoff to a hot material whose surface temperature is about from 800°C to 1000°C in in-line operation, this technique approaches contact testing, resulting in low durability of the EMATs.

This paper proposes a new high sensitivity EMAT technique. In order to improve the signal-to-noise ratio (SNR), the authors developed a chirp pulse compression EMAT system. This system transmits chirp signals by using an arbitrary waveform generator and a high power gated amplifier having 2000Vpp output. Pulse compression of the received signals is performed digitally by software in a PC. The SNR was improved by more than 20dB by chirp pulse compression in combination with 16 synchronous averages. As a result, liftoff was improved by +5mm, achieving perfect non-contact measurement. In addition, signal enhancement by the magnetostriction effect by surface cooling was verified when using a bulk shear wave with hot material.

An actual plant test of crater end detection by the developed system was conducted at a continuous caster, and clear detection by perfect non-contact EMATs was successfully achieved.

2. High sensitivity EMAT system using chirp pulse compression

Signal processing is an effective way to improve the SNR of ultrasonic testing signals. In particular, synchronous averaging is often used. However, the number of averages cannot be increased greatly in in-line measurement because the material is moving and real-time measurement is required. Therefore, the pulse compression technique was applied to obtain a high SNR and short pulse within one pulse. Chirp wave is used as the transmitting pulse. The chirp wave has the features of a low side-lobe and easy setting of the frequency band compared to the coded pulse technique. Chirp pulse compression has been used previously for flaw detection of pipes [4]. The authors developed a high power system to enable use of EMAT.

Figure 1 shows the high power EMAT system. A high power gated amplifier is used to transmit high power chirp signals. This device is a custom-ordered GA-5000 manufactured by Ritec Inc. The output voltage is about 2kVpp at 1% duty. The received signals are amplified by a low noise operational amplifier and digitized by a digital oscilloscope, after which pulse compression is performed by software. Synchronous averaging is performed in combination with this process by the digital oscilloscope. The number of averages is set at 16, which is allowable in in-line measurement.

The procedure of the signal processing is shown in Figure 2 as an example of a simulation. The chirp wave generated by Eq. 1 is used as the transmitting pulse. After synchronous averaging by Eq. 2, correlation is carried out for the pulse compression by Eq. 3. As the auto-correlation is like a delta function, the pulse width of the chirp signal is compressed by the cross correlation between the received signal and the chirp signal. Random noises are suppressed because the cross correlation between random noise and the chirp signal is low. Thus, a short and high-SNR signal is obtained.

Figure 3 shows an experimental result of SNR improvement at room temperature. In this test, a 250mm thick stainless steel block is used as simulated hot carbon steel. A transmission method with bulk shear wave EMATs is used. The chirp pulse was compared with a tone burst pulse as a conventional technique. The conditions of the transmitting signals are shown Table 1. SNR is defined as the signal amplitude to the noise amplitude ratio. The amplitude is measured as the maximum value in the gate as shown in the Figure 3(c).

A result is shown in Figure 3. The signal amplitude of the conventional burst wave decreases with increasing liftoff, and it becomes difficult to distinguish the signal from noise at 7mm, even though the SNR was 20dB at 2mm liftoff. On the other hand, with the chirp pulse compression, a 15dB SNR is obtained at 7mm liftoff. A 24dB SNR is obtained with 16 synchronous averages. As the result, a 5mm liftoff improvement is achieved.

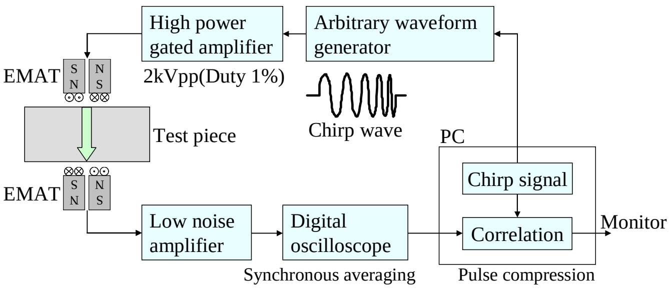
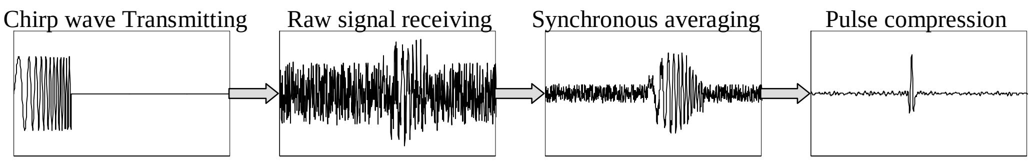


Fig. 1 Configuration of high sensitivity EMAT system

Table 1 Transmitting signals

Tone burst	
Center frequency	300kHz
Cycles	2
Chirp wave	
Center frequency	300kHz
Band width	500kHz
Pulse width	40 μ s



$$st(t) = \sin\left(2\pi(Fc - \frac{B}{2} + \frac{B}{2T}t)\cdot t\right) \quad \cdots 1)$$

Fc : Center frequency
B : Band width
T : Pulse width

$sr_i(t)$

$$x_i(t) = \frac{1}{N}\sum_{k=0}^{N-1} sr_{i-k}(t) \quad \cdots 2)$$

N : Number of average
i, k : Pulse number

$$y_i(t) = \int_0^T st(\tau)\cdot x_i(t+\tau)\cdot d\tau \quad \cdots 3)$$

Fig. 2 Signal processing procedure

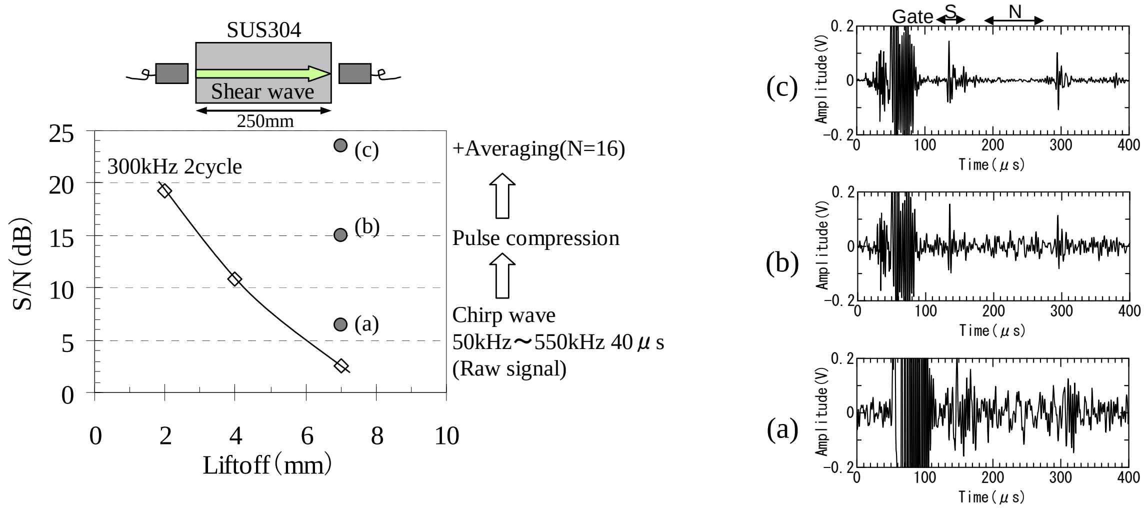


Fig. 3 Experimental result of S/N improvement

3. S/N improvement by surface cooling for hot steel

One feature of the EMAT technique is easy generation of a bulk shear wave. Shear wave is considered to be an appropriate mode for crater end detection as this type of wave is not transmitted to liquids (in this case, molten steel). However, it has been reported that the signal of the shear wave becomes low at more than 750°C in the case of carbon steel [5]. Therefore, the authors attempted application of a surface cooling technique to enhance the signal of the bulk shear wave EMAT based on the facts that the critical temperature is around the transformation temperature, and magnetostriction contributes to the sensitivity of the shear wave EMAT compared to the Lorentz force in the case of carbon steel [6]. Surface cooling reduces the surface temperature, enabling magnetism, and as a result, the bulk shear wave can be generated and detected by the magnetostriction effect rather than by the Lorentz force, which is used conventionally with hot steel.

In this test, a 100mm thick carbon steel block, which had been heated to 1000°C, and bulk shear wave EMATs were used. The EMATs were cooled with water to protect against heat damage. A tone burst wave was used as the transmitting pulse. The center frequency was 300 kHz and the number of cycles was 3. The temperatures were measured with thermocouples at the center and 3mm depth of the sample. The amplitude of the transmitting signal was measured using the gate S as shown in the Figure 3(c).

Figure 4 shows an experimental result of the surface cooling test. Although the amplitude of the transmitting signal was low at first, from 25 seconds after cooling, the signal was enhanced about 6dB. Thus, signal enhancement by the magnetostriction effect was confirmed.

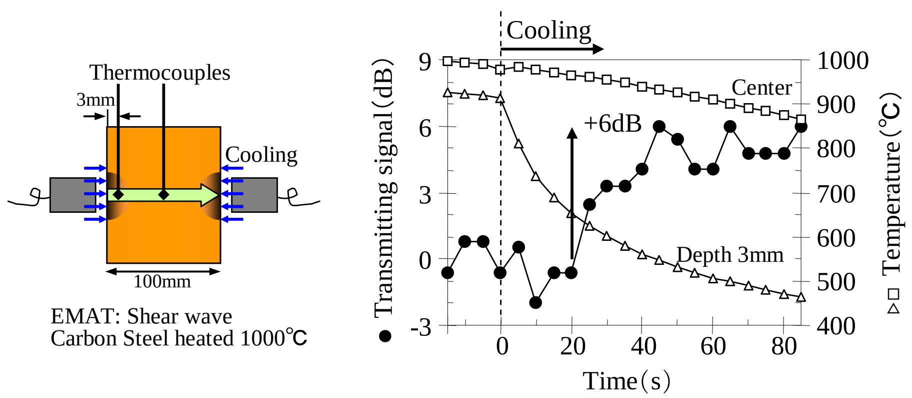


Fig. 4 Experimental result of signal enhancement of shear wave by surface cooling for hot steel

Journal of Physics: Conference Series **520** (2014) 012011 doi:10.1088/1742-6596/520/1/012011

4. Actual plant test of crater end detection

An actual plant test of crater end detection was conducted at a bloom continuous caster by using the developed EMAT technique. The shear wave transmission method [2,3] was used. In case of complete solidification, the transmitting shear wave signal is detected. However, when the crater end reaches the position of the EMATs, the transmitting shear wave signal disappears, as the signal is not transmitted to the liquid steel. A pair of EMATs was installed near the end pinch rolls with 5mm liftoff from the sensor box. The sensors were thermally protected by a 1mm thick waterway in the sensor box. A surface cooling device to enhance the signal of the bulk shear wave was installed just upstream from the EMATs. The surface temperature was about 900°C before cooling and less than 700°C after cooling. The thickness of the bloom was about 250mm.

Figure 5 shows the trend of the transmitting shear wave signal during a casting speed change test. The amplitude is measured in the gate shown on the figure. After the casting speed was increased, the transmitting shear wave signal decreased. Crater end detection was clearly observed at point A in the figure, as the signal completely disappeared. In addition, after the casting speed was decreased, the transmitting shear wave signal appeared at point B, indicating movement of the crater end to the upstream side. The SNR of the transmitting shear wave signal was significantly higher, displaying an improvement of more than 20dB. As this experiment demonstrated, the crater end can be clearly detected with perfect non-contact sensors by using the developed EMAT system.

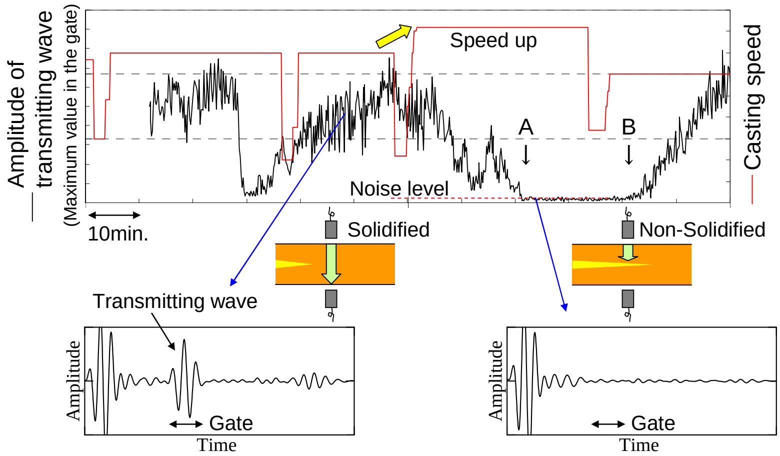


Fig. 5 Experimental result of crater end detection in actual continuous casting

5. Conclusions

A high sensitivity EMAT system using chirp pulse compression was developed. The results are summarized as follows.

1) By using chirp pulse compression and synchronous averaging, a short, high SNR pulse can be obtained at more than 5mm liftoff.

2) A surface cooling technique is effective to enhance the signal of the bulk shear wave EMAT when the system is applied to hot carbon steel, even when the internal temperature is more than 900°C.

3) Clear detection of the crater end by perfect non-contact EMATs was successfully achieved in an actual plant test at a continuous caster.

References

[1] K. Kawashima et al., Testu to Hagane 67(9), 1515-1522 (1981)
[2] H. Takada et al., Current advances in materials and processes-ISIJ 2, 1214 (1989)
[3] P.W.Manos et al., 9th Process Technology Conference proc., 139-150 (1990)
[4] Y. Iizuka, Insight 40(4), 282-285 (1998)
[5] K. Kawashima, Hihakaikensa 34(11), 796-803 (1985) in Japanese
[6] H. Ogi, J Appl Phys 82(8),3940 (1997)