Hybrid laser-EMAT system for non-destructive testing continuous casting billet

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Received March 1, 2013; accepted March 27, 2013; posted online August 20, 2013

A novel laser-electro magnetic acoustic transducer (EMAT) system for nondestructive testing NDT surface crack of continuous casting billet (CCB) is provided. Rayleigh wave generated by line laser source is used to detect the surface crack of CCB. According to the principle of mode conversion from Rayleigh wave to shear wave, the defect signal is received using the shear wave EMAT sensor in a non-contact way. Experiments are carried out on the steel sample with size 30 × 0.2 × 0.2 (mm) of crack. Further, the influences of life off value and distance between EMAT sensor and laser beam on the testing sensitivity are discussed, respectively. It is found that the life off value is the main factor that effects sensitivity of the proposed method. There is a clear prospect of the method applied to test continuously cast bloom at high temperature.

OCIS codes: 110.5125, 170.1065, 220.4840, 070.1060.
doi: 10.3788/COL201311.S21103.

Nondestructive testing (NDT) systems are increasingly applied in the industrial context for their strong potentialities in improving and standardizing quality control. Especially, the detection of defects during an early production stage allows the semi-finished products to be directed to later production processes according to their quality. For the case of continuous casting billet (CCB), the most common defect is the surface crack. If the crack can be inspected during the casting process and eliminated through the scarfing process, there will be a considerable saving of material, energy and costs. Moreover, after the CCB is inspected, the casting parameters can be adjusted according to the distribution of cracks.

Nowadays, the major challenge in the research field is the development of reliable NDT technique at the high temperature[1]. Thus, some remote non-contact NDT techniques have been sought in an effort to improve the related inspection operations[2−4]. Electro magnetic acoustic transducer (EMAT)-EMAT and laser-laser inspection techniques have been used to find surface defects on steel in the lab. For the real application, the main limitation of EMAT-EMAT technique is that the sensor only can works under the condition of lift-off value less than 2 mm. Optical generation and detection has been one of the most successful noncontact ultrasonic inspection systems. However, an optically reflective surface is required for efficient detection, which is a major drawback for on-line monitoring and detection on rough surfaces[5].

The aim of this work is to present a kind of NDT system based on the hybrid laser-EMAT technique. Firstly, a detailed introduction on the laser-EMAT testing system was shown. Then, the principles of laser-EMAT inspection and signal processing were described. Experiment results and corresponding analyses were presented at last.

Both of body waves and Rayleigh wave can be generated simultaneously when a pulsed laser irradiates on the surface of target material. The magnitude of Rayleigh wave is largest of all the wave modes. For the case of Rayleigh wave, its characteristics mainly depend on the surface condition. In this letter, Rayleigh wave is applied to inspect the surface crack of the CCB.

Rayleigh wave generated by line laser source propagates along the CCB surface. Generally, depth of propagation is less than the wavelength (λ). For the case of surface crack inspection, there is good sensitivity if the depth of crack is less than $\lambda/3$. It is known that shear wave component will be produced due to the mode conversion when the Rayleigh wave transmitted through the surface crack. Thus, if the EMAT sensor is used to monitor the shear wave which generates from the Rayleigh wave, it is easy to determine the approximate location of surface defect. Moreover, the amplitude of the shear wave will achieve to the maximum value when the EMAT sensor located right above the surface crack (Fig. 1). Further, the location of surface defect can be determined accurately by monitoring the maximum amplitude of the shear wave.

An inspection system of surface crack on CCB used in this work included a pulsed laser, EMAT sensor, signal processing system, and upper computer (Fig. 2).

For the generation of Rayleigh wave, a Q-switch pulsed

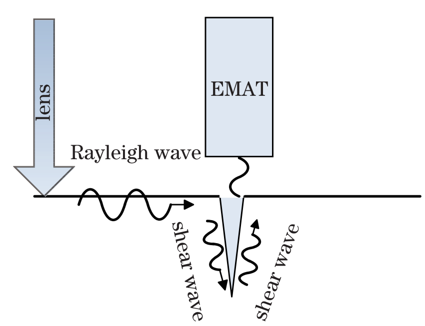

Fig. 1. Diagram of testing crack on the CCB based on laser-EMAT method.

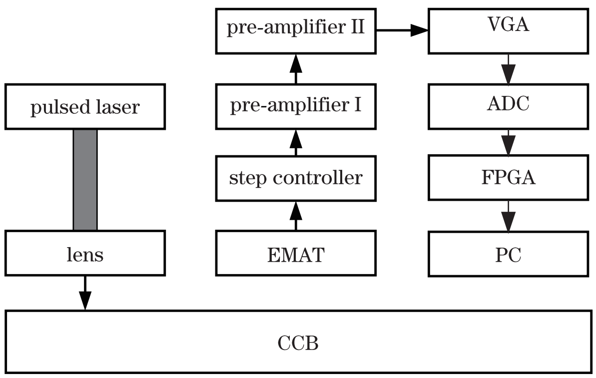

Fig. 2. Schematic diagram of laser-EMAT testing system.

Nd:YAG laser of 1 064-nm wavelength was used, operating with 10-ns pulse width and maximum energy of 200 mJ per pulse. Focusing the laser pulse with a plano-convex lens, a laser line source about 10 × 0.2 (mm) was obtained, which is helpful to generate the Rayleigh wave with the concentrated directivity.

The EMAT sensor is used to receive the shear wave in this letter. The sensor mainly consist of test coil, magnet, carbonyl iron powder sheet, SiC ceramic plate, SiO_2 ceramic plate, pre-amplifier, and the shell. The coil is designed as the butterfly structure, which allows the loop noise to be eliminated as much as possible. A multilayer structure of magnets with various diameter are designed to make the magnetic induction line more concentrated in the direction perpendicular to the magnets. The sheet prepared by the carbonyl iron powder is employed to not only play the role of insulation but also permeability, which is helpful to suppress the electrical noise. These designs all contribute to increase the value of lift-off. The SiC ceramic plate and SiO_2 ceramic plate are used to reduce the friction and protect from the high temperature, respectively. In addition, the cooling way of water circulation was used to ensure the temperature less than 80 °C in the EMAT sensor.

The amplification of the signal received by EMAT sensor is necessary for the signal processing later. Thus, two kinds of pre-amplifiers were used in the present work, and the magnifications were about 1 000 and 60. To control the signal amplitude further, variable-gain amplifier (VGA) was employed, and the range of gain is from 0 to 30 dB. After amplification, analog to digital converter (ADC) was used for pre-processing the signal. Then, the data of signal was transmitted to computer by field programmable gata array (FPGA).

To allow reliable and effective defect detection, noise reduction is essential to laser-EMAT testing the CCB. Two main important processing steps are required for a meaningful analysis of the collected data. Firstly, a slide average filter with a window of 25 samples was selected to reduce the random noise. Then, low-pass digital filter was designed to denoise the electromagnetic noise which may be from the laser power or testing environment. Moreover, the cut-off frequency of the filter can be adjustable according to the specific detection requirements. All the functions above achieves by using the software in the upper computer.

A steel slab with rough surface was selected as for the experimental sample. Surface artificial crack with size of 30×0.2×0.2 (mm) was produced by the wire-electrode cutting technique. Rayleigh wave was generated and detected on the sample by using the laser–EMAT system above. The sample was held stationary and the EMAT was positioned from 3 mm above the surface. To examine the shear wave from a line source at a surface crack, scans were carried out on the sample with three-dimensional step controller with the least step value of 0.02 mm. The maximum amplitude of shear wave was obtained when the distance between the line source and the center of EMAT sensor was about 43 mm. Then, the signals with various lift-off values (LOV) were shown in Fig. 3.

The peak to peak amplitudes of crack signals were fitted by the exponential function (Fig. 4). It was found that the relation of LOV and corresponding signal amplitude satisfies $y = 7.371e^{-0.41x}$. This is because the magnetic lines of flux in steel slab decreases with the increase of LOV so that the signal received by EMAT sensor becomes weak due to the decrease of induced electromotive force. Actually, if we use the wavelet threshold method (WTM) to reduce noise, we can increase the LOV up to 10 mm. Moreover, the influence of distance between laser and EMAT sensor on amplitude of received signals was considered. Figure 5 shows the defect signal received by EMAT sensor when the distances were 43 and 116 mm, which proves the attenuation of Rayleigh propagating on the steel surface are very small.

In conclusion, a hybrid laser-EMAT system described here is capable of inspecting surface defects of CCB with rough surface. It is shown

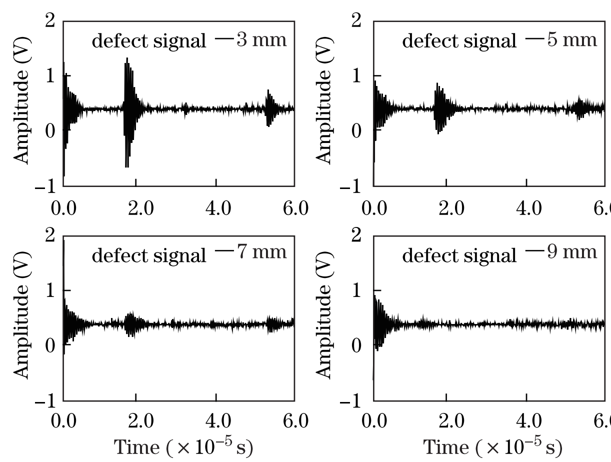

Fig. 3. Results of laser-EMAT testing at various lift-off values.

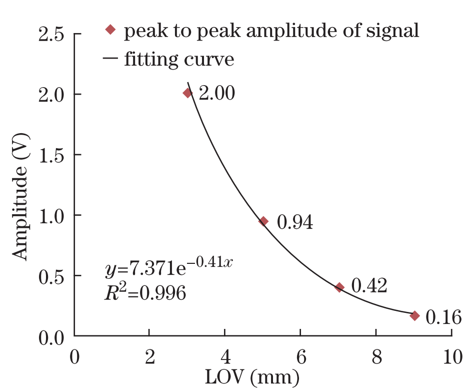

Fig. 4. Relation of LOV and amplitude of signal.

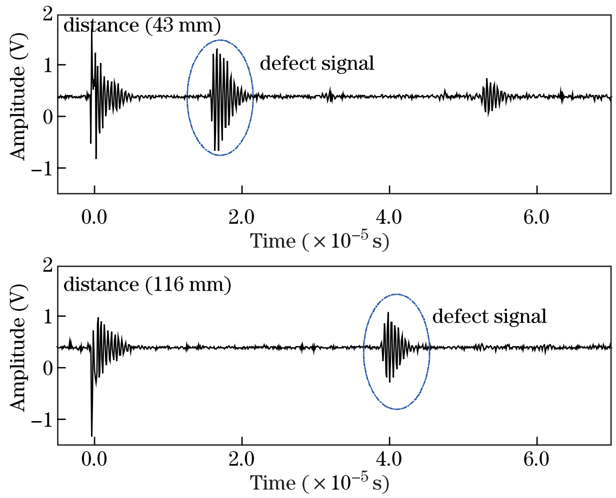

Fig. 5. Signals received at different distance.

that the methods of mode conversion can be used to locate surface crack. A novel EMAT sensor with large LOV is provided here to realize the non-contact testing for CCB. Although the system described here is intended for detection of CCB, it also has the potential to perform inspections at other metal materials in service, especially in the hostile environments.

This work was supported by the National Natural Science Foundation of China (No. 51205240), Outstanding Young Scientists Program of Shandong (No. BS2011ZZ016), and Youth Science Funds of Shandong Academy of Sciences (No. 2012-02).

References

1. R. Raišutis, R. Kažys, E. Žukauskas, and L. Mažeika, NDT & E International **44,** 645 (2011).
2. F. H. Valle and S. Dixon, NDT & E International **43,** 171 (2010).
3. E. Robert and Jr. Green, Ultrasonics **42,** 9 (2004).
4. Y. Zhao, R. Guo, and J. F. Song, Nondestr. Test. (in Chinese) **34,** 59 (2012).
5. B. Pouet, S Breugnot, and P Clémenceau, AIP Conf. Proc. **760,** 273 (2005).