Hybrid laser ultrasonic inspection based on optical fiber technique

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Laser generation and electromagnetic acoustic transducer (EMAT) detection techniques are combined as a hybrid ultrasonic technique for the inspection of the defects in the steel. Laser transmits through the optical fiber and irradiates on the steel surface. In case of inspection, Rayleigh wave is generated to test the surface defects based on the principle of mode conversion. In order to improve the testing accuracy and signal-to-noise ratio, wavelet soft-threshold method is introduced in the present work. Experimental results show that errors of testing surface defect are less than 10%, which proves laser-EMAT technique to be suitable for non-destructive assessment of metallic materials.

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Nondestructive inspection systems are increasingly used in the industrial applications due to their strong potentialities in improving and standardizing quality control. Ultrasonic wave is a generally accepted method for NDT, which can be used to inspect the defects in the manufacture and service. Several devices were employed to generate ultrasonic wave, such as piezoelectric transducer (PZT), air-coupled transducer, electromagnetic acoustic transducer (EMAT) and pulsed laser[1−3]. Recently, noncontact ultrasonic techniques have been sought to inspect operations in extreme environments. More specifically, efforts have been aimed to improve laser-based ultrasonic technique because it offers many advantages, such as the noncontact *in situ* measurements, high spatial resolution and the ability to inspect the target materials in the hostile environments[4].

In the present work, we have established a hybrid laser ultrasonic testing system with a fine flexible optical fiber to inspect the surface defects of the metallic materials. Referring the former achievements, we have developed an accurate measurement method of crack location and depth using a frequency response analysis of Rayleigh waves[5]. To apply this method for the inspection of the materials with complex geometry, a laser-EMAT testing system was developed based on optical fiber delivery system. The principle and system of the laser-EMAT testing were introduced initially; then, the inspection experiments were presented in detail.

Rayleigh wave generated by line laser source was employed to detect the surface defects. Rayleigh wave propagates along the rail surface and it is known that shear wave component is produced due to the mode conversion when the Rayleigh wave is transmitted through the surface crack[6]. Thus, if the EMAT sensor of shear wave is used to monitor the shear wave generated from the Rayleigh wave, it is easy to determine the approximate location of surface defect. According to the principle of electromagnetic induction, the amplitude of the shear wave achieves the maximum value if the EMAT sensor is located right above the surface crack. Further, the location of surface defect can be determined accurately by monitoring the maximum amplitude of the shear wave.

A novel inspection system was used in this work, which included a pulsed laser, optical fiber and its coupler, EMAT sensor, signal acquisition and processing system (Fig. 1). The rail which contains surface hole with an angle of 26° was selected as the target sample in this work, and the size of hole is $\phi 4 \times 40$ (mm).

In order to generate the Rayleigh wave, a Q-switch pulsed Nd:YAG laser of wavelength 1064 nm was used, operating with 10 ns pulse width, work energy of 84 mJ/pulse and repetition frequency of 5 Hz.

Optical fiber system was designed to deliver the laser with high energy. The plano-convex lens with focal distance of 50 mm was employed to couple the laser with optical fibers. The fiber was positioned beyond the focal point to avoid unnecessary high-power densities within the fiber. Precise positioning was achieved by holding the fiber on a three-dimensional translation stage to allow submicron movement. Multimode step-index silica fibers of 0.8 mm diameter and length of 1.2 m were used in this work after they were polished and cleaned by ultrasonic wave. To obtain the maximum energy of laser irradiated on the steel surface, the threshold energy throughput of the fiber and the coupling efficiency were measured as

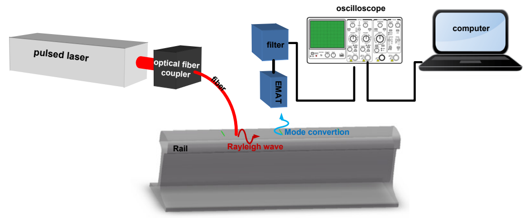

Fig. 1. Schematic representation of laser-EMAT setup.

Table 1. Test result of coupling efficiency for the optical fiber system

Input energy (mJ/pulse)	Output energy (mJ/pulse)	Coupling efficiency (%)
19.0	11.8	62.1
28.0	18.2	65.0
37.4	23.4	62.6
47.6	28.8	60.5
58.0	35.2	60.7
68.0	42.6	62.6
84.0	52.4	62.4

shown in Table 1. Thus, the maximum energy is 52.4 mJ/pulse and the coupling efficiency was approximately 63%.

An EMAT sensor was designed to be predominantly sensitive to in-plane motion of a sample surface, which is quite suitable to detect the shear wave. The EMAT receiver can be used on unprepared surfaces. Design of the receiver coil with butterfly structure allowed the loop noise to be eliminated as much as possible[7].

To prove the principle proposed in this work, signals from the positions of surface hole and from that without any defect were detected under the same conditions. The distance d_t between the laser spot and EMAT receiver is 80 mm. Compared with the signal of perfect surface, the amplitude of defect signal is clear enough to recognize (Fig. 2). Thus, mode conversion method combined with the EMAT of shear wave is suitable to test the surface defects.

Next, it is necessary to determine the velocity of Rayleigh wave in the steel. The velocity can be measured by

$$v = \frac{d_{t2} - d_{t1}}{t_2 - t_1}, \tag{1}$$

where, the subscripts "1" and "2" refer to two different measurements, d_t is the distance between the laser spot and EMAT receiver, and t is the flight time of Rayleigh wave.

Note that the signal contains severe noise because the pre-amplifier amplifies both of them simultaneously. This is detrimental to accurately determine the location of defects. Thus, WSTM was used to improve the signal-to-noise ratio (SNR)[7]. Then, the signals of d_{t1} = 50 mm

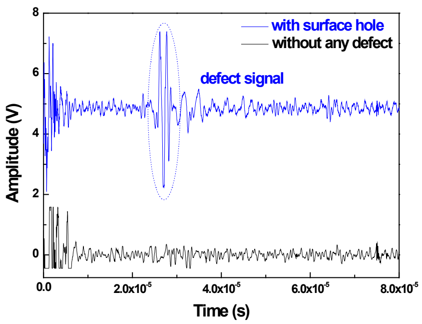

Fig. 2. Signals of surface with and without hole.

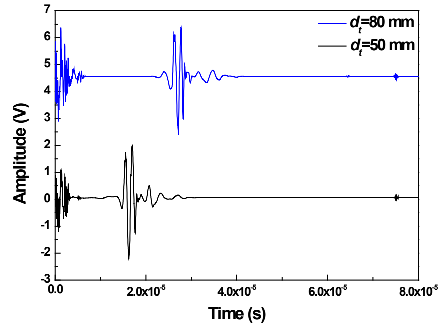

Fig. 3. Signals of surface hole for the case of d_{t1} = 50 mm and d_{t2} = 80 mm.

and d_{t2} = 80 mm through the process by WSTM are shown in Fig. 3. It is easy to determine t_1 = 14.7 μs and t_2 = 24.2 μs. Therefore, the velocity of Rayleigh wave v = 3158 m/s can be calculated using Eq. (1).

To assess the method proposed in this work, we can determine the relative error of measurement according to Eqs. (2) and (3), and the range of errors is calculated to be 4.5–7.2%.

$$d = v \times t, \tag{2}$$

$$error = \frac{d - d_t}{d_t}\%. \tag{3}$$

A hybrid laser-EMAT system based on optical fiber technique described here is capable of inspecting surface defects of the metallic materials with rough surface. It is shown that the methods of mode conversion can be used to locate the surface defect. As the SNR and sensitivity of laser-EMAT technique are less than that of piezoelectric technique, WSTM is introduced to determine the defect location accurately. The relative error of inspection is less than 10% in the present work. Although the system described here is intended for the detection of rail, it also has the potential to perform inspections at other metal materials in service, especially in the hostile environments.

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