Laser-EMAT ultrasonic testing of cracks with TOFD method

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Abstract: A hybrid, noncontact laser-EMAT ultrasonic system, using a pulsed laser for ultrasound generation and an EMAT (electromagnetic acoustic transducer) for ultrasound detection, is developed and studied on NDT of crack in materials. Instead of using longitudinal diffraction wave in the conventional TOFD method, the LTS mode-converted wave scattered from the crack tip is recommended to be applied in the laser-EMAT TOFD measurement. A modified time-of-flight (TOFD) method based on laser-EMAT ultrasonic is developed to detect and measure the cracks in the specimen.

Keywords: Laser ultrasound; EMAT; TOFD; Crack measurement

1. Introduction

The ultrasonic testing (UT) technique has been widely applied for the detection and characterization of cracks in structures and components in many industry areas, for example of the nuclear power plants. Accurate evaluation of crack size is critical for lifetime prediction inspection of mechanical structures and components. Until now, several methods have been applied for the crack testing. Among them, the TOFD measurement is one of the mostly widely used methods, because of its high probability of detection, low false call rate, and most important its intrinsic accuracy in crack sizing, especially in depth [1, 2]. Presently, the TOFD measurement of cracks is mainly performed by using a couple of conventional piezoelectric transducers. However, the requirement of physical contact and coupling medium between the piezoelectric transducers and the tested structures makes it difficult or even impossible to be applied in some areas, such as hot environment, complex-shaped or fast-moving components. A non-contact ultrasonic testing technique is required in such hostile environments.

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Laser ultrasound is considered to be suitable for TOFD measurement of cracks since it has the ability of generating high-frequency and broadband bulk waves in a wide directivity. Until now, there are a few investigations of TOFD measurement of cracks using laser ultrasonic that have been reported [2, 3]. However, as the relatively low sensitivity of the optical detectors, much strong ultrasound generation by material ablation is needed in their measurement. Generally, electromagnetic acoustic transducers (EMATs), which also own the non-contact feature, have much higher sensitivity for ultrasound detection than optical detectors [4, 5]. Therefore, the laser-EMAT ultrasonic technique, which uses a pulsed laser for ultrasound generation and an EMAT for ultrasound detection, can provide a promising non-contact approach for TOFD measurement. In this work, a modified TOFD method based on laser-EMAT ultrasonic is developed to detect and measure the cracks in the specimen.

2. Experiment Setup and Method

2.1 Experimental system and specimen

The experimental setup is shown below in the schematic diagram of Fig. 1. The specimen was arranged on an X-scanning stage and could be moved along x direction. A Q-switched Nd-YAG laser, providing laser pulse with a wavelength of 1064 nm, duration of 10 ns at a repetition of 10 Hz, was used for ultrasound generation. The laser beam generated by the YAG laser with energy of ~10mJ per pulse was directed and focused onto the specimen surface by a cylindrical lens to form a thermo-elastic line source with length and width of approximately 6.0 mm and 1.0 mm, respectively. An EMAT sensor was mounted at a distance w from the laser source and about 0.5 ± 0.1 mm above the specimen surface to receive the ultrasonic waves generated by the laser. The ultrasonic waveforms detected by the EMAT were amplified (by an amplifier with frequency bandwidth of 10 MHz) prior to a digital storage oscilloscope and stored by a personal computer (after 16 averages) for signal processing.

As shown in Fig. 1, the specimen used in the following experiments was an aluminum plate (200mm$\times$80mm and 20 mm thick) with three electrical discharge machining (EDM) cracks: crack 1, crack 2 and crack 3 at the rear side. The three cracks with a width of 0.2 mm and heights of 10, 5 and 2 mm, respectively, were induced entirely through the specimen width.

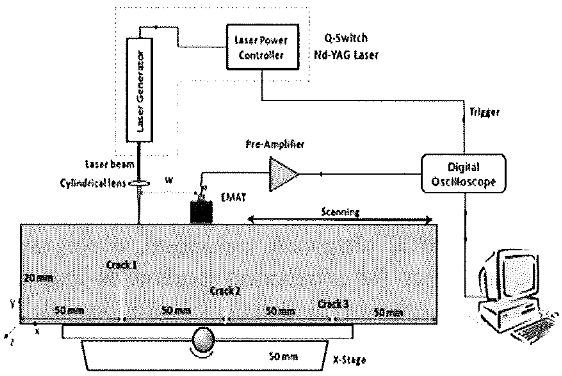

Fig. 1 Schematic diagram of laser-EMAT ultrasonic testing system and specimen for TOFD measurement

2.2 Laser-EMAT ultrasonic TOFD method

The schematic diagram of laser-EMAT TOFD measurement setup is shown in Fig. 2. Unlike the conventional TOFD method, which uses a couple of angular transducers symmetrically arranged at the two sides of a crack as a ultrasound generator and detector, a laser beam and a normal EMAT (in-plane EMAT or out-of-plane EMAT) in an unsymmetrical arrangement are used as a generator and detector, respectively, in this modified method. The ultrasonic transmission modes and paths are also shown in Fig. 2, where, L is an incident longitudinal wave, S is an incident shear wave, LTL is a crack-tip-diffracted longitudinal wave, STS is a crack-tip-diffracted shear wave, LTS or STL is a mode-converted diffracted wave at the crack tip, SBS is the reflection wave at the crack base (travelling along the crack before being radiated at the tip) and LBS is the mode-converted wave at crack base. With the laser-EMAT technique, it is possible to accurately measure the absolute propagation time of the different wave modes, since both the laser source and EMAT detector have a very small footprint on the sample surface. When the EMAT is just above the crack, the time of flight of La, LTL and LTS, namely, t_{La}, t_{LTL} and t_{LTS}, can be expressed in the following equation:

$$t_{La} = \frac{w}{C_L}, \quad t_{LTL} = \frac{\sqrt{w^2+d^2}+d}{C_L}, \quad t_{LTS} = \frac{\sqrt{w^2+d^2}}{C_L} + \frac{d}{C_S} \qquad (1)$$

where C_L and C_S are the velocities of longitudinal wave and shear wave (for aluminum, C_L=6229 m/s and C_S=3073 m/s), respectively. By solving equation (1), the depth of the crack tip in the specimen can be obtained by either Eq. (2) or Eq. (3):

$$d = C_L \cdot \frac{t_{LTL}^2 - t_{La}^2}{2t_{LTL}} \qquad (2)$$

$$d = C_L C_S \cdot \frac{C_L t_{LTS} - \sqrt{C_S^2 t_{LTS}^2 + (C_L - C_S) t_{La}^2}}{C_L^2 - C_S^2} \qquad (3)$$

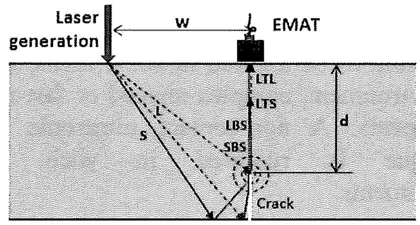

Fig.2 Ultrasonic transmission modes for laser-EMAT TOFD method

3. Experimental Results and Discussion

3.1 B-scan image of TOFD measurement

In order to visualize the diffraction signals from the cracks in different depths in the specimen, the specimen was scanned along x-direction in 1.0±0.1 mm steps under the laser beam and in-plane EMAT detector by using the setup shown in Fig. 1. The A-scan signals from each scanning position were acquired and presented in the form of B-scan image, with signal amplitude denoted on a grey scale.

Fig. 3 shows the experimental result of B-scan image of TOFD measurement from the scanning position x=38 mm to x=160 mm with a separation distance w=15 mm between the laser source and EMAT detector. The scanning position x indicated in that figure is the distance from the EMAT detector to the left side of the specimen in x direction. The three diffracted signals LTS_1, LTS_2 and LTS_3 are induced by Crack 1 with height of 10 mm, Crack 2 with height of 5 mm and Crack 3 with height of 2 mm, respectively.

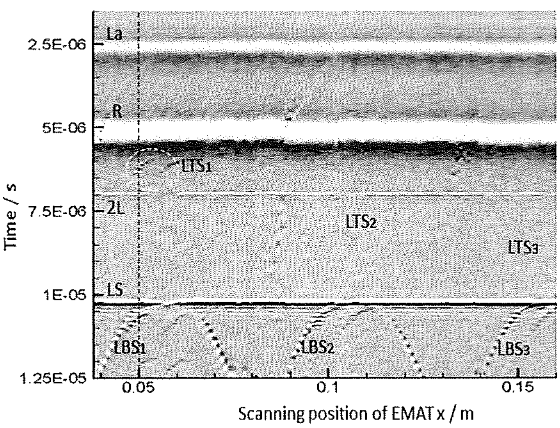

Fig. 3 The result of B-scan image of TOFD measurement with w=15 mm

3.3 Crack evaluation

In Fig. 3, it has been observed that the diffracted signal has relatively larger strength when the EMAT detector is just above the crack. Therefore the crack position in the scanning direction can be decided according to the strength and the shape of crack signals in the B-scan image. As shown in the figure, the time of flight t_{La} and t_{LTS} for the three cracks can be measured in the three waveforms, respectively.

According to laser-EMAT TOFD method, the depth of crack tip in the specimen can be solved by Eq. (3). Therefore, for the crack existing at the rear side of the specimen, the crack height h can be acquired with: h=H-d, where H is the thickness of the specimen. Fig. 4 shows the results of crack heights evaluation by using the modified TOFD method based on laser-EMAT ultrasonic. It can be observed that the evaluated values of the crack heights agree very well with the actual ones.

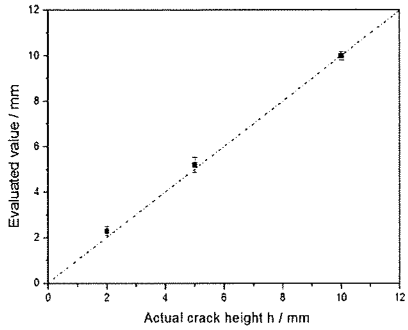

Fig. 4 Results of crack height evaluation by laser-EMAT TOFD method

4. Conclusions

A laser-EMAT ultrasonic testing system has been studied for crack measurement in materials with TOFD method. A modified TOFD method based on laser-EMAT ultrasonic is developed to detect and measure the crack. Three cracks with heights from 2 mm to 10 mm were accurately measured by this method.

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