SIZING OF SMALL SURFACE-BREAKING TIGHT CRACKS BY USING LASER-ULTRASONICS

M. Ochiai, T. Miura, H. Kuroda, S. Yamamoto, and T. Onodera
Toshiba Corporation, Yokohama, Kanagawa, Japan

Abstract: On the nondestructive testing, not only detection but also sizing of crack is desirable because the crack depth is one of the most important parameter to evaluate the impact of the crack to the material, to estimate crack growth and ultimately to predict lifetime of the component. Moreover, accurate measurement of the crack depth optimizes countermeasures and timing of repairs, and eventually reduces total cost for plant maintenance. Laser-ultrasonic is a technique that uses two laser beams; one with a short pulse for the generation of ultrasound and another one, long pulse or continuous, coupled to an optical interferometer for detection. The technique features a large detection bandwidth, which is important for small defect inspection. Another feature of laser-ultrasonics is the remote optical scanning of generation and detection points, which enables to inspect components in narrow space and/or having complex shapes. A purpose of this paper is to describe the performance of a laser-ultrasonic testing (LUT) system on stress corrosion cracking (SCC) inspection. We have developed a new technique for sizing shallow cracks, say 0.5-1.5mm, based on the laser-induced surface wave and its frequency analysis. First, sizing capability of the system will be demonstrated by using an artificial surface-breaking slot having depth of 0-2mm in a stainless steel plate. Evaluated depths show good agreement with the machined slot depths within the accuracy of about a few hundred micrometers. Then, SCCs in a stainless steel plate are examined by using the system. Depth of SCC is evaluated every 0.2mm over the crack aperture length. The evaluated depths are compared with the depths measured by the destructive testing.

Introduction: Laser-ultrasonics has brought practical solutions to a variety of nondestructive evaluation problems that cannot be solved by using conventional ultrasonic techniques based on piezoelectric transduction [1,2]. Laser-ultrasonics uses two lasers, one with a short pulse for the generation of ultrasound and another one, long pulse or continuous, coupled to an optical interferometer for detection. Laser-ultrasonics allows for testing at a long standoff distance and inspection of moving parts on production lines. The technique features also a large detection bandwidth, which is important for numerous applications, particularly involving small crack detection. In laser-ultrasonics, a pulsed power laser is usually used to generate ultrasonic waves. When a laser pulse is irradiated onto a sample surface, an acoustic pulse is generated due to thermoelastic or ablative interaction between laser and the material. Ablation process achieved by the irradiation of a high power laser pulse is more suitable to obtain intense ultrasonic signals. This method of excitation simultaneously generates a various ultrasonic modes; surface-skimming longitudinal waves (P), Rayleigh waves (R), bulk longitudinal waves (L) and bulk shear waves (S). These ultrasonic waves are detected by another laser combined with an optical interferometer as a micro displacement of the surface. One obvious application of laser-ultrasonics is nondestructive testing (NDT) of surface-breaking cracks and buried defects. Crack detection using R-wave, signal amplitude of which is the largest among the excited waves, had achieved success. Cooper et al. [3, 4] showed that small slits having a depth of the order of 100 μm are detectable with laser-induced R-wave in the ultrasonic pulse-echo measurements. In order to measure a depth of the slit, one possible technique based on ultrasonic mode conversion at an edge of the slit has been suggested; this technique however requires rather complicated ultrasonic propagation analysis including mode-conversion and fairy sensitive detection of weak mode-converted ultrasounds. On the other hand, the laser-induced bulk ultrasounds have been used in a non-contacting thickness gauge and delamination detection [5], rarely for small crack inspection, because the signal-to-noise ratio (SNR) of the bulk waves are relatively poor to be used for micro crack detection. In this paper, we will review a recent development in laser-ultrasonics for crack inspection on industrial materials. Frequency analysis of R-wave is used to measure the crack depth [6]. The techniques are applied on a stainless steel plate with stress corrosion cracking (SCC).

Results: An experimental setup, schematically shown in Fig.1, was used to investigate basic performances of laser-induced ultrasonic testing. Laser pulses from a Q-switched Nd: YAG laser with a maximum energy of about 100 mJ/pulse in 10 ns pulse duration and a wavelength of 532 nm, was launched onto the surface. These energies are quite intense but are still below the threshold for optical fibre delivery [7]. The laser pulses were focused into a small spot having a diameter of 400 μm to generate R-wave. The generated ultrasounds were detected as micro surface displacements using a confocal Fabry-Perot interferometer (CFPI) [8]. The detection system had a broadband frequency response extending from about 1 MHz to 100 MHz. The signal from the interferometer was converted to a digital waveform. Each waveform, representing the surface displacement, was stored into external memory for later signal processing. Trigger signal synchronized with the laser irradiation was also fed in order to identify the accurate time of ultrasounds generation.

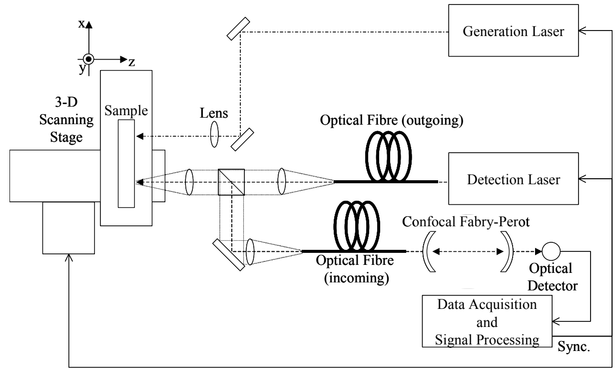

Fig.1 Experimental setup for laser-ultrasonic

A CFPI consists of two spherical mirrors having a high reflectivity arranged with their concave surface facing each other and separated by a distance, *h*, nearly equal to their curvature radius, as shown in Fig.2(a). The optical arrangement well known as an "etalon" has a sharp spectral response, as illustrated in Fig.2(b). The procedure of measuring small ultrasonic vibration using the CFPI is as follows:

(1) A single-mode laser beam is irradiated onto a vibrating surface.

(2) The original frequency, f_0 ($=c/\lambda_0$, c: velocity of light, λ_0: wavelength of light), of the reflected or scattered laser beam from the surface is modulated to $f_0 \pm f_d$ due to the Doppler effect.

(3) The frequency-shifted laser beam illuminates the CFPI maintained at point A in Fig.2(b).

(4) The output of the CFPI, which contains the signal, *I*, proportional to the velocity of the surface as illustrated in Fig.2(b), is detected by a photo-detector.

In addition, to stabilize the separation of the CFPI strictly at point A in Fig.2(b), an active control system based on the feedback control using a piezoelectric displacer (PZD) is incorporated.

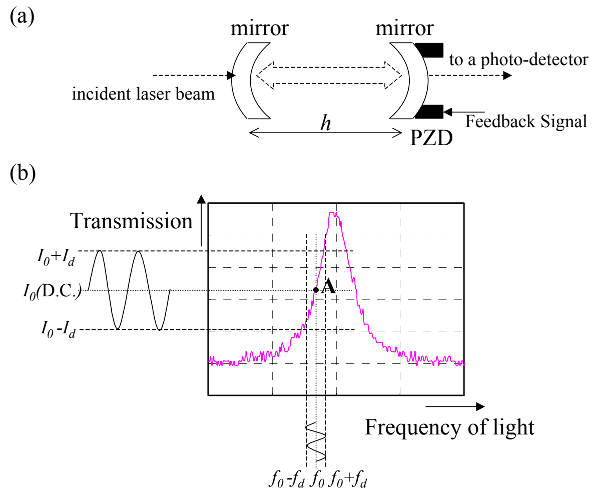

Fig.2 (a) Basic arrangement of the CFPI and (b) an example of a spectral response curve

Discussion: It is well known that surface wave travels only through the surface layer which is as thin as one wavelength of itself. Therefore, most of R-wave having higher frequency is reflected, delayed and mode-converted by the detailed geometry of a small crack. The lower frequency R-wave penetrating deeper layer is not so sensitive to the geometry; therefore, it is easier to travel over a complicated shaped crack to the other side. Since the laser ultrasonic technique allows generation and detection of wide frequency band R-wave, it would be a suitable tool for analyzing frequency response of a crack by comparing incident, reflected and transmitted R-wave. Figure 3 compares the observed waveforms transmitted from cracks having depths of from 0.2 mm to 1.5 mm. The pulse-width of transmitted R-waves tends to be wider with an increase of crack depth. This result shows that a surface slit behaves as a low pass filter (LPF) to the broadband R-wave. The cut-off frequency of the LPF depends on the slit depth. To determine the transfer characteristics of slits having a depth of d, $\boldsymbol{G_d}$, the 50th ordered moving-average (MA) model,

$$T_d(t) = \sum_{m=0}^{50} G_d(m) \cdot I_d(t-m) ,$$

is applied. Here $I(t)$ and $T(t)$ are the incident and transmitted SAW signal, respectively. The response times of calculated transfer functions, $\boldsymbol{G_d}$, are shown in Fig.3.

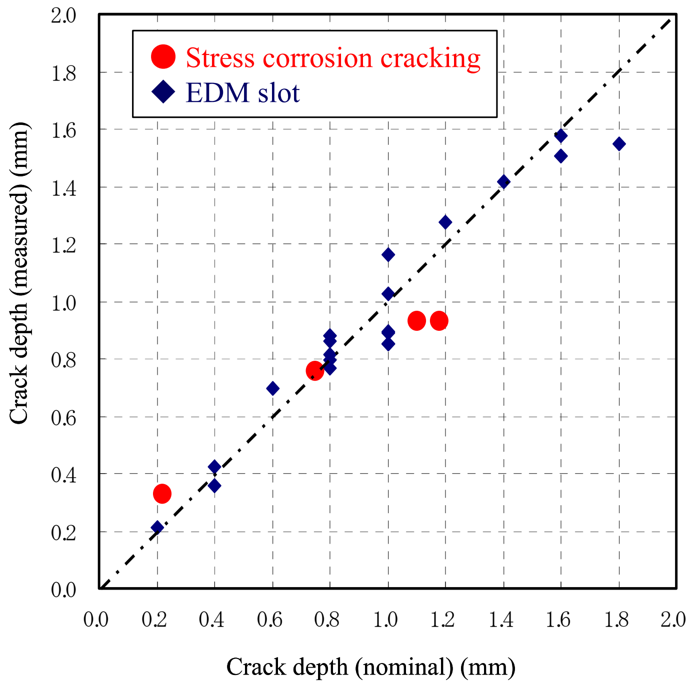

Fig.3 Crack depth measured by laser-induced surface waves

Conclusions: We have reported that a laser-ultrasonic system coupled with signal processing of frequency analysis is capable of providing valuable information on actual crack inspections. The system provides very accurate depth of shallow cracks. It should be noted that these excellent results were led by several features of laser-ultrasonics. Laser-ultrasonics is not only a technique of interest for the non-contact and/or remote inspection but also offers many other attractive features, such as:

(1) ultrasonic far-field is easily obtained,

(2) wide bandwidth and widely diverging ultrasound can be used,

(3) lower frequency ultrasound is available even when the generation spot is very small whereas it is unavailable using piezoelectric transducers,

(4) small laser spots allow higher spatial and temporal resolution, and

(5) complex shapes, which one often encountered in industrial inspection, can be scanned easily.

It should be mentioned that there are still a few outstanding issues respecting the laser-ultrasonic NDT. The technique based on the frequency analysis of R-wave, at least in the case that the present specification is used, cannot measure the depth deeper than a few mm. The penetration depth of R-wave is limited within one-wavelength of itself; it therefore means that very low frequency, e.g. 100 kHz or less, should be used to measure deeper depth.

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