学術論文

Laser-ultrasonic study of micro crack sizing and its application to nuclear reactor internals

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A new method for non-destructive testing(NDT)of surface-breaking tight cracks based on laser-induced surface acoustic waves(SAW)is proposed. A Q-switched Nd:YAG laser is used to generate SAW through ablative interaction between material and laser pulse. The SAW is probed by an optical interferometer as a micro displacement of the surface. A state-of-the-art technique in laser-ultrasonic NDT is developed: that is the crack depth measurement by using frequency analysis of laser-induced SAW transmitted through cracks. The technique allows measuring a depth of the surface-breaking tight crack ranging 0.5-1.5 mm with the standard deviation of 0.2 mm. Performance of this crack sizing technique on stress corrosion cracking(SCC) having depths of around 1 mm, are demonstrated. Also, the laser-ultrasonic NDT system developed for the inner surface inspection of bottom-mounted instrumentation(BMI)in pressurized water reactor(PWR)and its mock-up results are introduced.

Keywords : laser-ultrasonics, non-destructive testing, crack sizing, surface acoustic wave, bottom-mounted instrumentation, stress corrosion cracking, preventative maintenance, laser peening.

1. 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[1-4].

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 parts without any coupling liquid. The technique features also a large detection bandwidth, which is important for numerous applications, particularly involving small crack detection, sizing and material characterization.

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), surface acoustic waves(SAW), bulk longitudinal waves(L)and bulk shear waves(S). These ultrasonic waves are detected by another laser coupled to an optical interferometer as a micro displacement

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of the surface.

One obvious application of laser-ultrasonics is non-destructive testing (NDT) of surface-breaking cracks and buried defects[5]. Crack detection using SAW, signal amplitude of which is the largest among the excited waves by the generation laser, had initially achieved success.

Cooper et al. showed that small slits having a depth of the order of 100 μm are detectable with laser-induced SAW in the ultrasonic pulse-echo measurements[6]. 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.

In this paper, we will describe recent developments in laser-ultrasonics for crack detection and small crack depth measurement on materials used in nuclear industry.

Frequency analysis of SAW is used to measure the crack depth [7,8]. Experimental results obtained on a stainless steel plate with stress corrosion cracking (SCC) are demonstrated. Also, developed laser-ultrasonic NDT system for inner surface of bottom-mounted instrumentation (BMI) in pressurized water reactor (PWR) is introduced.

2. Setup for laser-ultrasonic NDT

A basic experimental setup for laser-ultrasonic NDT is schematically shown in Fig.1. Laser pulses from a Q-switched Nd: YAG laser with a maximum energy of about 30 mJ/pulse in 6-10 ns pulse duration and a wavelength of 532 nm, was launched onto the surface of the test piece. These energies are quite intense but are still below the threshold for optical fiber delivery [9,10]. The generation laser pulses were focused by the optical head into a diameter of about 1 mm to generate SAW. Due to the laser irradiation with this conditions, the very thin layer, within about 600 nm, of the tested surface is oxidized but no major changes are observed on surface roughness, texture and hardness. The generated SAW was detected as micro surface displacements using a detection laser (wavelength: 1,064nm) and a confocal Fabry-Perot interferometer (CFPI) [11,12]. 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 vibration, was stored into external memory for later signal processing. Trigger signal synchronized with the generation laser irradiation was also fed in order to identify the accurate time of ultrasounds generation. It is noted that the existence of water is not essential for laser-ultrasonic measurement: it is used solely to imitate inspection environment for reactor internal components.

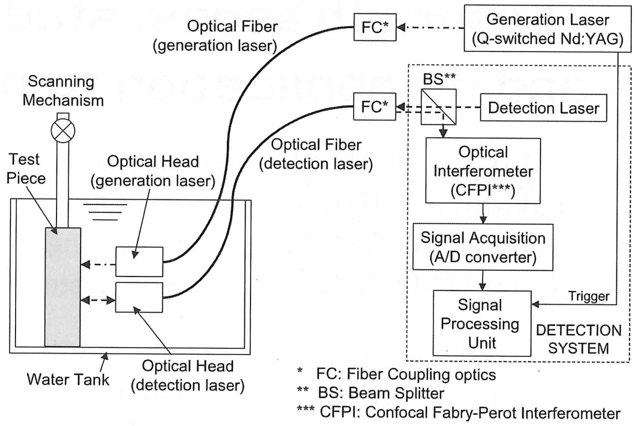


Fig.1 Experimental setup for laser-ultrasonic testing.

3. Crack depth measurement using laser-induced SAW

It is well known that SAW travels only through the surface layer which is as thin as one wavelength of itself. As shown in Fig.2 (a), most energies of SAW having higher frequency (shorter wavelength) is reflected, delayed and mode-converted according to the geometry of a small crack. On the other hand, the lower frequency SAW (longer wavelength) penetrating deeper layer is not so sensitive to the geometry; it therefore travels over cracks to the other side easier (Fig.2 (b)). As a result, the observed frequency components of the transmitted SAW depend on the crack depth. In other words, crack behaves as a low-pass filter for

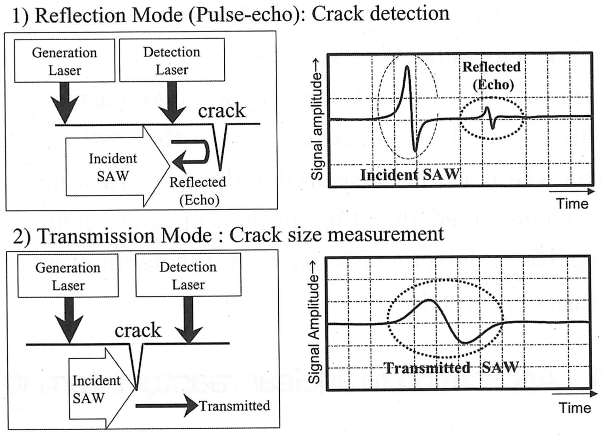


Fig.2 Schematic illustrations of (a) crack detection by using reflection of higher frequency SAW and (b) crack depth measurement by using transmission of lower frequency SAW.

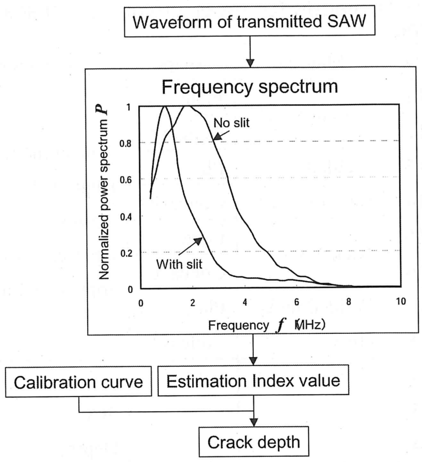


Fig.4 Signal processing flow to obtain crack depth.

SAW and its frequency response is determined by the crack depth. Since the laser-ultrasonic technique allows generation and detection of wide frequency band SAW, it should be a suitable tool for analyzing frequency response of cracks by comparing incident and transmitted SAW.

Typical waveforms of SAW transmitted through slits having depths of from 0.2 mm to 1.5 mm machined on stainless steel plates is shown in Fig.3. It is shown that the pulse-width of transmitted SAW becomes wider with an increase of crack depth.

A signal analysis process in frequency-domain shown in Fig.4 is developed to obtain the absolute crack depth. In this process, firstly, the frequency spectrum, $p_d(f)$, is calculated from the time-domain signal waveform of the transmitted SAW through a crack having a depth of d. The estimation index value (EIV) is then obtained through proper normalization, weighting and integration as shown in equation (1).

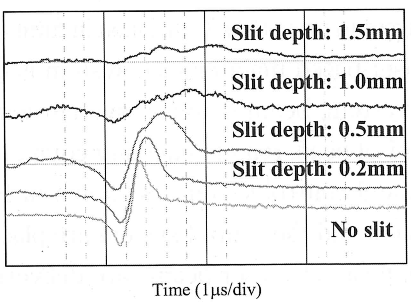


Fig.3 Typical waveforms of transmitted SAW through slits having depths of 0.2mm-1.5mm on stainless steel

$$EIV = \frac{\int_{fL}^{fH} f^{n} \cdot P_d(f)\,df}{\int_{fL}^{fH} f^{n} \cdot P_0(f)\,df} \quad (1)$$

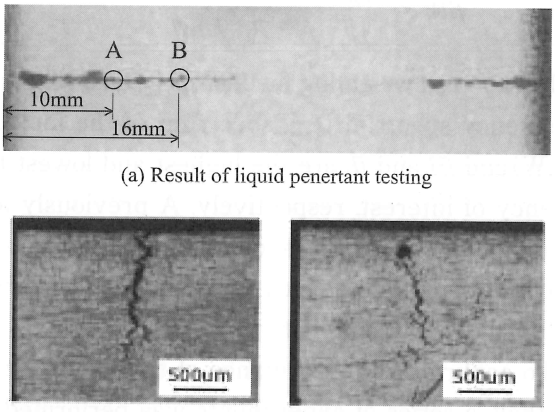
Here, f^n is a weighting function, $p_0(f)$ is a reference frequency spectrum (e.g. spectrum of the incident SAW) and fH and fL are the highest and lowest frequency of interest, respectively. A previously and properly prepared calibration curve, which indicates a relationship between crack depth and EIV is referred and finally the crack depth is obtained [13].

To confirm the performance of this crack sizing method, a series of experiments was performed on sample test pieces (T/P) as shown in Table 1. As the basic performance confirmation, 8 machined test pieces, each of which includes 3 electrical discharge machined (EDM) slits having depths of 0.5, 1.0 and 1.5 mm and width of about 0.2 mm, made of stainless steel, welded stainless steel, nickel alloy and welded nickel alloy were prepared It is noted that 2 types of T/P shape were used: one was flat plate and another was concave shape having a diameter of about 9.0 mm, which simulates the inner surface of bottom-mounted instrumentation tube as mentioned later.

Also, other 7 cracking test pieces, typically shown in Fig.5, including 14 SCCs were used to verify the performance on actual cracking. The SCCs were made by immersing the base metals into corrosive chemical solution with applying tensile stress. The result of depth measurement is shown in Fig.6. The actual crack

Table1 Test pieces for laser-ultrasonic crack sizing experiment.

T/P#	Material	Shape	Slit/Crack
LUT1	Stainless steel	Plate	3 machined slits Depth:0.5, 1.0, 1.5mm Aperture width: approx. 0.2mm
LUT2		Concave	
LUT3	Welded stainless steel	Plate	
LUT4		Concave	
LUT5	Nickel alloy	Plate	
LUT6		Concave	
LUT7	Welded nickel alloy	Plate	
LUT8		Concave	
T19	Stainless steel	Plate	SCCs Depth: Typically 1.0mm Aperture width: approx. 0.02mm
T23			
T24			
L1			
L2			
SCC03			
SCC06			



(a) Result of liquid penertant testing

(b) Cross section observation (Point A)

(c) Cross section observation (Point B)

Fig.5 Example of SCC test piece: (a) result of liquid penetran testing, (b) and (c) cross-sectional views of SCC at position A and B in Fig.5(a).

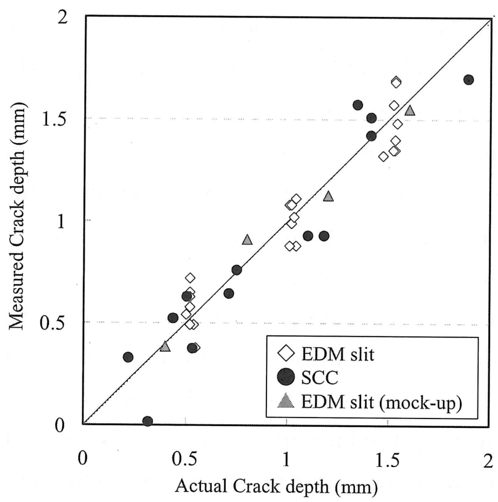


Fig.6 Crack depth measurement by laser-ultrasonics.

depth is measured by the destructive cross-section observation after the experiments.

In both cases on EDM slits and SCCs, good agreement with a standard deviation of less than 0.2 mm is achieved between measured and actual crack depth. It is confirmed that this method of crack sizing is capable to detect and to measure the depth of micro cracks accurately.

4. Application to nuclear reactor internals

The bottom-mounted instrumentation (BMI) in pressurized water reactor (PWR) consists of dozens of tube-shape structures to guide in-core neutron detectors.

The tubes are made of Alloy 600 and are welded at the bottom of the reactor vessel. Since inner surface of the each welded part has the potential of SCC initiation, proper inspection, preventive maintenance and countermeasure techniques are expected.

A novel laser-based maintenance system, which works as both the laser-ultrasonic NDT system and the laser peening system, is developed to perform both inspection and preventive maintenance on the inner surface of BMI tubes. The laser peening is a practical technique for surface stress improvement by using pulsed power laser to prevent SCC initiation [14,15]. The generation laser in the laser-ultrasonic NDT system can be identical to the laser source of the laser peening. As an example operation of the laser-based maintenance system, the laser-based maintenance system firstly works as the laser-ultrasonic NDT mode and tests the inner surface of the BMI tube. If no cracks are detected, the laser-based maintenance system then changes its work mode to the laser peening and improves surface stress to prevent SCC initiation in future operation.

The laser-based maintenance system is composed of laser system, beam delivery system with optical fibers, optical head, remote handling equipment, work platform and control system as shown in Fig.7. The laser system and the control system are placed on the operation floor. The laser beams are delivered by the optical fiber having a length of about 40 m. The remote handling equipment is hanged under the work platform

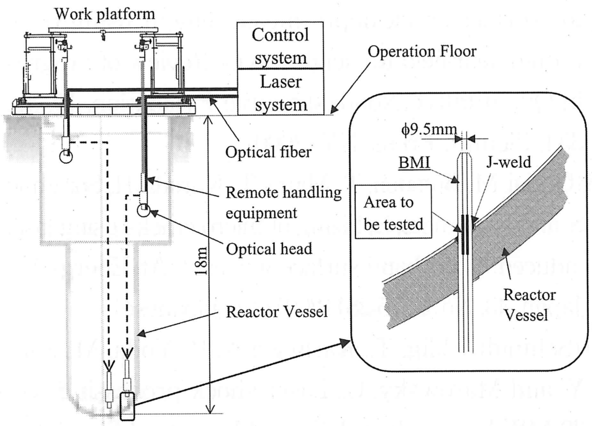


Fig.7 Laser-based maintenance system for inner surface of BMI.

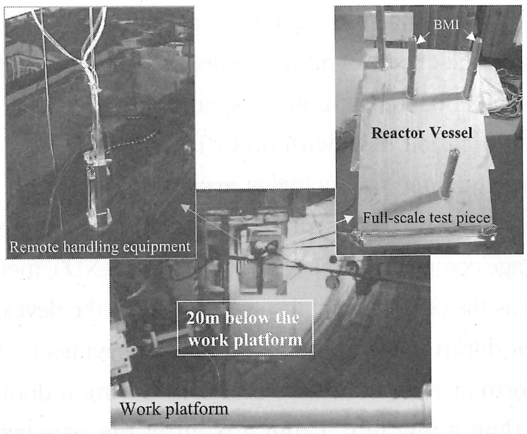


Fig.9 Full-scale mock-up experiment for laser-based maintenance system for BMI.

and is fixed on the top of the BMI tube. The optical head is inserted into the BMI tube and is scanned helically with irradiating inner surface. The axial scan rate was about 8 sec/mm in this experiment. Since the inner diameter of the BMI is very narrow, ϕ 9.5mm for example, a small optical head based on a new concept is required. The developed optical head equips with two mirrors in one housing; one reflects and collects detection laser to detect ultrasonic signals and another is used to irradiate generation laser to the tested surface, as shown in Fig.8. The generation laser and the detection laser are split at the first mirror (dichroic mirror) by their wavelengths. It should be noted that the irradiation directions of the generation and the detection laser beams are angled in order to realize the transmission mode against either axial

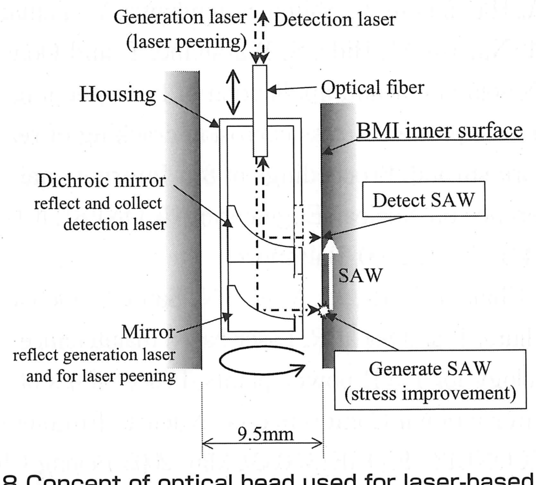


Fig.8 Concept of optical head used for laser-based maintenance on inner surface of BMI.

cracks or circumferential cracks in BMI tube. Also noted that the most of these components are shared between the laser-ultrasonic NDT and the laser peening.

A prototype of the laser-based maintenance system is produced and tested its performance in full-scale mock-up facility as shown in Fig.9. Four EDM slits, having depths of 0.4 mm, 0.8 mm, 1.2 mm and 1.6 mm respectively, are introduced on the inner surface of a BMI tube mounted on the full-scale test piece. Crack depths measured with the laser-based maintenance system are plotted in Fig.6 as grey triangles. As a result, it is confirmed that the laser-ultrasonic NDT system detects micro cracking on the inner surface of BMI tube and the depth of the cracks are successfully measured using the suggested signal processing on the transmitted SAW.

5. Conclusion

We have reported that the laser-ultrasonic NDT technique combined with signal processing based on the frequency response analysis is capable of providing very accurate depth of micro cracks including actual SCCs. Also, the laser-ultrasonic NDT system for the inner surface of BMI tubes is developed and its performance is verified through full-scale mock-up experiments.

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-contacting remote inspection without any coupling liquid but also offers many other attractive features, such as:

1) wide bandwidth ultrasound can be used,
2) small laser spots allow inspection on the contour surface located in limited space, and
3) combination uses with other laser-based maintenance technologies are easily achieved.

Particularly, the third feature gives a distinctive advantage compared to the other conventional NDT method, such as the eddy current testing. In addition, the developed crack depth measurement technique provides its best performance on the micro cracking having a depth of less than a few mm. From a point of the penetration depth, very low frequency, e.g. the order of 100 kHz, should be used to measure deeper depth.

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