Laser-Ultrasonic Non-Destructive Testing:

Techniques and Applications in Nuclear Industry

Makoto OCHIAI Power and Industrial Systems R&D Center, Toshiba Corp. Non Member
Takahiro MIURA Power and Industrial Systems R&D Center, Toshiba Corp. Non Member
Satoshi YAMAMOTO Isogo Engineering Center, Toshiba Corp. Non Member
Toru ONODERA Power and Industrial Systems R&D Center, Toshiba Corp. Non Member

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 the laser pulses. 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 reviewed: that is the crack depth measurement by using frequency analysis of SAW transmitted through cracks. The technique allows measuring a depth of the surface-breaking micro crack ranging 0.5-1.5 mm with the standard deviation of 0.2 mm. Performance on crack depth measurements with the stress corrosion cracking (SCC), having depths of around 1 mm, are demonstrated. Also, the laser-ultrasonic NDT system developed for the inner surface of bottom-mounted instrumentation (BMI) 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 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 [5]. Crack detection using SAW, signal amplitude of which is the largest among the excited waves, had initially achieved success. Cooper et al. [6] showed that small slits having a depth of the order of 100 mm are detectable with laser-induced SAW in the ultrasonic pulse-echo measurements. In order to measure a depth of the slit, one possible technique based on ultrasonic mode

---

POC: Makoto OCHIAI, Sinsugita-cho 8, Isogo-ku, Yokohama, 235-8523, Power and Industrial Systems R&D Center, Toshiba Corporation, Tel:045-770-2307, e-mail: mak.ochiai@toshiba.co.jp

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 review 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 testing

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. The generated SAW was detected as micro surface displacements using 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 displacement, 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 this measurement: it is used solely to imitate inspection environment for reactor internal components.

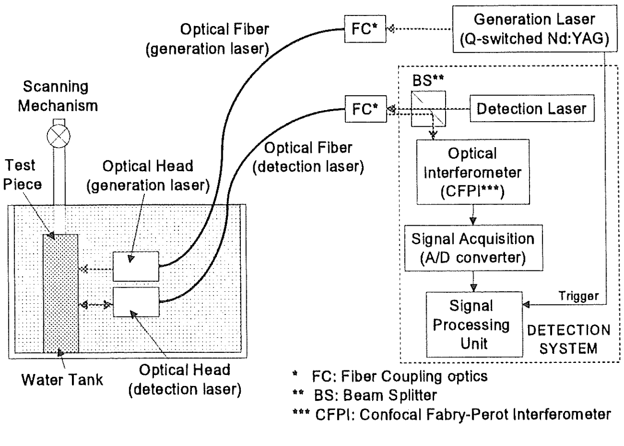


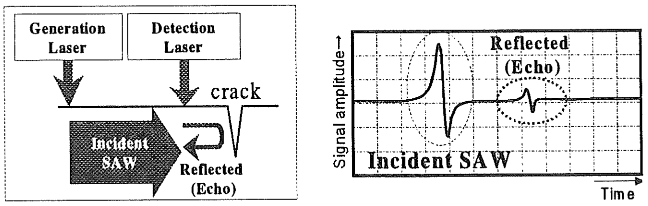
Fig.1 Experimental setup for laser-ultrasonic testing

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, 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 easily travels over cracks to the other side.

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.

(a) Reflection Mode (crack detection)



(b) Transmission Mode (crack depth measurement)

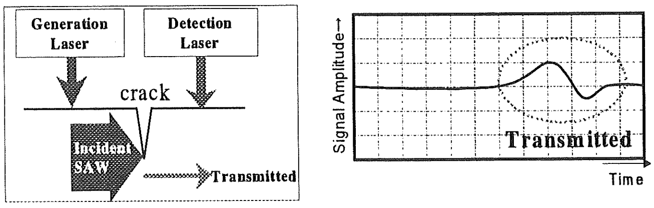


Fig.2 Schematic illustrations of (a) crack detection by using reflection of higher frequency SAW and (b) crack depth measurement by using transmission of lower frequency SAW

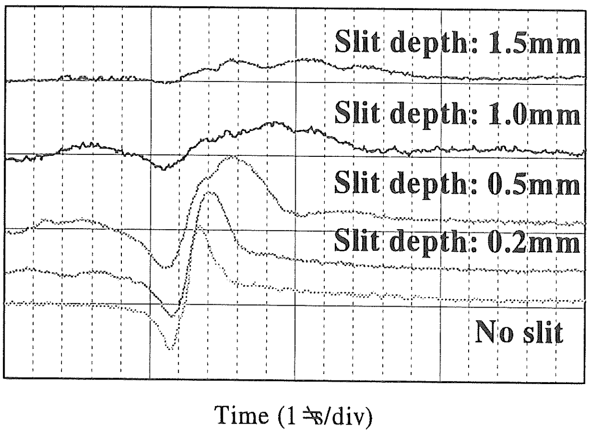


Fig.3 Typical waveforms of transmitted SAW through slits having depths of 0.2mm-1.5mm on stainless steel

Typical waveforms transmitted through cracks having depths of from 0.2 mm to 1.5 mm machined on stainless steel plates is shown in Fig.3. The pulse-width of transmitted SAW becomes wider with an increase of crack depth. This result shows that crack behaves as a low pass filter (LPF) to the broadband SAW. The cut-off frequency of this LPF should be related to the slit 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).

$$EIV = \frac{\int_{fL}^{fH} f^n \, p_d(f)df}{\int_{fL}^{fH} f^n \, p_0(f)df} \qquad (1)$$

Here, f^n is a weighting function, $p_0(f)$ is a reference frequency spectrum 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.

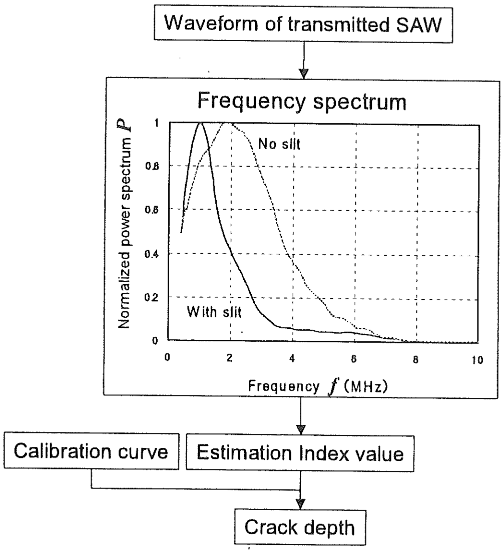


Fig.4 Signal processing flow to obtain crack depth

To confirm the performance of this crack sizing method, a series of experiments is performed on 8 machined test pieces, each of which includes 3 slits having depth of 0.5, 1.0 and 1.5mm, made of stainless steel, welded stainless steel, nickel alloy and welded nickel alloy and other 7 cracking test pieces including 14 SCCs, as shown in Table1. The result of depth measurement is shown in Fig.5. The actual crack 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

Table 1 Test pieces for laser-ultrasonic crack sizing experiment

T/P#	Material	Shape	Slit/Crack
LUT1	Stainless steel	Plate	3 EDM slits (depths of 0.5, 1.0 and 1.5mm)
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
T23			
T24			
L1			
L2			
SCC06			
SCC03			

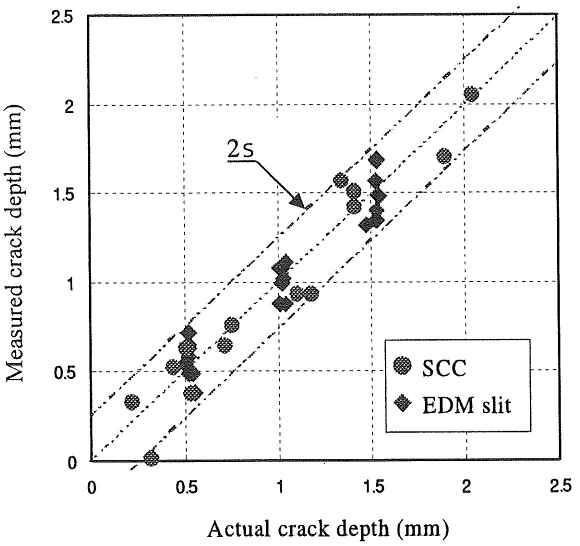


Fig.5 Crack depth measurement by laser-ultrasonics

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.

4. Application to actual reactor internals

The bottom-mounted instrumentation (BMI) in 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 new laser-based preventive maintenance system, which includes the laser-ultrasonic NDT system and the laser peening system [13,14] is developed to perform both inspection and stress improvement on the inner surface of BMI tubes. As shown in Fig.6, the laser-based preventive maintenance system is composed of laser system, beam delivery system with an optical fiber, an optical head, a remote handling equipment and a monitor/control system. The laser system and the monitor/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 and is fixed on the top of the BMI tube. The optical head is inserted in the BMI tube and is rotated and traversed vertically with irradiating inner surface helically. Since the inner diameter of the BMI is very narrow, f9.5mm 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 is used to irradiate generation laser to the tested surface and another reflects and collects detection laser to detect ultrasonic signals, as shown in Fig.7.

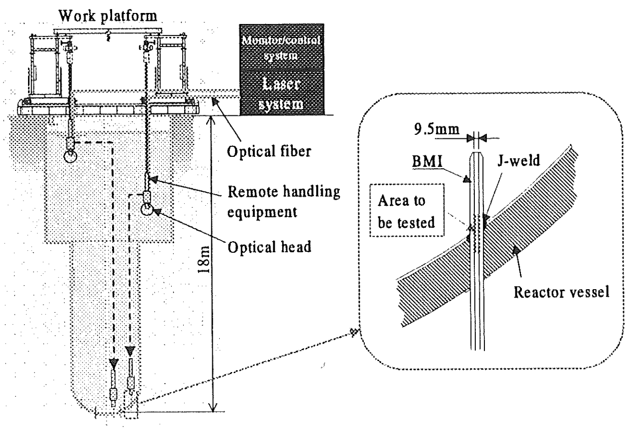


Fig.6 Laser-based preventive maintenance system for

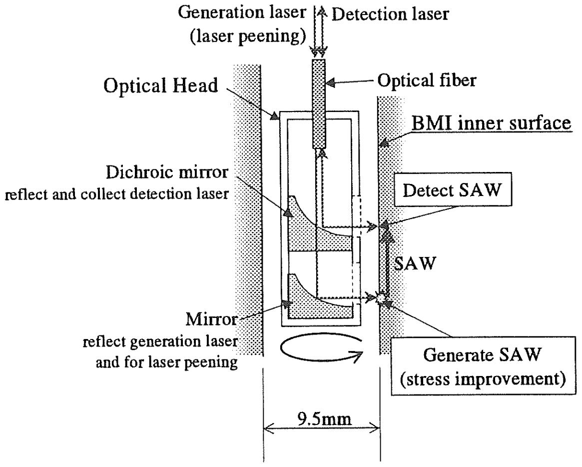


Fig.7 Concept of optical head used for laser-based maintenance on inner surface of BMI

A prototype of the laser-based preventive maintenance system is produced and tested its performance in full-scale mock-up facility as shown in Fig.8. As a result, it is

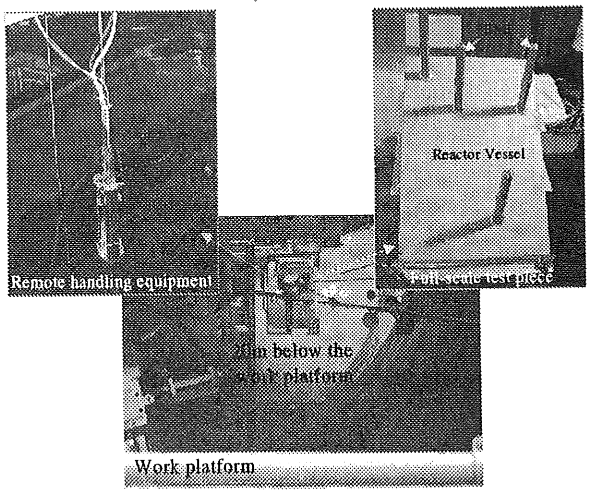


Fig.8 Full-scale mock-up experiment for laser-based

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 coupled 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.

The crack depth measurement technique based on the frequency analysis of laser-induced SAW provides its best performance on the micro cracking having a depth of 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.

References

[1] Scruby, C.B. and Drain, L. E., *Laser-ultrasonics: techniques and applications*, Adam Hilger, Bristol, UK (1990).

[2] Monchalin, J. -P., Progress towards the application of laser-ultrasonics in industry, *Review of Progress in Quantitative Nondestructive Evaluation*, **12**, 495-506, Plenum Press, NY (1993).

[3] Choquet, M., Heon, R., Padioleau, C., Bouchard, P., Neron, C. and Monchalin, J. –P., Laser-ultrasonic inspection of the composite structure of an aircraft in a maintenance hanger, *Review of Progress in Quantitative Nondestructive Evaluation*, **14**, 545-552, Plenum Press, NY (1995).

[4] Monchalin, J. –P., Neron, C., Bussiere, J. –F., Bouchard, P., Padioleau, C., Heon, R. and Choquet, M., Laser-ultrasonics: From the laboratory to the shop floor, *CSNDT journal*, Sept/Oct, 5-26, 1997

[5] Ochiai, M., Levesque, D., Talbot, R., Blouin, A., Fukumoto, A. and Monchalin, J. –P., Detection and characterization of discontinuities in stainless steel by the laser ultrasonic synthetic aperture focusing technique, *Mater. Eval.*, **62**, No.4, 450-459

[6] Cooper, J. A.., Crosbie, R. A., Dewhurst, R. J., McKie A. D. W. and Palmer, S. B., Surface acoustic wave interactions with cracks and slots: a noncontacting study using lasers, *IEEE Trans. UFFC*, *UFFC-33*, No.5, 462-470 (1986)

[7] Scala, C. M. and Bowles, S. J., Laser ultrasoniccs for surface-crack depth measurement using transmitted near-field Rayleigh waves, *Review of Progress in Quantitative Nondestructive Evaluation*, **19**, 327-334, Plenum Press, NY (2000).

[8] Ochiai, M., Butsuen, T., Miura, T., Kuroda, H., Soramoto, S. and Kanemoto, S., Sizing of micro cracks using laser-induced broad-band surface waves, *J. At. Energy Soc. Japan*, **43**, No.3, 275-281(2001) (in Japanese)

[9] Schmidt-Uhlig, T., Karlitschek, P., Yoda, M., Sano, Y. and Marowsky, G., Laser shock processing with 20 MW laser pulses delivered by optical fibers, *Eur. Phys. J. AP.*, **9**, No.3, 235-238 (2000)

[10] Yoda, M., Sano, Y., Schmidt-Uhlig, T. and Marowsky, G., Fiber delivery of 20 MW laser pulses and its applications, *Review of laser engineering*, 28, No.5, 309-313 (2000) (in Japanese)

[11] Monchalin, J. -P. and Heon, R., Laser ultrasonic generation and optical detection with a confocal Fabry-Perot interfereometer, *Mater. Eval.*, **44**, No.9, 1231-1237

[12] Shan, Q., Bradford, A. S. and Dewhurst, R. J., New field formulas for the Fabry-Perot interferometer and their application to ultrasound detection, *Meas. Sci. Technol.*, **9**, 24-37 (1998)

[13] Sano, Y., and Kimura, M., Sato, K., Obata, M., Sudo, A., Hamamoto, Y., Shima, S., Ichikawa, Y., Yamazaki, H.,

Naruse, M., Hida, S., Watanabe, T. and Oono, Y., Development and application of laser peening system to prevent stress corrosion cracking of reactor core shroud, *Proceedings of 8th International Conference on Nuclear Engineering (ICONE8)*, ICONE-8441, April, 2000, Baltimore

[14] Chida, I., Yoda, M., Mukai, N., Sano, Y., Ochiai, M., Miura, T. and Saeki, R., Laser based maintenance technology for PWR power plants, *Proceedings of 13th International Conference on Nuclear Engineering (ICONE13)*, ICONE13-50334, May, 2005, Beijing, China