Development of a Fibre-Phased Array Laser-EMAT Ultrasonic System for Defect Inspection

C Pei[1,2], K Demachi[1], T Fukuchi[3], K Koyama[1], M Uesaka[1] and Z Chen[2]

[1]School of Engineering, The University of Tokyo, Tokyo 113-0032, Japan
[2]School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China
[3]Electric Power Engineering Research Laboratory, Central Research Institute of Electric Power Industry, Yokosuka-Shi, Kanagawa 240-0196, Japan

Email: peicx2009@gmail.com

Abstract. In this work, a phased array laser ultrasound system with using fibre optic delivery and a custom-designed focusing objective lens has been developed for enhancing the ultrasound generation. The fibre-phased array method is applied to improve the sensitivity and detecting ability of the laser-EMAT system for defect inspection.

1. Introduction
The laser-generated ultrasound has been widely studied in various ultrasonic testing techniques, such as laser ultrasonic [1-3] and laser-EMAT ultrasonic [4, 5]. And, it is known that the ultrasonic wave can be generated in thermo-elastic regime or in ablation regime when laser power density is less or larger than the material melting threshold. However the potential ablation damage on the material surface can be minimized in the thermo-elastic regime, one of the principle disadvantages of laser ultrasonic is the low signal strength for thermo-elastically generated ultrasound. To overcome this problem, one of the most efficient ways is using the phased-array (PA) method with a multi-beam laser source [6, 7]. Besides, the PA method can also be used to steer the ultrasonic wave into the area which we are interested on. Until now, two methods of PA laser ultrasound have been mainly reported. One is based on using an optical fiber phased array [6]; and the other one is based on using an array of laser sources [7]. The advantage of using fibers over multiple laser sources is that the fiber is much cheaper, portable and flexible, and only a single laser is needed to provide multiple sources.

A combination of laser ultrasonics with time-of-flight diffraction (TOFD) measurement has been already reported in a few literatures [2, 3]. However, in those works, the ultrasound in ablation regime was used in the measurement. In this work, a PA laser ultrasound system with using fiber optic delivery and a custom-designed focusing objective lens is developed to improve the sensitivity and detecting ability for defect inspection by enhancing the ultrasound generation. The enhanced laser ultrasound in thermoelastic regime is studied for TOFD measurement of cracks in different specimens without ablation damage.

2. Experimental system and method

2.1. Overall system design and setup

As shown in Fig. 1, the phased array laser ultrasound system was constructed with a Q-switched Nd:YAG laser (providing pulses with duration of 10 ns at a repetition rate of 10 Hz) and a three-source fiber-phased array. Three laser beams from the two beam splitters, each with pulse energy up to 10 mJ was coupled into three 400 μm diameter silica-silica fibers with fiber couplers. The length of the three fibers measure are 2.5 m, 42.5 m and 82.5 m, respectively, resulting in a time delay of 0.194 μs. The distal ends of the fibers are connected with a custom-designed focusing objective lens to generate a laser array (three line sources with given dimensions) on the surface of a specimen. The width and length of each laser array element focused on the specimen surface are around 0.8 mm and 10 mm, respectively. The separation between each element is about 1.5 mm. Therefore, a series of ultrasound pulses generated by each laser array element at slightly different time would combine together to add energy at a steering direction. The enhanced ultrasonic waves generated by the laser array were received by an electromagnetic acoustic transducer (EMAT) that was mounted about 0.5 ± 0.1 mm above the specimen surface. Two EMATs, an out-of-plane EMAT and an in-plane EMAT [8], were applied for the ultrasound detection.

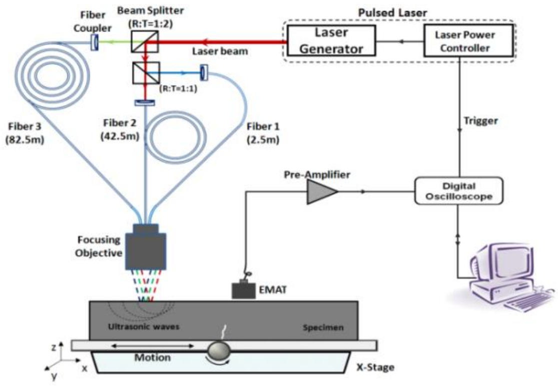

Fig. 1 Schematic diagram of the fiber-phased array laser-EMAT ultrasonic testing system

2.2. Measurement method

The schematic diagram of measurement of cracks with using PA laser ultrasound and EMAT detection by TOFD method is shown in Fig. 2. Unlike the conventional symmetrical TOFD layout, a laser beam and an EMAT (in-plane EMAT or out-of-plane EMAT) in an unsymmetrical arrangement are used as a generator and detector, respectively, in this work. The main reason of this modification is that the out-of-plane EMAT detector has the best sensitivity to the longitudinal wave (and the in-plane EMAT detector has the best sensitivity to the shear wave) propagating perpendicularly to the receiving area. Besides, in the modified setup, the diffraction wave has shorter travelling path. So it can be detected in larger amplitude. Therefore, a much stronger diffraction signal can be acquired when the EMAT is just above the crack. The ultrasonic transmission modes and paths are also shown in the figure. With laser-EMAT ultrasonic, it is possible to accurately measure the absolute propagation time of the different waves. Therefore, the depth of the crack tip in the specimen can be obtained by either Eq. (1) or Eq. (2):

$$d = C_L \cdot \frac{t_{LTL}^2 - t_{La}^2}{2t_{LTL}} \tag{1}$$

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

where d is the depth of the crack top tip in the specimen, C_L the velocity of L wave, C_S the velocity of S wave, and t_{La}, t_{LTL} and t_{LTS} are the time of flight of La, LTL and LTS, respectively. LTL is a crack-tip-diffracted longitudinal wave and LTS is a longitudinal-shear mode-converted wave diffracted on the crack tip. Therefore, both LTL and LTS can be applied for the TOFD measurement of cracks. LBL 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.

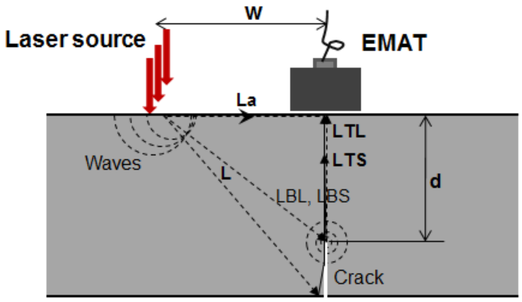

Fig. 2 Schematic diagram of ultrasonic transmission modes and path for crack measurement

3. Measurement results

In order to validate the performance of this system for defect inspection, a measurement of inner-surface cracks in a stainless steel specimen (SUS304) and an aluminum (99.3%) specimen by TOFD method has been studied. Each specimen was a plate (200mm×80mm and 20 mm thick) with three electrical discharge machining (EDM) cracks at the rear side (with positions of 50 mm, 100 mm and 150 mm). The three cracks with a width of 0.2 mm and heights of 10 mm, 5 mm and 2 mm, respectively, were induced entirely through the specimen width. During the experiment, it is found that the measured signal amplitude of LTL diffraction wave is much larger than that of LTS wave in the steel specimen. Conversely, the measured signal amplitude of LTS wave is much larger than that of LTL wave in the aluminum specimen.

Fig. 3 shows the A-scan signals of TOFD measurement of the 10 mm crack in the steel specimen with using a single laser beam and three PA laser beams, respectively. In this measurement, an out-of-plane EMAT was used as the receiver with a separation distance of 28 mm from the laser source. It can be observed that LTL diffraction wave from the crack tip does not present in the waveform generated by a single laser beam, but can be identified in the waveform generated by three PA beams.

Fig. 4 shows the A-scan signals of TOFD measurement of a 10 mm crack in the aluminum specimen with using a single laser beam and three PA laser beams, respectively. In this measurement, an in-plane EMAT was used as the receiver with a separation distance of 22 mm from the laser source. As an in-plane EMAT was used here, the crack diffraction signal LTS can be identified in the waveforms. Besides, as aluminum is a more conductive material, much stronger signals can be received by the EMAT. It can also be observed that the signal-to-noise ratios (SNRs) of LTS signal with three PA laser sources is significantly improved. It is also can be observed in Figs. 3 and 4 that the SNRs in aluminum specimen are much larger than that in steel specimen. This is because EMAT detectors have larger sensitivity in aluminum which is more conductive than steel.

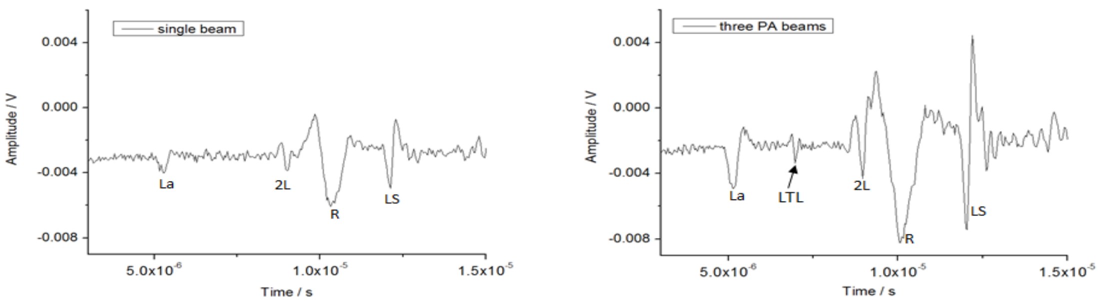

Fig. 3 A-scan signals picked up by an out-of-plane EMAT for 10 mm crack in the steel specimen with a single laser beam, and three PA laser beams

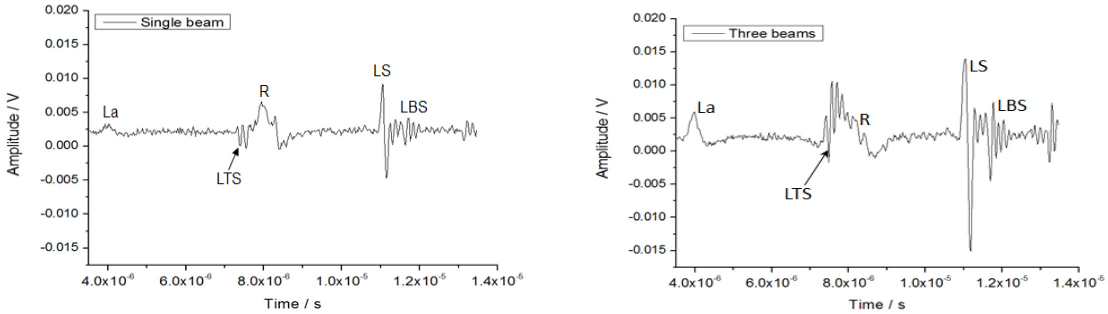

Fig. 4 A-scan signals picked up by in-plane EMAT for 10 mm crack in the aluminium specimen with a single laser beam, and three PA laser beams

Fig. 5 shows the B-scan images of the TOFD measurement by scanning the steel specimen and aluminium specimen, respectively, with using three PA laser beams. The scanning position x is the position of EMAT detector. Beside the lateral wave La, longitudinal echoes 2L and LBL, Rayleigh wave R, mode-converted echo LS, the three diffracted signals LTL_1, LTL_2 and LTL_3 induced by the 10 mm Crack, 5mm Crack and 2 mm Crack, respectively, in the stainless steel were received by the out-of-plane EMAT. The three diffracted signals LTS_1, LTS_2 and LTS_3 induced by the 10 mm Crack, 5mm Crack and 2 mm Crack, respectively, in the aluminium specimen were received by the in-plane EMAT. All these crack signals can be identified clearly.

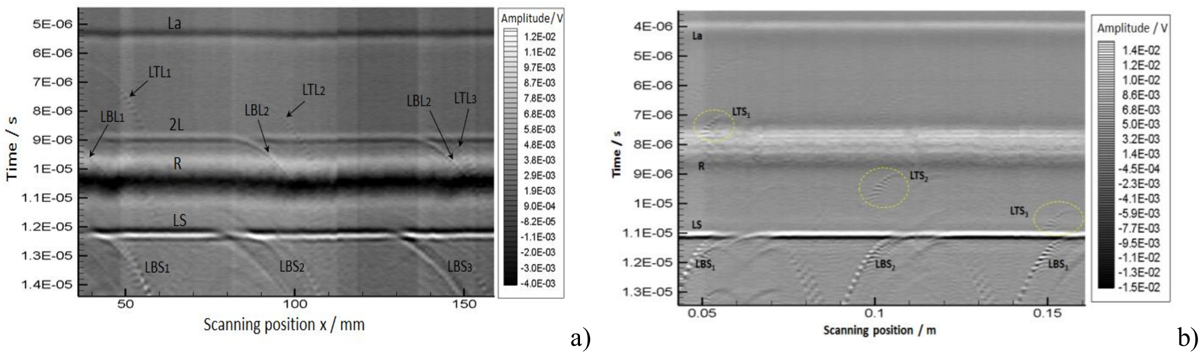

Fig. 5 Result of B-scan image of TOFD measurement with using three PA laser beams in a) stainless steel specimen, b) aluminum specimen

As shown in Fig. 4 and Fig. 5, the time of flight t_{La}, t_{LTL} or t_{LTS} for the cracks can be measured, respectively. In Fig. 5, it can be observed that the EMAT is just above the cracks at the center of the diffraction signal patterns. And the diffracted signal has relatively larger strength when the EMAT detector is just above the crack. According to the modified TOFD layout, the depth of crack tip in the specimen can be solved by Eq. (1) or Eq. (2). 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. Table 1 shows the results of crack height evaluation in the stainless steel specimen and aluminum specimen, respectively. It can be observed that all the measurement results are very close to the actual ones.

Table 1 Results of crack height evaluation in steel and aluminium specimens

Actual crack height / mm	Measured height in steel specimen / mm	Measured height in Al specimen / mm
2	2.25	2.26
5	5.40	5.20
10	9.72	9.81

4. Conclusions

A phased-array laser ultrasound system using optical fiber delivery and a custom-designed focusing objective lens has been developed for enhancing the ultrasound generation. The enhancement of crack inspection by using phased array laser ultrasound is validated by experiment. This system was successfully applied to measure the inner-surface cracks both in the stainless steel specimen and aluminum specimen with TOFD method. The diffraction signals from the three EDM cracks with heights from 2 mm to 10 mm can be clearly identified both in the two kinds of specimen. The heights of the three cracks are precisely evaluated from the time of flight of the diffraction waves. It shows that the fiber-phased array laser-EMAT ultrasonic is a very promising non-contact approach for defect measurement.

References

[1] C. B. Scruby and L. E. Drain 1990 Laser Ultrasonics: Techniques and Applications
[2] Q. Shan and R. J. Dewhurst 1993 Applied Physics Letters vol 62 p 2649
[3] T. Mihara, Y. Otsuka, H. Cho, K. Yamanaka 2000 Review of Progress in Quantitative Nondestructive Evaluation vol 19 p 255
[4] D. A. Hutchins, F. Hauser and T. Goetz 1986 IEEE Trans. Ultrason. Ferroelectr. and Freq. Cont. vol 33 p 478
[5] P. R. Murray, R.J. Dewhurst 2002 J. Ultrasonics vol 40 p 771
[6] Bruinsma, A. J.A., and Vogel J.A. 1988 Applied Optics. Vol 27 p 4690
[7] T.W. Murray, J.B. Deaton Jr., J.W. Wagner 1996 J. Ultrasonics vol 34 p 69
[8] B. Dutton, S. Boonsang, and R. J. Dewhurst 2006 Sens. Actuators A vol 125 p 249