論文の内容の要旨

論文題目 Development of an Enhanced Laser-EMAT UT Technique
and Its Application for Inner Defect Inspection
(強化レーザー/EMAT 超音波技術の開発と材料内部の
欠陥検査への応用)

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1. Introduction and Summary

As ultrasonic waves can propagate through material very efficiently and not harmful to humans, ultrasonic testing (UT) is one of the most important non-destructive testing (NDT) techniques that are routinely used in the inspection of nuclear power plants as well as in many other important industry areas.

Laser-EMAT UT technique, taking advantages of the laser generation and EMAT detection, has been demonstrated as a very promising non-contact UT method. In this work, a high-performance laser-EMAT UT system is developed and studied for inner defect inspection in metal structures. For the optimization of the laser-EMAT UT technique and the development of new methods for inner defect inspection, a high efficient numerical code for the simulation of laser ultrasound is developed. To precisely measure the internal volume defects and inner cracks in the structures with a non-contact UT method, two new methods based on laser-EMAT technique are proposed in this work. To forward improve the performance of the laser-EMAT UT technique, a multi-beam lase source with using a fiber phased array is developed to enhance the signal strength of the laser-induced ultrasonic waves.

2. Development of Laser-EMAT UT System

The overall experiment setup is shown below in the schematic diagram of Fig. 1. A single-mode pulsed laser with duration of 10 ns and a wavelength of 1064 nm, generated by a Q-switched Nd-YAG laser was directed and focused onto the specimen surface by a cylindrical lens to generate ultrasonic waves in the specimen. Two custom-designed EMAT detectors, an in-plane EMAT and an out-of-plane EMAT, were developed for the measurement of laser-induced ultrasonic wave.

3. Improvement of Simulation Method for Laser Ultrasound

Based on the thermo-elastic mechanism for the ultrasound generation, an improved simulation method based on finite element method (FEM) is developed for the simulation of laser-induced ultrasonic waves.

$$\left[[K](1-\zeta)+\frac{[C]}{\Delta t}\right]\{T\}_{t+\Delta t}=\{Q\}_{t+\Delta t}+\left[\frac{[C]}{\Delta t}-\zeta[K]\right]\{T\}_{t} \qquad (1)$$

$$\begin{cases}\{\dot{U}\}_{t+\Delta t}=\{\dot{U}\}_{t-\Delta t}-2\Delta t[M]^{-1}[D]\{\dot{U}\}_{t}-2\Delta t[M]^{-1}[S]\{U\}_{t}+2\Delta t[M]^{-1}\{F\}_{t} \\ \{U\}_{t+\Delta t}=\{U\}_{t}+\dfrac{\{\dot{U}\}_{t+\Delta t}+\{\dot{U}\}_{t}}{2}\Delta t\end{cases} \qquad (2)$$

where [K] and [C] are the conductivity matrix and heat capacity matrix, respectively, {T} the temperature vector, {Q} the heat source vector. [M], [D] and [S] are the mass matrix, damping matrix and stiffness matrix, respectively, {U} the displacement vector, and {F} the thermo-elastic force. Combined with the one dimensional compressing data storage technique, the data operand and memory cost in the improved method are significantly reduced.

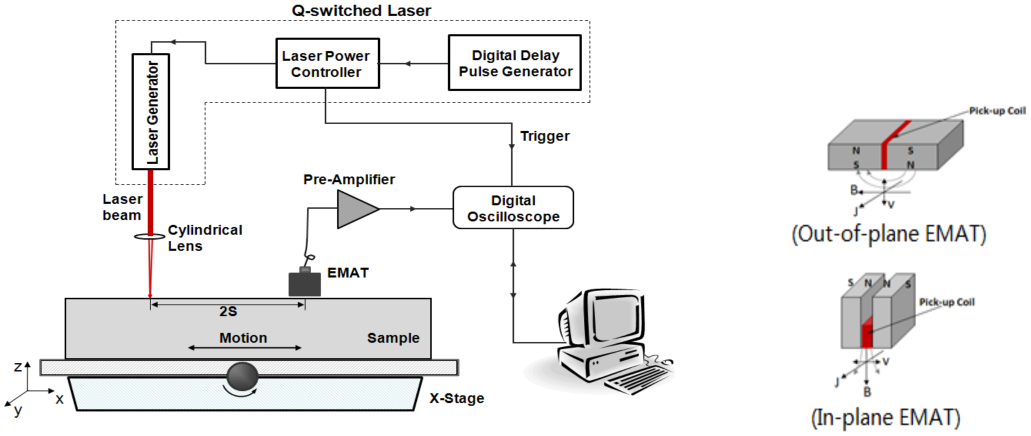

Fig. 1 Schematic diagram of overall setup of the laser- EMAT UT system and EMAT construction

4. Two Proposed Methods for Inner Defect Inspection with Laser-EMAT UT System

4.1 Laser-EMAT TOF S-SCS Method for Internal Defect Measurement

The interaction of laser-generated ultrasonic waves with the internal volume defect in the material is analyzed by simulation. Not only the directly scattered shear wave SS but also the shear-creeping-shear mode-converted wave SCS on the defect surface has been observed, when the defect diameter is larger than 0.3 mm. Based on the observed results in the simulation, a laser-EAMT TOF S-SCS method based on quantitative time of flight (TOF) analysis of the SS wave and SCS mode-converted wave is proposed to quickly evaluate the defect size, as shown in Fig. 2. Based on the propagation paths of the defect signals SS and SRS, the boundary length of the defect can be given by

$$l = \pi d \approx \frac{2\pi C_S C_{R'}}{\pi C_S + C_{R'}} \cdot \Delta t \tag{3}$$

where Δt is the time interval between the SCS and SS, C_S and $C_{R'}$ are the propagation velocity of shear waves and creeping waves, respectively. The boundary lengths of the cross sections of four holes with diameter from 1 mm to 3 mm in an aluminum specimen were successfully measured with the proposed method.

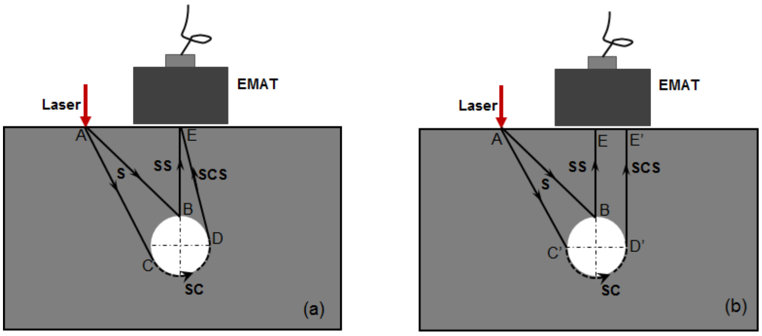

Fig. 2 Schematic diagram of ultrasonic transmission modes and paths for internal defect measurement with laser-EMAT TOF S-SCS method: (a) actual paths, (b) simplified paths

4.2 Laser-EMAT TOFD Method for Inner Crack Measurement

A modified time-of-flight diffraction (TOFD) method based on laser-EMAT ultrasonic is developed to detect and measure the crack, as shown in Fig. 3, where L is an incident longitudinal wave, S is an incident shear wave, LTL is a crack-tip-diffracted longitudinal wave, LTS is a mode-converted diffracted wave at the crack tip. Based on the simulation and experiment results, the LTS mode-converted wave is recommended to be applied in the aluminum specimen, while the LTL wave is recommended to be applied in the stainless steel specimen. Therefore, the depth of the crack tip in the steel or aluminum specimen can be obtained by Eq. (4) or Eq. (5).

$$d = C_L \cdot \frac{t_{LTL}^2 - t_{La}^2}{2t_{LTL}} \tag{4}$$

$$d = C_L C_S \cdot \frac{C_L t_{LTS} - \sqrt{C_S^2 t_{LTS}^2 + (C_L - C_S) t_{La}^2}}{C_L^2 - C_S^2} \tag{5}$$

where t_{La}, t_{LTL} and t_{LTS} are the arrival time of lateral longitudinal, LTL and LTS, C_L and C_S are the velocities of longitudinal wave and shear wave, respectively.

Three artificial cracks with heights of 2 mm, 5 mm and 10 mm in a 20 mm-thick aluminum specimen is detected and precisely measured by this method.

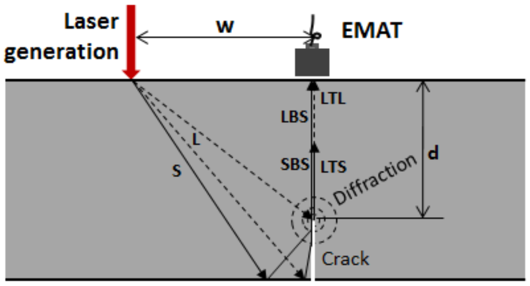

Fig. 3 Schematic diagram of laser-EMAT TOFD method

5. Development of Fiber Phased Array Laser-EMAT System and Its Application

In real application, much stronger signals are needed to compensate for ultrasound attenuation in thick, hot specimen, or compensate the decrease of EMAT sensitivity for material with relatively low conductivity. As shown in Fig. 4, a multi-beam laser source with using three fiber phases is developed to enhance the ultrasound signal strength in the laser-EMAT UT system. The experiment results show that the SNR of the laser-EMAT system can be increased by two times with using the fiber phased array source. Finally, the fiber phased array technique is applied to improve the sensitivity and detecting ability of the laser-EMAT system for inner defect inspection. The SNR of the crack measurement results in the aluminum specimen by the laser-EMAT TOFD method are significantly improved by using the fiber phased-array laser source. The fiber phased array laser-EMAT system is also successfully applied to measure cracks in a stainless steel specimen by shadow method and TOFD method.

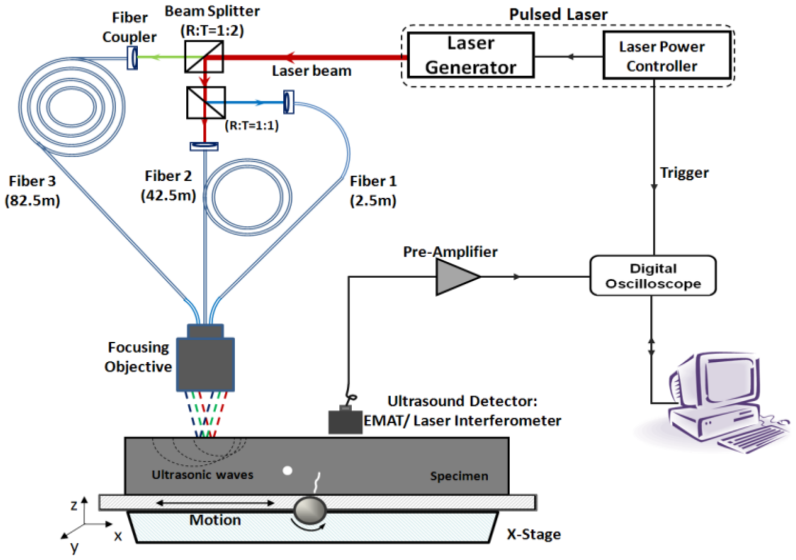

Fig. 4 Schematic diagram of fiber phased array laser-EMAT UT system