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Application of laser ultrasonic technique for non-contact detection of structural surface-breaking cracks

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ABSTRACT

Based on the finite element method (FEM), the surface-breaking cracks have been investigated by using the laser-generated Rayleigh wave. The features of laser-generated Rayleigh wave interaction with cracks are analyzed in time and frequency domain. The simulation results show that the surface acoustic wave induced by the pulsed laser is sensitive to the surface-breaking cracks. As the crack depth increases, the transmission coefficients almost linearly decrease and the reflection coefficients show a dip. The corresponding experimental results have verified the feasibility of numerical calculation and reached a good agreement with simulation results. The research findings would provide a potential application for testing surface-breaking cracks of aircraft parts.

1. Introduction

Surface-breaking crack is a typical defect in metallic structural surface that is subjected to complex and cyclic loading. For example, surface fatigue cracks often appear in aero-engine blades during service because of their working conditions [1,2]. The surface-breaking crack growth threatens the safety of material and structure, and would result in serious consequences such as casualties and significant financial losses [3]. Therefore, more comprehensive attention has been taken to non-destructive testing (NDT) methods characterized by high precision and non-contact which can be applied for the inspection of surface-breaking cracks.

Laser ultrasonic technique (LUT) is one of the new ultrasonic testing methods based on the pulsed laser generated ultrasonic waves and a continuous laser or long pulsed laser coupled to an interferometer measuring surface displacements of solids. LUT has the features of high sensitivity and without using couplants, and is suitable for detection of complex surface and in-situ inspection [4–6]. At the same time, the character of non-contact is the merit of laser ultrasonic technique like infrared and terahertz technique [7,8]. Laser-generated ultrasonic waves are perpendicular to the inspected specimen surface and independent with incident angles of the pulsed laser. Therefore, LUT satisfies special testing conditions such as narrow space, high temperature and pressure, and can be used to detect the surface-breaking cracks and monitor the structural quality of aircraft components.

Many researchers have made efforts to investigate the features of laser-generated surface acoustic wave and got substantial research achievements. Jian et al. investigated the measurement of surface-breaking cracks with the use of laser-generated Rayleigh wave and electromagnetic acoustic transducers receiving ultrasonic wave [9]. Edwards et al. researched the interaction of laser-generated ultrasonic waves with wedge-shape samples, and gave the dependence of the arrival time and amplitudes of many modes on the wedge apex angles [10]. Choi et al. studied the influence of slit width on ultrasonic surface wave excited by masking a laser beam with line arrayed slit [11]. Gao et al. used laser generated surface acoustic wave method to investigate cast iron samples with a variety of morphologies of included graphite precipitation [12]. Kehoe et al. utilized laser ultrasonic surface acoustic wave to inspect alumina ceramics of varying density [13]. Ni et al. analyzed detection of angle surface-breaking cracks by dual-laser source-generated ultrasound and provided a method to calculate crack-orientation angles [14]. However, the previous researchers seldom concerned the influence of different frequency components of laser-generated Rayleigh wave interaction with surface-breaking cracks and the quantitative characterization of surface-breaking cracks. Therefore, this paper systematically analyzes the features of laser-generated ultrasonic surface wave interaction with surface-breaking cracks, takes the influence of different frequency range of Rayleigh wave on recognizing cracks into account, and achieves quantitative characterization of crack depths by gauging

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the reflection coefficients and transmission coefficients of Rayleigh wave.

2. Theory and numerical model

2.1. Laser ultrasound generation based on thermoelastic mechanism

Thermoelastic effect plays an important role in ultrasonic wave generation when power density of pulsed laser is lower than the ablation threshold of material. Laser-generated ultrasonic waves mainly include longitudinal wave, shear wave, surface acoustic waves and Lamb wave in solids. Laser-generated surface acoustic waves can be used to detect the structural surface-breaking cracks. Thermoelastic mechanism is described as parts of laser energy absorbed by material, continuously transferring into surrounding medium which forms transient temperature field with non-uniform distribution, and thermal expansion stress field giving rise to ultrasonic wave excitation. As a consequence, thermoelastic mechanism can be summarized as the thermal conduction equation and displacement control equation as follows:

$$\rho C_v \frac{\partial T}{\partial t} - \nabla \bullet (K \nabla T) = Q \qquad (1)$$

$$\mu \nabla^2 u + (\lambda + \mu)\nabla(\nabla \bullet u) - \alpha(3\lambda + 2\mu)\nabla T = \rho \frac{\partial^2 u}{\partial t^2} \qquad (2)$$

where K is the thermal conductive coefficient, Q is the heat source, T is the temperature field; u is the displacement field, ρ is the material density, C_v is the specific heat, λ and μ are its Lamé coefficients and α is linear thermal expansion coefficient.

2.2. Finite element method

Finite element method (FEM) has already been used to calculate the generation and propagation of laser ultrasonic wave in material [15–17], and thermodynamic and governing finite element equation can be defined:

$$K_T T + C_P \dot{T} = p_1 + p_2 \qquad (3)$$

$$M\ddot{U} + KU = F_{ext} \qquad (4)$$

where K_T is the conductivity matrix, C_P is the heat capacity matrix, T is the temperature vector, $\dot{T}$ is the temperature rise rate vector, p_1 is the heat flux vector and p_2 is the heat source vector; M is the mass matrix, K is the stiffness matrix, U is the displacement vector, $\ddot{U}$ is the acceleration vector, and F_{ext} is the external force vector. For thermo-elasticity, the external force vector F_{ext} for an element is

$$\int_{V_e} B^T D \boldsymbol{\varepsilon_0} dV \qquad (5)$$

where V_e is the volume of an element, B^T is the transpose of derivative of the shape functions matrix, D is the material matrix, and $\boldsymbol{\varepsilon_0}$ is the thermal strain vector.

The FEM calculation process is divided into two stages with the quasi-steady assumption. The first stage calculates the distribution of temperature field within a specified time range, and the temperature field is the source of external loads of the second stage in which the propagation of elastic waves is calculated. The FEM calculations are performed by the software package ANSYS and the integration time step and mesh size are set to 1 ns and 20 μm in order to guarantee the calculation accuracy.

As it can be seen in Fig. 1, the dimensions of finite element model of aluminum plate are set to 30 mm × 10 mm, and the artificial crack is modeled by eliminating some elements to keep the same dimensions with the specimen. The elastic and thermal properties of aluminum plate used in FE calculations are shown in Table 1, where ρ is density, E is elastic modulus, ν is Poisson's ratio, C is specific heat, λ is thermal conductivity and α is thermal expansion coefficient. And the power density of 10^6 W/cm^2 and Gaussian temporal pulse shape of pulsed laser with pulse duration of 10 ns are used in FE calculations.

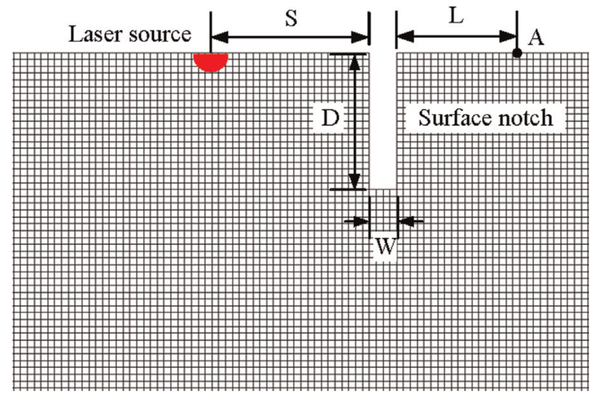

Fig. 1. The FE model of pulsed laser irradiating aluminum plate.

Table 1
Elastic and thermal properties of aluminum plate used in FEM.

Physical properties	Aluminum
ρ (kg/m^3)	2700
E (GPa)	70
ν	0.33
C (J/kg K^{-1})	880
λ (W/m K^{-1})	238.6
α (K^{-1})	2.38e^{-5}

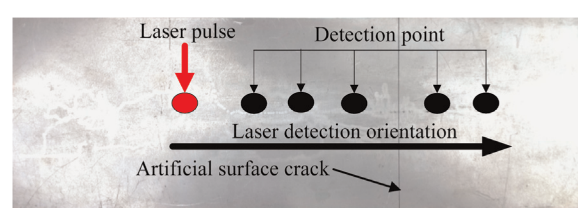

Fig. 2. Specimen of aluminum plate with artificial surface-breaking cracks.

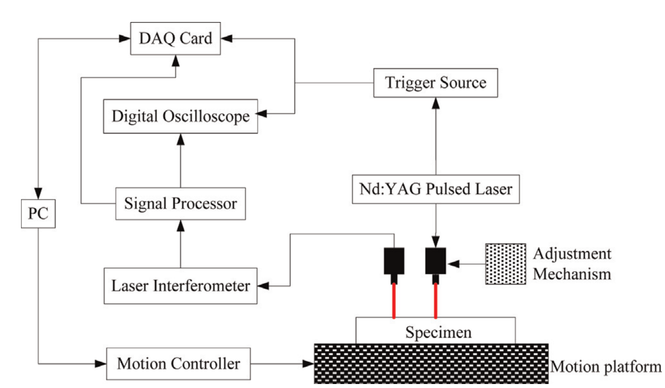

Fig. 3. Schematic diagram of experimental system.