NDT&E International 43 (2010) 470–475

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

An analysis of angled surface-breaking crack detection by dual-laser source generated ultrasound

Chenyin Ni, Yifei Shi, Zhonghua Shen*, Jian Lu, Xiaowu Ni

Department of Applied Physics, Nanjing University of Science and Technology, Nanjing 210094, People's Republic of China

ARTICLE INFO

Article history:
Received 24 February 2009
Received in revised form
18 March 2010
Accepted 14 May 2010
Available online 21 May 2010

Keywords:
Non-destructive evaluation
Laser-generated ultrasound
Surface acoustic waves

ABSTRACT

The propagation and scattering of ultrasound generated in a cracked specimen detected by an evaluating system with a dual-laser source has been studied by using finite element method (FEM). The various ultrasonic modes are analyzed in detail, and a method for calculating the crack-orientation angle is presented by employing the propagating times of scattered ultrasonic modes. Corresponding experimental system is then built. The arrival time of scattered ultrasonic modes propagating in two cracked aluminium specimens are measured by using the method provided and crack-orientation angles are calculated. Results from numerical simulation and experiment are compared, the accuracy of the method is proved accordingly.

1. Introduction

A surface-breaking crack is a kind of flaw in the surface of the material caused by surface strain. Once it occurs, the stress underneath the crack caused by outside force will make it grow fast and finally result in material rejection. In this case, the inspection of the surface-breaking flaws, especially the non-destructive evaluation (NDE) now plays a very important role in industrial fields [1–3]. Crack characterization by ultrasound is a method using reflection, diffraction, attenuation, etc. of the elastic surface wave to obtain information like location, size and orientation of the surface-breaking cracks [4]. Pulsed laser-generated ultrasound becomes a promising facility in the non-destructive evaluation field because of several advantages, such as non-contact generation and detection, generating multimode and a wide waveband ultrasonic wave at the same time [5].

When the incident power is limited at low level to avoid damaging the material surface, the ultrasound is generated in the thermo-elastic mechanism [4]. This physical process contains not only transient thermal conduction, but also the generation and propagation of the transient elastic wave in the material. The ultrasound generated by pulsed laser in this manner causes no damage to the surface of the material, and the incident laser generates multimode ultrasonic waves such as longitudinal wave, transversal wave and Rayleigh wave at the same time, which can be used in evaluating the elastic property, detecting internal defects of materials. The pulsed echo [6] and pitch catch [7] methods are the main techniques in ultrasonic non-destructive detection of surface-breaking cracks in materials. A scanning laser line source (SLLS) technique was reported by Kromine et al. [8] in 2000. It mainly divides the incident laser affected on the surface of materials into incident field and diffracting field, and solving the problem by employing the boundary element method in the frequency domain. In addition, many researchers [9–11] have concentrated on acoustic reflection factor and acoustic propagation factor in far field away from the surface-breaking crack area, and have observed the change in acoustic reflection and propagation factors along with variation in crack depth. In 2006, Jian et al. [12] reported a crack depth gauging method using the diffracting character of Rayleigh wave, and furthermore, they summarized possible mode-converted ultrasonic waves scattering in different parts of the crack during propagation. This provides a strong support for characterizing the size and shape of the crack. At the same time, Matsuda et al. [13] reported a surface-breaking evaluating system with photorefractive quantum wells and laser-generated Rayleigh waves, by which they obtained information, such as location and depth of the crack. Furthermore, they detected the bulk wave component produced by Rayleigh wave diffraction in the tip of the crack and calculated the angle of the crack with the surface of the material.

Along with the development of computer science, numerical simulation is becoming an irreplaceable research tool. Finite element method (FEM) has many advantages: first of all, it is versatile due to its flexibility in modeling complicated geometry and its availability in obtaining full field numerical solutions. In addition, this method can also be applied to calculating the excitation process, where thermal diffusion, optical penetration and other physical parameters are dependent on the temperature. In 1996, Datta and Kishore [14] simulated the process of acoustic

---

* Corresponding author.
E-mail addresses: nichenyin@hotmail.com (C. Ni), shenzh@mail.njust.edu.cn (Z. Shen).

0963-8695/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ndteint.2010.05.001

sound wave propagation in concrete with cracks using FEM and agreed with the experimental results. In 2003, Hassan and Veronesi [15] calculated the process of Rayleigh wave interaction with a notch normal to the material surface and established the relationship between the reflecting factor and the depth of the notch. The result agreed with the theoretical calculation and experimental data. In 2004, Guan et al. [16,17] used FEM to simulate the physical process of the SLLS technique in detecting surface-breaking notches and sub-surface notches in aluminium. The simulation result shows agreement with the theoretical results and the experimental data. Recently, Jian et al. [18] studied the propagation of surface acoustic waves in aluminium with surface-breaking notch, and analyzed how the scattered ultrasonic wave mode affected the in-plane and out-of-plane displacements and studied the mode-converting ultrasonic waves generated at corners of the notch.

Summarizing previous achievements in this field, whether in experiments or computer simulation with FEM, most researchers have tended to choose a notch that is normal to the material surface representing the crack as their research object. However, in practical situations, the surface-breaking cracks are not always angled in a certain way. Though Kinra and Vu did some research with an inclined edge crack, due to the limitation of their experimental setup, they tended to choose the situation that laser irradiates away from the crack. In the other hand, Matsuda et al. [13] provided a method of detecting the crack-orientation angle, they concentrated on describing the evaluating system and experimental phenomenon. Moreover, no numerical simulating work has been done to analyze this phenomenon in detail. In this paper, an evaluating system with ultrasound generated by dual-laser source is presented. Using this system, the crack-orientation can be easily detected. Moreover, the propagation of ultrasonic waves is studied by numerical simulation in detail so that the mechanism of the evaluating method is revealed. The correctness of the system is validated later by comparing the obtained experimental data with theoretically calculated data and FEM results.

2. Theoretical background

2.1. Heat transfer theory

To simplify the analysis, the real crack is represented by a rectangular slot. The geometry of laser irradiation on the top surface of an aluminium plate with a slot is schematically shown in Fig. 1. The spatial mode of the laser beam is assumed to have a Gaussian distribution. A Cartesian coordinate system is adopted. The thermal conductivity equation can be described as

$$\rho C\frac{\partial T(x,y,z,t)}{\partial t}=\frac{\partial}{\partial x}\left[k_x\frac{\partial T(x,y,z,t)}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y\frac{\partial T(x,y,z,t)}{\partial y}\right]+\frac{\partial}{\partial z}\left[k_z\frac{\partial T(x,y,z,t)}{\partial z}\right] \quad (1)$$

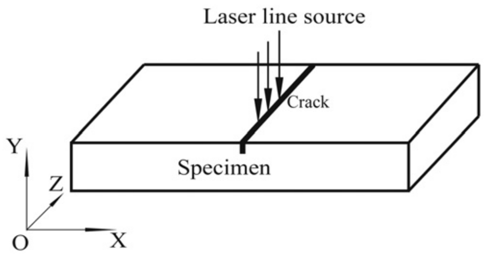

Fig. 1. Schematic diagram of laser irradiation sample near the surface notch.

where $T(x,y,z,t)$ represents the temperature distribution at time t, and ρ, C and k are the density, thermal capacity and thermal conduction coefficient, respectively.

Considering the skin effect of metal materials, the entire laser beam is assumed to be absorbed on the surface; thus the optical penetration is neglected and the incident laser beam can be represented by a heat flux.

Now we build the finite element model in the X–Y plane, where $z=0$. The surface of the sample is divided into an irradiated region (top surface, $y=h_0$) and a non-irradiated region (elsewhere other than the top surface). The boundary condition of the irradiated region is

$$-k\frac{\partial T(x,y,t)}{\partial y}\bigg|_{Top}=I_0(1-R)f(x)g(t), \quad (2)$$

where R is the reflection ratio of the specimen surface and I_0 the radiation energy of the incident laser. $f(x)$ and $g(t)$ are the spatial and temporal distributions of the laser pulse, respectively. These two functions can be written as

$$f(x)=\exp\left(-\frac{x^2}{a_0^2}\right), \quad (3)$$

$$g(t)=\frac{t}{t_0}\exp\left(-\frac{t}{t_0}\right), \quad (4)$$

where a_0 is the half-width of the laser line and t_0 the rise time of the laser pulse. The other boundaries are set to be thermo-isolated. In order to simplify the problem and concentrate on the impact of dual-laser irradiation, the laser irradiation on the bottom and sides of the notch is ignored.

2.2. Theory of laser ultrasound generation based on the thermo-elastic mechanism

When the specimen surface is illuminated by a laser pulse with an energy density less than that required to melt or vaporize the specimen, a transient displacement field is excited due to thermo-elastic expansion. In an isotropic body, the displacement satisfies

$$(\lambda+2\mu)\nabla(\nabla\mathbf{u})-\mu\nabla\times\nabla\times\mathbf{u}-(3\lambda+2\mu)\alpha_T\nabla T(x,y,t)=\rho\frac{\partial^2\mathbf{u}}{\partial t^2}, \quad (5)$$

where $\mathbf{u}(x,y,t)$ is the time-dependent displacement, α_T the thermo-elastic expansion coefficient of the isotropic plate material, λ and μ are the Lamé constants. The boundary conditions at the irradiated surface $y=h_0$ is

$$\mathbf{n}[\boldsymbol{\sigma}-(3\lambda+2\mu)\alpha_T\Delta T(x,y,t)\mathbf{I}]=0, \quad (6)$$

where $\mathbf{n}$ is the unit vector normal to the surface, $\mathbf{I}$ the unit tensor and $\boldsymbol{\sigma}$ the stress tensor. A free boundary condition is adopted for the other surfaces. In addition to the boundary condition, there is also an initial condition, which is expressed as

$$\mathbf{u}(x,y,t)=\frac{\partial\mathbf{u}(x,y,t)}{\partial t}\bigg|_{t=0}=0, \quad (7)$$

2.3. Finite element method

For wave propagation, ignoring damping, the governing finite element equation is

$$[M]\{\ddot{\mathbf{U}}\}+[K]\{\mathbf{U}\}=\{\mathbf{F}_{\text{ext}}\} \quad (8)$$

where $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $\{\mathbf{U}\}$ the displacement vector, $\{\ddot{\mathbf{U}}\}$ the acceleration vector and $\{\mathbf{F}_{\text{ext}}\}$ is the external force vector. The process to solve the finite element equation is to discretize the plane with axis symmetry into non-