Optics and Laser Technology 96 (2017) 58–64

Contents lists available at ScienceDirect

Optics and Laser Technology

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

Full length article

Numerical simulation and experimental research on interaction of micro-defects and laser ultrasonic signal

Hualing Guo *, Bin Zheng, Hui Liu

National Key Laboratory for Electronic Measurement Technology, North University of China, Taiyuan, China

ARTICLE INFO

Article history:
Received 27 October 2016
Accepted 6 April 2017

Keywords:
Laser ultrasonic
Surface wave
Surface micro-defects

ABSTRACT

In the present research, the mechanism governing the interaction between laser-generated ultrasonic wave and the micro-defects on an aluminum plate has been studied by virtue of numerical simulation as well as practical experiments. Simulation results indicate that broadband ultrasonic waves are caused mainly by surface waves, and that the surface waves produced by micro-defects could be utilized for the detection of micro-defects because these waves reflect as much information of the defects as possible. In the research, a laser-generated ultrasonic wave testing system with a surface wave probe has been established for the detection of micro-defects, and the surface waves produced by the defects with different depths on an aluminum plate have been tested by using the system. The interaction between defect depth and the maximum amplitude of the surface wave and that between defect depth and the center frequency of the surface wave have also been analyzed in detail. Research results indicate that, when the defect depth is less than half of the wavelength of the surface wave, the maximum amplitude and the center frequency of the surface wave are in linear proportion to the defect depth. Sound consistency of experimental results with theoretical simulation indicates that the system as established in the present research could be adopted for the quantitative detection of micro-defects.

1. Introduction

Laser ultrasonic detection (LUD) has been becoming one of the important techniques for the detection of micro-defect(s) existed in various kinds of materials, because of its high time and spatial resolution, wide signal bandwidth, and non-destruction performance under non-contact condition [1,2]. It signals the future development of micro-defect detection. In detecting surface micro-defect(s) of a particular material, the size of the defect(s) is expressed by the reflection of the laser ultrasonic wave as well as the alteration of the transmission wave of laser ultrasonic on the edge of the defect(s). In general, laser ultrasonic wave propagates in such forms like longitudinal wave, transverse wave, surface wave, etc., and such a wave is subject to mode transformation during propagation because of the impact of micro-defect(s). It is, therefore, of great significance to the detection of surface micro-defect(s), if the forming mechanism of reflection waves could be found, and the variation characteristics of the reflection waveform could be found.

Early researches on laser ultrasonic detection were based on thermo-elastic theory through numerical simulation. Xu studied finite element modeling of laser-generated ultrasonic in coating-substrate system [3]; Sun and Zhang studied thermoviscoelastic finite element modeling of laser-generated ultrasonic in viscoelastic plates [4].

In recent years, laser ultrasonic detection has been widely used in surface-defect detection too [5–9]. Clorennec et al. tested the surface defect of cylinder using laser-generated ultrasonic technique [5]; di Sealea et al. detected the micro-flaws on railway track using laser acoustic surface wave [6]. Kromine et al. proposed laser-source scanning technique, which used the variation of signal amplitude with the change of scanning distance for defect detection [7]. Dixon et al. studied sheet-metal defect using the method of electromagnetic acoustic transducer detection [8]. Coony and Blackshire researched propagation direction of surface defect and quantitative characterization of the defect depth using synchronous scanning of excitation and detection [9].

Based on early researches, this paper intends to make research on the interaction between laser ultrasonic transmission and defect on an aluminum plate by virtue of finite element numerical simulation of indirect coupling, so to establish a simulation model as well as the simulation time domain and frequency domain

---

* Corresponding author.
E-mail address: guohualing@nuc.edu.cn (H. Guo).

http://dx.doi.org/10.1016/j.optlastec.2017.04.004

waveform during simulation. This paper also uses the established surface-wave laser ultrasonic detecting system to conduct empirical experiments and test the consistency between experimental results and numerical simulation results.

2. Theoretical bases and simulation model

2.1. Generation of laser ultrasound

As a beam of pulsed laser illuminates onto the surface of an aluminum plate, the surface region absorbs the electromagnetic radiation from the laser and produces heating source. On the loaded surface and subsurface of the plate, there exist large temperature gradient because of irregularly loaded temperature, which causes such area of the surface to undergo larger thermal elastic deformation. The deformation increases at first and decreases as the loading time lasts, thus producing ultrasonic pulse (see Fig. 1). Thermoelastic effect plays an important role in ultrasonic wave generation when power density of pulsed laser is lower than the ablation threshold of material. Refs. [10,2] reported the generation of laser ultrasonic wave through thermoelastic mechanism. In order to make the pulsed-laser power density less than the molten threshold of the material, the loading temperature T on the aluminum plate is at 500 °C.

Laser-generated ultrasonic waves mainly include longitudinal wave, transverse wave, and surface wave in the metal materials. Pulsed laser-generated ultrasonic signal can be expressed as [11]:

$$q_i = \frac{B\mu_t}{L\sqrt{\left(1+\frac{\mu_t}{L}\right)^2+1}} \tag{1}$$

where q_i is the photoacoustic signal of the different frequency, i is the component identifier photoacoustic signal frequency, B is constant, L is optical penetration depth, and μ_t is thermal diffusion length. Eq. (1) shows that optical penetration depth and thermal diffusion length of the material are the main factors influencing the ultrasonic energy. The laser power density was controlled between 10^5 and 10^6 W/cm^2 to avoid ablation material.

The main factors influencing the laser ultrasonic spectrum as well as their interrelation can be expressed as [12]:

$$\Delta t_{1/2} = \frac{L\ln 4}{\upsilon} + 2.22\tau \tag{2}$$

where $\Delta t_{1/2}$ is the full width at half maximum of the generated ultrasonic pulse, υ is the acoustic velocity, and τ the laser pulse width. Eq. (2) shows that the optical penetration depth and the laser pulse width have a direct impact on the laser ultrasonic spectrum. The ultrasonic frequency-band width is in inverse proportion with the laser pulse width.

Optical penetration depth (L) of the laser is related to the primary properties of material; it can be defined as [2]:

$$L = 3\sqrt{\frac{2kt}{\rho c_p}} \tag{3}$$

where k is the thermal conductivity, ρ is the density, and C_p the heat capacity at constant pressure. In Eq. (3), t is set to the time where the surface temperature falls below 1% of the initial temperature due to the pulse laser irradiation. In the present research, the parameters of the aluminum plate are as follows: $k = 200\ \mathrm{W\ m^{-1}}$ - $\mathrm{K^{-1}}$, $\rho = 2700\ \mathrm{kg\ m^{-3}}$, $C_p = 800\ \mathrm{J\ kg^{-1}\ K^{-1}}$ and $t = 10\ \mu\mathrm{s}$. Calculation shows that $L = 130\ \mu\mathrm{m}$.

The frequency of the laser-generated ultrasonic wave is determined by the optical penetration and the optical pulse duration shall be as short as possible. To maintain the frequency of the laser-generated ultrasonic wave in the range of 1–10 MHz for detecting the aluminum plate, laser pulse width should satisfy the following condition [12]:

$$\tau \ll \frac{L}{v} \tag{4}$$

The propagation speed of longitudinal wave, transverse wave and surface wave in the aluminum plate are 6400 m/s, 3200 m/s and 2900 m/s respectively. The pulse width is calculated to be far less than 20 ns, in the present research, the laser pulse width is set to be 7 ns ($\tau = 7$ ns) for simulation and experiment.

2.2. Simulation model

The finite element numerical calculation has already been used to calculate the generation and propagation of laser ultrasonic wave in material. In the process of laser ultrasonic excitation, the temperature field caused by the surface heat changes of the material has a great influence to the analysis of material structure field. For micro-strain material, however, the impact of its structure change is negligible. The present research adopts indirect coupling analysis method for modeling. In the process of modeling, the internal heat conduction of the material is considered while the material thermal radiation and heat convection with the ambient environment is ignored. The radical change in surface temperature is simplified to an abrupt rise of the material surface temperature.

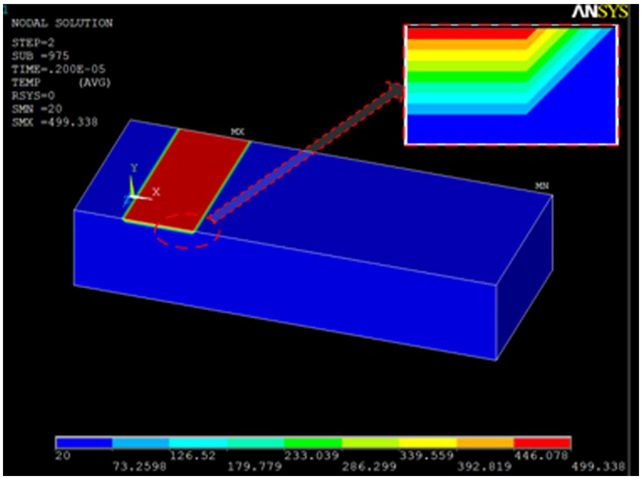

Fig. 1. Temperature calculation result.

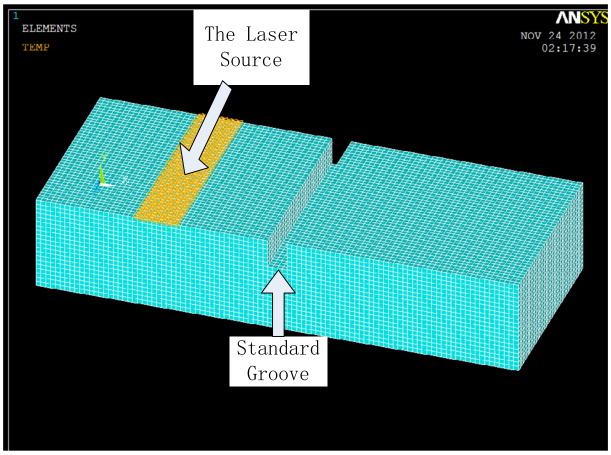

Fig. 2. Thermal structure coupling model of laser line source.