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Experiment and numerical simulation for laser ultrasonic measurement of residual stress

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ABSTRACT

Laser ultrasonic is a most promising method for non-destructive evaluation of residual stress. The residual stress of thin steel plate is measured by laser ultrasonic technique. The pre-stress loading device is designed which can easily realize the condition of the specimen being laser ultrasonic tested at the same time in the known stress state. By the method of pre-stress loading, the acoustoelastic constants are obtained and the effect of different test directions on the results of surface wave velocity measurement is discussed. On the basis of known acoustoelastic constants, the longitudinal and transverse welding residual stresses are measured by the laser ultrasonic technique. The finite element method is used to simulate the process of surface wave detection of welding residual stress. The pulsed laser is equivalent to the surface load and the relationship between the physical parameters of the laser and the load is established by the correction coefficient. The welding residual stress of the specimen is realized by the ABAQUS function module of predefined field. The results of finite element analysis are in good agreement with the experimental method. The simple and effective numerical and experimental methods for laser ultrasonic measurement of residual stress are demonstrated.

1. Introduction

Residual stress exists in material that is produced by nearly every mechanical, chemical, and thermal process. It is an important performance index of material because residual stress affects the material fatigue life, strength and structure. The conventional methods of measuring residual stress include hole-drilling method, cutting groove method, X-ray method and traditional ultrasonic method, etc. [1–3]. However, mechanical method is complicated, time consuming, and will induce damages to the material. X-ray method has the disadvantage of damaging human health and being sensitive to the direction of detection. Traditional ultrasonic method is not suitable for some circumstances, such as high-temperature, radioactive, and toxic environment. Laser ultrasonic technique has several advantages such as: non-contact, high-precision, non-destructive, and high adaptability [4]. In recent years, laser ultrasonic has been widely used in defect detection [5,6], elastic constant measurement [7–10], residual stress measurement [11–14] and many other applications [15,16].

The research of laser ultrasonic measurement of residual stress has attracted a great deal of attention of researchers. Sanderson [11] used the simplified finite element modeling to determine the capability and sensitivity of the technique for residual stress measurement. A clear correlation between the magnitude of the residual stress and the surface wave behavior was presented. Wang [17] Analyzed laser-generated ultrasonic force source at specimen surface and displayed of bulk wave in transversely isotropic plate with numerical method. Daniel [18] used surface skimming longitudinal wave to detect the residual stress of friction stir welds and the results are in good agreement with the finite element method. The surface residual stress in steel rods with different heat treatments was measured by laser generated ultrasonic surface wave by Duquennoy [19]. Achenbach analyzed the process that ultrasonic wave was excited by using the force dipole model on the surface of a homogeneous and isotropic linear elastic body [20]. The mass spring lattice modeling was used to simulate laser ultrasonic technique for the detection of small surface defects by Sohn and Krishnaswamy [21]. Karabutov [13] designed a special optoacoustic transducer which was used both for the excitation and detecting of the ultrasonic pulses. This technique was used for measurement of welding residual stress and the results are in good agreement with the traditional method. Moreau [14] used

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laser ultrasonic measurements of residual stress in a 7075-T651 aluminum sample surface-treated with low plasticity burnishing.

Based on the achievement of former researchers, the systematic work of laser ultrasonic measurement of residual stress is demonstrated in this paper. The pre-stress loading device is designed and fixed on the laser ultrasonic experimental platform, which can easily realize the control of tension stress. The acoustoelastic constants of the material are obtained by measuring the velocity of the surface wave in the known condition of stress, which solve the problem that the residual stress can't be measured accurately due to unknown acoustoelastic constants. In addition, considering the direction of the principal stress is unknown under normal circumstances, we investigate the effect of different test directions on the results of surface wave velocity measurement. On the basis of known acoustoelastic constants, the welding residual stress is measured by the laser ultrasonic technique. The results are consistent with drilling method. A finite element analysis model of laser ultrasonic surface wave detection of welding residual stress is established. In order to avoid the large amount of calculation caused by thermo-mechanical coupling and transient analysis, the pulsed laser is equivalent to the related load of Gaussian profile and the welding residual stress is realized by the ABAQUS function module of predefined field. The results show that the experimental method and finite element model in this paper are effective for laser ultrasonic measurement of residual stress.

2. Theory

The dependency of the acoustic wave velocity on the value of applied stress can be obtained from the acoustoelastic theory [22]. A Rayleigh wave propagating on the free surface of a homogeneous, elastic and half-space material under uniform static deformation is considered. When the principal directions of strain coincide with the symmetry axes of the material, and when the displacement due to the propagation of the wave is infinitesimal, then the relative variations of the velocity can be expressed in terms of static stresses as [23]:

$$\frac{\Delta v_1}{v_0} = \frac{v_1 - v_0}{v_0} = A_1\sigma_1 + A_2\sigma_2 \quad (1)$$

$$\frac{\Delta v_2}{v_0} = \frac{v_2 - v_0}{v_0} = A_1\sigma_2 + A_2\sigma_1 \quad (2)$$

where v_1, v_2 and v_0 are the surface wave velocities in stress state and unstressed state, respectively, v_1 is the velocity of the surface wave propagating along the "1" direction and v_2 is the velocity of the surface wave propagating along the "2" direction. σ_1 and σ_2 are the stress in the "1" and "2" direction, respectively. A_1 and A_2 are the acoustoelastic constants, which not only depend on the stress direction but also on the propagation direction. Considering the research for the welding residual stress of the uniform and isotropic thin plate, the stress in the thickness direction is very small compared to the other two directions, we can approximate $\sigma_3 = 0$ and the problem is simplified into plane stress state.

In order to obtain the stresses using Eqs. (1) and (2), the constants A_1 and A_2 must be determined in advance. These constants can be calculated if the second-order and third-order elastic constants are known. If the elastic constants are not available, the constants A_1 and A_2 can be determined by the calibration experiment under the condition of uniaxial stress. When the specimen is in the state of uniaxial stress, the Eqs. (1) and (2) can be simplified as:

$$\frac{\Delta v_1}{v_0} = \frac{v_1 - v_0}{v_0} = A_1\sigma_1 \quad (3)$$

$$\frac{\Delta v_2}{v_0} = \frac{v_2 - v_0}{v_0} = A_2\sigma_1 \quad (4)$$

Eqs. (3) and (4) show that if the loading stress is known and the surface wave propagation velocity along the stress direction and vertical stress direction is measured respectively, we can get the acoustoelastic constants. It is assumed that the residual stress is 600 MPa. The typical acoustoelastic constant value is about 10^{-6} MPa^{-1} order of magnitude. Therefore, the maximum change rate is $\frac{\Delta v_1}{v_0} \approx 10^{-3}$. This requires that the measurement of time must be of high accuracy.

3. Experiment

The measurement sample is a thin 4140 steel plate which is fixed on the pre-stress loading device by bolts. Sample size is 400 mm × 15 mm × 1.8 mm. The laser ultrasonic system includes three parts: the Nd:YAG laser (for ultrasonic generation), the laser Doppler vibrometer (for ultrasonic detection) and the pre-stress loading device (for acoustoelastic constant measurement). The experimental system is shown in Fig. 1.

3.1. Experimental setup

A laser pulse (pulse width $\tau = 8$ ns, wavelength $\lambda = 1064$ nm, repetition frequency $f = 20$ Hz, single pulse energy $E_0 = 100$ mJ) with Gaussian profile sent by Nd:YAG laser (Beamtech Dawa-100) is focused by a cylindrical lens as a line source with 0.6 mm width to generate the surface wave. The ultrasonic vibration information is received by laser Doppler vibrometer (Sdptop LV-S01, frequency band 5 MHz). The digital oscilloscope (Tektronix Dpo4102, frequency band 1 GHz) collects electrical signal from laser Doppler vibrometer and photoelectric detector. A part of

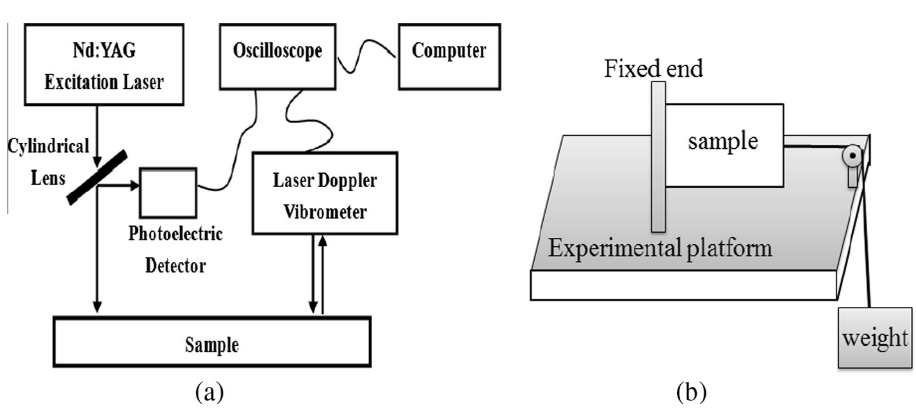

Fig. 1. Schematic of experimental system: (a) laser ultrasonic system, (b) pre-stress loading device.

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