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An improved ultrasonic method for plane stress measurement using critically refracted longitudinal waves

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A B S T R A C T

An improved ultrasonic method was developed theoretically and experimentally for plane stress measurement using critically refracted longitudinal (LCR) waves. Cruciform specimen method, combined with a digital image correlation (DIC) method, was applied to confirm the validity of this method. Based on the acoustoelastic theory, LCR waves with arbitrary detection directions were considered and relations between time-of-fight and biaxial principal stresses were described. To generate the LCR wave in cruciform specimen, a regular octagon polymethyl-methacrylate (PMMA) wedge was designed in accordance with Snell's law. Finally, validation experiments were performed under different step loads using cruciform specimens. In these experiments, the strain fields of cruciform specimens were extracted by DIC method and used to calculate the reference values of plane stress. By comparing the measured principal stresses with the reference values, the validation and precision of the improved ultrasonic method presented in this work were demonstrated.

1. Introduction

The presence of stress within a material slightly alters the speed of acoustic waves traveling within the material, and this is called the acoustoelastic effect. Based on acoustoelastic effect, ultrasonic method has been widely used for stress measurement because of its low testing cost, use of simple equipment, and flexible measurement range. A complete description of the acoustoelastic effect in isotropic materials was developed by Hughes and Kelly [1]. In their description, seven expressions with different ultrasonic forms were deduced.

Ultrasonic techniques mainly include the acoustic birefringence method, surface acoustic wave method, and critically refracted longitudinal (LCR) wave method. Among these techniques, the LCR wave is the most sensitive to inherent stress in materials [2]. The LCR wave propagates beneath the surface, with a depth of approximately one wavelength [3]; this wave can be generated in a tested material by altering the incident angle to a critical value calculated on the basis of Snell's law.

Previous research efforts investigated the residual stress in metals using LCR waves. Joseph et al. [4] probed the distribution patterns of residual stress across low-carbon steel weld joints. Sadeghi et al. [5] evaluated the distribution of through-thickness residual stress in the friction stir welding of aluminum plates. Javadi et al. [6] investigated the hoop residual stress variations in the thicknesses of dissimilar welded pipes. In their research, LCR wave was excited along the direction of the tested stresses. This is suitable for the state of uniaxial stress and the direction of stress is clear. For most structures and components in engineering, however, plane stresses are prevalent and their directions are unclear. According to acoustoelastic theory, the stress which is not parallel to the testing direction also induces velocity variation, although it is very small. To measure the plane stresses accurately, a well-considered form of acoustoelasticity that considering a longitudinal wave propagating in an arbitrary direction is necessary.

To illustrate the usability of this improved LCR wave method, it is necessary to compare it with existing technologies. The most realistic technique is applying in-plane loads along two perpendicular arms of a cruciform-type specimen [7]. Besides, a high-precision measurement method is also required to evaluate the uniformity of the plane strain field. As a non-contact method, digital image correlation (DIC) has been successfully applied to a variety of applications during the past few decades [8]. Among various deformation and strain measurement methods, the DIC method is attractive because it can analyze deformation by tracking the speckles on the surface of a specimen precisely. In this aspect of biaxial testing, DIC has been widely applied to determine the full-field strain and the uniformity in the detection area in cruciform specimens. Makris et al. [9] investigated the symmetry and the uniformity of the strain field on the biaxially loaded zone by using digital image correlation methods. Based on the finite-element method

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and the digital image correlation technique, Lamkanfi et al. [10] presented a mixed experimental/numerical approach in the investigation of biaxially loaded specimens. Périé et al. [11] extend the use of biaxial tests and full field measurements to the identification of an anisotropic damage law.

The main goal of this research is a feasibility study for plane stress measurement using an improved ultrasonic method. Based on the acoustoelastic theory, the expression between biaxial principal stresses and time of flight of LCR waves was deduced. An ultrasonic wedge was designed for generating LCR waves in the material under test. The combination of the cruciform specimen and digital image correlation method was applied for the experimental validation of this improved ultrasonic method. The plane stresses calculated by the DIC method were then compared with those measured by the ultrasonic method, and good agreement was observed.

2. Experimental methods

2.1. Principle of plane stress measurement using LCR waves

By defining the orthogonal coordinate axis (1, 2, 3) of the material, we can establish the relations between longitudinal wave velocity and the stress applied on isotropic materials. This is done in Eqs. (1) and (2) according to the acoustoelastic effect [1].

$$\rho_0 V_{L1}^2 = \lambda + 2\mu + \frac{\sigma_1}{3\lambda + 2\mu}\left[\frac{\lambda + \mu}{\mu}(4\lambda + 10\mu + 4m) + \lambda + 2l\right] \tag{1}$$

$$\rho_0 V_{L2}^2 = \lambda + 2\mu + \frac{\sigma_1}{3\lambda + 2\mu}\left[2l - \frac{2\lambda}{\mu}(\lambda + 2\mu + m)\right] \tag{2}$$

where ρ_0 is the density of the solid before deformation and σ_1 is the uniaxial stress in the 1 direction (tensile stress is positive, and compressive stress is negative). Parameters λ and μ (also known as shear modulus) are second-order elastic constants (Lame constants). Both l and m are third-order elastic constants (Murnaghan constants). V_{L1} and V_{L2} are propagation velocities of longitudinal wave in the 1 and 2 directions, respectively. These two equations indicate the stress–acoustic relations for longitudinal waves in isotropic materials.

Considering a LCR wave propagating with an angle θ with respect to 1 axis in the material, the complete description of acoustoelastic theory for longitudinal waves is described in terms of the velocity shift in the following form [12],

$$(V_{L\theta} - V_0)/V_0 = A_1(\sigma_1 cos^2\theta + \sigma_2 sin^2\theta) + A_2(\sigma_1 sin^2\theta + \sigma_2 cos^2\theta) \tag{3}$$

where V_0 is the propagation velocity of an LCR wave in unstressed material, $V_{L\theta}$ represents the propagation velocity of a LCR wave along the θ direction in stressed material, and coefficients A_1 and A_2 can be deduced from Eqs. (1) and (2):

$$A_1 = \frac{(4\lambda + 10\mu + 4m)(\lambda + \mu) + \mu(\lambda + 2l)}{2\mu(3\lambda + 2\mu)(\lambda + \mu)} \tag{4}$$

$$A_2 = \frac{\mu l - \lambda(\lambda + 2\mu + m)}{\mu(3\lambda + 2\mu)(\lambda + \mu)} \tag{5}$$

Velocity is often difficult to measure because of the complicated operation procedure. However, when the separation between the transmitter and the receiver tranducers is fixed, converting velocity into variation of time of flight (TOF) is easy and convenient for experiments. Simple algebra gives

$$T = \Delta t = -(L/V^2)\Delta V \tag{6}$$

where T is the variation of TOF, and L is the propagation distance in the material, which is constant in the experimental procedure. By setting K_1 = $-A_1L/V_0$, K_2 = $-A_2L/V_0$, the TOF variation T is obtained as

$$T = K_1(\sigma_1 cos^2\theta + \sigma_2 sin^2\theta) + K_2(\sigma_1 sin^2\theta + \sigma_2 cos^2\theta) \tag{7}$$

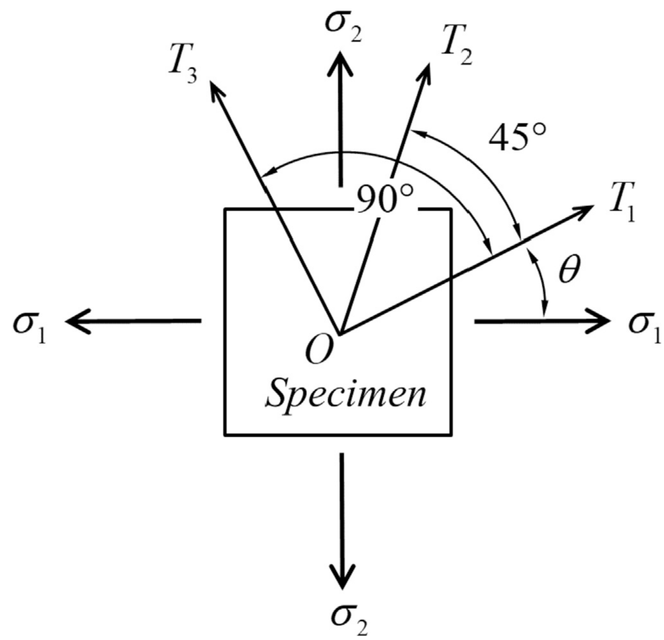

Fig. 1. Angle definition used in ultrasonic stress analysis.

where K_1 and K_2 are acoustoelastic coefficients.

Equation (7) indicates the relation between stress-induced TOF variation and the magnitude and direction of principal stresses. To determine the principal stresses (σ_1, σ_2, and θ) in the material, it is necessary to detect the TOF variation along three directions at least.

For convenience in measurement and solving equation, 0°, 45°, and 90° are chosen as the detection directions corresponding to T_1, T_2, and T_3, respectively. Fig. 1 gives the angle definition of the detection directions. By solving three equations of T_1, T_2, and T_3, the expressions for principal stresses are obtained as

$$\begin{cases} \sigma_{1,2} = \frac{T_1 + T_3}{2(K_1 + K_2)} \pm \frac{1}{2|K_1 - K_2|}\sqrt{(T_1 - T_3)^2 + (T_1 + T_3 - 2T_2)^2} \\ \theta = \frac{1}{2}\arctan\left(\frac{T_1 + T_3 - 2T_2}{T_1 - T_3}\right) \end{cases} \tag{8}$$

From the above equations, we can see that principal stresses are related to two acoustoelastic coefficients and TOF variations. However, the principal direction is only related to the TOF variations detecting along the 0°, 45°, and 90° directions. Equation (8) is the basis principle for measuring the biaxial principal stress in isotropic material using LCR waves. This improved ultrasonic method is to be verified experimentally in the following manner.

2.2. Material and ultrasonic wedge

Use of a cruciform specimen is a common method for creating plane stresses in materials. The selection of the geometry of cruciform specimens is the key issue [11] in the design of the experiment. According to previous research, several proposals of an optimized geometry were accepted in this work, as shown in Fig. 2. The geometry we chose has a circular gauge section and a reduced thickness in the central region, in combination with a fillet corner between two arms and a gradual width [13–15].

A commercially produced wrought 6061 aluminum plate was prepared for cruciform specimens. This kind of aluminum plate was widely used in general engineering, and its detailed characteristics are displayed in Table 1. Due to the thickness of the gauge section (i.e., 3 mm), a plane stress state is assumed. The effective depth of these LCR waves is estimated to be equal to one wavelength [3]. For a longitudinal wave with a central frequency of 2.5 MHz propagating in an aluminum alloy