NON-DESTRUCTIVE TESTING OF RESIDUAL STRESS IN MECHANICAL COMPONENTS BASED ON ULTRASONIC LCR WAVE

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ABSTRACT: Residual stress has a direct bearing the performance of the mechanical components. However, it is very difficult to realize fast, accurate and non-destructive evaluation of the residual stress on the surface or at a certain depth of tube components. After analysing the ultrasonic testing principle of the critically refracted longitudinal (Lcr) ultrasonic wave by the acoustoelasticity theory, we designed a pitch-catch oblique incidence probe to excite the ultrasonic Lcr wave in the test material, built a testing system of residual stress with detection precision improved by stress coefficient calibration, temperature compensation, and temperature correction, and experimentally applied the proposed method in residual stress testing of oil pipeline weld joint, vehicle torsion shaft, glass and ceramics, gear root, etc. The experimental results indicate that it is meaningful to further apply and popularize the ultrasonic Lcr wave method.

KEY WORDS: Non-destructive Testing, Residual Stress, Ultrasonic Lcr Wave.

1 INTRODUCTION

Residual stress has a considerable influence on the engineering properties of materials and structural elements, notably distortion, fatigue life, brittle fracture, corrosion resistance and dimensional stability (Totten, 2002), (Chan, 2010), (Song, 2016). The impact has contributed to soaring repair and restoration cost of parts, equipment, and structures. Therefore, residual stress analysis is indispensable to the preliminary and detailed designs and service reliability estimation of parts and structural elements (Jacomino, 2010; Green, 1999; Wu, 2002).

As an inevitable result of material manufacturing and processing, residual stress concentratedly appears due to the overtight fitting or assemblage between two parts of inconsistent dimensions. The self-balanced local stress is produced in the machining of the material. During cooling or heating, the residual stress is distributed nonuniformly under the effect of uneven plastic deformation. This is particularly the case in the manufacturing of welded structures. (Trufyakov, 1999).

The prevalence of residual stress across manufactured structures and components has given rise to a variety of methods for residual stress measurement in different types of components, laying the basis for reliable assessment of residual stress. The varied measurement methods are classified into destructive, semi-destructive and non-destructive techniques depending on application scope and availability (Rossini, 2012).

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With an edge on specimen preservation, the non-destructive methods are ideal options for production quality control and valuable specimen measurement. However, these methods mostly rely on detailed calibrations of typical specimen material to acquire the necessary computational data (Schajer, 2010).

Traditionally, the inner stress state, as well as its magnitude and depth, of the material was measured by diffraction techniques like X-ray or synchrotron radiation (Staron, 2007; Epp, 2010). More recently, sharp instrumented indentation methods have emerged in light of the different contact areas of indentation or the different maximum loads of load-depth curves (Wang, 2006). There is a common defect between the diffraction-based and the instrumented indentation-based methods, in that both assume the indent angle will not variate after the removal of the load. In fact, surface profile of the indentation undergoes continued load changes during unloading, owing to the elastic recovery of the material. In addition, the residual stress profile of the austenitic stainless steel blasted with alumina or zirconia particles can be determined by ultra-micro indentation techniques (Frutos, 2010).

The acoustoelastic effect, i.e. the dependency of ultrasonic wave speed on the state of stress, is a well-established phenomenon that has been extensively reported in the literature (Herold, 2000; Yashar, 2012; Qozam, 2010). If the theory of acoustoelasticity is applied to the measurement of applied or residual stress, it is necessary to identify the exact distance between the source and the receiver of the ultrasonic wave, and take the distance as the reference for the necessary measurement of the wave speed by time-of-flight (Michael, 2006).

Based on theory of acoustoelasticity, this paper analyses the testing principle of ultrasonic Lcr wave method, designs a pitch-catch oblique incidence testing probe, and discusses the detectable area and depth of the probe. Next, a residual stress testing system was built, with detection precision improved by stress coefficient calibration, temperature compensation and temperature correction. Finally, the ultrasonic Lcr wave method was verified in an application experiment.

2 TESTING PRINCIPLE OF RESIDUAL STRESS TESTING METHOD

2.1 Theory of acoustoelasticity

As the cornerstone of ultrasonic stress testing, the theory of acoustoelasticity studies the relationship between the elastic solid stress state and the macro elastic wave speed based on the finite deformation of continuum mechanics. Given the four basic assumptions of acoustoelasticity, it is possible to obtain the elastic wave equation (acoustoelasticity equation) in stress medium under initial coordinates (Pao 1984).

$$\frac{\partial}{\partial X_J}\left[\left(\delta_{IK} t_{JL}^{i} + C_{IJKL}\right)\frac{\partial u_K}{\partial X_L}\right] = \rho^{i}\frac{\partial^2 u_I}{\partial t^2} \quad (1)$$

In the case of homogeneous deformation, Equation (1) can be simplified as:

$$\left(C_{IJKL} + \delta_{IK} t_{JL}^{i}\right)\frac{\partial^2 u_K}{\partial X_J \partial X_L} = \rho^{i}\frac{\partial^2 u_I}{\partial t^2} \quad (2)$$

Equation (2) can be analytically expressed if the solid is isotropic (Bray 1995). Thus, the equation of ultrasonic propagation speed and stress in solid can be established in Cartesian coordinates (Rose 1999). For the longitudinal wave which propagates along the stress direction:

$$\rho_0 V^2 = \lambda + 2\mu + \frac{\sigma}{3\lambda + 2\mu}\left[\frac{\lambda + \mu}{\mu}\left(4\lambda + 10\mu + 4m\right) + \lambda + 2l\right] \quad (3)$$

The relationship between the stress and the speed of the longitudinal wave that propagates along the stress direction can be obtained by Equation (3).

The elastic constants of different materials are shown in Table 1 (Viktor 1997).

Table 1. Lame and Murnaghan constants of the materials (GPa)

Material	λ	μ	l	m	n
Steel (0.12%C)	115	82	−301	−666	−716
Aluminium (6061)	62	26	−201	−305	−300
Copper (99.9%)	104	46	−542	−372	−401

2.2 Testing principle of ultrasonic Lcr wave method

If a longitudinal wave accelerates as it propagates from one medium to the other, there must be an incidence angle that makes the refraction angle of the longitudinal wave equal to 90o according to the Snell's law. Reflected at 90o, the longitudinal wave is called the critically refracted longitudinal (Lcr) wave, with the angle of incidence as the first critical angle. Taking a PMMA acoustic wedge and an aluminium component (Figure 1) for example, the axial direction of the first critical angle of the component is defined as follows:

$$\theta_{L_{CR}} = \arcsin(V_1/V_2) \quad (4)$$

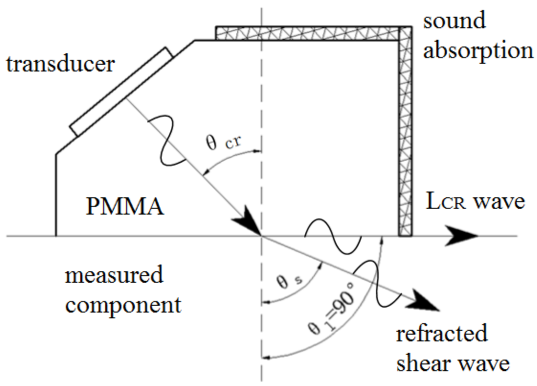

Figure 1. Mechanism of the Lcr wave

Whereas the spacing between the transmitting and receiving transducers is fixed in the actual detection, we can acquire the wave speed variation can be acquired by calculating the wave propagation time, and then determine the acoustoelastic effect. From Equation (3), we can obtain the relationship between the stress variation and the changing time of wave propagation:

$$d\sigma = K \cdot dt \text{ or } \Delta\sigma = K \cdot \Delta t \quad (5)$$

$$K = \frac{-2V_0(3\lambda+2\mu)}{(\frac{4\lambda+10\mu+4m}{\mu}+\frac{2l-3\lambda-10\mu-4m}{\lambda+2\mu})L} \quad (6)$$

For example, the speed of Lcr wave in zero-stress aluminium alloy 6061 is 6.32km/s. As shown in Table 1, the Lame and Murnaghan constants of the alloy are $\lambda = 62\text{GPa}$, $\mu = 26\text{GPa}$, $l = -201\text{GPa}$, $m = -305\text{GPa}$ and $n = -300\text{GPa}$. According to Equation (6), the stress coefficient of aluminium alloy 6061 stands at $K = 4.15$ (MP/ns) when the spacing between the transducers $L = 30\text{mm}$.

2.3 Relationship between frequency and residual stress depth

The penetration depth of the Lcr wave in the test medium hinges on the excitation pulse frequency of ultrasonic transducers. In light of this, the centre frequencies of ultrasonic transducers must fall in the standard range from 1 to 15MHz. Table 2 presents the relationship between transducer frequency and penetration depth in ultrasonic testing of residual stress in different materials.

Table 2. Relationship between transducer frequency and penetration depth

Frequency (MHz)		1	2.5	5	10	15
Depth (mm)	Steel	5.58	2.48	1.28	0.66	0.44
	Aluminium	6.40	2.66	1.37	0.70	0.48
	Copper	4.81	2.00	1.03	0.53	0.36

2.4 Relationship between ultrasonic transducers and detectable area of residual stress

The ultrasonic Lcr wave method can detect the residual stress in a certain area on the surface of the test material (Figure 2). The detectable residual stress equals the average value in that area. As the transducers vary in size, the length of the detectable area (L) ranges between 5 and 500 mm, the width of the area (W) falls between 5 and 30 mm, and the depth (D) is related to the frequency of the transducers.

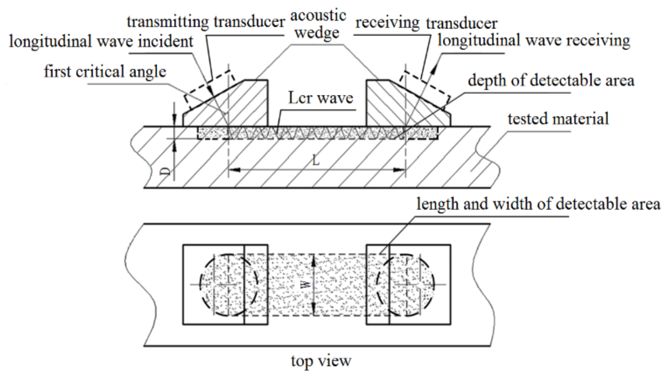

Figure 2. Detectable area

3 TESTING OF RESIDUAL STRESS

3.1 Overview of the testing system

The residual stress testing system is grounded on the principle of ultrasonic Lcr wave method. The system mainly consists of special ultrasonic transducers, an ultrasonic transceiver, a temperature sensor and transmitter, an automatic scanning device, a data trigger, a data collector, a calibration block, a portable industrial control computer with corresponding algorithm software, etc.

3.2 Calibration of the stress coefficient

The detector was calibrated before testing the residual stress. In a lab environment, the calibration was performed on a tension and compression testing machine capable of producing create standard-value stress. Prior to the tensile test, zero-stress specimens were prepared, and given annealing treatment or vibration aging treatment to relax the residual stress. The specimen material shared the same texture, surface roughness and metallurgical composition with the test material, and borne the shape and size of tensile samples specified in ISO 6892-1:2009. The surface roughness of the calibration region was less than Ra 10μm.

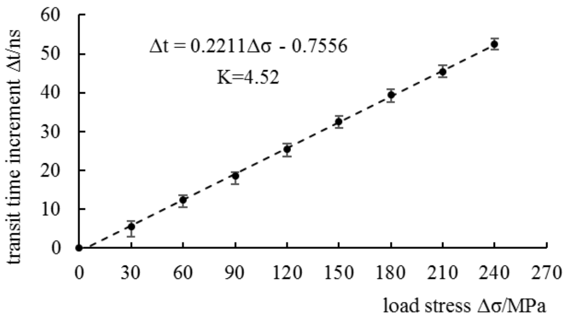

Figure 3. Relationship between tensile stress and propagation time.

(The frequency of transducers: 5MHz; the propagation distance between transducers: 30mm;

the specimen material: aluminium alloy 6061; ambient temperature: 23°C)

Following the method defined in ISO 6892-1:2009, the tensile test was conducted at the ambient temperature of 22±2°C. The stress increment $\Delta\sigma$ and propagation time increment Δt were measured at no fewer than 8 points in the elastic stress range of the material. The tensile test was repeatedly conducted at least 5 times, and the measured stresses and propagation time increments were averaged and taken as the calibration data. Figure 3 shows an example calibration data, together with the relationship between stress increment $\Delta\sigma$ and propagation time increment Δt. The stress and propagation time data were linearly fitted to obtain the fitting line. The reciprocal of the fitting line slope was the calibrated stress coefficient K. As shown in Figure 3, stress coefficient K of aluminium alloy 6061 was 4.52 (MPa/ns) after calibration.

3.3 Temperature compensation and correction

The Lcr wave speed may change with the temperature, resulting in error in stress measurement. The measurement error induced by temperature variation must be corrected to assure the measurement precision. In order to implement the compensation, the relationship between temperature and Lcr wave speed (or the propagation time between transducers) must be identified in the experiment or looked up in the data manual of the material.

The testing probe and zero-stress specimen were placed in a high/low temperature chamber. After the detector was fixed in the chamber, the temperature was adjusted and kept constant for 10~20min for each 1°C of increase between 4~40°C. The temperature was displayed on the control panel. The propagation time difference was measured between different levels of constant temperature. For the sake of reliability, the testing process was repeated three times. The experimental results are presented in Figure 4.

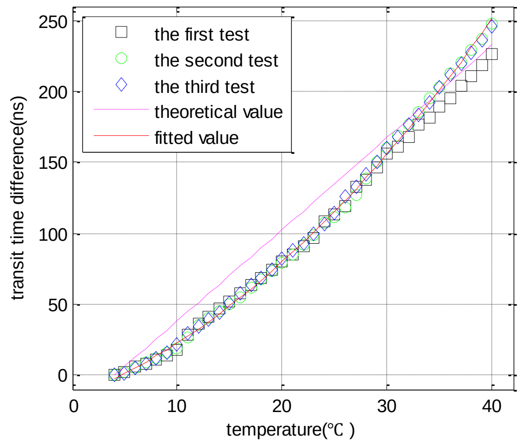

Figure 4. Relationship between temperature and propagation time difference

(The frequency of transducers: 5MHz; the propagation distance between transducers: 50mm; the specimen material: X70 steel)

MATLAB second-order polynomial was used to fit the experimental data. The relational expression of temperature and propagation time difference is obtained as follow (Song, 2014).

$$t = 0.0955T^2 + 2.8532T - 15.4805 + T_4 \quad (7)$$

Substitute calibration temperature T_1 and detection temperature T_2 into Equation (7) to obtain:

$$\Delta t = \Delta T(0.0955(T_1 + T_2) + 2.8532)$$

(8)

The relationship equation (8) of temperature and propagation time difference was inputted into system software to eliminate the error induced by temperature variation.

4 EXPERIMENT AND APPLICATION

Featuring high resolution, deep penetration, little destruction and harmlessness to human body, the ultrasonic Lcr wave method is the most promising technology of residual stress testing. The ultrasonic detector was adopted to experimentally test the residual stress of oil pipeline weld joint.

After the X70 steel pipeline was manually arc welded, we tested the residual stress around the straight weld joint in a section of the pipeline. The results are shown in Figure 5. Then, a hydrostatic test was carried out to verify the precision of the test results. From the Figure 6, it is observed that the blasting area is consistent with the hazardous area evaluated by the ultrasonic Lcr wave method.

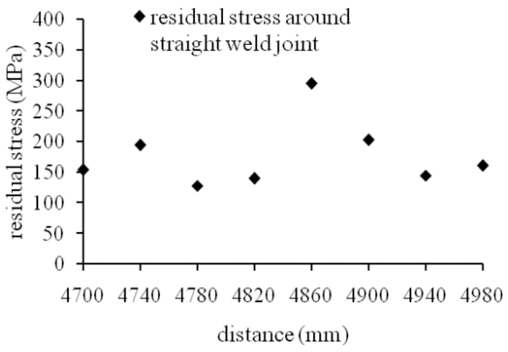

Figure 5. Distribution curve of residual stress

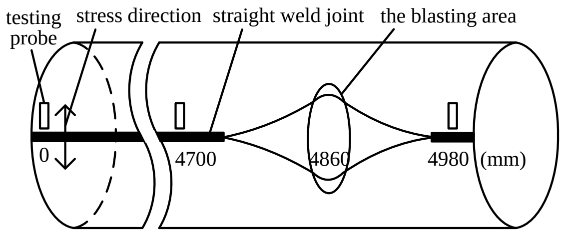

Figure 6. Hydrostatic experimental verification

Moreover, we applied the proposed method in residual stress testing of high pressure pipe, vehicle drive shaft, vehicle shell weld joint, aviation turbine disk, aviation engine blade, aluminium alloy plates, high-speed railway track, coated component, glass and ceramics, circuit board, gear root, bearing, thin pipe or tube, fibre composites, and so on. The states of residual stress distribution in those mechanical components are in good agreement with the actual results.

5 CONCLUDING REMARKS

Based on theory of acoustoelasticity, we analysed the testing principle of ultrasonic Lcr wave method, and then designed a pitch-catch oblique incidence probe to excite the ultrasonic Lcr wave in the test material. The detectable area depends on the sizes and the spacing between the two transducers, and the detectable depth relies on the frequency of transducers.

Next, we built a testing system of residual stress. To ensure the precision of the test results, the stress coefficient was calibrated, and the temperature was compensated and corrected. The stress coefficients of different materials can be theoretically obtained by Equation (6) in this paper. However, it is better to obtain the stress coefficient experimentally, thereby eliminating the effect of metallurgical composition and texture.

Finally, we tested the residual stress in oil pipeline weld joint and many other mechanical components. Through the experiment and application, the ultrasonic Lcr wave method was verified as precise, practical and widely applicable.

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8 NOTATION

The following symbols are used in this paper:
δ_{IK} = Kronecker delta function;
ρ^i = density of the solid in the loading condition;
u_I = dynamic displacement;
X_J = particle position vector;
C_{IJKL} = equivalent stiffness, which depends on the material constant and the initial displacement field;
t^i_{JL} = Cauchy stress shown in the initial coordinates under the solid loading state;
λ , μ = Lame elastic constants;
l, m, n = Murnaghan elastic constants;
ρ_0 = density of the solid before deformation;
σ = stress applied in one direction (tensile stress is positive and compressive stress is negative);
V = velocities of the longitudinal wave;
K = stress coefficient of measured component;
Δt = time variation under the condition of stress;
L = distance between the transmitting and receiving transducer;
V_0 = longitudinal wave velocity under the condition of zero stress;
T_4 = transit time difference under the temperature of 4°C.