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Ultrasonic nondestructive testing and regulation technology of residual stress

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Abstract. Residual stress regulation technology is a procedure to reduce residual stress by means of high-energy ultrasonic after stress testing. Based on acoustoelasticity theory, the relationship between ultrasonic propagation and stress in aluminum alloy is researched. With the principle of exciting ultrasonic critically refracted longitudinal wave obtained, the ultrasonic stress testing system is established. For in situ regulation of residual stress, the interactive relationship between high energy ultrasonic and residual stress field is studied. We reduced the residual stress and improved stress state of components through effective control of high-energy beam and incentive mode. Thus in situ relief and control of local residual stress distribution in mechanical components in service are realized. The technology can improve the whole strength, anti-fatigue and corrosion resistance of mechanical components and enhance their service life, safety and reliability, and now is widely used in the stress testing and relief of aluminum alloy welding components.

1. Introduction

Aluminium Alloy and its welding components are widely used in the aerospace industry. Residual stress in the components is a type of inherent stress maintaining stress balance in the inner material when the components are not affected by external force. Mechanical processing progress, such as extrusion, rolling, drawing, correction, grinding, surface rolling, shot peening, and hammering, as well as the hot working like welding and cutting will inevitably produce the residual stress.

The residual stress is harmful usually. For example, under the combined action of residual stress, working temperature and working medium, the resistance to fatigue strength, brittleness fracture, stress corrosion cracking and the stability of size and shape in aluminum alloy components are greatly reduced [1]. Meanwhile, the accumulation of residual stress on the surface of aluminum alloy components always results in forming surface cracks or subsurface crack. The hidden defects in the subsurface of components are more covert and dangerous.

The technology of residual stress detecting dated from the 1930s, till now, more than ten types of detection methods have been developed, especially the non-destructive testing methods, including X-ray diffraction method, neutron diffraction method, magnetic measurement and ultrasonic method. In 2012, Professor Rossini from Italy analyzed various detection methods and considered that the ultrasonic method with the advantages of high resolution, high penetration and no harm to human body is one of the most promising non-destructive detection methods of residual stress [2].

For residual stress regulation of aluminum alloy components in service, both traditional natural aging method, hammering method, heat aging method, and the current harmonic spectrum, magnetic pulse method have their limitations, unable to achieve in situ regulation or elimination of aluminum

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alloy welding residual stress. Thus, a new residual stress elimination technology should be studied to meet the urgent need to in situ regulation of aluminum alloy components.

Based on acoustoelasticity theory, the relationship between velocity and propagation direction of ultrasonic and stress is studied, and the calibration technology of ultrasonic residual stress detection is discussed in this paper. The ultrasonic detection and calibration system is applied to the aluminum alloy welding residual stress detection and has achieved good application effect; meantime, to place mechanical components in high energy field and use the high energy ultrasonic regulation technology of residual stress to change the surface and internal residual stress state of aluminum alloy components, and the local quantitative elimination of residual stress is realized.

2. Theory of Ultrasonic Testing

2.1. Acoustoelasticity Theory

Acoustoelasticity theory is based on the finite deformation of continuum mechanics to study the relationship between the elastic solid stress state and the macroscopic elastic wave velocity. Theoretical study shows that the velocity of elastic waves in solid materials not only depends on the second order elastic constants, higher order elastic constants and density of the material, but also is related to the residual stress. According to the acoustoelastic effect, compressive or tensile residual stress will affect the velocity of ultrasonic wave.

The elastic wave formula (acoustoelasticity formula) in stress medium under initial coordinates can be obtained using the following equation [3]:

Acoustoelasticity theory is one of the main bases for ultrasonic stress testing.

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

Where δ_{IK} is Kronecker delta function; ρ^i is the density of the solid in the loading condition; $\boldsymbol{u_I}$ and $\boldsymbol{u_K}$ are the dynamic displacements; $\boldsymbol{X_J}$ and $\boldsymbol{X_L}$ are the particle position vectors; $\boldsymbol{C_{IJKL}}$ is the equivalent stiffness, which depends on the material constant and the initial displacement field; and $\boldsymbol{t^i_{JL}}$ is the Cauchy stress shown in the initial coordinates under the solid loading state.

Equation (1) shows that acoustoelastic equation is very complex and nonlinear, but can be simplified as a linear formula. Ultrasonic plane wave in the initial coordinates can be expressed as [4]:

$$u_I = U_I \exp\left[ik(N_J X_J - Vt)\right] \tag{2}$$

In the formula, k is the wave number, $k = 2\pi / \text{wavelength}$; N is unit normal direction of plane wave, which is the direction cosine of wave propagation direction.

In the case of homogeneous deformation, Eq. (1) can be simplified as follows:

$$\left(C_{IJKL} + \delta_{IK} t^i_{JL}\right)\frac{\partial^2 u_K}{\partial X_J \partial X_L} = \rho^i \frac{\partial^2 u_I}{\partial t^2} \tag{3}$$

To take Eq. (2) into Eq. (3), it can be obtained.

$$\left[C_{IJKL} N_J N_L + \left(t^i_{JL} N_J N_L - \rho^i V^2\right)\delta_{IK}\right] U_K = 0 \tag{4}$$

The characteristic equation is followed.

$$\left|D_{IK} - \rho^i V^2 \delta_{IK}\right| = 0 \tag{5}$$

$$D_{IK} = C_{IJKL} N_J N_L + \delta_{IK} t^i_{JL} \tag{6}$$

When the solid is isotropic, Eq. (4) can be expressed analytically [5]. Thus, in the Cartesian coordinate system, the relationship between ultrasonic propagation velocity and stress in solids is established as follows [6]:

For the longitudinal wave propagating along the stress direction, shown in Fig. 1:

$$\rho_0 V_{111}^2 = \lambda + 2\mu + \frac{\sigma}{3\lambda + 2\mu}\left[\frac{\lambda+\mu}{\mu}(4\lambda + 10\mu + 4m) + \lambda + 2l\right] \tag{7}$$

In Eq. (7), λ and μ are the Lame constants; l, m, n are the Murnaghan constants; ρ_0 is the density of the solid before deformation; and σ is the stress applied in one direction (tensile stress is positive and compressive stress is negative).

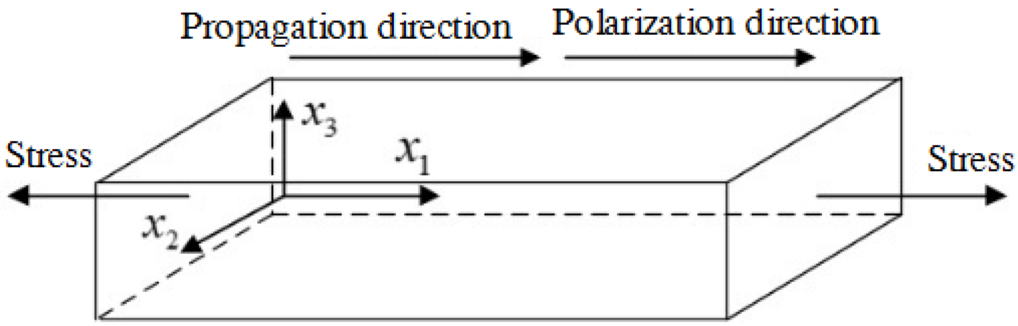

Figure 1. The longitudinal wave propagating along the stress direction

2.2. Longitudinal Critically Refracted (LCR) Wave Method

When a longitudinal wave propagates from a medium in which the wave longitudinal wave is slower to a medium in which the wave velocity is faster, according to the Snell law, there is an incidence angle that makes the refraction angle of the longitudinal wave equal to 90o. A longitudinal wave with a refraction angle equal to 90o is called the critically refracted longitudinal wave (LCR) [7]. The angle of incidence is the first critical angle. Taking plexiglass acoustic wedge and steel plate as an example, calculation formula of the first critical angle is followed.

$$\theta_{L_{CR}} = \arcsin(V_1/V_2) \tag{8}$$

In the formula, V_1 is the longitudinal wave velocity in the acoustic wedge, V_2 is the longitudinal wave velocity in the steel.

For curved surface, the first critical angle $\theta_{L_{CR}}$ is:

$$\theta_{L_{CR}} = \arcsin(\frac{V_1}{V_2}) \pm \frac{90L}{\pi R} \tag{9}$$

In the formula, L is the propagation distance by ultrasonic, R is the radius of curved surface. For convex surface is＋, the concave surface is－.

Usually the velocity of aluminum alloy is 6300m/s, the first critical angle is 26 degrees.

3. Principle of Residual Stress Regulation

According to the theoretical analysis, the essence of residual stress is the lattice elastic distortion, and to a great extent, it is caused by the constraining force between the lattices.

Based on the experimental phenomenon, the existence and essence of residual stress, and the dislocation model of lattice, the interaction between the constraining force field and elastic wave around dislocations is analyzed, and the theory model of high energy ultrasonic on residual stress is established.

The energy obtained by mass element is as follows, wherein, the element is provided by high-energy ultrasonic wave, and distance between the element and power ultrasonic wave source is x [8]:

$$E=\frac{1}{2}\rho_0 V_0 u^2+\frac{1}{2}\frac{(A\sin 2\pi ft)^2 V_0}{\rho_0 c^2}\times\exp[-2x(CFd^3 f^3+\frac{2\pi^2 f^2 K^2}{\rho_0 c^3}(\frac{1}{c_v}+\frac{1}{c_p}))] \quad (10)$$

It has been known according to the formula (10), the high-energy ultrasonic-wave provided energy of metal inner mass element is proportional to the natural properties of metal material, such as density ρ_0, constant-volume specific heat c_v, constant-pressure specific heat c_p and etc, and is inversely proportional to a speed c with which the ultrasonic wave is spread in the metal material, while the aforementioned energy is proportional to the square of sound pressure amplitude A and frequency f provided by ultrasonic-wave.

When ultrasonic energy acting on the metal element is greater than the constraining energy between lattices, the residual stress within the metal will be released. It theoretically proved the high ultrasonic energy could regulate the residual stress, and the regulation efficiency and effect is related to material properties (elastic modulus, yield strength, density, and acoustic impedance), excitation frequency, coupling state and the layout positions of regulation.

4. Experimental System

4.1. The Testing System

The ultrasonic testing system of residual stress is based on the development of the acoustoelasticity theory, the operational principle is shown in Fig. 2. The system could detect 1.5mm depth (related to the frequency of the transducer) under the work-piece surface by ultrasonic critically refracted longitudinal wave, realize rapid and non-destructive detection of residual stress, and make accurate judgment and assessment of the residual stress and stress state.

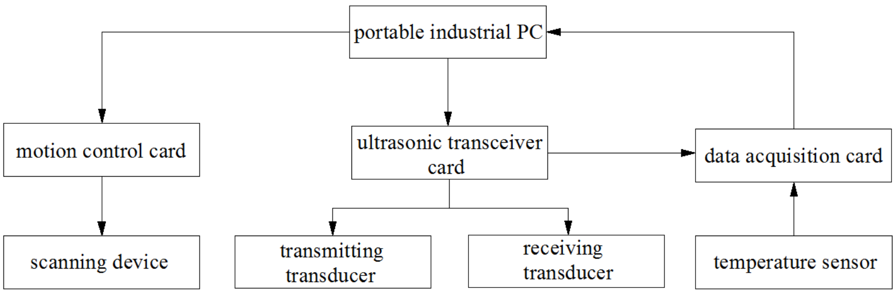

Figure 2. Principle diagram of residual stress ultrasonic testing system

4.2. The Regulation System

The composition of the high-energy ultrasonic regulation system is shown in Fig. 3, mainly including high-energy ultrasonic generator, high-energy ultrasonic transducer, and some peripheral equipments (vacuum clamping device, excitation voltage transmission lines and couplant).

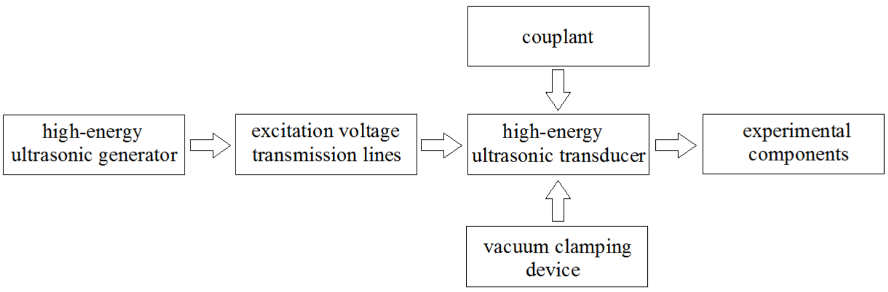

Figure 3. Constitutional diagram of residual stress high energy ultrasonic regulation system

5. Results

5.1. Residual Stress Test and Control of Aluminum Alloy Thin-Walled Disk of a Large Size Spacecraft
The material of thin-walled disc is stainless steel 304. A total of 40 points around the weld line have been tested, and test direction is perpendicular to the weld line. Every test point is 3mm away from the welding center, and is adjacent to each other. The distribution of test points are shown in Fig. 4, and stress distribution is shown in Fig. 5.

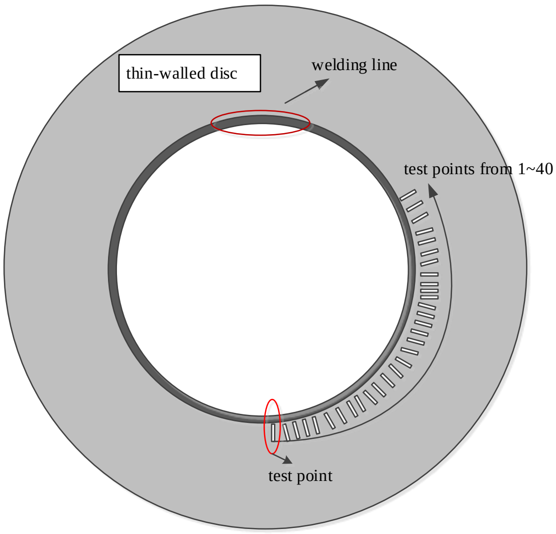

Figure 4. Diagram of testing and regulatory regions

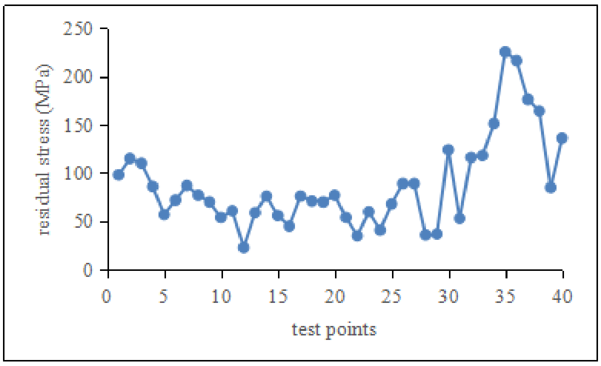

Figure 5. Stress distribution of the disc

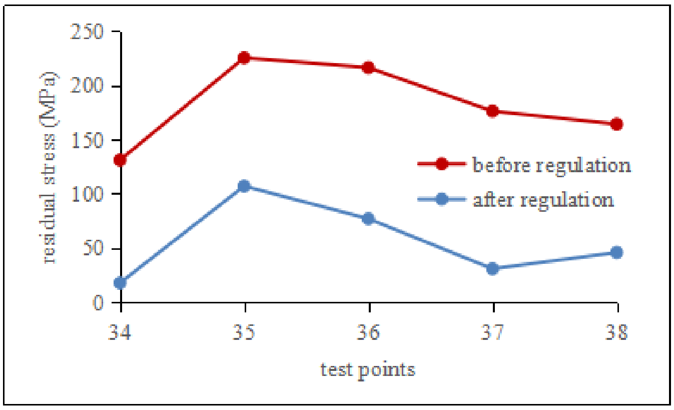

Figure 6. Stress distribution before and after regulation

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From the Fig. 5, it is observed that the residual stress at test points 34 to 38 is relatively larger than the others. So, we can assume that the area of point 34 to 38 is the weakest position because of stress concentration. Using the high-energy ultrasonic regulation system to regulate the weakest position, the regulation time is 15min. The stress distribution before and after regulation is shown in Fig. 6, from which it can be obtained that the residual stress after regulation is significantly lower than before regulation, and the levels of residual stress dropped by an average of 125 MPa.

5.2. Residual Stress Test and Control of Aluminum Alloy Bottom Board of Amphibious Vehicle

The high energy ultrasonic regulation system is used to regulate the residual stress of welding car-body. Before regulation and after regulation, the stress of welding body is tested. The site layout of high energy ultrasonic transducers in Fig. 7 and the stress distribution curves before and after regulation is shown in Fig. 8.

Figure 7. Site layout of the ultrasonic transducers

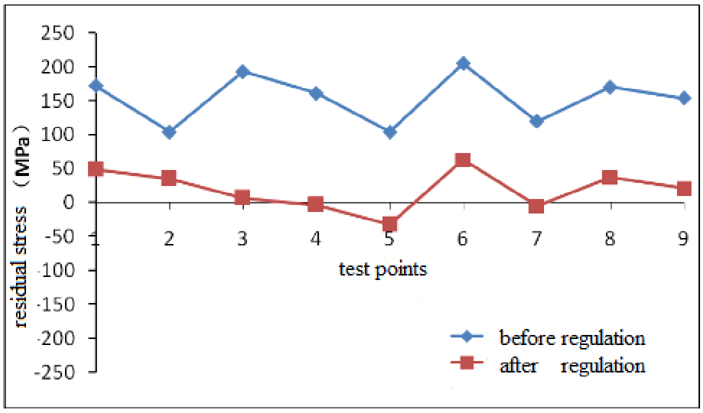

Figure 8. Stress distribution before and after regulation

The experimental results show that: after regulation the residual stress change is obvious, the large tensile stress is eliminated, and local beneficial residual compressive stress occurs.

6. Conclusions

(1) Based on acoustoelasticity theory, it can be obtained that there is a linear relationship between velocity and stress. According to the Snell's law, the critically refracted longitudinal (L_{CR}) wave can be got when a wave incidents in the first critical angle. The stress and the state of tension and compression of aluminum alloy welding components paralleling to the direction of the LCR wave can be detected by the L_{CR} wave method.

(2) Putting the aluminum alloy welding components in the high-energy acoustic field and changing the residual stress state on the surface and in the welding components by high energy ultrasonic energy.

The local quantitative elimination of residual stress is realized.

(3) The results show that the testing and in situ regulation technology of residual stress has good accuracy, practical applicability and universality in the field of application. The technology can solve the problem on testing and eliminating the residual stress of aluminum alloy, and ensure a good overall performance of aluminum alloy equipments in aerospace, military and civilian field.

(4) This technology has been successfully used in the residual stress testing and regulation of steel and titanium alloy components, oil and gas pipelines, high-speed rail vehicle bogie, transmission shaft, aircraft turbine and so on.

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