Calculation Techniques of two-dimensional residual stress field for mechanical engineering application

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***Abstract*—Residual stress takes a great effect on security and service life of components on manufacturing in industry, it occurred interior and exterior of material, such as destructive, consuming time, inaccuracy. The traditional residual stress measurement methods can not afford the demands of safty monitor and life extendibility of the components. In this paper, we proposed an ultrasonic scanning technique of measuring the 2D residual stress field with critically refracted longitudinal wave based on the acoustoelasticity theory for sheet metal parts. A scanning frame was designed to make the testing process automatically. As a kind of stress, the residual stress is also a vector with value and direction. According to the principle of mechanical synthesis, the mathematical characterization for 2D residual stress field was proposed.**

Keywords-residual stress; ultrasonic; automatic scanning technology

I. INTRODUCTION

Residual stress is produced by the inhomogeneity of stress, strain or temperature to keep homeostatic of material during manufacture process, which is an inherent property. The distribution of stress remained within the mechanics is called the residual stress field , that is the most effective characterization of fatigue state and the important basis of prediction for failure and fatigue damage. Therefore, how to accurately analyze the distribution of residual stress field to improve the quality, durability and reliability has played a vital role.

With the application and development of ultrasonic detection technology in the industry, ultrasonic method for residual stress testing is widely studied as a kind of new method. At present, the research mainly focus on the method of Rayleigh wave[1, 2], ultrasonic microscopic[3], laser ultrasonic[4] and critically refracted longitudinal wave[5] and so on, which are used to measure the distribution of residual stress for welding structures and plate structures based on the acoustoelasticity[6]. Moreover, by the means of finite element analysis, the calculation[7] and characterization technique[8] of residual stress are studied theoretically. But few researches are about the measurement and characterization of two-dimensional residual stress field.

In this paper, a set of ultrasonic scanning device is developed to detect the residual stress field distribution automatically and data-fitting is putted forward to express the two-dimensional residual stress field.

II. PRINCIPLE

As the critically refracted longitudinal wave is sensitive to the stress along the propagation direction, it spreads in the surface and subsurface of material, so it is suitable for testing the surface residual stresses. The critically refracted longitudinal wave is created by refraction. When longitudinal wave incidents from one medium into the other with an angle, refraction effect will happen. Then refracted longitudinal wave and shear wave will be generated in the medium. According to the Snell's Law, there exists an incident angle which makes the refracted angle to be 90° . This incident angle is defined as first critical angle and this refracted longitudinal wave is defined as critically refracted longitudinal wave, i.e., LCR wave[7]. Shown as the Fig.1.

The measurement of residual stress by ultrasonic is based on acoustoelasticity theory, which is a theory about the relationship between elastic wave propagation velocity and stress. According to the theory, different propagation velocity corresponds to different residual stress.

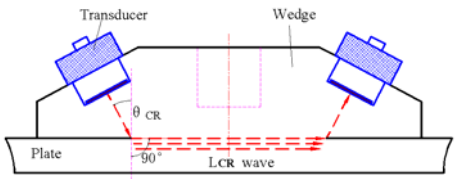


FIGURE I. GENERATION OF L_{CR} WAVE.

The relationship between the velocity of longitudinal wave propagating along the direction of stress and the stress is as [9]:

$$V = \left(\frac{\lambda+2\mu+\frac{\sigma}{2\lambda+2\mu}\left[\frac{\lambda+\mu}{\mu}(4\lambda+10\mu+4m)+\lambda+2l\right]}{\rho_0}\right)^{\frac{1}{2}} \quad (1)$$

Where V is the propagation velocity of longitudinal wave in the case of residual stress, λ and μ are the second-order elastic constants, l and m are the third-order elastic constants, σ is the stress value, and ρ_0 is the density of the material that is under measurement.

In the case of zero stress, the propagation velocity of longitudinal wave is as :

$$V_0 = \sqrt{\frac{\lambda+2\mu}{\rho_0}} \quad (2)$$

Where V_0 is the propagation velocity of longitudinal wave in the case of zero stress.

Studies have shown that about 100MPa change of stress only cause 0.1% variation of the propagation velocity. The velocity change caused by stress change is not so significant that V can be approximated as V_0. Substitute (2) into (1) and simplified to:

$$d\sigma = \frac{2}{kV_0^2} dV \tag{3}$$

In the case of constant propagation distance, the change of velocity can be reflected in the time of flight. From (3) , we can obtain:

$$\Delta\sigma = K\Delta t \tag{4}$$

Where $\Delta\sigma$ is the change of residual stress, Δt is the change of propagation time, K is stress constant.

Formula (4) shows that the change of residual stress has a liner relationship with the propagation time variation. That means we can obtain the residual stress by measuring the change of propagation time. A positive value indicates a tensile stress state, and propagation velocity decreases with the increase of tensile stress; on the other hand, a negative value means a compressive stress state, while the velocity increases with the increasing of compressive stress.

III. Establishment of Experimental System

The two-dimensional residual stress field scanning system for plate structure is shown as Fig.2, it is mainly composed of ultrasonic testing part and automatic scanning part. The former consists of a PC, ultrasonic transducers, ultrasonic transceiver and high frequency data acquisition card. The ultrasonic transceiver is controlled by PC to inspire the transducers, a synchronization signal is send to the acquisition card at the same time. In accordance with the setting sampling rate, the testing data is collected and analyzed by PC. The automatic scanning part is made up of a PC, a RS232-RS485 converter, a motor controller, a step motor with encoder, sensors and magnetic scanning frame. The frame compromises a high precision linear unit, magnet and a flexible compressive bar which ensures the contact status between transducers and plate. And it is convenient for the frame to adsorb on the surface of plates. As shown in Fig.3, during the scanning, the speed and position of step motor are controlled by PC through the motor controller. The scanning location is feedback and recorded by the encoder. By changing the adsorb location of frame or the direction of transducers, the distribution of residual stress along the liner unit and perpendicular to the liner unit can be obtained.

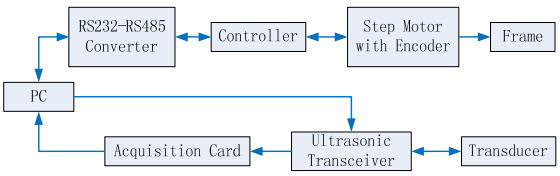


FIGURE II. THE COMPOSITION OF TWO-DIMENSIONAL RESIDUAL STRESS FIELD SCANNING SYSTEM.

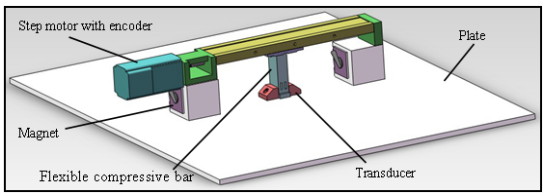


FIGURE III. THE SCANNING SYSTEM.

IV. Experimental Results

In this paper, the material of the plate is selected to be 45# steel with 10mm thick. The center frequency of transducers is 5MHz. The distance between the transducers is ensured to be fixed. Before carrying out the scanning test, some samples should be made for the stress constant calibration according to the "Tensile test of metal materials at standard temperature". The calibration result is shown as Fig.4. And the stress constant of 45# steel is 11.32 MPa/ns.

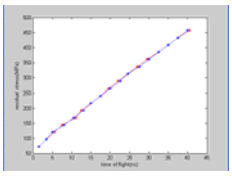


FIGURE IV. CALIBRATION OF STRESS CONSTANT.

During the scanning, the residual stress of y direction can be detected along x direction according to the setted step. As shown in Fig.5. Then change the adsorb location of frame or the direction of transducers, the residual stress of x direction can be detected along y direction can also be detected. As shown in Fig.6. In this paper, the residual stress of the two directions are scanned. The scanning step is 1mm, the scanning distance along x direction is 90mm and that along y direction is 45mm. The result after data-fitting is shown as Fig.7.

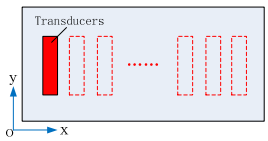


FIGURE V. SCANNING OF RESIDUAL STRESS IN Y DIRECTION.

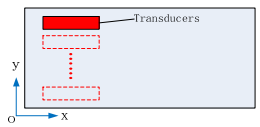
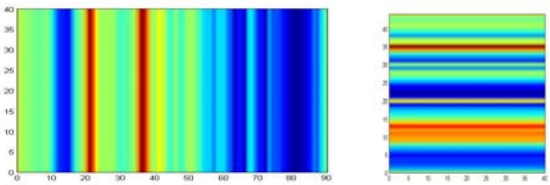


FIGURE VI. SCANNING OF RESIDUAL STRESS IN X DIRECTION.



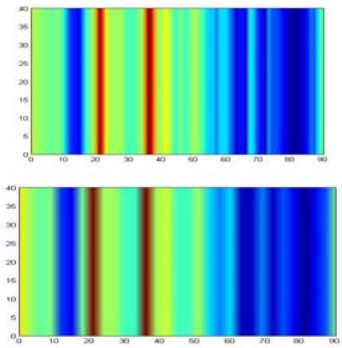
(a) Scanning along x direction (b)Scanning along y direction

FIGURE VII. SCANNING OF RESIDUAL STRESS FIELD.

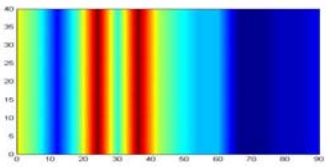
The red part of scanning result represents the concentration of residual stress. The distribution of residual stress field along the two directions can be shown intuitively by the scanning result. Therefore, in this way , the concentration areas can be distinguished effectively. However, the reliability of evaluation results is affected by scanning step. Big step will cause leak detection, while small step may reduce the scanning efficiency. In this paper, the residual stress distribution along x direction is scanned with the step of 1mm, 3mm,6mm, 9mm. The scanning results with different step are shown as Fig.8. Comparing the four figures, it's not hard to see that with the step increase some information of residual stress is omitted. So an appropriate step is important for the two-dimensional residual stress field automatic scanning.

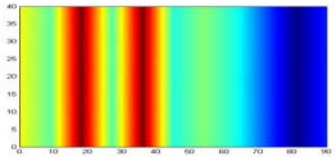
V. CONCLUSIONS

In this paper, an automatic scanning technology of the two-dimensional residual stress field is proposed, which is based on acoustoelasticity theory and ultrasonic scanning technology. And data-fitting is used to analysis the scanning results, while the color bar express the distribution of residual stress. The residual stress field can be reflected intuitively. Due to the application of ultrasonic scanning technology, the influence of scanning step on test results is considered. In the case of making no difference on scanning efficiency, the step should be as small as possible. And the scanning results are much more close to the real stress state.



(a) Step=1mm (b)Step=3mm





(c) Step=6mm (d)Step=9mm

FIGURE VIII. SCANNING RESULTS OF DIFFERENT STEP.

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