Ultrasonic Nonlinear Characteristics of Plastic Damage in Aluminum Plate

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Nonlinear ultrasonic method uses the nonlinear characteristics inspired by the interaction between discontinuous medium and ultrasonic to do the evaluation of performance and the identification of the damage. The characteristic parameters are not limited to the size of the defect, which provides effective means for the accurate evaluation on the early damage. The relationship between plastic damage and the nonlinear is analyzed by Murnaghan simulation model quantitatively. The amplitude of the second harmonic is observed in different degrees of plastic damage. According to the changes of the amplitude of second harmonic and strain energy function, area and the state of the plastic damage can be determined.

***Index Terms*—distortion measurement, ultrasonic variables measurement, nonlinear acoustics, harmonic analysis.**

I. Introduction

Conventional linear ultrasonic detection method is not sensitive to the micro defects (such as dislocation, micro cracks, etc.) formed in the early stage of the damage. Nonlinear ultrasonic method uses the nonlinear characteristics produced by the interaction between ultrasonic wave and the discontinuous part to evaluate and identify the defect [1-2].

However the plastic deformation cannot cause changes on material properties, such as elastic modulus, sound velocity and acoustic attenuation, it can affect the nonlinear relationship between stress and strain in the dislocation area. Therefore, the plastic damage of material caused by dislocation can be represented by measuring nonlinear acoustic parameters [3].

Based on the electromagnetic ultrasonic theory, the wave equation of guided wave propagating in the solid and the nonlinear theory of solid mechanics, the degree of plastic damage in aluminum plate can be determined by studying the nonlinear response of the guided wave.

II. Theoretical Analyses

A. The second-order nonlinear equation of the closed crack

Nonlinearity between stress and strain in the local area is plastic deformation. The strain energy function is used to establish the constitutive model to represent nonlinearity of material. Green-Lagrange strain tensor is defined as $\boldsymbol{E}$, vector gradient of displacement is defined as $\boldsymbol{H}$, the relationship [4]:

$$\boldsymbol{E}=\frac{1}{2}\left(\boldsymbol{H}+\boldsymbol{H}^{\mathrm{T}}+\boldsymbol{H}^{\mathrm{T}}\boldsymbol{H}\right) \tag{1}$$

Linear strain tensor E^{l}:

$$\boldsymbol{E}^{\mathrm{l}}=\frac{1}{2}\left(\boldsymbol{H}+\boldsymbol{H}^{\mathrm{T}}\right) \tag{2}$$

Compare Lagrange strain with linear strain, the component of second order item $\boldsymbol{H}^T\boldsymbol{H}$ is nonlinear strain of damage. Murnaghan model is used to realize the one to one correspondence between strain and elastic function $\boldsymbol{W(E)}$

$$W(\boldsymbol{E})=\frac{1}{2}\lambda\left(tr(\boldsymbol{E})\right)^{2}+\mu tr\left(\boldsymbol{E}^{2}\right)+\frac{1}{3}(l+2m)\left(tr(\boldsymbol{E})\right)^{3} \\ -mtr(\boldsymbol{E})*\left(\left(tr(\boldsymbol{E})\right)^{2}-tr\left(\boldsymbol{E}^{2}\right)\right)+n\det(\boldsymbol{E}) \tag{3}$$

l, m, n are constants of third-order Murnaghan, λ and μ are constants of Lame wave, tr() is the trace of matrix solved, det() is the determinant of matrix solved.

By type (3), the second-order Piola-Kirchhoff stress tensor:

$$T=\frac{\partial W(\mathbf{E})}{\partial \mathbf{E}} \tag{4}$$

First-order Piola-Kirchhoff stress tensor

$$\boldsymbol{T}_0=(\boldsymbol{I}+\boldsymbol{H})\boldsymbol{T} \tag{5}$$

$\boldsymbol{I}$ is the second-order identical tensor. First-order Piola-Kirchhoff stress tensor $\boldsymbol{T_0}$ can be divided into the linear component $\boldsymbol{T_{0,N}}$ and nonlinear component $\boldsymbol{T_{0,NL}}$. The wave equation in the solid can be solved by solving electromagnetic force:

$$\boldsymbol{f}=\boldsymbol{f}_{L,s}+\boldsymbol{f}_{L,d}=\boldsymbol{J}_e\times\boldsymbol{B}_s+\boldsymbol{J}_e\times\boldsymbol{B}_d \tag{6}$$

$$\nabla\cdot\boldsymbol{T}_0+\rho_0\boldsymbol{f}=\rho_0\boldsymbol{u} \tag{7}$$

$\boldsymbol{\rho_0}$, the density of specimens tested; $\boldsymbol{f}$, Lorentz force; $\boldsymbol{J_e}$, eddy current; $\boldsymbol{B_S}$, strength of static magnetic field; $\boldsymbol{B_d}$, strength of alternating magnetic field; Use Micro perturbation method into $\boldsymbol{u}=\partial^2\boldsymbol{u}/\partial\boldsymbol{t}^2$:

$$(\lambda+\mu)\nabla(\nabla\cdot\boldsymbol{u})+\mu\nabla^2\boldsymbol{u}+\nabla\cdot\boldsymbol{T}_{0,\mathrm{NL}}=\rho_0\boldsymbol{u} \tag{8}$$

The relationship between the third-order elastic constants *a,b,c*, and Murnahan parameters *l, m, n* is:

$$l=b+c;m=\frac{1}{2}a+b;n=a \tag{9}$$

Under the different plastic conditions, the Murnaghan parameters are analyzed with the fixed stress tensor and strain tensor and the quantitative relationship between the plastic damage and Murnaghan parameters *l, m, n* is studied.

III. Simulation Results

The value of the Murnaghan parameters is related to many factors, such as external load, damage and movement of dislocation and so on. In order to verify how Murnaghan parameters affect the nonlinear characteristics, it changes *l, m, n* of Murnaghan model by multiplied by different scale factors 1, 2, 3, 4, respectively, then observes the change of the second harmonics.

Frequency domain graph in different scale factors of parameters *l, m, n* of Murnaghan model is shown in figure 1. With the increase of scale factor, static component does not change, but component of second harmonic has an obvious increase. The nonlinear differences in different tensile load stages mainly come from the changes of elastic constants of higher order.

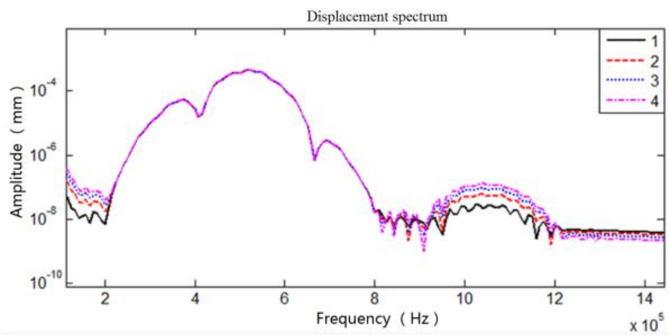

Fig. 1. The frequency domain response of Lamb wave in different scale factors.

IV. Experimental Results and Analyses

Nonlinear electromagnetic ultrasonic test system is shown in figure 2. Ultrasonic wave produced by EMAT is injected into aluminum alloy specimen. Distortion of ultrasonic wave is inspired by the action of nonlinearity of stress and strain. The distorted ultrasonic is feedback to the receiver by the inverse effect of electromagnetic ultrasonic change, and then goes through pre-amplifier, then runs into SNAP 5000 system. This paper selects the first waveform signal in addition to the main shock waves from detection signals stored. Spectrum analysis of the nonlinear characteristics of electromagnetic ultrasonic is shown in figure 3.

As shown in figure 3, the frequency of electromagnetic ultrasonic signal received is the base frequency 2.2 MHz, while there is apparent spectrum wavelet packet in the second harmonic at the frequency 4.4 MHz, which verifies the feasibility of electromagnetic ultrasonic harmonic measurement.

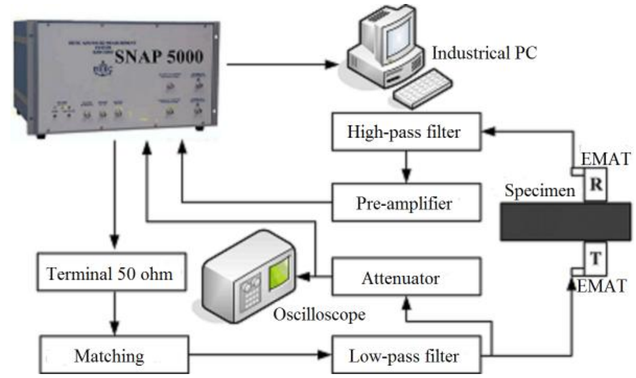

Fig. 2. Nonlinear electromagnetic ultrasonic test system.

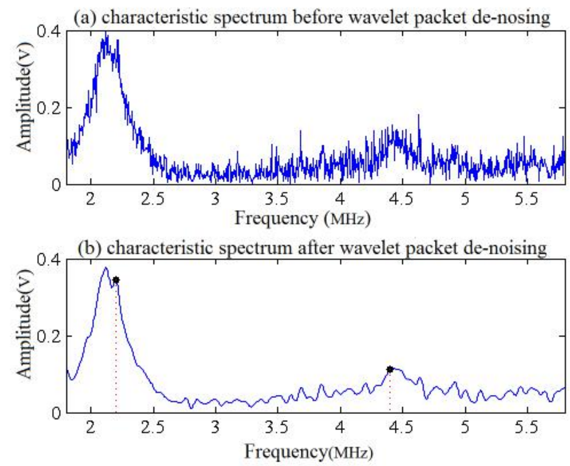

Fig. 3. Spectrum analysis of nonlinear characteristic of electromagnetic ultrasonic.

V. Conclusions

Electromagnetic ultrasonic nonlinear simulation model is presented in this paper. The relationship between plastic damage and nonlinearity is quantified by the change of the amplitude of second harmonic, which is verified by experiment. The experimental results show that the amplitude of nonlinear coefficient does not change significantly in the elastic stage, and has an obvious increase in shaping stage, and has a certain decrease in the fracture stage.

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