Effect of Mixed Dislocations on Nonlinear Acoustic Responses in Plastic Deformation Materials

Wujun Zhu\textsuperscript{a}, Yanxun Xiang\textsuperscript{a,*}, Fu-Zhen Xuan\textsuperscript{a} and Haiyan Zhang\textsuperscript{b}

\textsuperscript{a}East China University of Science and Technology, School of Mechanical and Power Engineering, 200237 Shanghai, China
\textsuperscript{b}Shanghai University, School of Communication & Information Engineering, 200444 Shanghai, China

Abstract

An analytical model is proposed for describing the influence of mixed dislocation on the acoustic nonlinearity in the plastically deformed materials, which is derived based on the dislocation line energy and variable line tension. Based on the proposed model, the interaction of nonlinear plane longitudinal wave with the plastically deformed materials was simulated in this article. The simulation was validated by the experimental measurement for the satisfactory consistency. Both simulation and experimental results reveal monotonically increasing tendency of the normalized nonlinear parameter with the plastic strain, which is mainly attributed to the dislocation evolution according to microscopic study.

Keywords: Ultrasonic nonlinearity; Second-harmonic generation; Plastic deformation; Finite element modeling; Structural health monitoring.

1. Introduction

Failure of structures often occurs due to the intense microstructure evolution during plastic deformation. Quantitatively tracking the microstructure evolution in plastically damaged materials is essential to evaluate the structural health of materials at early stage. Recently, nonlinear ultrasound has been found to be a promising nondestructive technique to track the changes of microstructures of materials\cite{1-2}. There now have been many theoretical models describing the contributions of dislocation evolution, such as the monopole model, the dipole model and some advanced models. These models were based on the analysis of pure edge dislocations or screw

* Corresponding author. Tel.: +86-21-64252423; fax: +86-21-64253762.
E-mail address: yxxiang@ecust.edu.cn
dislocations. However, throughout the material damage, the mixed dislocations density increases substantially and the mixed dislocations spontaneously arrange themselves in veins and persistent slip bands. To date, some numerical methods to simulate ultrasonic nonlinearities of media and/or damage have been proposed, such as finite element method (FEM), finite difference time domain method (FDTD), and local interaction simulation approach (LISA), etc.

In this paper, An analytical model is proposed for describing the influence of mixed dislocation on the acoustic nonlinearity in the plastically deformed materials. Then, finite element analysis and experimental validation of nonlinear ultrasonic waves propagating in the plastically deformed media are carried out. Metallographic studies are executed to thoroughly analyze the influence of microstructure evolution on the nonlinear ultrasonic responses.

2. Acoustic nonlinearity parameter associated with dislocation evolution

Dislocation is generally pinned by particles and bows out like a string under the action of externally applied stress. The line energy of the mixed bow-out dislocation can be represented as,

$$E_{\text{mix}}(\theta) = \frac{\mu b^2 \sin^2 \theta}{4\pi (1-\nu)} + \frac{\mu b^2 \cos^2 \theta}{4\pi} \ln \left( \frac{r_o}{r_i} \right)$$

where $\mu$ is the shear modulus, $b$ is the absolute value of Burgers vector, $\nu$ is the Poisson's ratio, $\theta$ is the angle between the Burgers vectors and the dislocation line, $r_o$ and $r_i$ are the effective outer and inner radius, respectively.

In general, the line energy of a bow-out dislocation is not constant along the dislocation line. Considering the force's equilibrium, the shear strain $\gamma_{\text{dis}}$ caused by the mixed dislocation displacement is given by,

$$\gamma_{\text{dis}} = \frac{8\pi(1-\nu)}{3\mu} \frac{\Lambda L^3}{2(1+v) + 3v\cos2\theta} \times \left[ \ln \left( \frac{r_o}{r_i} \right) \right]^{-1} \tau + \frac{256\pi^2 (1-\nu)^3}{5} \frac{\Lambda L^4}{\mu b^2} \times (2-\nu + 3v\cos2\theta) \left[ \ln \left( \frac{r_o}{r_i} \right) \right]^{-3} \tau^3 + \cdots$$

where $\Lambda$ is the dislocation density. The total longitudinal strain is the summation of the lattice strain and the strain caused by the dislocation. When a small oscillatory stress of amplitude $\Delta \sigma$ produced by the ultrasonic wave is applied in addition to the static stress $\sigma$, the dislocation will be displaced further causing additional strain $\Delta \varepsilon$. This can be given as,

$$\Delta \sigma = \left[ \frac{1}{A_0} + \frac{2(1-\nu)}{3} \frac{\Omega \Lambda L^2 R}{\mu} \left( 1 + \nu f_e - 2\nu f_s \right) \right] \left( \Delta \varepsilon \right)$$

$$- \left[ \frac{1}{2} \left( \frac{A_0}{A_0} \right) + \frac{12(1-\nu)}{5} \frac{\Omega \Lambda L^4 R^3}{\mu b^2} \left( 1 + \nu f_e - 2\nu f_s \right) \right] \left[ \Delta \varepsilon \right]^2 + \cdots$$

where $f_e$ and $f_s$ are the fractions of the edge and screw dislocations, respectively.

3. Finite element simulations

Nonlinear simulation of plane longitudinal wave propagation in the plastically deformed 30Cr2Ni4MoV specimens was performed by introducing the proposed constitutive relation to Abaqus/EXPLICIT through the interface of user subroutine VUMAT.

The schematic of two-dimensional model is shown in Fig.1. The thickness and the length of the plate was 9mm and 180mm, respectively. The wave generation was excited by imposing 20MPa stress with a 10cycles Hanning-windowed sinusoidal tone bursts at 5.0 MHz, whose loading size is 8.6 mm, similar to the diameter of a transducer. The signal was picked through the middle node of the bottom edge. Then, Fast Fourier Transformation was performed on the time-domain signal to extract the amplitudes of the fundamental and second harmonic signals. The four-node reduced-integration plane strain elements (CPE4R) were used to mesh the rectangular model, whose
elements were equally sized at 0.05 mm with a spatial resolution of $\lambda/24$ where $\lambda$ is the wavelength of the fundamental wave. According to the Fourier or von Neumann stability analysis, the time step $\Delta t$ should be smaller than the time required for the longitudinal wave to travel across the element length. In this simulation, a fixed time step of $2.626 \times 10^{-9}$ s was set to guarantee an effective and stable calculation in the simulations.

The material used here are: $E=278$ GPa, $\nu=0.3$, $A=-708$ GPa, $B=-282$ GPa and $C=-179$ GPa. The conversion factors $\Omega$ and $R$ are assumed to be 0.33 obtained from Ref. 3. Five plastically deformed specimens were fabricated under strain-controlled mode from strain levels of 1.14% to 3.89%, using a 100 kN MTS servo hydraulic testing system. The nominal dimensions of the specimens are shown in Fig. 2. The Philips CM200 transmission electron microscope was used to take the TEM micrographs, as shown in Fig. 3. Dislocation density and length were evaluated from the TEM images according to Ref. 4. The fractions of edge and screw dislocations were estimated from $q$ according to Ref. 5. The average back stress was calculated according to Ref. 6. The microstructure parameters with different plastic strains was summarized in Table 1, in which each value was determined by an average of five micrographs.

Using the developed modeling approach above, four examples of numerical simulation for the 30Cr2Ni4MoV specimens with different plastic strains such as 0%, 1.14%, 1.73%, and 3.89%, were demonstrated. The relative nonlinear parameters $A/A^\prime$ monotonically increases with the plastic strain, as shown in Fig. 4.

Table 1. Microstructure parameters of 30Cr2Ni4MoV specimens with different plastic strain

| plastic strain (%) | $A \times 10^{14}$ m$^2$ | $L$ (µm) | $f_e$ | $f_s$ | $\sigma_0$ (MPa) | $b$ (Å) | $R$ | $\Omega$ |
|-------------------|-----------------|------|------|------|-----------------|-------|-----|------|
| 0                 | 0.35±0.15       | 0.19±0.042 | 0.35 | 0.65 | 59              | 2.5   | 0.33| 0.33 |
| 1.14              | 1.30±0.26       | 0.12±0.032 | 0.48 | 0.52 | 120             | 2.5   | 0.33| 0.33 |
| 1.73              | 1.94±0.73       | 0.10±0.030 | 0.56 | 0.44 | 147             | 2.5   | 0.33| 0.33 |
| 3.89              | 3.70±1.24       | 0.08±0.010 | 0.59 | 0.41 | 203             | 2.5   | 0.33| 0.33 |

4. Experimental validation

4.1. Nonlinear ultrasonic measurements

Nonlinear ultrasonic measurements were also performed on the plastically deformed specimens. The locations of measurement were distributed uniformly at the central location of the gage length region of specimens. The experimental setup is primarily composed of the Ritec SNAP system, a high power attenuator, a pre-amplifier, low and high pass filters, transducers, oscilloscope and computer. A narrow-band 5.0 MHz transducer and A broad-band 10.0 MHz transducer were used to generate/pick up signals respectively. The transducers were coupled to the specimen using light lubrication oil. A tone burst of 10 cycles with a frequency of 5.0 MHz was used to excite the transmitter. The received signal was filtered by a Hanning window and captured by a 300 MHz oscilloscope.
4.2. Microstructure evolution analysis

As shown in Fig. 3(a), the dislocations in the virginal specimen were mainly in the form of planar structures distributing mainly in the inner of the martensitic lath. The dislocation density is relatively low. Fig. 3(b) presents that the dislocation density increases significantly after the loading of 1.14% plastic strain. Meanwhile, there were some dislocation cell structures being observed. For sample with 1.73% plastic strain, homogenously distributed and tangled dislocations can be seen from Fig. 3(c), whose density keeps rising. Finally, after 3.89% plastic strain, much denser and more tangled dislocations and thicker dislocation cells and walls were formed, as shown in Fig. 3(d).

5. Discussion

As shown in Fig. 4, the normalized nonlinear parameters obtained from experimental measurement and FEM model both monotonically increase with the plastic strain. The nonlinear parameters are normalized with respect to their respective value of the virginal specimen. The consistency validated the developed simulation technique. The dislocation evolution plays a dominant role in the change of material nonlinearity, as shown Fig. 3. In the first stage of plastic deformation, the density of free dislocations cells increases, which contribute to the decrease of acoustic nonlinearity[7]. The normalized acoustic nonlinearity of experimental measurement is smaller than FEM simulation. In the progress of plastic deformation, the density of free dislocations near PSBs increases, which contribute to the improvement of the acoustic nonlinearity[8]. The normalized acoustic nonlinearity of experimental measurement exceeds FEM simulation.

6. Conclusion

An analytical model is proposed for describing the influence of mixed dislocation on the acoustic nonlinearity in the plastically deformed materials. Simulation and experimental measurement of nonlinear plane longitudinal waves propagation in the plastic deformed martensitic stainless steel 30Cr2Ni4MoV has been carried out. Both simulation and experimental results reveal monotonically increasing tendency of the normalized nonlinear parameter with the plastic strain, which is mainly attributed to the dislocation evolution according to microscopic study.

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