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Modeling of ultrasonic nonlinearities for dislocation evolution in plastically deformed materials: Simulation and experimental validation

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ABSTRACT

A nonlinear constitutive relationship was established to investigate nonlinear behaviors of ultrasonic wave propagation in plastically damaged media based on analyses of mixed dislocation evolution. Finite element simulations of longitudinal wave propagation in plastically deformed martensite stainless steel were performed based on the proposed nonlinear constitutive relationship, in which the contribution of mixed dislocation to acoustic nonlinearity was considered. The simulated results were validated by experimental measurements of plastically deformed 30Cr2Ni4MoV martensite stainless steels. Simulated and experimental results both reveal a monotonically increasing tendency of the normalized acoustic nonlinearity parameter as a function of plastic strain. Microscopic studies revealed that the changes of the acoustic nonlinearity are mainly attributed to dislocation evolutions, such as dislocation density, dislocation length, and the type and fraction of dislocations during plastic loading.

1. Introduction

Engineering structures and components in service usually undergo plastic deformation, which is one of the most common degradation mechanisms in materials. Material failure occurs with increasing cyclic plastic deformation, which generally accompanies microstructural evolution (e.g., dislocation multiplication, annihilation, and subgrain initiation). Therefore, quantitatively tracking microstructural evolution is essential to evaluate the structural health of plastically damaged materials at an early stage. Recently, nonlinear ultrasound has been found to be a promising nondestructive technique to track microstructural changes. Many previous studies have been conducted to determine the correlations between ultrasonic nonlinearity and plastic deformation or fatigue damages [1–15]. Previous researches have mostly focused on the experimental measurements of ultrasonic nonlinearity, while less information is available with respect to numerical simulation of nonlinear ultrasonic propagation in plastically deformed media.

Numerical analyses can generally acquire similar results as measured from experiments that usually are time- and labor-consuming (e.g., ultrasonic measurements of creep damage), and can provide a physical insight into the relationship between acoustic nonlinear responses and degradations in materials. Some numerical methods have been proposed to simulate ultrasonic nonlinearity of media and/or damage, such as finite element method (FEM) [16,17], finite difference time domain method (FDTD) [18], and local interaction simulation approach (LISA) [19]. Based on finite element simulations, Liu et al. [20] clarified a theoretical method for selecting primary ultrasonic wave modes that generate cumulative second harmonics in plates. Chillara and Lissenden [17] numerically analyzed the contributions of third-order elastic constants and material and geometric nonlinearities to harmonic generation from S_0 and A_0 modes. Matsuda and Biwa's numerical studies showed that the second-harmonic amplitude grows cumulatively in a certain range of fundamental frequency [21]. Blanloeuil et al. [22] investigated the interaction between ultrasonic waves and a crack modeled by an interface of unilateral contact with Coulombs friction. However, the damaged structures in practice are generally difficult to be constructed due to the numerous and complex microstructures. Modeling the microstructures (e.g. dislocations, precipitations, etc.) in geometries is still a big challenge. However, when combining the microstructural contributions to acoustic nonlinearity with the resultant constitutive relationship of damaged materials, numerical analyses may be effectively used to describe the nonlinear ultrasonic responses to microstructural evolutions. There now have been many theoretical models describing the contributions of dislocation evolution to acoustic nonlinearity, such as monopole model [23], dipole model [24] and some advanced models [11,12].

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In this work, an improved theoretical model was derived to study the contribution of mixed (i.e., edge and screw) dislocations to acoustic nonlinearity based on the orientation-dependent dislocation line energy. Then, finite element analyses were carried out to study nonlinear ultrasonic waves propagation in the plastically deformed media. The derived constitutive relationship was introduced into the commercial finite element analysis software, Abaqus/EXPLICT. Experimental measurements of the nonlinear ultrasonic propagation on plastically damaged 30Cr2Ni4MoV martensite steel specimens were conducted to validate the finite element modeling. A comparison between the experimental and simulated results was discussed.

2. Theoretical considerations

2.1. Fundamental equations of nonlinear elastodynamics

Considering the longitudinal waves and neglecting the dispersion and attenuation, the equations of motion in the Lagrangian coordinate $\mathbf{Y}$ can be written as [25]

$$\rho_0 \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial \sigma_{ij}}{\partial Y_j}, \tag{1}$$

where u_i are components of the particle displacement vector and σ_{ij} are components of the first Piola–Kirchhoff stress tensor. ρ_0 is mass density in an unstressed state.

The stress tensor in Eq. (1) may be expanded in terms of the particle displacement gradients as [25]

$$\sigma_{ij} = C_{ijkl}\frac{\partial u_k}{\partial Y_l} + \frac{1}{2}\left(C_{ijklmn} + C_{ijln}\delta_{km} + C_{jnkl}\delta_{im} + C_{jlmn}\delta_{ik}\right)\frac{\partial u_k}{\partial Y_l} \times \frac{\partial u_m}{\partial Y_n}, \tag{2}$$

where C_{ijkl} and C_{ijklmn} are components of the second- and third-order elastic tensors defined as

$$C_{ijkl} = \lambda\delta_{ij}\delta_{kl} + 2\mu I_{ijkl}, \tag{3}$$

$$C_{ijklmn} = \frac{A}{2}\left(\delta_{ik}I_{jlmn} + \delta_{il}I_{jkmn} + \delta_{jk}I_{ilmn} + \delta_{jl}I_{ikmn}\right) + 2B\left(\delta_{ij}I_{klmn} + \delta_{kl}I_{mnij} + \delta_{mn}I_{ijkl}\right) + 2C\delta_{ij}\delta_{kl}\delta_{mn}, \tag{4}$$

where λ and μ are the Lamé parameters and A, B, and C are the third-order elastic (TOE) constants in isotropic media, which are related to the inherent properties of materials. δ_{ij} are the Kronecker's deltas and $I_{ijkl} = (\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})/2$.

Considering a one-dimensional medium such as a rod, the wave solution of Eq. (1) can be obtained by a simple perturbation analysis, as

$$u(Y_1, t) = u_0 \sin(kY_1 - \omega t) + \frac{u_0^2 k^2 \beta_0 Y_1}{8}\cos 2(kY_1 - \omega t) \tag{5}$$

where u_0 is the amplitude of fundamental wave A_1, k is the wave number, ω is the angular frequency. The amplitude of second harmonic wave A_2 is $u_0^2k^2\beta_0 Y_1/8$, where β_0 denotes acoustic nonlinearity parameter of the medium at an intact state. The acoustic nonlinearity parameter β_0 can be expressed as,

$$\beta_0 = \frac{8}{k^2 Y_1}\frac{A_2}{A_1^2}. \tag{6}$$

The relative acoustic nonlinearity parameter A_2/A_1^2, which is conveniently acquired via either experiments or simulations, reflects the nonlinear properties of wave propagation at a fixed distance with a certain wave number.

2.2. Acoustic nonlinearity related to dislocation evolution

For plastic deformation during the early stages of cyclic stress-induced plasticity in metallic alloys, the evolution of dislocations usually is related to the change of dislocation density and the development of dislocation structures. A model of mixed dislocations contributing to the acoustic nonlinearity has been developed based on the orientation-dependent dislocation line energy. If the dislocation is pinned at the points separated by a distance of $2L$ as shown in Fig. 1 [26], the dislocation line will "bow out" like an arc string under an externally applied stress. The slip plane is taken as the $\xi\eta$ plane. For the case of pure edge and screw dislocations, the mixed bowlike dislocation is the superposition of its edge and screw parts. Assuming there is no interaction between the different dislocations, the total line energy of the mixed dislocation, $E_{mix}(\theta)$, in an isotropic material can be expressed as [27]:

$$E_{mix}(\theta) = \left[\frac{\mu b^2 \sin^2\theta}{4\pi(1-\nu)} + \frac{\mu b^2\cos^2\theta}{4\pi}\right]\ln\left(\frac{r_o}{r_i}\right), \tag{7}$$

where μ is the shear modulus, b is the absolute value of Burgers vector, ν is the Poisson's ratio, θ is the angle between the Burgers vectors and the dislocation line, r_o and r_i are the effective outer and inner radius of the cylindrical model of the mixed dislocation, i.e., the crystal radius and the core radius, respectively [27].

In general, the line energy of a bow-out dislocation is not constant along the dislocation line and the variable line tension, T, in the direction of the Burger vector can be expressed as [27]:

$$T = E_{mix}(\theta) + \frac{d^2E_{mix}(\theta)}{d\theta^2}. \tag{8}$$

For a bow-out arc of the dislocation line under uniform stress and according to the equilibrium condition of forces on the dislocation line [26,27], substituting Eq. (7) into Eq. (8) yields

$$\tau = \frac{T}{rb} = \frac{\mu b}{8\pi(1-\nu)L}\alpha(2 - \nu + 3\nu\cos 2\theta)\ln\left(\frac{r_o}{r_i}\right). \tag{9}$$

The shear strain caused by the mixed dislocation, ε_{dis}, under the influence of applied shear stress, τ, is [26]

$$\varepsilon_{dis} = \frac{8\pi(1-\nu)}{3}\frac{\Lambda L^2}{\mu}(2-\nu+3\nu\cos 2\theta)^{-1} \times [\ln(r_o/r_i)]^{-1}\tau + \frac{256\pi^3(1-\nu)^3}{5}\frac{\Lambda L^4}{\mu^3 b^2} \times (2-\nu+3\nu\cos 2\theta)^{-3}[\ln(r_o/r_i)]^{-3}\tau^3 + \cdots, \tag{10}$$

where Λ is the dislocation density, and $\ln(r_o/r_i)$ is assumed as 2π [26]. Thus, the total longitudinal strain, ε, induced in the material by ultrasound, is given by

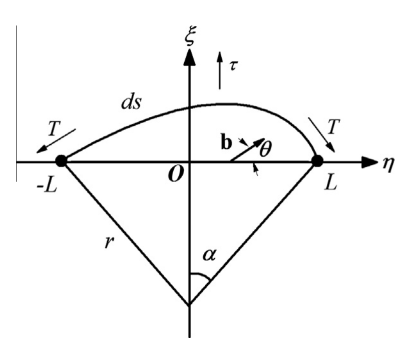

Fig. 1. Bow-out dislocation line under stress. The orientation of ds is related to the Burger vector **b**.