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Dependence of diffuse ultrasonic backscatter on residual stress in 1080 steel

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ABSTRACT

In this article, the effects of residual stress on the ultrasonic scattering in a quenched steel sample are investigated by calculating the change of spatial variance amplitudes of ultrasonic signals after removing residual stress via annealing. The experimental results show that the average spatial variance amplitude decreases by about 11.89% for a scan area on the quenched surface after removing residual stress. This quantity was used to estimate the residual stress based on the developed stress-dependent backscatter model. In addition, the residual stress on the whole scan area was mapped by calculating the change of the spatial variance amplitude for each subarea after annealing, respectively. Diffuse ultrasonic backscatter signals show a high sensitivity to residual stress such that this technique has potential as a non-destructive method for measuring residual stress.

1. Introduction

The theory of acoustoelasticity refers to the relationship between wave propagation speed in a deformable medium and the state of stress present. This relationship develops from the consideration of the influence of finite strains or wave displacements superimposed on a deformed medium. Often, linear-elastic approximations are not adequate to describe material responses in applications experiencing sufficiently large strains. In such cases, the acoustoelastic formalism considers nonlinear strain energy terms up to the third-order to describe the effect properly [1,2]. The higher-order strain energy terms introduce the use of third-order elastic constants into the constitutive equations. These theoretical developments led to the application of acoustoelasticity as a method of extracting higher order material constants in a variety of materials [3,4].

Other continuing developments have been made within acoustoelasticity for stress measurement [5–8]. Many researchers have applied wavespeed measurements of ultrasonic propagation modes to extract the residual stress information in welded rail using different elastic wave types, such as the longitudinal critically refracted (Lcr) elastic wave [9–11], and the leaky Lamb wave [12,13]. Recently, Turner and Ghoshal [14] presented a theoretical basis to extract stress information from polycrystalline microstructure based on diffuse ultrasonic backscatter. This approach was later expanded and generalized by Kube and Turner [15]. The covariance tensor of elastic modulus variations was included as part of previously-developed ultrasonic grain scattering models and is proportional to the attenuation and backscatter coefficients [15–20]. However, these models did not consider any stress dependency. Kube et al. [21] confirmed the stress dependence of the covariance tensor by investigating the change of the spatial variance amplitude under an applied uniaxial load.

In this article, the dependence of ultrasonic backscatter is investigated with respect to residual stress that is introduced by quenching a 1080 steel block with water. The quenched surface of the sample is scanned before and after removing residual stress via annealing, respectively. The change of variance amplitudes of the collected ultrasonic backscatter is quantified after removing residual stress which can be used to estimate the residual stress based on a previously-developed stress-dependent backscatter model [14].

2. Theory

Ultrasonic scattering is used to describe the multitude of reflections from grain boundaries comprising a polycrystalline material. Scattering models are used to quantify the scattering emanating from the grains that are often considered to be randomly oriented. The strength of the scattering is dependent on the degree of crystalline anisotropy inherent within the grains. A time-dependent spatial variance model of ultrasonic backscatter measurement with respect to an assumption of a singly scattered response (SSR) to

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microstructural properties was developed by Ghoshal et al. [19]. The SSR can be written as

$$\Phi_{SSR}(t) = R(V)\tilde{\eta}(L)\Xi(\mathbf{T})\exp\left(-\frac{t^2}{\sigma^2}\right)I_0(t), \tag{1}$$

where $R(V)$ is the amplitude coefficient which is dependent on the voltage V and can be determined through a calibration process. $\tilde{\eta}(L)$ is the spatial Fourier transform of the two-point spatial correlation function with L as the correlation length. It describes the probability of two random points lying within the same grain. In polycrystalline materials, L is on the order of the microstructural length scale and can be used to estimate the mean grain size. $\Xi(\mathbf{T})$ is called the covariance tensor which is a function of elastic constants of material and the tensorial stress state, $\mathbf{T}$. The time-dependent term $\exp\left(-\frac{t^2}{\sigma^2}\right)$ describes the input Gaussian pulse, and σ denotes the pulse width. The term $I_0(t)$ is an integral that accounts for changes in the focal profile as a function of material depth.

The covariance of the effective (stress-dependent) elastic modulus tensor is defined as [14]

$$\Xi_{ijkl}^{\alpha\beta\gamma\delta} = \langle G_{ijkl}G_{\alpha\beta\gamma\delta}\rangle - \langle G_{ijkl}\rangle\langle G_{\alpha\beta\gamma\delta}\rangle, \tag{2}$$

where G_{ijkl} is the load-dependent effective elastic modulus tensor within the medium [22]. For a single crystal, it can be written in terms of the second-order elastic modulus tensor C_{ijkl} and third-order elastic modulus tensor C_{ijklmn}, as $G_{ijkl} = C_{ijkl} + (\delta_{jl}\delta_{kP}\delta_{iQ} + 2C_{ijkr}S_{lrPQ} + C_{ijklmn}S_{mnPQ})T_{PQ}$, where $S_{ijkl} = C_{ijkl}^{-1}$ is the second-order compliance tensor, and T_{PQ} is the stress tensor. For cubic single crystal symmetry, the second-order elastic modulus tensor can be written as [14]

$$C_{ijkl} = C_{ijkl}^I + v\delta_{ijkl} = C_{ijkl}^I + v\sum_{n=1}^{3}a_{in}a_{jn}a_{kn}a_{ln}, \tag{3}$$

where $v = c_{11} - c_{12} - 2c_{44}$ is the anisotropy coefficient, and $C_{ijkl}^I = \lambda\delta_{ij}\delta_{kl} + \mu(\delta_{ik}\delta_{jl} + \delta_{ij}\delta_{kl})$ is the isotropic fourth-rank tensor with Lame' parameters λ and μ. Here, a_{ij} is the rotation matrix between crystal and laboratory axes. The expressions of the third-order elastic modulus tensor have been discussed previously [23]. Eq. (2) can be expanded and written in condensed form in terms of the magnitude of a uniaxial stress as

$$\Xi(T) = K_0 + K_1T + K_2T^2, \tag{4}$$

where K_0, K_1 and K_2 are load independent constants related to the directionality of the applied stress as well as the components of the displacements. The covariance tensor in Eq. (4) determines the magnitude of the backscatter coefficient and builds a connection between the magnitude of the stress $\mathbf{T}$ and the strength of the ultrasonic scattering.

To illustrate the stress influence on ultrasonic scattering, consider the case of a stress-free polycrystalline sample (with cubic crystal symmetry) subject to an applied uniaxial load in the 1-direction (i.e., $P = Q = 1$). Normal incidence longitudinal-to-longitudinal (L–L) ultrasound is used for comparison with the scattering under the uniaxial stress. The covariance tensor denoted as Ξ_{1111}^{1111} corresponds to a longitudinal to longitudinal (L–L) experiment for which the propagation vector $\hat{\mathbf{p}}$ and scattering vector $\hat{\mathbf{s}}$ are related as $\hat{\mathbf{p}} \cdot \hat{\mathbf{s}} = -1$ (backscatter) and are parallel to the loading axis. Table 1 shows the single crystal second and third order elastic constants for iron [16]. Table 2 shows the corresponding values of K_0, K_1 and K_2 with respect to the covariance Ξ_{1111}^{1111} for iron based on Eq. (4) [14]. Several observations can be made from the results [14]. First, the positive value of K_2 will increase the scattering amplitude no matter the stress status. Second, the negative values of K_1 will increase the backscatter amplitude under compressive stress for the Ξ_{1111}^{1111} mode. Finally, because the ratio of K_1 to K_2 is large ($|K_1/K_2| > 4000$ MPa), the scattering response is expected to be nearly linear for low stress (<500 MPa). It is important to note that more recent estimates of the coefficients K_i are much different from those used here [15].

3. Experiments

Experiments were conducted in a water immersion tank using a 10 MHz transducer (*Olympus NDT*, Newton, MA, *V*327-SU; 9.53 mm diameter; 50.4 mm focal depth) focused at 9.0 mm in a 1080 steel block shown in Fig. 1. A pulse-echo configuration was used for the diffuse ultrasonic backscatter experiment. An ultrasonic longitudinal pulse was transmitted through an immersion transducer into the test sample, and the backscatter signals were received by the same transducer. The experimental spatial variance of the acquired signals collected from various positions may be defined as

Table 2
Theoretical backscatter coefficients of iron [14] for the steel sample.

Mode	Ξ_{1111}^{1111}		
Constants	K_0 (GPa^2)	K_1 (GPa)	K_2
Iron	582.1	−341.4	80.76

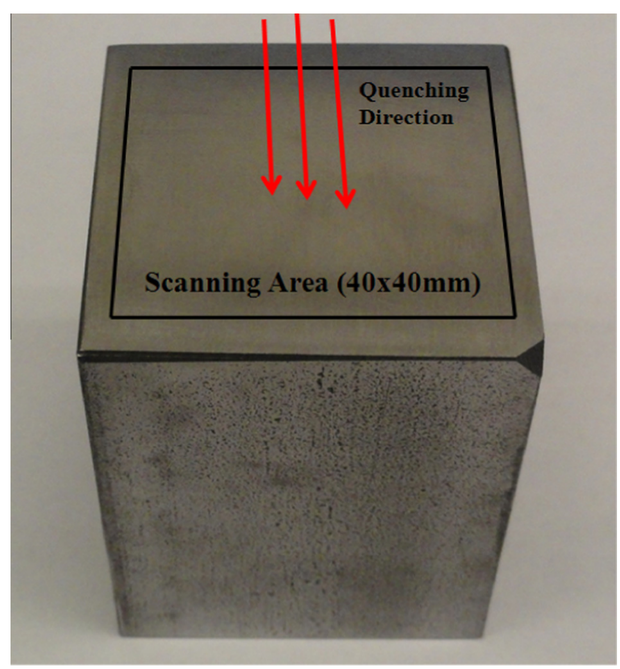

Fig. 1. Photograph of the 1080 steel block (50 × 50 × 75 mm) used for this work.

Table 1
Single-crystal second and third order elastic constants (GPa) for iron [26].

Material	C_{11}	C_{12}	C_{44}	C_{111}	C_{112}	C_{123}	C_{144}	C_{166}	C_{456}
Iron	229.3	134.1	116.7	−2720	−608	−578	−836	−530	−720