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Evaluating grain size in polycrystals with rough surfaces by corrected ultrasonic attenuation

Xiongbing Li [a], Xiaoqin Han [a], Andrea P. Arguelles [b], Yongfeng Song [a], Hongwei Hu [c,*]

[a] School of Traffic and Transportation Engineering, Central South University, Changsha, Hunan 410075, China
[b] X-wave Innovations, Inc., Gaithersburg, MD 20878, USA
[c] College of Automotive and Mechanical Engineering, Changsha University of Science & Technology, 410114, China

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ABSTRACT

Surface roughness of a sample has a great effect on the calculated grain size when measurements are based on ultrasonic attenuation. Combining modified transmission and reflection coefficients at the rough interface with a Multi-Gaussian beam model of the transducer, a comprehensive correction scheme for the attenuation coefficient is developed. An approximate inverse model of the calculated attenuation, based on Weaver's diffuse scattering theory, is established to evaluate grain size in polycrystals. The experimental results showed that for samples with varying surface roughness and matching microstructures, the fluctuation of evaluated average grain size was ±1.17 μm. For polished samples with different microstructures, the relative errors to optical microscopy were no more than ±3.61%. The presented method provides an effective nondestructive tool for evaluating the grain size in metals with rough surfaces.

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1. Introduction

Grain size is an important parameter for characterizing the microstructure of metals. Grain refinement is an effective method for improving the tensile and fatigue strength of Inconel 718 [1], whereas grain growth can increase the creep resistance and yield strength of Ni-Co-based alloys [2]. However, processes such as melting, heat treatment, or machining can result in grain sizes that deviate from the design specifications. Hence, effective nondestructive methods to evaluate the grain size of metals are highly desirable.

In polycrystalline media, elastic wave scattering is directly dependent on grain size. Various authors [3–5] have focused on analytically establishing the correlation between scattering and grain structure. For example, Weaver [5] presented a forward model that relates grain size to attenuation due to scattering. Therefore, in principle, the grain size of metals can be determined by measuring the materials' attenuation coefficient. However, accurate experimental estimates of the materials' attenuation coefficient can be challenging to obtain. The rough surface of a sample can cause diffusion of ultrasonic waves, which decreases the amplitude of reflected echoes [6]. Furthermore, diffraction losses occur due to beam divergence and spreading depending on the ultrasonic setup. Therefore, it is necessary to formulate corrections for these losses in order to correlate measured ultrasonic attenuation to material microstructure accurately.

Ogilvy [7] has reviewed the literatures pertinent to wave scattering from rough surfaces, including early theoretical models and experimental investigations. The perturbation technique and the Kirchhoff approximation models were compared in his work, which showed the importance of Kirchhoff approximation for rough surface scattering. Nagy and Adler [8] modified the ultrasonic transmission and reflection coefficients for a randomly rough interface by using the elastic wave equation and the Kirchhoff approximation. Reed et al. [9] formulated a correction for the attenuation coefficient when evaluating the porosity in materials with rough surface, but his work failed to include diffraction losses induced by the sound field, which resulted in overestimated porosity measurements.

Wydra et al. [10] and Zeng et al. [11] used the Lommel diffraction correction method when investigating the effect of grain size on attenuation in pure niobium and copper alloys, respectively. Their results are in good agreement with classical stochastic scattering theory. However, the Lommel diffraction correction method is only suited for planar transducers. Zhang et al. [12] proposed a grain size ultrasonic evaluation method with diffraction correction based on the Gaussian beam theory, which could evaluate grain size in samples with different curvatures. However, this method

* Corresponding author.
E-mail address: hhwlucky@163.com (H. Hu).

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neglected the effects of surface roughness, interface reflections and transmission coefficients, which resulted in decreased accuracy in the grain size estimates.

According to the analysis above, a correction method for experimental calculation of attenuation to account for diffraction and interfaces losses is proposed. The diffraction loss correction is derived based on the Multi-Gaussian beam (MGB) theory. The interface losses induced by the rough surface are corrected using modified transmission and reflection coefficients. Finally, the effects of surface roughness and the water path (diffraction losses) on calculated ultrasonic attenuation are evaluated to study their effect on grain size estimates.

2. Theory and correction models

2.1. Attenuation model

Weaver gives a general expression for the attenuation coefficient of longitudinal wave propagation α_L as [5,13,14]

$$\alpha_L = \alpha_{LL} + \alpha_{LT} \tag{1}$$

with

$$\begin{aligned}\alpha_{LL} &= \tfrac{8\pi^6 f_0^4}{\rho^2 c_L^8}\int_{-1}^{+1}\tilde{\eta}_{LL}(\theta_{ps})N_1(\theta_{ps})\mathrm{d}(\cos\theta_{ps}),\\ \alpha_{LT} &= \tfrac{8\pi^6 f_0^4}{\rho^2 c_L^3 c_T^5}\int_{-1}^{+1}\tilde{\eta}_{LT}(\theta_{ps})[N_2(\theta_{ps})-N_1(\theta_{ps})]\mathrm{d}(\cos\theta_{ps}),\end{aligned} \tag{2}$$

where the subscripts LL and LT correspond with the contributions of scattering into longitudinal and transverse waves, respectively. ρ is the density of the sample, f_0 is the center frequency of the transducer, c_L and c_T are the longitudinal and transverse velocities, respectively, and θ_{ps} is the angle between the incident wave $\hat{\mathbf{p}}$ and the scattered wave $\hat{\mathbf{s}}$. The integral in Eq. (2) accounts for the energy lost in all scattering directions [13]. $\tilde{\eta}_{LL}(\theta_{ps})$ and $\tilde{\eta}_{LT}(\theta_{ps})$ are the spatial Fourier transforms of the two-point spatial correlation function $\eta(|\mathbf{r}-\mathbf{r}'|) = \exp(-|\mathbf{r}-\mathbf{r}'|/L)$ for longitudinal and shear wave scattering, respectively. η represents the probability that two points $\mathbf{r}$ and $\mathbf{r}'$ lie within a given grain and L is the spatial correlation length, which relates to the grain size [15]. For equiaxed grains, as depicted in Fig. 1, $\tilde{\eta}_{LL}$ and $\tilde{\eta}_{LT}$ are given by [13]

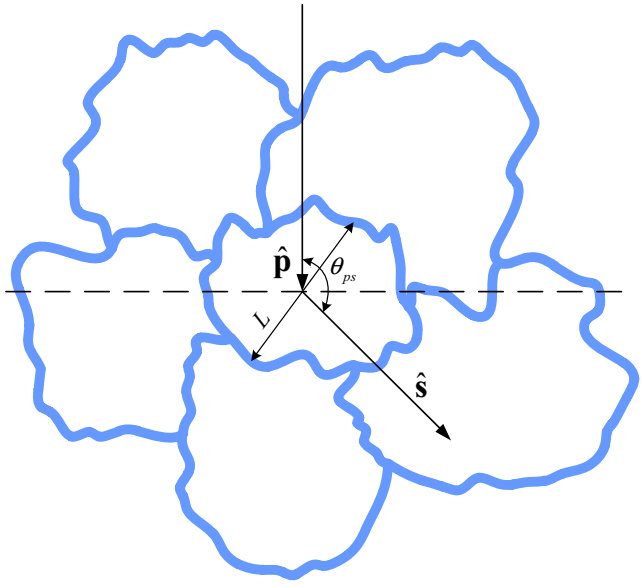

Fig. 1. Schematic of the equiaxed crystal texture within a superalloy.

$$\begin{aligned}\tilde{\eta}_{LL}(\theta_{ps}) &= \tilde{\eta}_{LL}(\hat{\mathbf{p}}k_L - \hat{\mathbf{s}}k_L) = \tfrac{L^3}{\pi^2\left[1+2k_L^2L^2(1-\cos\theta_{ps})\right]^2},\\ \tilde{\eta}_{LT}(\theta_{ps}) &= \tilde{\eta}_{LL}(\hat{\mathbf{p}}k_L - \hat{\mathbf{s}}k_T) = \tfrac{L^3}{\pi^2\left[1+k_L^2L^2+k_T^2L^2-2k_Lk_TL^2\cos\theta_{ps}\right]^2},\end{aligned} \tag{3}$$

where $k_L = 2\pi f_0/c_L$, $k_T = 2\pi f_0/c_T$ are the longitudinal and transverse wave numbers, respectively. It is important to note that the grains are assumed entirely equiaxed; however, the grains in real materials are irregular and only approximately equiaxed.

The terms $N_1(\theta_{ps})$ and $N_2(\theta_{ps})$ in Eq. (2) are the covariance of the elastic moduli, which have been defined for crystallites of arbitrary symmetries elsewhere [14]. Using Voigt averaging, these terms can be expressed for crystallites of cubic symmetry as [13,16]

$$\begin{aligned}N_1(\theta_{ps}) &= v^2\left[\tfrac{9}{525}+\tfrac{6}{525}\cos^2\theta_{ps}+\tfrac{1}{525}\cos^4\theta_{ps}\right],\\ N_2(\theta_{ps}) &= v^2\left[\tfrac{24}{525}+\tfrac{12}{525}\cos^2\theta_{ps}\right].\end{aligned} \tag{4}$$

where $v = c_{11} - c_{12} - 2c_{44}$ is anisotropy coefficient, where c_{11}, c_{12}, and c_{44} are the single crystal elastic constants of the material.

Substituting Eqs. (2)–(4) into Eq. (1), the longitudinal attenuation coefficient for equiaxed polycrystals can be written as

$$\begin{aligned}\alpha_L(L) = \frac{8\pi^4 f_0^4 L^3 v^2}{525 c_L^3\rho^2}\Bigg\{&\int_{-1}^{+1}\frac{9+6\cos^2\theta_{ps}+\cos^4\theta_{ps}}{c_L^5\left[1+2k_L^2L^2(1-\cos\theta_{ps})\right]^2}\mathrm{d}(\cos\theta_{ps})\\ &+\int_{-1}^{+1}\frac{15+6\cos^2\theta_{ps}-\cos^4\theta_{ps}}{c_T^5[1+k_L^2L^2+k_T^2L^2-2k_Lk_TL^2\cos\theta_{ps}]^2}\mathrm{d}(\cos\theta_{ps})\Bigg\}.\end{aligned} \tag{5}$$

The relationship between attenuation, grain size and frequency in Eq. (5) can be used to evaluate the grain size from attenuation measurements.

2.2. Experimental attenuation coefficient corrections

The accuracy of the measured attenuation coefficient plays a key role in the evaluation of grain size. In this paper, the experimentally obtained attenuation coefficient will be denoted α_{total}. For computing efficiency, a temporal approach is used to calculate attenuation, as given by

$$\alpha_{total} = \frac{1}{2H}\ln\left(\left|\frac{V_{FW}}{V_{BW}}\right|\right), \tag{6}$$

where V_{FW} and V_{BW} are the peak values of the front wall (FW) and back wall (BW) echoes, respectively, and H is the thickness of the sample. Generally, the experimentally measured attenuation α_{total} is a combination of material attenuation due to scattering and interface and diffraction losses.

The authors, using a MGB model, presented a correction method for diffraction losses in the attenuation coefficient [12]. The diffraction correction coefficient from FW to BW can be rewritten as

$$\alpha_{diff}(f_0) = \frac{1}{2H}\ln\left(\left|\frac{t_{FW}(f_0)}{t_{BW}(f_0)}\right|\right). \tag{7}$$

In Eq. (7), $t_{FW}(f_0)$ and $t_{BW}(f_0)$ are the acoustoelastic transfer functions, i.e., the integrations of dimensionless particle vibration velocities v_{FW} and v_{BW} over the surface of the transducer, given by

$$\begin{aligned}t_{FW}(f_0) &= \tfrac{2}{S}\int_S \tfrac{v_{FW}(f_0)}{v_0(f_0)}\exp\left(-i\tfrac{k_f|\mathbf{y}|^2}{2F}\right)\mathrm{d}s,\\ t_{BW}(f_0) &= \tfrac{2}{S}\int_S \tfrac{v_{BW}(f_0)}{v_0(f_0)}\exp\left(-i\tfrac{k_f|\mathbf{y}|^2}{2F}\right)\mathrm{d}s,\end{aligned} \tag{8}$$

where $\mathbf{y}$ are the spatial points of the transducer surface, S is the surface area of the transducer, F is the focal length ($F = \infty$ for the unfocused transducer), and v_0 is the initial particle vibration velocity at the transducer surface. The expressions in Eq. (8) have been given in

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