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Evaluating the grain size in curved components using the ultrasonic attenuation method with diffraction correction

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ABSTRACT

Ultrasonic wave propagation in curved components was simulated based on the Multi-Gaussian beam theory to eliminate the negative influence of the surface curvature and water path on grain size attenuation evaluation. The multi-frequency weighted attenuation evaluation model with diffraction correction was introduced into the measured attenuation spectrum to control the systematic error. The experimental results show that for 6 blocks with different curvatures and the same mean grain size, the relative error was reduced from 15.41% to 4.28% by using the presented method, and the standard deviation of the error was 15.92% of that of the traditional method.

1. Introduction

Grain size is an important parameter for characterizing the micro-structure of metals, e.g., grain refinement is an effective method for improving the tensile strength and fatigue strength of Nickel-based Alloy718 [1]; the enhanced creep resistance and yield strength of a Ni-Co-based alloy can be mainly ascribed to grain growth [2]; a better corrosion resistance tendency can be achieved with coarse grain for both Al and Zn [3]. Therefore, strict controlling of the grain size in both the manufacture and service of metal components is one of the keys to guaranteeing the mechanical properties; thus, it is essential that effective grain size determination methods be investigated.

Techniques for measuring the grain size of metals include both destructive and nondestructive methods. Destructive methods such as the metallographic method can measure the grain size accurately, but they require sophisticated instrumentation and complicated analytical procedures, which lead to a low detection efficiency. Ultrasonic attenuation methods, on the other hand, provide effective and nondestructive approach for determining grain size [4].

When ultrasonic waves travel through the material, the spectral characteristics and scattering attenuation coefficients of the waves carry abundant information about grain size. Thus, the grain size can be evaluated by measuring its ultrasonic scattering attenuation coefficient. The attenuation in the Rayleigh regime is dependent on the effective grain volume and the fourth power of the frequency [5]. Li studied the effect of the microstructure on various attenuation measurements [6]. In practice, however, there is inevitable diffraction attenuation induced by the refraction, divergence and convergence of an ultrasonic wave during its propagation that will alter the spectrum in a corresponding way [7]. The work of Seki [8] shows that the piston radius and wavelength have an effect on diffraction in attenuation measurement and the correction is particularly important at the lower frequencies. In that case, the total attenuation coefficient obtained experimentally contains uncertain diffraction attenuation components, which reduces the accuracy and reliability of the grain size evaluation. Thus, it is necessary to correct the diffraction component and obtain more refined scattering attenuation coefficients.

The Lommel diffraction correction method was used by Zeng [9] and Wydra [10] to study the attenuation caused by the grain size of a high purity niobium plate and copper alloy. The results agree well with the classical Stochastic scattering theory and linear distribution, respectively. Kim [11] obtained a more accurate attenuation coefficient by correcting the diffraction component in attenuation evaluation by means of the block calibrating method. But the methods above are confined to the planar component, and thus they do not take into consideration the diffraction loss in ultrasonic wave propagation caused by such factors as the water path and the curvature of the block surface. However the

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ultrasonic attenuation caused by the surface curvature can be measured theoretically. Schmerr studied the curvature correction for the ultrasonic response of a flat bottom hole in a cylinder block [12].

Moreover, when evaluating the curved blocks, the different frequency components of the ultrasonic wave are refracted and scattered to greatly varying degrees, which is another factor that changes the shape of the echo's attenuation spectrum and affects the scattering attenuation [13]. The traditional ultrasonic frequency-domain attenuation method usually relies upon the relationship between attenuation and grain size at a single frequency and fails to make full use of the spectral information carried by all frequency components. The result of relying on a single set of experimental data is an increase random error.

According to the analysis above, a grain size ultrasonic attenuation evaluation method with diffraction correction is proposed based on the Multi-Gaussian beam (MGB) theory [12]. The influence of the curvature and the water path on the total ultrasonic attenuation is eliminated to control the system error, and a weighted multi-frequency evaluation model is presented to reduce the random error and to improve the accuracy of the attenuation method to determine the grain size of curved blocks.

2. Method

The first back-wall echo BW_1 and the second back-wall echo BW_2 obtained by the immersion pulse reflection setup are shown in Fig. 1, and their corresponding velocity fields, $v_{BW1}(\mathbf{y}_s, f)$ and $v_{BW2}(\mathbf{y}_s, f)$, are calculated using the MGB theory. Assume that the constant velocity on the transducer surface is $v_0(f)$, the wave transmission coefficients of the Gaussian beam at the water–steel interface and the steel–water interface are, respectively, T_{12} and T_{21}, the wave reflection coefficient at the steel–water interface is R_{21}, the *P*-wave speeds of the ultrasonic wave in the water and block are c_1^p and c_2^p, the densities of the water and block are ρ_1 and ρ_2, the frequency of the transducer is f, the effective area of the transducer is S, and the propagating distances in the water and block are W and h. In the rectangular coordinate system (x_1, x_2, x_3), the incident Gaussian beam propagates in the direction of the x_3 axis, which is also along the interface normal, and y_s is an arbitrary point in the plane of (x_1, x_2). The curvature radius matrix of the top face and the bottom face of the block are, respectively, $\mathbf{r}_1$ and $\mathbf{r}_2$; then, the particle vibration velocity of BW_1 received by the transducer is

$$v_{BW1}(\mathbf{y}_s, f) = \sum_{j=1}^{15} v_0(f)\frac{\sqrt{\det\mathbf{M}_1^p(W)}}{\sqrt{\det\mathbf{M}_1^p(0)}}T_{12}\frac{\sqrt{\det\mathbf{M}_2^p(h)}}{\sqrt{\det\mathbf{M}_2^p(0)}}R_{21}\frac{\sqrt{\det\mathbf{M}_3^p(h)}}{\sqrt{\det\mathbf{M}_3^p(0)}}T_{21}\frac{\sqrt{\det\mathbf{M}_4^p(W)}}{\sqrt{\det\mathbf{M}_4^p(0)}}\cdot \exp\left[2i\pi f\left(\frac{2W}{c_{p1}}+\frac{2h}{c_{p2}}+i\pi f\,\mathbf{y}_s^T\left[\mathbf{M}_4^p(W)\right]\mathbf{y}_s\right)\right] \tag{1}$$

where j is the number of Gaussian beams, $\mathbf{M}_1^p(W)$, $\mathbf{M}_2^p(h)$, $\mathbf{M}_4^p(h)$ and $\mathbf{M}_4^p(h)$ are all 2×2 complex-valued symmetric matrices that can be calculated by the angle of incidence, the wavelength and the curvature of the block surface. They can describe the four processes of sound field propagation respectively: the ultrasonic wave setting off from the transducer chip to the top surface of the block, its transmission from the top surface to the bottom surface, its reflection from the bottom surface back to the top surface and its penetration of the top surface to the chip of the receiving transducer; $\mathbf{M}_1^p(0)$, $\mathbf{M}_2^p(0)$, $\mathbf{M}_3^p(0)$ and $\mathbf{M}_4^p(0)$ are, respectively, the initial values of the plural matrix of the four processes, which are relevant to the normal curvature radii of the interfaces of the corresponding incident medium and the ultrasonic velocity in water and the block [14].

The sound pressures are integrated over the surface of the transducer chip, and then the average sound pressures of BW_1 and BW_2 received by the transducer can be expressed as

$$P_{BW1}^{ave}(f) = \frac{\rho c_1^p}{S}\int_s v_{BW1}(y_s, f)\,dS(y_S) \tag{2}$$

$$P_{BW2}^{ave}(f) = \frac{\rho c_1^p}{S}\int_s v_{BW2}(y_s, f)\,dS(y_S) \tag{3}$$

Taking into account the ultrasonic measurement system function $s(f)$ and the transfer function of the acoustic elasticity $t(f)$, the voltage signal, transformed from the ultrasonic signal received by the transducer, is

$$V_R(f) = s(f)t(f) = s(f)\frac{2p^{ave}(f)}{\rho c_1^p v_0(f)} \tag{4}$$

The diffraction attenuation coefficient of BW_1 to BW_2 is

$$\alpha_{diff}(f) = \frac{10}{h}\log_{10}\left(\frac{s(f)t_{BW1}(f)}{s(f)t_{BW2}(f)}\right) = \frac{10}{h}\log_{10}\left(\frac{p_{BW1}^{ave}(f)}{p_{BW2}^{ave}(f)}\right) \tag{5}$$

Let $V_{BW1}(f)$ and $V_{BW2}(f)$ represent the frequency-domain forms of BW_1 and BW_2 after Fourier transform; thus, we can write the total ultrasonic attenuation coefficient as

$$\alpha_{total}(f) = \frac{10}{h}\log_{10}\left(\frac{V_{BW1}(f)}{V_{BW2}(f)}\right) \tag{6}$$

The scattering attenuation with correction is therefore

$$D_i = g_i\left(\alpha(f_i)\right) \tag{7}$$

Generally, the relationship between the scattering attenuation coefficient α and the detection frequency f, as well as the grain size D, is

$$\alpha = aD^{x-1}f^x + c \tag{8}$$

where a is a constant determined by the elastic stiffness and anisotropy of the metallic crystal, D is the grain size, c is an experimental fluctuant constant, and x is determined by the ratio between D and the ultrasonic wave length λ [15]. For Rayleigh scattering and Stochastic scattering, which are involved in this research, the values of x are 4 and 2, respectively [16].

Combined with Eq. (8) and the attenuation spectrum of the planar block corrected by the diffraction coefficient, the grain size attenuation evaluation function at the frequency f_i can be

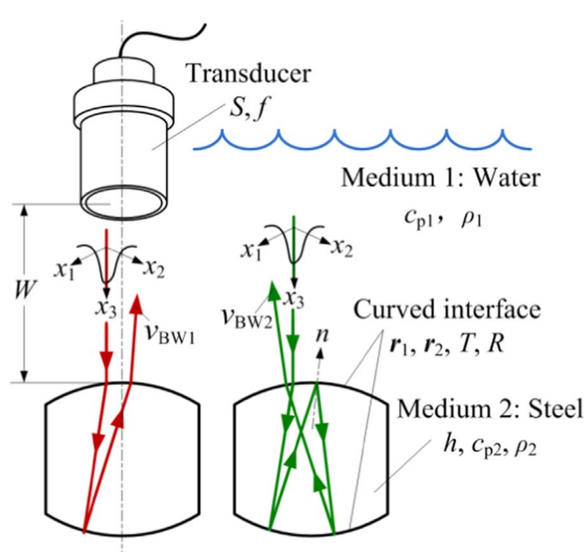

Fig. 1. Immersion ultrasonic evaluation model.