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Material grain size characterization method based on energy attenuation coefficient spectrum and support vector regression

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ABSTRACT

A grain size characterization method based on energy attenuation coefficient spectrum and support vector regression (SVR) is proposed. First, the spectra of the first and second back-wall echoes are cut into several frequency bands to calculate the energy attenuation coefficient spectrum. Second, the frequency band that is sensitive to grain size variation is determined. Finally, a statistical model between the energy attenuation coefficient in the sensitive frequency band and average grain size is established through SVR. Experimental verification is conducted on austenitic stainless steel. The average relative error of the predicted grain size is 5.65%, which is better than that of conventional methods.

1. Introduction

When evaluating the properties of metallic materials, the grain size of these materials is an important engineering parameter that influences mechanical properties, such as fatigue, creep, yield strength, and formability. According to the Hall–Petch formula [1], $\sigma_s = \sigma_o + Kd^{-1/2}$ (σ_o and K are constant; d is the average grain size), material strength decreases with the increase in grain size. Therefore, measuring grain size during the analysis of material properties is significant. Grain size is traditionally measured through the metallographic method. However, this method requires a polished surface, and the specimen preparation process is complex and time consuming. Test results also reflect only the grain size of the slice layer and cannot provide an overall assessment of the specimen. Therefore, the traditional method cannot detect grain size in real-time. Ultrasonic test technology is a nondestructive test method. The advantages of this method include simple specimen preparation process, large measuring range, considerable depth, and access to grain structure characteristics within the materials. Ultrasonic test technology has been applied to the real-time measurement of grain size [2,3]. The methods utilized in this technology include ultrasonic velocity, ultrasonic attenuation (UA), and frequency spectrum analysis methods.

Ultrasonic velocity in materials is a physical quantity related to density, elastic modulus, and Poisson ratio. Variation in grain size can influence the elastic modulus, Poisson ratio, and other parameters of materials, thereby affecting their ultrasonic velocity. Ultrasonic velocity changes when the average grain size varies. By adopting the ultrasonic velocity method, ultrasonic longitudinal and transversal velocities can be used to characterize the grain size of materials [4–6]. Both the thickness of the specimen and the time history of the ultrasound in the specimen should be measured precisely to obtain accurate ultrasonic velocity. In actual measurements, the ultrasonic signal is prone to noise influence; consequently, precisely measuring the time is difficult. The nonparallelism of the specimen surface also makes thickness measurement inaccurate. These factors limit the application of the velocity method to tests.

In research on the UA method, the mechanism of scattering attenuation is highlighted [7–10]. Studies have found that scattering attenuation depends on the average grain size and is related to the distribution and orientation of grain size when ultrasound travels through materials. Scattering is the main factor in the Rayleigh region that results in UA. An applied attenuation method to evaluate grain size has also been reported [11,12]. Studies have shown that the attenuation coefficient has a good correlation with grain size. In the same test frequency condition, a large average grain size of materials results in a large UA coefficient. The measurement error of this method is usually not significant. The ultrasonic relative attenuation (URA) method, an improvement of the UA method, can address the difficulty in obtaining multiple back-wall echoes in coarse grain or thick specimens. Palanichamy et al. [13] and Sarpün and Kılıçkaya [14] measured the grain size

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of AISI 316 austenitic stainless steel and marble through the URA method. The URA method takes the amplitude of the first back-wall echo as the parameter that correlates with grain size by comparing the amplitudes of the test and reference specimens to evaluate the material grain size. Analyses of the traditional UA and URA methods are based on the amplitude of the waveform in the time domain. When grain size increases, grain scattering becomes severe, thereby making the time-domain waveform seriously influenced by noise and easily leading to errors in amplitude extraction and inaccurate results.

When ultrasound propagates in materials, the material grain scatters lead to obvious high-frequency attenuation of the ultrasonic signal and relatively small low-frequency attenuation; hence, the average grain size of materials can be evaluated by analyzing the spectrum of the ultrasonic echo [15]. In the application of the frequency spectrum analysis method, Fourier transform is usually employed to extract spectrum parameters, such as the peak frequency and peak value, to characterize the average grain size [16,17]. However, several innovative means have been reported, such as the multi-scale analysis of ultrasonic signals based on wavelet transform [18]. Compared with time-domain characterization methods, the frequency spectrum analysis method has better anti-noise capability. For instance, Zhao et al. [19] estimated ultrasound attenuation in a plexiglass through the short-time Fourier transform method to extract the spectrum peak value. This method can prevent noise interference with the calculation of the attenuation coefficient in the time-domain analysis. Currently, the application of spectrum analysis method to characterize the grain size of materials remains imperfect. The main problems are the spectrum parameters; the peak frequency and peak value only reflect the fundamental frequency component of the ultrasonic echo signal, and the corresponding energy amount cannot fully represent all the characteristics of the ultrasonic echo. In addition, the extraction of spectrum characteristic parameters often ignores the fact that the material is sensitive to the frequency band. In other words, the properties of the material make attenuation different in various frequency bands.

To solve the problems in the spectrum analysis method, a grain size characterization method based on the energy attenuation coefficient spectrum and SVR is proposed in this study. The new method is divided into three steps. First, the spectra of the first and second back-wall echoes are analyzed and cut into several frequency bands in accordance with the spectrum bandwidth. The envelope area of each band, which represents the energy of ultrasonic echo, is calculated. Second, the first and second back-wall echo energy values in each band are utilized to calculate the attenuation coefficient; thus, the energy attenuation coefficient spectrum is obtained. The sensitive frequency band (i.e., sensitive to grain size variation) is determined by analyzing the energy attenuation coefficient spectrum. Finally, according to the theory of statistical modeling, a statistical model between the energy attenuation coefficient in the sensitive frequency band and the average grain size is built by SVR method; the model can achieve accurate characterization of grain size.

The proposed method has the following advantages. First, the method converts ultrasonic echoes to the frequency domain for analysis. The purpose is to bring the time-domain signal into the frequency domain for equalization processing; therefore, the influence of random noise is reduced. The noise effect on the calculation results can also be reduced further by using the envelope area of each band in the frequency domain to reflect ultrasonic signal energy. Second, the energy attenuation coefficient spectrum can show the attenuation of signals in various frequency bands; it is a detailed analysis of the attenuation in the frequency domain and can be used to build the relationship among grain size D, attenuation coefficient α, and frequency f. Thus, compared with other spectrum analysis methods, the energy attenuation coefficient spectrum can more comprehensively reflect the information that the ultrasonic echoes contain. Third, the attenuation of ultrasonic signals in various frequency bands is different. Consequently, using the energy attenuation coefficient in the sensitive frequency band to build statistical models helps distinguish the subtle changes in grain size and improve the predictive accuracy of the model.

The test specimen in this study was AISI 304 austenitic stainless steel. Different heat treatments were applied to obtain 11 specimens with different grain sizes. The traditional attenuation method, the conventional spectrum analysis method, and the proposed energy attenuation coefficient spectrum method were used to characterize the average grain size of the specimens. In order to compare the accuracy of the three methods for characterizing the average grain size, the same data source is required. Therefore, a separate ultrasonic test was conducted for each specimen. Then, the three methods were applied to the same ultrasonic signal respectively. The experimental results show that the result of the energy attenuation coefficient spectrum method is better than the results of the traditional ones; the average detection error is 5.65%.

The remainder of this paper is divided into several sections. Section 2 presents specimen preparation, metallographic measurement, and ultrasonic detection. Section 3 introduces the principle of the proposed method, the process of obtaining the energy attenuation coefficient spectrum, and the selection method of the sensitive frequency band. Section 4 presents the principle and process of statistical modeling based on support vector machine. Section 5 discusses the advantages of the support vector regression model and the establishment of a statistical model to characterize the average grain size of materials. Section 6 provides a comparison of the proposed method and traditional grain size characterization methods and proves the effectiveness of the former. The conclusions are presented in Section 7.

2. Experimental objects and data acquisition

2.1. Test specimen preparation

The specimens are made of AISI 304 austenitic stainless steel. The density is 7.93 g/cm^3, the tensile strength is $\sigma_b \geqslant 520$ MPa, and the modulus of elasticity is 193 GPa. The chemical composition of the used material is presented in Table 1.

Table 1
Element content in AISI 304 austenitic stainless steel.

Element	C	Mn	P	S	Si	Cr	Ni
Percentage, %	$\leqslant$ 0.08	$\leqslant$ 2.00	$\leqslant$ 0.045	$\leqslant$ 0.030	$\leqslant$ 1.00	18.0–20.0	8.0–11.0

Table 2
Heat treatment process and average grain size.

Specimen no.	Heat treatment	Average grain size (μm)	Specimen no.	Heat treatment	Average grain size (μm)
1	Unprocessed	22.56	7	1150 °C/3 h	137.28
2	1080 °C/1 h	57.96	8	1200 °C/1 h	140.76
3	1080 °C/2 h	78.69	9	1150 °C/4 h	153.49
4	1150 °C/40 min	83.13	10	1200 °C/2 h	167.11
5	1150 °C/1 h	107.77	11	1200 °C/3 h	176.08
6	1150 °C/2 h	120.81			