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Evaluation of mean grain size using the multi-scale ultrasonic attenuation coefficient

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ABSTRACT

An evaluation model based on the multi-scale ultrasonic attenuation coefficient was developed to control both systematic error and random error. AISI 304 stainless steel was used to validate the presented model. Wavelet transformation was used to obtain the variation of ultrasonic signal over time and scale. Particle swarm optimization was utilized to correlate the coefficient with grain sizes. The model shows the attenuation of all scales increased with the grain size, and ultrasound attenuates faster on smaller scales. Compared with the ultrasonic velocity method and the traditional attenuation method, the proposed method has less systematic error and random error.

1. Introduction

Grain size is an important parameter to characterize the microstructure of metals and has a great effect on such properties of metal as yield strength, plasticity, toughness, fatigue strength, creep strength and corrosion resistance [1,2]. The Hall–Petch formula displays the relation between grain size and yield strength of metallic polycrystalline material and reflects the size–strength effect [3,4]. If the grains of the austenitic stainless steel weldments in the heat affected zone are oversized, high temperature and alternating stress will lead to inadequate strength, corrosion resistance and fatigue resistance, which is likely to cause crack nucleation and transmission along the welding edge eventually resulting in fracture accidents [5]. Therefore, to guarantee the reliability of the key equipment it is of great importance to effectively measure the grain size of metals.

The ultrasonic method has the capability of detecting the characteristics of micro-texture inside the material. Grain size measurement using ultrasound depends on various properties including ultrasonic velocity, attenuation, and backscattering. As the backscattering method is concerned, rigorous corrections are required to get the backscattering coefficient [6,7]. Besides, this method generally works when the thickness of the blocks is not less than 6 mm. The ultrasonic velocity method evaluates mean grain size based on the discrepancy between the ultrasonic velocities caused by the difference between the elasticity moduli of grain boundary [8,9], but this method is less sensitive for some metals and has a relatively greater error on grain size evaluation [10]. Attenuation is a frequently used method currently, based on the difference of attenuation of acoustic energy when ultrasound propagates in materials of different mean grain sizes. In application of the attenuation method, not only can the fitting evaluation model based on experiment be established by means of total attenuation coefficient in time domain and average grain size [11,12], but the evaluation model of grain size in the form of power function can be built with the aid of the spectrum of attenuation coefficient in frequency domain [13]. Moreover, there is another method named peak frequency in the amplitude spectrum, which is actually a variation of the frequency dependent attenuation method [14]. Since the ultrasonic echo signal is non-stationary, the traditional attenuation method in either time or frequency domain fails to capture more information of grain size carried by frequency spectrum in partial scope of time [15], and is prone to be influenced by noise signal, thus reducing the precision and reliability of grain size evaluation. Based on the current state of research on this subject introduced above, an ultrasonic evaluation model for grain size based on multi-scale attenuation is proposed to improve the effectiveness of the nondestructive evaluation of grain size in metals.

2. The evaluation model

Suppose the number of blocks adopted to establish the evaluation model is N and the mean thickness of block no. k ($k = 1, 2, ..., N$) is H_k. Hypothetically the grain size and orientation of all the blocks are

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evenly distributed in the direction of ultrasonic propagation and if the metallographic method is employed to measure grain size, the mean grain size is identified as $\overline{D_k}$. An immersive pulse reflection method can be used to acquire the ultrasonic signal $A_k(t)$ of block no. k. Suppose the random error is eliminated by means of multiple tests and the number of ultrasonic signals obtained on each block is S. The ultrasonic signal no. j $(j=1,2,...,S)$of block no. k can be named $A_{k,j}(t)$. A rectangular window is applied to intercept the front-wall echo and the first back-wall echo in $A_{k,j}(t)$ which can be recorded as $x_{k,j}(t)$ and $y_{k,j}(t)$ respectively. To explore the fitting form of the optimal model, one can build a traditional attenuation model in the time domain in which the total attenuation coefficient $\alpha_{k,j}$ is

$$\alpha_{k,j} = \ln\left(\max(|x_{k,j}(t)|)/\max(|y_{k,j}(t)|)\right)(2H_k) \quad (1)$$

So the mean total attenuation coefficient $\overline{\alpha_k}$ is

$$\overline{\alpha_k} = \sum_{j=1}^{S} (\alpha_{k,j}/S) \quad (2)$$

The least squares method is used to fit $\overline{\alpha_k}$ and $\overline{D_k}$ and the smallest error of the fitting function $D(\overline{\alpha_k})$ is achieved when we choose the linearly independent base$\{\varphi_0^*, \varphi_1^*, ..., \varphi_n^* | n < N-1\}$, which is called the optimal base and regarded as the base of the evaluation model based on multi-scale attenuation.

Then the wavelet generating function $\psi(t)$ is randomly chosen, and consecutive wavelet transformations are applied to $x_{k,j}(t)$ and $y_{k,j}(t)$ to respectively find the wavelet coefficient matrix of the front-wall echo and the first back-wall echo $X_{k,j}(a,b)$ and $Y_{k,j}(a,b)$ which are

$$X_{k,j}(a,b) = \langle x_{k,j}(t), \psi_{a,b}(t)\rangle = \frac{1}{\sqrt{a}}\int_R x_{k,j}(t)\overline{\psi_{a,b}(t)}\,dt \quad (3)$$

$$Y_{k,j}(a,b) = \left\langle y_{k,j}(t), \psi_{a,b}(t)\right\rangle = \frac{1}{\sqrt{a}}\int_R y_{k,j}(t)\overline{\psi_{a,b}(t)}\,dt \quad (4)$$

In these two formulas, a is the scale factor, b is the shift factor and $\psi_{a,b}(t)$ is the family of wavelet functions corresponding to $\psi(t)$. Consecutive positive integers are chosen for a in the consecutive wavelet transformations and the number of the total decomposition scales resolved is recorded as M. Line no. i $(i=1,2,...,M)$in the wavelet coefficient matrix is the wavelet component of the original signal under the scale i, so the attenuation coefficient of block mo. k under the scale i could be defined as follows:

$$\alpha_{k,j}^i = \ln\left(\max(|X_{k,j}(i,b)|)/\max(|Y_{k,j}(i,b)|)\right)/2H_k \quad (5)$$

By this formula one can get the distribution of attenuation coefficient–scale. Moreover, the mean attenuation coefficients of each scale can be

$$\overline{\alpha_k^i} = \sum_{j=1}^{S} \left(\alpha_{k,j}^i/S\right) \quad (6)$$

So the distribution of mean attenuation coefficient–scale is given by formula (6). Assume the representative scales $\{a_r | r=1,2,...,m\}$ is chosen in all M scales, and the attenuation coefficients of these scales are respectively extracted, then the ultrasonic multi-scale attenuation coefficient of signal no. j of block no. k can be defined as

$$\alpha_{k,j}^{\{a_r\}} = \sum_{r=1}^{m} \left(w_r \cdot \alpha_{k,j}^{a_r}\right) = [w_1, w_2, ..., w_m] \cdot \left[\alpha_k^{a_1}, \alpha_k^{a_2}, ..., \alpha_k^{a_m}\right]^T \quad (7)$$

In the same way, the mean multi-scale attenuation coefficient can be

$$\overline{\alpha_k^{\{a_r\}}} = \sum_{r=1}^{m} \left(w_r \cdot \overline{\alpha_k^{a_r}}\right) \quad (8)$$

In the formulas (7) and (8), $\boldsymbol{w} = [w_1, w_2, ..., w_m]$ denotes the normalized weight vector of the scales, which means $\sum_{r=1}^{m}(w_r) = 1$. The same representative scale and weight are employed on all of the blocks to calculate the multi-scale attenuation coefficient. Therefore, the key to using the mentioned mean multi-scale attenuation coefficient as the ultrasonic characteristic value to evaluate the mean gain size, consists in how to choose a series of representative scales $\{a_r\}$ and corresponding normalized weight $\boldsymbol{w}$.

Based on the particle swarm optimization, the combination of presupposed optimal scale and its normalized weight distribution strategy are designed. The specific scheme of the algorithm is as follows:

1) Suppose all the scales are chosen as representative ones, i.e., $m=M$, and the normalized weight vector $\boldsymbol{w}$ is acquired by normalizing the original weight vector $\boldsymbol{W}$. The goal of the algorithm is to make the original weight corresponding to the non-representative scales to be zeroes.
2) If the total number of the particles is Q, the current position of particle no. q represents a set of M dimensional vectors of original weight vector $\boldsymbol{W}_q(T)$, and the speed vector is $\boldsymbol{v}_q(T)$ in which T is the number of the iterations, the functions displaying the update of the speed and position are respectively

$$\boldsymbol{v}_q(T+1) = \boldsymbol{\Omega}\boldsymbol{v}_q(T) + c_1 r_1[\boldsymbol{p}_q(T) - \boldsymbol{W}_q(T)] + c_2 r_2[\boldsymbol{p}_g(T) - \boldsymbol{W}_q(T)] \quad (9)$$

$$\boldsymbol{W}_q(T+1) = \boldsymbol{W}_g(T) + \boldsymbol{v}_q(T+1) \quad (10)$$

In the formula, let $|\boldsymbol{v}_q(T+1)| < \boldsymbol{v}_{\max}$ where $\boldsymbol{v}_{\max}$ is the maximum flying speed, $\boldsymbol{\Omega}$ is inertia coefficient, c_1 and c_2 are respectively cognitive and social learning factors, r_1 and r_2 are uniformly distributed random numbers in [0,1], $\boldsymbol{p}_q(T)$ is the individual optimal solution, and $\boldsymbol{p}_g(T)$ is the group optimal solution. If the position of particle no. q is updated and the values of some elements in the original weight vector $\boldsymbol{W}_q(T+1)$ are negative, they are set to zero, thus ensuring that only the weights of the representative scales are non-zero after iteration.
3) The $\boldsymbol{w}_q(T+1)$ is normalized by $\boldsymbol{W}_q(T+1)$. Then on the basis of the distribution of mean attenuation coefficient–scale, one can calculate the mean multi-scale attenuation coefficient $\overline{\alpha_k^{\{a_r\}}}(T+1)$ according to formula (8). $\overline{\alpha_k^{\{a_r\}}}(T+1)$ and $\overline{D_k}$ can be fitted with the optimal base $\{\varphi_0^*, \varphi_1^*, ..., \varphi_n^*\}$ in the least squares method and the 2-norm of residuals between the fitting value $D\left(\overline{\alpha_k^{\{a_r\}}}(T+1)\right)$ and actual value of the mean multi-scale attenuation coefficient can be identified as the fitness value $F(T+1)$ which is

$$F(T+1) = \|D\left(\overline{\alpha_k^{\{a_r\}}}(T+1)\right) - \overline{D_k}\|_2 \quad (11)$$

After repeated iterations according to the fitness value $F(T+1)$, the group optimal solution $\boldsymbol{p}_g$ represents the optimal original weight vector. $\boldsymbol{p}_g$ is regarded as the optimal normalized weight $\boldsymbol{w}^*$. The weights of the non-representative scales in $\boldsymbol{w}^*$ are set to be zeroes, so if there exist non-zero weights, the combination of their corresponding scales will be the combination of optimal scale $\{a_r^*\}$. Based on that, we can calculate the mean multi-scale attenuation coefficient $\overline{\alpha_k^{\{a_r^*\}}}$, and by means of the least squares method