CHARACTERIZATION OF MATERIALS USING GRAIN BACKSCATTERED ULTRASONIC SIGNALS

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INTRODUCTION

Ultrasonic techniques are widely employed in the nondestructive characterization of materials. For example, the use of grain backscattered ultrasonic signals for the estimation of grain size has been studied extensively [1,2,3,4]. Several techniques to process the grain backscattered signals and extract information related to grain size have been reported in [4]. In this paper, we describe a new technique to process these signals and extract features that can be used for material characterization. The technique consists of the following three steps: i) deconvolution of the backscattered signal to remove the effect of the measurement system, ii) estimation of the spectrum of the resulting reflection coefficient sequence, and iii) extraction of features from the spectrum related to the average scattered energy and the rate of change of scattered energy with frequency, both computed within the bandwidth of the ultrasonic transducer. The spectral features so extracted are influenced by the microstructural properties of a material pertaining to scattering, e.g., average grain diameter, and can be used in the characterization of these properties.

In the following, we first examine the grain scattering process in some detail and then describe the signal processing steps. Experimental results involving some pure titanium samples are next presented. The results include the effect of different spectral estimation methods and window sizes on the features.

GRAIN SCATTERING

The scattering of ultrasonic waves at the grain boundaries of a material is influenced by several factors such as grain anisotropy, grain orientation, grain geometry, average grain diameter, and frequency. The effect of grain scattering is best seen through the attenuation of an ultrasonic wave travelling through a material. The frequency-dependent attenuation coefficient α of a material can be expressed as [5,6].

$$\alpha = \alpha_a + \alpha_s \tag{1}$$

where α_a is the absorption coefficient and α_s is the scattering coefficient. Attenuation due to absorpion is relatively small and is caused by the direct conversion of ultrasonic energy into heat. The absorption coefficient is essentially independent of the average grain diameter and varies linearly with frequency f over a wide range as given by

$$\alpha_a = C_1 f \tag{2}$$

where C_1 is a constant.

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The scattering coefficient, on the other hand, has different expressions depending on the relative values of the average grain diameter $\bar{D}$ and the acoustic wavelength λ. In the Rayleigh region where $\lambda > \bar{D}$, the scattering coefficient is expressed as

$$\alpha_s = C_2\bar{D}^3 f^4. \qquad (3)$$

In the stochastic region where $\lambda \approx \bar{D}$, the scattering coefficient is given by

$$\alpha_s = C_3\bar{D}f^2. \qquad (4)$$

In the diffusion region where $\lambda < \bar{D}$, it is given by

$$\alpha_s = C_4\bar{D}^{-1}. \qquad (5)$$

The constants C_2, C_3, and C_4 acount for factors such as grain anisotropy, grain geometry, and grain orientation. From the above expressions for α_s, it can be inferred that the scattered ultrasonic energy as viewed through the frequency window provided by a (broadband) transducer will have different average values and different slopes (rate of change with frequency) depending on the material microstructure. Features related to these quantities can therefore be quite useful for material characterization purposes.

SIGNAL PROCESSING

As pointed out earlier, our processing technique consists of three steps: i) deconvolution of the backscattered signal, ii) spectrum estimation of the reflection coefficient sequence, and iii) feature extraction from the spectrum. These steps are described below.

Deconvolution

The grain backscattered signal obtained from a material sample is obviously colored by the measurement system response. Deconvolution of this signal with the help of a reference pulse (representing the measurement system response) allows us to obtain a signal, viz., the reflection coefficient sequence, which is dependent only on the material microstructure. The deconvolution algorithm used in our technique is based on the Kalman filter and is described in detail in [7]. A brief description of the algorithm follows.

We first model the ultrasonic backscattered signal $z(k)$ as the outcome of convolving the incident acoustic pulse $p(k)$ with the material reflection coefficient sequence $u(k)$ and further corrupting it with some additive noise $v(k)$. Here k is the sampling time index. Mathematically, this relationship is expressed as

$$z(k) = p(k)*u(k) + v(k). \qquad (6)$$

The convolution operation in (6) suggests that we can also regard $z(k)$ as the corrupted [by $v(k)$] output of a system with impulse response $p(k)$ and input $u(k)$. In this case, we can use state-space representation to express $z(k)$ as follows.

$$\mathbf{x}(k) = \mathbf{F}\mathbf{x}(k) + \mathbf{G}u(k) \qquad (7)$$
$$z(k) = \mathbf{H}\mathbf{x}(k) + v(k) \qquad (8)$$

In the above expressions, $\mathbf{x}(k)$ is the $(n\times1)$ state vector, $\mathbf{F}$ is the $(n\times n)$ state transition matrix, $\mathbf{G}$ is the $(n\times1)$ input vector relating the states to the scalar input $u(k)$, $\mathbf{H}$ is the $(1\times n)$ measurement vector relating the states to the scalar measurement $z(k)$, and $v(k)$ is the scalar measurement noise. The matrices $\mathbf{F}$, $\mathbf{G}$, and $\mathbf{H}$ together describe the measurement system and should be chosen such that the impulse response of the system approximates the acoustic pulse $p(k)$. As is customary in standard Kalman filter formulation, we assume that the input