Quantitative grain size evaluation using ultrasonic backscattered echoes

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Grain size characterization using ultrasonic backscattered signals is an important problem in nondestructive testing of materials. In this paper, a heuristic model which relates the statistical characteristics of the measured signal to the mean ultrasonic wavelet and attenuation coefficient in different regions of the sample is investigated. The losses in the backscattered signal are examined using temporal averaging, correlation, and probability distribution functions of the segmented data. Furthermore, homomorphic processing is used in a novel application to estimate the mean ultrasonic wavelet (as it propagates through the sample) and the frequency-dependent attenuation. In the work presented, heat-treated stainless steel samples with various grain sizes are examined. The processed experimental results support the feasibility of the grain size evaluation techniques presented here using the backscattered grain signal.

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INTRODUCTION

The importance of grain size estimation as a means of determining the structural and mechanical properties of materials, as well as for controlling the manufacturing tolerances during fabrication of metal and ceramic parts, has long been recognized by industry. The literature survey indicates that ultrasonic evaluation of grain size is the most practical and widely used nondestructive technique in current manufacturing applications. Two major ultrasonic grain size estimation techniques have been developed in recent years which have met with a reasonable degree of success[1–10]: (i) techniques based on attenuation measurements; and (ii) techniques based on scattering measurements.

Attenuation measurements led the way in the development of ultrasonic grain size estimation techniques early on. The scattering measurement techniques, which require considerable signal processing, have only appeared in recent years. However, with the increasing availability of powerful and cost-effective data acquisition and computing capabilities, scattering measurements are fast becoming the trend in ultrasonic grain size estimation.

Most studies dealing with nondestructive grain size estimation have been based on attenuation measurement techniques using a transmission or reflection mode testing. A number of early studies examined the correlation between attenuation and material characteristics based on the decay of the pulse amplitude using reflections received from the back surface of a sample consisting of two parallel surfaces.[1–3] Grain size estimation techniques based on attenuation measurements have several limitations[4]: (i) Flat and parallel surfaces are essential for accurate measurements in order to avoid complex corrections; (ii) since the attenuation coefficient represents an average value over the total sound path, local variations which can greatly alter the attenuation coefficient cannot be evaluated; and (iii) attenuation measurements are sensitive to the coupling between the transducer and sample, which can lead to losses even greater than the attenuation in the material.

Despite the above factors, attenuation measurement techniques find wide use in practical applications since they provide an integrated estimate for the grain size in a relatively simple fashion. These techniques allow samples with different microstructure to be quickly analyzed and qualitatively characterized when experimental conditions are carefully maintained.

More recently, an alternative approach using backscattered echoes from grain measurements (i.e., scattering measurements) has been utilized to determine the attenuation in materials with respect to depth or frequency. The direct characterization of the backscattered signal yields information pertaining to variations in the scattered energy as a function of depth and, hence, the grain size distribution. These techniques can be applied to samples which result in grain boundary echoes that are visible above the received noise level (i.e., for large grained samples and/or for high SNR systems).

Some of the earlier work in grain size estimation using ultrasonic scattering measurements was performed by Beechman[5] and Fay.[6,7] Based on the principle that ultrasonic waves traveling in solids are subject to scattering and absorption losses, Fay was able to demonstrate that the attenuation of backscattered echoes with depth is related to the average grain size of the specimen. Goebbels *et al.*[4,8,9] altered and refined Fay's technique to more accurately determine the amplitude of the backscattered echoes with respect to depth by utilizing various averaging techniques, namely, spatial, directional, and frequency averaging.

In the previous work summarized above, the most promising grain size characterization techniques have been based on information obtained from a relatively large region of the sample as necessitated by ensemble averaging. Our objective is to evaluate grain echoes using a single A-scan rather than to average multiple measurements obtained by changing the position, orientation, or frequency of the transducer.[8,9] The single A-scan is more practical and efficient for ultrasonic testing. In fact, in some situations, the geometry of the object interferes with or prohibits the use of multiple measurements. Furthermore, if the penetration of the ultrasonic energy is position or orientation dependent, an assessment of this variation is necessary and must be compensated prior to averaging. Finally, and most importantly, the use of a single measurement reveals information confined to a smaller region of the sample relative to the average of multiple measurements, which displays integrated information pertaining to a broader region of the sample. With this in mind, the paper focuses on the methods for evaluating grain size by coupling a mathematical model of backscattered echoes with suitable digital signal processing techniques. The backscattered grain signal is represented by a heuristic model based on the mean ultrasonic wavelet and the grain characteristic function. Various methods have been applied in order to assess losses in the backscattered signal. The grain signals were evaluated quantitatively using both time and frequency domain processing techniques. In particular, a homomorphic processing technique was used in a novel application to estimate frequency-dependent attenuation.

I. GRAIN BACKSCATTERING COEFFICIENTS

The ultrasonic wave traveling through solids is subject to scattering and absorption which results in energy losses as the wave advances. The intensity of scattering is a nonexplicit function of the average grain diameter, ultrasonic wavelength, inherent anisotropic character of the individual grains, and the random orientation of the crystallites.[11–14] The overall frequency-dependent attenuation coefficient $\alpha(f)$ is defined as

$$\alpha(f) = \alpha_a(f) + \alpha_s(f), \qquad (1)$$

where $\alpha_s(f)$ is the scattering coefficient and $\alpha_a(f)$ is the absorption coefficient. The scattering formulas have been studied and classified into distinct scattering regions[1,11–14] according to the ratio of the sound wavelength λ to the mean grain diameter $\overline{D}$. These scattering regions include: the Rayleigh region, where the sound wavelength is large compared to the mean grain diameter; the stochastic region, where the wavelength is comparable to the mean grain diameter; and the diffusion region, where the mean grain diameter is greater than the wavelength.

In the Rayleigh region, the scattering coefficient varies with the average volume of the grain and the fourth power of the wave frequency, while the absorption coefficient increases linearly with the frequency.[11–13] Therefore, the total attenuation coefficient of ultrasound in the Rayleigh region is expressed as

$$\alpha(f) = a_1 f + a_2 \overline{D}^3 f^4, \quad \lambda > 2\pi\overline{D}, \qquad (2)$$

where a_1 is the absorption constant, a_2 is the scattering constant, and f is the transmitted frequency. In the stochastic region, where the wavelength is approximately equal to the mean grain diameter, the scattering coefficient varies linearly with the mean grain diameter and, as the square of the frequency,

$$\alpha(f) = b_1 f + b_2 \overline{D} f^2, \quad \overline{D} < \lambda < 2\pi\overline{D}, \qquad (3)$$

where b_1 represents the absorption constant due to the elastic hysteresis loss, and b_2 is the scattering constant. When the wavelength is smaller than the average grain diameter, the scattering coefficient is independent of the frequency and varies inversely with the average grain diameter:

$$\alpha(f) = c_1 f + c_2/\overline{D}, \quad \lambda < \overline{D}, \qquad (4)$$

where c_1 is the absorption constant and c_2 is the scattering constant. In the diffusion region, where the average grain size is large compared to the wavelength, the attenuation coefficient becomes

$$\alpha(f) = (d_1 f + d_2 f^2) + d_3/\overline{D}, \quad \lambda \ll \overline{D}, \qquad (5)$$

where d_1 and d_2 represent the absorption constants due to the elastic hysteresis and the thermoelastic losses, respectively, and d_3 is the scattering constant.

The Rayleigh scattering region, where multiple reflections between the grain boundaries are negligible, is of primary concern in the present experimental applications. For this region, Papadakis[13,14] presents scattering coefficient formulas for both cubic and hexagonal crystals, relating the scattering coefficient to the acoustical properties of the material.

II. HEURISTIC MODEL OF BACKSCATTERED SIGNAL

The attenuation of the ultrasonic wave is caused in part by the scattering characteristics of grains. This scattered energy propagates in all directions in a random fashion. In the pulse–echo mode operation used here, we are interested in evaluating the backscattered signal (scattering of 180° relative to the direction of transmission). The received signal at time τ is due to scatterers in the material at a distance of $C\tau/2$, where C is the propagation velocity of sound (shear or longitudinal) in the medium. Since the scatterers (i.e., grains) are stationary, the amplitude of a detected signal at a fixed time after transmission of a pulse will be constant for fixed transducer position and frequency.

Let us assume that the received signal is due to a large number of statistically independent scattering centers in which the sound wavelength is significantly larger than the size of the scatterers (i.e., Rayleigh region). Furthermore, it is assumed that the scatterers (i.e., grains) are located in the farfield of the transducer, and the incident wave is a pulsed plane wave propagating into the bulk material. The beam spreading over a small range within the material is considered to be insignificant, and the beamwidth is assumed to be much larger than the grain size. Under these assumptions, the backscattered signal is dominated by the sum of echoes reflected from randomly distributed incoherent scatterers.[15,16]

The measured signal $r(t)$ can be segmented into fixed time intervals, $r_j(t)$ corresponding to fixed spatial intervals

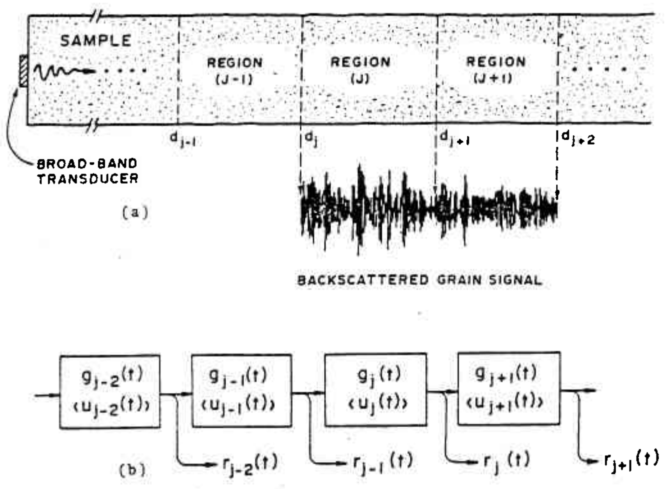

FIG. 1. A sample under ultrasonic testing for grain size estimation using backscattered echoes. (a) A typical backscattered grain signal corresponding to region j and $j+1$; (b) segmented model of the backscattered grain signal.

(i.e., $\Delta d = d_{j+1} - d_j$) within the sample (for clarity see Fig. 1):

$$r(t) = \sum_{j=1}^{q} r_j(t) , \tag{6}$$

where $r_j(t)$ represents the signal corresponding to the jth region and q is the number of regions. Region j should typically correspond to a segment of the sample which does not exhibit strong isolated reflectors nor show any influence by the front and back surfaces. In addition, the segment size should be much larger than the average grain size $\overline{D}$. For a given region j, the measured backscattered echoes form a composite signal which may be modeled as [17,18]

$$r_j(t) = \sum_{K=1}^{N_j} A_{kj} \langle u_j(t - \tau_{kj}) \rangle; \quad j = 0,1,2,...,q, \tag{7}$$

where τ_{kj} is a random variable representing the detection time of random echoes such that

$$2d_j/C < \tau_{kj} < 2d_{j+1}/C. \tag{8}$$

The term $\langle u_j(t) \rangle$ represents the mean shape of the echo (i.e., impulse response or wavelet) within the jth region of the sample. The shape of this function is governed by the transfer functions of the ultrasonic pulser, transmitting and receiving transducers, amplifier, and the variable propagation path characteristics. Since the measuring system characteristics are fixed, any change in the ultrasonic wavelet is indicative of the acoustical properties of the propagation path. The amplitude A_{kj} in Eq. (7) is a random variable representing the average reflection coefficient of scatterers in a region from which echoes are detected after a delay of τ_{kj}. Here, A_{kj} is dependent on the scattering cross section, elastic constant, ultrasonic velocity, and the density of the adjacent grains.[11,15,16] The term N_j is a random variable representing the total number of scatterers in region j. The minor interference effect from the grains in the adjacent segments is considered to be negligible. Furthermore, due to the effect of frequency-dependent attentuation, the relationship among the mean wavelet in different regions can be represented as[17]

$$\langle U_{j+1}(\omega) \rangle = e^{-2[\alpha_j(\omega) - i\beta(\omega)]\Delta d} \langle U_j(\omega) \rangle, \tag{9}$$

where

$$\omega = 2\pi f, \quad \Delta d = d_{j+1} - d_j,$$
$$\beta(\omega) = \omega/C, \quad i = \sqrt{-1} . \tag{10}$$

The term $\alpha_j(\omega)$ is the attenuation coefficient due to scattering and absorption, and $\langle U_j(\omega) \rangle$ is the Fourier transform of the mean ultrasonic wavelet.

It is appropriate to point out that Eq. (7) by no means corresponds to the individual grain size or its exact position in the propagation path. However, this is a heuristic model of the composite characteristics of the received signal which inherently contains information related to the acoustical characteristics of that given region. Therefore, it can serve as a source for the systematic investigation of grain size distribution. The variation in the backscattered signal is partially related to the grain size. Hence, the interference pattern of Eq. (7) contains information which yields the average grain size and possibly the grain size distribution. Furthermore, $\langle u_j(t) \rangle$ differs from one segment of data to another as the wave travels through the sample, since the high-frequency components attenuate at a faster rate than the lower frequency components [for clarification of this statement, see Eqs. (2) and (9)]. Therefore, determination of $\langle u_j(t) \rangle$ by means of signal processing has the potential of providing a measure of the mean grain size distribution. In general, the echo $\langle u_j(t) \rangle$ can be approximated as a time-limited rf echo with Gaussian envelope:

$$\langle u_j(t) \rangle \approx \rho_j e^{-t^2/2\sigma_j^2} \cos(\omega_j t) . \tag{11}$$

The frequency spectrum of $\langle u_j(t) \rangle$ is

$$\langle U_j(\omega) \rangle \propto \rho_j e^{-\sigma_j^2(\omega - \omega_j)^2/2}; \quad \omega \geqslant 0, \tag{12}$$

where the conditions

$$\omega_j \geqslant \omega_i; \quad \rho_j \geqslant \rho_i; \quad \text{when } i > j > 1 \tag{13}$$

generally hold. The assumption that $\langle u_j(t) \rangle$ is Gaussian in shape for all j is too restrictive and may not be precise. Even so, an optimal Gaussian model can always be fitted to the echo shape if no strict limit on the error function is enforced. Inspection of Eq. (9) reveals that materials act like a lowpass filter and their transform functions are inversely proportional to frequency. Therefore, it is more appropriate to rewrite the conditions given in Eq. (13) in terms of the mean frequency $\langle \omega_j \rangle$ and the wavelet power (P_j) as follows:

$$\langle \omega_j \rangle \geqslant \langle \omega_i \rangle; \quad P_j \geqslant P_i; \quad \text{when } i > j > 1. \tag{14}$$

Upon estimation of the mean ultrasonic wavelet, it is possible to find the frequency-dependent attenuation coefficient. The magnitude spectrum of Eq. (9) can be defined as

$$|\langle U_{j+1}(\omega) \rangle| = e^{-2\alpha_j(\omega)\Delta d} |\langle U_j(\omega) \rangle| . \tag{15}$$

From above, the attenuation function $\alpha_j(\omega)$ can be expressed as

$$\alpha_j(\omega) = [\log|\langle U_j(\omega) \rangle| - \log|\langle U_{j+1}(\omega) \rangle|]/2\Delta d . \tag{16}$$

III. DIGITAL PROCESSING OF THE BACKSCATTERED SIGNAL

The primary objective of this work is to develop appropriate digital processing techniques to evaluate materials of different grain sizes. The principle for the various methods discussed is based on Eqs. (2), (7), (9), (11), and (16). The signal processing techniques are categorized within three distinct groups: time domain analysis, frequency domain analysis, and homomorphic processing.[17]

A. Time domain analysis

Time domain analysis consists of the following techniques: the smoothing process, constructing the histogram of the backscattered signal, and estimating the autocorrelation function.

The smoothing process is a simple and practically efficient technique for characterizing random signals such as the backscattered echoes from large grained materials. In fact, for homogeneous and isotropic materials, the concept of ensemble averaging has been used earlier[4,5,10] to obtain similar results. The grain signal is a stochastic process in which randomness is inherent to any single measurement. Consequently, temporal fluctuations contain equivalent information to the random spatial fluctuations. Therefore, it is appropriate to determine the statistical parameters (e.g., mean and variance) of the process from a single measurement, which is far more practical than using multiple measurements. In general, this is a valid approach for stationary random processes for which time averages are identical to their ensemble averages (i.e., ergodic processes).[19]

Temporal averaging is a linear operation and can be represented as

$$\bar{r}(t) = \tilde{r}(t) * h(t), \tag{17}$$

where $\tilde{r}(t)$ is the measured signal after rectification and $h(t)$ is the smoothing function defined as

$$h(t) = \begin{cases} 1/\epsilon & |t| \leqslant \epsilon/2, \\ 0 & \text{elsewhere}. \end{cases} \tag{18}$$

The smoothed output is then defined as

$$\bar{r}(t) = \frac{1}{\epsilon}\int_{t-\epsilon/2}^{t+\epsilon/2} \tilde{r}(\tau)d\tau. \tag{19}$$

Determination of an appropriate ϵ is quite important in the performance of a smoothing operation. The results of this study show that ϵ on the order of 10.0 μs (which is equivalent to 50 wavelengths for a 5-MHz transducer) provides an exponentially decaying function which is sensitive to grain size variations.

Constructing the probability density function of the rectified received signal amplitude, which is inherently related to the distribution of grains in a given region, is a useful method for evaluating materials of different grain sizes. The most appropriate method for accomplishing this task is to use many statistically independent measurements. This can be achieved by changing the orientation of the transducer for each measurement. From these measurements, the probability distribution function can be constructed at each time instant. Alternatively, if we assume ergodicity, the distribution function can be obtained by constructing the histogram of the rectified instantaneous signal amplitude from a given time segment. In the histogram analysis, parameters such as mean, mode, standard deviation, and skewness are considered.

Finally, for the purpose of completeness, the autocorrelation function of the measured grain signal was investigated. The autocorrelation function is defined as

$$R_{rr}(t) = \frac{1}{\Delta t}\int_0^{\Delta t} r(\tau)r(\tau - t)d\tau, \tag{20}$$

where Δt is the duration of correlation. In general, this function responds to any possible periodicity in a structure by displaying strong peaks. However, it is necessary to point out that the autocorrelation function was found to be of little value since grains exhibit no periodicity.

B. Spectral analysis

Spectral analysis is a useful technique in which certain features hidden in the time domain can be displayed. These features are basically related to the presence or absence of energy in specific bands. In this section, the spectral method based on the magnitude spectra of grain characteristic functions is discussed.

The spectrum of the measured data corresponding to a given segment can be obtained by Fourier transforming Eq. (7):

$$R_j(\omega) = G_j(\omega)\langle U_j(\omega)\rangle, \tag{21}$$

where

$$G_j(\omega) = \sum_{k=1}^{N_j} A_{kj} e^{-j\omega\tau_{kj}} \tag{22}$$

is the Fourier transform of the grain characteristic function for region j. The magnitude of $\langle U_j(\omega)\rangle$ is a smooth Gaussian shaped function. However, the term $|G_j(\omega)|$ contains many peaks and valleys which are random. This term modulates and distorts the magnitude spectrum of $\langle U_j(\omega)\rangle$, which also bears features related to frequency-dependent attenuation characteristics of the material. Recovery of the true $\langle U_j(\omega)\rangle$ from the measured $R_j(\omega)$ is difficult, and the possiblity of large error in its estimation cannot be ruled out (the technique of echo recovery and its evaluation is the subject of Sec. III C). Therefore, one needs to characterize the sample by $R_j(\omega)$ without having to determine $\langle U_j(\omega)\rangle$.

Partial identification of $|R_j(\omega)|$ can be obtained by moments. In this study, for the purpose of emphasizing or deemphasizing certain behavior of the magnitude spectrum, the following generalized definition for moments[17] is given:

$$M_{KL} = \int_0^{\infty} \omega^K |R_j(\omega)|^L d\omega, \tag{23}$$

when $L = 1$ and K is a positive integer, then M_{1K} is the Kth moment of the magnitude spectrum according to the common definition of moments. In general, K and L can be any real number. The usefulness of the above equation becomes apparent only if it shows enough sensitivity to an unknown physical characteristic such as the grain size. The larger the

K, the more weight is given to the higher frequencies of the magnitude spectrum. On the other hand, for smaller K values, the contribution of low-frequency components to the value of M_{KL} is significant relative to higher frequency components.

The index L acts quite differently from index K. For large values of L, peaks of $|R_j(\omega)|$ will have a greater contribution to the value of M_{KL}. In contrast, if L becomes very small, there will be minimum variation in the moment values due to variation of peaks. It is necessary to point out that, for random peaks such as those in the case of grain signals, the exact usefulness of generalized moments is not clear. However, empirical evaluations will be the basis for determining its capability.

Equation (23) must be normalized in order to be independent of amplitude variations in the measurements. This can be achieved by

$$\overline{M}_{KL} = \left(\int_0^\infty \omega^K |R_j(\omega)|^L d\omega\right) \Big/ \left(\int_0^\infty |R_j(\omega)|^L d\omega\right) \quad (24)$$

when $K = 1$ and $L = 2$,

$$\overline{M}_{12} = \left(\int_0^\infty \omega |R_j(\omega)|^2 d\omega\right) \Big/ \left(\int_0^\infty |R_j(\omega)|^2 d\omega\right). \quad (25)$$

In the literature, the above equation is referred to as the power spectrum centroid which has been widely used in Doppler radars, sonar systems, and ultrasonic flowmeters.

C. Homomorphic processing

The backscattered echoes from a given region of the target (e.g., jth region) can be modeled as the convolution of the mean echo wave shape and the impulse response of the target (i.e., grain characteristic function)

$$r_j(t) = \langle u_j(t) \rangle * \sum_{k=1}^{N_j} A_{kj} \delta(t - \tau_{kj}). \quad (26)$$

The above equation is identical to Eq. (7).

Comparison of $\langle u_j(t) \rangle$ with $\langle u_{j+1}(t) \rangle$ can potentially reveal information about the regional characteristics of the target and, consequently, the grain size. In practice, $\langle u_j(t) \rangle$ can only be extracted from $r_j(t)$. This presents the problem of echo recovery by some means of signal processing. The mean echo wavelet can be extracted from the measured signal through homomorphic signal processing (a branch of nonlinear signal processing that utilizes Fourier transform and logarithmic operations to convert convolutional signals to additive form, which can be decomposed more conveniently[20–22]). The homomorphic wavelet recovery system (also known as homomorphic deconvolution or cepstrum system) is shown in Fig. 2. As shown in this figure, the grain signal is Fourier transformed in order to determine the magnitude spectrum. Next, the logarithmic operator is applied to convert the multiplicative relationship between the mean echo wavelet and the grain impulse response to the additive relationship:

$$\log|R_j(\omega)| = \log|\langle U_j(\omega) \rangle| + \log|G_j(\omega)|. \quad (27)$$

The inverse Fourier transform of Eq. (27) results in the grain signal power cepstrum, $\hat{r}_j(t)$. The spectrum of the mean echo wavelet is approximately Gaussian shaped in the

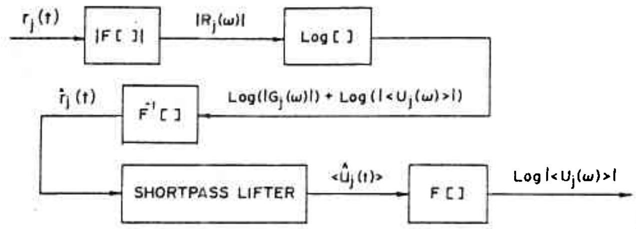

FIG. 2. The homomorphic wavelet recovery system.

frequency domain and its power cepstrum $\langle \hat{u}_j(t) \rangle$ has a time width which is shorter than the power cepstrum of the grain impulse response. Therefore, when a shortpass lifter (i.e., time-gating operation in cepstrum domain which is analogous to low-pass filtering in the frequency domain) of duration equivalent to echo duration is applied to the grain signal power cepstrum, the power cepstrum of the wavelet can be recovered. Finally, the Fourier transform of the power cepstrum of the wavelet will result in $\log|\langle U_j(\omega) \rangle|$.

The performance of cepstrally smoothing the magnitude spectrum of the measured signal is shown in Fig. 3. Figure 3(a) shows a typical grain signal which is segmented into two regions, j and $j+1$. The magnitude spectra of these

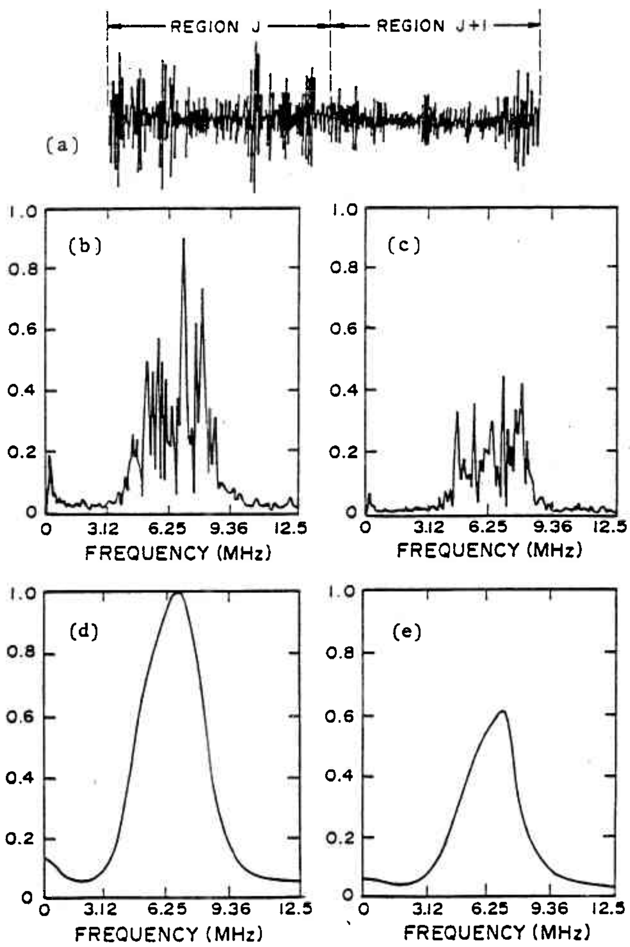

FIG. 3. (a) A typical grain signal; (b) and (c) magnitude spectra of regions j and $j+1$, respectively; (d) and (e) cepstral smoothing of magnitude spectra of regions j and $j+1$, respectively.