GRAIN SIZE EVALUATION THROUGH SEGMENTATION AND DIGITAL PROCESSING OF ULTRASONIC BACKSCATTERED ECHOES

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ABSTRACT

An important problem in NDE is grain size evaluation using ultrasonic backscattered signals. In this report, a hueristic 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 mean ultrasonic wavelet as it propagates through the sample and the frequency dependent attenuation are estimated using homomorphic processing. Furthermore, the losses in the backscattered signal are examined using temporal averaging, correlation, and the probability distribution function of the segmented data. In our present work, a heat-treated stainless steel sample with various grain sizes is examined and the processed experimental results support the feasibility of grain size evaluation using the backscattered grain signal.

INTRODUCTION

The ultrasonic wave traveling through solids is subject to scattering and absorption which results in energy losses as the wave advances. The overall frequency dependent attenuation coefficient, $\alpha(f)$, is

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

where $\alpha_s(f)$ is the scattering coefficient and $\alpha_a(f)$ is the absorption coefficient. The intensity of scattering is a nonexplicit function of the average grain diameter, ultrasonic wavelength, inherent anisotropic character of the individual grains, and random orientation of the crystallites [1,3]. The direct characterization of the backscattered signal will yield information pertaining to variation in the scattered energy as a function of depth and, hence, the grain size distribution. The purpose of this report is to present a method for estimating grain size by coupling a mathematical model of the backscattered echoes with the suitable digital processing techniques.

The scattering formulas have been studied and classified for three distinct scattering regions [1,3,5,6] according to the ratio of the sound wavelength, λ, to the mean grain size, $\overline{D}$. Presently, we are concerned with the Rayleigh scattering region where multiple reflections among the grains are negligible. In this 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. Therefore, the total attenuation coefficient of ultrasound in the Rayleigh region can be expressed as

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

where a_1 and a_2 are constants and f is the transmitted frequency.

HUERISTIC MODEL OF BACKSCATTERED SIGNALS

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. But, in a pulse-echo mode operation we are interested in evaluating the backscattered signal (scattering of 180 degrees relative to the direction of transmission). The received signal at time τ is due to scatterers in the neighborhood of $C\tau/2$ where C is the propagation velocity of sound (shear or longitudinal) in the medium. The measured signal, r(t), can be segmented into fixed time intervals corresponding to fixed spatial intervals $(d_{j+1} - d_j)$ within the sample,

$$r(t) = \sum_{j=1}^{P} r_j(t) \qquad (3)$$

where $r_j(t)$ represents the signal corresponding to the j-th region and P is number of segments. For a given region j, the measured backscattered echoes form a composite signal which may be modeled as [7]:

$$r_j(t) = \sum_{k=1}^{N_j} A_{kj} < u_j(t-\tau_{kj}) > \ ; \quad j = 1, 2, \cdots, P \qquad (4)$$

where

$$\frac{2d_j}{C} < \tau_{kj} < \frac{2d_{j+1}}{C} \qquad (5)$$

the term $<u_j(t)>$ represents the mean shape of the echo (i.e., wavelet) within the j-th region of the sample, A_{kj} is a random variable representing the intensity of the scatterers by assuming no multiple scattering, and N_j is the total number the scatterers which is a random variable. Furthermore, due to the effect of the frequency dependent attenuation, the relationship between the mean wavelets in the different regions can be represented as [7]:

$$<U_{j+1}(\omega)> = e^{-\alpha_j(\omega)L} e^{-i\beta(\omega)L} <U_j(\omega)> \quad (6)$$

where

$$\omega = 2\pi f \;, \quad L = 2(d_{j+1} - d_j)$$

$$\beta(\omega) = \frac{\omega}{C} \;, \quad i = \sqrt{-1} \;. \quad (7)$$

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

It is appropriate to point out that equation (4) by no means corresponds to the individual grain size or its exact position in the propagation path. However, this is a heuristic model which explains the composite characteristics of the received signal, which inherently contains information related to the acoustical characteristics of that given region, and also serves as a source for a systematic approach to the problem for further investigation.

Upon estimation of the mean ultrasonic wavelet, one can find the frequency dependent attenuation coefficient. Writing equation (6) in the form of the magnitude spectrum, the attenuation, $\alpha_j(\omega)$, can be expressed as

$$\alpha_j(\omega) = \frac{\log|<U_j(\omega)>| - \log|<U_{j+1}(\omega)>|}{L} \;. \quad (8)$$

DIGITAL PROCESSING OF THE BACKSCATTERED SIGNAL

The signal processing techniques are categorized within three distinct groups: time domain analysis, frequency domain analysis and homomorphic processing [7].

Time Domain Analysis

Time domain analysis can be divided into 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 the large grained materials. The grain signal is a stochastic process in which randomness does not manifest itself entirely in a particular measurement, but is an inherent property of it. Therefore it is appropriate to determine the statistical parameters (e.g., mean and variance) of the process from a single measurement which is by far more practical than using multiple measurements.

Temporal averaging is a linear operation and can be represented as

$$\bar{r}(t) = \frac{1}{\varepsilon} \int_{t-\varepsilon/2}^{t+\varepsilon/2} \tilde{r}(\tau)d\tau \quad (9)$$

where $\tilde{r}(t)$ is the measured signal after rectification. Determination of an appropriate ε is quite important in the performance of a smoothing operation. In this study, we have found that ε on the order of 10.0 microseconds (this is equivalent to 50 wave lengths of a 5 MHz transducer) provides an exponentially decaying function which varies as the grain size changes.

Constructing the probability density function of the received signal, which is inherently related to the distribution of grains in a given region, is a useful method for evaluating materials of different grain sizes. In the histogram analysis parameters such as mean, mode, standard deviation, and skewness are considered.

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

$$R_{rr}(t) = \int_{-\infty}^{\infty} r(\tau)r(t+\tau)d\tau \;. \quad (10)$$

In general, this function responds to any possible periodicity in structure with strong peaks. It is necessary to point out that the autocorrelation function is of little value since grains in the material exhibit no periodicity.

Spectral Analysis

Spectral analysis is a useful technique in which certain hidden features in the time domain can be displayed. These features are basically related to the presence or absence of energy in specific bands. The magnitude spectrum of the backscattered echoes consists of random peaks and valleys which complicates a direct evaluation of its pattern. However, partial identification of the magnitude spectrum, $|R_j(\omega)|$, can be obtained by moments. For the purpose of emphasizing or de-emphasizing certain behavior of the magnitude spectrum, the following generalized definition for normalized moments is given [7]:

$$\overline{M}_{KL} = \frac{\int_0^\infty \omega^K |R_j(\omega)|^L d\omega}{\int_0^\infty |R_j(\omega)|^L d\omega} \;. \quad (11)$$

From equation (11) the power spectrum centroid can be calculated (i.e., K = 1 and L = 2).

Homomorphic Processing

Comparison of $<u_j(t)>$ with $<u_{j+1}(t)>$ can potentially reveal information about the regional characteristics of the target and, consequently, the grain size.

In practice, $<u_j(\omega)>$ can only be extracted from $R_j(\omega)$. 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 [4]). The homomorphic wavelet recovery system (also known as homomorphic deconvolution or cepstrum system) is shown in Figure 1. As shown in this figure, the grain signal is Fourier transformed and its magnitude spectrum is calculated. Then the logarithmic operator is applied in order to convert the multiplicative relationship between the mean echo wavelet and the impulse response of the grained sample to the additive relationship. The inverse Fourier transform results in the grain signal power cepstrum, $\hat{r}_j(t)$. The spectrum of the mean echo wavelet is of an almost Gaussian shape in the fre-

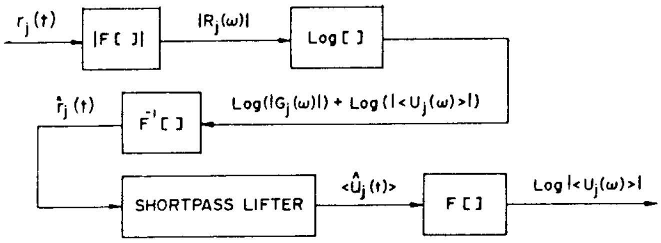


Fig. 1. The homomorphic wavelet recovery system.

quency domain, so its power cepstrum, $<\hat{u}_j(t)>$, has a time width which is shorter than the power cepstrum of the impulse response of the grained sample. Therefore, a shortpass lifter (analogous to lowpass filter) of a duration equivalent to the echo duration when applied to the grain signal power cepstrum, will recover the power cepstrum of the wavelet. Finally, the Fourier transform of the power cepstrum of the wavelet will result in $\log|<U_j(\omega)>|$.

EXPERIMENTAL PROCEDURE

The object of this work is to evaluate the grain size variation in solids when other physical parameters (e.g., crystal shape, elastic constants, density and velocities) remain constant. This allows us to accurately interpret the measurements resulting from the grain size variation. In this study, two inch diameter stainless steel rods (type 303) were heat-treated to obtain various grain sizes. The stainless steel samples initially had a mean grain size of about 25 microns, and were heat-treated for periods of roughly one hour.

The grain size of the heat-treated samples was analyzed by the intercept method [2]. This method of analyzing the sections from the heat-treated samples resulted in a grain size estimation of 86 and 160 microns for 1350°C and 1387°C samples respectively.

The experimental grain signal measurement was accomplished using a Gamma type transducer made by Aeortech with the center frequency of about 6 MHz and a 3-dB bandwidth of approximately 1.5 MHz. A range gate enabled the selection of a particular segment of the reflected signal for processing. The measured data was sampled at 50 MHz using a Biomation 8100 transient recorder. Each experimental data set contained 1024 points which is equivalent to 20.5 microseconds. Coherent averaging was applied in order to enhance the signal-to-noise ratio of the measurement.

Figure 2 shows typical grain signals from the stainless steel (SS) sample as well as the heat-treated samples at temperatures of 1350°C (SS-1350) and 1387°C (SS-1387). Although differences between these composite signals exist, they are not readily quantifiable.

RESULTS AND DISCUSSION

The processing algorithms described earlier have been applied to stainless steel grain signals. The grain signals shown in Figure 2 are time averaged and results are shown in Figure 3. Time

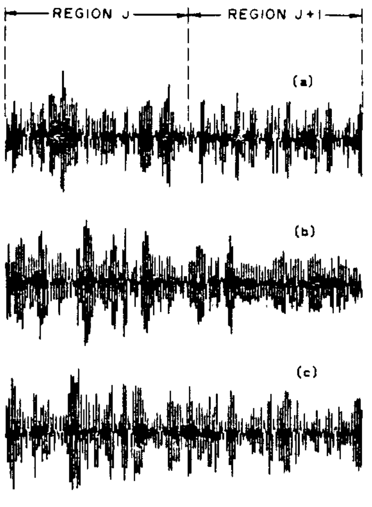


Fig. 2. Grain signals from stainless steel samples. a) SS, b) SS-1350 and c) SS-1387.

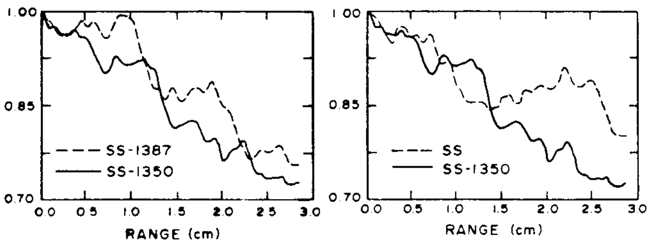


Fig. 3. Temporal averaging of stainless-steel grain signals.

averaging is obtained by a smoothing function which is rectangular and has a duration of 10.24 microseconds. The resulting smoothed function is normalized such that its initial amplitude is unity. Since SS-1350 and SS-1387 have larger grain sizes than SS, some differences in their decaying characteristics are apparent. Results show that there is hardly any noticeable difference between the smoothed results of SS-1350 and SS-1387, although their grain sizes differ by almost a factor of two. This may be because the grain size of SS-1387 is slightly above the upper limit of the Rayleigh scattering region (i.e., stochastic region). The overall evaluation of the presented results and many others demonstrate the feasibility of time averaging for grain size estimation.

Autocorrelations for stainless steel grain signals are presented in Figure 4. Since no regular pattern or periodicity exists in solids, the envelope of the autocorrelation functions generally reveal no information about the grain size or its distribution. Histograms of the segmented stainless steel grain signals are shown in Figure 5. In addition, the statistical parameters of the distribution are shown in Table 1. Comparison of these histograms reveals that relative changes between the two regions of the signal depend on the scattering characteristic of grains. Furthermore, evaluation of the statistical parameters (i.e.,

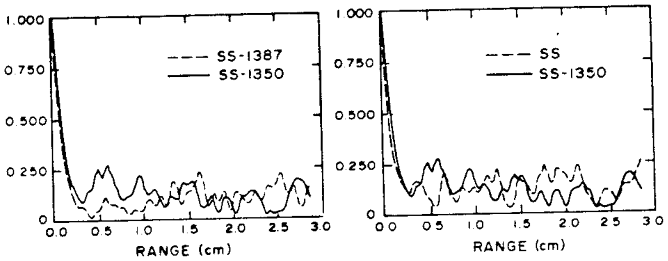
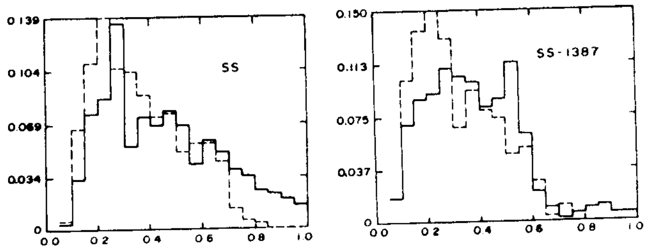


Fig. 4. The envelope of the autocorrelation functions of the stainless steel grain signals.



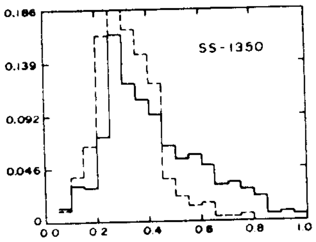


Fig. 5. The histogram of the backscattered grain siganls.

Solid Line: Region J
Dashed Line: Region J+1.

Table 1. Statistical parameters corresponding to the histograms of grain signals.

	SS-1387		SS-1350		SS	
	Region J	Region J+1	Region J	Region J+1	Region J	Region J+1
MEAN	0.35	0.29	0.40	0.30	0.44	0.34
MODE	0.50	0.20	0.25	0.25	0.25	0.20
SD	0.18	0.15	0.19	0.12	0.23	0.17
SK	-0.83	0.63	0.77	0.41	0.81	0.82

mean, mode, standard deviation and skewness) as shown in Table 1, especially the values of mean and standard deviation, suggest similar conclusions.

Power spectrum centroids of the stainless steel grain signal are shown in Table 2. Relative changes in each data seem minor and inadequate for an appropriate conclusion. Nevertheless, it has been observed that the mean frequency of the signal decreases as the grain size increases. For example, the power spectrum centroids for SS, SS-1350 and SS-1387 are 7.10, 6.85 and 6.60, respectively. These results support the concept that the expected signal frequency decreases as grain size increases.

The effect of frequency on the attenuation coefficient in the stainless steel sample is obtained by cepstrally smoothing the magnitude spectrum of the segmented data and applying equation (8). These results are presented in Figure 6. The SS-1387 sample has the largest attenuation coefficient which appears to be constant within the 5.5-7.5 MHz range as shown in the figure. The SS-1350 sample shows a relatively constant attenuation coefficient and its value is higher than the attenuation coefficient of the SS sample. Finally, the SS sample has grain size well in the Rayleigh region and, as expected, its attenuation coefficient displays a clear dependence on the frequency. Present data supports that the attenuation coefficient measured by the cepstrum technique can be potentially useful in grain size evaluation.

CONCLUSION

The results presented in this paper indicate that various signal processing techniques can be utilized in ultrasonic grain size estimation. All techniques are concerned with removing the randomness in the backscattered signal and extracting parameters related to the attenuation coefficient and consequently to the grain size. Although we have demonstrated the feasibility of the proposed techniques for grain size estimation, the applicability and reproducibility of the techniques to a broad range of large grained materials deserves further investigation.

Table 2. Power spectrum centroids of the stainless-steel grain signals

	Entire Signal	Region J	Region J+1
SS	7.10	7.25	6.98
SS-1350	6.85	6.87	6.93
SS-1387	6.60	6.65	6.65

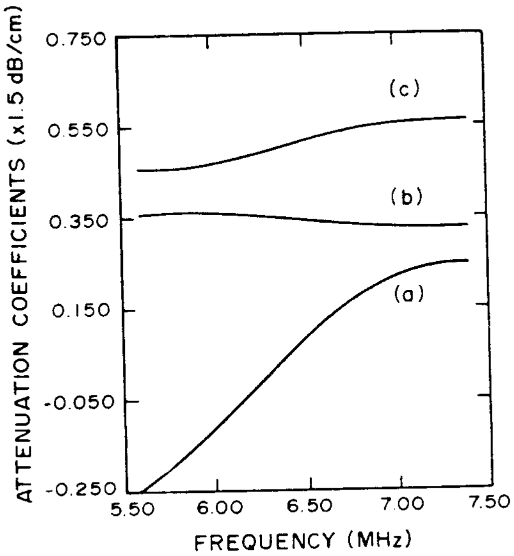


Fig. 6. Dependence of the attenuation coefficient on frequency in stainless-steel grain signals. a) SS b) SS-1350 and c) SS-3187.

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