ULTRASONIC SIGNAL PROCESSING AND PATTERN RECONGITION IN EVALUATING THE MICROSTRUCTURE OF MATERIALS

BY

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This thesis is dedicated to the author's parents and his Motherland.

T.W.

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ABSTRACT

The need for refined signal processing techniques to analyze the microstructure of materials using ultrasonic backscattered echoes has been long recognized. This thesis focuses on the analysis and development of signal processing technique for microstructure evaluation based on attenuation estimation, resonating frequency extraction and frequency shift evaluation. Existing conventional techniques are incapable of characterizing the microstructure of the materials because the backscattered signal consists of interfering multiple echoes with random amplitude and phase corresponding to highly complex scatterers. Thus, the development of effective techniques for imaging and evaluating the microstructure of the materials remains a challenging scientific and practical concern.

The ultrasonic backscattered signal is treated as a random process, and a statistical model is developed that describes the backscattered signal as a function of physical parameters such as attenuation and frequency shift. This work has shown that it is feasible to characterize materials with different grain sizes by analyzing the backscattered grain signal. Grain size characterization has been achieved by measuring the attenuation coefficient using two equivalent approaches, namely, temporal (time) and spatial (ensemble) averaging for smoothing the backscattered signal. Statistical analysis and experimental results suggest that the accuracy of the estimated attenuation coefficients using time averaging is very close to ensemble averaging. The choice of scanning steps for spatial averaging and window length for temporal averaging is critical to the effectiveness of the smoothing operation. The effectiveness of the averaging schemes is found to be less than 50% due to a high degree of correlation between successive measurements. Experimental studies were performed using steel samples and it was found that the estimated

attenuation coefficients is position-dependent such that its value decreases as the ultrasonic beam penetrates the specimen.

Signal processing techniques in frequency domain based on existing signal theories for characterizing the behavior of backscattered signals have been examined. In particular, the spectral shift effects of backscattered grain signals is evaluated through moment analysis and homomorphic processing. The performance of homomorphic processing technique is limited by the random nature of the backscattered signals. The power spectrum centroids of the ultrasonic wavelet can be extracted from random backscattered signals by using the homomorphic processing technique with less than 2% error. Different short-pass lifters essential in homomorphic wavelet recovery system are evaluated, and the criterion for the best achievable performance is discussed. As an alternative method, linear predictive analysis is used for spectral smoothing and for extracting features from the random grain signals. A third-order linear predictive model is used to describe grain signals with different center frequencies. Parameters of the linear predictive model (autoregressive coefficients) have been used as a feature vector for the pattern recognition and classification of grain signals. When the frequency difference is more than 0.5 MHz (10% of center frequency), the probability of correct classification is found to be as much as 90%.

CHAPTER I

INTRODUCTION

The research reported in this thesis is concerned with applying various signal processing techniques to analyze ultrasonic grain signals. The intent of the research is to extract information contained in the broadband grain signal, which consists of multiple interfering echoes with random amplitude and phase corresponding to highly complex grain structures. The specified goal of this thesis is the development of a pattern recognition system that utilizes the inherent properties of grain signal such as the attenuation coefficient and frequency shift phenomenon. This thesis presents the development and analysis for grain size estimation using ultrasound with the above stated goal in mind.

1.1 Importance of Grains in Materials

During the transition of a vapor, solution, or melt into a solid state, a crystal forms when a seed is present [1] †. The grains may form by crystallization from the melt or by recrystallization during heat treatment, as in metal, or they may be brought together by pressure and sintering, as in ceramic. Most solids are polycrystalline in nature because nucleation occurs at many points; that is, many grains are formed during the solidification process, and as the solidification rate varies, the grain size will be varied. A typical grain photo micrograph is shown in Figure 1.1. As shown in this figure, these grains in general are of various shapes and sizes, filling all space within the boundaries of the medium.

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† Numbers in brackets refer to numbered references in the bibliography.

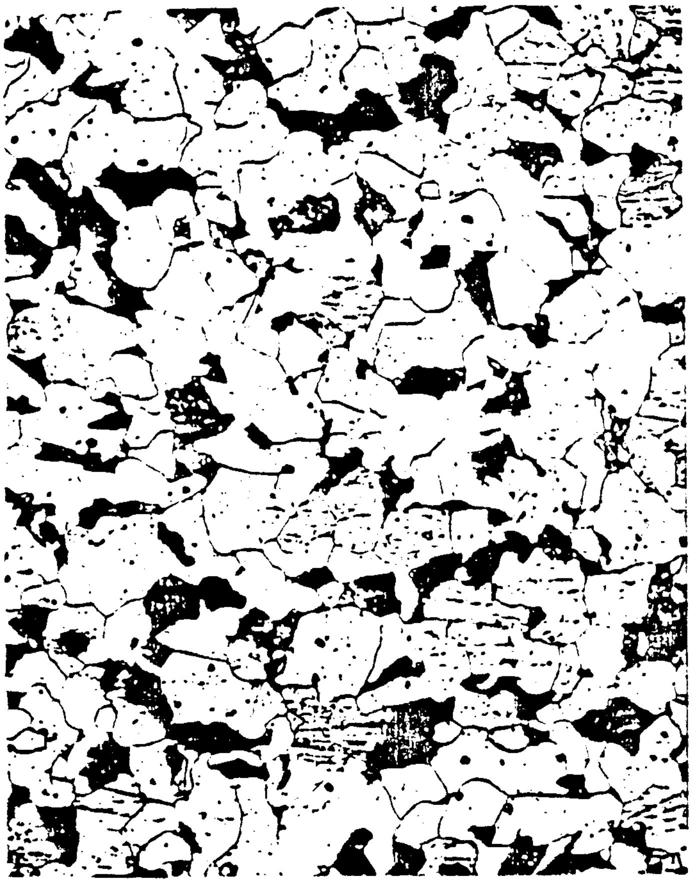


Figure 1.1. Photomicrograph of Steel Showing the Grain Structure (Magnification 400). Heat Treatment Condition: Open Fire Anneal at 1600^oF for Four Hours after the Stable Temperature had been Achieved. Then, Remove from Furnace and Air Cool Sample.

Many of the properties inherent in materials are closely related to the grain size (D), grain shape (elongated, flattened, equiaxed or mixture), grain orientation (random or preferred), quality of grain boundaries (presence or absence of voids or inclusion), and proportion of chemical constituents [2]. For example, the creep rate of equiaxed fine grained "MgO" at high temperatures and low stresses is proportional to D^{-2} [1]. Hence, a large grain size would be desirable to reduce the creep rate. On the other hand, because the fracture stress of many polycrystalline materials, which are brittle, is proportional to $D^{\frac{-1}{2}}$, we might desire a small grain size for certain purposes. The magnetic properties of the materials can also be affected by the variation of grain size; one example [3] is that the magnetomechanical acoustic emission (MAE) and the magnetic Barkausen effect noise for nickel samples are decreased with an increasing grain size. Orientation of the grain can also be very important since many properties of single crystals are highly anisotropic. In another words, even when only a single type of crystal is presented, the materials may still be inhomogeneous if the grains are randomly oriented. The boundaries between the grains reveal regions of imperfect crystallinity and are the weakest area of the structure which makes them susceptible to chemical attack and etching.

1.2 Ultrasonic Grain Size Characterization

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 the fabrication of metal and ceramic parts, has been long recognized. Among the various methods for microstructure (i.e., grain) evaluation of materials, the utilization of the ultrasonic backscattered signal has been proven to be a simple and efficient method of nondestructive testing. Two major ultrasonic microstructure evaluation techniques have been proposed in recent years and have met with reasonable success [4, 5, 6]: 1) techniques based on attenuation measurements, and 2) techniques based on scattering measurements.

In polycrystalline materials, the attenuation of an ultrasonic wave is primarily caused by scattering from the grain boundaries. The backscattered pressure field at the measurement position is the superposition of the pressure field from all scatterers [7]. The signal originating from the scatterers at location $\vec{r_i}$ depends on a set of transfer functions. First, the ultrasonic impulse that reaches the scatterer is the result of an impulse delta voltage applied to the transducer. On its way to $\vec{r_i}$ the ultrasonic impulse undergoes a change due to the absorption and the scattering of the medium. Both effects depend on the location of the scatterer $\vec{r_i}$, path of propagation, and the frequency. The sound wave impulse is then scattered according to certain functions between the wave frequency and the size of the scatterer. A typical example of a backscattered signal is shown in Figure 1.2. This measurement of the signal was accomplished by using a Gamma type transducer manufactured by K-B Aerotech with approximately a 5 MHz center frequency and 3-dB bandwidth of approximately 1.5 MHz. The signal, which was sampled at 100 MHz with 8-bits of resolution, has the duration of about $20\mu s$, representing the scattering characteristics in the region between 0.40 to 2.75 inches from the front surface of the steel sample. As shown in this figure, this signal consists of interfering multiple echoes with random amplitudes and phases, which correspond to a highly complex grain pattern.

When an ultrasonic burst of sound travels through an inhomogeneous material, its amplitude is attenuated as a function of the frequency and position. In general, the attenuation is caused by hysteresis loss (absorption loss), which is a true loss created by the inelastic behavior of the materials, and scattering loss

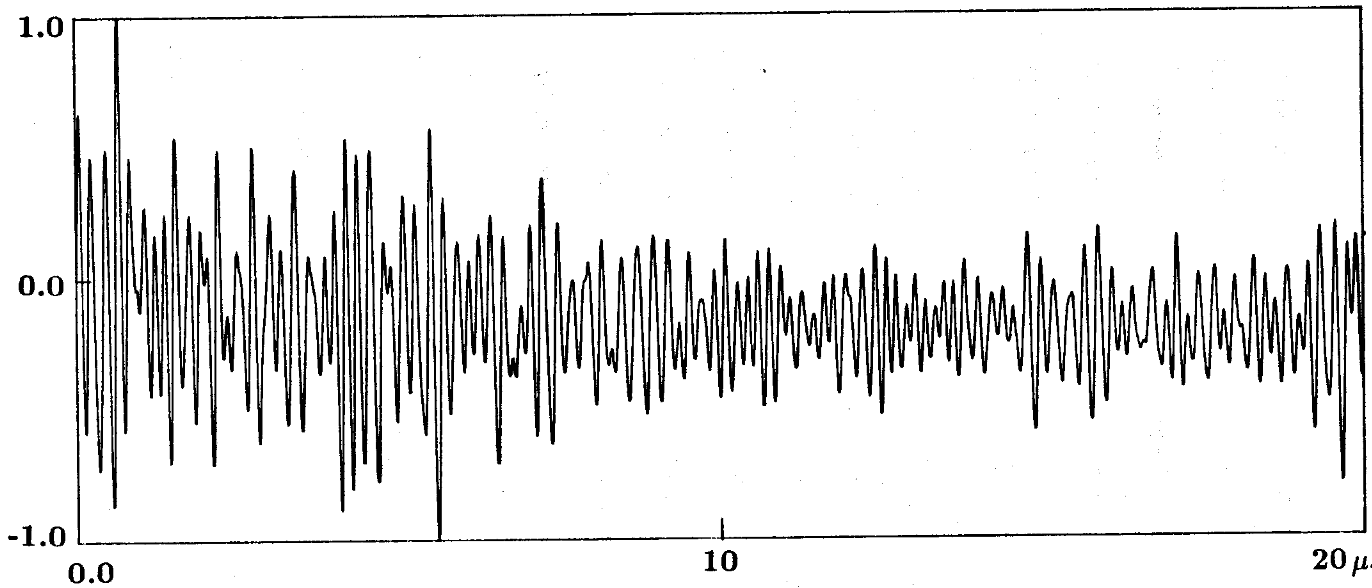


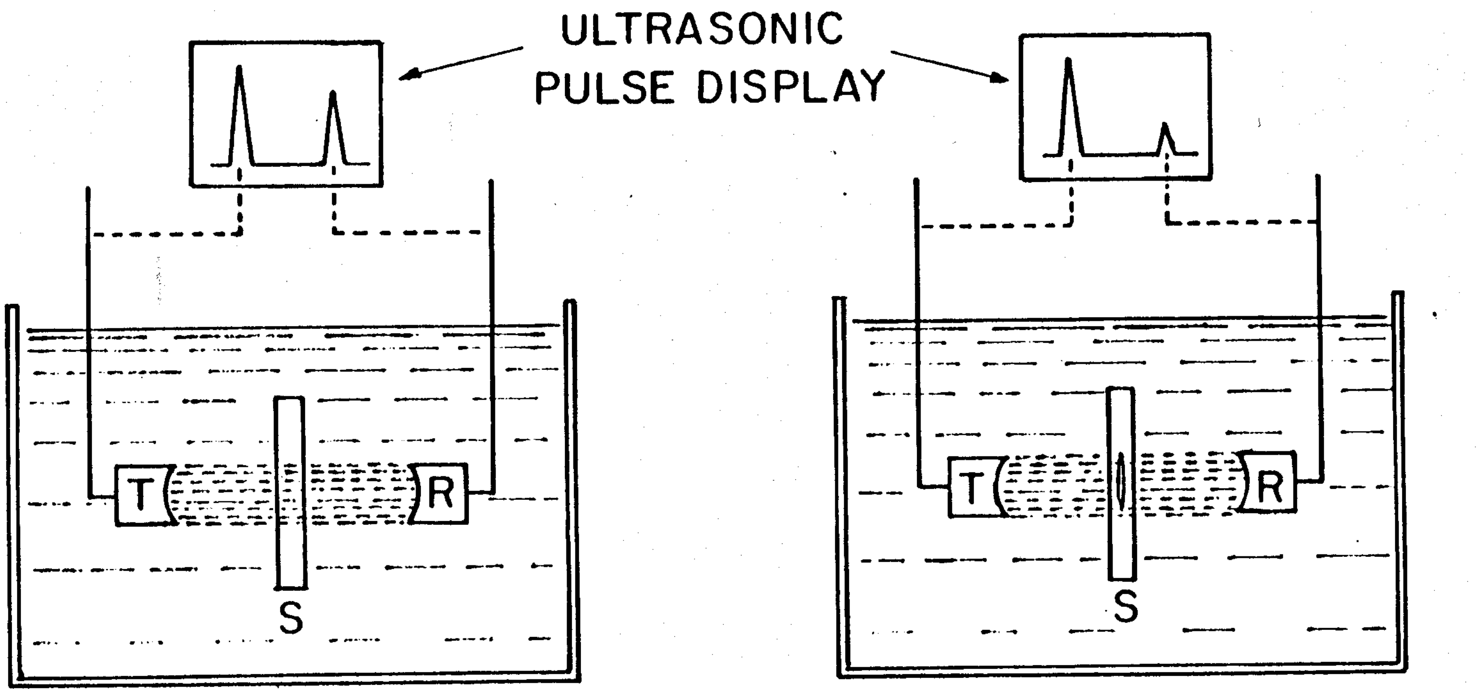
Figure 1.2. The Backscattered Grain Signal of the Specimen with Average Grain Size of $50\mu m$, Measured by Using 5 MHz Aero-tech Gamma Transducer

associated with the characteristics of the grain and phase boundaries (acoustic impedance discontinuities). Usually, grain scattering at ultrasonic frequencies is so large relative to the hysteresis loss that the latter can be ignored.

Common ultrasonic microstructure evaluation is based on a comparison of attenuation measurements of specimens with unknown grain sizes to specimens with known grain sizes. This is accomplished either by direct wave transmission using two transducers, or by pulsing the oscillator and measuring the amplitude of the echoes as they return from the far end of the specimen to the single transducer as shown in Figure 1.3 and Figure 1.4.

Microstructure evaluation techniques based on ultrasonic attenuation measurements have some practical limitations [8,9]: i) perfect coupling between the transducer and the sample is difficult, ii) a flat and parallel surface is required in order to avoid complex corrections, and iii) since the attenuation coefficient represents an average value over the total sound path, local variation can greatly alter the attenuation coefficient and can not be effectively evaluated.

An alternate method of evaluating the grain size can be achieved by using the measurements of the backscattered signal. This method is based on the principle that an ultrasonic wave travelling through a medium is subject to scattering and absorption losses. Therefore, characterizing the backscattered signal amplitude yields information related to the average grain size of the specimen. By utilizing various averaging techniques (spatial, directional and frequency), one can enhance the SNR ratio and quantitatively obtain the attenuation coefficient. In general, grain size characterization using backscattered signals requires significant computing time and memory storage and it may necessitate the correction for diffractive and refractive losses. In spite of these limitations, the analysis and processing of



T- TRANSMITTING TRANSDUCER
R- RECEIVING TRANSDUCER
S- SPECIMEN

Figure 1.3. Ultrasonic through Transmission Method

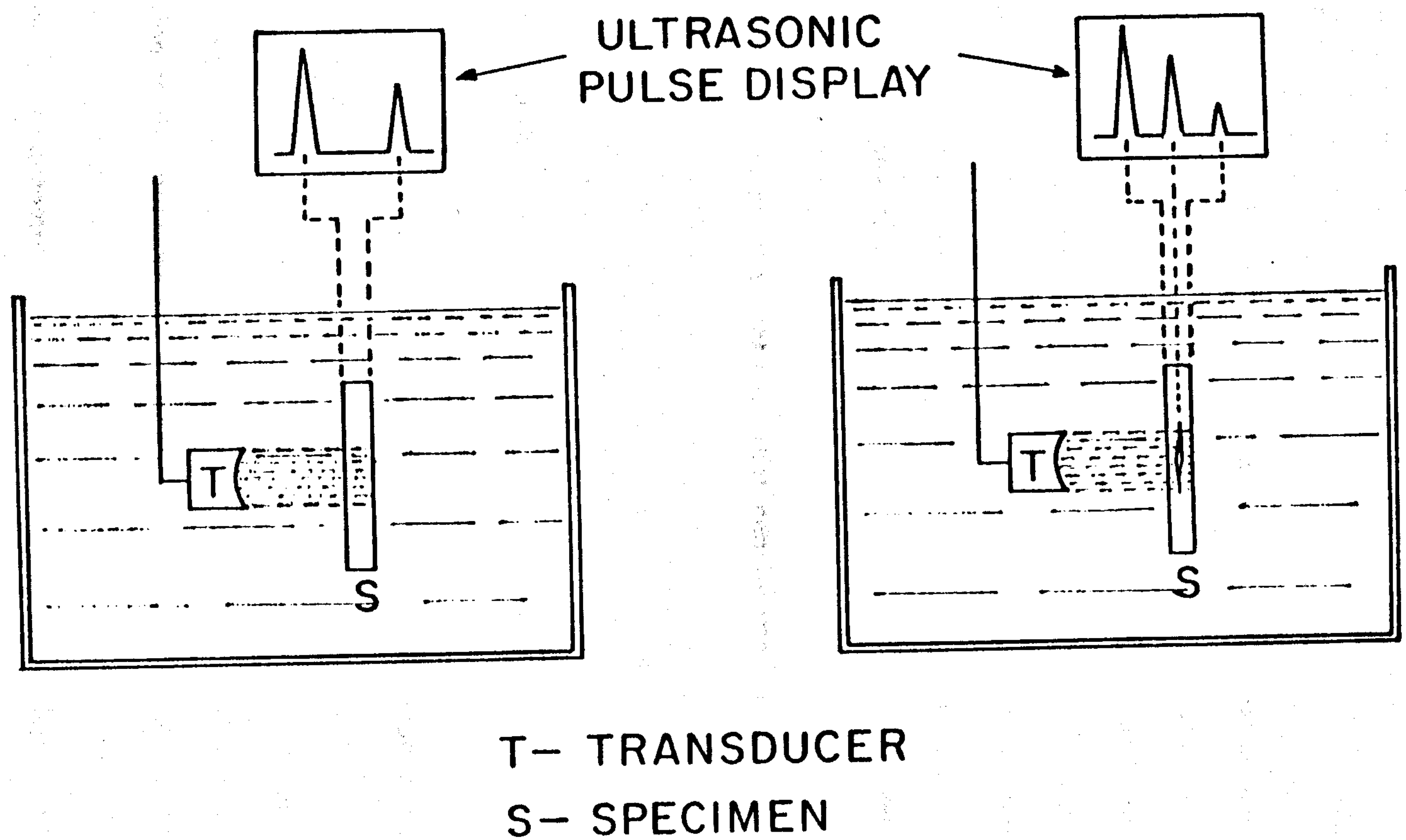


Figure 1.4. Ultrasonic Pulse Echo Method

the backscattered signal is potentially useful in assessing grain size distribution and the degree of inhomogeneity in the materials.

1.3 Brief Introduction to the Research

This thesis is an investigation of the application of signal processing techniques, building upon previous work, and introducing the performance evaluation and a new grain signal processing approach – spectral shift – with sufficient mathematical analysis and experimental results to demonstrate the feasibility of time and ensemble averaging as well as the spectral shift approach. Understanding the grain signature will enable us not only to classify grains but also to detect flaw echoes which can be severely masked by the presence of grain echoes. An efficient method of estimating grain parameters will result in the formation of diagnostic feature vectors (i.e., grain signatures) that can be used for the design of grain classifiers and classification.

The performance evaluation of time and ensemble averaging was based on the assumption that the grain signal is attenuated as the time proceeds, and the multiple scattering and absorption are neglected. The backscattered grain signal is represented by a mathematical model based on the ultrasonic wavelet and grain characteristic function. The expected value of the grain signal was found to be related to the attenuation coefficient and the attenuation coefficients were related to the position of the ultrasonic wave traveling path. The position-dependent attenuation coefficients were extracted by averaging techniques, and the measurements efficiency was evaluated though the information criterion. The grain size identification was accomplished by comparing the position-dependent attenuation coefficients obtained through choosing the suitable window for curves fitting processing. The possible causes for position-dependent attenuation coefficients were also discussed. The variance of the averaged signal as well as the correlation effects related to the measurement efficiency were examined in details through the experimental measurements and signal processing procedure.

The spectral shift analysis was based on the fact that the ultrasonic wave traveling through solids is subject to energy loss due to scattering and absorption. In the Rayleigh scattering region, both scattering and absorption are functions of frequency and grain size distribution. The grain scattering results in an upward shift in the expected frequency of a broadband ultrasonic wave, while the attenuation effect influences the frequency shift in a downward direction. These opposing phenomena can be utilized for grain size evaluation. In this investigation, the spectral shift quantization technique using homomorphic processing and moment analysis was examined. Computer simulation and experimental results obtained from the steel samples with different grain sizes support the feasibility of using a spectral quantization technique for estimating grain size.

1.4 Thesis Outline

Beginning in the late 1940's, extensive studies have been carried out and reported on concerning grain signal analysis. Chapter II provides a survey of the available literature with an emphasis focused on work concerned with the analysis of ultrasonic backscattered grain signals.

In order to provide suitable samples for experiments, the sample selection and preparation works are reported in Chapter III. In this chapter, the type of steel samples and heat treatment conditions are selected based on the literature suggestions. The intercept grain size estimation method from micrographs and the instruments used in this investigation are also introduced.