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Keywords
Shear waves, Sound penetration

Disciplines
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Relationship Between Near-Surface Ultrasonic Shear-Wave Backscatter and Grain Size in Metals

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INTRODUCTION

Microstructurally induced ultrasonic backscatter can be used to infer details about the microstructure of the material being inspected. Past work has been done to study what microstructural information can be gathered from backscatter data, as well as looking at what effects various microstructural features have on the measured backscattered response. Much of the early work on this topic is discussed by Goebbel[1]. More recently, work has been done to relate backscatter to grain size[2], texture[3], elongation[4], and duplex microstructures where lamellar spacing is a key parameter[5].

Part of our current research is directed at deducing grain size versus depth profiles from an analysis of depth dependent backscatter[6]. That work, like many ultrasonic backscatter measurements, uses an immersion inspection setup with the transducer normal to the specimen surface. Normal incidence inspections have a sizable front-wall ringdown interval which masks the backscattered grain noise, creating a dead zone near the surface of the sample as seen in the left side of Fig. 1. Previous work has shown a method for measuring near-surface backscatter using Rayleigh waves[7]. This work will demonstrate a method of measuring the near-surface grain noise using an immersion angle-beam setup to generate 45-degree shear waves in the sample. This greatly reduces the signal from the front wall since most of the energy will be specularly reflected away from the transducer. An example is shown in the right side of Fig. 1. The measured backscattered noise level can then be correlated to grain size, which will allow for the estimation of grain size using the ratio of backscatter from a calibration specimen to a test specimen.

This paper will first discuss the samples used to demonstrate the method, followed by the measurement of the shear wave velocity in the samples. Methods to determine the front wall location, termed the zero-of-time, will be discussed. Measurements and analyses of backscatter will then be presented, followed by a study on the sensitivity of the measurements to errors in the incident angle.
FIGURE 1. Left: Example of a normal incidence backscattered grain noise waveform with a large front wall response present.
Right: Example of angle-beam shear wave grain noise. No appreciable front wall response is seen.

SPECIMEN PROCUREMENT

Three nickel alloy specimens provided by Pratt & Whitney were used for this work. These samples had equiaxed grains and varying grain sizes which, for this work, will be termed "small" (S), "medium" (M), and "large" (L). These samples can be seen along with an example of a typical microstructure in Fig. 2. Grain sizes were measured using standard optical metallographic techniques but will not be revealed here. Very roughly speaking, average grain diameters were approximately in the ratio of 1:2:3 for the three specimens, respectively.

FIGURE 2. Nickel alloy specimens used for near-surface backscatter measurement and an example of a typical microstructure.

SHEAR WAVE VELOCITY MEASUREMENTS

The velocity of the shear waves is an important parameter for setting the inspection angle in water as well as for relating the arrival time of a signal to its corresponding depth in the sample. Two normal-incidence contact shear wave transducers (2.25 MHz and 5 MHz) were used to measure the arrival times of multiple back wall reverberations. A small amount of anisotropy was seen in the samples, so velocities were measured in both the "slow" and "fast" polarization directions, which roughly aligned with the hoop (slow) and radial (fast) directions of the forgings from which the samples were cut.

FIGURE 3. Signal showing multiple back wall reverberations. The arrival time of each echo, given by the major zero crossing, is used in velocity calculations. The arrival times of each echo at the major zero crossing are plotted against the wave travel distance for that echo. A line is fit to the points, and the slope is the velocity estimate.
For each measurement the contact transducer was rotated to locate the polarization directions for which the slowest and fastest traveling shear waves were seen, and these directions were used for subsequent signal acquisition and velocity measurements. To measure velocity on a given sample in a given polarization direction, a signal with multiple back wall reverberations was acquired as shown in Fig. 3. The arrival time of the major zero crossing of each back wall reverberation is then plotted against the corresponding distance the wave has traveled, known using the thickness of the sample. The major zero crossing is defined as the point at which the signal voltage crosses zero between the minimum and maximum voltage points of the back wall echo. A line is fit to the arrival time versus travel distance data, and the slope is the estimate of velocity, \( c_s \). An example is shown in Fig. 3. The velocity results for all three samples in both polarization directions can be seen in Fig. 4. All measured velocities were within 0.4% of the mean value of 0.3212 cm/\( \mu \)s, and this mean value was used when setting the transducer tilt angle in water for all subsequent backscatter measurements.

**FIGURE 4.** Measured shear wave velocities. Average velocity is 0.3212 cm/\( \mu \)s.

**DETERMINATION OF THE ZERO-OF-TIME**

Without a clear front wall signal present it becomes necessary to use other means to determine where the front wall signal would be. To quantify this, a parameter termed the zero-of-time, or \( t_0 \), must be introduced. The zero-of-time is defined as the arrival time of an echo from a small scatterer located at the intersection of the central ray of the ultrasonic beam and the specimen surface. Knowledge of the zero-of-time allows time of arrival to be related to penetration depth in the sample. Two methods for the determination of the zero-of-time will be demonstrated: the ball bearing method and the corner trap method. For both of these methods, the following initial steps are performed:

- Measure the longitudinal wave velocity in the water and the shear wave velocity in the specimen.
- Level the specimen with respect to the transducer lateral scanning directions (x and y).
- Normalize the transducer to the specimen surface.
- Calculate, using Snell’s Law, the appropriate angle in water to achieve 45 degree shear waves in the specimen.
- Tilt the transducer to the now-calculated angle. For our measurements the tilt angle in water was about 19.1 degrees.

The first method for the determination of the zero-of-time uses a ball bearing of known diameter placed onto the specimen surface. The transducer, having been tilted to the appropriate angle as described above, is then roughly aimed at the ball bearing. A small 2-D x-y raster scan of the transducer parallel to the specimen surface is then performed. An amplitude C-scan can be used to locate the point where the ball bearing signal is the largest, which occurs when the transducer is directly aimed at the ball bearing. The arrival time from the ball bearing signal, along with simple geometry, can be used to determine the zero-of-time. The equations needed are shown in the right-hand portion of Fig. 6.

Instead of a ball bearing, a rectangular block can be placed on the specimen to create a corner trap. A 2-D x-y scan can be performed as in the ball bearing case and the peak signal seen will be seen when the transducer is aimed directly at the corner trap. The arrival time of the center of this corner trap signal is taken to be the zero-of-time. Both methods are illustrated in Fig. 5.
FIGURE 5. Two methods for \( t_0 \) determination. Experimental setup and corresponding C-scans used to find peak signals are shown for both the ball bearing and corner trap methods.

For both methods, ensuring that the ball bearing or corner trap is located in (or around) the far field zone of a planar transducer (or the focal zone of a focused transducer) tends to yield better results. For one test case using a 10 MHz planar transducer, a comparison of the different zero-of-time determination methods is shown in Table 1. There the two waterpaths were roughly 4.4 cm and 8 cm respectively for the near and far field measurements. For the corner-trap "askew" measurement the rectangular block was intentionally misaligned by rotating it in the plane of the specimen surface.
### BACKSCATTERED GRAIN NOISE MEASUREMENT

To acquire backscattered grain noise data two transducers were chosen: a 0.25 inch diameter 10 MHz planar probe, and a 3/8 inch diameter 10 MHz focused probe with a 3 inch nominal focal length. Three measurement setups were used to collect data:

- Planar transducer with a 2 cm water path such that the specimen surface was in the far field.
- Planar transducer with a 7 cm water path such that the specimen surface was in the near field.
- Focused transducer focused on the specimen surface (water path = 8.25 cm).

For all three setups the transducer was scanned over a 0.6”x0.6” area of the specimen surface collecting waveforms, denoted \(V_j(t)\), at \(j = 1, 2, ..., M\) different locations, where \(M=900\) for these measurements. This data was then processed in both the time and frequency domains. A waveform example can be seen in the left side of Fig. 7. For time-domain processing, at each time increment the squares of the responses at all spatial locations are averaged and the square root is taken, resulting in what is termed the RMS noise voltage, or \(V_{rms}\). This is calculated as

\[
V_{rms}(t) = \left[ \frac{1}{M} \sum_{j=1}^{M} (V_j(t) - V_{avg}(t))^2 \right]^{1/2},
\]

where \(V_{avg}\) is given by the simple average

\[
V_{avg} = \frac{1}{M} \sum_{j=1}^{M} V_j(t).
\]

An example of a \(V_{rms}\) curve is shown in the right of Fig. 7.

For the case when the planar transducer is close to the specimen surface a persistent front wall signal can be seen. An estimate of this signal is given by \(V_{avg}\) which is subtracted from each waveform during the \(V_{rms}\) calculation. Figure 8 shows an example waveform on the left in which the persistent front wall signal can be seen. On the right of Fig. 8 is the \(V_{avg}\) calculated using Eq. 2 which again shows that the front wall signal is the largest feature present.
The waveforms can also be analyzed in the frequency domain by computing the FFT of each signal after removal of the persistent front wall signal, $V_{\text{avg}}$, to obtain the spectral components $\Gamma_j(f)$. Before computing the FFT the raw waveforms are windowed in time using a Gaussian envelope centered at some chosen depth in the specimen using the previously determined $t_0$. Here we chose that central depth to be 0.032 inches or 0.08 cm. A raw waveform with the Gaussian envelope overlaid can be seen in the left of Fig. 9. Note that the Gaussian envelope is scaled within the plot for clarity; it actually has a peak amplitude of one. The resulting windowed grain noise waveform can be seen in the center of Fig. 9. The FFT of this windowed noise yields the spectrum for this waveform, $\Gamma_j(f)$. Using all $\Gamma_j(f)$, a spatial average is performed at each frequency to obtain the RMS spectral amplitude $|\Gamma_{\text{rms}}(f)|$ defined as

$$|\Gamma_{\text{rms}}(f)| = \left[ \frac{1}{M} \sum_{j=1}^{M} |\Gamma_j(f)|^2 \right]^{1/2}; \Gamma_j = \text{spectra of } V_j(t) - V_{\text{avg}}(t) \text{ after windowing.} \quad (3)$$

An example of an RMS noise spectrum is shown on the right side of Fig. 9.

**FIGURE 9.** Frequency domain data processing. Left: Grain noise waveform with Gaussian envelope. Center: Windowed grain noise signal. Right: RMS noise spectrum $|\Gamma_{\text{rms}}|$. This example uses the planar transducer and a 7 cm water path.

**Backscatter Noise Level and Sonic Field Shape**

**FIGURE 10.** $V_{\text{rms}}$ curve of Fig. 7 with Gaussian envelope used for FFT computations. Vertical lines denote, from left to right, times at which the beam first enters the sample, the central ray enters the sample ($t_0$), and the full beam has entered the sample.

Figure 10 displays the $V_{\text{rms}}(t)$ curve of Fig. 7 together with the Gaussian envelope function and three vertical lines which denote specific events regarding the beam impinging on the specimen surface. There the beam is modeled...
as a multi-Gaussian beam with width taken to be twice the full width at half of the maximum of the incident sonic pressure field. The left line corresponds to the time at which the ultrasonic beam first enters the sample. The center line is the zero-of-time, the point at which the central ray of the beam intersects with the specimen surface. The right line is the time at which the entire beam, per our definition, has entered the sample.

For this planar transducer case, one sees that the backscattered noise level rises until about time $t_b$, and then approximately plateaus. Beyond time $t_b$ there is a slow drop of the grain noise level with time due to beam spread and attenuation effects.

**BACKSCATTER RESULTS**

Figures 11, 12, and 13 summarize the time and frequency domain results for all three specimens for each of the three experimental setups used. Figure 11 shows the results for the planar transducer at the 7 cm water path, Fig. 12 shows the results for the planar transducer at the 2 cm water path, and Fig. 13 shows the results for the focused transducer with a 8.25 cm water path corresponding to being focused on the specimen surface. Notice in the left panel of Fig. 12 that the residual front wall signal still makes its presence known near 26 microseconds, even after our subtraction procedure of Eq. 1. However, no similar artifacts appear in Figs. 11 and 13.

**FIGURE 11.** Time and frequency domain results for the planar transducer at a 7 cm water path.

**FIGURE 12.** Time and frequency domain results for the planar transducer at a 2 cm water path.

**FIGURE 13.** Time and frequency domain results for the focused transducer at a 8.25 cm water path (focused on the specimen surface).
For each experimental setup and sample Fig. 14 shows the maximum of each \( V_{rms} \) curve at the center of the Gaussian envelope (on the left) from above on the left and the RMS spectral amplitude at the 10 MHz nominal center frequency \( |\Gamma_{rms}(f = 10MHz)| \) (on the right). These represent measures of backscattered grain noise for a narrow near-surface zone centered 0.08 cm below the entry surface. Figure 14 concisely shows that for any given experimental setup there is a direct correlation between the grain size and both the time and frequency domain noise characteristics.

**SENSITIVITY TO ERRORS IN TILT ANGLE**

Sample L was re-inspected with intentional shifts of plus/minus one degree in water to test the sensitivity to small angle changes. The results of this intentional misalignment can be seen in Fig. 15 for one case. The left side of Fig. 15 shows the as-calculated \( V_{rms} \) curves for each tilt angle, and the differing arrival times that occur due to the changes in water path. To more easily compare the amplitudes of these signals, they were shifted such that they would have the same arrival time. This is shown in the right side of Fig. 15. The effects on the amplitude and shape of the \( V_{rms} \) curve is very small and would not affect the correlations we saw in the previous results. It is thus concluded that this method is robust to small errors in alignment angle.

**SUMMARY AND CONCLUSIONS**

- The relationship between grain size and backscattered microstructural noise in the near-surface regions of metal specimens using 45 degree shear waves has been investigated.
- Both planar and focused transducers were used, and measurements were made on three Ni-alloy specimens having significantly different grain sizes (as inferred from micrographs).
- To relate signal arrival time to sound penetration depth a zero-of-time parameter, \( t_0 \), is needed. \( t_0 \) denotes the arrival time of scatter from a grain located on the metal surface and directly along the transducer’s central ray.
- Two methods for determining \( t_0 \) were explored which make use of ball bearing and corner trap echoes, respectively. The two methods gave similar estimates for \( t_0 \).
- It is speculated that it may also be possible to estimate \( t_0 \) directly from the shape of the backscatter-versus-time profile.
- Given the zero-of-time, backscattered noise from the near-surface zone can be identified, gated, and distilled to extract spatially-averaged time and frequency domain noise characteristics.
• These distilled noise attributes were each found to be well correlated with grain size for the three Ni-alloy specimens studied.
• The measurements were found to be relatively insensitive to transducer angulation errors. Intentional misalignment by one degree had little effect on measured backscatter attributes or on the degree of correlation with grain size.
• The specimen sound entry surfaces used here were polished (for optical metallography). New experiments are planned to investigate the effect of typical machined surface finishes on backscatter characteristics and grain sizing.

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