Evaluation of Ultrasonic Attenuation and Estimation of Ultrasonic Grain Noise in Copper

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Abstract. This paper presents a method for evaluating ultrasonic attenuation and estimating ultrasonic grain noise in solids. The method is aimed at evaluation of various grades of copper used during manufacturing canisters for spent nuclear fuel. The spectral shift method has been employed for the evaluation of attenuation, and the independent scattering model (ISM), proposed by Margetan et al. (1), has been used for the estimation of ultrasonic backscattering in immersion test. The attenuation coefficients evaluated for a number of copper specimens covering a certain range of grain sizes and having large attenuation have shown a clear correlation between the grain size in specimens and the attenuation. The comparison of the root-mean-square (RMS) of grain noise signals from the specimens determined from the measurements with those predicted by the ISM has shown that the ISM is a good estimator of the grain noise signals, especially in the shallow regions of the specimens.

INTRODUCTION

One of our research projects is concerned with ultrasonic detecting and imaging defects in copper canisters for long term storage of spent nuclear fuel (2). Before we have developed ultrasonic imaging technique we had to investigate attenuation and scattering in copper. Scattering and attenuation vary with the properties of materials and therefore both (and also ultrasound velocity which, however, is not considered here) have been employed to characterize the microstructure of metals. Grains in a polycrystalline metal act as irresolvable scatterers that produce coherent interference appearing as grain noise in ultrasonic A-scan and B-scan signals. Grain noise, although undesired in defect detection, is an useful signal containing the information related to the microstructure of materials (3).

A big body of literature on the subject of material characterization by making use of ultrasonic attenuation and scattering is available. Ultrasonic attenuation and scattering in polycrystalline materials have been investigated both experimentally and theoretically (4, 5). Since the advent of pulse-echo technique, ultrasonic backscattering has been employed for predicting grain noise related to material’s properties.

In the present work, ultrasonic attenuation and scattering are investigated theoretically and experimentally in application to copper. First, attenuation for three copper samples is evaluated using spectral shift method applied to reflection echoes. Secondly, grain noise is evaluated using the independent scattering model (ISM).
Finally, we demonstrate a clear correlation between samples microstructure and their attenuation and scattering.

EVALUATING ATTENUATION IN POLYCRYSTALLINE METALS

For the frequencies used for defect detection in most cases the attenuation in a polycrystalline metal is determined almost entirely by scattering from grains (4). To evaluate ultrasonic attenuation in copper, we will use the spectral shift method which had been presented in Ref. (6). The method uses as inputs the echoes from the front and back surfaces of the immersed metal. Assume Gaussian input pulse $p_i(t)$ with power spectrum $P_i(f)$ and center frequency $f_i$. After passing through a medium with linear frequency dependent attenuation $\alpha(f)$, the observed output pulse $p_o(t)$ will be also Gaussian. Its power spectrum $P_o(f)$ with center frequency $f_o$ can be expressed as, $P_o(f) = |H(f)|^2 P_i(f)$, where $|H(f)|^2 = \exp[-\alpha(f)2D]$ is the power transfer function, and $2D$ is the path length through which the pulse $p_i(t)$ propagates. In spectral shift method the attenuation coefficient $\alpha(f)$ is obtained by using an appropriate way to determine the central frequencies of the input and output signals, $f_i$ and $f_o$, and the bandwidth of the input signal, $B$, that is,

$$\alpha(f) = \frac{(2\pi)^2}{B^2} \frac{f_i - f_o}{2D}$$

(1)

Attenuation in three copper specimens was evaluated for three copper specimens from High Profile Ultrasonics Ltd., England (see Table 1).

<table>
<thead>
<tr>
<th>No</th>
<th>Specimen reference</th>
<th>Origin</th>
<th>Thickness (mm)</th>
<th>Nominal grain size (microns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>SE 1550</td>
<td>TWI-OUTOKOMPU</td>
<td>36</td>
<td>250-350</td>
</tr>
<tr>
<td>1</td>
<td>SE 1593</td>
<td>TWI-REVERE</td>
<td>41.5</td>
<td>175-200</td>
</tr>
<tr>
<td>2</td>
<td>SE 1603</td>
<td>TWI-MKMK</td>
<td>40.2</td>
<td>125-175</td>
</tr>
</tbody>
</table>

Measurements were carried out using 1” focused transducer V307 from Panametrics, 191.1-mm focal length (measured), and 5.35-MHz central frequency (measured). The measurements were made in immersion configuration. Considering the effect of diffraction (not the correction of diffraction) on the evaluation of attenuation, the water path was set 130 mm. This made the focal zone located around the middle depth in the inspected specimens. The transducer was scanned in the $x$-$y$ plane and a large number of A-scans (2880 to 3500) were acquired for each specimen. The A-scans were digitized with sampling frequency 100 MHz and resolution 8 bits. Attenuation in copper was large that front surface and back surface could not be recorded simultaneously with the resolution of 8 bit and therefore the front and the back echoes were recorded in separate measurements using different amplifier gains (c.f. columns 3 and 5 in Table 2).

Before calculating attenuation using the recorded data, we checked the peak amplitudes of the front echoes and the back echoes in all A-scans for each case. The
distributions of the peak amplitudes were apparently different. Analyzing standard deviations for each specimen listed in Table 2 we see that the deviation of the peak amplitudes of the back echoes are much larger that those of the of front echoes. This indicates that all the specimens are inhomogeneous and therefore the attenuation should be evaluated based on a large set of A-scans. We used all the acquired A-scans from each specimen to estimate mean attenuation. First, we estimated the spectra of front and back echoes using FFT. Secondly, we fit Gaussian to the obtained amplitude spectra. Finally, we determined center frequencies and bandwidths from the Gaussians and calculated the attenuation coefficients from Equation (1) (see Table 2). Due to the inhomogeneity of the specimens, the attenuation coefficients obtained from different A-scans fluctuated about the mean value in a certain range. We can see a clear correlation between the specimens grain size (Table 1) and their attenuation, the bigger the grain size the higher the attenuation.

<table>
<thead>
<tr>
<th>No</th>
<th>Thickness (mm)</th>
<th>Front echoes Gain (dB) &amp; amplitude</th>
<th>Back echoes Gain (dB) &amp; amplitude</th>
<th>Attenuation (dB/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>36</td>
<td>8</td>
<td>43</td>
<td>48.86 ±0.045</td>
</tr>
<tr>
<td>1</td>
<td>41.5</td>
<td>9</td>
<td>48</td>
<td>78.43 ±0.0279</td>
</tr>
<tr>
<td>2</td>
<td>40.2</td>
<td>8</td>
<td>48</td>
<td>85.78 ±0.0279</td>
</tr>
</tbody>
</table>

**EVALUATING ULTRASONIC GRAIN NOISE IN POLYCRYSTALLINE METALS**

Since ultrasonic grain noise from a metal contains an useful information about the microstructure of a material (3), this information can be very helpful during detecting defects in materials with unknown (varying) microstructure. The ultrasonic grain noise, although temporally stable, is spatially random and therefore, its properties are estimated statistically in space. Typical ultrasonic measures of grains (scatterers), called material parameters, can be scatterer number density, scatterers' mean size, and scatterers' mean spacing. A number of models predicting the grain noise (7), (8) have been proposed. Here we use the model proposed by Margetan et al (1) for predicting RMS of grain noise signals.

Denote the root-mean-square of zero mean grain noise as $n(t)$ and normalize it by dividing by the peak amplitude of the reference signal $E_{max}$. $N(t) = n(t)/E_{max}$. The ISM predicts normalized grain noise rms $N(t)$. Let us consider an experiment shown in Figure 1 where water paths $Z_{0R}$ for the reference signal and $Z_{0S}$ for the noise measurement are measured outward from the transducer face along the central ray direction and the coordinates for the points in the metal are measured for the intersection of the central ray and the water/solid interface (see Fig. 1). The front-surface echo $V_{ref}(t)$ is used as a reference signal and the voltage signal due to scattering by a single grain located at position $(x, y, z)$ is denoted by $\delta S(t, x, y, z)$.
Assuming $\tilde{V}_{\text{ref}}(\omega)$ and $\delta S(x,y,z;\omega)$ to be the Fourier transform of $V_{\text{ref}}(t)$ and $\delta S(t,x,y,z)$, respectively, we have

$$
\tilde{V}_{\text{ref}}(\omega) = \beta R_{00} D(\omega) \exp(-j2k_0 z_{0R} - 2\alpha_0 z_{0R})
$$

(2)

$$
\delta S(\omega,x,y,z) = \left\{ \frac{2\beta A(\omega,x,y,z) \rho c_1}{jk_0^2 a^2 \rho_0 c_0} \right\} \mathcal{F}^{-1} \left\{ C^2(\omega,x,y,z) \exp\left[ -j2(k_0 z_{0S} + k_1 z) - 2\alpha_0 z_{0S} - 2\alpha_1 z \right]\right\}
$$

(3)

where $c$, $k = \omega/c$, $\rho$, $\alpha$, and $a$ denote longitudinal wave velocity, wave number, density, attenuation coefficient, and transducer radius, respectively, with subscripts 0 and 1 referring to water and metal. $\beta$ is the transducer efficiency, defined as the ratio of the outgoing ultrasonic power to the incident electric power in the transducer cable.

$R_{00}$ and $T_{01}$ are the reflection and transmission coefficients for plane wave velocity fields propagating in the central-ray direction $A(\omega,x,y,z)$ is the amplitude of the backscattered sound from the single grain under consideration. $C(\omega,x,y,z)$ is a measure of ultrasonic field strength in the metal; if the velocity on the transducer face is $V_0 \exp(j\omega t)$, then $V_0 C(\omega,x,y,z) \exp[j\omega t - j2(k_0 z_{0S} + k_1 z)]$ is the velocity at point $(x,y,z)$ that would exist in the absence of attenuation and interface transmission losses.

![Diagram](image)

**FIGURE 1.** Setup for (a) reference signal acquisition and (b) noise measurement.

$D(\omega)$, which accounts for the effects of diffraction losses in the reference signal, is defined as the integral of the reflected velocity field over the equilibrium location of the transducer face, divided by $\pi a^2 V_0 \exp[j(\omega t - 2k_0 z_{0R})]$, again in the absence of other losses. In addition to the explicit dependence on frequency, $C(\omega,x,y,z)$ and $D(\omega)$ depend on the transducer characteristics ($a$ and $F$), water path, and sound speeds. The reference signal in Equation (2) is used for eliminating $\beta$.

Assuming that the total noise signal $S(t,x,y,z)$ is an incoherent superposition of noise signals backscattered by the individual grains of the metal (i.e., only single-scattering events is considered explicitly), and that the attenuation of the beam with depth will be treated through an effective attenuation constant, we have

$$
\frac{\sqrt{\langle S^2(\omega) \rangle}}{V_{\text{ref}}(\omega)} = n^{1/2} |\overline{A}(\omega)| \frac{2T_{00}^2 \rho_1 v_1 \exp[-2\alpha_0 (z_{0S} - z_{0R})]}{R_{00} a^2 \rho_0 v_1 |D(\omega)| k_1} \left[ \int_0^\infty P \exp(-4\alpha z) dz \int |\mathcal{F}^{-1} \{ C(\omega,x,y,z) \}^4 | dxdy \right]^{1/2}
$$

(4)

where $n$ is the volume density of grains, and $\overline{A}(\omega)$ is an averaged grain backscatter amplitude at frequency $\omega$. The normalized rms grain noise is directly proportional to $n^{1/2} |\overline{A}(\omega)|$, which is called figure of merit (FOM) for noise severity.
EXPERIMENTAL EVALUATION OF GRAIN NOISE

The three copper specimens were inspected using the same experimental setup as for attenuation measurement, and grain noise from the specimens were evaluated by means of the ISM. The gains used for measuring the reference signals and the grain noise signals are listed in Table 3. The rms of the grain noise signal from the three specimens were calculated, and the results are shown in Figure 2.

![Graph](image)

**FIGURE 2.** Comparison of (a) measured results and of (b) predicted results in copper specimens 4, 1, and 2.

The results predicted using Equation (4) are shown for comparison in Figure 2. From the measured results and the model, the FOMs for the specimen were obtained and listed in Table 3. Comparison of the measured and the predicted results indicates that the ISM gives good prediction in the shallow parts of copper specimens (the early time portions of signals), but shows gradual deviation as the depth increases. The reason for this can be (i) that the ISM was established for a narrow band signal, and (ii) that the ISM was established based on such an approximation that is expected to be valid for the early time portion of the signal when the main beam has not been significantly attenuated. From the values of FOM in Table 3, we can conclude that the
larger the grains, the bigger the FOM. Therefore, FOM can be an appropriate parameter used for depicting noise severity.

<table>
<thead>
<tr>
<th>Specimen No</th>
<th>Gain for reference signal (dB)</th>
<th>Gain for grain noise signal (dB)</th>
<th>Figure of merit (FOM, $1/\text{mm}^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2</td>
<td>56</td>
<td>0.43</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>56</td>
<td>0.37</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>57</td>
<td>0.33</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

Attenuation and grain noise in solid materials have been investigated theoretically and experimentally. Spectral shift method used for the evaluation of attenuation yielded a stable estimation of attenuation when the echoes from front and back surfaces of a specimen were used. The study has shown that the larger the size of grains in copper the higher the acoustic attenuation in the copper.

Independent scattering model has been applied to estimate grain noise in three copper specimens with different grades. The results have shown that the model gives good prediction in the shallow regions of copper specimens (i.e., the early time portions of signals). This is reasonable because the approximation under which the model is established is expected to be valid for the early time portion of a signal when the main beam has not been significantly attenuated. The results have also demonstrated that the figure of merit FOM obtained from the ISM can be a good parameter used for depicting grain noise severity.

**REFERENCES**