SIMULTANEOUS MEASUREMENT OF GRAIN SIZE AND SHAPE FROM ULTRASONIC BACKSCATTERING MEASUREMENTS MADE FROM A SINGLE SURFACE

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ABSTRACT. Ultrasonic techniques for the characterization of grain size have been investigated for over two decades, including important practical applications. Generally, however, these make the assumptions that the grains are equi-axed. In this paper, we consider the more general case in which the grains are elongated. Inversion procedures are presented to infer the geometrical parameters of the grains from various combinations of attenuation and backscattering data. To provide a theoretical foundation, an expression is presented relating the ultrasonic backscattering coefficient to the geometrical parameters of the grains for shear incidence waves and its experimental verification is reported. This complements previously reported theories for backscattering and attenuation of longitudinal waves. Measurement results are presented which demonstrate the effectiveness of these new sizing approaches on a set of aluminum samples that were rolled as either rods or plates. One of the techniques has the major practical advantage that all data (backscattering) can be taken from the single side of a sample with no requirements for a parallel back surface.

INTRODUCTION

The characterization of the microstructure of materials is an important NDE application, with a primary motivation being the control of mechanical properties. Ultrasonic measurements have a long history of application in this area based on the dependence of both attenuation and backscattering on grain size [1-3]. Early approaches were based on a direct measurement of attenuation, an application restricted to parts with parallel surfaces [1,2]. The desire for a technique for single sided measurements on parts of complex geometry led to a backscattering approach [3]. However, the objective remained to infer grain size from attenuation, with the latter being inferred from the rate of decay of the backscattered noise. Most recently, Good has used the time dependence of the backscattered noise to gain information about microstructural changes, for example those associated with hardening processes [4].

All of these techniques have produced valuable results in appropriate application areas. However, to the knowledge of the authors, the primary applications have been to microstructures in which the grains are equi-axed. It can be speculated that this is a direct
consequence of the fact that only a single parameter is inferred from the measurements, e.g. the attenuation. Obviously, one parameter can only provide information about a single attribute of the microstructure, e.g. grain size. In this work, we seek new techniques that can provide information on both grain size and shape.

The motivation for our approach was a series of measurements reported in a previous volume of this series [5]. Measurements of attenuation and backscattering were reported on a set of aluminum samples with elongated grains produced by rod and plate rolling. It was observed that, whereas the backscattering was highly anisotropic as expected, the attenuation varied only slightly with direction. In the concluding remarks, it was suggested that a better understanding of these effects could lead to improved techniques for microstructural characterization. Further discussion of the initial observations has been provided by Thompson [6].

In this paper, we will describe three methods that were examined with the objective of the simultaneous determination of grain size and shape. The initial motivation was to take advantage of this fundamental difference in the dependence of attenuation and backscattering on grain parameters. After a brief review of the sample characteristics, the three methods will be described. The first two were motivated by gaining an increased understanding of the underlying measurement principles and impose restrictions on the sample geometry. The final technique utilized only data that could be obtained from one surface without the availability of a second, parallel surface.

SAMPLES

The aluminum alloy samples, including micrographs, have been previously described [5,6]. Table 1 lists the average grain dimensions, as inferred from an analysis of micrographs. Two samples had “cigar-shaped” grains, with an elongation of more that 10:1. The other two had “pancake-shaped” grains, also with an aspect ratio of more that 10:1. In both cases, the defects were ellipsoidal rather than spheroidal, i.e. there was no axis of rotational symmetry.

THEORY

A theoretical description of the effects of grain elongation on attenuation and backscattering is a key element of our approaches. Description of those theories is beyond the scope of this paper. The starting points are theories initially reported by Stanke and Kino for attenuation [7] and Rose for backscattering [8] for equi-axed grains. Extensions to elongated grains and other complex microstructures include contributions by Ahmed, Han and Panetta, and references to those works may be found in [6]. The predictions of those theories have been found to be in semi-quantitative agreement with the previously reported measurements on the aluminum samples that are the subject of this study [5].

<table>
<thead>
<tr>
<th>Sample</th>
<th>1-axis (a)</th>
<th>2-axis (b)</th>
<th>3-axis (c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>52</td>
<td>45</td>
<td>539</td>
</tr>
<tr>
<td>T2</td>
<td>35</td>
<td>17</td>
<td>420</td>
</tr>
<tr>
<td>T3</td>
<td>170</td>
<td>60</td>
<td>17</td>
</tr>
<tr>
<td>T4</td>
<td>183</td>
<td>65</td>
<td>12</td>
</tr>
</tbody>
</table>

TABLE 1. Average grain dimensions (semi-axes) in microns.
METHOD A: SIMULTANEOUS MEASUREMENT OF ATTENUATION AND BACKSCATTERING

The basic idea in Method A is to measure both the attenuation and the absolute level of the backscattering, as quantified by a material property known as the backscattering coefficient, for waves propagating in a single direction, i.e., normal to a part surface. Grain size parameters in attenuation and backscattering models are then adjusted to optimize the agreement between experiment and theory. In our employment of the technique, we have assumed that a sample is available with two parallel surfaces. However, we note that the same information could be obtained with single-sided access if the attenuation were inferred from the rate of decay of the backscattered noise [3].

Figure 1 illustrates the basic idea. In this plot, the grains were assumed to have two of the three major axes (a,b,c) equal. The wave was assumed to propagate in the b direction and it was assumed that a = b for samples T1 and T2, and b = c for samples T3 and T4. The aspect ratio (b/c for T1 and T2, b/a for T3 and T4) would be small for samples T1 and T2 and larger for samples T3 and T4. Part (a) shows a plot of a theoretical prediction of attenuation, at a frequency of 7 MHz, as a function of grain volume and aspect ratio. It is interesting to note that, for the range of parameters examined, the attenuation is much more sensitive to grain volume than grain shape. Part (b) shows the comparable plot for the predicted backscattering coefficient, a material property that quantifies the capacity of the microstructure to generate noise. Techniques to infer the backscattering coefficient or its square root (FOM) from experimental data are discussed elsewhere [9]. It is interesting to note that the dependence of the backscattering on the two microstructural parameters is quite different than that of the attenuation, consistent with the previously reported experimental data. This suggests that a measurement of attenuation and backscattering on the same sample would provide a way to independently determine grain volume and aspect ratio. Part (c) illustrates this in a plot of grain volume versus aspect ratio. For a given value of either attenuation or backscattering alone, there is a family of {volume, aspect ratio} pairs, lying on a curved line, that could be responsible for that value of attenuation or backscattering. However, if attenuation and backscattering have both been measured, the grain volume and aspect ratio are uniquely defined by the intersection of these lines. It is interesting to note, that for the case illustrated, the two curves are nearly orthogonal, indicating that the two measurements have good leverage on the quantities of interest.

FIGURE 1. (continued)
FIGURE 1. Determination of grain size and shape from attenuation and backscattering data. (a) Attenuation versus grain volume and aspect ratio at 7 MHz. (b) Backscattering versus grain volume and aspect ratio at 7 MHz. (c) Illustration of determination of grain volume and aspect ratio from knowledge of attenuation and backscattering. (Units: Attenuation, Np/cm, backscattering, cm$^{-1}$, volume, $\mu$m$^3$.)

Figure 2 presents results of an experimental test of this idea. The previously measured values of the attenuation and backscattering served as inputs and the data was interpreted using the procedures illustrated in Figure 1. In this comparison, it had to be assumed that $a = b$ for the grains. There is good overall agreement between the predicted and observed values of the grain size parameters.

FIGURE 2. Comparison of ultrasonically predicted and actual grain sizes for all samples based on Method A.
METHOD B: MEASUREMENT OF BACKSCATTERING FOR WAVES PROPAGATING IN THREE ORTHOGONAL DIRECTIONS

Since the backscattering is more sensitive to the grain aspect ratio than is the attenuation, and since backscattering measurements do not require parallel surfaces, the possibility of recovering grain size and shape from backscattering measurements alone was examined. Figure 3 illustrates both Method B and Method C. In the former, the longitudinal wave backscattering is measured for waves propagating along three orthogonal directions. Although this is generally not possible in the laboratory, it provides a means of examining the leverage that backscattering has on the grain size and shape. For future reference, the configuration used in Method C is also shown. The backscattering is measured for longitudinal waves at normal incidence and for transverse waves at oblique incidence in two orthogonal planes.

To test Method B, an algorithm was written in which data propagating in the three orthogonal directions was compared to the theoretical predictions of the backscattering models [6,8]. The degree of agreement in a least squares sense was computed and the values of the grain size and shape, (a,b,c), were varied to obtain best fit. Figure 4 shows the results. Although there appear to be some systematic disagreements for the larger dimensions, there is generally good agreement.

METHOD C: SINGLE-SIDED MEASUREMENT OF BACKSCATTERING FOR NORMAL LONGITUDINAL AND OBLIQUE SHEAR WAVES

The basic strategy of Method C is sketched in the right hand side of Figure 3. To test this, a theory for the backscattering coefficient for transverse waves was developed, with the result (for cubic crystallites with randomly oriented principal axes)

\[
\eta(\omega) = \frac{3k^4(C_{11} - C_{12} - 2C_{44})^2}{175(4\pi\nu^2)} \int P(\xi) e^{\frac{ikd}{\xi}} d^3\xi
\]

(1)
where $\rho$ is the density, $v$ is the transverse wavespeed, $C_H$ are crystallite elastic constants, $k$ is the wavevector, and $P(s)$ is the probability that two randomly selected points, separated by a vector $s$, lie in the same grain. It is interesting to note that, for a given material and frequency, the predicted transverse wave backscattering is significantly larger than that for longitudinal waves. This is a result of two effects, the wavelength is shorter for transverse waves and hence closer to the grain size, and the elastic anisotropy, which is the physical cause for the backscattering, is greater for shear waves than for longitudinal waves.

Figure 5 shows a test of this theory against new measurements of the backscattering for transverse waves propagating at 45 degrees with respect to the sample normal. The 4-axis and 5-axis correspond, respectively, to propagation in the 1-2 plane and the 2-3 plane respectively (see Fig. 3). Measured grain size parameters were input to the model, and reasonably good agreement with experiment is observed with no adjustable model parameters.

As was done for Method B, an algorithm was written in which the backscattering data for longitudinal and transverse waves propagating in the various directions was compared to the theoretical predictions of the backscattering models. The degree of agreement in a least squares sense was computed and the values of the grain size and shape, $(a,b,c)$, were varied to obtain a best fit. Figure 6 shows the results, which are very similar to those obtained with Method B. Although there appear to be some systematic disagreements for the larger dimensions, there is generally good agreement. This is very encouraging since this data was obtained in a single-sided measurement and does not require a second, parallel surface. We note that for all three techniques we assumed the elastic constants of pure aluminum, and assumed that crystalline axes were randomly oriented.
CONCLUSIONS

Three methods for simultaneously determining grain size and shape were evaluated based on measurements on rolled rod and plate of an aluminum alloy. Each measurement scheme was shown to produce good results. Method A requires both attenuation and backscattering information for waves propagating in the same direction. Although our measurements were made in samples with parallel surfaces, this could be implemented from a single surface if the attenuation were inferred from the rate of decay of the backscattering.

Method B was not intended for practical application, but as a test of the leverage of backscattering data at multiple angles in gathering the needed size and shape information. The positive results led to the evaluation of Method C, which has the desired attributes of a single sided measurement without the requirement for a second, parallel surface.

These measurements, and variants that could be imagined, show great promise of extracting more information about grain size and shape than is commonly done. A key ingredient is a theoretical basis to interpret multiple measurements, in one sense a form of data fusion.

ACKNOWLEDGEMENTS

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FIGURE 6. Comparison of ultrasonically predicted and actual grain sizes for samples based on Method C.

REFERENCES