ACOUSTIC MICROSCOPY TO STUDY GRAIN STRUCTURE

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INTRODUCTION

The use of reflection acoustic microscopy with spherical lens for quantitative nondestructive evaluation has been studied in the past both from the experimental and theoretical point of view. The basic results have shown that the output of the microscope's transducer is sensitive to the near-surface material's elastic properties. Based on this, a variety of applications of the acoustic microscope to material science study have been developed [1]. Measurements of surface wave velocity and elastic constants in solids [2,3,4], detection and characterization of discontinuities of the elastic constants in solids due to cracks, interfaces, etc. [5], and measurements of dispersion relation for leaky Rayleigh wave in simple and layered systems [4,6] are a few examples of problems which can be investigated by means of the acoustic microscope.

This paper is concerned with the use of the reflection acoustic microscope for studying grain structure and grain interface in polycrystalline materials. We would like to show that acoustic microscopy with spherical lens, although mainly used for imaging purposes and less sensitive to material properties than microscopy with cylindrical lens, can be used to study grain structure and to detect grain boundary and grain boundary imperfections if it operates according to special techniques. We would also like to demonstrate the feasibility of experimental investigation by means of a broadband system which allows analysis of the transducer's output in the frequency domain.

MICROSCOPE TRANSDUCER SIGNAL ANALYSIS

The acoustic microscope is an imaging device which can be used for quantitative studies as well. When a spherical lens is used to focus the ultrasonic beam, the relationship between the output of the transducer, V, and the elastic material properties is given by Briggs [1]:

\[ V = \frac{2\pi}{\alpha} \int \int \int \cdot R(\theta, \phi) \cdot P(\theta) \cdot e^{ikz\cos^2\theta} \cdot \sin\theta \cdot d\theta \cdot d\phi \]  

(1)

where \( R(\theta, \phi) \) is the reflectivity function of the sample under investigation, \( P(\theta) \) is the pupil function of the spherical lens, the aperture of which is
characterized by the maximum angle $\alpha$, $z$ is the defocusing distance, and $k$ is the wave number of the ultrasonic wave in the couplant.

**Acoustic Microscopy in the Space Domain: $V(z)$ Curve**

Usually considered as a function of $z$, the modulus of $V$, named simply the $V(z)$ curve, presents periodic oscillations for negative defocuses as a major feature. Such oscillations arise from the interference between the specular reflected field and the field produced by the leaky Rayleigh waves excited at the liquid-solid interface. The period $\Delta z$ is given by Briggs [1]

$$\Delta z = \frac{1}{f} \frac{c}{2 - 2\cos\theta_R}$$

where $f$ is the frequency of the acoustic signal, $c$ is the phase velocity of the sound in the couplant and $\theta_R$ is the Rayleigh angle for that particular liquid-solid interface. Equation (2) allows us to calculate the phase velocity of the leaky Rayleigh wave once the periodicity $\Delta z$ has been obtained experimentally.

**Acoustic Microscopy in the Frequency Domain: $V(f)$ Curve**

Analyzing the output of the microscope's transducer as a function of the defocus distance $z$ is not the only way to obtain quantitative information about the sample under investigation. Equation (1) shows that the frequency, $f = \frac{ck}{2\pi}$, and $z$ play the same role, so that the $V = V(zf)$ function should actually be considered. In view of this, it is also possible to carry out the above analysis considering the output of the microscope's transducer as a function of the frequency alone: $V = V(f)$.

Performing an analysis at a fixed defocusing distance, while the working frequency is changed, presents some practical advantages. In fact, changing $z$ requires mechanical parts of the system to be displaced. This is usually a source of noise in the acoustic signal because of the mechanical vibrations generated by the scanning. Furthermore, changing $z$ produces a variation of the spot's dimensions under which the sample is investigated. Inhomogeneities may, therefore, be included in the inspection area while $z$ is changing, so that the transducer output can no longer characterize univocally the local properties of the surface.

Figure 1 illustrates an example of the $V(zf)$ curve from glass obtained by means of a broadband system operating in the range from 10 - 50 MHz. Such a two-dimensional representation of the transducer's output can be used as follows: Scanning the $V(zf)$ function at a fixed frequency along the vertical axis results in the already known $V(z)$ curve. Figure 2 shows an example of the experimental $V(z)$ curve from glass at 30 MHz, where the defocusing distance $z$ is changed from 0 mm to -1 mm. On the other hand, a section of the two-dimensional representation, taken at a fixed value of $z$, provides the transducer's output as a function of the frequency, i.e. $V = V(f)$. Figure 3 shows an example of the $V(f)$ curve from glass at $z = -1$ mm normalized to the transducer's response. The period of the oscillations, which characterize the behavior of the $V(f)$ curve, is related to the Rayleigh velocity through

$$\Delta f = \frac{1}{z} \frac{c}{2 - 2\cos\theta_R}$$

Equation (3) strongly resembles Eq. (2); the only difference is that the frequency $f$ and the defocus distance $z$ exchange their roles.

Discontinuities of the elastic properties of the sample occurring in the near-surface region can strongly affect the acoustic signal which
Fig. 1 $V(zf)$ curve from glass obtained with a broadband system.

Fig. 2 $V(z)$ curve from glass at a frequency $f = 30$ MHz.

Fig. 3 $V(f)$ curve from glass at a defocusing distance $z = -1$ mm.
excites the transducer. Thus, \( V(f) \), as well as \( V(z) \), provides a suitable means to study interfaces, cracks and other features which characterize the near-surface region of the sample.

**GRAIN STRUCTURE AND GRAIN BOUNDARY STUDY**

Equation (1) states that an acoustic microscope with a spherical lens provides a signal by summing the infinitesimal contributions over the azimuthal angle \( \phi \). Since an elemental portion of the surface is inspected in all directions simultaneously, the dependence of the elastic properties on the angle \( \phi \) can no longer be recovered and the characterization of the surface's structure may be based only on its average elastic properties. Thus, an acoustical image of a homogeneous surface is expected to appear with a uniform gray level, which changes according to the corresponding \( V(z) \) or \( V(f) \) curve.

Figures 4b and 4d show two images of a sample of polycrystalline titanium at different defocuses. They have been obtained operating with a narrow-band system at a frequency \( f = 1.6 \) GHz. It can be noticed that (1) different grains show up with different gray levels at a fixed \( z \), and (2) grain contrast changes as the defocus distance \( z \) changes. These phenomena can be explained qualitatively by recalling the schematic \( V(z) \) curves of

![Images](a, b, c, d)

**Fig. 4** Acoustic microscopic grain and grain boundary contrast at different defocuses in polycrystal titanium, (a) \( z = -3.2 \) mm; (b) \( z = -3.8 \) mm; (c) \( z = -4.2 \) mm; (d) \( z = -4.8 \) mm; frequency: \( f = 1.6 \) GHz.
Fig. 5. $V_1(z)$ and $V_2(z)$ may be related to two (adjacent) grains with arbitrary but different orientation. If the average near-surface elastic properties of the grains are different, so the shapes of $V_1(z)$ and $V_2(z)$ are. In particular, the periodicities of the oscillations of these curves may be different so that $V_1(z)$ turns out to be higher than $V_2(z)$ within some range of $z$, while this relation may be inverted within some other range. If $V_1(z)$ and $V_2(z)$ have different values at a given defocus $z$, then the corresponding images are characterized by different gray levels. Furthermore, if the order relationship between $V_1(z)$ and $V_2(z)$ is inverted, changing $z$, then the grain contrast is inverted too.

Figures 6b and 6d show the same effects when an aluminum-steel solid-state bond is imaged by means of a broadband system. Fixing the defocusing distance $z$ at -0.940 mm, the images were taken operating with the system

![Schematic V(z) curves from surfaces with different elastic properties.](image)

![Acoustic contrast from different materials and from their interface at different frequencies in aluminum-steel solid-state bond.](image)
tuned to 31.9 MHz and 35.8 MHz, respectively. The explanation of this behavior in the frequency domain follows the same reasoning outlined before, referring to the analysis in space domain. Figure 7, which illustrates the behavior of the experimental $V(f)$ curves at $z = -1.524$ mm for aluminum and steel, provides the equivalent of Fig. 5.

Another more interesting phenomenon is illustrated in Figs. 4a and 4c. Here the defocus distances are chosen in such a way that all the grains show up with approximately the same gray level. Under this condition, the boundaries between grains become visible with positive or negative contrast.

A qualitative explanation of this phenomenon needs to refer to Fig. 5 again. The gray levels of two adjacent grains are close to each other at a given defocus $z$ if the corresponding $V(z)$ curves have about the same value for that $z$. Let us assume this value to be lower than the average defined by the $V(z)$ curve of the specular reflected component alone. This implies that when the lens' axis is away from the boundary, destructive interference occurs between the specular reflected component and the component radiated by the leaky Rayleigh waves from both the surfaces. When the lens' axis is above the discontinuity, scattering reduces the amplitude of the field component due to the leaky Rayleigh waves and may change its phase as well. Therefore, the effect of the interference is modified and the boundary shows up to be brighter than the adjacent grains.

In addition, it can be noticed that boundaries with different elastic properties scatter the incident leaky Rayleigh waves in different ways. Different elastic properties may, therefore, result in different grain boundary contrast.

As with the grain contrast, the grain boundary contrast is expected to change with the defocus distance $z$. This is shown by comparison between the two images in Figs. 4a and 4c.

Figures 6a and 6c illustrate that the same effects can be brought out in the frequency domain as well. Here the values of the frequency must be carefully selected in order to make grain boundaries visible. In this particular case, where $z = -0.940$ mm, the selected frequencies were 30.0 MHz and 34.3 MHz, respectively.

Fig. 7 $V(f)$ curve for aluminum and steel at the defocusing distance, $z = -1.524$ mm.
CONCLUSIONS

It has been shown that acoustic microscopy with spherical lens is an appropriate technique to investigate the surface and near-surface structure and elastic properties of a sample. In particular, (1) grain structures are observed to be different to the extent that they have different average elastic properties, and (2) discontinuities in the elastic properties occurring in the near-surface region can be detected and characterized according to their scattering properties.

Furthermore, a new experimental approach, which allows investigations to be carried out in the frequency domain and therefore avoids practical problems due to mechanical scanning, has been presented.

In order to complete a quantitative analysis of the experimental data provided by the acoustic microscope, further theoretical studies must be carried out. In particular, an analysis of the scattering of the surface waves by the interface-like discontinuities and its influence on the signal detected by the microscope's transducer is required for a quantitative interpretation of the experimental data.

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REFERENCES