NOVEL THERMAL-ACOUSTIC POINT TRANSDUCER

Curtis Fiedler, Pramode Bhagat
Materials Directorate, Wright Laboratories
Wright-Patterson AFB
Dayton, Ohio 45433-6533

John Murphy
Center for NDE/Applied Physics Lab
Laurel, MD

INTRODUCTION

The Air Force has a continuing need to develop materials which can withstand high temperatures and stresses. The quality of the grain boundaries, i.e. the ability of the grain boundary to resist slip, is one of the most important factors in determining how well a material will resist creep and high stresses. While there are techniques which can image grain boundaries (ultrasonic microscopy and scanning electron microscopy of etched specimens), there is no known method to assess their quality. Thus there is a need to develop a technique to measure the quality of grain boundaries.

Thermal-Acoustic microscopy (TAM) has been shown to be able to image grain boundaries[1]. The contrast mechanisms for this imaging are not established but the role of local elastic response near the boundary, the thermal properties of the boundary region, and the heat deposition profile in the sample all have been shown to play a role. It is this sensitivity to the grain boundary structure that is of special interest in the development of new materials which can withstand high temperatures and stresses. Some of the issues of interest include the role of dislocations which may cause local variations in thermal and mechanical properties near the grain boundary. The goal of this research is, therefore, to determine the contrast mechanism which makes grain boundaries visible in TAM images. Since TAM may be sensitive to the state of stress at a grain boundary, we may have a technique which will allow us to assess its quality.

The thermal-acoustic (TA) effect occurs because of the thermoelastic expansion of the material which is heated by thermal waves. Thermal waves are generated when a specimen is heated using a chopped heating beam (Figure 1). A small region of the specimen is heated, the size of the region being dependant upon the chopping frequency, focusing of the heating beam, and the thermal properties of

Review of Progress in Quantitative Nondestructive Evaluation, Vol. 12
Edited by D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1993

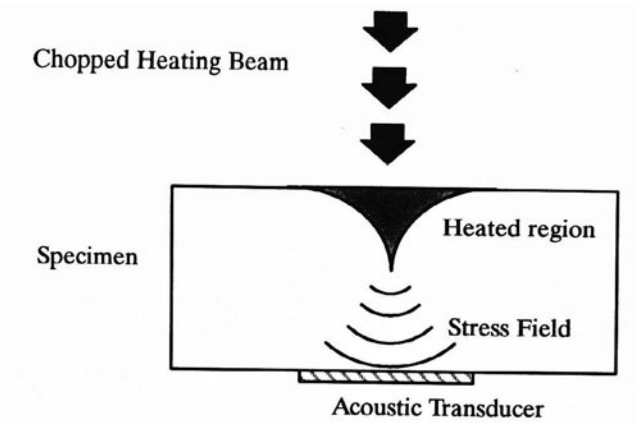

Figure 1. Thermal–Acoustic Effect.

the specimen. The heated region attempts to expand due to thermal–elastic expansion, but since it is constrained by the rest of the specimen, it generates a stress field instead. This stress field can be detected on the back surface of the specimen using a piezoelectric detector.

The major aim of our research is to characterize the TA effect, by first developing a full three dimensional theory which predicts the magnitude and phase of TA stress field at all points across the back surface of the specimen. This theory should be general enough to handle variations in either thermal or elastic properties. We will then measure the TA stress field using the high spatial resolution point transducer we have developed, and use this to verify the three dimensional theory. Verification of this theory will provide us with a relationship between the state of stress in a material and the TA image. We will then apply this relationship to the TA images to determine the quality of the grain boundaries.

THEORY

While eventually we wish to describe the TA effect using a full three dimensional theory, currently we have developed a one dimensional theory to provide some basis for our initial experiments. This theory starts with the one dimensional thermal diffusion equation (1).

$$\kappa\frac{\partial^2 T}{\partial z^2} - \varrho C\frac{\partial T}{\partial t} = -Q \tag{1}$$

where

T = Temperature rise over ambient temperature
t = Time
z = Distance from the top (heated) surface
κ = Thermal Conductivity
ρ = Density
C = Specific Heat
Q = Time Harmonic point heat source

ω = Circular frequency
δ = Spatial Dirac delta
$Q = Q_0 \; e^{i\omega t} \; \delta(z)$

We transform this equation using both spatial (z,γ) and temporal (t,s) Fourier transforms, and solve for T to get equation (2).

$$T = \frac{Q_0}{k} \frac{\delta(s + \omega)}{(\gamma^2 + \frac{is}{k})} \qquad (2)$$

where

$$k = \frac{\kappa}{\varrho C}$$

Transforming back to the time and space domains, T can be expressed as:

$$T = \frac{Q_0}{2\lambda} \sqrt{\frac{k}{i\omega}} \; e^{-\sqrt{\frac{i\omega}{\kappa}}|z|-i\omega t} \qquad (3)$$

To get the initial stress distribution, *u(z,t)*, we assume a linear thermal expansion:

$$u(z,t) = aB\frac{Q_0}{2\lambda} \sqrt{\frac{k}{i\omega}} e^{-\sqrt{\frac{i\omega}{\kappa}}|z|-i\omega t} \qquad (4)$$

where
α = linear coefficient of thermal expansion
B = bulk modulus

The frequency dependance of equation (4) agrees with previous derivations of the one dimensional theory of thermal waves, such as the theory of Murphy,Ammodt and Spicer [2]. We hope to extend this analysis to three dimensions, allowing for spatial variations in thermal properties in the sample.

EXPERIMENT

We use a point transducer to measure the TA stress field at the back surface of the specimen. The point transducer (shown in figure 2) is similar to the conventional large area transducer in that it uses a 1 cm square piece of 110 μm thick poly-vinylidene flouride (PVDF) as the active element. In the point transducer, however, the metallization is removed from the bottom surface of the PVDF. Because of the mechanical and electrical properties of PVDF, the active area of the transducer is now the area of the electrode which is in contact with the back surface of the PVDF. Since this is just the cross sectional area of the wire, and we are using a small diameter wire, this is essentially a point receiver.

To measure the stress field, we want to scan this transducer across the stress field. Since the transducer is clamped between the specimen and the plexiglass with the electrode, this is not easy to do. For an isotropic and homogeneous specimen, scanning the transducer relative to the laser beam is equivalent to scanning

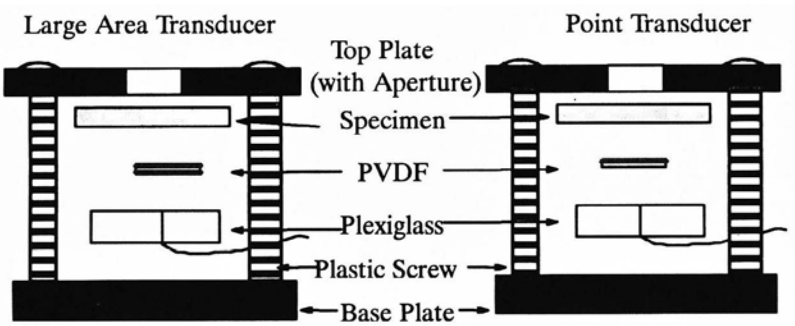

Figure 2. Conventional large area and point TA transducers (Exploded view).

the laser beam relative to the transducer. Since the latter is easier to realize experimentally, this is what we do.

We use a 3.5 watt Argon–ion laser, chopped with an acousto–optic modulator, as our heat source. The laser beam is scanned across the surface of the specimen with two mirrors mounted on galvanometers. The laser beam is focussed using a 50 mm focal length lens which is placed before the galvanometric scanners. A lock–in amplifier is used to measure both the magnitude and phase of the signal from the transducer.

EXPERIMENTAL RESULTS

The frequency dependance of the TA effect can be measured experimentally using the point transducer. Figure 3 shows that for a 1.27 mm thick specimen, we see the classic 1/frequency dependance for frequencies above 100 Hz [3]. At frequencies below 100 Hz the heat has time to propagate through the specimen, and we detect this because the PVDF is not only sensitive to stress, but to temperature rise also.

We can also hold the chopping frequency constant, and scan the laser beam across the specimen. Figures 4 and 5 show the phase and magnitude scans for 20 Hz, 200 Hz and 2 kHz for an aluminum specimen 1.27 mm thick. At 20 Hz the thermal diffusion length is the same order of magnitude as the specimen thickness, so we see a signal which is primarily thermal in nature. At 200 Hz the thermal diffusion length is 0.3 mm, and at 2kHz the thermal diffusion length is 0.1 mm which is smaller than the specimen thickness, so we are definitely in the thermal acoustic regime.

CONCLUSIONS

We have shown that we can map the nature of the thermal–acoustic stress wave using our new PVDF based point transducer. Figures 4 and 5 demonstrate that this transducer has a high signal to noise ratio.

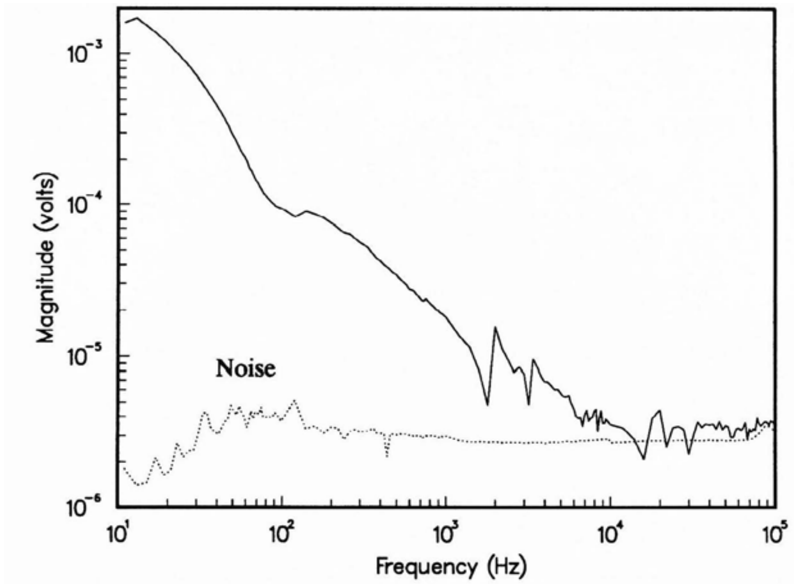

Figure 3. Thermal–Acoustic signal as a function of frequency for a 1.27 mm thick aluminum specimen.

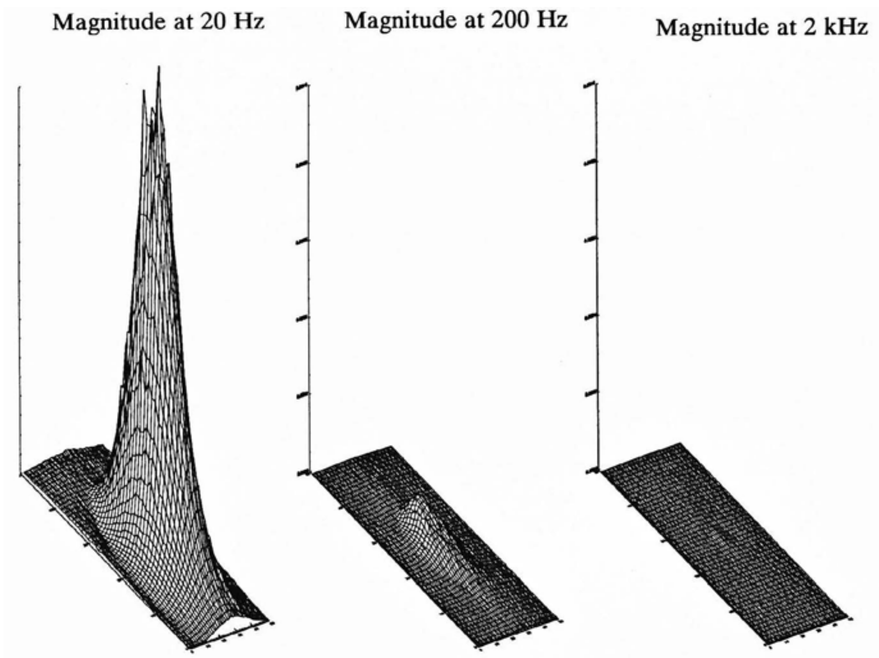

Figure 4. Magnitude plots for the 1.27 mm thick aluminum specimen.

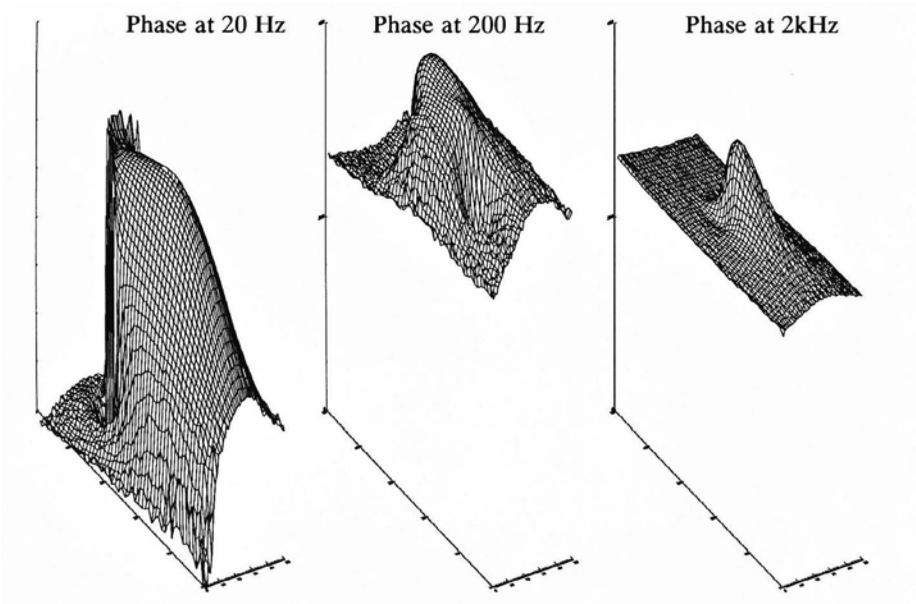

Figure 5. Phase plots for the 1.27 mm thick aluminum specimen.

FUTURE WORK

We will expand the one dimensional theory of the TA effect to describe the three dimensional case. We will initially assume that the problem is radially symmetric, and use a cylindrical coordinate system and Hankel transforms. We will then develop the the shape of the stress field, and compare it to the data shown in figures 4 and 5.

Concurrently with the above, we will also fabricate specimens with large (1–2 mm average diameter) grains. These specimens will be used to test the theory on grain boundaries.

REFERENCES

1 J.W.M. Spicer *Contrast Mechanisms in Thermal Wave Imaging* Ph.D dissertation, Johns Hopkins University, 1987.
2. J.C. Murphy, L.C. Aamodt, and J.W.M. Spicer in *Principles and Perspectives in Photothermal and Photoacoustic Phenomena*, edited by A. Mandelis (Elsevier Press, New York 1992 p43–92.
3. A. Rosencwaig *Photoacoustics and Photoacoustic Spectroscopy* (John Wiley and Sons, New York 1980) p135.