ION-ACOUSTIC IMAGING OF SURFACE FLAWS IN ALUMINUM

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INTRODUCTION

Imaging methods based on specimen excitation by scanned laser and electron beams are now well established as nondestructive methods of characterizing materials properties and locating surface and near subsurface flaws in solids. Several classes of methods have been identified each distinguished by the method of generation or the means of detection. Examples include Optical Beam Deflection (OBD) imaging [1,2], Scanned Photoacoustic imaging [3] and a variety of scanned laser and electron beam acoustic imaging techniques [4,5,6] which use attached piezoelectric transducers to monitor stress generated within the specimen. Because many of these methods monitor changes in specimen temperature or a parameter related to specimen temperature, these imaging methods have been broadly termed thermal wave imaging (TWI). Nonthermal image contrast mechanisms may exist in cases where specific beam-specimen interactions are present. The term TWI is therefore a convenient but inaccurate way of categorizing scanned image methods using modulated beams.

In this paper we describe the use of modulated ion beams [7] as excitation sources for TWI. Indeed one of the effects of ion beam-specimen interaction is local generation of heat much in the manner of laser or electron beams. The images observed in this regime with ion excitation are similar to those obtained with either electron or laser sources. These studies of ion beam images using thermoelastic (TE) detection with a PZT transducer have shown that the observed image contrast has distinct thermal and elastic components. These results have been confirmed using laser and electron beam sources. This resolves a controversy which had existed over the question of the origin of contrast in SEAM imaging.

Ion beams offer the prospect of nonthermal contrast processes related to beam-specimen interactions specific to individual ion sources. In this work we investigate the possible contribution of one such mechanism, particle momentum transfer, from heavy rare gas ion beams at energies in the 1 to 10 kV range. Note that reactive particle beams (e.g. $O_2^-$) can also be used. In such cases non-thermal image contrast characteristic of the reaction of the ions and local constituents of the specimen may be observed. As a third example for light ion beams such as $H^+$, the capture cross section as a function of incident energy has a large peak at a specific depth (the range). This feature, which does not exist for heavier ions, opens the prospect of depth profiling.
Figure 1 illustrates the wide variety of excitation and detection techniques applicable to TWI. The details of the images produced depend on the distinct group of physical parameters exploited by each detection technique, from purely thermal parameters in optical beam deflection measurements or IR radiometric measurements to a combination of thermal, thermoelastic and elastic parameters with optical interferometric or piezoelectric detection. Similarly, differences in thermal wave images might be expected for different excitation sources based on specific beam-specimen interactions. We compare use of ions, electrons and photons later in this paper.

**Fig. 1** Summary of thermal wave imaging detection methods.

Figure 2 depicts the experimental configuration used for ion imaging. The primary beam optics of a Secondary Ion Mass Spectrometer (SIMS) was modified to allow blanking of the primary beam using electrostatic deflection plates. The sample was mounted on a piezoelectric detector and the magnitude and phase of the detector voltage were measured with the lockin amplifier or a spectrum analyzer. In the present configuration line scans are generated by moving the sample in front of the ion beam. The net specimen current was measured simultaneously and used as a monitor of the beam energy deposited in the specimen at fixed primary beam voltage. In these experiments the primary beam voltage ranged from 1 to 10 kV, the beam currents from 0.3 to 14 uA and the modulation frequencies from 15 Hz to 20 kHz. The ion beam diameter was about 300 μm.

Companion electron-acoustic images (SEAM) were made for some of the specimens used for ion imaging using an ETEC Autoscan scanning electron microscope which had been modified to allow beam blanking. Laser acoustic and optical beam deflection images were also made of these same specimens using an argon laser as the excitation source. Here beam modulation was accomplished using an acousto-optic modulator. All specimens used for
comparative studies of different excitation beams used the same mounting of specimen and acoustic detector with no breakage of the specimen-detector bond. The beam diameters for the electron and laser experiments were about 0.1 \( \mu \text{m} \) and 5 \( \mu \text{m} \) respectively.

**ION-ACOUSTIC GENERATION PROCESSES**

The acoustic signal generated in a solid by a modulated beam of \( \text{Ar}^+ \) ions depends in general on the specific energy and momentum of each ion, on the ion flux and on the composition of the solid. In this paper the samples were an aluminum alloy, probably in the 2024 series. Specimen specific changes in acoustic signal generation have been observed for a number of other elemental samples but will not be discussed here.

Figure 3 shows the dependence of the magnitude of the acoustic signal on specimen current for fixed primary beam voltage at a modulation frequency of 2 kHz. The dependence is approximately linear with a mean slope of 0.96. Measurements taken at other frequencies in the range 15 Hz to 20 kHz also show the same mean -- linear dependence on beam current.

Figure 4 shows the corresponding dependence on primary beam voltage for constant beam current. In this case the observed slopes fall in a range around 0.85 as shown in the figure. Measurements at other frequencies yield slopes also clustered in the range around 0.85. The origin of this non-linear dependence of acoustic signal on the primary beam voltage has not been fully established. Complex ion-specimen interactions and sputtering processes are known to occur under our experimental conditions however. The data does suggest that a nonthermal mechanism contributes to the acoustic signal generation process. If the observations are viewed from an energy perspective, they suggest a weakly non-linear dependence on the specific energy of each incident ion with the non-linearity decreasing with increasing ion energy. While this suggestion is possible, it seems unlikely since most processes become increasingly non-linear as the level of excitation increases. An alternative explanation recognizes that the Ar ions possess momentum as well as energy (\( P_{\text{ar}} / P_e \approx 4 \times 10^6 \)) for beams of equal energy where \( P_{\text{ar}} \) is the momentum of an argon ion and \( P_e \) the momentum of an
Fig. 3 Signal magnitude dependence on primary beam current at various primary voltages: 2 kHz; Ar⁺ on Al.

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electron.) If acoustic generation via momentum transfer coexists with thermoelastic acoustic generation, then the slope of the dependence of acoustic signal on primary beam voltage should be less than 1 as observed. In the limiting case where only momentum transfer is present, the slope should be 0.5.

The data shows that the thermoelastic mechanism is the major source of signal (i.e., the slopes are closer to 1.0 than to 0.5). This result is confirmed by imaging studies described in the next section. It is however
inconsistent with the generally accepted theories of sputtering [8] where momentum transfer is approximately an order of magnitude more efficient than local thermal heating in producing sputtering. Further work is in progress in an effort to elucidate these dependences.

**IMAGING USING ION BEAMS**

These studies were conducted using aluminum disk samples 1.4 cm in diameter and 3 mm thick containing 1 mm holes drilled subsurface at various depths and locations. Figure 5 shows the sample/detector mount used in this work. The sample is mounted on a PZT detector with provision for measurement of specimen current.

![Diagram](image)

**Fig. 5 Schematic of sample and detection assembly showing simulated defect and method for simultaneous measurement of beam current.**

Figure 6 shows a series of line scans taken at varied frequencies on a specimen with two intersecting 1 mm holes buried at a depth $D = 0.5$ mm below the surface. Cross sectional views of the sample are shown in the inset to the figure. At low frequencies, where the ratio $\delta/D > 1$ with $\delta$ the one dimensional thermal diffusion length, the acoustic signal increases above each hole. When $\delta/D < 1$, the signal decreases above each hole. The contribution of each hole is resolved in the figure despite that for 15 Hz $\delta = 1.45$ mm approximately equal to the lateral spacing of the buried holes. This reflects the fact that the resolution is determined by the ion beam diameter not $\delta$ in this case.

Figure 7 is a set of scans taken at fixed modulation frequency on a slant hole specimen with a 1 mm hole drilled at an angle to the specimen surface. At fixed modulation frequency the epicentral depth of the hole below the beam may be varied by changing the location of the scan. When the depth $D$ is small, the signal increases above the hole. For larger $D$ a signal decrease above the hole center is seen. Alternatively, the modulation frequency may be varied at fixed scan position. Figure 8 shows the variation with frequency observed for the slant hole specimen for the $D = 0.30$ mm scan of Figure 7. Comparison of the line scans in Figs. 7, 8 shows an approximate $\omega^{-0.5}$ dependence for the transition between the two signal regimes. This result is consistent with diffusive thermal wave interaction with the buried hole in the $\delta/D > 1$ regime on the scale of the thermal diffusion length $\delta = [2a/\omega^{1/2}]^{1/2}$ where $a$ is the thermal diffusivity and $\omega$ the angular frequency. Conversely, the regime $\delta/D < 1$ cannot involve a direct contribution of thermal wave-defect interaction to the contrast process.
Fig. 6 Acoustic signals observed for specimen with two intersecting 1 mm holes at D = 0.5 mm depth. At low frequency (D/δ < 1) the signal increases above the hole. At high frequency (D/δ > 1) the signal decreases.

Fig. 7 Slant hole specimen profiles at constant f and varying depth. Note that the spatial response of the detector gives the broad background seen in the figure.
Figure 9 shows an SEAM image and SEAM and laser acoustic line scans of the same slant hole specimen taken at 78 kHz. The higher modulation frequency and the beam steering electronics built into the SEAM permit high quality images to be obtained readily. Both the image and the line scans show two contrast regions. Note that the hole is close to the sample surface near the top of the figure and farther from it near the bottom. In the image and in the line scans the hole is still visible for $D/\delta > 22$. This clearly shows that the contrast cannot be thermal. Some of the substructure seen in both laser and electron line scans is due to surface damage by the ion beam. In the nonthermal regime, the laser and electron line scan profiles closely resemble those obtained using the ions. In addition the image shows a relatively small angular spread of the signal.

Fig. 8 Slant hole specimen profiles at constant depth and varying f.

Fig. 9 Slant hole specimen image obtained using SEAM and laser excitation. In SEAM image with the thermal region is visible at top corresponding to line scan. "Elastic" region appears in image and line scan data at positions where $D/\delta >> 1$. 
with depth. This small spread applies equally to the overall defect signal and the dip over the hole center within the limits set by the experiment. Thermal stress generated near surface by the modulated beams coupled elastically to the defect is suggested to be the origin of the contrast in this regime. This finding has direct impact on SEAM imaging. SEAM images of specimen microstructure must consider both direct thermal and elastic contrast processes.

In order to further examine the issue of thermal contrast, comparative laser acoustic and OBD experiments were performed. Figure 10 compares the thermal regime in the laser acoustic scans with OBD scans. The laser acoustic scans show the hole at roughly twice the depth as do the OBD scans. This result is consistent with OBD detection being a surface temperature measurement requiring two way thermal transport to sense a buried defect. Laser acoustic detection requires only one way thermal transport coupled with acoustic generation near the defect to sense the defect's presence. While not shown in Figure 9, the laser acoustic scans show the elastic contrast regime at greater depths.

![Image of OBD and Laser Acoustic Line Scans](image_url)

Fig. 10 OBD and laser acoustic line scans (magnitude) for slant hole specimen 300 Hz. Note that acoustic detection senses hole at greater depths than thermal detection.
CONCLUSIONS

This work introduces the use of ion beams as sources for "thermal wave" imaging. The range of beam-specimen interactions available using ions makes them potentially significant for many analytical applications. In this work we show that some evidence for non-thermal interaction mechanisms exist even for the case of rare gas ions where no surface reaction is expected. Momentum transfer is considered as a possible non-thermal source. It is noted that momentum transfer generation should be a source of elastic waves since momentum transfer plays the dominant role in sputtering using rare gas ions in this energy range. However, the momentum contribution to elastic wave generation inferred from these ion acoustic experiments seems far too small to be consistent with the theory of sputtering.

Ion beams have also been used to image buried subsurface defects in aluminum. Two mechanisms are identified which contribute to the contrast observed. One of these is shown to have a thermal origin, the other to have an elastic origin. Both contrast mechanisms exist in SEAM and laser acoustic imaging as well. These results demonstrate that the microstructural contrast observed in SEAM cannot have a purely thermal origin. It is now clear that both thermal and elastic contrast can exist and must be considered.

REFERENCES

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