HIGH-RESOLUTION THERMAL-WAVE IMAGING USING THE PHOTOINDUCTIVE EFFECT

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INTRODUCTION

Photoinductive imaging is a newly devised technique for photothermal imaging based on eddy-current detection of thermal waves [1]. Thermal waves produce a localized modulation in the specimen's electrical conductivity, which can be detected by its effect on the impedance of a nearby eddy-current coil. This photoinductive effect can be used to image surface or near-surface cracks, voids, or inclusions. The method is limited in practice to conducting specimens, but it can be used to inspect thin, nonconducting coatings on metallic substrates, as we demonstrate here. One promising feature of photoinductive imaging is its potential for high resolution, especially when compared with the resolution possible with eddy-current probes alone. The objective of the present study was to exploit the high resolution capability inherent in this technique by adapting a photoinductive sensor developed for a fiber optic probe [2] to an existing photoacoustic microscope. In this paper we explore using this technique for typical applications in nondestructive evaluation.

EXPERIMENT

High-resolution thermal-wave images were produced by incorporating a photoinductive sensor into an existing photoacoustic imaging system. Figure 1 shows the arrangement of the photoinductive sensor. The sensor consisted of a differential pair of eddy-current coils fabricated on a printed circuit board. A 5X microscope objective was used to focus an argon ion laser beam onto the specimen's surface through a hole drilled in the printed circuit board. The resulting focal spot size was 18 μm, which was the lower limit of the spatial resolution in the images we present here. The laser was modulated at 11 Hz with an acousto-optic modulator. The eddy-current coils were excited at 30 MHz and the photoinductive signal was detected with a specially designed bridge and demodulator coupled with a lock-in amplifier. A schematic of the instrumentation is shown in Fig. 2. A photodiode monitored the light scattered from the specimen surface, providing a simultaneously recorded scanned optical image of the specimen.

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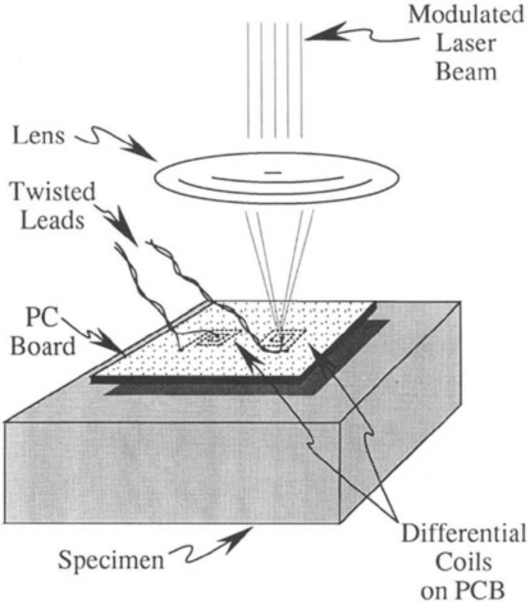

Fig. 1. Schematic diagram of photoinductive sensing. The modulated laser excitation passes through a small off-center hole in one of a pair of differential eddy-current coils and is focused on the specimen surface.

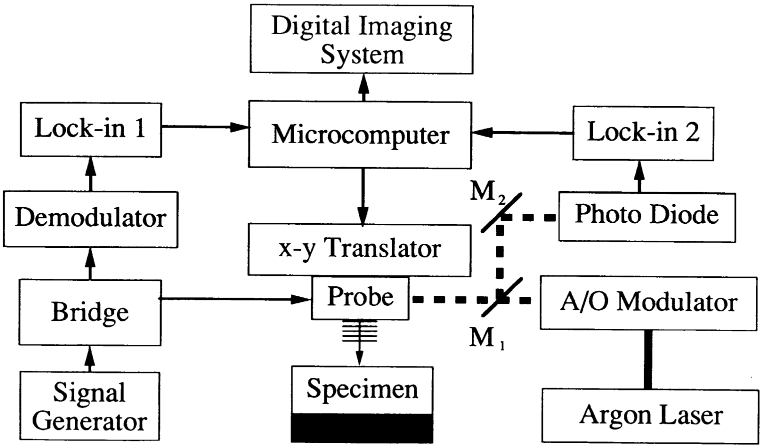

Fig. 2. Block diagram of the instrumentation used for high resolution photoinductive imaging.

RESULTS AND DISCUSSION

The photoinductive imaging system was tested on a number of materials and simulated flaws. Figure 3 displays two scans of an "E" that was written in ink on a 0.3 µm thick Au/Cr film on glass. The top images are scanned optical images obtained concurrently with the photoinductive magnitudes shown in the bottom two images. The images on the right are of a small portion of the area covered in the images on the left. Features down to 20 µm were discernible in the images. There is no physical barrier to resolving 1-µm features, as is done with other versions of photoacoustic detection using laser excitation. The resolution here is equal to just 0.5% of the size of one eddy current coil and represents orders-of-magnitude finer resolution than has been obtained previously with eddy-current imaging.

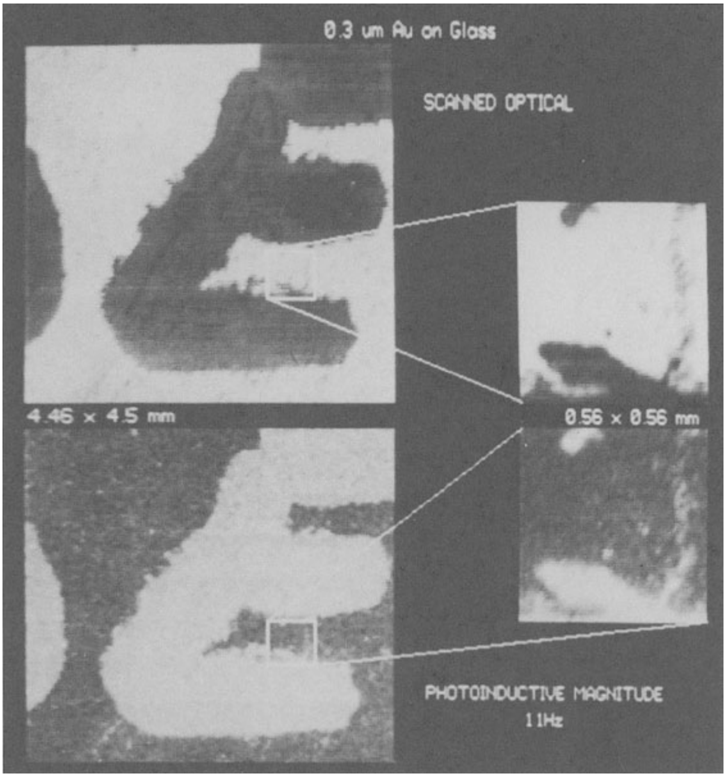

Fig. 3. Scanned optical and photoinductive magnitude images of 300-nm Au/Cr film on glass substrate. Images on the left are of an area 4.4 x 4.5 mm; those on the right, 0.56 x 0.56 mm.

Figure 4 shows a series of images obtained by scanning an yttria-stabilized zirconia thermal barrier coating 75 µm thick vapor deposited onto a nickel-based superalloy. The figure shows a scanned optical image and photoinductive phase and magnitude images of the coating. A small pore in the coating was clearly resolved, even though the thermal wave had to penetrate through the 75-µm thick coating and into the metal substrate to be detected by the photoinductive sensor. Since the signal detected by the photoinductive technique depends directly on the thermal resistance of the coating, it is a promising method to inspect this type of coating.

In preliminary images of a fatigue crack in 7075-T6 aluminum (not shown), the crack was the prominent feature in the phase image. Although it was distinguishable in the magnitude image, it tended to be obscured by scratches on the surface of the specimen. There were virtually no scratches visible in the phase image.

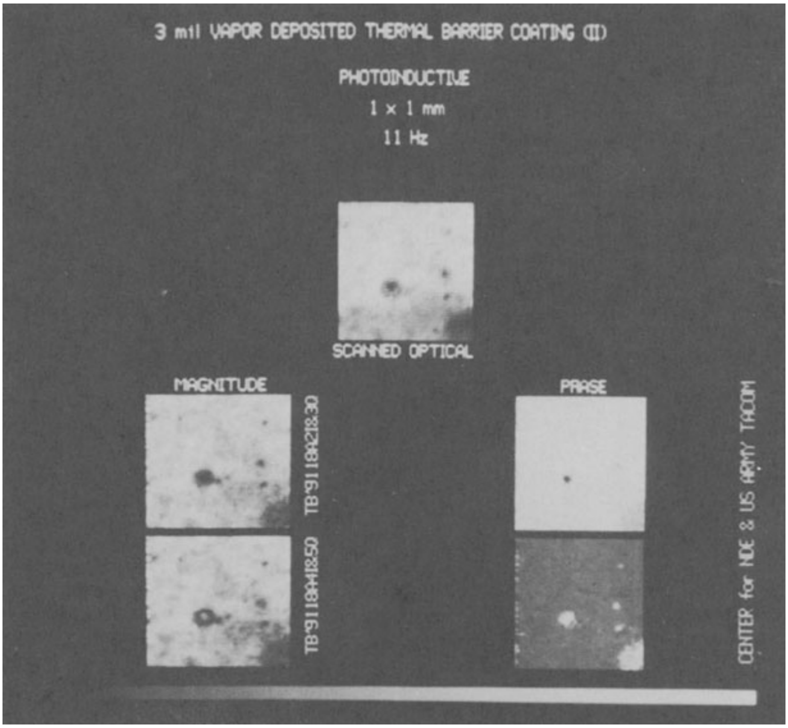

Fig. 4. Images of a small pore in an yttria-stabilized zirconia thermal barrier coating 75 µm thick on a nickel alloy substrate. Area imaged is 1 x 1 mm. At the top is a scanned optical image, at the bottom are photoinductive magnitude (left) and phase (right) images from two different lock-in amplifiers.

A compressed part-circular slot in aluminum, 3 mm long by 1 mm deep, was also imaged both in the middle and at the ends and with different orientations of the coils with respect to the notch. An image of one end of the notch is shown in Fig. 5. The notch was clearly imaged, though there was no evidence of enhancement of the notch image as there can be with mirage detection when the laser beam is aligned with the axis of a crack. The photoinductive width of the notch was one-half of the 60-µm optical width of the notch. In the photoinductive magnitude, the response to surface scratches was opposite to the response at the notch. In the photoinductive phase, the scratches were not apparent, as is typical in gas cell detection.

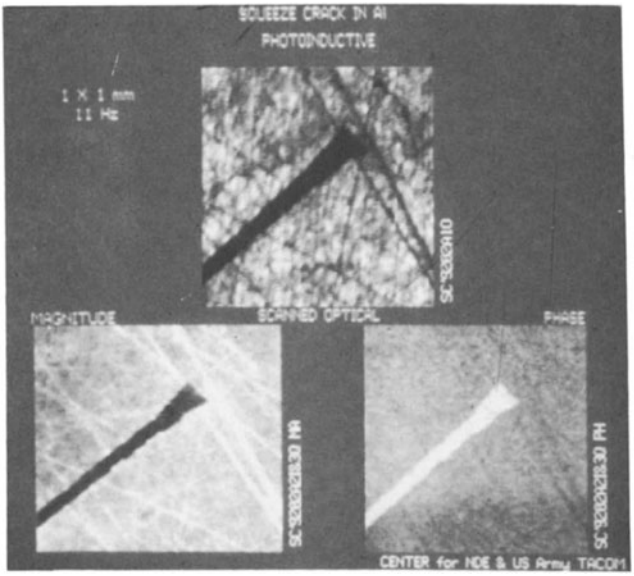

Fig. 5. Images of a compressed part-circular slot in aluminum. At the top is a scanned optical image, at the bottom are photoinductive magnitude (left) and phase (right) images.

CONCLUSIONS

High-resolution thermal-wave images have been produced by incorporating a photoinductive sensor into an existing high-resolution photoacoustic imaging system. Four different specimens were studied: a tight fatigue crack in a 7075-T6 aluminum alloy plate, a compressed notch in the same alloy, an yttria-stabilized zirconia thermal barrier coating vapor deposited onto a nickel-based superalloy, and a thin film of gold evaporated onto a glass substrate. Features as small as 20 µm were discernible in magnitude images using a 5X microscope objective to focus the laser beam. Resolution in the phase images was less, as would be expected.

These experiments have demonstrated the viability of this detection method for practical NDE applications. Photoinductive detection offers a relatively inexpensive, noncontacting sensor that can be incorporated into existing thermal wave microscopes without major modification. When compared to conventional eddy-current techniques, this approach offers resolution that is orders-of-magnitude finer than previously available. The interplay of eddy current skin depth and thermal diffusion length offers intriguing possibilities for flaw characterization.

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