INTRODUCTION

The purpose of this paper is to evaluate the technique of scanning photoacoustic microscopy (SPAM) for the detection of fatigue cracks in metal alloys, and to describe an experimental arrangement for SPAM measurements on the inner surface of a cylindrical bolt hole. The experimental technique is based upon the physical mechanism of thermal wave imaging and has been described in detail at previous¹,² Reviews of Progress in Quantitative NDE and elsewhere.³ In this paper we will also present some results of theoretical calculations for thermal wave scattering from closed, slanted cracks which intersect the surface of an opaque solid, and compare these results with our experimental data.

FATIGUE CRACKS ON PLANE SPECIMENS

The aluminum alloy fatigue crack specimens which were available for this study are described in Table 1. We will present optical and photoacoustic micrographs of specimens 3-5. Since the cracks on specimens 1 and 2 are at the limit of SPAM detectability, no data will be presented for these specimens. A vector lock-in amplifier was used to monitor the photoacoustic signal, together with digital data acquisition and scanning techniques. We will display plots of both the magnitude and phase variations of identical regions of the specimens over a range of photoacoustic frequencies from 15 Hz to 15 kHz.

In Figs. 1-4 we show optical and SPAM micrographs of a 20 mil fatigue crack in specimen 5. The SPAM pictures are shown in both the magnitude and phase modes of operation of the microscope.
Table 1. Aluminum Alloy Fatigue Crack Specimens.

Ames #1 - 9,000 fatigue cycles. Surface electropolished. Fatigue crack lengths smaller than grain diameter.

Ames #2 - 10,000 fatigue cycles. Surface electropolished. Fatigue crack lengths about grain diameter.

Ames #3 - 16,000 fatigue cycles. Surface electropolished. Fatigue crack lengths in some cases several grain diameters.

Ames #4 - 80,000 fatigue cycles (smaller amplitude than for #1-3). Mechanical polish.

Ames #5 - (Rockwell Science Center)--Fatigue cracks ranging from 50 UM to 500 UM.

pictures in Figs. 1 and 2 were taken with the crack closed, while those in Fig. 3 and 4 were taken with the fatigue crack propped open by means of a three point bend. It is evident from these pictures that an open crack is more easily detectable by SPAM than is a closed crack. One can prove theoretically that if the crack is tightly closed over its entire surface and subsurface area, and if it is exactly vertical (plane normal to the surface) it should be unobservable by SPAM with gas-cell detection. However, in practice, most cracks violate one or both of these criteria and therefore are observable by this technique. One can also see from Figs. 1 and 3 that this specimen contains a large number of surface scratches from mechanical polishing. Comparison of Figs. 2 and 4, however, shows the insensitivity of the SPAM signal to these scratches. As one would expect theoretically, the photoacoustic phase is especially insensitive to purely surface defects. Another feature of the SPAM phase micrographs (see Figs. 2 and 4) is a sharp change in phase across the crack, for example, brighter than the background to the right for the 150 Hz phase micrograph in Fig. 4. As we shall show theoretically and demonstrate experimentally for other fatigue cracks below, this behavior is a characteristic phase signature of a slanted subsurface crack.

In Fig. 5 we show an optical micrograph of specimen 4, with the region studied photoacoustically outlined. Low magnification SPAM phase micrographs of this region at two frequencies are shown in Fig. 6. The bright regions at the tops of the micrographs are due to the fact that the laser beam was blocked by the cell boundary. The characteristic phase variation from bright to dark (or vice versa) across a crack is quite evident for both cracks in Fig. 6, and the contrast of this signature with the background surface structure (dark regions against a gray background) allows easy identification of the large cracks. A higher magnification compar-
Fig. 1. Optical micrographs of specimen 5 with the closed fatigue crack.

Fig. 2. SPAM micrographs as a function of frequency for the closed crack on specimen 5.

Fig. 3. Optical micrograph of specimen 5 with the open fatigue crack.

Fig. 4. SPAM micrographs of specimen 5 with the crack open.
Fig. 5. Optical micrograph of specimen 4. The SPAM-scanned region is outlined.

Fig. 6. SPAM phase micrographs 7.5 kHz, specimen 4 (low magnification).

Fig. 7. Comparison of the SPAM magnitude and phase at 7.5 kHz for these two cracks is shown in Fig. 7, and the frequency dependence of the phase is shown in Fig. 8. It may be noted that several regions that are bright at the higher frequencies become dark at lower frequencies, and vice versa. This behavior is the result of the frequency dependence of the thermal wavelength. A higher resolution, 0.12 mil (3 μm) SPAM phase micrograph of this region is shown in Fig. 9. This can be compared with the 0.5 mil (12.8 μm) resolution for Fig. 6 and with the 0.25 mil (6.35 μm) resolution used to obtain the other micrographs. A comparison of Figs. 6-8 with Fig. 5 shows several regions which contain subsurface cracks: a characteristic crack phase signature with no evidence of a crack in the optical micrograph. One example is the extended region to the left of the bright "fork" in the larger crack.

An optical micrograph of specimen 3 is seen in Fig. 10, showing several small cracks. A SPAM phase micrograph of this region is shown in Fig. 11 for 7.5 kHz. The frequency dependence of the SPAM magnitude and phase for one portion of this region is shown in Fig. 12, and for the second portion in Fig. 13. Cracks of surface length as small as 3 mils are seen in these micrographs.
Fig. 7. SPAM magnitude and phase micrographs, 7.5 kHz, specimen 4 (high magnification).

Fig. 8. Frequency dependence of SPAM phase micrographs of specimen 4.

Fig. 9. High magnification SPAM phase micrographs, specimen 4, 7.5 kHz with two resolutions.
Fig. 10. Optical micrograph of specimen 3.

Fig. 11. SPAM phase micrographs, specimen 3, 7.5 kHz.

Fig. 12. Frequency dependence of the SPAM phase for the upper portion of Fig. 11.
Fig. 13. Frequency dependence of the SPAM phase for the lower portion of Fig. 11.

THEORETICAL CALCULATIONS FOR TILTED CRACKS

We have proved a theorem, reported elsewhere, which says that the difficult three dimensional thermal diffusion problem with a localized source and non-localized detector (such as the pressure in a gas cell) can be replaced by an equivalent problem in which a hypothetical uniform surface source is assumed and the localized surface temperature is computed following scattering from the flaw boundaries. We have utilized this theorem to compute (in the Born approximation) both the SPAM magnitude and the phase variations across a closed, slanted crack. The results of these calculations are given in Fig. 14. It may be noted that the magnitude peaks primarily in the region vertically above the slanted crack, whereas the phase variation
extends on both sides of the crack, but with a sign reversal at the point at which the crack intersects the surface. This sign reversal is responsible for the black-white contrast near the crack on the phase micrographs. The slight dip in the magnitude just beyond the crack is too small to show in the SPAM micrograph, so no such contrast is seen in the magnitude pictures.

BOLT HOLE SCANNING

In order to test the feasibility of applying SPAM to the detection of fatigue cracks on the inner surface of a cylindrical bolt hole, we have constructed a rotary scanning stage and 1 inch diameter cell shown in Fig. 15. In this arrangement the linearly scanned and focused laser beam (not shown) is brought vertically down the center of the cell onto a prism which internally reflects the beam by 90°
Fig. 15. Experimental arrangement for scanning the inner surface of a cylindrical bolt hole. The linear translation stage used to scan the beam along the diagonal face of the prism (see text) is not shown in this photograph.

Fig. 16. SPAM magnitude perspective plot at 1 kHz of a 300 μm slot on the inner surface of a simulated bolt hole, scanned using the apparatus shown in Fig. 15.
and brings the focal spot onto the cylindrical surface of the sample. The gas volume is trapped by 'O'-rings, the outer cell surface and the bolt hole surface. Vertical scanning on the hole surface is accomplished by translating the beam along the diagonal face of the prism by means of an external linear stepping stage (not shown). We have simulated a crack on the surface of a model one-inch hole by using a Nd:YAG pulsed laser to machine a 300 \mu m wide slot. The results of a SPAM magnitude micrograph are shown in Fig. 16.

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