This report presents results of measurements of crack depth with the aid of acoustic bulk and surface waves. Both simulated and real fatigue cracks were examined. Two techniques were employed, one took advantage of the very efficient mode conversion between acoustic surface waves and shear waves at the crack tip; the other technique used the diffraction of shear waves at the crack tip. Both techniques were used on a number of simulated (spark eroded) and real cracks in Al 2024. In one fatigue specimen which contained an elliptical crack 4.5 mm in length and 1.25 mm in depth, crack closure studies were carried out. The precision of crack depth determination was judged to be better than 10%.

OBJECTIVE

The ultimate objective of this task is to predict the fatigue life of a metallic component with the use of ultrasonic nondestructive evaluation. The work concentrates on predicting the remaining fatigue life for a single fatigue part-through crack above the "threshold" value for macrocrack propagation. Acoustic surface and bulk waves are being used to interrogate the crack during cyclic fatigue. The inversion of the scattering data provides crack size, shape, and orientation as a function of time. With this information and metallurgical data, the remaining fatigue life is obtained from fracture mechanics. The effective stress intensity is studied which should allow inclusion of environmental as well as random loading effects on fatigue life.

INTRODUCTION

During the previous reporting period two techniques were evaluated for measuring the length and depth, respectively, of fatigue cracks with the use of acoustic surface waves. Both techniques are specialized to the case in which the wavelength is smaller than both the crack length and depth. The technique for measuring the length is based on the diffraction of surface waves from a crack giving rise to structure in the angular and frequency dependence of the scattered power such that the minima and maxima have positions and spacings which are used to infer the crack length. The technique, developed earlier for spark eroded slots, was also found to give good results for fatigue cracks. The technique for measuring the crack depth is based on multiple conversions of wave energy, starting with a surface wave on the specimen surface, conversion to a guided dispersive wave on the crack face and conversion at the crack tip to a bulk (shear) wave travelling to the opposite wall of the specimen. There, upon reflection, the conversion proceeds in reverse manner so that the transducer used as transmitter may also be used as receiver for this multiply converted return signal. By the use of echo timing techniques based on a good knowledge of the velocities for the various travel paths, the crack depth is determined with good precision.

Auxiliary experiments were conducted to study the effects of crack closure. In Ti-alloy, the closure load was found to depend strongly on crack depth, especially in the near-threshold regime. With the information obtained, the life prediction could be improved considerably. The technique has several disadvantages, such as restrictions on specimen geometry for the proximity of a suitable back wall, sensitivity of the calculations on errors in the shear and Rayleigh wave velocities, and need for refinement in the model describing the interaction between the surface waves and the crack. A fundamental limitation of the technique is its inability to provide information for cracks inclined to the surface.

SUMMARY OF TECHNICAL RESULTS

The work accomplished for the present work period consisted of a continuation of studies started previously with the addition of one new effort.

Continued effort to characterize the interaction of surface and bulk waves with part-through cracks was performed. This work involved close interaction with B. Auld, J. Achenbach, and A. Mal to refine current models for this interaction. The techniques emerging from this effort were tested on the life prediction of an Al fatigue specimen with a single crack whose growth was monitored during the fatigue cycling. This fatigue specimen was constructed from Al 2024-T6 material. Also an apparatus was constructed to impose static tensile stress on the crack for crack closure studies.

In addition, a new approach was developed to determine the crack depth based on diffraction of bulk waves around the tip of the crack. This approach has the major advantage that it would provide the "true" crack depth below the specimen surface, independent of the detailed structure and contour of the crack. The discussion of the detailed experimental results emphasizes this new work.

DETAILED RESULTS

Our recent studies have shown that the use of diffraction of bulk shear waves has led to good success in crack depth measurements on rectangular and elliptical simulated (spark eroded) cracks and real fatigue cracks.
The measurements employed a commercial lucite 45° angle wedge with a 6.35 mm diameter, 10 MHz shear transducer polarized in the vertical direction. Figure 1 shows a schematic of the geometry. The crack depth (d) was obtained from the incident angle of the ultrasonic beam (θ), the shear wave velocity in the sample in the polarization direction (v₀), and the time delay measured between the crack tip and crack mouth reflection signals (t). The depth is then given by \( d = \frac{v₀t}{2 \cos θ} \).

![Fig. 1 Schematic diagram showing sample geometry and transducer configuration.](image)

Figure 2 shows the waveforms corresponding to the crack tip and mouth for a 2.54 mm long, 1.27 mm deep rectangular simulated crack. Also shown are a deconvolved frequency spectrum and the impulse response function time domain waveform. Figure 3 shows similar waveforms for a 2.54 mm length, 1 mm depth elliptical simulated crack. Figure 3a shows the “actual” waveform whereas Fig. 3b displays a greatly amplified version. Clearly discernable is the crack tip signal with a good signal-to-noise ratio. It should be noted that the time domain plots show extensive ringing after the crack mouth reflection signals. The reason for this ringing is not clear and remains under study.

In addition to the studies on simulated cracks, measurements were carried out on actual fatigue cracks in Al 2024-T3 tensile specimens. Figures 4a and 4b are the time domain waveforms of two samples, B-1 and C-2 with estimated crack depths of 1.25 and 1.95 mm, respectively. Again in both cases, there is extensive ringing in the signal after the main crack mouth signal. Table 1 summarizes the results of the experiments and compares the estimated with the actual depths.

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Real Depth (mm)</th>
<th>Measured Depth (mm)</th>
<th>Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rect. EDM</td>
<td>1.27</td>
<td>1.34</td>
<td>+5.5</td>
</tr>
<tr>
<td>E11. EDM</td>
<td>1.00</td>
<td>1.05</td>
<td>+5.0</td>
</tr>
<tr>
<td>Fatigue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-1</td>
<td>~1.25</td>
<td>1.14</td>
<td>-8.8</td>
</tr>
<tr>
<td>Fatigue</td>
<td>~1.95</td>
<td>1.8</td>
<td>-7.7</td>
</tr>
</tbody>
</table>

![Fig. 2 Shear wave interrogation of 2.54 mm long, 1.27 mm deep rectangular simulated crack prepared by spark erosion.](image)

![Fig. 3 Same as Fig. 2 for an elliptical slot 2.54 mm long and 1 mm deep.](image)
as the stress increases. In the second case, the crack tip echo will not move but will become smaller at the expense of another crack tip echo growing at a position closer to the main echo.

Figure 8 shows a mosaic of micrographs taken of the fatigue cracks at their mouth. The optical estimate for the crack length is approximately 4.5 mm.

In the experiments, the crack was illuminated with Rayleigh wave pulses from a direction at right angles to the crack plane. The receiver was situated opposite to the transmitter and across the crack. The data could be collected while the tensile specimen was in a special loading frame. This frame used a manual hydraulic pump that allowed us to achieve stresses in excess of 35 ksi, which was enough to exceed the crack opening stress in this material. Figure 5 shows an example of the received waveforms displaying the primary transmitted signal and then about 4 μs later the signal which, as discussed earlier, is mode-converted to a shear wave at the crack tip and is then reflected from the near surface of the tensile specimen. The waveforms shown in Fig. 5 were obtained at an applied stress of about 30 ksi. Also shown in the figure at the bottom is the frequency spectrum of the primary transmitted signal displaying a center frequency of about 6 MHz. Similarly, the primary reflected signal (crack mouth echo) and the secondary, mode-converted signal (crack tip echo) were observed and Fig. 6 shows the frequency spectra of those signals, respectively. (Note that because of the low signal-to-noise ratio of the secondary, mode-converted signal, the signal processing required extensive smoothing). In contrast, Fig. 7 shows the primary transmitted Rayleigh wave signal and its frequency spectrum at low applied stress. Notice that the time-domain data do not show a secondary signal but exhibit a sizeable pulse immediately following the main signal. (The precursor signal has been identified as a reverberation in the home-made water wedge transducer.) Notice also that the frequency spectrum shows a dramatically lower high-frequency content than the corresponding spectrum at high applied pressure (Fig. 5, bottom). The contrast between these data at low and high applied stress are not completely understood at this time, but are assumed to be associated with crack closure behavior. Figure 8 shows a mosaic of micrographs taken of the fatigue crack at its mouth. The optical estimate for the crack length is approximately 4.5 mm.

The tensile fatigue specimen was constructed by using the following procedure. Prior to fatigue, a starter notch was spark eroded (EDM) in the surface of a large dog-bone specimen of 2024-T3 Al. The notch was 2.5 mm long at the surface, 1.25 mm deep and semi-circular in shape. Next the sample was fatigued cycled to initiate a crack and allow the crack growth by about 1.25 mm in radius. Then the initial starter notch was machined off so that the final gauge section was 25.4 mm wide, 9.0 mm thick, and contained an elliptical crack 4.5 mm long at the surface and about 1.25 mm deep.

As may be seen from Table 1, we found good agreement of real depth and measured depth for the simulated cracks. Noticeable now is the large discrepancy between the estimated crack depth and the measured depth for both fatigue cracks. An obvious cause for this discrepancy is the fact that the cracks are at least closed to the crack tip, so the acoustic signal does not see the true crack depth. Measurements as described above will have to be performed under tensile load (to open the crack fully), which will be the objective of further studies. One interesting feature that these studies will reveal is whether the crack depth diminishes monotonically with compressive stress or in whole segments. In terms of the ultrasonic waveforms, in the first case the crack tip echo will be closer and closer to the main echo as the stress increases. In the second case, the crack tip echo will not move but will become smaller at the expense of another crack tip echo growing at a position closer to the main echo.

Figure 4 shows an example of the received waveforms displaying the Rayleigh wave signal and then about 4 μs later the signal which, as discussed earlier, is mode-converted to a shear wave at the crack tip and is then reflected from the near surface of the tensile specimen. The waveforms shown in Fig. 5 were obtained at an applied stress of about 30 ksi. Also shown in the figure at the bottom is the frequency spectrum of the primary transmitted signal displaying a center frequency of about 6 MHz. Similarly, the primary reflected signal (crack mouth echo) and the secondary, mode-converted signal (crack tip echo) were observed and Fig. 6 shows the frequency spectra of those signals, respectively. (Note that because of the low signal-to-noise ratio of the secondary, mode-converted signal, the signal processing required extensive smoothing). In contrast, Fig. 7 shows the primary transmitted Rayleigh wave signal and its frequency spectrum at low applied stress. Notice that the time-domain data do not show a secondary signal but exhibit a sizeable pulse immediately following the main signal. (The precursor signal has been identified as a reverberation in the home-made water wedge transducer.) Notice also that the frequency spectrum shows a dramatically lower high-frequency content than the corresponding spectrum at high applied pressure (Fig. 5, bottom). The contrast between these data at low and high applied stress are not completely understood at this time, but are assumed to be associated with crack closure behavior. Figure 8 shows a mosaic of micrographs taken of the fatigue cracks at their mouth. The optical estimate for the crack length is approximately 4.5 mm.
Next, the peak signal amplitudes were studied as a function of applied stress with the tensile specimen in the loading frame. Figure 9 presents the results of these measurements showing at the top that the primary transmitted signal (labeled "forward scatter") diminishes with increasing applied stress until at some critical stress the amplitude stops changing as the stress is increased further. In contrast, the primary reflected signal (labeled "backscatter") begins at low amplitudes, increases, and then achieves a constant amplitude as the applied stress is increased over the same range of stress values. Thus, the behavior of the reflected and transmitted signals act qualitatively complementary, i.e., the reflected grows at the expense of the transmitted as the crack is opened by the applied stress. Finally, the transmitted, secondary, mode-converted signal (labeled "crack tip") is not visible for low values of applied stress, then appears at about 10 ksi, increases in amplitude with increasing stress, until above about 25 ksi the amplitude remains constant or increases only slightly.

The behavior of the secondary, mode-converted signal was studied in greater detail, as shown in Fig. 10. At the bottom, both the transmitted (labeled "forward scatter") and reflected (labeled "back scattered") signal amplitudes are shown and behave comparably as a function of applied stress. Also shown in the middle plot, is the time delay between the primary and secondary signals. As discussed earlier, the time delay is used to calculate the crack depth which is plotted in the top graph. Also shown are two other sets of data: the solid circles were obtained with use of shear wave diffraction as described earlier for the spark eroded slots. The single data point in the form of an open square is the value obtained from a combined use of optical crack length measurement.
measurements and crack growth rate data. All three data sets are in reasonable agreement and give an average depth of 1.3 mm ± 0.1 mm at about 30 ksi when the crack fully opens. The increase in effective crack depth at about 10 ksi applied stress and little or no increase beyond 15 ksi is typical of crack closure behavior in this material.

Extensive measurements are planned in the future for the fatigue specimen. The objective is to determine crack length and depth ultrasonically during most of the fatigue life of the specimen. Also, any changes in the behavior under static tensile stress will be monitored. The behavior of the 2024-T6 material will be compared with that in Ti-15A reported on earlier.2

ACKNOWLEDGEMENT

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REFERENCES

SUMMARY DISCUSSION

Leonard Bond, Chairman (University College London): We have time for a few questions. Who would like to start with a question?

Richard Barry (Lockheed Missiles and Space): Would you tell me when you were concerned about the error in some of your measurements from one of the earlier slides, where you measured your actual crack depth, did you measure the average depth or maximum depth?

Bernie Tittmann (Science Center): I measured the actual depth, taking into account the Achenbach flash point concept where it is the extremities that are responsible for generating the sources of the signals.

Unidentified Speaker: On your last slide, if you calculated the depth of the crack from fracture mechanics, what would the shape of that curve look like?

Bernie Tittmann: We didn't do that. That would be an interesting point. You see, fracture mechanics cannot really tell us how well the crack is closed. What fracture mechanics tells us is that after so many cycles, a surface crack assumes a semi-circular shape. Then from an observation of the crack length, we can immediately infer what the crack depth should be if the crack is completely open. Fracture mechanics cannot really tell us how much the crack is closed for a given applied stress. At least we are not that far along.

Would you agree with that, Otto (Otto Buck, Ames Laboratory)? Yes.

Chris Burger (Ames Laboratory): Bernie, in your growth of the cracks where you are opening and closing them, were you running with constant amplitude or constant displacement growth or did you use something like a large overload and then look at the closure phenomena?

Bernie Tittmann: The measurements with large overloads constitute the next phase in our experimentation. All the measurements discussed here were done with a constant stress increment. That's a very interesting question and we hope to shed light on it soon.

Kamel Salama (University of Houston): Do you have any idea how the crack closure stress changed from tensile to compressive? Is that because the residual stress is, for instance, around the crack change direction or change in size?

Bernie Tittmann: You mean in the experiments on Ti-15A? The idea there is that as the crack grows deeper, the plastic zone in front of the crack enlarges and affects the mode of fracture growth, for example, in a transition from Mode I to Mode II. We don't fully understand that yet, but certainly the stress present in the plastic zone affects crack growth dramatically in the titanium.

Leonard Bond, Chairman: One last question.

Fred Vaccaro (The Timkin Company): Bernie. Would you explain the absence of the secondary, mode converted crack tip signal at low applied stresses along the same lines as the lack of high frequency in the signal?

Bernie Tittmann: That's a very interesting point, and I meant to elaborate on it a little bit. If you remember, I showed you a slide of that satellite echo next to the crack mouth. We are speculating that at this point the crack is almost closed. And this process of mode conversion from a surface wave to a shear wave has been modified so that instead of radiating bulk waves, the crack tip reflects the Rayleigh wave very efficiently. But as soon as you open up the crack the source of radiation moves down to the actual crack tip, which radiates bulk wave efficiently into the material.

Leonard Bond, Chairman: I think we better draw the discussion to a close. I would like to thank the speakers for the first session.