

SURFACE WAVE TECHNIQUES FOR PREDICTING THE REMAINING LIFE OF
FATIGUE DAMAGED METALS

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ABSTRACT

In our continuing efforts to investigate methods to characterize the state of fatigue nondestructively and to apply these observations to lifetime predictions, we have initiated acoustic surface wave studies using Al 2024-T351. A smooth bar specimen was designed which can be tested in tension-compression fatigue. Acoustic wedge transducers were mounted on the specimen to sample fatigue induced changes within the gauge section. Data on acoustic harmonic generation were taken as a function of applied external load at any point of the sample's fatigue life. An optical microscope was attached to the load frame to monitor microcrack formation in the gauge section. Significant changes of the second harmonic have been observed as a function of stress and fatigue. First results indicate a decrease of the second harmonic as a function of stress. At about 50% of the fatigue life microcracks initiated at surface intermetallics and a substantial increase of the second harmonic amplitude in the vicinity of zero external applied load was observed.

The objective of the present work is to investigate the potential of surface acoustic waves and, in particular, acoustic harmonic generation for surface stress measurements and for fatigue life predictions. Acoustic surface waves are particularly well suited for such measurements since the acoustic energy is highly localized at the materials' surface. The experimental setup for this work is exhibited in Fig. 1, which shows a fatigue sample of rectangular cross section (about 1 inch²) installed in an electrohydraulic MTS machine. Also shown are acoustic wedge transducers with the transmitting transducers operating at 5 MHz and the receiving transducers tuned to 10 MHz to monitor changes in acoustic harmonic generation as the specimen is fatigued in the MTS machine. An optical microscope (not shown in Fig. 1) has also been used to observe microcrack initiation and growth. Figure 2, bottom, shows the electronics used for harmonic analysis of these acoustic surface waves. The finite amplitude signal is generated using a pulsed oscillator. A heterodyne receiver served as the frequency spectrum analyzer after detection of the signal by the 10 MHz transducer. The surface wave signals received were quite clean and disappeared completely by pressing a soft object against the specimen's gauge section. To demonstrate surface harmonic generation, several measurements on the dependence of the second harmonic amplitude (A_2) at 10 MHz on the first harmonic amplitude (A_1) at 5 MHz were performed with both A_1 and A_2 measured at the receiver transducer. As shown in Fig. 2, right-hand side, the theoretically expected $A_2 \propto A_1^2$ relation was observed. During the early stages of fatigue, harmonic generation was determined as a function of applied load during individual fatigue cycles. Figure 3 shows a typical example of such a measurement plotted in the quantity A_2/A_1^2 (to compensate for any variations in A_1 during the fatigue cycle) as a function of the applied stress. As can be seen from this figure, A_2/A_1^2 decreases with increasing applied stress. Such a dependence is expected theoretically, using non-linear theory of elasticity.

Harmonic generation as a function of applied load was also determined during the later parts of the fatigue life when the microcrack density, as initiated at intermetallics, became high. An example of such a harmonic generation result is shown in Fig. 4, top, with an example of one of the longer microcracks (about 15 μm , or 0.5 mils, long) shown in Fig. 4, bottom. The results given in Fig. 4 are clearly different from those in Fig. 3. Data similar to the ones shown in Fig. 4 for Al 2024-T351 were observed repeatedly on specimens with a large microcrack density. It is believed that the microcracks are the cause for the changed harmonic amplitude results, as explained qualitatively in the following.

As postulated by J. M. Richardson (Science Center, Rockwell International) recently, a stress induced crack opening and closing may be considered as an acoustic harmonic generator. Richardson considered a very simple system composed of an unbonded planar interface separating two semi-infinite linear media (see Fig. 5, top). By definition, the unbonded interface cannot support tension and thus it opens up during the tension phase of a wave propagating from one side of the interface to the other. The system is actually linear while the gap in the interface is closed. The origin of the nonlinearity is due to the fact that the time at which the gap opens and closes depends upon the ratio of the stress amplitude of the acoustic wave and the external stress that works to hold the gap closed (Fig. 5, bottom). In the case of a normally incident sinusoidal wave, the gap dynamics will be nonlinear and harmonics will be generated in a reflected or transmitted wave if the ambient stress is less than the stress of the incident wave.

From the above discussions it is expected that harmonic generation at cracks is a minimum both at maximum tensile and compressive stresses. In the vicinity of zero applied stress, however, harmonic generation should be a maximum. Indications for such an effect may be seen in Fig. 5, top. However, the origin of the large harmonic generation at +50 ksi is unknown at the present time. Further experiments to clarify this situation are underway.

The opening and closing of both microscopic and macroscopic cracks has been observed experimentally. Figure 6 shows the change in contact area of a macrocrack as a function of the applied stress. Microcracks, as shown in Fig. 4, will behave similarly and thus are thought to be a potential source for acoustic harmonic generation.

The conclusion of the present work is summarized in Fig. 7. After having generated strong and clean surface waves and Fourier analyzed the received signal, we have observed that the second harmonic decreases roughly by about 20% per ksi stress. Thus the sensitivity of this

effect is one to two orders of magnitude larger than that of another acoustic technique, which uses the change of sound velocity as a stress indicator.

Harmonic generation also seems to be a very promising tool to detect microcracks as developed during fatigue. The nonlinearities occurring during opening and closing of microcracks have been considered by Richardson recently. The present results indicate that microcracks as little as 15 μm long (or about 0.5 mils) can be detected by harmonic generation if the density is high enough.

Acknowledgement

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OBJECTIVE TO INVESTIGATE THE POTENTIAL OF SURFACE WAVES FOR SURFACE STRESS MEASUREMENTS AND FOR FATIGUE LIFE PREDICTIONS

- ACOUSTIC WEDGE TRANSDUCERS, GENERATING ACOUSTIC SURFACE WAVES (AT 5 MHz), WERE MOUNTED ON THE SPECIMEN TO SAMPLE THE STATE OF STRESS AND THE STATE OF FATIGUE WITHIN THE GAUGE SECTION BY MEANS OF ACOUSTIC HARMONIC GENERATION. THE FIGURE SHOWS THE SPECIMEN WHICH WAS FATIGUED IN TENSION-COMPRESSION IN AN ELECTRO-HYDRAULIC MTS MACHINE.

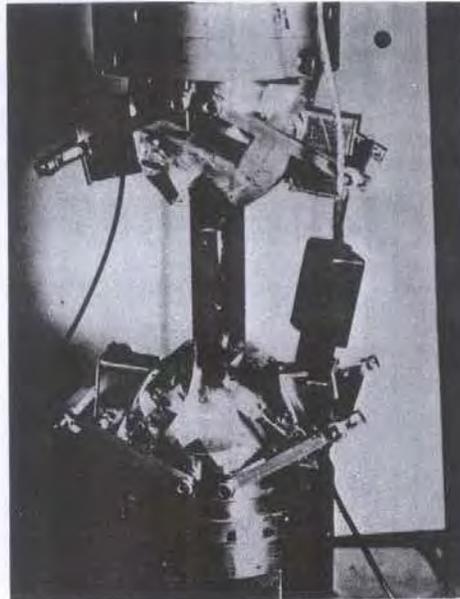


Figure 1

- SHOWN IS THE EXPERIMENTAL APPARATUS FOR HARMONIC ANALYSIS OF ACOUSTIC SURFACE WAVES. SINUSOIDAL ULTRASONIC SURFACE WAVES OF FINITE AMPLITUDE AT 5 MHz WERE EXCITED BY A PZT TRANSDUCER. THE DISTORTED SIGNAL WAS DETECTED USING A 10 MHz PZT. A HETERODYNE RECEIVER SERVED AS THE FREQUENCY SPECTRUM ANALYZER BY VIRTUE OF ITS BROAD BAND MIXING STAGE.

- THE SECOND HARMONIC AMPLITUDE, (A_2), IS RELATED TO THE FIRST, (A_1), BY $A_2 = A_1^2$, AND WAS EXPERIMENTALLY VERIFIED USING THE ABOVE SYSTEM.

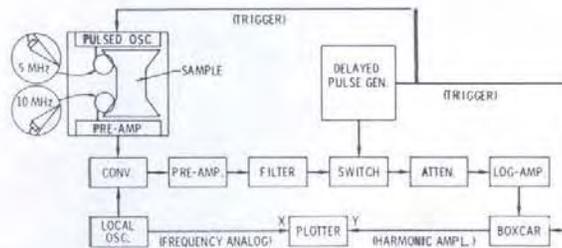
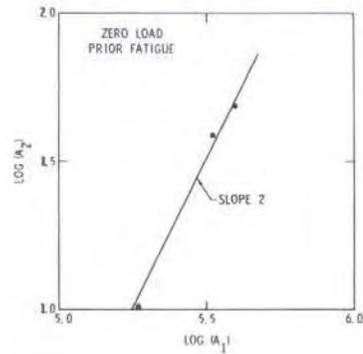


Figure 2

● DURING FATIGUE OF Al 2024 T351 THE QUANTITY $\log(A_2/A_1^2)$ WAS DETERMINED AS A FUNCTION OF APPLIED STRESS. THE OBSERVED $\log(A_2/A_1^2)$ DECREASE WITH INCREASING STRESS CAN BE PREDICTED THEORETICALLY. SENSITIVITY OF THE EFFECT IS ABOUT 20% CHANGE IN ABSOLUTE SECOND HARMONIC PER 100 KSI. INELASTIC EFFECTS PRODUCED SOME HYSTERESIS AT START OF TEST AS SHOWN IN THE EXAMPLE AFTER 2000 CYCLES! MICROCRACK DENSITY WAS VERY LOW AT THIS TIME ($\approx 40\%$ OF FATIGUE LIFE).

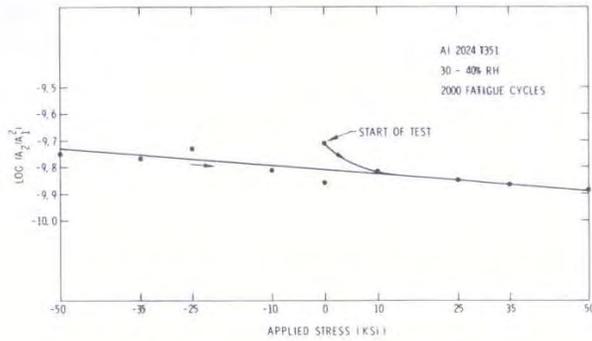
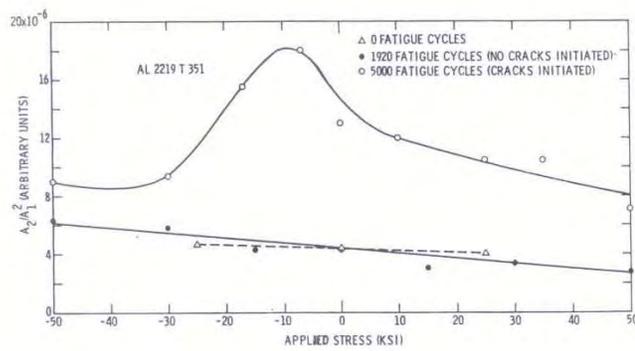


Figure 3



● MICROCRACK DENSITY AFTER FATIGUE OF Al 2024 T851 WAS QUITE HIGH WITH MAXIMUM CRACK LENGTH BEING ABOUT $15 \mu\text{m}$ (0.5 mils). CRACK TIPS ARE INDICATED BY ARROWS.

● IN THIS CASE THE QUANTITY $\log(A_2/A_1^2)$ SHOWED A PRONOUNCED VARIATION AS A FUNCTION OF APPLIED STRESS WHICH IS ATTRIBUTED TO THE PRESENCE OF MICROCRACKS.

Figure 4

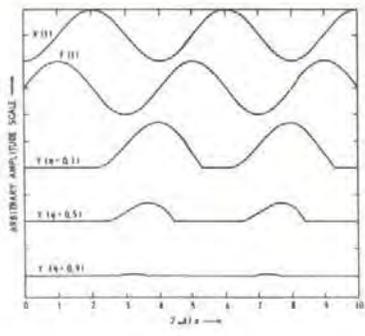
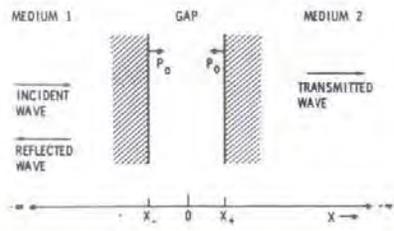
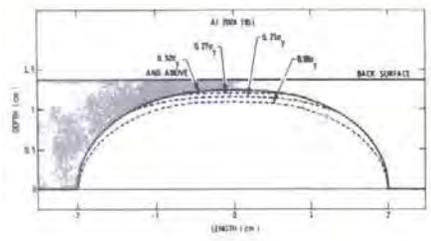


Figure 5

- A POSSIBLE EXPLANATION FOR THE VARIATION IN $\log |A_2/A_1|^2$ WITH STRESS MAY BE ACOUSTIC HARMONIC GENERATION AS THE CRACK OPENS AND CLOSES UNDER STRESS (J. M. RICHARDSON, SCIENCE CENTER).
- THE ORIGIN OF THE NONLINEARITY IS DUE TO THE FACT THAT THE TIME AT WHICH THE GAP OPENS AND CLOSES DEPENDS UPON THE RATIO (r) OF THE STRESS AMPLITUDE OF THE ACOUSTIC WAVE AND THE EXTERNAL STRESS WHICH TRIES TO CLOSE THE GAP.



THE PRESENCE OF CRACK DEFECTS MAY OPERATE IN BOTH MICROSTRESS AND MACROSTRESS REGIONS. THE FIGURE SHOWS THE CHANGE IN CRACK AREA AS A FUNCTION OF APPLIED STRESS FOR A MICROCRACK IN A FATIGUE CRACK SPECIMEN. MICROCRACKS WILL BECOME LINEARLY AND THIS MIGHT BE A POTENTIAL SOURCE FOR HARMONIC GENERATION.

Figure 6

- (1) STRONG AND CLEAN ACOUSTIC SURFACE WAVE SIGNALS HAVE BEEN PRODUCED ON SPECIMENS SUITABLE FOR TENSION-COMPRESSION FATIGUE.
- (2) PRIOR TO MICROCRACK FORMATION HARMONIC GENERATION DECREASES WITH INCREASING APPLIED STRESS (SENSITIVITY $\approx 20\%/100$ KSI). THUS THE TECHNIQUE IS POTENTIALLY USEFUL TO DETECT LONG RANGE INTERNAL STRESSES.
- (3) MICROCRACKS ARE A POSSIBLE SOURCE FOR ACOUSTIC HARMONIC GENERATION. MICROCRACKS AS SMALL AS $15 \mu\text{m}$ (0.5 MILS) MIGHT BE DETECTED. FURTHER RESEARCH IN THIS AREA IS NEEDED HOWEVER.

Figure 7. Conclusions