FACTORS AFFECTING ULTRASONIC WAVES INTERACTING WITH FATIGUE CRACKS

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I don't mean to be presumptious and imply that we are going to cover all of the many factors which affect ultrasonic measurements of fatigue cracks, as suggested by the title, but we will attempt to go over some recent work we have been doing at the Materials Lab in this area. We'll be talking about fatigue cracks and what variables, both regarding the fatigue crack itself as an entity and the ultrasonic inspection process, have a significant effect on the results that are obtained.

Theoretical Modeling

We started out trying to design a simplistic model that would help us to understand the ultrasonic interactions with large fatigue cracks. A schematic of the model is shown in Fig. 1.

We took a very simple picture of a three-layer system, modeling the crack as the thin intermediate layer. Several simplifying assumptions are implied. First, this is a one dimensional analysis with the layers being infinite planes in the x and z directions. Second, the ultrasonic energy input is normal to the thin layer and only longitudinal waves are considered. Third, it is assumed that the acoustic impedance analysis for energy partitioning is valid. Beam divergence, dispersion and attenuation are not included in this model.

The prime interest in this theoretical study is the difference between the "classical" continuous wave solution and the results for ultrasonic pulses of arbitrary shape. Through an interactive linear superpositioning process it was possible to generate the shape of the waveform reflected off the thin layer as a function of input shape, layer thickness and acoustic impedance ratio.

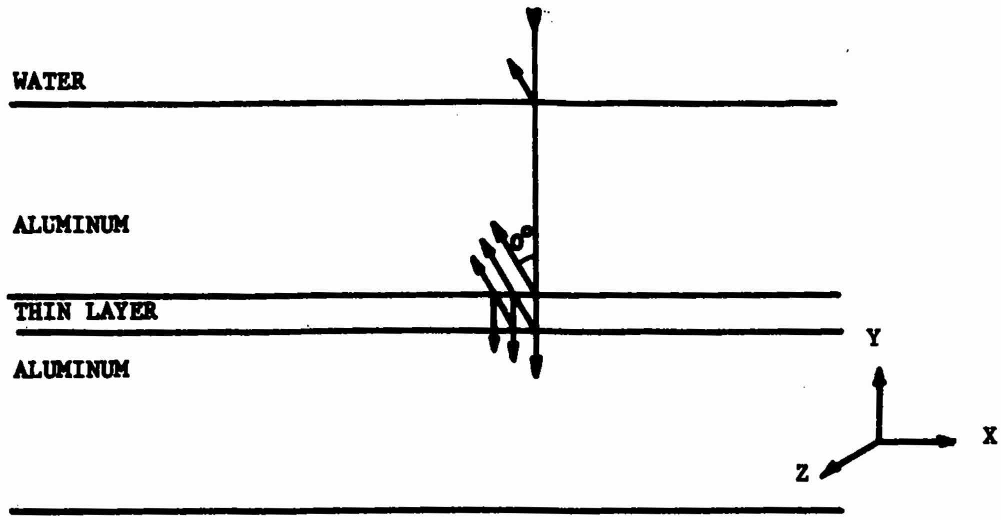


Figure 1. Schematic Illustration of Fatigue Crack Model.

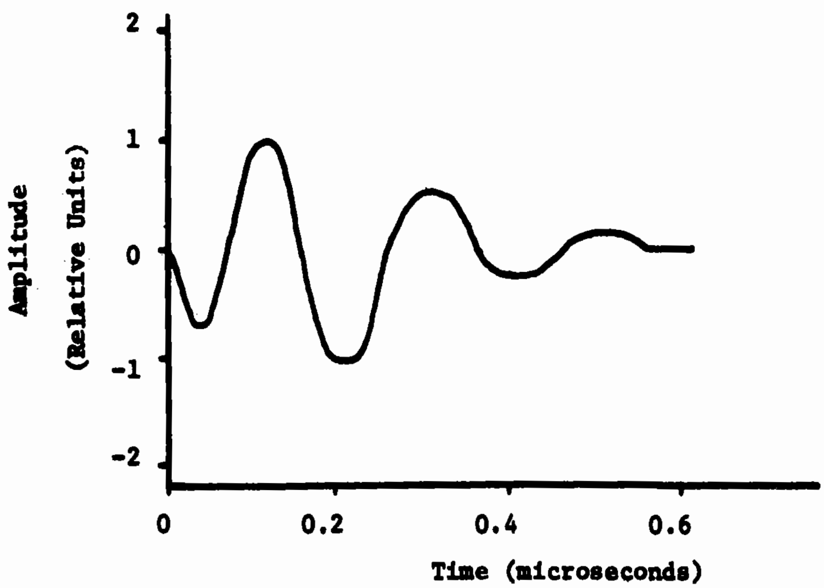


Figure 2. Ultrasonic Input Pulse.

The pulse shape that was used for a large majority of our work is shown in Fig. 2. It is a three-cycle, asymmetrical, well-damped pulse that has a center frequency of six megahertz. The fast Fourier transform of this pulse is illustrated in Fig. 3. This calculated frequency spectrum was in good agreement with the analog spectrum analyzer results of the actual pulse.

Plotted in Fig. 4 is the ratio of the peak-to-peak amplitudes of the ultrasonic signal reflected off the thin layer to the top surface signal versus the thin layer thickness over wavelength. This is the case for an aluminum-water-aluminum system, only one of the many cases studied. For normalization purposes the ultrasonic wavelength at the center frequency of the input pulse in the thin layer material was used. In this case the wavelength is 0.24 mm.

I want to stress that these values in Fig. 4 are the theoretically derived values of the peak-to-peak amplitude of the reflected rf signals. Experimentally, we are still doing some further studies to try to develop more confidence, but initial experiments showed that our model, in fact, was adequate for smooth planar surfaces and well-defined acoustic properties of the thin layer system.

It should be noted that continuous wave theory predicts that destructive interference would occur at integral values of layer thickness over twice the wavelength. Due to the finite time duration of the pulses typically used for ultrasonic inspection, it is necessary to consider the ramifications of transient behavior in addition to steady-state continuous wave conditions.

Unfortunately this complicates things, though, if we look at different pulse shapes. Fig. 5 illustrates the results of changing the input pulse to three constant amplitude cycles at five megahertz center frequency. Due to the longer pulse duration, there is constructive superpositioning at greater thicknesses of the thin layer, but eventually it, too, reaches a level value. Again, this is peak-to-peak amplitude and not the integrated signal. This potential variation in response with pulse characteristics was one of the reasons for performing the majority of the experimental program with one pulse shape.

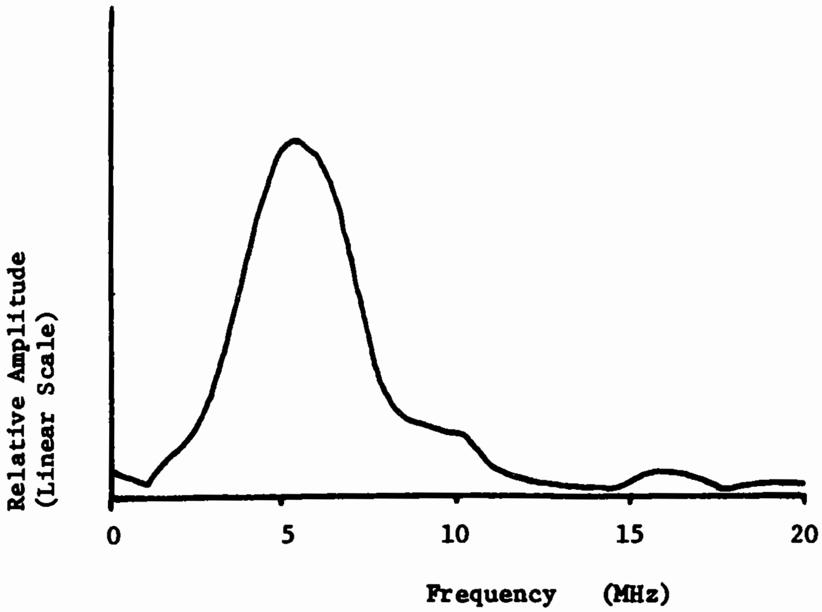


Figure 3. Fourier Transform of Input Pulse.

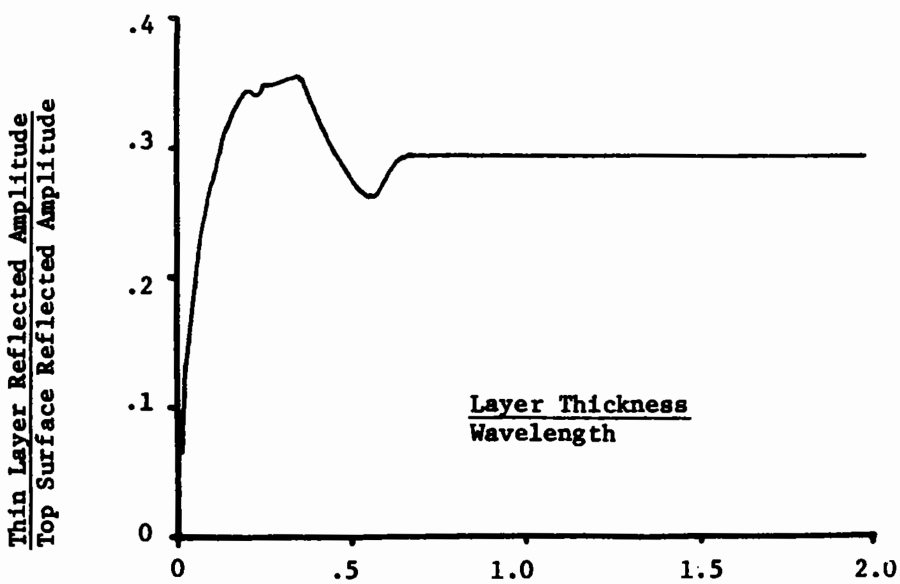


Figure 4. Peak-to-peak reflected amplitude as a function of layer thickness for input pulse in Figure 2. in an aluminum-water-aluminum model.

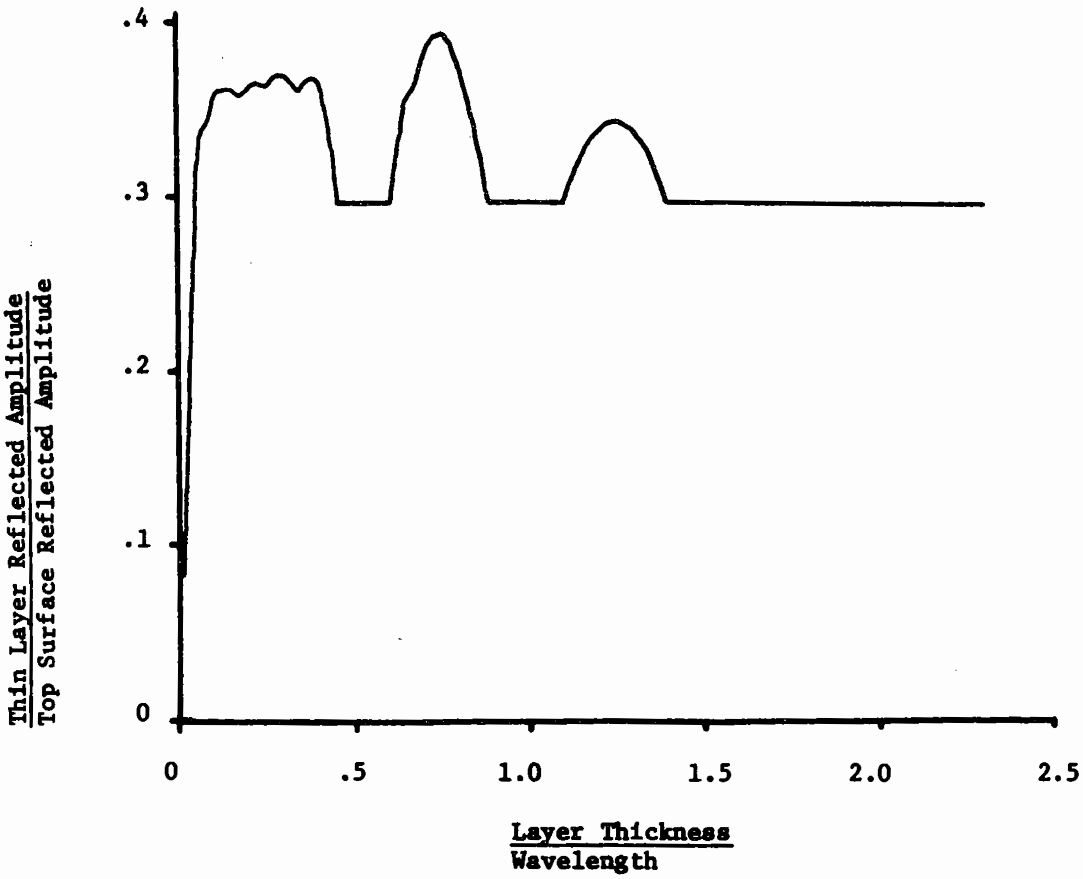


Figure 5. Peak-to-peak reflected amplitude as a function of layer thickness for a 3 cycle, 5MHz input pulse in an aluminum - water-aluminum model.

Experimental Program

The compact tension specimen configuration as defined in ASTM E-399-72 was used to study ultrasonic wave fatigue crack interaction. This specimen simulates well the theoretically described conditions. One material used was 7075-T651 aluminum alloy one-inch thick. The cracks were extensively characterized under various conditions by pulse echo, immersion ultrasonic inspection. RTV silicone was used to keep water out of the crack.

Scans were made at several positions across the width of the samples and reflected amplitude data were taken at small increments along the crack plane to essentially map out the reflected energy from many points along the crack surface.

Representative results from one test are shown in Fig. 6a. In this case the fatigue crack was grown at a constant stress intensity of 15 ksi $(in)^{1/2}$. The position indicator zero is nominally at the notch tip and the crack tip would be at the right of the figure. This particular data set was taken down the centerline of a one-inch specimen with a quarter-inch diameter transducer with pulse characteristics given in Fig. 2. Edge effects of the sample would be minimized in this situation.

In an effort to show the importance of crack closure in ultrasonic inspection, the sample was fractured, replaced in the immersion tank, and scanned under the same conditions as above. Figure 6b gives these results for the same sample as in Fig. 6a. The A and B corresponds to inspection from one side or the other of the sample. It is important to note that the shape and amplitude over the crack is preserved indicating minimal effects due to crack closure away from the crack tip. The reference line shown on the figure indicates the relative amplitude from a water-polished aluminum-air system. It shows the nominal reflected amplitude from a smooth surface the same distance away in the same alloy. The reason that amplitude is on the order of .17 instead of approximately 0.3 as was predicted by the model (Fig. 4) is due to beam divergence and attenuation which were not accounted for. Empirically it was shown that as the thickness of the material goes down, the measured amplitude ratios tend to reach the theoretically predicted results.

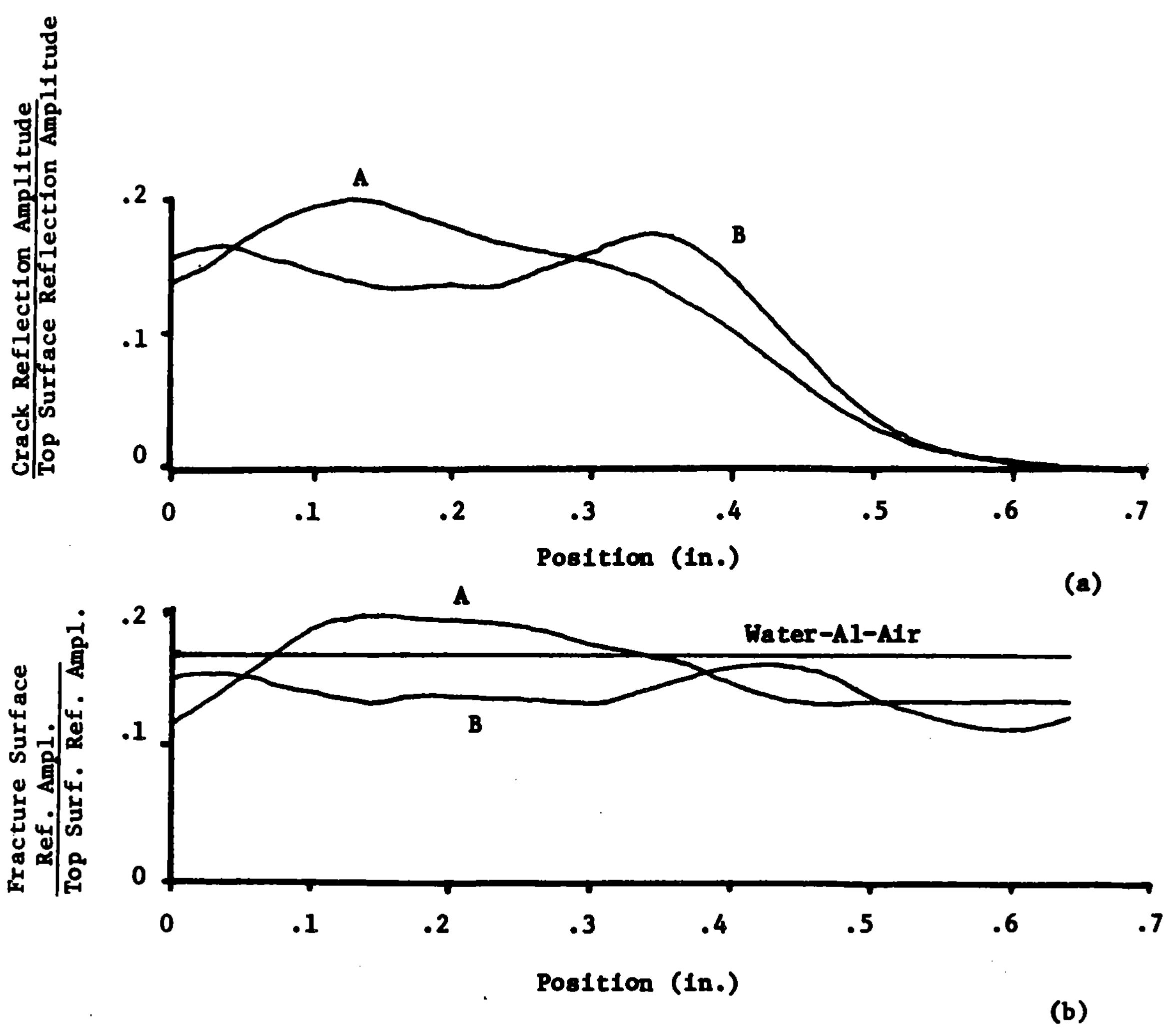


Figure 6 (a). Pulse echo scan along centerline of a one inch thick compact tension specimen. A and B indicate opposite faces of crack.

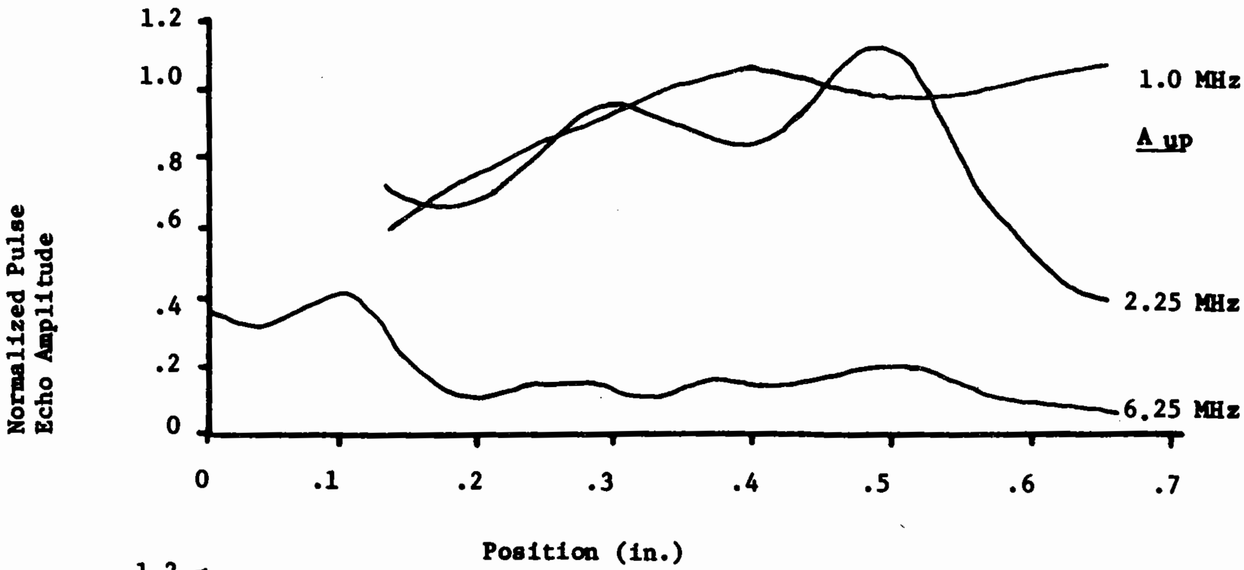
(b). Same as (a) but after fracturing specimen.

It can be seen that the reflected amplitude from one side of the crack surface is actually greater than that obtained from a smooth surface in the same material. Due to the apparently strong dependence on position of ultrasonic energy reflected from the crack surfaces, it was decided to scan the fracture surfaces directly.

Figure 7 represents these results on the same sample as above. Here the energy is coming directly from the water down to the fracture surface. Scans were done at three different frequencies to assess the wavelength dependence of the scattering process. These values are normalized to the amplitude of reflections from a polished sample of the same material. It is obvious that fatigue crack surface shape plays a major role in the ultrasonic reflection process.

Three types of measurements were made on the fracture surfaces in an attempt to understand the ultrasonic reflection process. These measurements were made by replication fractography, profilometer tracing and by height measurements in a 0.1" x 0.1" grid on the fracture surface. An analysis of these results indicated that the third technique revealed more information relevant to the ultrasonic results obtained. This plot for the specimen under discussion is shown in Fig. 8. One can see from this plot that the transducer is going over a surface that can act as a concave or convex mirror reflector. It is possible to qualitatively relate the ultrasonic results shown previously to the macroscopic features of this surface.

On the basis of several tests in 7075-T651 compact tension specimens relatively little effect on reflected ultrasonic energy was noted due to applied tensile stress. The changes which were observed were in areas near the crack tip where the influence of the plastic zone would be greatest. Order of magnitude changes in ultrasonic response that have been reported in the literature for part through cracks were not observed in this case. Applied compressive loads, however, did cause considerable decreases in signal amplitude.



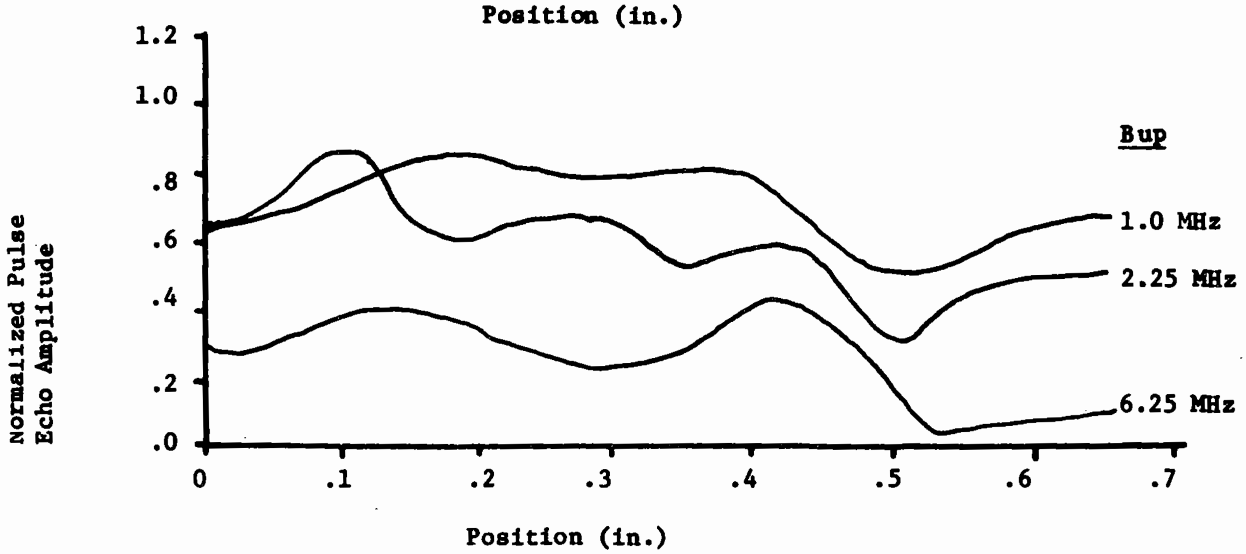


Figure 7. Reflected Ultrasonic Amplitude From Fracture Surfaces vs Position

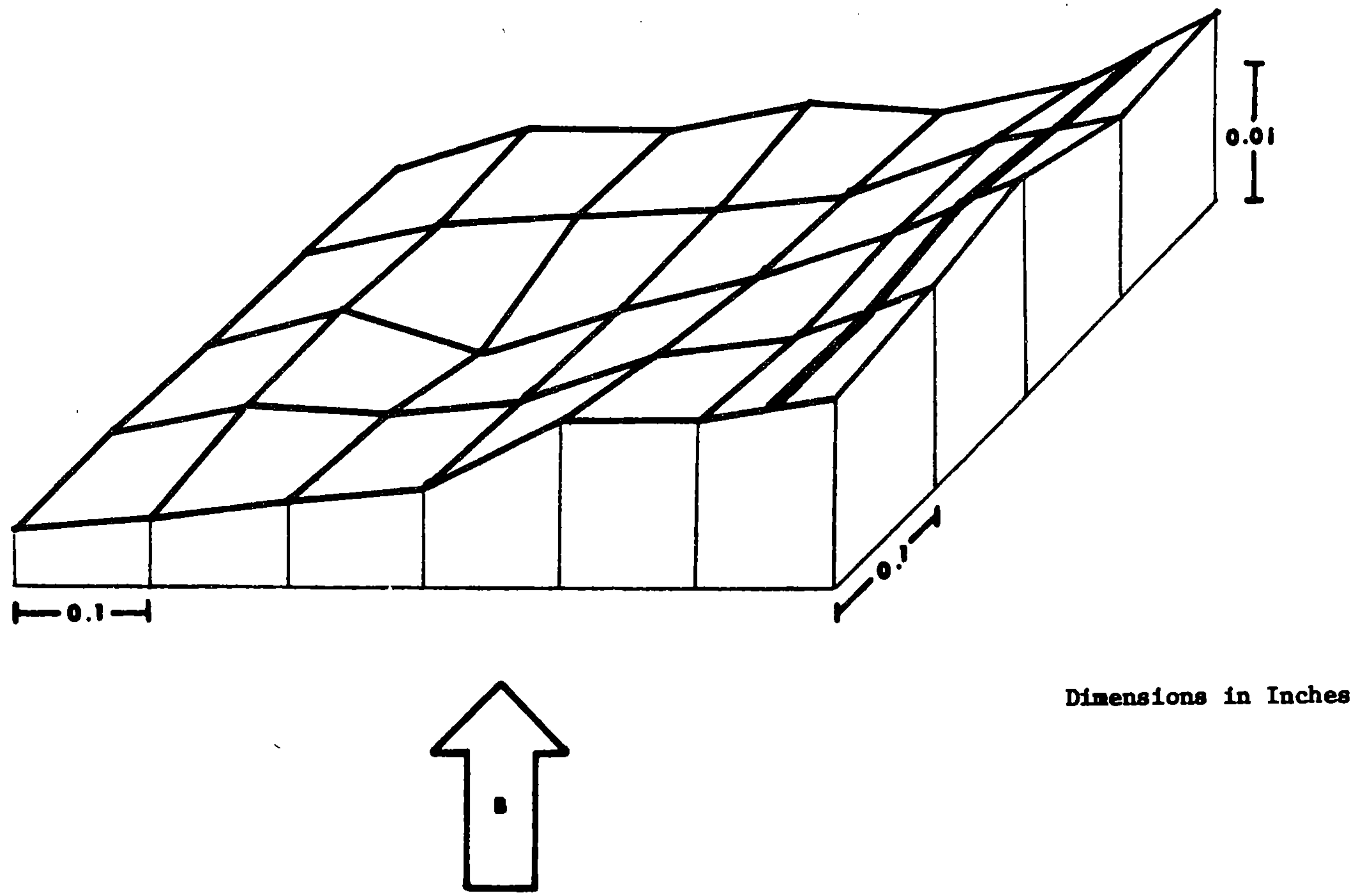


Figure 8. Topographical Illustration of Fatigue Crack Surface in 7075-T651 Aluminum Alloy.

Along these same lines crack growth stress intensity did not affect the average ultrasonic reflected amplitude over a range of growth stress intensities from five ksi (inch) ½ to twenty ksi (in) ½ . Therefore, in this size crack, it was not possible to relate crack growth stress intensity to the ultrasonic amplitude. Under this case, the geometrical variations in the crack surface exhibit a far greater influence on ultrasonic reflected energy.

In order to more directly assess the crack tip behavior under variable amplitude fatigue conditions a test program has been initiated. A few preliminary observations will be discussed. In situ through transmission ultrasonic measurements on a MTS fatigue machine are being made on compact tension 2024-T851 aluminum specimens. The ultrasonic measurements made through the center of the specimen in the plane strain region of the crack tip, are compared with optical crack surface displacements. The intent of this effort is to understand the relationship between crack growth rate and such variables as peak stress overloads, hold times, cyclic stress intensity and crack closure stresses.

A schematic of the optical interference method being used for surface measurements is given in Fig. 9. This technique, developed by Dr. W. N. Sharpe, make it possible to obtain the crack with a resolution of 0.1 microns. Therefore, using this method it is possible to obtain very detailed information about the behavior of the crack at the free surfaces of the specimen following changes in the loading spectra.

Simultaneous with the optical measurements, ultrasonic through transmission characteristics in the region of the crack tip are recorded. Longitudinal wave 2¼ and 5 MHz transducers with ¼ inch diameter active areas have been used to both transmit and receive the ultrasound. A pulse burst oscillator is used to excite the transmit transducer with a one microsecond duration pulse.

Figure 10 shows a schematic representation of the results of these experiments to date. These results are from one inch thick specimens with the

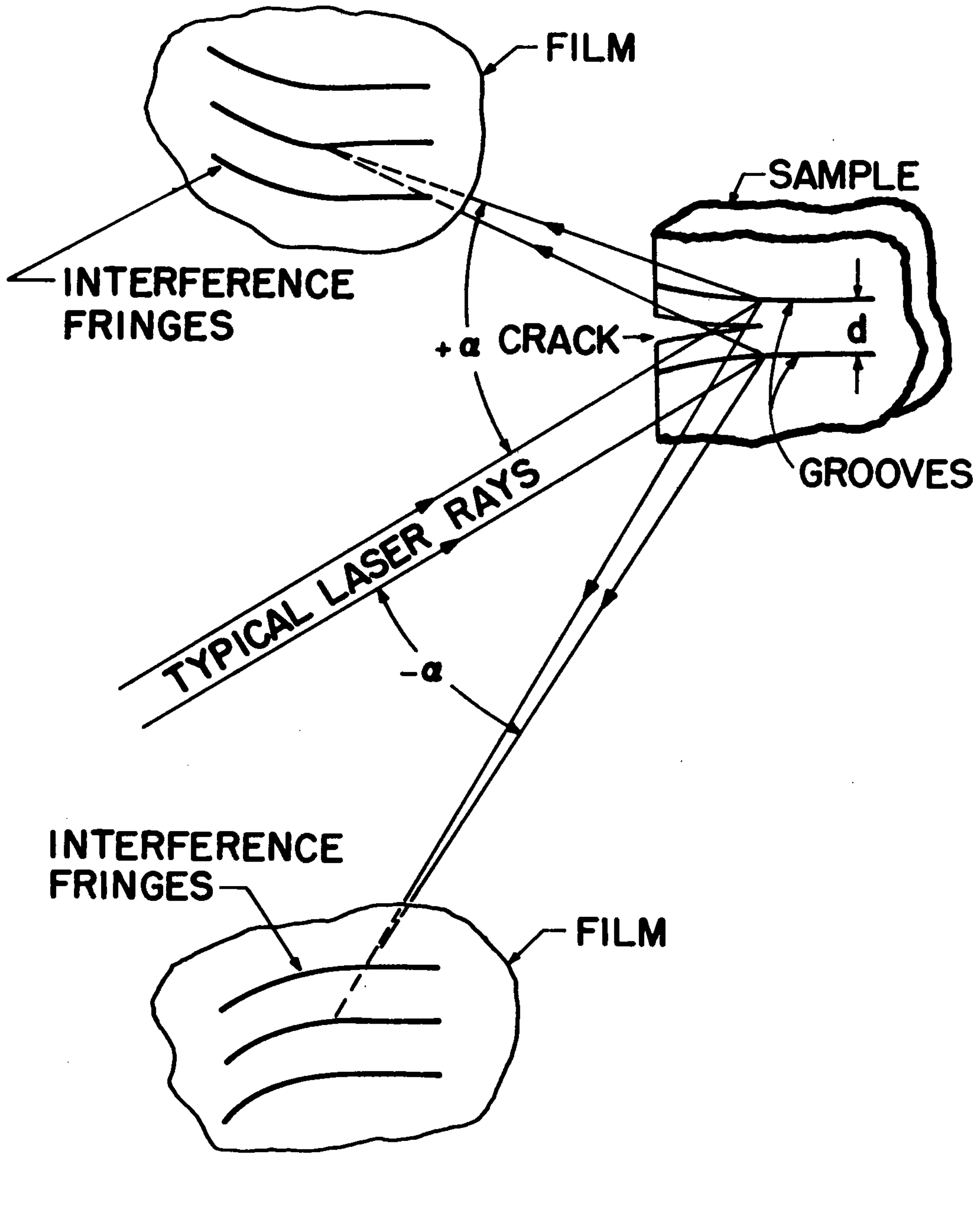


Figure 9. Schematic of the laser interferometric displacement technique. d is typically 0.51mm (0.020 in.), and α is typically 65°.

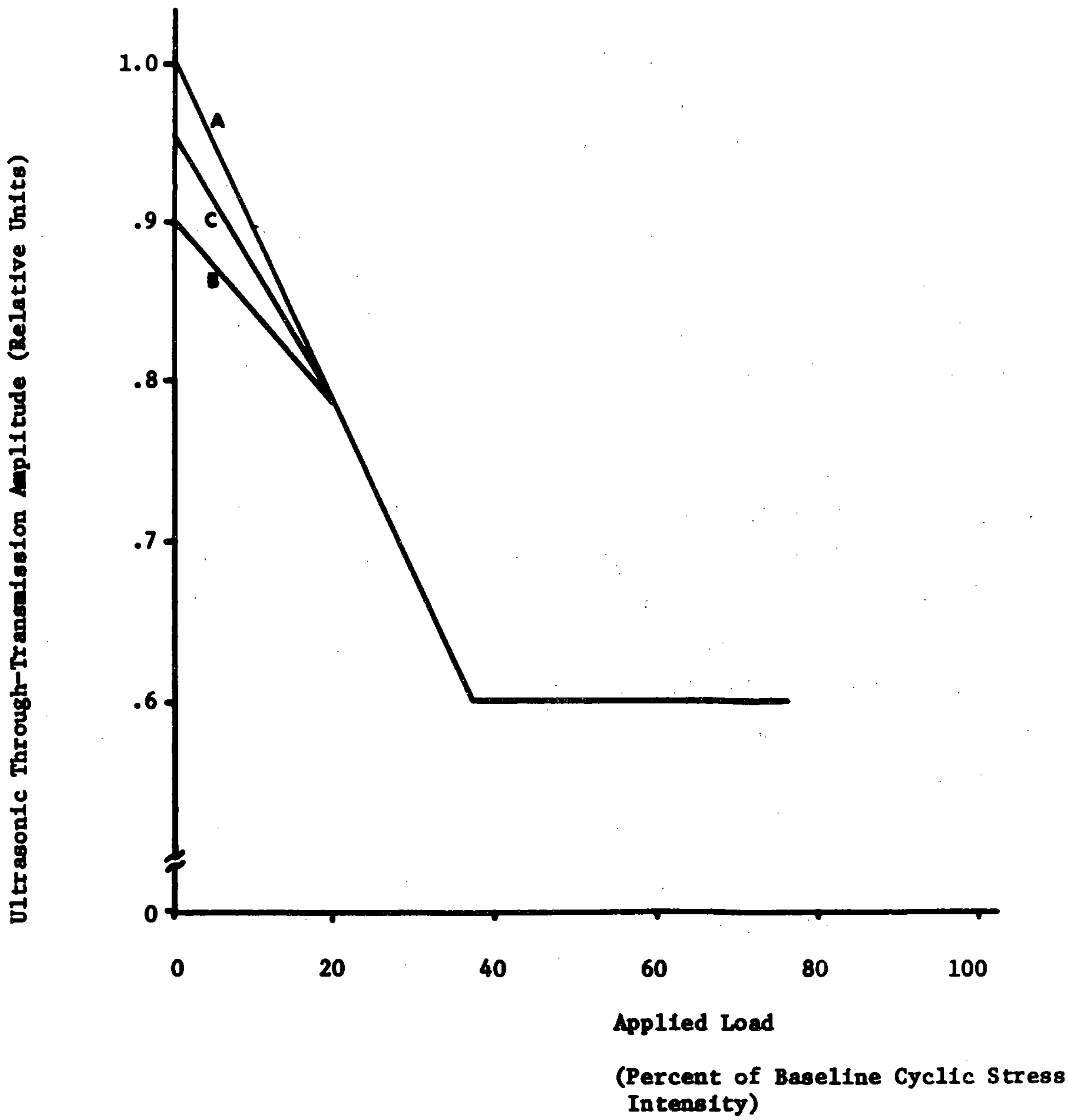


Figure 10. In Situ Through Transmission Ultrasonic Measurements in Compact Tension Specimen of 2024-T851 Aluminum Alloy.

transducers located on the centerline. This plot shows the RF peak-to-peak transmitted ultrasonic amplitude on a relative scale versus applied tensile load given as a percentage of the cyclic growth stress intensity (ΔK = ksi $(in)^{1/2}$ in this case.

Since changes in crack closure should occur following changes in the cyclic stress history of the crack, it was decided to study the crack opening behavior before and after the application of a single peak overload. Curve A in Fig. 10 is the ultrasonic response immediately before overload. Curve B results from measurements taken immediately after the application of an overload of up to three times the baseline cyclic stress intensity. Curve C is obtained following a rest period at zero load of one hour after the overload. Following rest periods of greater than 24 hours the results are coincident with Curve A.

A couple of observations about these results are worth noting. Although the optical measurements on the surface indicated an increase in the load required to fully open the crack after the overload, the ultrasonics indicated that the interior portions of the crack were actually more open for small applied loads, thus allowing less ultrasonic transmission. This effect appears to be related to a relaxation mechanism which affects the crack tip opening displacement. The overall shape of the curve does, however, indicate that some type of closure mechanism is operative which results in the stress dependency of the ultrasonic transmission characteristics.

In summary, there are many subtle aspects to the nature of ultrasonic wave fatigue crack interactions which are just beginning to be understood. It is important that research in this area be stimulated because of the potential to improve both the understanding of fatigue crack growth mechanisms and ultrasonic flaw characterization methods.

DISCUSSION

DR. MICHAEL J. FELIX (Purdue University): In your pulse echo stuff, of course, the surface roughness or crack roughness is really a relative thing that is dependent upon the wavelength of sound that you are using. Did you do any of these scans at significantly higher or lower frequency than the six megahertz that you talk about?

DR. CORBLY: No, unfortunately, we didn't. We did go down to approxiamtely one megahertz nominal center frequency and still noticed the variation to some extent. It was just a physical problem of time and availability of equipment. We hope to expand on that.

I should say the roughness is highly dependent on the crack growth orientation and the grain structure of the material, not on the stress intensity which the crack was grown. The observed effects are on a scale much larger than the fatigue striations involved in the crack growth.

MR. JOHN R. BARTON (Southwest Research Institute): Would not the compact specimen that you used, perhaps, show less influence with applied stress than, say, a penny-shaped crack?

DR. CORBLY: Quite possibly it could, based on simple area considerations for one reason. A larger fraction of the penny-shaped crack would be exposed to crack tip plasticity influences which could affect it more. I think we have go to think about a break point where small flaws could potentially be highly affected by flaw-growth history and larger ones where the effects might be negligible. Where we draw the line is still somewhat nebulous.

DR. WILLIAM SCOTT (Naval Air Development Center): You talked about modeling pulses traveling through media and you showed amplitudes of pulses. What are these amplitudes? Are they amplitudes of electrical signals or are they acoustical signals?

DR. CORBLY: They are amplitudes of electrical signals. We hope that some future research will be undertaken to help relate this to the actual acoustical displacement fields. For now, I am assuming we have a linear relationship between electrical pulses and ultrasonic stress pulses.

PROF. H. TIERSTEN (Rensseller Polytechnic Institute): Why did you use such short pulses rather than longer pulses; what was the advantage?

DR. CORBLY: We did want to extend this work into frequency spectrum analysis and, therefore, we wanted to have as much useable frequency content as possible so we could get more information from each test. It turned out that frequency analysis for these types of flaws was really not significantly more informative than RF pulse height analysis.