EFFECTS OF CRACK CLOSURE ON ULTRASONIC TRANSMISSION

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ABSTRACT

Ultrasonic waves are attenuated as they propagate past the tip of a crack due to the reflection of the energy at the crack face and diffraction at the crack tip. Crack closure modifies the situation since partial transmission can occur at points along the crack face where asperities come in contact. This phenomenon is important in defining the ability to nondestructively detect closed cracks and in developing a more detailed understanding of the closure phenomenon itself. Modified compact tension specimens were used to investigate the effects of partial crack closure on focussed, through-transmission ultrasonic signals. Data obtained from fatigue cracks in 7075-T651 Al provides evidence for a gradual transition from a fully closed crack condition at the crack tip to an essentially fully open condition at a distance of a few mm from the tip, with additional localized contact along the length of the crack. This interpretation of the data was aided by a two-dimensional, quasi-static model for ultrasonic interaction with a partially contacting interface. The model relates width and separation of asperity contacts to the frequency dependence of the ultrasonic reflection and transmission. These measurements were supplemented by tests in which water infiltrated into the crack opening. The frequency spectra of the ultrasonic transmitted signals for this case were used to estimate the average COD at various points along the crack length.

INTRODUCTION

Crack closure during fatigue crack propagation could be caused by a number of physical phenomena that are generated in the vicinity
of the subcritically moving crack tip [1]. Aside from any enhancement of closure due to formation of corrosion deposits, there are strong indications now that asperity contact [2,3] (or microroughness [1] in the wake of the crack tip and residual stress patterns produced in the plastic zone ahead of the crack tip [4] are major contributors to crack closure. The asperities may be due to some residual strain [5,6], but they are predominantly Mode I displacements [6,7,8]. The residual stresses are generated due to the inability of the material to support the stress singularity at the crack tip as a tensile load is applied (see Fig. 1). For a perfectly elastic material (with no work hardening) the stress could not exceed the (tensile) yield stress, $\sigma_y$, of the material. This leads to a "forward plastic zone". As the tensile load is released, a small portion of this zone goes into compression, not exceeding the compressive yield stress, $-\sigma_y$,* and leading to a "reversed plastic zone". Figure 1 shows the development of the residual stresses in front of the crack tip. These residual stresses continue behind the crack tip, as is discussed in more detail in a companion paper [9].

This paper examines the interaction of an ultrasonic wave with such a closed crack. The purposes are two-fold. In the nondestructive evaluation community, it is well known that crack closure can reduce the strength of ultrasonic signals reflected from the crack faces or diffracted from the crack tip. This can lead to nondetection or undersizing of serious flaws. It is essential to quantify the magnitude of these effects and their relationship to the microstructural, environmental, and loading influences on the crack topology so that ultrasonic measurements can be more correctly interpreted.

The details of the crack closure phenomena, which can be sensed by their influences on the ultrasonic signals, are also of interest to the fatigue and fracture mechanics communities. The authors believe that such information can be very important, not only to explain the effects of environment and spike overloads, but also to provide an effective means for fatigue life prediction.

It has been observed acoustically that the crack closure stress can be drastically affected by the external variables of environment and overloads [10,11]. The observations have then been used as an indication that, at least in some simple cases, the "effective stress intensity range" $\Delta K_{eff}$ is equal to the difference of maximum stress intensity and stress intensity at the point of crack closure. In this case, the useful life $N$ can be calculated by an integration of the propagation rate $da/dn$ such that the fatigue crack length $a(N)$ does not exceed a critical value $a_c$. $N$ is thus the solution

*The compressive yield stress may or may not be just the negative of the tensile yield stress.
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Fig. 1. Stress profiles ahead of crack tip.

of the equation

\[ a(N) = a_0 + \int_{N_0}^{N} \frac{da}{dn} \, dn = a_c \]  

(1)

where \( \frac{da}{dn} = c'(\Delta K_{eff})^{m'} \), \( \Delta K_{eff} = (\sigma_{\text{max}} - \sigma_c) f(a) \), \( c' \) and \( m' \) are material parameters, and the crack had a length \( a_0 \) after \( N_0 \) cycles.

However, our understanding of the interaction of the incident acoustic wave with a true crack that may be partially closed is still very limited. Certain progress over the past few years in the development of more sophisticated acoustic techniques as well as signal processing make it now possible to readdress these problems [12]. In the following we report on some recent experiments and on the modeling of the observed results which yield some information on the behavior of the acoustic transmission coefficient of true fatigue cracks.

EXPERIMENTAL PROCEDURES AND RESULTS

Two compact tension specimens of 7075-T651 Al composition were fatigued to grow cracks with lengths 0.0633 m and 0.0563 m. At suitable intervals fatigue loads were reduced to approximate \( \Delta K_I = 9.3 \) MPa \( \sqrt{m} \) and \( \Delta K_I = 11.6 \) MPa \( \sqrt{m} \), respectively. Following fatigue
crack growth the compact tension specimens were machined to allow focused transducers to interrogate the crack at normal incidence. Figure 2 shows a schematic of a modified compact tension specimen and the experimental configuration used to scan the fatigue crack. The starter notches and cracks were sealed in silicone caulking to prevent water in the ultrasonic scanning tank from entering the crack.

A longitudinal ultrasonic beam was nominally focused on the fatigue crack surface, and the through-transmission signal was monitored as the sample was translated relative to the beam. At each of the positions where signal amplitude data were recorded, the received through-transmission waveform was digitized at a 10 nsec sampling rate using a Tektronix digital processing oscilloscope. The data was stored for further processing in a Tektronix 4052 desktop computer. The transducers had nominal diameters of 1.27 cm and focal lengths of 10 cm in water. Since the focal length in aluminum is shortened by the ratio of the sound speeds, the shape of the compact tension specimen had to be modified as shown to allow the beams to be focused at the position of the fatigue crack. Longer focal length transducers could have been used. But these would have had poorer transverse resolution, since the beam width (to the first null) of a focused beam is equal to $1.2 \left( \frac{F}{a} \right) \lambda$, where $F$ is the transducer focal length, $a$ is the transducer radius, and $\lambda$ is the wavelength. At the 10 MHz center frequency of the transducers used, this beam width is computed to be equal to 2.8 mm. (Note that the resolution is the same in water or aluminum since $F$ and $\lambda$ scale with velocity in reciprocal senses.) The modification of the sample has the additional benefits of reducing grain scattering and attenuation effects by decreasing the amount of metal traversed by the beam.

Figure 3 presents a plot of normalized peak transmitted ultrasonic signal versus position for sample 1. Note that the vertical scale is logarithmic. The coordinate $z$ is measured from the end of the compact tension specimen, as shown in Fig. 2. Data were taken from the end of the specimen ($z=0.0$ m) to a position close to the crack mouth. Data are shown for a calibration saw slot of $3.05 \times 10^{-4}$ m thickness, for sample 1 ($\Delta K_I = 9.3$ MPa $\sqrt{m}$) with a slight (unspecified for reasons to be discussed subsequently) tensile load applied, and for sample 1 with the fatigue crack filled with water. In each case, the peak signal has been normalized to be equal to unity when no crack is present. The dip in the peak signals for the fatigue crack for values of $z < 6.35 \times 10^{-3}$ m is caused by the fact that a portion of the focused ultrasonic beam was not entering the specimen at those positions. The value of $z$ for which the normalized signal is 0.5 is taken as an approximate measure of the position of the end of the sample. The plateau at peak signal strength, then, represents the signal received through the uncracked ligament
Fig. 2. Experimental configuration.

Fig. 3. Transmitted ultrasonic amplitude versus position for sample 1.
between the backface of the sample and the crack tip. As the beam encounters the crack tip, a rapid signal dropoff occurs.

The signal amplitude for the calibration saw slot drops off most rapidly since, past the notch tip, the gap between the slot faces is too large to allow transmission. One might expect the transmission to change abruptly from unity to zero. The more gradual decrease is caused by the finite width of the focused ultrasonic beam. Note that the beam decreased from 90% to 10% of its peak value in a distance of 3.1 mm, which compares favorably with the theoretically expected beam width. The continued decrease in the calibration signal over the next cm is believed to be a result of beam side lobes, which produce measurable transmissions as low as 50 dB down at the greater distances. This calibration curve will be considered to be a measure of the spatial response of the system.

For sample 1 in the dry crack case with tensile load applied, the signal amplitude vs. position curve (Fig. 3) exhibits two interesting differences from the calibration data. First, the rate of decrease in signal strength versus z is slower than that of the calibration saw slot. The two were fitted to match the peak signal values between 0.5 and 1. The slower decrease of the crack transmission at larger z is evident. This is presumed to be a result of a gradual transition from the uncracked to the open condition. The width of this region (2-3 mm) is taken as a measure of the partially closed region near the crack tip.

The peaks in the transmission at greater distances from the crack tip are a second difference from the calibration data which suggests that some contact between the crack faces occurs along the entire length of the crack. This hypothesis was explored by monitoring one of the signals as the load was varied. Removal of the tensile load caused the through-transmission to increase, which is evidence for more complete contact between the crack faces. Application of an unspecified compressive load further increased signal amplitude and contact. Removal of the compressive load reduced the signal, although it did not drop to the previous amplitude. This could be due to local plastic deformation of the asperities and/or a change in the plastic zone at the tip of the crack. Allowing the sample to rest overnight, with no load applied, again produced an increase in amplitude, indicating crack closure caused by relaxation of the plastic zone. Similar behavior was observed at other points along the crack. This demonstrated that the through-transmission scan is, in fact, sensitive to fatigue crack closure.

When sample 1 was exposed to water, a major increase in transmission along the entire length of the crack was observed. This
is presumably due to direct propagation through the thin liquid layer between the crack faces, as will be discussed in the next section.

Figure 4 shows focussed beam, through-transmission ultrasonic signal amplitude vs. position data for sample 2 ($\Delta K_I=11.6$ MPa $\sqrt{m}$). No load was applied to the crack at this time. Behavior is shown to be qualitatively similar to specimen 1, with the exception that transmission was not observed along the entire length of the dry crack. The reason for this difference has not yet been established.

In a second set of measurements, the transmitter was left fixed but the receiver was translated and placed at an angle as shown in Fig. 2. In this configuration, the received signal is produced by a series of mode conversions. The first mode conversion of interest occurs at the crack where the incident longitudinal wave is partially converted into an obliquely propagating transverse wave (L+T). This slower moving transverse wave then mode converts at the specimen/water bath interface into a compressional wave that can be detected by the receiving transducer.

Fig. 4. Transmitted ultrasonic amplitude versus position for sample 2.
The fact that the off angle signal was produced by a transverse wave in the solid was confirmed by both the position and orientation of the receiver required for maximum signal strength, and the added time delay with respect to the previous measurements caused by the slower velocity of transverse waves. In these mode conversion measurements an unfocussed receiving transducer (10 MHz, 1.27 cm diameter) was found to produce cleaner signals than the focussed receiver.

After the no load fatigue crack data were obtained, sample 2 was placed under successively greater compressive loads applied by bolt loading the specimen. The extent of loading was determined by measuring the crack opening displacement (COD) \[4\] at the sample mouth. Due to the modified sample geometry we cannot calculate a value for the compressive load, based on a change in the COD. The approach, however, does provide a means of applying a controlled increase in compressive load to the sample. The amplitude vs. position curve for a $\Delta$COD of $7.62 \times 10^{-5}$ m is shown in Fig. 5 for both the L→L longitudinal wave through transmission and the L→T mode converted signal. The z-coordinate of the two graphs is identical, i.e., for a given value, the incident beam illuminated the

Fig. 5. Transmitted and mode converted ultrasonic amplitude versus position for sample 2 under compressive load.
same position on the crack within experimental reproducibility. Also shown are the calibration data for the two cases. The L→L calibration data was positioned to match the peak of the fatigue crack data. The broadening of the L→L signal is again observed, with a greater change than in the data shown previously. The L→T signal is also broadened, and shows a definite asymmetry. This asymmetry has also been observed in several other sets of data for different values of ΔCOD.

ANALYSIS AND DISCUSSION

In order to aid in the interpretation of the experimental data, theoretical analysis of the interaction of ultrasonic waves with interfaces in partial contact and with fluid filled interfaces has been performed.

The crack closure model represents the fatigue crack as having rough fracture surfaces. These surfaces meet periodically at asperities which prevent total closure, and create voids over the fracture surface [3]. A quasi-static model for the interaction of an ultrasonic wave with such an interface has been developed. This model, which replaces the region of partial contact by a distributed interface stiffness, K, is summarized below.

Figure 6 shows schematically a localized region of partial contact. W is defined to be the asperity width, and S to be the asperity separation distance. It is assumed that \( \lambda \gg W, S \) where \( \lambda \) is the incident ultrasonic wavelength. Hence, it is appropriate to view the interface as a continuum and seek effective boundary conditions that will govern its influence on ultrasonic waves. On either side of the interface, define the average stress to be \( \bar{\sigma} \) and the average position of that interface to be \( \bar{u} \). Conservation of force requires \( \bar{\sigma} \) to be continuous. However, from static elasticity, it is known that there will be an added deformation beyond that for a perfect interface due to the lack of perfect bonding. This concept is generalized to an effective boundary condition

\[ \bar{\sigma} = K \Delta \bar{u} \]  

where \( K \) is a distributed interface stiffness, and \( \Delta \bar{u} \) is the difference in displacement across the interface. Here \( K \) is treated as a scalar, but the tensor generalization needed to treat more complex wave fields is straightforward. Note that when \( K \to \infty \), \( \Delta \bar{u} = 0 \) and Eq. (2) reduces to the familiar result for perfect contact. When \( K \to 0 \), \( \bar{\sigma} = 0 \) and a stress free surface is described.

In reality, one would expect the stiffness, \( K \), to vary as a function of distance from the crack tip. However, for conceptual
Fig. 6. Model of localized partial contact near crack tip.

Incidence with $K$ being constant. If the average wave displacement fields have the form of an incident, reflected ($r$), and transmitted ($t$) plane wave as shown in Fig. 7a, the continuity of average stress at the interface implies that

$$\bar{\sigma}_1 = -ik\rho v^2 + ik\rho v^2 r = \bar{\sigma}_2 = ik\rho v^2 t$$

(3)

where $\rho$ is the density, $r$ is the reflection coefficient, $t$ is the transmission coefficient, $v$ is the longitudinal wave speed, and $i = \sqrt{-1}$.

Combining Eqs. (2) and (3), one obtains a second relationship between $t$ and $r$

$$\bar{\sigma}_2 = ik\rho v^2 t = K(\bar{u}_2 - \bar{u}_1) = K[t - (1+r)]$$

(4)

The reflection coefficient and the transmission coefficient may then be obtained by simultaneous solution of the equations with the results
Fig. 7. Interaction of a plane wave with a partially contacting interface.

a) Definition of terms

b) Transmission coefficient versus frequency.

\[ |t| = \frac{1}{\left[1 + \left(\frac{\pi f_0 v}{K}\right)^2\right]^{\frac{1}{2}}} \rightarrow \begin{cases} 
1 \text{ as } f \to 0 \\
K/\pi f_0 v \text{ as } f \to \infty
\end{cases} \quad (5) \]

\[ |r| = \frac{\left(\frac{\pi f_0 v}{K}\right)}{\left[1 + \left(\frac{\pi f_0 v}{K}\right)^2\right]^{\frac{1}{2}}} \rightarrow \begin{cases} 
\pi f_0 v/K \text{ as } f \to 0 \\
1 \text{ as } f \to \infty
\end{cases} \quad (6) \]

These results predict that the low frequencies will be preferentially transmitted, as shown in Fig. 7b and that the high frequencies will be preferentially reflected.

Thus far, the interface stiffness $K$ has been treated as a phenomenological constant. In order to relate this to the details of the region of partial contact, a two dimensional periodic model
of the interface is applied (Fig. 8a). This is not meant to be a rigorous representation of a three-dimensional partial contact region, but rather an idealization that will illustrate the basic forms of the dependence of $K$ on contact dimension $W$ and separation $S$. As a further approximation, one unit cell of the two dimensional interface is replaced by a strip (Fig. 8b). Simple analytical solutions for the additional displacement of such a strip under static loading, beyond that for the crack free case, are available [13]. By comparing these solutions to Eq. (2), one concludes that

$$K = \frac{E}{2(S-W)} \left\{ 1.071[-1- \frac{1}{\alpha} \ln(1-\alpha)]+0.25\alpha-0.357\alpha^2+0.121\alpha^3+... \right\}^{-1} \quad (7)$$

where

$$\alpha = \frac{(S-W)}{S}=1-W/S, \quad (8)$$

and $E$ is Young's modulus. Similar relationships can be obtained for shear deformations at the interface as would be required for the previously mentioned tensor generalization of $K$ to treat non-normal or non-plane wave illumination.

Using Eqs. (5) and (7) an expression is now available which contains a pair of $W$ and $S$ values, defining asperity dimensions and separation. Thus, specification of $W$ and $S$ allows $|t|$ to be theoretically predicted. Note, however, that there is a locus of $(W,S)$ pairs which all produce the same value of $K$. One such locus is shown in Fig 8c. Thus, an experimental determination of $K$ is not adequate to determine $W$ and $S$ individually, and additional information is required at higher frequencies such that the quasi-static approximation, $\lambda \gg W,S$ breaks down.

Figure 9 represents the results of an experimental determination of $K$ at the position denoted by 1 in Fig. 3. The dashed curve in this figure represents the spectrum of the reference signal obtained when the beam propagates through the continuous ligament region (0.013 m). The solid curve shows the result of dividing the spectrum of the signal transmitted through point 1 by that of the reference signal, thereby obtaining the transmission coefficient of the crack, independent of the spectrum of the transducer. The attenuation of the high frequencies is obvious. The dotted curve is the result of a fit to the theoretically expected behavior, as predicted by Eq. (5). From this fit, a value of $K/\pi \rho v$ of 0.95 MHz is obtained, or $K=5.1 \times 10^{13} N/m^2$. Thus, if the contacts were a two-dimensional structure, $W$ and $S$ would be expected to fall on a locus quite close to the one shown in Fig. 8c. The combinations of $W$ and $S$ which fall in the lower range of the locus, e.g., $W=5 \mu m$ and $S=200 \mu m$, appear to be of the correct order of magnitude.
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Fig. 8. Two dimensional model relating interface stiffness to contact width and separation
a) Periodic contact model
b) Single strip model
c) Locus of W and S having K=4.5x10^{13} N/m^2 for single strip model.

It should be noted that a partial interception of the beam by the tip of an unclosed crack would also produce a frequency dependent signal. However, it is believed that the phenomenon would make only a small contribution to the data in Fig. 9 since the signal from the calibration slot is 13 dB lower than that from the fatigue crack at the comparable value of z, as can be seen by comparing the two curves in Fig. 3. A more detailed separation of these effects is the subject of present research.

The data presented in Figs. 3, 4, and 5 indicate that the tip of the crack is not a discrete edge, such as a slot, but is rather
Fig. 9. Experimental observation of decrease in transmission with frequency for partially closed crack and fit to compliant interface model.

a region in which a gradual transition to the fully open condition occurs. Furthermore, the width of this region appears to broaden under compressive loads. By comparing the fatigue crack to calibration slot data, the width of this region can be estimated to be on the order of 3 mm. This estimate is in qualitative agreement with previous estimates of closure induced changes in "apparent" crack depth in 7075-T651 aluminum under similar loading conditions, [10] and in 2219-T851 aluminum [14]. Measuring K versus position near the crack tip should provide more detailed information regarding the local changes which produce these macroscopic changes in apparent crack length.

When water is allowed to infiltrate into the crack, a longitudinal wave can be transmitted directly through the gap. If the water-filled crack is modeled as a planar structure as shown in Fig. 10, one finds that the transmission coefficient is given by:

$$|t| = \frac{1}{\sqrt{\left[\cos^2(k_w \ell) + \frac{Z_{0,w}^2 + Z_w^2}{2Z_{0,w}^2} \sin^2(k_w \ell)\right]^2}}$$  

(9)

where $k_w = \frac{2\pi}{\lambda_w} = \frac{2\pi f}{v_w}$, $Z_{0,w} = \rho_o \omega v_{0,w}$, and the subscripts "w" and "o" refer to the water and aluminum, respectively. For $k_w \omega \ll \pi/2$
This model may be fitted to a transmission coefficient vs. frequency curve for the water filled crack case to obtain the gap spacing $l$. Figure 11 shows such a determination at the point denoted by 2 in Fig. 3. The value of 0.031 mm is consistent with expectations for the CTOD. In this way, the average opening over the length of the crack may be found.
Equations (5) and (9) have the same frequency dependence, and an independent experimental means of differentiation transmission due to closure from fluid filled gaps is needed. This has been accomplished by transmitting shear waves through the gap. Partial contact will produce a shear transmission coefficient similar to that of longitudinal waves while a fluid filled gap will have no shear wave transmission at normal incidence. Hence, the differentiation is experimentally straightforward.

SUMMARY

Fatigue cracks in 7075-T651 Al samples were scanned using a through-transmission longitudinal focussed ultrasonic beam. In addition, mode conversion from longitudinal to transverse waves at the crack were monitored. By applying a compressive load, sensitivity of the through transmission scans to crack closure was demonstrated. By comparing the changes of these signals as the beams were scanned over the crack to those observed on a reference saw slot, it is concluded that there is a gradual, rather than abrupt transition from the fully closed condition at the crack tip to the fully open condition a few mm away. In addition, there is evidence for additional point contacts along the remaining length of the crack. Analysis of the frequency dependence of the transmission coefficient, based on a quasi-static model for a partially closed interface, appears to provide a technique for studying this transition region in greater detail in the future. If a fluid is allowed to enter the crack, analysis of the frequency dependence of transmission also allows a direct measure of the mean COD along the length of the crack.

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DISCUSSION

W.D. Rummel (Martin Marietta): A couple of other things you might want to consider at the crack tip are that the plastic zone is a scatterer of its own and is frequency dependent, and we have seen what would appear to be threading debris at the tip of the crack. You might want to include that in your scattering model if it appears that is what happens.

R.B. Thompson (Ames Laboratory): With respect to the plastic zone, I definitely agree with that, and we would like to do some experiments in which we remove the crack and just have the plastic zone and look at the scatterer by itself. I don't have a detailed model in my mind of what you mean by the crack debris. Perhaps we should talk about that a little later on.

S. Wolf (U.S. Department of Energy): I have a related question. You showed a schematic of a crack that looked as though it had opened and then closed, leaving residual pores, which were linked by some crack plane. Your last slide did not show that linkage of the pores, just the discrete pores ahead of the crack. If it is poor linkage, does it make a difference in the scattering?

R.B. Thompson: I didn't mean to imply that there was a stress-free linkage here. That's an intimate contact which is just where the crack happened to have been. I didn't mean to imply a difference between these two pictures. I imagine the picture to be a compressive stress which forces intimate contact as far as the ultrasonic wave is concerned.

S. Wolf: I think it relates, though, to Mr. Rummel's comment about whether there is a debris or a metal-metal bond.

B.F. Oliver (University of Tennessee): Did you add anything to the water to make sure you wet it down into the 1 mil crack?

R.B. Thompson: Actually, we seemed to have the opposite problem. Our problem was to keep the water out of the crack. No, we did not add any explicit additives, but I am sure that it was a water effect that was producing the results for the following experimental reason: we really differentiated that there was water in the crack as opposed to not as we shot shear waves through it. Since shear waves wouldn't go through and longitudinal waves would, and there was about 30 dB difference between the two, I interpreted the results to mean that it must be a fluid effect in the crack. We didn't worry about specific additives to produce wetting.

J.H. Rose (Ames Laboratory): I was curious about that localization of the longitudinal to transverse signal. What causes it, and do
you think there are stress signal consequences for that localization?

R.B. Thompson: My interpretation of that is as follows. When the sample is positioned such that the beam doesn't hit the crack, you expect no signal to go over here. If you hit a fully opened crack, you expect no signal to come over here. So one sees that signal only when there's some sort of a discontinuity in the beam. I think, if I can be speculative, that this may be a much better way to study the crack tip than the original through-transmission experiment, because it is a kind of darkfield technique. Our experimental difficulty in interpreting the through-transmission is the finite width of the bar beam; we are having to sort out the subtle effects of closure from our point response of our instrument. I think this mode-converted signal is less subject to that, and it contains a lot of interesting information that we haven't fully explored yet.

W.D. Rummel: We have also verified that.