TENSILE OVERLOAD AND STRESS INTENSITY SHIELDING INVESTIGATIONS BY ULTRASOUND

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INTRODUCTION

Growth of a fatigue crack is modified according to the development of contacts between the crack faces [1,2] creating shielding, thus canceling a portion of the crack driving force. These contacts develop through a number of mechanisms, including plastic deformation, sliding of the faces with respect to each other and the collection of debris such as oxide particles [3]. Compressive stresses are created on either side of the partially contacting crack faces resulting in opening loads that must be overcome in order to apply a driving force at the crack tip. In this way, the crack tip is shielded from a portion of the applied load, thus creating the need for modification [1] of the applied stress intensity range from $\Delta K = K_{Imax} - K_{Imin}$ to $\Delta K_{eff} = K_{Imax} - K_{Ish}$. Determination of the contact size and density in the region of closure from ultrasonic transmission and diffraction experiments [4] has allowed estimation of the magnitude of K_{Ish} on a crack grown under constant ΔK conditions. The calculation has since [5] been extended to fatigue cracks grown with a tensile overload block. The calculation was also successful in predicting the growth rate of the crack after reinitiation had occurred. This paper reports the further extension to the effects of a variable ΔK on fatigue crack growth. In addition, this paper presents preliminary results on detection of the tightly closed crack extension present during the growth retardation period after application of a tensile overload as well as an observation of the crack surface during reinitiation of growth that presents some interesting questions.

ULTRASONIC INTERROGATION AND MODELING

The experimental configuration for the ultrasonic interrogation of the fatigue cracks under consideration is shown in Fig. 1. The fatigue crack in a modified compact tension specimen is illuminated by a normally incident longitudinal wave focussed in the plane of the crack. The longitudinal wave transmitted directly through is detected by a receiver placed coaxially on the opposite side of the sample. The frequency spectrum of this received signal is deconvolved with that observed in a reference experiment where the beam is transmitted through the uncracked ligament. In this way, most of the influence of the measurement system and material microstructure is eliminated with the information obtained being directly characteristic of the magnitude of the crack closure.

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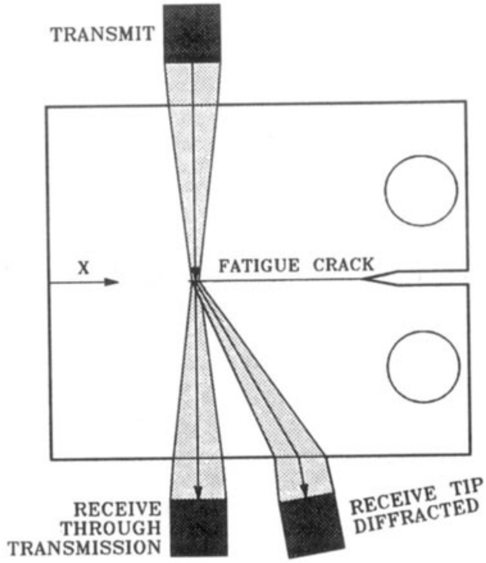

Fig. 1. Arrangement for measurement of acoustic response of fatigue crack.

The plane of a partially contacting fatigue crack is viewed as consisting of contacting asperities separated by crack-like voids which act as scatterers of an elastic wave. This scattering can be modeled based on the electromechanical reciprocity theorem [6] applied to the conditions of normal incidence. The scattered field is calculated according to

$$\Gamma = \frac{j\omega}{4P} \int_{A^+} \left(2u_i^I - \Delta u_i^T \right) \tau_{ij}^R \, n_j^+ \, dA \qquad (1)$$

where P is the electrical power incident on the transmitting transducer, ω is the angular frequency of the signal, u_i^I is the displacement field of the incident acoustic illumination, Δu_i^T is the crack opening displacement due to u_i^I, τ_{ij}^R is the stress field that would be produced if the receiving transducer illuminated a flaw-free material with the integration being performed over the surface A containing the scatterers which has a normal n_{ij}^+.

The major obstacle in the evaluation of Eq. 1 is the selection of an appropriate description for the crack opening displacement. For the present work an approach utilizing an averaged crack opening displacement has been used. The model [7] describes the degree of contact at the crack surface in terms of a spring constant κ which is primarily a function of the average contact diameter d and separation C. This spring constant is then related to the crack opening displacement according to

$$\Delta u_i^T = \frac{1}{1+j\omega\rho v/2\kappa} \, u_i^I \qquad (2)$$

where ρ is the material density and v is the acoustic velocity. Since $1/\kappa$ is proportional to Δu, evaluation of the above equation leads to a prediction of the experimentally observed signal in terms of κ.

This development has been used to obtain descriptions of through transmission results from a variety of samples [8-11]. Figure 2 presents a comparison between experimental through transmission results (left) and model predictions (right) for a fatigue crack grown under constant ΔK conditions with κ as an exponentially decaying function of position for the model predictions with excellent agreement between the two.

A functional form for κ on cracks grown under non-constant ΔK conditions is

$$\kappa(x) = \kappa_0 e^{-\beta x} + \frac{\kappa_1}{1+\{2(x-\alpha)\gamma^{-1}\}^4} + \kappa^* \tag{3}$$

where the first term describes the closure zone near the crack tip, the second models the effect of a tensile overload if present and the last term represents any remanent closure present far from the crack tip. κ_0 is the spring constant at the crack tip, β describes the decay of the constant in the crack tip closure region, α is the distance from the crack tip to the position where the overload was applied and γ is the width of the overload region, taken as the width at half amplitude of the peak in the transmission response. At $x=\alpha$ the amplitude of the spring constant due to the overload is κ_1.

A representation of the spring constant for a fatigue crack before an overload is applied, during the retardation period and after resumption of growth is shown in Fig. 3. Included at the top of the figure is a schematic of the closure in the crack at each stage. Included in the schematic for the crack during retardation is a short section of tightly closed crack ahead of the apparent crack tip [5]. Detection of this "tight" crack extension has only been possible by application of an external tensile load due to the high compressive stresses present across it.

One interesting feature of both the experimental and model results in Fig. 2 is the form of the cross-over of the data in the vicinity of the crack tip. As seen in the figure, the transmission response for the lowest frequency begins to decrease earliest and persists longest with this phenomena reversing as frequency increases. This effect is explained using the schematic in Fig. 4.

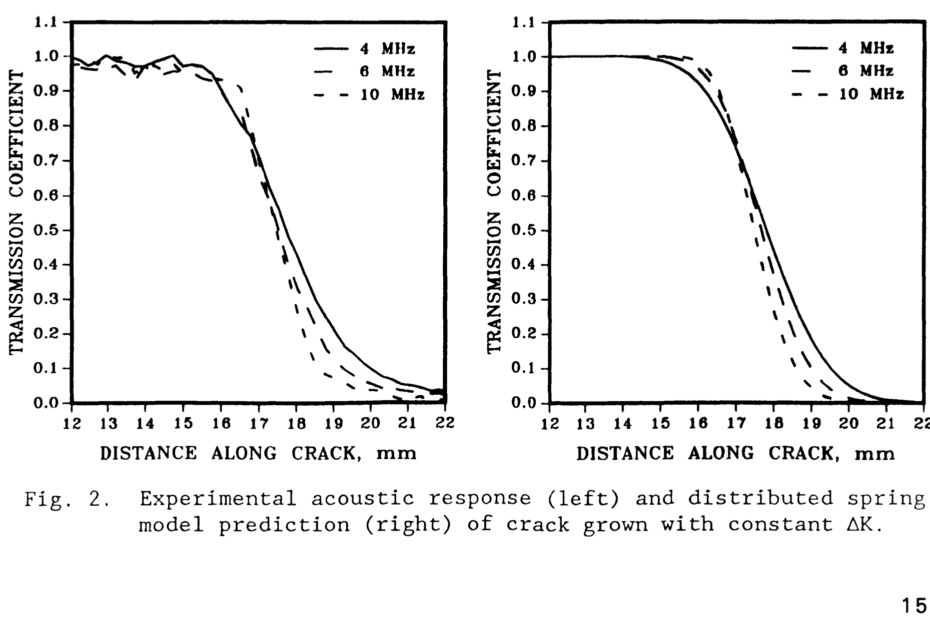

Fig. 2. Experimental acoustic response (left) and distributed spring model prediction (right) of crack grown with constant ΔK.

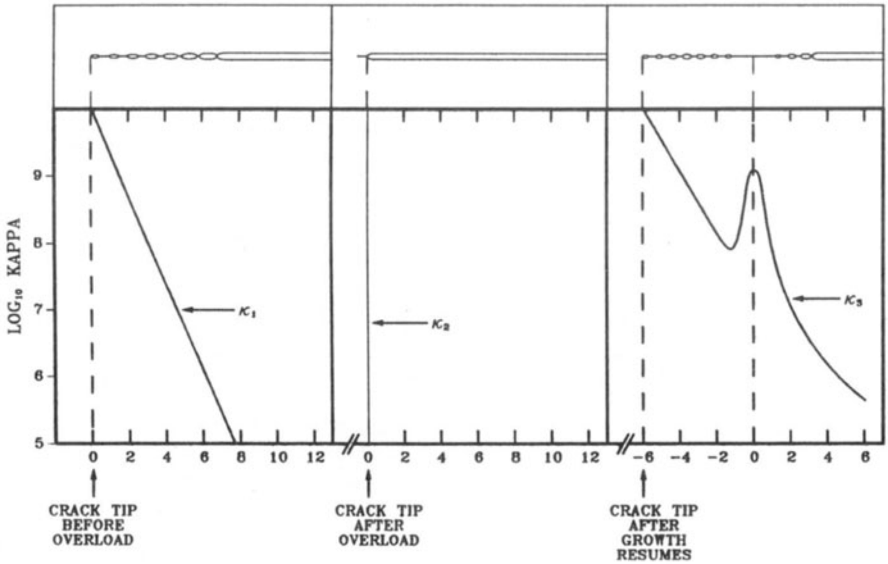

Fig. 3. Distributed spring constant and asperity contact before and after an overload.

In this figure, transmission response curves at two frequencies are shown for the case of an ideal (perfectly open) crack. As can be seen at the right of the figure, the spot size of the effective beam at a given frequency becomes smaller as the frequency increases for the focussed transducers being used. Thus, the beam intersects the crack tip earlier for low frequencies than for high (position A), causing the low frequency transmission to decrease first. A portion of the low frequency spot also stays in the uncracked ligament longer for the lower frequency (position C), resulting in a higher transmission response at that position. When the beam is centered on the crack tip (position B), the transmission response from both will be identical since the effective beam centers are coincident. Changes in this observed effect are important for detection of the "tight" crack formed during tensile overloading.

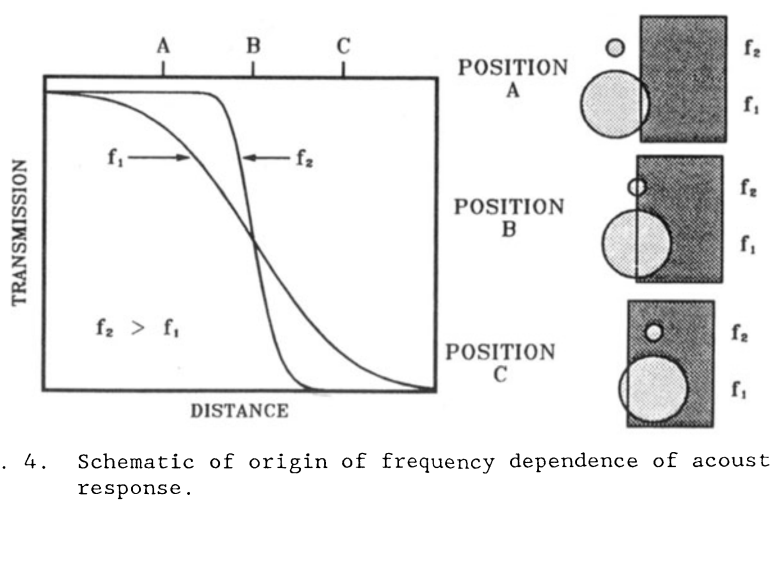

Fig. 4. Schematic of origin of frequency dependence of acoustic response.

Figure 5 shows the transmission response from two such cracks. These cracks were grown using a constant ΔK except for a 5 cycle tensile overload block using twice the original ΔK. Both transmission response curves were taken immediately following the application of the overload, therefore being in the retarded condition. In both cases, they exhibit a frequency dependence different from that seen from a crack that is in an active growth condition (Fig. 2). The crossover in the response curves present in the earlier case is completely absent for these cracks.

As mentioned earlier, the creation of a section of tightly closed crack during application of a tensile overload has been observed with blunting of the original crack tip. This tight crack has been thought until now to be undetectable except under the application of a static load sufficient to open it. From these results, it is possible that this tightly closed section can be detected in the unloaded condition by observation of the form of the frequency dependence of the transmission response. If such is the case, comparison of the transmission response of such a crack at intervals during and after the retardation should show a change from the behavior shown in Fig. 5 during the retardation period to that seen in Fig. 2 as the crack resumes growth. Whether this change occurs abruptly at the end of the retardation period or gradually throughout the retardation is not precisely known at this point. Work is continuing along these lines.

LOAD SPECTRUM AND SHIELDING

A contribution to the shielding stress intensity factor is made by each contacting asperity in the closure region of the crack with the magnitude of the contribution dependent on the load carried by the individual asperity. Residual stresses in the closure region have been calculated [4], based on contact pressure calculations [12], that agree well with corresponding results using x-ray diffraction [13]. Integration over all of the contacting asperities, then, yields the total shielding stress intensity factor, K_{Ish}. For an unloaded crack grown with a constant ΔK, the shielding stress intensity factor was found to be 40% of the range used for the growth [4].

Extension of earlier work [4,13] of the effect of two types of variable ΔK on the shielding has now been completed. The first of these

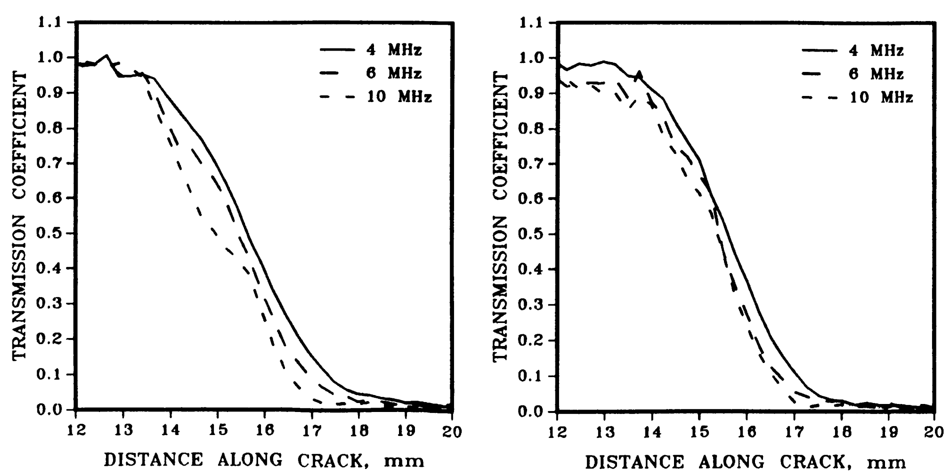

Fig. 5. Ultrasonic response of fatigue cracks immediately after tensile overload application.

involved the application of a block tensile overload to a crack being grown with a constant ΔK with subsequent return to the original ΔK. The ΔK used during the overload was twice that during the crack growth. This overload retarded the crack growth for approximately 120,000 cycles. Calculation of the shielding stress intensity factor before the overload and after resumption of growth showed an increase from 6.8 MPa $m^{1/2}$ before the overload to 8.0 MPa $m^{1/2}$ after resumption of growth.

The modified Paris law, $da/dN = \alpha(\Delta K_{eff})^m$ where α and m are materials constants can be used to calculate the growth rates for this type of crack using $\Delta K_{eff} = K_{Imax} - K_{Ish}$ in each case. The calculations are in agreement with the experimentally determined 50% reduction in the growth rate. Calculation of the shielding stress intensity factor during the retardation period has not yet been accomplished.

The second type of variable ΔK uses a continuously decreasing applied stress intensity factor. The crack propagation data from this crack is shown in Fig. 6, indicating that the growth changed from the Paris regime to near-threshold. Acoustic transmission data was taken at crack lengths corresponding to points A and B in the figure. The response at point A was similar to that shown in the left side of Fig. 2, indicating an exponential decay in κ with the closure region modeled as shown on the left hand side of Fig. 3.

The acoustic response of the crack at point B was remarkably different. At large distances away from the crack tip (6 to 10 mm), the transmission remained at a relatively constant, high value of 0.2, indicating considerable closure. This indicates to us that the closure region is extended with respect to that in the Paris regime and the resulting K_{Ish} is about 45% larger [14]. A conversion of da/dN versus ΔK as in Fig. 6 to da/dN versus ΔK_{eff}, where $\Delta K_{eff} = K_{Imax} - K_{Ish}$, provides a new correlation for the data in Fig. 6. This new correlation has a shape close to that in the Paris regime throughout the entire correlation. Thus it appears that the "threshold" behavior has been artificially created by the extensive closure found, in agreement with earlier observations [15].

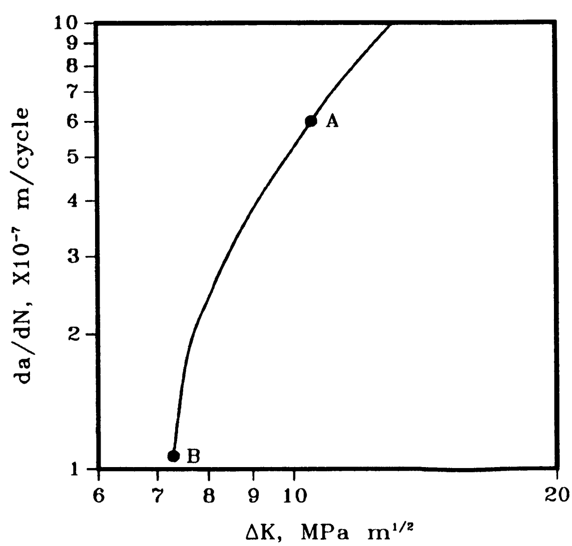

Fig. 6. Fatigue crack growth rate in the "threshold" regime.

FRACTURE SURFACE TOPOGRAPHY

Several samples were broken immediately upon resumption of growth as detected by monitoring of the position of the crack on the sample surface. The fracture surfaces of these cracks were examined optically with an example of one such surface shown in Fig. 7. In this figure, the crack extends into the picture from the right. The dark band is considered to be the section of new crack that was created during the overload. The extent of this new crack section in the growth direction is in agreement with acoustic measurements of the crack length. Of greater interest and considerable surprise are the two brighter areas, one on each side of the sample, where growth has resumed.

Traditionally, crack growth has been considered to occur more easily in the plane strain region in the center of the sample than in the plane stress regions where the crack intersects with the sides of the sample due to the higher stresses present at the edges. This depiction of the crack growth front is in accordance with the shape shown in Fig. 7 both before and after the overload. Resumption of growth in these cracks is occurring, however, in the opposite manner, i.e. growth occurs first in the plane stress regions while the crack front remains retarded in the plane strain regions.

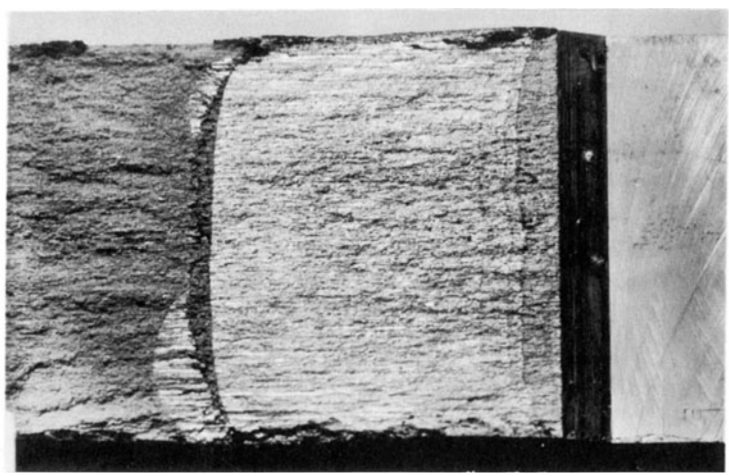

Fig. 7. Fracture surface of fatigue crack broken immediately after growth resumption was detected.

It can be imagined that the stress field present at the crack tip after being modified by application of the tensile overload must relax to something approximating its original state before the overload in order for growth to resume. If this relaxation occurs at a faster rate in the plane stress region, it is conceivable that the original values could be regained earliest there, making growth resumption possible in those localized areas. Eventually, relaxation would occur completely along the crack front so that the crack would then resume its traditional expected shape. Additional work to attempt to monitor the stresses present during retardation is needed to confirm or deny this speculation.

SUMMARY

A possible method of determination of the growth state of a crack based on the ultrasonic response of the crack in the unloaded condition is given. This method uses the frequency dependence of the through transmission coefficient in the crack tip region to determine whether the crack is capable of growth under the loading conditions specified. The effect of shielding on the growth rate of cracks grown using nonconstant loading has been calculated with the results in agreement with previous work. The shape of the crack front immediately after resumption of growth is shown with an unexpected variation from the accepted shape from previous work.

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