EFFECTS OF IMPERFECT INTERFACES ON ACOUSTIC TRANSMISSION AND DIFFRACTION

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INTRODUCTION

Contact between the surfaces of a fatigue crack is developed by a variety of mechanisms [1,2], including plastic deformation, sliding of the two faces with respect to one another or the collection of debris such as oxide particles [3]. Consequently, certain characteristic effects occur when the crack is illuminated by an elastic wave. When no contacts are present, a singularity exists in the elastodynamic fields at the crack tip, leading to a set of diffracted fields emanating from the tip. The presence of the contacts modifies the tip diffracted fields and allows energy to be directly transmitted through the crack, requiring modifications in the non-destructive evaluation techniques to detect or size the crack.

A second consequence arises from the creation of a compressive residual stress in the material on either side of the partially contacting crack surfaces. In reaction to this compressive stress, a load arises which produces a local stress intensity factor, \( K_I(\text{local}) \) which shields the crack tip in part from the variations of the externally applied stress intensity factor, \( K_I(\text{global}) \) [4]. This shielding occurs below a stress intensity factor \( K_{I\text{closure}} \) at which the first contact during unloading occurs. Thus, the applied stress intensity range, \( \Delta K = K_{I\text{max}} - K_{I\text{min}} \) will have to be modified to include the effects of crack tip shielding [1,5], leading to an effective stress intensity range, \( \Delta K_{\text{eff}} \).

This paper deals with variations in the degree of contact between the crack faces caused by changes in \( \Delta K_{\text{eff}} \) (from a constant \( \Delta K \)) used during growth of the crack and the resultant changes in the transmitted and diffracted waves. The changes used include an overload block, a single cycle overload and continually decreasing \( \Delta K \). A discussion of the functional form needed for the spring constant \( k \) in the "distributed spring model" [6] necessary for matching the model results to the experimental observations is given. Finally, the angular dependence of the tip diffracted, mode converted signal is described experimentally and from predictions of the model.
EXPERIMENTAL PROCEDURES

Fatigue Crack Growth

The fatigue cracks to be evaluated were grown in compact tension specimens of Al 2024-T351 by cyclical loading in an electrohydraulic system in laboratory air. Earlier work [5] had suggested that for a fatigue crack that had undergone tensile overload the degree of contact between the crack faces was indicative of the length of the retardation in the crack growth and thus of the size and amount of the overload applied. Three cracks were grown with the growth results shown in Fig. 1. For two of the cracks, growth was achieved under constant ΔK loading. At a crack length of about 13 mm the stress intensity range was increased to 2.4 ΔK for 21 cycles for one of the cracks and a single cycle for the other. These overloads resulted in crack retardations as shown, 131,000 cycles for the 21 cycle block and 12,700 for the single cycle overload. The third sample was grown using load shedding to achieve a continually decreasing ΔK. This leads to a continual decrease in the growth rate as evidenced by the lessening of the slope of the crack growth curve in Fig. 1.

Ultrasonic Inspection

The ultrasonic inspection of the fatigue cracks was accomplished in a water immersion tank. The transmitting transducer was aligned such that the acoustic beam interrogated the crack at normal incidence as shown in Fig. 2. A broadband (2-15 MHz) transducer with longitudinal polarization, focused in the plane of the crack, was used. This focusing provides the spatial resolution necessary to study the details of the variation of closure, particularly at high frequencies where a spot size of about 1 mm is achieved. Detection is performed with an identical receiving transducer positioned in various orientations. For this study, the following orientations were used: (a) θ = 0°, which provides the through transmission signal, (b) θ = -45° to θ = 45° which provides the diffracted signals. The samples were translated with respect to the transducer set-up such that the signals from the unbroken ligament (for reference purposes) and the fatigue

![Fig. 1. Crack length vs fatigue cycles for crack grown with varying ΔK applied.](image)
crack were determined as a function of position $x$ in the plane of the crack. The received through-transmitted or diffracted waveform was digitized at a 10 nsec sampling rate using a Tektronix digital processing oscilloscope. These data were stored for further processing in a Digital Equipment Corporation LSI-11 computer. All stored waveforms were Fourier transformed into the frequency domain and normalized using the through transmitted signal from the unbroken ligament as a reference.

EXPERIMENTAL ULTRASONIC RESULTS

The experimental ultrasonic results for the through transmitted signal, generated at 10 MHz, are shown in Fig. 3. The crack extends into the figure from the right as indicated by the low transmission coefficient. The peaks in the through transmitted signal at approximately 15 mm for the two overload specimens correspond very well to the position of the crack tip when the overloads were applied. Therefore it is suggested that these peaks are a result of additional crack closure caused by the increased size of the plastic deformation zone at the time of the overload application.

The third curve in Fig. 3 for the crack grown with a decreasing $\Delta K$ exhibits partial closure all along the crack as evidenced by the relatively high transmission coefficient values of approximately 0.25. This is in contrast to fatigue cracks grown under constant $\Delta K$ conditions, where the transmission coefficient drops below 0.05 [5]. It is speculated that the present result is caused by the continually decreasing plastic zone size, affecting plasticity induced in a fashion similar to the overload induced closure.
Fig. 3. Through transmission results at 10 MHz for overload and decreasing $\Delta K$ cracks.

Fig. 4. Diffracted wave results at 10 MHz for overload and decreasing $\Delta K$ cracks. Arrow denotes crack tip position for decreasing $\Delta K$ crack.

The 10 MHz diffracted signals at $\theta = -45^\circ$ are shown in Fig. 4 with the crack again extending into the figure from the right side. For all three of the signals shown, the first feature evident, as the scan proceeds from position 0, is a minor diffraction peak due to the crack tip indicated by the arrow. Such a peak has also been observed in the diffracted signal from a crack grown under constant $\Delta K$ conditions [5]. For the results shown here, the amplitude of this peak is relatively constant between samples, suggesting that conditions at the crack tip are unaffected by the changes in closure which occur deeper into the crack. In addition to this peak, a second peak can be seen at a position corresponding to that position.
of the crack tip when the overloads were applied. The height of this peak increases dramatically with increasing number of overload cycles. Apparently these peaks are generated by relatively isolated regions of closure allowing the peak to be well defined.

The crack that was grown under decreasing $\Delta K$ loading shows diffracted signals occurring all along the crack length due to the closure that was also seen in Fig. 3. Since this closure occurs throughout the length of the crack rather than in an isolated region, it is not surprising that the diffracted signals are present. It is interesting to note however that immediately after the crack tip is passed, the diffracted signal shows a dip before increasing to a relatively constant value throughout the rest of the crack. This dip may be due to a small open region at the crack tip as noted in earlier experiments [7].

**COMPARISON TO MODEL PREDICTION**

The experimental data presented in Fig. 3 and 4 were compared against predictions generated from the distributed spring model [6]. This model uses the electromechanical reciprocity theory of Auld [8], which states that the change induced in the signal transmitted from an illuminating to a receiving transducer by a flaw, $\delta \Gamma$, is given by

$$\delta \Gamma = \frac{j \omega}{4 \pi} \int_A (u_i^R \tau_{ij}^T - u_i^T \tau_{ij}^R) n_j dA$$

(1)

where $u_i^R$, $\tau_{ij}^R$ are the displacement and stress fields that would be produced if the receiving transducer irradiated a flaw free material; $u_i^T$ and $\tau_{ij}^T$ are the displacement and stress fields produced when the flaw is irradiated by the transmitting transducer, $P$ is the electrical power exciting the transducer, $\omega$ is the angular frequency, and integration is performed over the surface of the scatterer, which has a normal $n_j$. Using appropriate boundary conditions and assuming normal illumination of the interface by a plane wave leads to the form

$$\Gamma = \frac{j \omega}{2 \pi} \int_A [1 + j \alpha]^{-1} u_3^T \tau_{33}^R dA$$

(2)

where $\alpha = \pi \rho v f / \kappa$, where $\rho$ is the density, $v$ the acoustic velocity, $f$ the illuminating frequency, $\kappa$ is a distributed spring constant relating the dynamic relative displacements of the sides of the contacting interface to the dynamic stress, and the quantity in brackets can be shown to be the plane wave transmission coefficient.

In through transmission, excellent fits of Eq. (2) to experimental data as a function of measurement frequency are generally obtained when $\kappa$ is viewed as an adjustable parameter. This agreement has been achieved for a variety of samples [9-12]. For the data shown earlier, $\kappa(x)$ was chosen such that Eq. (2) represents the best fit to the transmission data. We chose

$$\kappa(x) = \kappa_0 e^{-\beta x} + \frac{\kappa_1}{1 + [2(x-a)\gamma^{-1}]^4}$$

(3)

where $\beta$ describes the decay of the spring constant in the closure zone, $\alpha$ is the distance from the crack tip to the position where the overload was applied and $\gamma$ the width of the overload region, taken as the width at half the amplitude of the peak in the transmission coefficient. At $x = a$ the amplitude of the spring constant due to the overload is $\kappa_1$. 1305
In using this spring model calculation to predict the diffracted signals from the closure regions it has been found necessary to include the effect of discrete contacts into the model [12]. These contacts are introduced such that their average $K$ still represents the spring constant in Eq. (2), thereby leaving the through transmission results unchanged. It has been found that the number density of contacts strongly influences the strength of the diffracted signals. For the interested reader, the details of the theory are described in Ref. 13.

Adjustment of the parameters $K_0$, $\beta$ and $K_1$ to achieve the best fit yielded the results shown in Fig. 5 for the 21-cycle overload crack at 10 MHz. The model provides an excellent fit to the experimental data with a minor deviation on one side of the overload peak. This small discrepancy is probably due to better resolution in the experiment than the model. Currently the model uses a Gaussian representation of the ultrasonic beam and performs an integration under this Gaussian beam to calculate the energy transmitted. In order to achieve transmission coefficients on the order of 1 in the uncracked ligament for the model, the model spot size that is used is somewhat larger than that achieved by the experimental apparatus, thereby leading to some loss of the fine structure that is present in the experimental results.

Equally good fits were achieved for the single cycle and decreasing $\Delta K$ cracks. The parameters used in Eq. (3) for each crack are given in Table I. For the decreasing $\Delta K$ sample, however, the overload region was distributed along the crack rather than concentrated in a single section. For this crack, a minimum $K$ value was set at $7 \times 10^{12}$ dyn/cm$^2$ in order to provide a good fit to the experimental data.

Model predictions from Eq. (2) and (3) using the data in Table I were also made for the diffracted, mode-converted waves at $\theta = -45^\circ$. Comparison of the prediction and the experimental data for 10 MHz is shown in Fig. 6.

![Fig. 5. Experimental result and model prediction for 6 MHz frequency for 21 cycle block overload crack.](image-url)
Table I. Adjustable Parameters for Eq. (3) to Achieve Fit.

<table>
<thead>
<tr>
<th>Overload</th>
<th>$\kappa_0$</th>
<th>$\beta$</th>
<th>$\kappa_1$</th>
<th>$\alpha$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>21 Cycle</td>
<td>$1 \times 10^{14}$</td>
<td>15</td>
<td>$3.5 \times 10^{13}$</td>
<td>0.438</td>
<td>0.102</td>
</tr>
<tr>
<td>Single cycle</td>
<td>$9 \times 10^{13}$</td>
<td>40</td>
<td>$3.5 \times 10^{13}$</td>
<td>0.362</td>
<td>0.102</td>
</tr>
<tr>
<td>Decreasing $\Delta K$</td>
<td>$6 \times 10^{13}$</td>
<td>18</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

*Overload region distributed along crack.

The predictions were made at a linear contact density of 1800 contacts per cm. The agreement here is not nearly as good as for the through transmitted waves. The model predicts a peak at the overload region in the diffracted waves that is smaller by a factor of 4.5 than that observed experimentally. Here again, it is presumed that the loss of resolution in the model as compared to the experiment is primarily responsible for this difference. The shift in the position of the peak in the model prediction is not completely explained at this time although it could be conjectured that the model has combined the two experimental peaks observed into one smaller peak centered between the two experimental peaks.

ANGULAR DEPENDENCE OF DIFRACTED WAVES

The angular dependence of the diffracted, mode converted waves was examined in the crack grown with decreasing $\Delta K$ by focusing the transmitting transducer on an area of interest in the crack and recording diffracted waves at various diffracted angles in the solid. The recorded waves were normalized in the same manner as the previous scans and the magnitude of the 10 MHz signal was plotted as a function of diffraction angle. These results are shown in Fig. 7 for three positions, at the tip of the crack and 2.5 mm on either side of the crack tip. The position of the crack tip is set at the 50% transmission position in Fig. 3 for the decreasing $\Delta K$ crack. The solid line, labeled -2.5 mm, was taken 2.5 mm from the crack tip in the uncracked region. The line labeled 2.5 mm was taken at a position 2.5 mm into the crack. It is readily apparent from the figure that

![Graph](image)

**Fig. 6.** Experimental result and model prediction for 10 MHz frequency for 21 cycle block overload crack.
Fig. 7. Experimental angular dependence for 10 MHz diffracted waves at crack tip (0 mm), 2.5 mm into crack (2.5 mm) and 2.5 mm into uncracked ligament (-2.5 mm).

The experimental data taken at the crack tip are quite symmetric around 0°. The data taken at -2.5 and 2.5 mm distance shows the same type of structure as that obtained at the crack tip in that a peak occurs on either side of 0°. The peak at the lower angles, however, has split into a doublet for both cases with the dip occurring at the point of the maximum for the crack tip data. Further examination of this splitting is necessary for a fuller understanding.

The two curves taken at -2.5 and 2.5 mm are remarkably similar in structure. Both curves show peaks occurring at angles close to 0° with the splitting mentioned earlier in the lower angle peak. The data was taken using the decreasing AK crack in order to minimize any effects due to isolated crack closure regions. Closure is present at the -2.5 mm position (see Fig. 3). The effect of this closure on the angular dependence is not known at this time. The diffracted data shown earlier (Fig. 4) were taken at -45°. Obviously, diffracted data taken at angles closer to 0° yield larger peak heights and may be more sensitive to crack closure conditions.

Figure 8 shows the model predictions corresponding to the experimental data given in Fig. 7. It is readily apparent that large discrepancies occur between the two graphs. The mirror plane symmetry that was present at 0° for the data taken at the crack tip (0 mm) is completely lost. Even more apparent is the change that occurs between the -2.5 mm and 2.5 mm positions. The experimental data show only minor variations between the two positions for a given diffraction angle. The model, however, shows major changes between the two at a constant diffraction angle. The only symmetry present occurs in the -2.5 mm data around 0°.

The model predicts larger values for the lower angle diffracted waves both at the crack tip and 2.5 mm into the crack. The major point of agreement between the experimental data and model predictions occurs for the maximum height of the data for tip of the crack. The maximum value observed experimentally and that predicted by the distributed spring model have relatively good agreement.
Fig. 8. Predicted angular dependence for 10 MHz diffracted waves at crack tip (0 mm), 2.5 mm into crack (2.5 mm) and 2.5 mm into uncracked ligament (-2.5 mm).

SUMMARY

Crack closure due to tensile overloads during crack growth can be detected using ultrasonic techniques. Such closure can initially be used as a preliminary determination of the history of the growth and determination of the duration of the overload once crack growth has reinitiated.

A functional form for the distributed spring constant κ can be chosen to obtain a quantitative fit between the distributed model prediction and experimental data in through transmission. The model predictions for diffracted shear waves remain lower than the obtained experimental results.

The experimental data and model predictions both show a strong angular dependence for the diffracted shear waves at positions near the crack tip. The experimental results show some surprising changes in symmetry as compared to the predictions of the distributed spring model. This phenomena will be investigated further.

ACKNOWLEDGEMENT

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8. B. A. Auld, Wave Motion, 1, 3 (1979).


