THE EFFECTS OF COMPRESSIVE STRESS AND CONTAMINATING LIQUIDS ON THE ULTRASONIC DETECTION OF FATIGUE CRACKS

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SUMMARY

The application of compressive stress to fatigue cracks may result in considerable ultrasonic transmission and a reduction in reflectivity. The magnitude of this effect is very sensitive to the conditions under which the cracks are grown, since in particular, the growth conditions affect the roughness of the mating surfaces. A series of fatigue cracks 5, 10 and 15 mm deep grown under constant stress intensity factors have been examined ultrasonically for compressive stresses up to 150 $MN.m^{-2}$. Reductions in reflectivity of up to 12 dB for normal incidence compression waves and up to 25 dB for angled shear waves will be described. The major changes in the ultrasonic responses may be explained in terms of the true area of contact between the mating crack faces.

The presence of liquid in the cracks also has a significant effect. Experimental results for wet cracks will be compared with theoretical predictions based on a thin parallel-sided gap model. Finally, the significance of these effects to the detectability of fatigue cracks will be discussed.

RÉSUMÉ

Les effets des contraintes compressives
et des liquides contaminants
sur la détection ultrasonique des fissures de fatigue

L'application de contraintes compressives aux fissures de fatigue est susceptible de résulter en une transmission ultrasonique considérable et en une réduction du coefficient de réflexion. L'ampleur de cet effet est très sensible aux conditions sous lesquelles la croissance de ces fissures est effectuée, du fait qu'en particulier les conditions de croissance affectent la

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rugosité des surfaces correspondantes. Une série de fissures de fatigue de 5, 10 et 15 mm de profondeur dont la croissance a été effectuée sous conditions constantes de facteurs de tension a été examinée ultrasoniquement pour ce qui est des contraintes compressives jusqu'à concurrence de 150 $MN.m^{-2}$. Les réductions dans le coefficient de réflexion jusqu'à 12 dB pour ondes de compression d'incidence normales et jusqu'à 25 dB pour ondes de cisaillement angulaires seront décrites. Les changements majeurs dans les réponses ultrasoniques peuvent s'expliquer en termes de la surface réelle de contact entre les faces correspondantes fissurées.

La présence de liquide dans les fissures a également un effet significatif. Les résultats d'expériences relativement aux fissures humides seront comparés aux prédictions basées sur un modèle d'instertice mince à parois parallèles. Finalement, l'importance de ces effets par rapport aux possibilités de détection des fissures de fatigue sera discutée.

INTRODUCTION

The ability of ultrasonics to detect cracks is intrinsically good, but it may be reduced if compressive stress forces the crack faces together. High cycle fatigue cracks whose surfaces are very smooth are likely to be particularly sensitive to such compression. A previous report (Wooldridge, 1979) investigated the changes in reflection and transmission of ultrasound at machine ground surfaces which were under compressive loading. It was found that whereas the transmission approaches unity at high load, the specular reflection may still be readily detected at normal incidence. This paper concentrates on the shear wave corner echoes from surface-breaking fatigue cracks which were grown at constant stress intensity factor to control the roughness of the faces. In this way we have established a strong correlation between the roughness of the surfaces and the ultrasonic response at both zero load and under stress. The effect of liquids in the cracks has also been studied and the results are compared with theoretical predictions for a thin parallel-sided gap.

PRODUCTION OF THE FATIGUE CRACKS

The cracks were grown by three-point bend in steel bars whose dimensions are shown in Figure 1. EN3B mild steel was generally used but some cracks were also grown in high quality mild steel welds. Constant-load fatiguing is

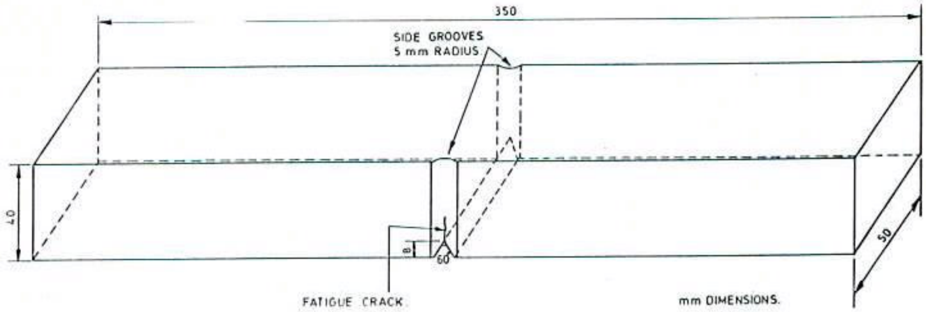

Fig. 1. – Initial fatigue crack specimen.

commonly used to grow cracks in the laboratory and often occurs in service, but this leads to a continuous gradation in surface roughness as the crack propagates. Consequently the cyclic load amplitude was reduced continuously during crack growth so as to maintain constant the change in stress intensity factor, Δk, near the crack tip. Three values of Δk were chosen in the range 20-60 $\mathrm{MN.m^{-3/2}}$ and the cracks were grown to depths of 5, 10 or 15 mm. The cracks extended through the full width of the block (i. e. 50 mm) and were constrained to lie perpendicular to the surface by cylindrical side-grooves. After crack growth, the V-shaped starter notches were machined away and the top and bottom surfaces ground flat and parallel to facilitate examination of the surface-breaking fatigue cracks.

EXAMINATION OF THE CRACK FACES

On completion of the ultrasonic measurements some of the blocks were split open to reveal the fatigue cracks. The crack faces were macroscopically flat, lying in a plane perpendicular to the testing surfaces. Figure 2 shows the R_a values for those cracks which have been examined and there is a steady increase in the mean R_a value with increasing Δk for the cracks in parent metal. The weld specimen G which had not been stress-relieved is anomalously rough, presumably because of variations in the material properties and residual welding stresses in the block.

There are various ways of describing the statistical properties of rough surfaces, but we believe that the power spectral density P(W) is one of the most useful. Figure 3 shows that P(W) may be described approximately as

$$P(W) = \frac{A}{W_{\min}^2 + W^2}, \tag{1}$$

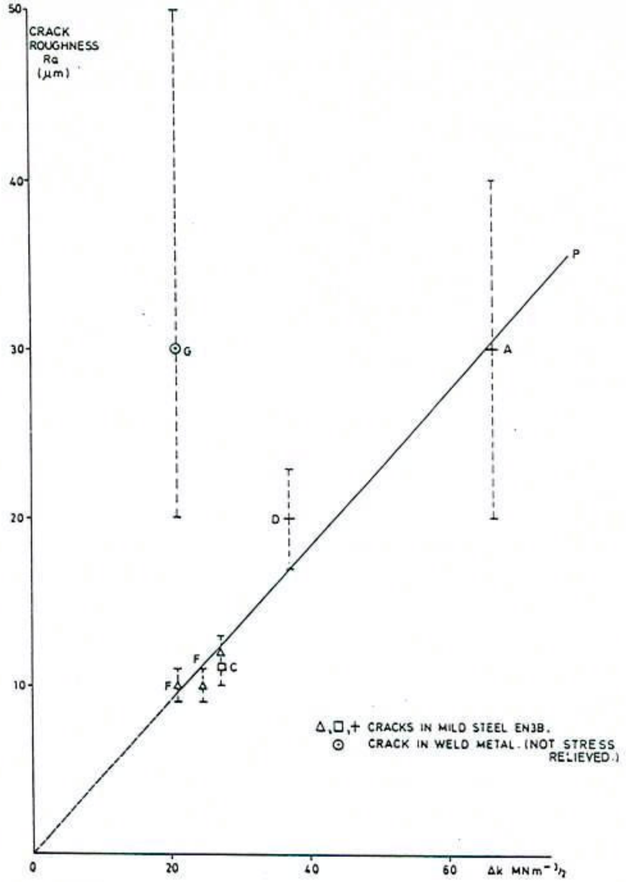

Fig. 2. – Stress intensity factor Δk versus crack roughness.

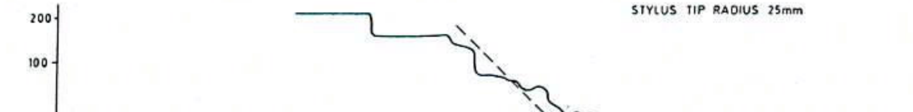

Fig. 3. – Power spectrum of fatigue crack surface F.

where the cut-off spatial frequency W_{min} is of the order of 1 mm. A truly random surface would be expected to have a spectrum of the form

$$P(W)=\frac{A}{W^2} \quad \text{(Sayles and Thomas, 1978).} \tag{2}$$

Consequently the crack surfaces appear to be substantially random for wavelengths $\ll$ 1 mm whereas the geometry of the block and the loading conditions discourage the occurrence of wavelengths $\gg$ 1 mm. It is worth noting that the linear striation structure which is typical of fatigue crack surfaces is too small to detect with a profilometer. The striation spacing varied from about 0.05 µm for $\Delta k=20$ to 1.3 µm for $\Delta k=60$ and could only be observed using an electron microscope. The random variations in surface profile in the range 5 to 500 µm presumably arise from the random orientation of the grains and the distribution of microvoids in the material.

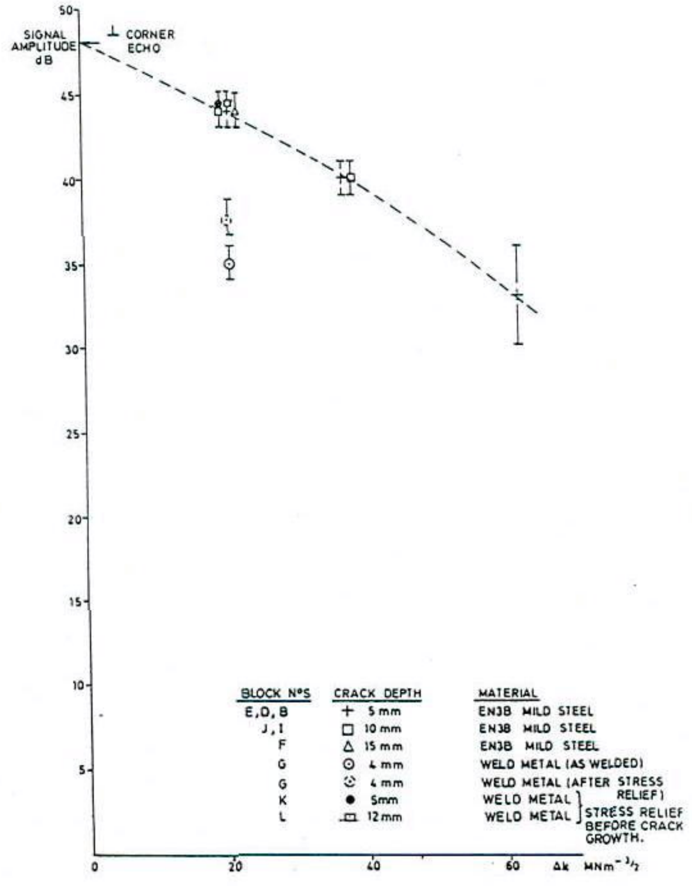

Fig. 4. – Corner echoes at zero load versus Δk: 45° probe.

CRACK CORNER ECHOES WITH NO APPLIED LOAD

Measurements of the corner echoes were made using 45, 60 and 70° shear wave angle probes in pulse-echo. In addition a 60° shear wave and a normal compression probe were used together in a Delta-Scan arrangement. These tests enabled the amplitudes of the corner echoes to be compared with those of a smooth machined corner. Figure 4 shows the echoes obtained with a 45° probe; there is a steady decrease in echo amplitude with increasing Δk, but little or no dependence on crack length. Similar effects occurred with the other probe angles studied. This Δk dependence is believed to arise from the increase in roughness described above, the longer wavelength components of the roughness being most significant in causing diffuse scattering.

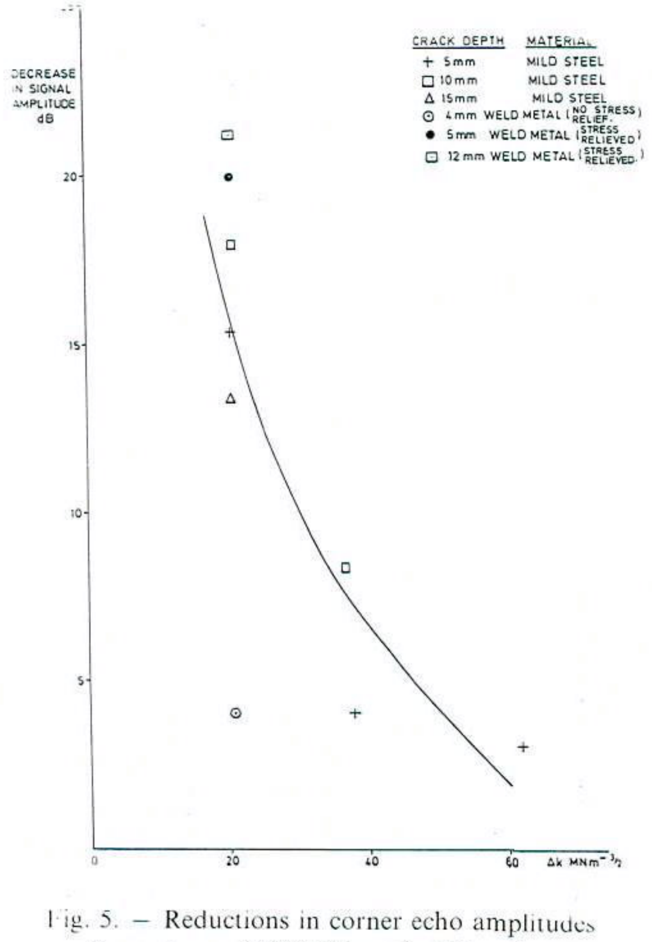

Fig. 5. — Reductions in corner echo amplitudes for a stress of 160 MN.m^{-2}; 45° probe

CRACK CORNER ECHŒS UNDER COMPRESSIVE STRESS

Compressive stresses were applied perpendicular to the crack faces by loading the blocks along their axis, and the corners echoes monitored on a chart recorder as the load increased. Although a small increase in signal sometimes occurred at low loads, a monotonic decrease in signal always occurred at higher loads. Figure 5 shows the maximum decreases in echo amplitude for the 45° probe which occurred when the mean stress was increased to 160 $MN.m^{-2}$. Whereas decreases of about 20 dB occurred for cracks of low Δk, the response of the crack of maximum Δk only decreased by 3 dB. Similar changes occurred for all the other probe angles studied and in each case the cracks in stress-relieved welds behaved in a way similar to the cracks in mild steel. However the crack in non stress-relieved weld metal (which had an anomalously high roughness) showed only small changes with loading.

THE RELATIONSHIP BETWEEN THE REFLECTION CŒFFICIENT AND THE STIFFNESS OF AN INTERFACE

To explain the dependence of the reflection coefficient on the roughness of the crack surfaces we must consider the mechanism by which sound is transmitted through a compressed crack. Kendall and Tabor (1971) have shown that in the case of compression waves at normal incidence the reflection coefficient may be expressed in terms of an effective "stiffness" of the interface. The reflection coefficient, R, may be written thus:

$$R = \frac{a/S}{\sqrt{1 + a^2/S^2}},$$

where the constant, a, depends on the bulk mechanical properties of the solid and the ultrasonic frequency. The stiffness, S, depends on the roughness of the surfaces and the stress applied. In practice, both elastic and plastic deformation of the surface asperities will occur, but Greenwood (1967) argues that in either case the stiffness is likely to be proportional to the square root of the applied stress.

Write

$$S = A\,\sigma^{1/2},$$

Then

$$R = \frac{1}{\sqrt{1+\sigma/b^2}}, \qquad \text{A, } b \text{ are constants.}$$

Figure 6 shows the reflection and transmission coefficients plotted as a function of the normalised stress σ/b^2. Measurements of the reflection of compression and shear waves from the fatigue cracks at normal incidence agree well with these theoretical curves, the results for shear waves being shown in Figure 7.

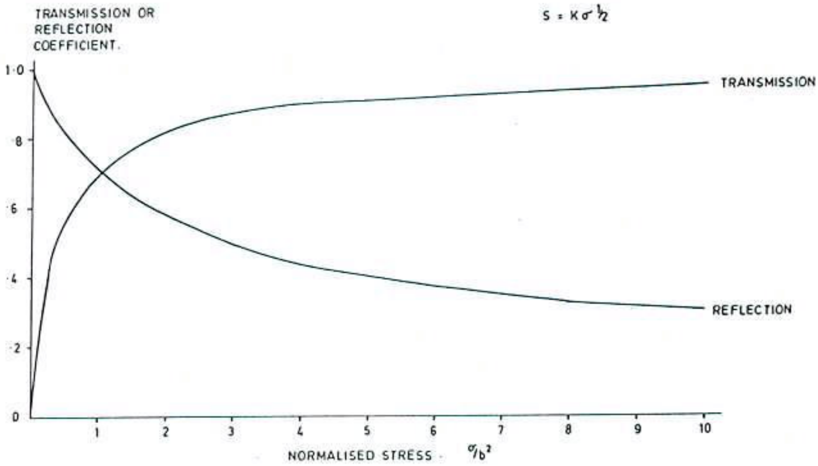

Fig. 6. – Theoretical reflection and transmission coefficients for normal compression waves.

As yet, no theory is available for angled shear waves but the experimental results are clearly of different form. However by assuming a stiffness of the form $S = k\,\sigma^n$ where k, n are empirical constants, reasonable agreement with experimental results may be obtained. Figure 8 shows the experimental results for the Delta-Scan arrangement together with the semi-empirical curve for $n = 1.5$. In general the value of n is comparatively independent of probe angle but varies from about 0.5 to 2.0 depending on the block used.

THE EFFECTS OF LIQUIDS ON THE ULTRASONIC REFLECTIVITY

There are many practical situations in which fatigue cracks may be partly or totalled filled with water or other liquid. In such a situation, if the crack separation is very much less than a wavelength, theory predicts that at normal

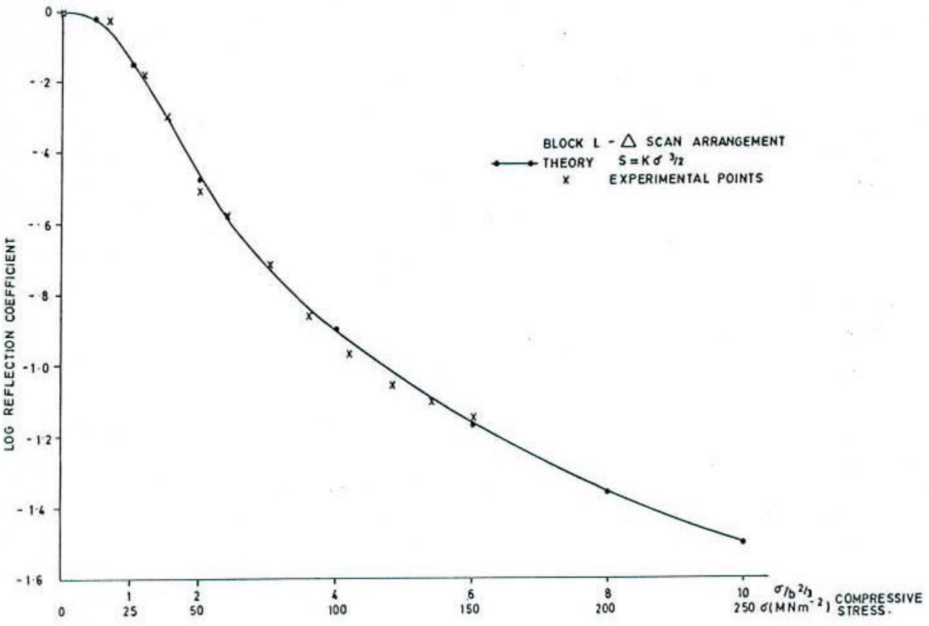

Fig. 7. – Reflection of 2.25 MHz shear waves.

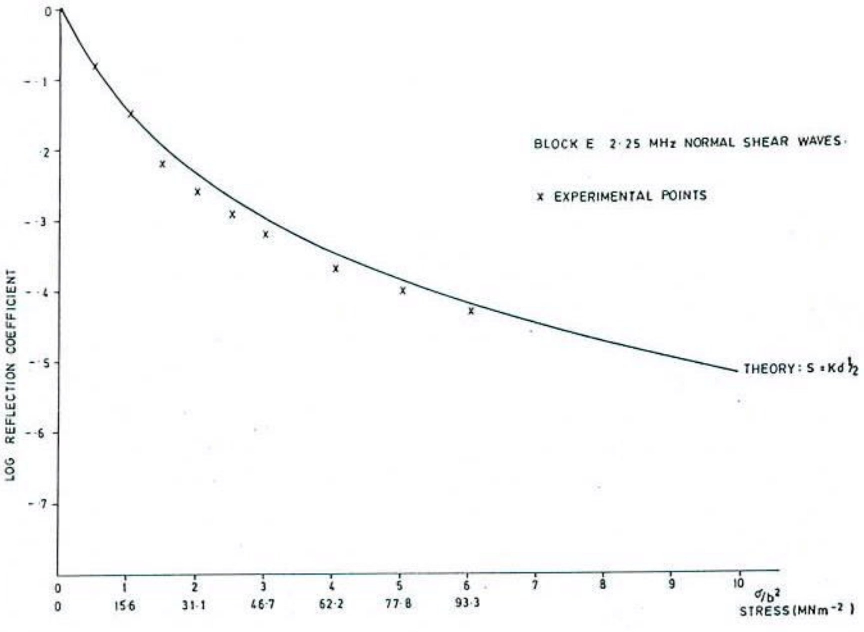

Fig. 8. – Reflection of 4 MHz shear waves incident at 30°.

incidence almost perfect transmission of compression waves will occur. But this is not generally the case for angled beams or for shear waves. Our calculations show that when the thickness of a liquid-filled parallel-sided gap becomes less than about a tenth of a wavelength, the reflection of shear waves decreases for angles of incidence greater than the critical angle of 33°. However there is an increase in reflection for angles less than the critical angles as the gap thickness tends to zero. As an example, Figure 9 shows the calculated reflection and transmission coefficients for a zero thickness fluid gap.

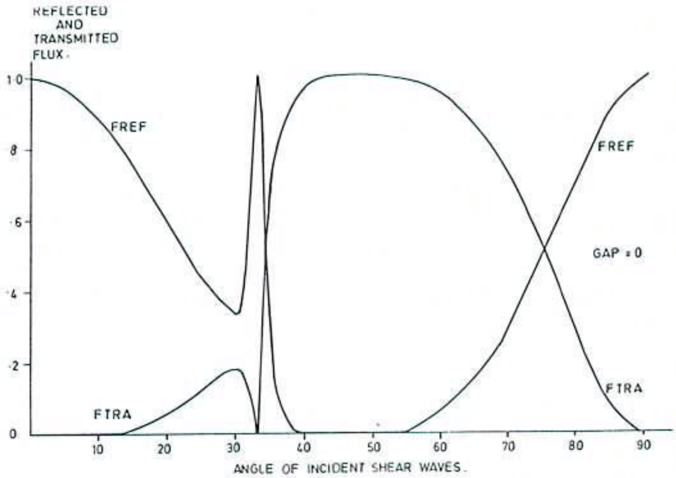

Fig. 9. — Reflection of shear waves at a zero thickness fluid gap in steel.

To investigate this experimentally, the cracks were put in tension by applying small loads in three point bend and then sprayed with a penetrating fluid. Measurements of the corner echoes were made with the blocks under zero load and for compressive stresses up to 160 MN.m^{-2}. Figure 10 shows the results for three cracks, compared with those for the dry cracks when tested with a 70° probe. Under high stress, all cracks showed an increase in reflection of about 5 dB when wet. This is in agreement with the theory which predicts an increase of about 3 dB for a thin liquid-filled gap compared with a similar dry gap. At 45° the reflectivity of the wet cracks was always less than when dry, the difference being up to 8 dB at high stress. This trend is in agreement with the theory which predicts that the reflectivity tends to zero when the gap thickness becomes much less than a wavelength. The 60° probe recorded relatively large decreases in all cases whereas the theory predicts an

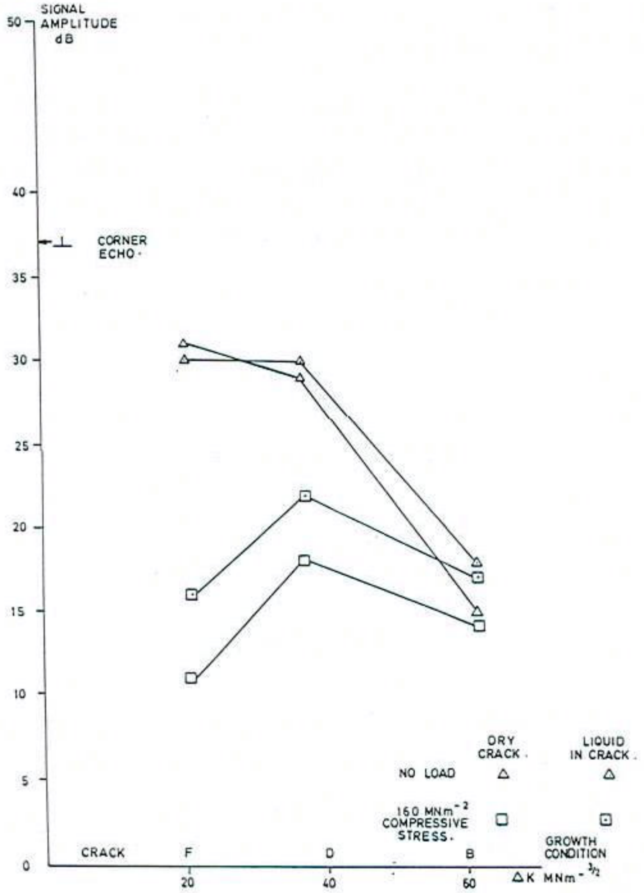

Fig. 10. – The effect of liquid in cracks when unloaded and under compression: 70° probe.

increase. The discrepancy may be associated with the rapid variations in reflection coefficient with angle and the strong mode conversions which occur for angles of incidence close to 33°. The effect of introducing the liquid seems to be relatively insensitive to the roughness of the crack faces.

CONCLUSIONS

1. The growth conditions of fatigue cracks have a significant effect on their ultrasonic response, both at zero load and when under compressive stress. Variations in the roughness of the fatigue crack surfaces which correlate well

with the stress intensity factor, Δk, during crack growth are believed to cause the changes in ultrasonic response.

2. Both increasing crack roughness and increasing compressive stresses reduce the reflected signal from cracks. During an inspection, this will lead to undersizing if echo amplitude comparison techniques like DGS are used. However the effects of roughness and compressive stress are not cumulative and the roughest cracks show little variation with stress.

3. Introducing liquid into a tight crack may cause an increase or decrease in reflection depending on the angle of the ultrasonic beam.

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