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The Effects of Compressive Stress on the Ultrasonic response of steel-steel interfaces and of fatigue cracks

by

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1. Introduction

A compressive stress forcing the faces of a crack together generally decreases the amplitude of the ultrasonic echoes from the crack, while increasing the signal transmitted through it. Consequently echoes from tight cracks may not be appreciably larger than those from small inclusions, making it difficult to detect the cracks in pulse-echo. Similarly, techniques which rely on obscuration of the ultrasonic beam may be completely ineffective because of the appreciable transmission through a compressed crack.

This paper describes a series of experimental measurements showing the extent to which compressive stress may impair the ultrasonic detection of defects. Two types of surface have been studied; smooth, machine-ground steel blocks, and a high-cycle fatigue crack in mild steel. The machine-ground blocks were chosen because of the simple stress state and the known, controlled surface morphology. The ultrasonic reflection and transmission coefficients were measured for a wide range of compressive stress using various ultrasonic frequencies. The effect of inter-surface structure was later investigated using steel wool between the contact faces, and also by corroding the surfaces in salt water. To study actual cracks, a high-cycle fatigue crack was chosen for the second series of measurements because this type of crack may be very smooth, and hence particularly difficult to detect at non-normal incidence, even if unstressed. Such smooth cracks are also likely to show the biggest change on loading. Although fatigue cracks only grow if the crack tip is in tension, there are situations where an engineering component may be subject to fatigue during service, and yet during a shut-down, the resultant stress becomes compressive. The echoes from both the crack tip and the crack face were measured for a range of frequencies and angles of incidence, as was transmission of angled beams of shear waves through the crack.

2. Machine-Ground Surfaces

2.1 Experimental Arrangement

Two mild steel blocks were machined as shown in Fig. 1. and the contact surfaces AB machine ground to a finish of 0.2μm Ra (8μin. Ra). Either compression or shear wave piezoelectric crystals were soldered into the recesses C and D so that compressive loads could be applied via the faces EF and GH. Using a Denison hydraulic test machine, a maximum compressive stress of 400 MNm^{-2} (26 tons in^{-2}) could be applied to the contact faces.

The transmitting crystal was driven with a sine wave burst of four cycles produced by a Tektronix Function Generator. Since the crystals were well damped, they had appreciable bandwidth and could be driven at a range of frequencies by varying the transmitter frequency. For measurements at widely different frequencies, the crystals had to be changed..

Since plastic deformation of the contact surfaces occurred for increasing stresses, all the results given in Sections 2.3 and 2.4 were obtained during the unloading cycle over which no plastic deformation is likely to occur.

2.2 Calibration Procedure

The amplitude reflection coefficient for a boundary is defined as the ratio of reflected ultrasonic amplitude to incident amplitude actually at that boundary. Consequently absolute measurement of the reflection coefficient by a probe remote from the boundary must involve knowledge of how the beam spreads on travelling between the probe and the boundary. However since the reflection at a steel-air interface is unity for all practical purposes, this provides a calibration for the reflection at zero load. All the measurements for reflection under stress can then be related to this value.

The measurements of transmission coefficient depend on the sensitivities of each probe and on the beam spread. However, since the blocks are symmetrical (see Fig. 2) the path difference and the beam spread are the same in transmission as for reflection. Providing that the transmitting and receiving crystals are similar, and that the impedances of the driving and receiving circuits are the same, we can relate the transmission and reflection coefficients. It can be shown that the relative sensitivity of the transmission system is equal to the geometric mean of the pulse-echo sensitivities of the individual probes.

2.3 Reflection and Transmission Coefficients for clean dry surfaces

Fig. 3 shows the amplitude reflection and transmission coefficients obtained with 2MHz compression waves. At the maximum stress of about 350 MNm^{-2} (23 tons in^{-2}), the reflection dropped to 0.23 while the transmission is 0.96. This reduction in reflection with load corresponds to 11.4 dB and was the largest change recorded during these experiments. Fig. 4, showing the coefficients for 2, 4 and 6 MHz compression waves, indicates that as the frequency increases the transmission is reduced, while the reflection is increased.

Measurements made with shear waves (see Fig. 5) show a similar trend, but for a given stress and frequency the transmission is lower and the reflection higher than in the case of compression waves. This is probably due in part to the fact that the wavelength for shear waves is roughly half that for compression waves of the same frequency. The changes in the reflection coefficients are summarised in Fig. 6 where they are plotted on a logarithmic (dB) scale.

2.4 Reflection and Transmission at irregular or Corroded surfaces

To simulate the effect of poor contact between the surfaces of a crack, pads of steel wool of varying density were compressed between the faces of the blocks. Even though the pads suffered severe plastic deformation at the higher stresses, considerable air spaces still remain between the strands. Nevertheless, appreciable transmission occurred as shown in Fig. 7 and the amplitude coefficient correlated roughly with the square root of the contact area. This has been predicted theoretically by Kendall and Tabor (1971).

The effect of an oxide-filled crack was investigated by corroding the contact faces in sea water while the blocks were fixed firmly together. Before making measurements the blocks were thoroughly dried without disturbing the oxide layer. Fig. 8 compares the coefficients for corroded and clean ground surfaces, and as expected,at the maximum stress, transmission is lower and the reflection higher for the corroded surfaces. Nevertheless the transmission at low stresses is slightly larger for the corroded surfaces than for the ground surfaces. This probably occurs because the oxide produces a smaller impedance change than an air-filled gap.

3. The Response of a high-cycle fatigue crack

3.1 Growth of the fatigue crack

The fatigue crack was grown in a BS. 15 mild steel block as shown in Fig. 9. The block is longer than normal compact-tension specimens to enable 70° angle probes to be used to investigate the crack. Although the side arms were used to hold the block during crack growth, they were subsequently removed down to the line GH, so that the crack could be scanned from the lower side of the block.

The crack was grown by tension-tension constant amplitude cycling until it was 31mm long, when the load was reduced. A total of 237,000 cycles achieved the final crack length of 37mm. The photograph of the crack surface shown in Fig. 10 was taken after final destructive examination, and indicates that the crack roughness increases rapidly just before the point at which the load amplitude was reduced.

3.2 Magnitudes of the crack tip and crack face echoes under zero load

Initial experiments using an ultrasonic B-scan with angled shear wave probes confirmed that the line of the crack was substantially straight. In addition, it was possible to resolve separate echoes from the tip of the crack, and from the area of maximum roughness about 5mm from the crack tip. This is subsequently referred to as the "crack face echo".

Fig. 11 shows the equivalent flat-bottomed hole (F.B.H.) size for the crack tip echo measured for a range of angles and different types of probe. The angle is that between the beam axis and the direction of crack growth. Except for the 60° and 120° readings for probe type 2, the equivalent F.B.H. sizes range from 0.7mm to 1.2mm. The echoes from the crack face gave equivalent F.B.H. sizes in the same range.

3.3 Transmission of shear waves through the crack under load

Transmission of shear waves across the middle of the crack surface was measured at 2 MHz and 5MHz using 45°, 60° and 70° probes, the experimental arrangement being shown in Fig. 12.

Typical results for 2MHz 45° probes are shown in Fig. 13 in which the inset is an expanded version of the graph for low loads. The maximum transmission is 4dB below that though an uncracked section of the block, and corresponds to a transmission coefficient of 0.6. Other values for the transmission at a mean stress of 80MNm^{-2} are given in Fig. 14. The oscillation in transmission at low loads has been qualitatively explained using a simple linear elastic model for the crack. This predicts that as the crack closes, the stress distribution near the crack tip may undergo an oscillation; initially the crack tip is highly compressed, but as the applied load becomes distributed over the whole face of the crack, the stress near the tip may be temporarily reduced.

3.4 Pulse-echo Responses of the crack tip and the crack face

The effect of the redistribution of stress along the crack as it closes is particularly noticable with pulse-echo responses from the crack tip. Fig. 15 shows the echo amplitude measured with a 70° 5MHz probe and the oscillation occurs at stress levels comparable with those of the transmission curve. The echoes from the crack face showed less fluctuation, as predicted by the model, but the maximum change in reflection was more variable than that from the crack tip. The average changes in amplitude, measured for various probes of angle 45°, 60° or 70°, are given in Fig. 16 together with the maximum and minimum changes recorded for stresses up to 90MNm^{-2} (5.8 tons in^{-2}).

4. Discussion

We have seen that although modest compressive stresses may reduce the amplitude of the ultrasonic echoes from cracks, the reflectivity is still appreciable even at very high stresses. The largest reduction in echo amplitude occurs at low frequencies, and may be as much as 12dB for 2MHz compression waves incident on ground surfaces with a stress of 300 MNm^{-2} (20 tons in^{-2}). With higher frequencies or rougher contact surfaces the change with loading is less pronounced.

Residual stress levels in welds which have been properly heat-treated are typically in the region of 60MNm^{-2} (4 tons in^{-2}). From Fig. 10 we can see that such stress could reduce the reflectivity from very smooth cracks by 4 to 8 dB, depending on the frequency and whether shear or compression waves are used. A drop in reflectivity of 6dB would double the area of the minimum detectable defect.

Small fatigue cracks are probably particularly susceptible to the effects of stress because they may be very smooth and tight, especially during the early stages of growth. Smooth cracks are difficult to detect by angled ultrasonic beams in any case, because most of the energy is specularly reflected. Such cracks are also the most likely to suffer a reduction in reflectivity when compressed. This may be compensated to some extent by increasing the test sensitivity, but the ability to do this is often limited by grass levels or echoes from small inclusions. For example, consider the fatigue crack described in Section 3. Since the echo from the crack tip under no load was roughly equivalent to a 1.0mm flat-bottomed hole, the test sensitivity would need to be 0.7mm F.B.H. to ensure detection of the crack when compressed to $60MNm^{-2}$.

Techniques relying on obscuration of the beam are likely to be completely ineffective if compressive stresses occur. For example, a crack stressed to $60MNm^{-2}$ could have a transmission coefficient exceeding 0.5. Consequently the obscuration of the beam would be less than 6dB and this could be comparable with the variation in coupling on a non-ideal surface.

ACKNOWLEDGEMENTS

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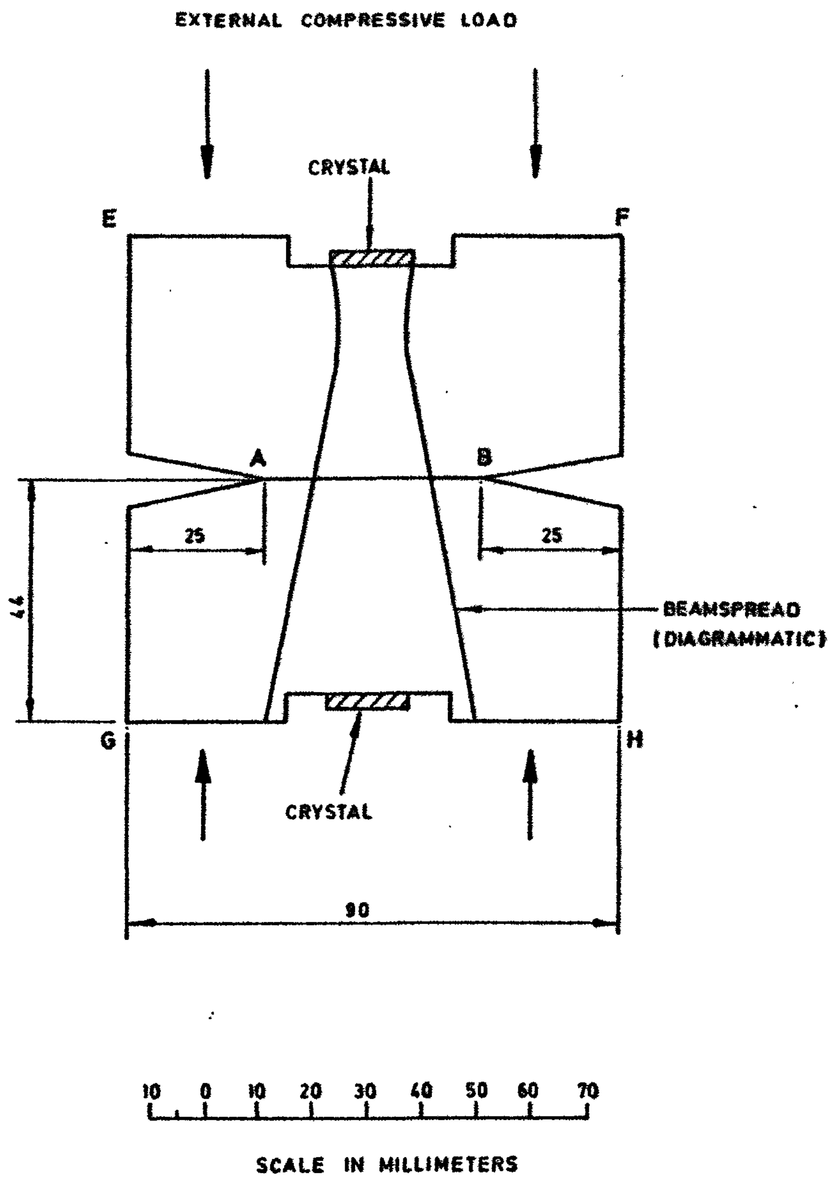

FIG. 1 A VERTICAL SECTION THROUGH THE STEEL BLOCKS

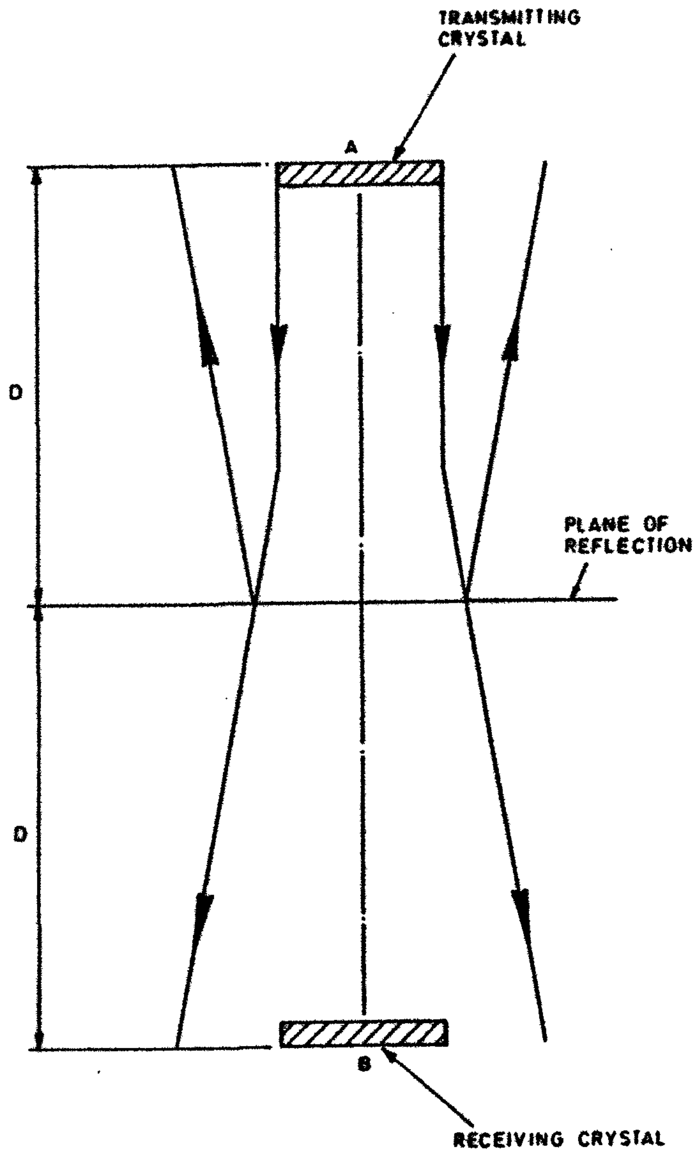

FIG. 2 THE SYMMETRY OF THE TRANSMITTED AND REFLECTED BEAMS

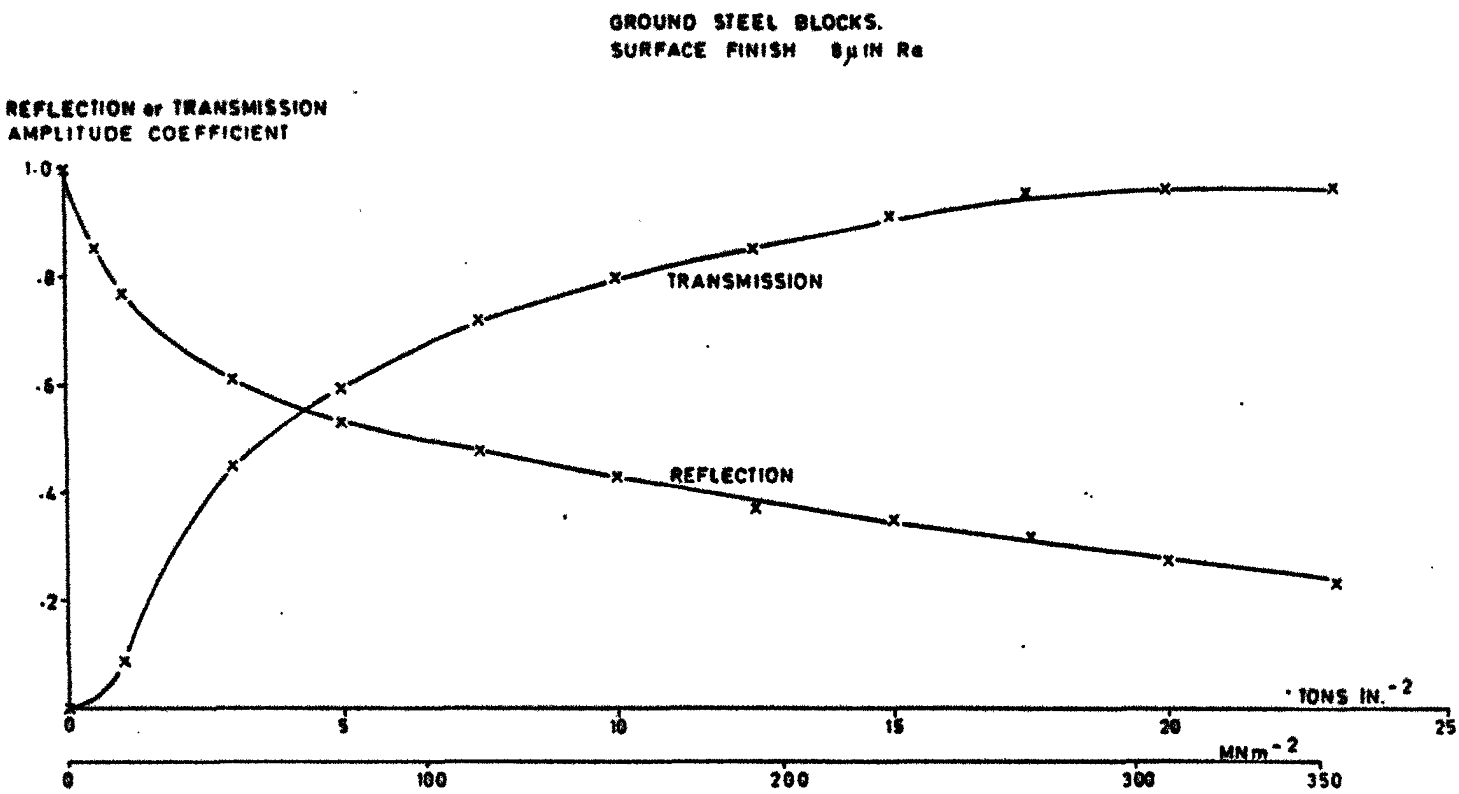

FIG. 3 REFLECTION & TRANSMISSION COEFFICIENTS FOR 2MHz COMPRESSION WAVES

RC/SSR/A6/848

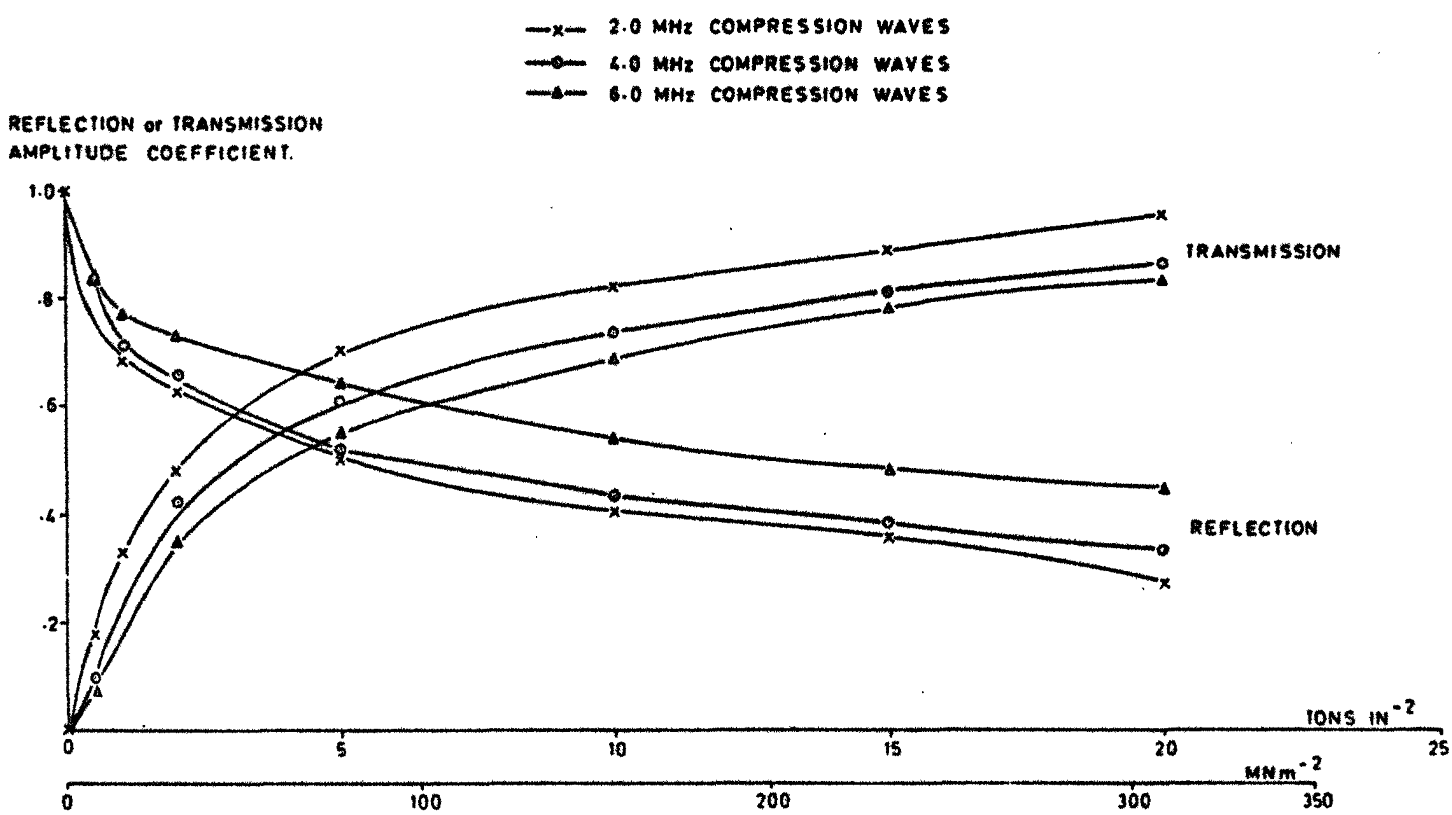

FIG. 4 THE FREQUENCY DEPENDENCE OF THE REFLECTION & TRANSMISSION COEFFICIENTS

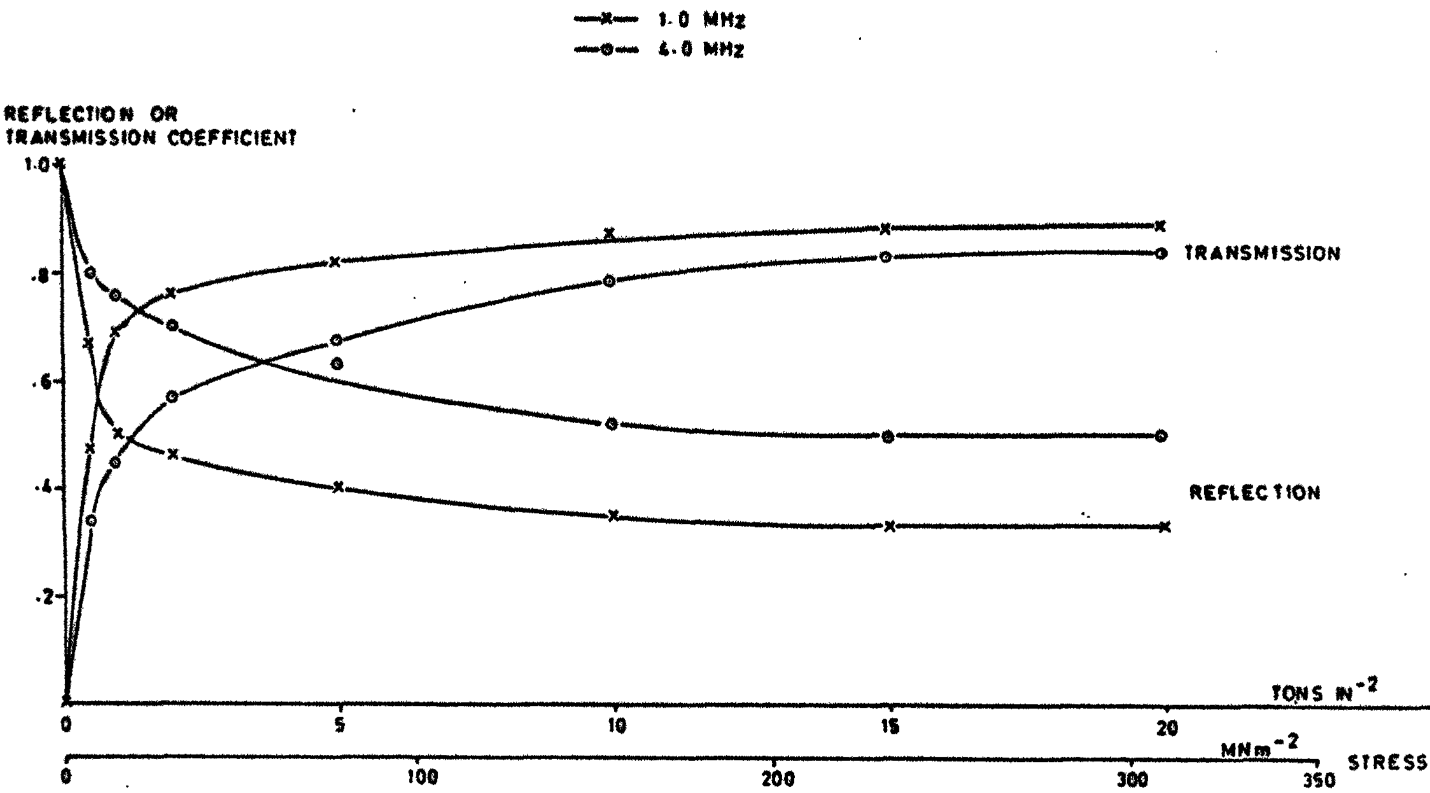

FIG. 5 REFLECTION & TRANSMISSION COEFFICIENTS FOR SHEAR WAVES

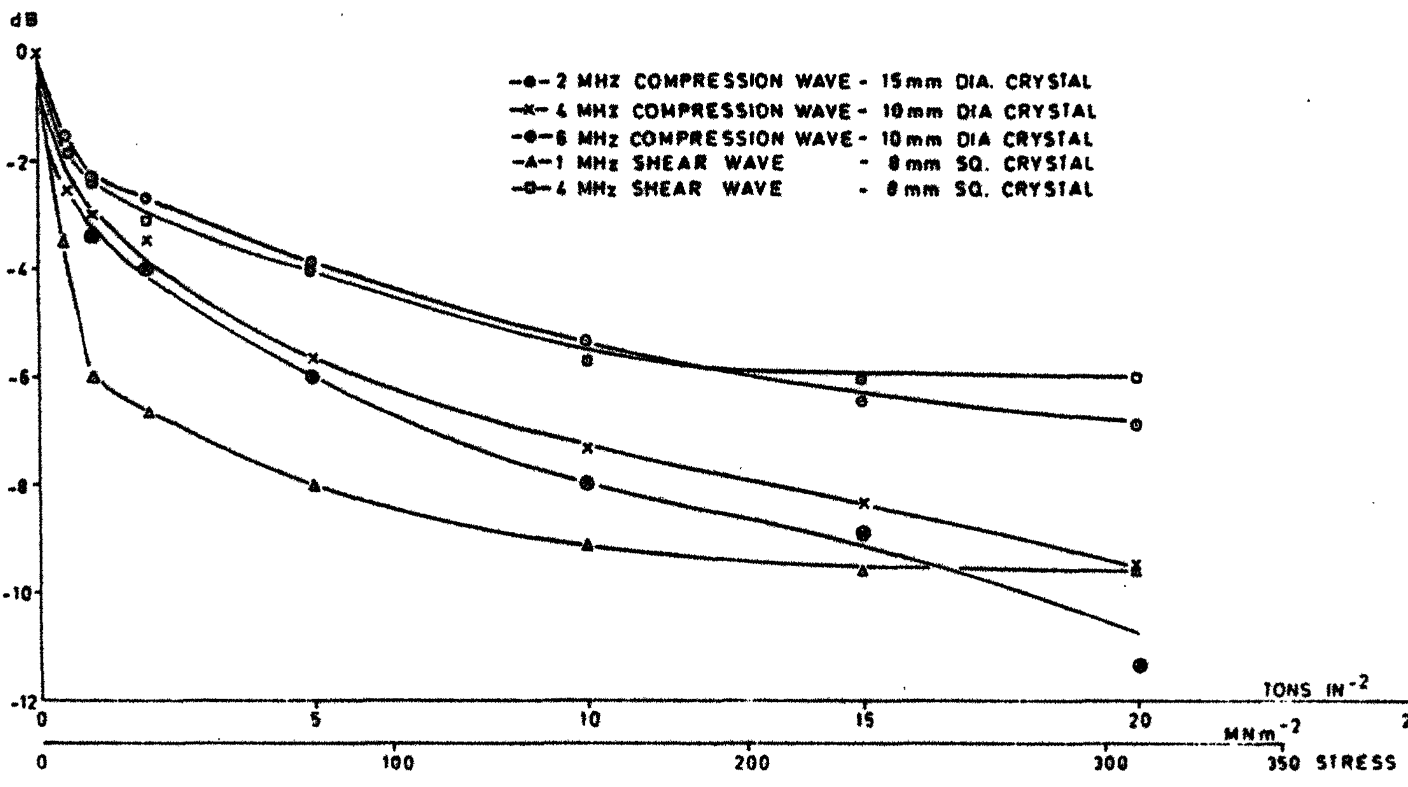

FIG. 6 CHANGES IN REFLECTION WITH APPLIED LOAD (dB SCALE)

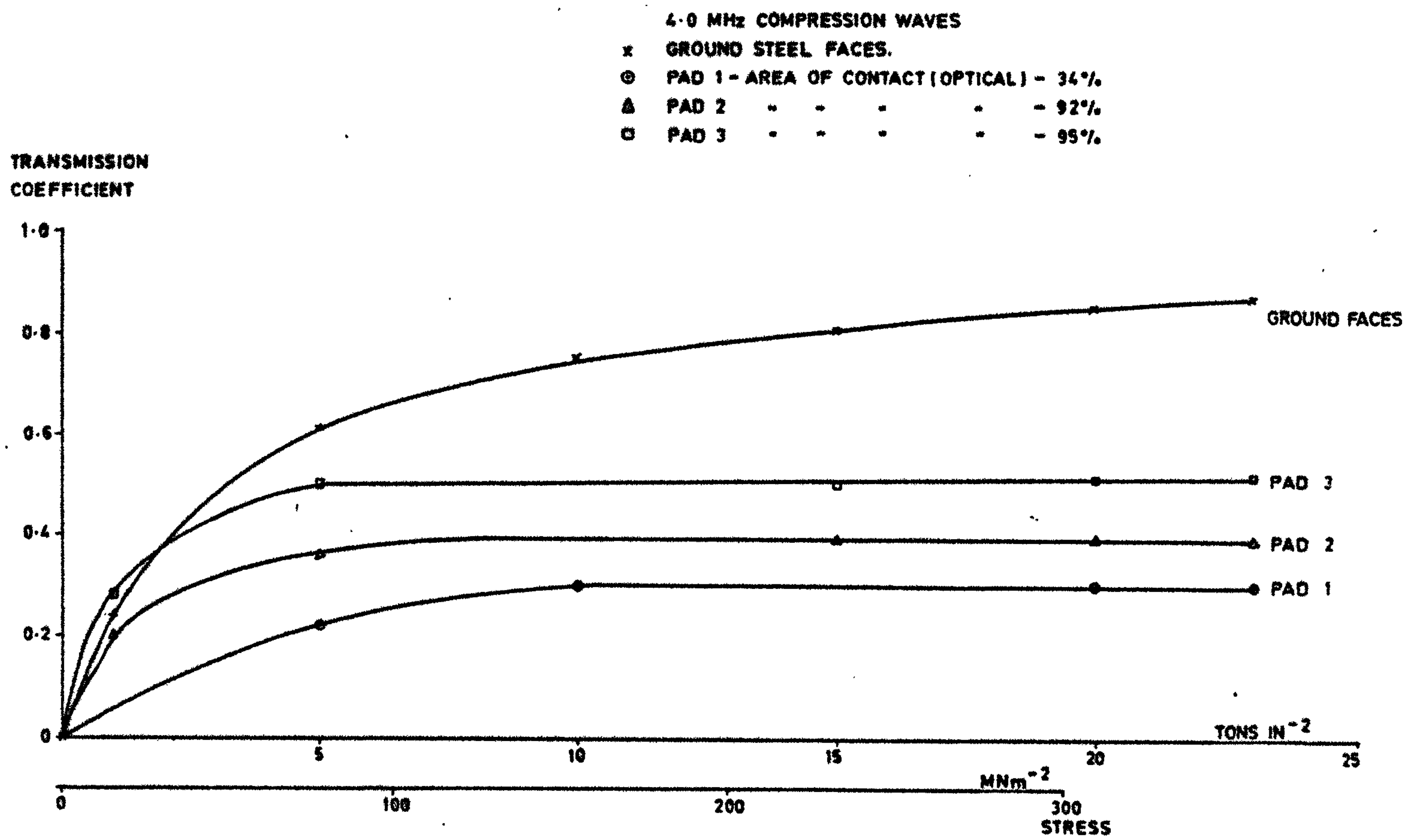

FIG. 7 TRANSMISSION THROUGH STEEL WOOL PADS OF VARYING THICKNESS

RC/SSR/A4/85)

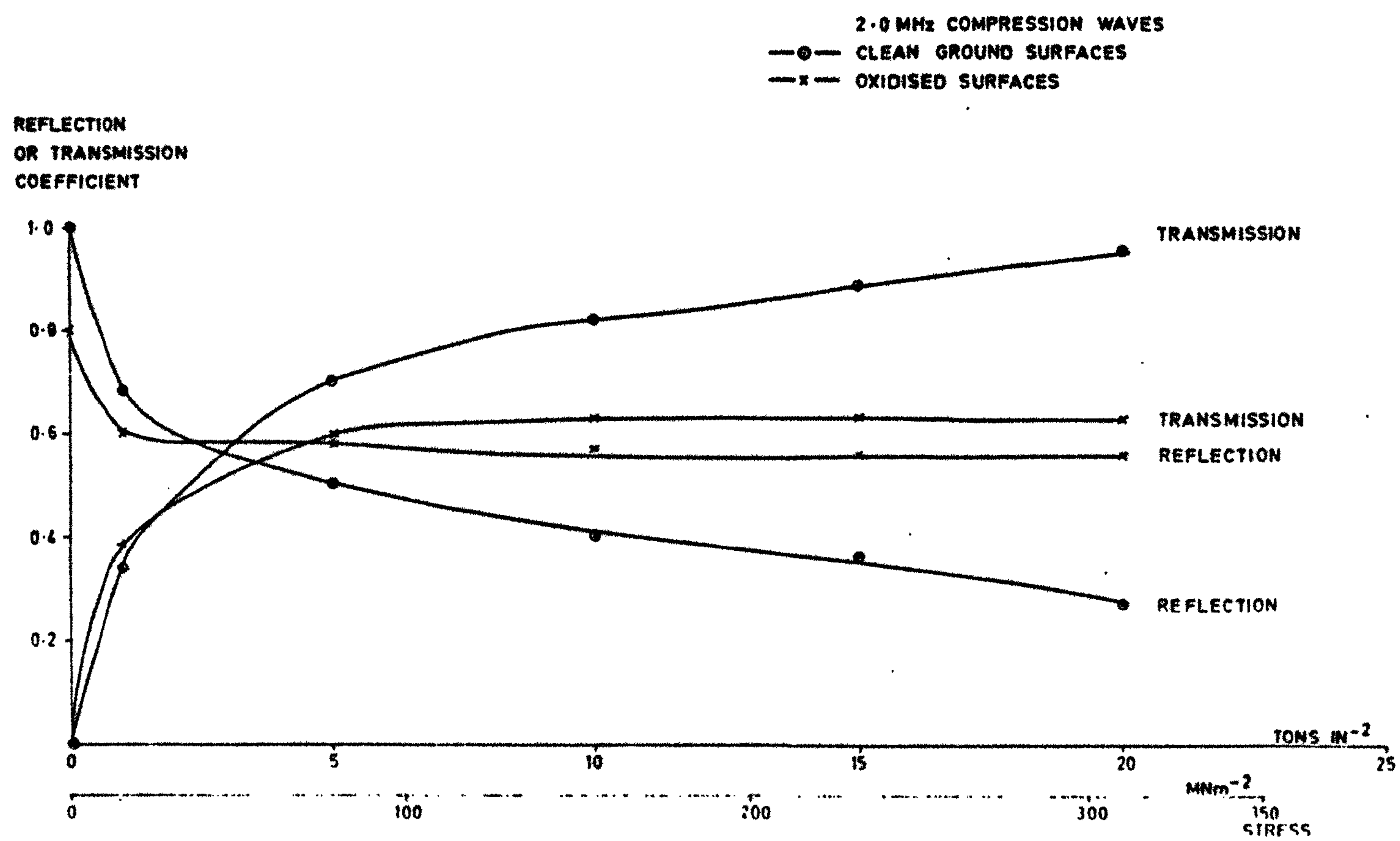

FIG. 8 THE EFFECT OF CORROSION ON TRANSMISSION AND REFLECTION

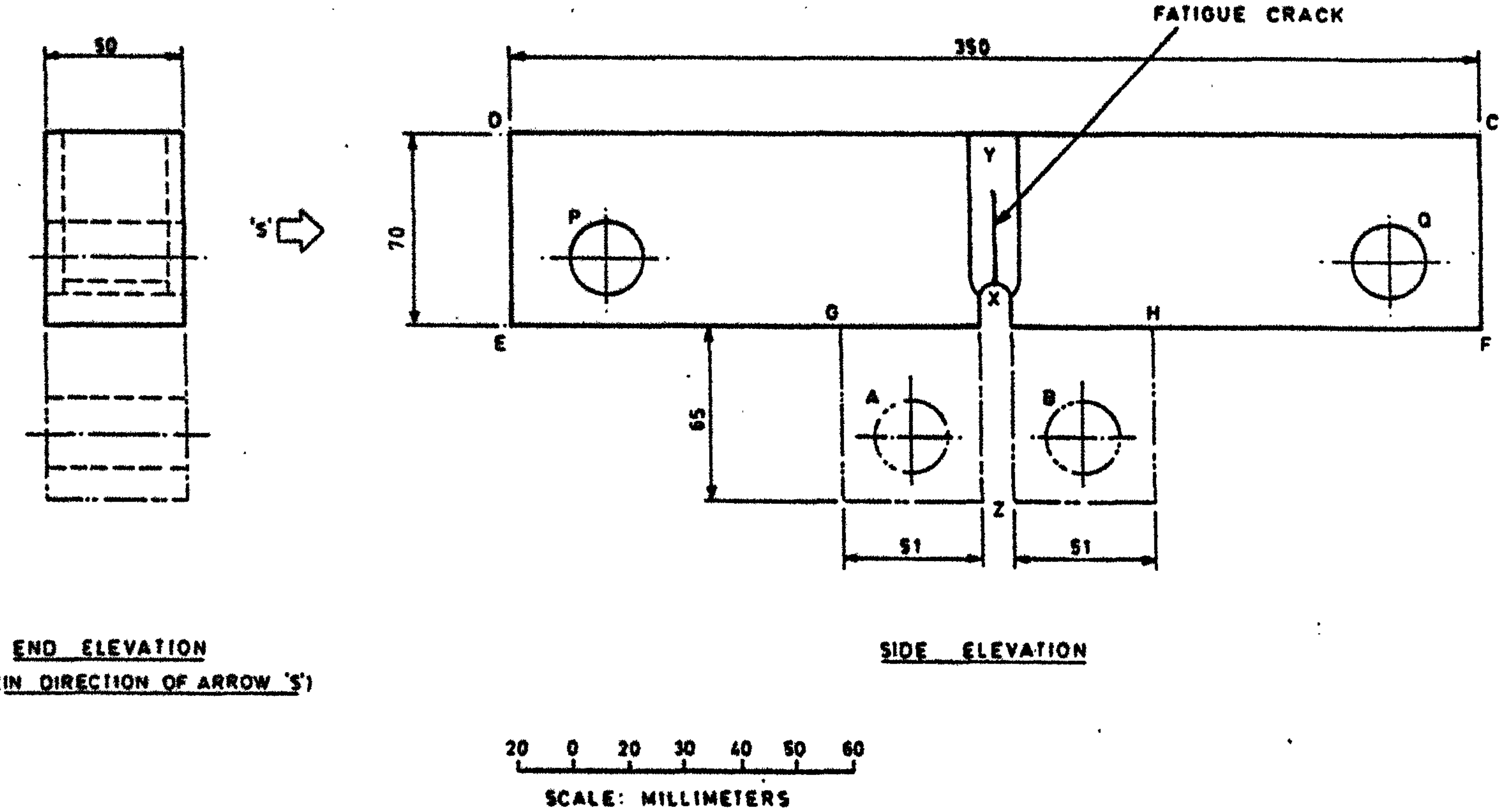

FIG. 9 MILD STEEL FATIGUE CRACK SPECIMEN

RC/SSR/A4/855

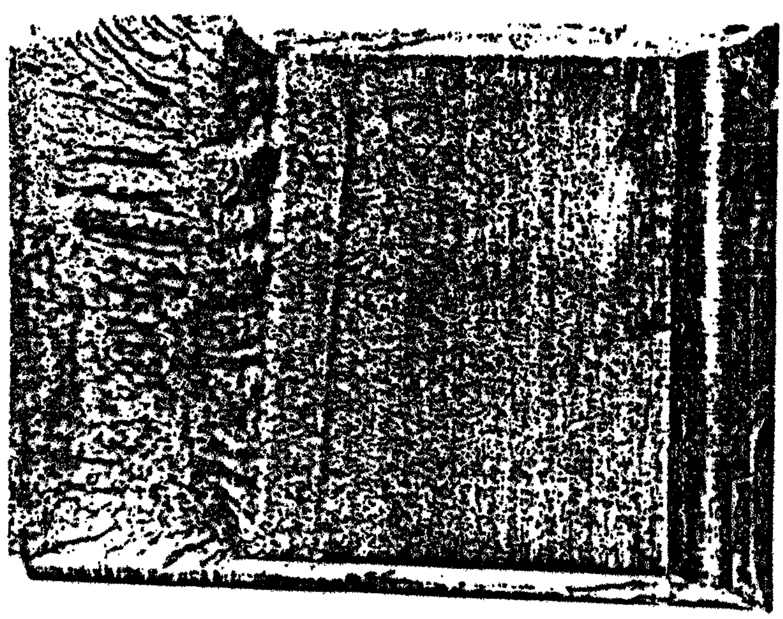

FIG. 10 PHOTOGRAPH OF THE FATIGUE CRACK SURFACE

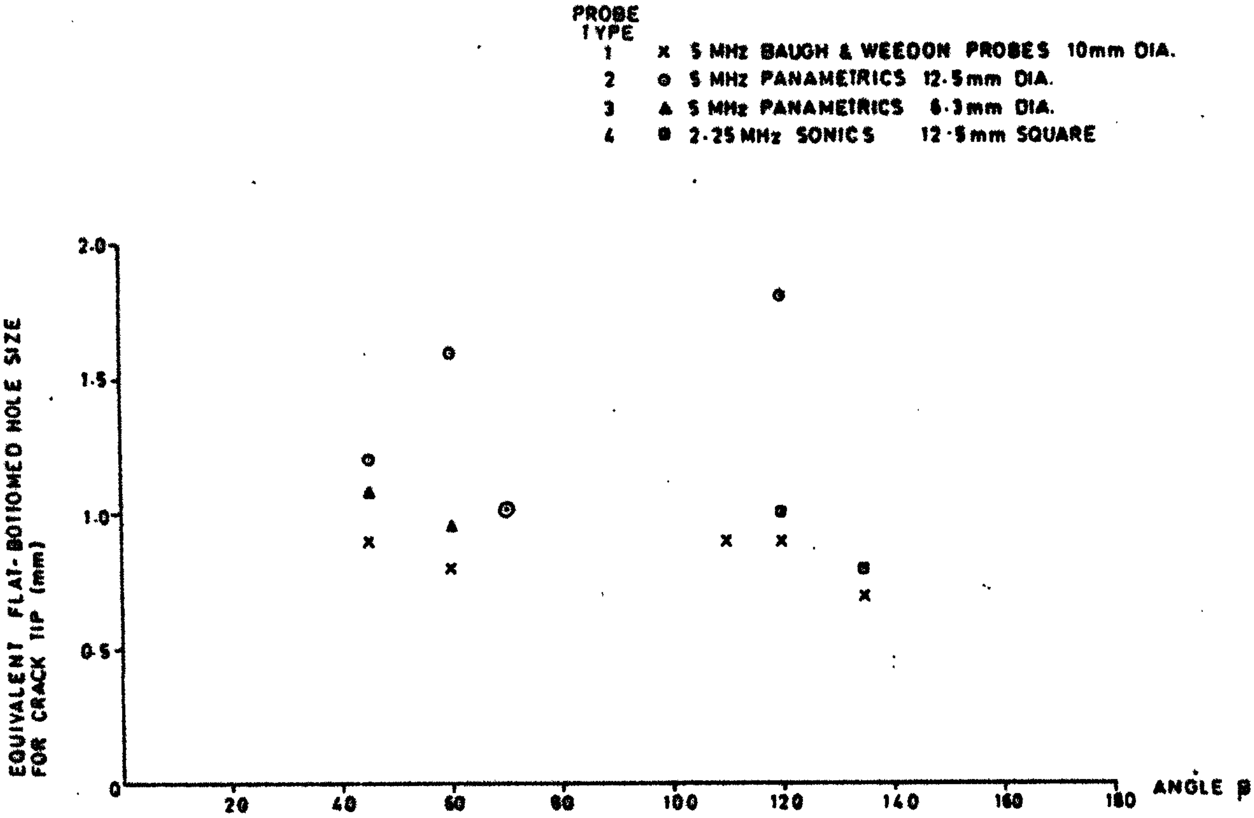

FIG.11 THE VARIATION OF THE CRACK TIP ECHO WITH ANGLE OF INCIDENCE (β) FOR SHEAR WAVES

RC/SSR/A4/856

PROBE ANGLE	x mm	y mm
45°	25	43
60°	45	70
70°	75	111

THE POSITION USED FOR EACH ANGLE OF PROBE

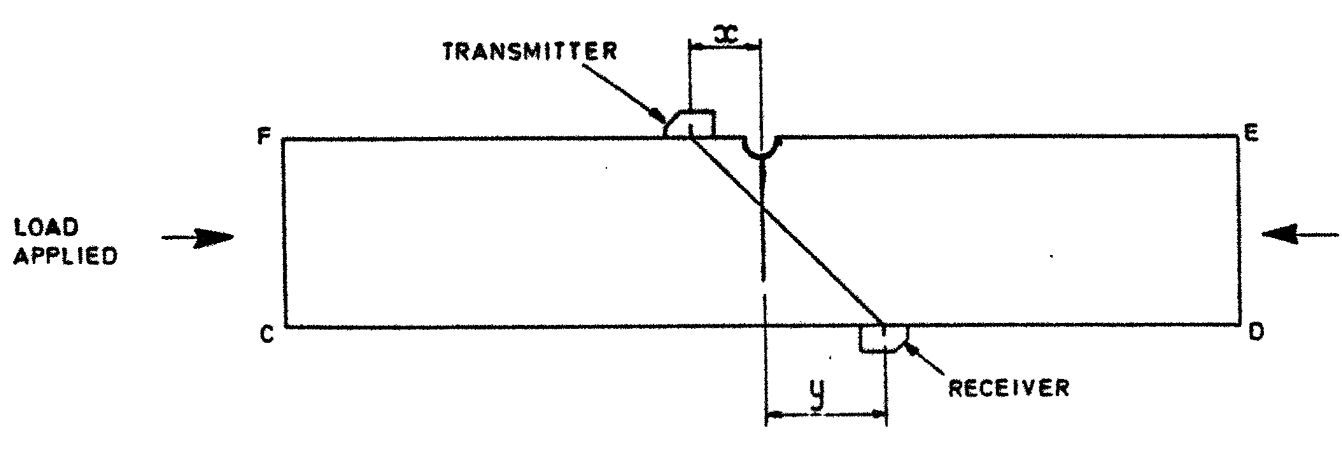

FIG 12 EXPERIMENTAL ARRGT USED TO MEASURE TRANSMISSION ACROSS THE CRACK

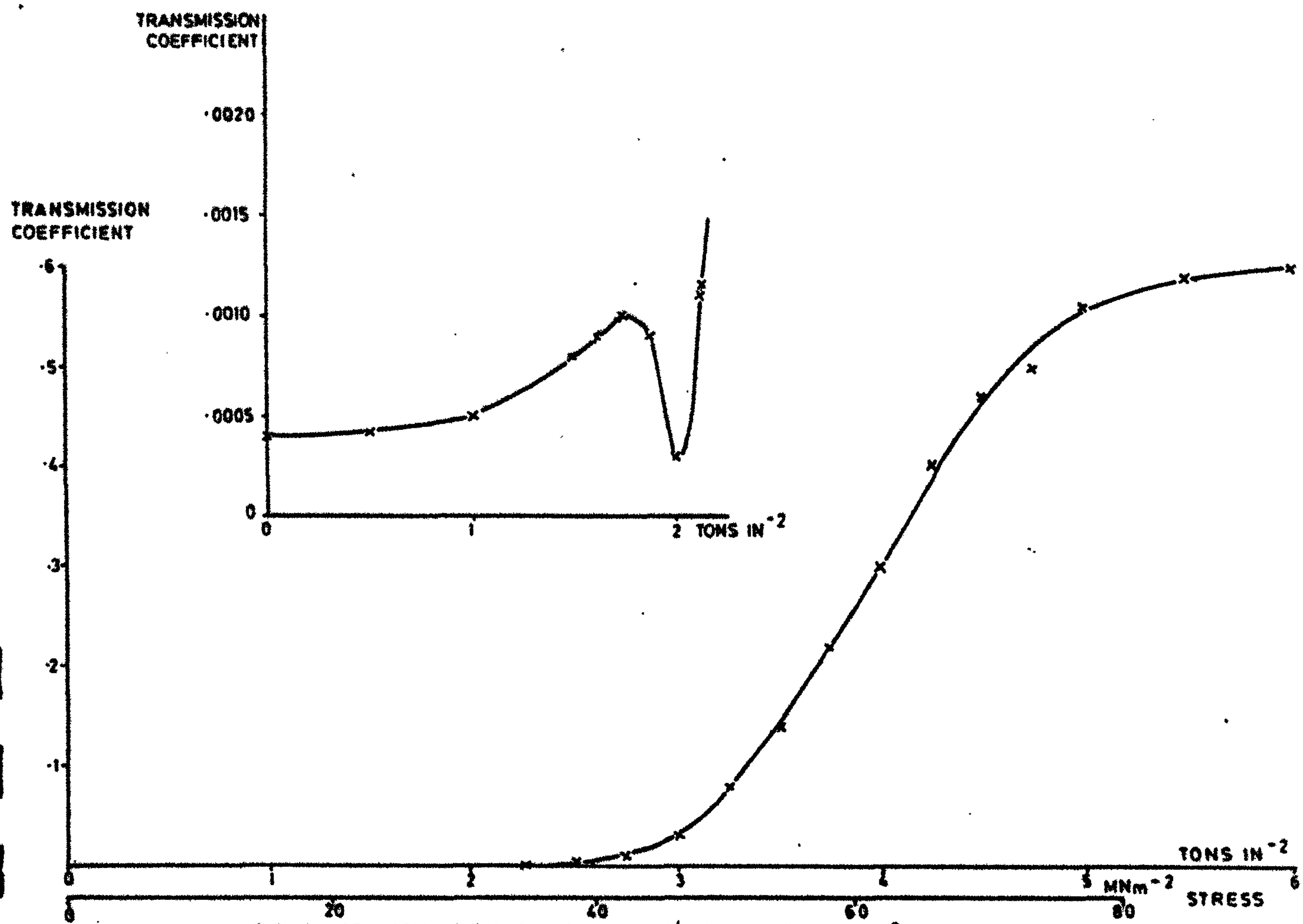

FIG. 13. TRANSMISSION OF 2MHz SHEAR WAVES AT 45° TO THE CRACK

RC/SSR/AL/859

MEAN STRESS APPLIED:- 80 MNm^{-2}

FLAW DETECTOR:- PA1020 TR MODE

PROBES:- BAUGH AND WEEDON - 2MHz 15mm DIA. / 5MHz 10mm DIA. } SHEAR WAVE

PROBE FREQUENCY	PROBE ANGLE	ANGLE OF INCIDENCE ON CRACK	TRANSMISSION THROUGH UNCRACKED BLOCK / TRANSMISSION THROUGH CRACK	TRANSMISSION COEFFICIENT
2 MHz	45°	45°	4 dB	0·6
	60°	30°	1 dB	0·9
5 MHz	45°	45°	10 dB	0·3
	60°	30°	9 dB	0·4

FIG. 14. COMPARISON OF TRANSMISSION THROUGH CRACKED AND UNCRACKED PARTS OF THE STEEL BLOCK

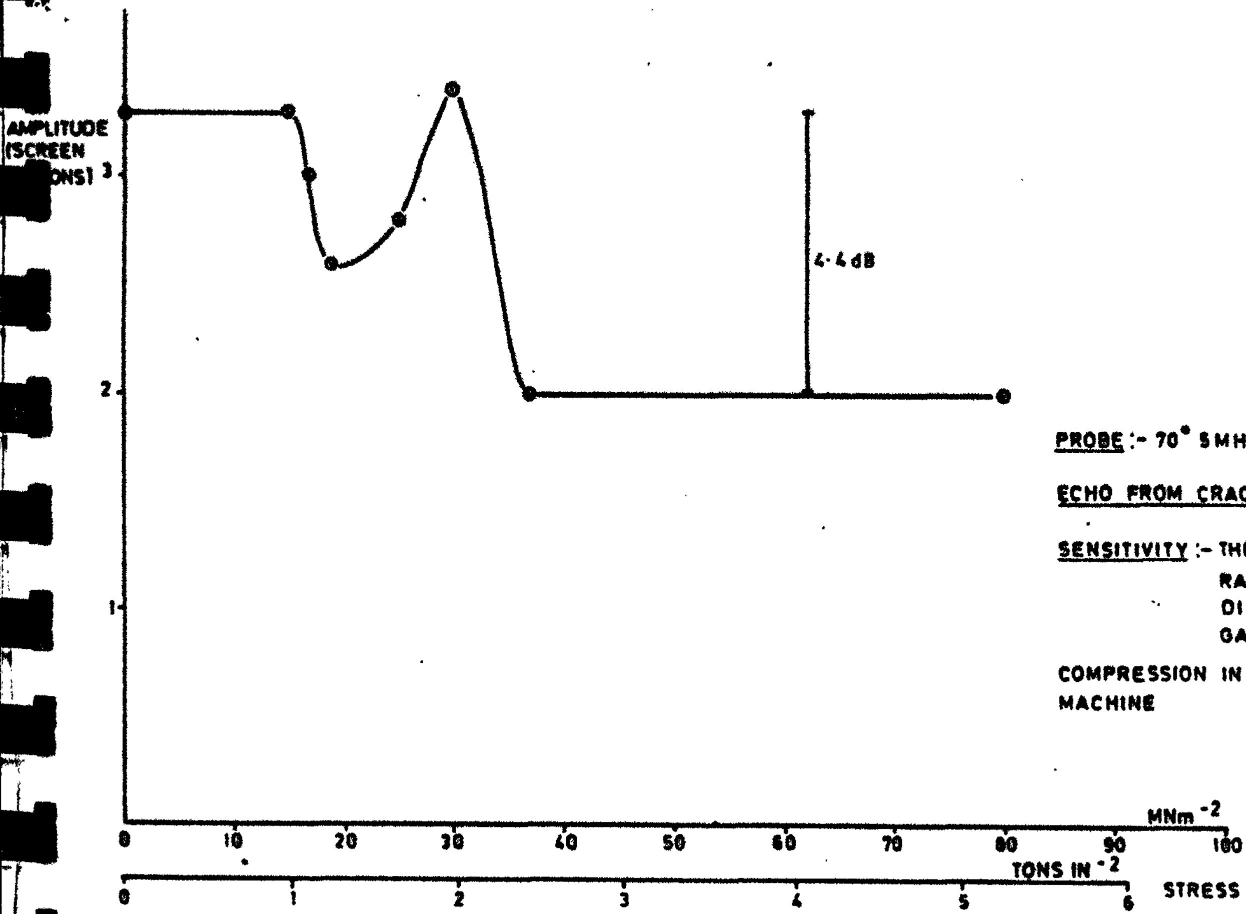

FIG 15 REFLECTION OF 70° 5MHz SHEAR WAVES FROM THE CRACK TIP

RC/SSR/A4/8

	AVERAGE VALUES OF MAXIMUM CHANGES	MAXIMUM CHANGE	MINIMUM CHANGE
CRACK TIP	−4·2 dB (10 READINGS)	−11·4 dB	0·0 dB
CRACK FACE	−1·9 dB (13 READINGS)	−10·6 dB	0·0 dB

APPLIED STRESS :- 0→90 MN m^{2}

FIG16 MAXIMUM, MINIMUM AND AVERAGE VALUES OF CHANGES IN REFLECTIVITY WITH APPLIED STRESS.