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MELBOURNE, VICTORIA

REPORT

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USE OF ULTRASONICS TO DETERMINE THE CRACK SIZE IN HIGH STRENGTH STEEL GUN BARRELS

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*MATERIALS TESTING LABORATORY

SYDNEY, NSW

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ABSTRACT

The use of high strength steel for large calibre gun barrels has increased the possibility that fatigue crack growth, as opposed to wear and erosion, will determine the safe life of a barrel. This is the case for the 5"/54 Naval Gun. Because fatigue cracking may lead to catastrophic failure, it is necessary to provide some form of life prediction that will ensure that fatigue cracks or other damage will not grow to a critical size. Fortunately such a provision can be confidently based on fracture mechanics.

The role of non-destructive testing is to check the crack length predictions and to ensure that cracks corresponding to the critical crack size for rapid fracture at the design load are not attained while the barrel remains in service. The ultrasonic end-on probe technique described provides a simple method of rapidly detecting, locating and sizing cracks without shadowing, and without the need for calculations required by other techniques.

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Use of ultrasonics to determine the crack size in high strength steel gun barrels

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ABSTRACT

The use of high strength steel for large calibre gun barrels has increased the possibility that fatigue crack growth, as opposed to wear and erosion, will determine the safe life of a barrel. This is the case for the 5"/54 Naval Gun. Because fatigue cracking may lead to catastrophic failure, it is necessary to provide some form of life prediction that will ensure that fatigue cracks or other damage will not grow to a critical size. Fortunately such a provision can be confidently based on fracture mechanics.

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CONTENTS

USE OF ULTRASONICS TO DETERMINE THE CRACK SIZE IN HIGH STRENGTH STEEL GUN BARRELS

1. INTRODUCTION

Until recently, the life of large calibre gun barrels was usually determined by loss of firing accuracy resulting from wear and erosion of the bore [1]. The relatively low operating stresses of these barrels permitted the use of steels having good fracture toughness so that the presence of small craze cracks in the bore surface did not lead to fatigue failure. The newer high-performance barrels, whilst much lighter, operate at higher pressures. This demands the use of higher strength steels with a resultant reduction in fracture toughness. Thus fatigue cracking in these barrels is of overriding concern as final failure can be by catastrophic crack growth. With the acceptance of these improved barrels, it is necessary to provide some form of life prediction based on the assurance that, during the service life of the barrel, fatigue cracks or other damage will not grow to a critical length between any inspection intervals. Fortunately such a provision can be confidently based on fracture mechanics.

Fracture mechanics permits an assessment to be made of the significance of defects by providing a unique relationship between applied stress, defect size and fracture toughness. Thus when the fracture toughness and applied stress acting on a structure are known, the critical defect size which will cause failure, can be calculated. In fatigue failure three distinct stages are discernible namely, crack initiation, crack propagation, and finally, fast fracture. In gun barrels the presence of pre-existing flaws and craze cracking will reduce or eliminate the initiation stage. As a fatigue crack grows under the cyclic load, the stress intensity at the crack tip increases because of the growth of the crack. Eventually, the crack may grow to a length sufficient for the stress-intensity factor to reach the critical value, at which catastrophic failure occurs.

For fatigue life prediction two kinds of information, which can be obtained from laboratory tests, are required [2]; firstly, the critical crack size for the barrel (this can be determined from fracture toughness measurements) and secondly, fatigue crack growth rate data. This information is used in a fracture mechanics model to predict the number of stress cycles before failure. The role of non-destructive testing is to check the crack length predictions and to ensure that cracks corresponding to the critical crack size for rapid fracture at the design load are not attained while the part remains in service. This can be done by making measurements of crack sizes at intervals so that the predicted crack growth before the next inspection, is less than that required to attain the critical crack size.

2. POSSIBLE METHODS OF CRACK MEASUREMENT

2.1 Background

There are a number of possible methods of detecting and sizing cracks; these include radiography, eddy currents, potential drop, magnetic particles and ultrasonics methods. With the exception of ultrasonics, there are serious limitations in the use of these methods, for crack size determination in gun barrels. Radiography depends heavily on cracks having favourable orientations. Due to a combination of small crack opening widths, build-up of lead in the mouth of the cracks, and unfavourable orientations, this method has failed to detect cracks as much as 20 mm deep [3]. Eddy currents are limited to cracks less than 5 to 6 mm deep because of instrument saturation. Moreover, the "zeroing" of these instruments is extremely difficult because of the numerous craze cracks that are present. Potential drop methods work well on isolated cracks of known position but only when they are associated with otherwise good surfaces. These conditions do not apply once the gun has been in service. Likewise magnetic particle methods can show all the surface craze cracking but cannot differentiate between these and the all important growing fatigue cracks.

2.2 Ultrasonic Techniques

There are several ultrasonic techniques using shear wave probes [3] which have been used with some success on thick walled cylinders. Measurement can be made by determining the amount of energy reflected from the side of the crack (Figure 1(a)); the size of the crack is estimated by comparison with calibrated slots, and its location calculated from the geometry of the reflection pattern. Another method is to use separate transmit and receive probes on opposite sides of the crack (Figure 1(b)) or to move the probe until the tip of the crack no longer reflects back to the receiver probe (Figure 1(c)). Silk and Lidington [4] have developed this last method using the beam diffracted from the tip of the crack rather than the reflected beam, for measuring cracks in welds to within 0.2 mm. On gun barrels these latter techniques are restricted to wall thicknesses to barrel diameter ratios less than one fifth in order to prevent mixed longitudinal and shear wave signals. In multi-crack situations they are also limited as adjacent cracks shadow each other, requiring slow painstaking work to locate and calculate the size of individual cracks.

3. END-ON ULTRASONIC CRACK MEASUREMENT

Unlike some of the above ultrasonic techniques this method uses a single probe and depends on the reflection of longitudinal waves from the crack tip, the radial depth of the crack being indicated by the distance between the crack tip echo and the back wall echo (Figure 2(a)). The first reported success using this technique was by Miller [5] in 1970, Hunt [3] also successfully used this technique on gun barrels, although he reports earlier failures on thin wall gun liners. The success with gun barrels is mainly due to the type of steel used and the thickness of the section. The use of clean, fine grained steels reduces scatter from inclusions and allows the use of the high amplifier gains necessary to obtain a sufficient indication from the weak crack tip echo, while the thick section of the barrel allows an adequate separation of the crack echos from the massive front face echo.

A possible explanation of why the crack-tip reflects sound is that the tip area is a series of minute angularly varying facets some of which are oriented so as to reflect a part of the incident sound field back to the probe. As the crack continues to grow, the tip pattern will change and there could be little or no indication of the new growth until a sufficient number of reflecting facets are formed, accordingly the ultrasonic indications of the crack depth would be just at, or slightly behind, the actual crack tip. Both Hunt [3] and Miller [5] found that the ultrasonically measured depth using this technique, was up to 1 mm less than that measured after the specimens had been broken open. From the wavelength in steel at a test frequency of 5 MHz, the minimum size defect that could be detected is about 0.5 mm and as many of these facets may be smaller than this, and since the minimum detectable defect decreases with increasing frequency, testing should be carried out at the highest frequency compatible with the attenuation of the material and its surface finish. In the highly stressed plastic zone surrounding the crack tip, the specific acoustic impedance will be lowered, causing some refraction of the diverging sound beam; then some facets not normal to the axis of the sound beam can become effective reflectors.

In this particular technique, as the probe approaches a position directly above the crack, the distance between the probe and the crack tip decreases and the crack tip echo emerges from the shadow of the back wall echo. When the probe is directly over the crack tip the distance between the crack and the back wall echos is a maximum and is also a measure of the radial crack depth (Figure 2(b)). The rifling in the gun barrel does not interfere with this measurement since the leading edge of the back wall echo is from the root of the lands. However, variations in the amount of erosion in the barrel continously alter the precise position of the back wall echo and consequently, when any measurements of crack depth are being made, actual distances between the discontinuity indication and the back wall echo should be taken rather than the distance from some arbitrary end point.

The advantages of this technique are that

(i) the larger active cracks are always closer to the probe than the smaller craze cracks, so there is no shadowing and consequently the fatigue cracks are easier to detect.

(ii) the point of maximum separation of the crack tip and back wall echos gives both the location and depth of the crack without further calculations, and

(iii) no calibration is required except for the velocity of sound in the material being tested.

4. TEST BLOCKS

4.1 Experimental

Initial tests of the end-on ultrasonic technique were carried out on a series of test blocks using a Krautkramer MF4F 4 MHz finger probe and a Sperry SFZ 57A4273 10 mm diameter 5 MHz longitudinal probe with a Krautkramer USIP11 ultrasonic unit.

Three test blocks 50 mm thick were examined. They were taken from a gun barrel forging which contained laboratory induced fatigue cracks and were designated A, B and C. The cracks were measured optically at the edges, but as the normal behaviour of cracks in gun barrel steel is to bow out about 3 mm towards their centre, the sizes at the surface and the centre were estimated as A : 0.2 to 3 mm, B : 2.75 to 5.7 mm and C : 8.8 to 11.8 mm. Besides these specimens a section of a 3.375 inch bore gun barrel forging with spark eroded slots 1, 2, 3, 5, 7 and 10 mm deep, was used as a test block.

4.2 Results

In the fatigue cracked test blocks no defect could be detected in 'A' with the end-on ultrasonic technique and the crack in 'C' was measured to be approximately 11 mm. The crack in 'B' gave a much stronger echo than 'C' and measured 5-6 mm towards one edge of the sample jumping to 9-10 mm towards the opposite edge of the block.

In the slotted barrel test block the 1 mm slot could not be detected, and the 2, 3 and 5 mm were each measured to be about 1 mm less than the slot depth. The 7 and 10 mm "defects" were close to each other but were easily separated and found to be only about 0.5 mm less than the slot depth.

5. FIVE INCH NAVAL GUN BARRELS

5.1 Experimental

Two 5 inch naval gun barrels were examined using the end-on ultrasonic technique. Barrel No. 16763 having fired the equivalent of 2112 rounds and barrel No. 16822 the equivalent of 2043 rounds. These barrels were re-examined about twelve months later, at the end of their effective life (due to wear and erosion) after firing an additional 77 and 136 rounds respectively.

The Sperry probe was used with a Sperry Reflectoscope UM775 ultrasonic unit for the first series of examinations and with a Krautkramer USIP11 ultrasonic unit for the second series of examinations. A special rig was built to scan the probe over the barrel and indexed to the top centre fiducial mark of the gun barrel.

To ensure a consistent signal, the probe was mounted in a large block of aluminium with a curved surface matching the outside curvature of the gun barrels (Figure 3). The block was mounted on rails and guided by linear bearings traversed along the barrel by a lead screw. The front face of the probe was located about 0.5 mm above the centre of the curved face of the aluminium block to prevent surface wear and a feed line delivered a steady stream of glycerine containing a wetting agent, to the transducer face. This coupled the probe and the barrel surface, and at the same time effectively forming a liquid lens which would tend to give some degree of focussing of the beam. The guide rails were attached to a pair of rings, one of which rotated around a second ring attached to the barrel. This fixed ring was graduated in degrees indexed to the top centre mark on the breech of the gun barrel itself (Figure 4). In practice the gun barrel was rotated so that the probe holder remained in the vertical position at all times, although it was free to move circumferentially by $\pm$ 5° in order to follow any cracks which appeared.

5.2 Results

The evaluation of the barrels was carried out using longitudinal scans every five degrees around the barrel. This was considered adequate as the probe used had a theoretical beam divergence of nine degrees, measured between the edge of the beam and the axis. This divergence is equivalent to a projected circle of about 40 mm diameter at the inner surface.

The polar co-ordinates of each discontinuity detected were noted and later these were recorded on crack maps (Figures 5 to 8). Dots represent the first and last discontinuity detected in each traverse, i.e. they delineate the extent of the 'cracked' region along the barrel. A reduction of the data was made by plotting only those cracks parallel to the direction of rifling which were detected on two or more consecutive traverses. A further reduction of data was made for the second series of examinations as 4 to 5 times as many 'cracks' were detected, so that only the larger cracks using the criterion above were plotted, plus some large circumferential 'cracks'.

The first 'cracks' located in each case were clustered around the commencement of rifling, i.e. about 1038 mm from the breech end. The last cracks detected during the first examination, were a further 300 to 400 mm along the barrels except for a 90 degree segment of the barrel No. 16822, where they were detected between 400 and 500 mm from the first cracks. The segment of this particular barrel showed extensive cracking, together with severe erosion. The last cracks detected during the second examination were between 400 and 500 mm from the first cracks for both barrels. The erosion of the barrels was measured every 50 mm by observing the shift in the back wall echo with respect to the thickness recorded on the drawings (Figures 9 to 11).

The erosion of the barrels made the identification of the cracks difficult, especially as these were measured to be about 2-3 mm. Erosion caused non-uniform movement of the back wall echo, often with a separate echo from the main back echo and similar to that from a crack. 'True' cracks were distinguished by their movement back into the main back wall echo as the probe passed over and then moved away from their location. This was a particular problem during the second series of examinations.

5.3 *Discussion*

The severe erosion and guttering of the barrels produced variations in the backwall echo that made the identification and measurement of 'cracks' very difficult. It was often observed that the front of the backwall echo split to produce a crack-like echo and caused the backwall echo to move back, however if these were actual cracks, then in the region of the 'crack' the wall would be thicker than in the surrounding areas; it is likely that this is associated with multiple backwall echos due to guttering. Since most of the 'cracks' detected were 2 to 3 mm long and about the same depth as the 'craze cracking' and the guttering, much mis-identification could have occurred. Even larger circumferential 'cracks' were associated with deep guttering of about the same depth.

The change in the ultrasonic unit used in the two series of examinations and the increased erosion of the barrels in the second series of examinations, illustrated the difficulty in reliably detecting cracks under these conditions. The UM775 unit gave a short but 'filled in' echo and the separation of this echo from the backwall echo was used in the first examination to filter out the smaller 'cracks'. The USIP11 produced a broader, cleaner, filtered echo but did not give the same clear separation at the smaller 'crack' size, although the indication of the larger 'cracks' was more easily distinguished from the noise. This difference explains why so many more small 'cracks' were recorded in the second examination.

6. THE TWO BARREL SECTIONS

6.1 *Experimental*

A 540 mm long half section of barrel No. 16763 was examined in more detail, along with a section of un-eroded barrel in which 1 mm cracks had previously been detected using magnetic particles. For these examinations a Krautkramer-Branson KB6000 ultrasonic unit was used with the Sperry contact probe. For the immersion testing, the KB6000was used with Sperry 5 MHz SIJ J375 and SIW 57A9586P 19 mm dia. immersion probes.

6.2 *Results*

Examination of the No. 16763 barrel section, using both contact and immersion techniques, showed that the previous circumferential 'crack' indication obtained were associated with erosion 'gutters' and craze cracking. This was confirmed later by sectioning, when large 3 to 4 mm cracks were found but these were located in the walls of 4 to 5 mm deep gutters (Figure 12).

The 1 mm cracks in the un-eroded barrel section were undetected using ultrasonics. However resolution of the rifling was possible, particularly using the immersion technique.

6.3 *Automatic Testing*

An automatic or semi-automatic system would be preferable for regular checking of gun barrels. Some tests were carried out using the immersion technique on the barrel sections, however these tests were limited to the tapered wall thickness of the un-eroded section and restricted to single line scans on the half section due to the inability to rotate this heavy section. The surface finish on the barrel and beam spread produced some spurious signals, but these signals can be reduced by using a plexiglass shield to reduce the beam spread and the area from which return signals are accepted, particularly in the direction of the barrel curvature.

In any automatic system it would appear preferable to use a contact technique rather than an immersion technique, especially with the reduction in attenuation achieved using a contact probe. However using this technique would still require equipment to handle, rotate and scan along the barrel; it would require a means to hold the probe on the surface and to catch the coupling liquid; but it would obviate the need for a large immersion tank. Before implementing such a system more work would be required to optimise the operating conditions, particularly the coupling of the flat probe to the curved gun barrel surface. Further work would be necessary to analyse the pattern of the signals in order to correctly discriminate between cracks and any spurious signals, and this work would require barrel sections with large cracks and without severe erosion. Additional computing and data acquisition facilities may be required.

7. DISCUSSION

The end-on ultrasonic technique is capable of detecting and measuring, without further calculations, radial cracks in thick wall cylinders. A number of questions remain to be answered viz why is the echo from some cracks much stronger than those from similar cracks in the same material (test blocks B and C); why is no echo detected from other, particularly small, cracks (test block A: 3 mm, 1 mm cracks in the un-eroded barrel section and the 1 mm slot in the slotted test block); and why does the undersizing of the crack length appear to be greater with smaller cracks.

Silk and Lidington [6] have suggested that scattering from micro-defects in the stressed region at the crack tip provides a major contribution to the detected crack echo. In their work using diffracted beams they found no tendency to undersize, nor, when the specimens were broken open, did the cracks show high angled facets. In a summary of a symposium on ultrasonic flaw sizing [7] Silk is reported to have indicated that measurements taken with a single probe straight down onto the crack tip would be impossible to achieve with a diffracted wave and must be assisted by reflections from facets on the crack tip. Thus the presence, or absence, of high angled facets could explain the variation in reflected signal strength and particularly the degree of undersizing. However neither of these reflective sources explains why the small crack in test specimen A and the 1 mm slot in the slotted test block were not detected, particularly as the latter was about 1 mm wide and should have given a detectable reflection regardless of the presence or absence of micro-defects or high angle facets.

8. CONCLUSIONS

1. The ultrasonic end-on probe technique is capable of detecting cracks in thick walled cylinders.

2. Defect sizes can be determined with reasonable accuracy using this technique and it has the advantage that such measurements can be made in the presence of a high level of craze cracking, which will cause shadowing when other ultrasonic techniques are used.

3. It is quite rapid when compared with other techniques of defect sizing, as no calculations are required to determine the size or position of the crack.

4. It has the advantage of being unaffected by changes in wall thickness as measurements are made by reference to the location of the backwall echo.

5. It would appear that in any future programme of examination of gun barrels for cracks, an automatic ultrasonic end-on probe system could be developed.

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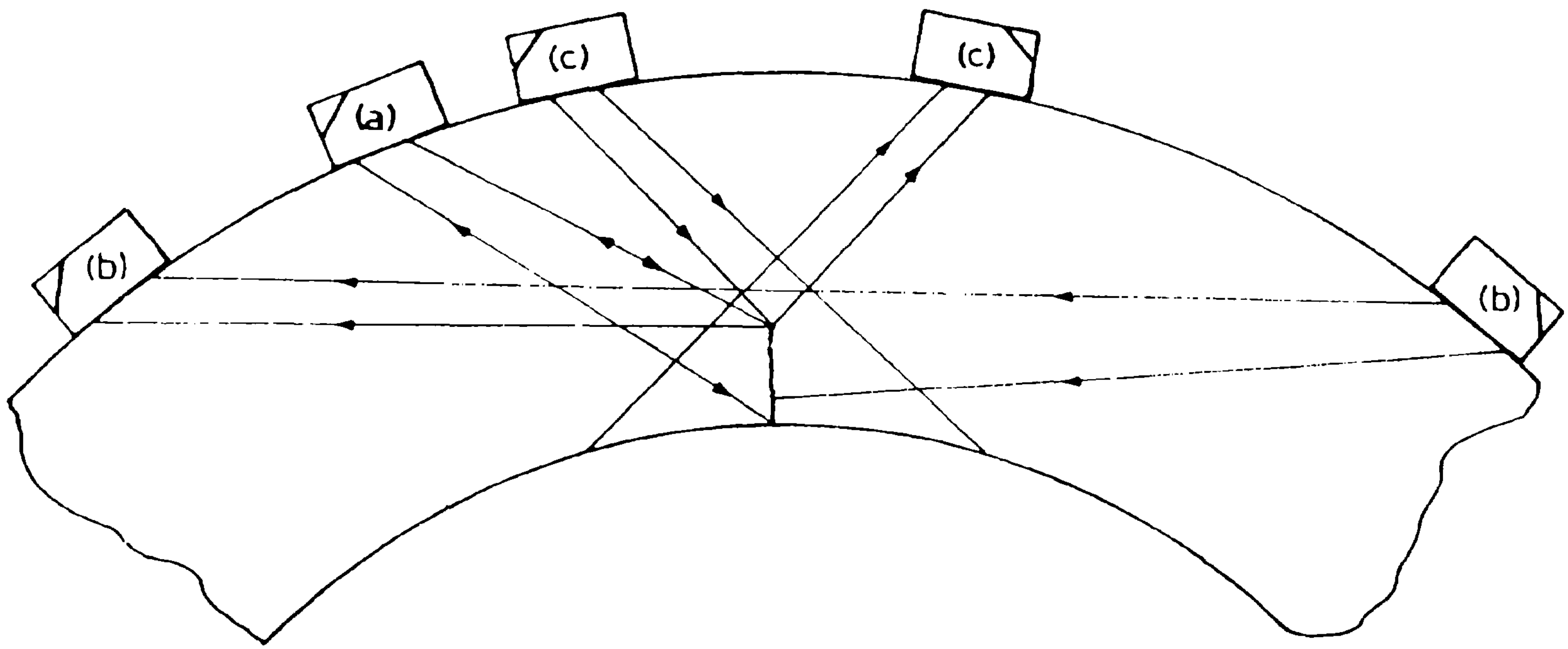

FIGURE 1 Shear wave

(a) reflected from side of crack
(b) partially transmitted past crack
(c) reflected from tip of crack

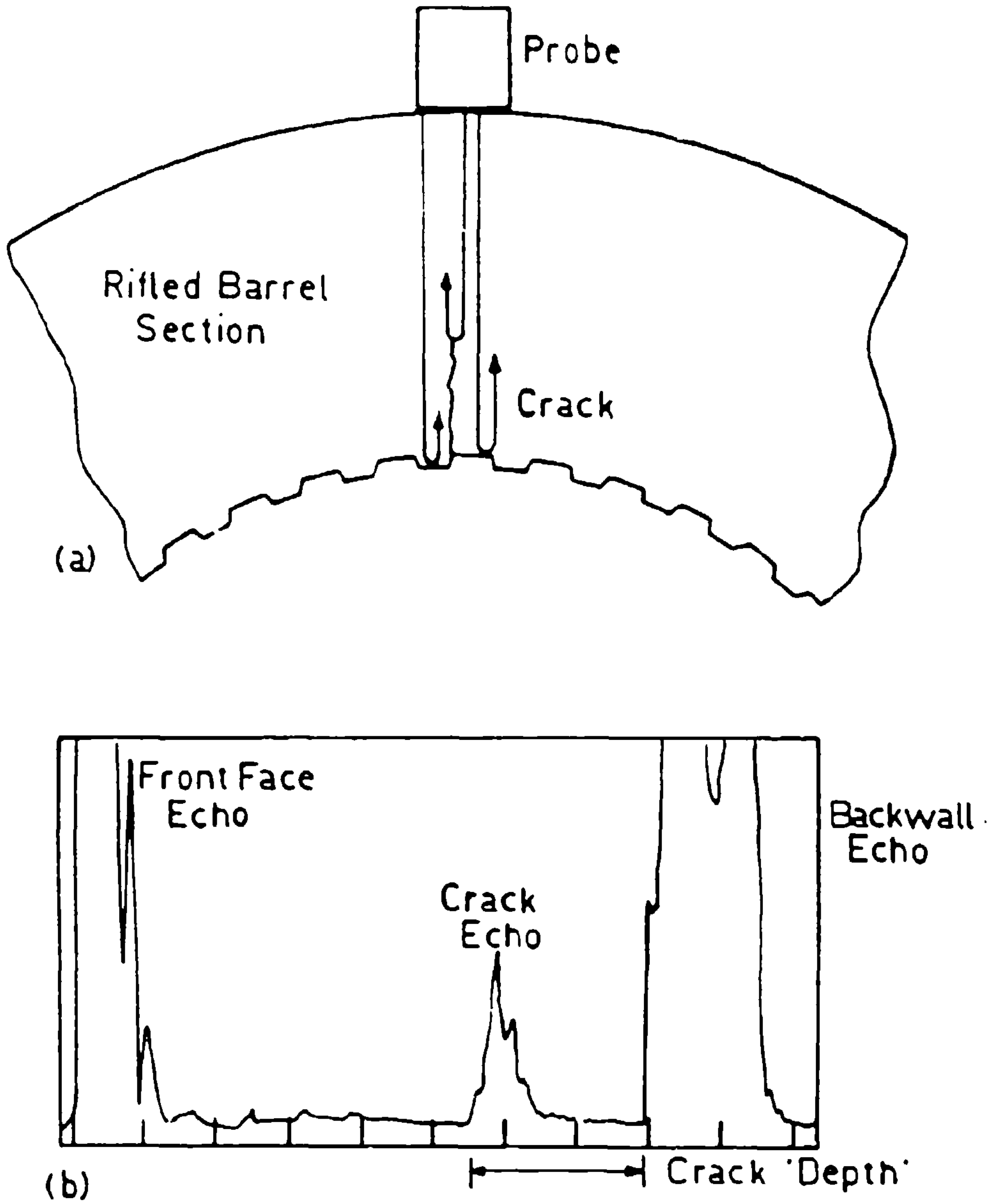

FIGURE 2 Longitudinal wave

(a) reflected from tip of crack
(b) diagrammatic CRO trace.

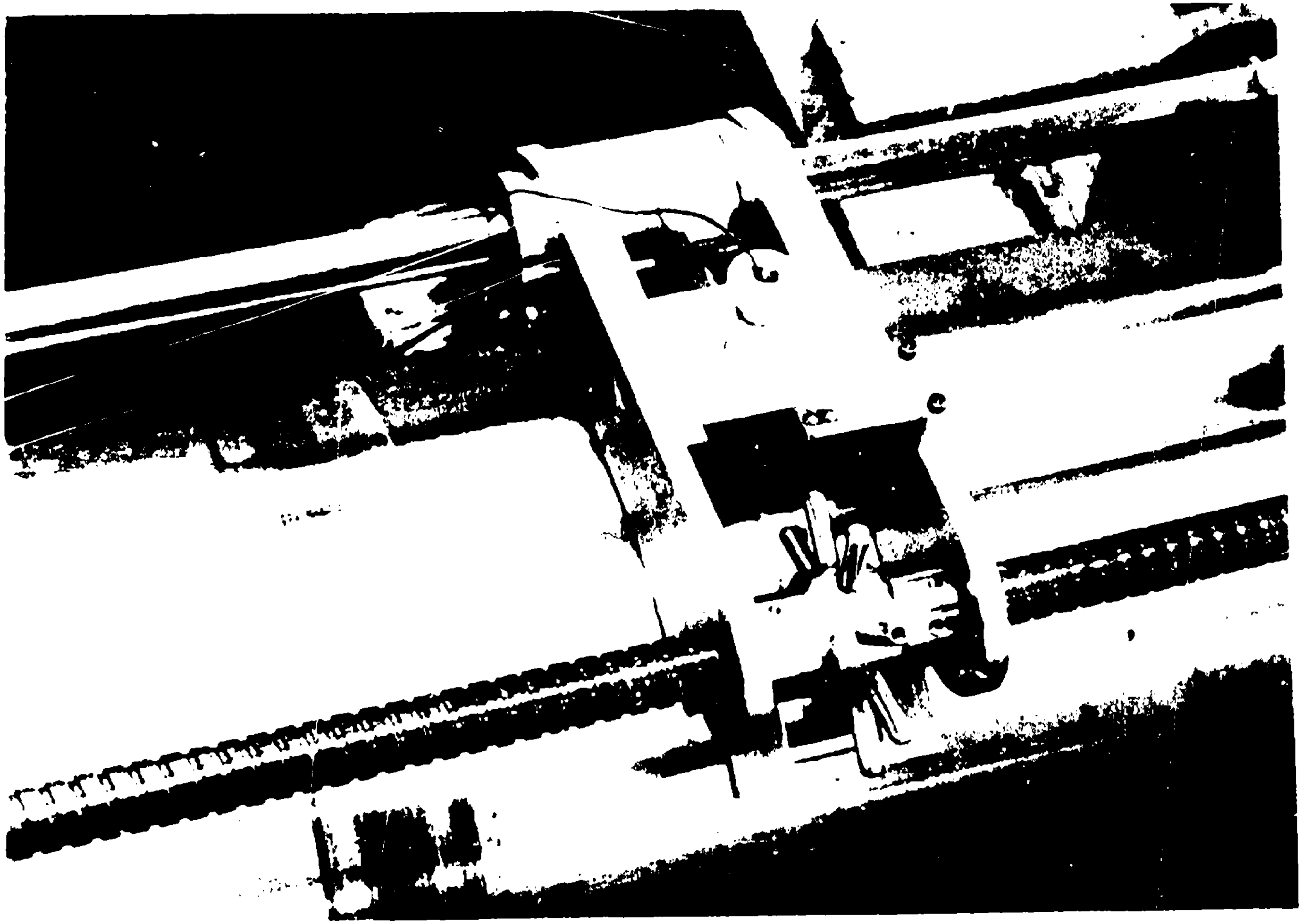

Figure [illegible]. Close-up showing probe mounting block and lead screw traverse system.

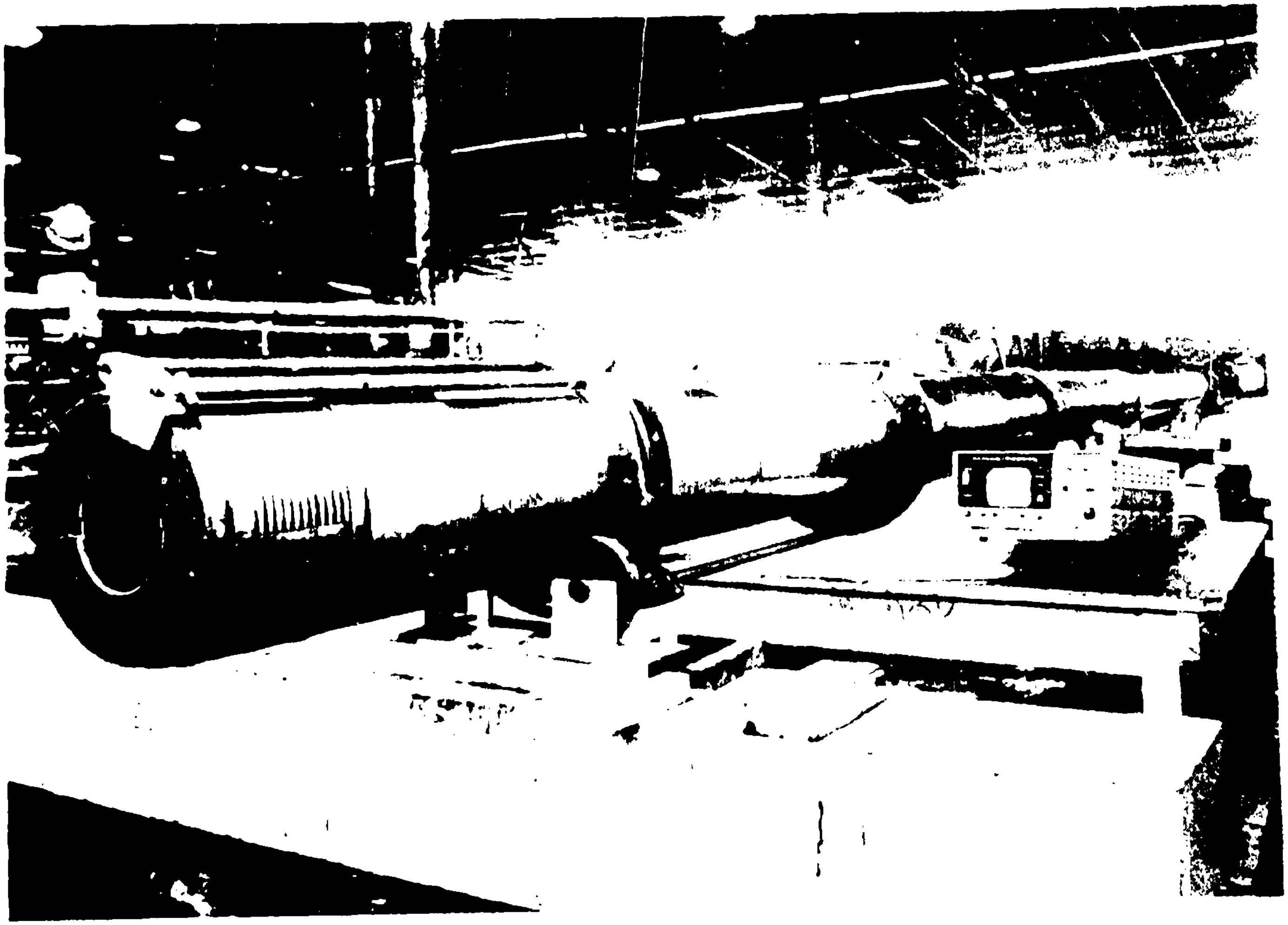

FIGURE [illegible] — General view of the [illegible] on the barrel.

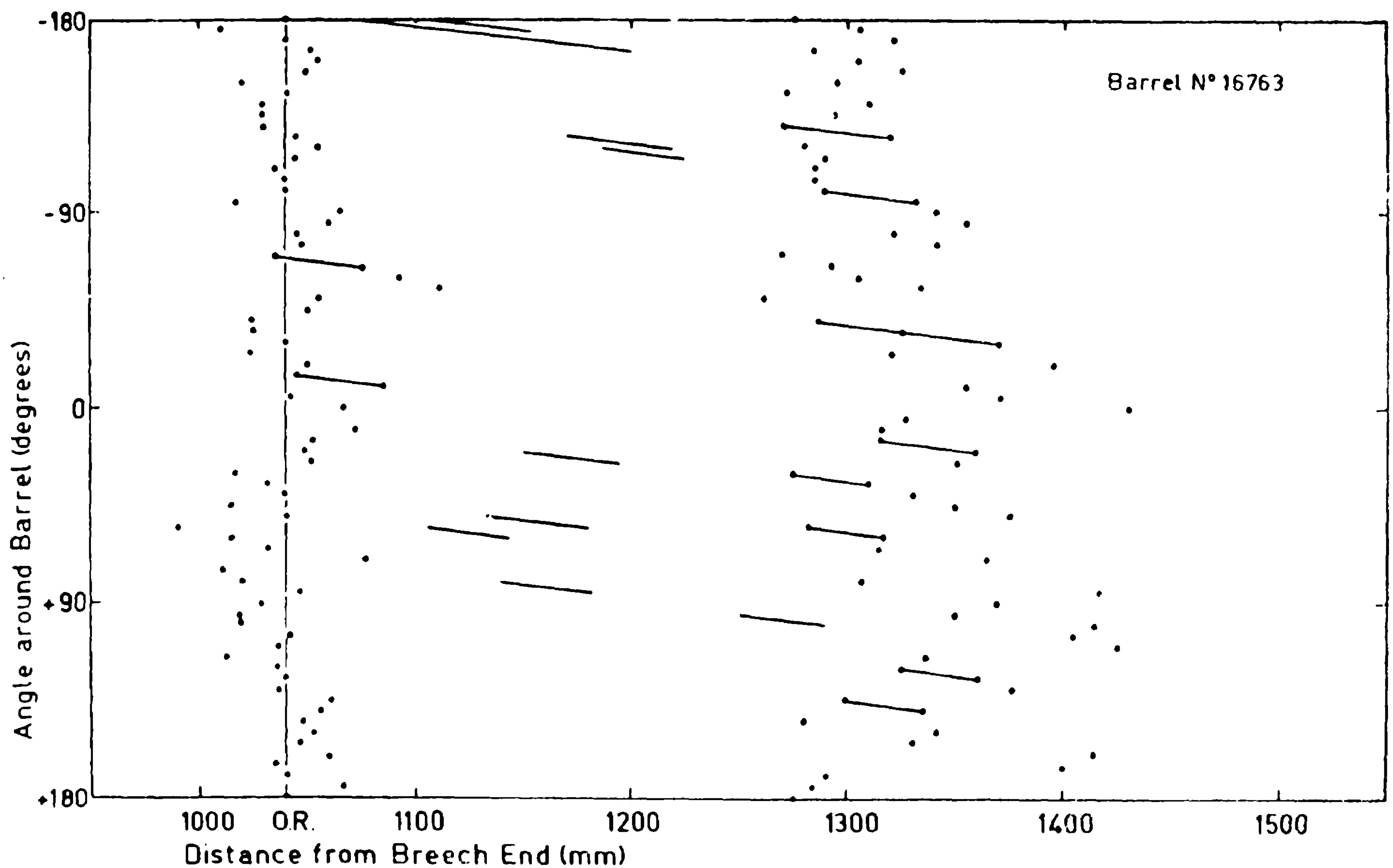

FIGURE 5 Crack map for barrel No. 16763 after 2112 rounds.

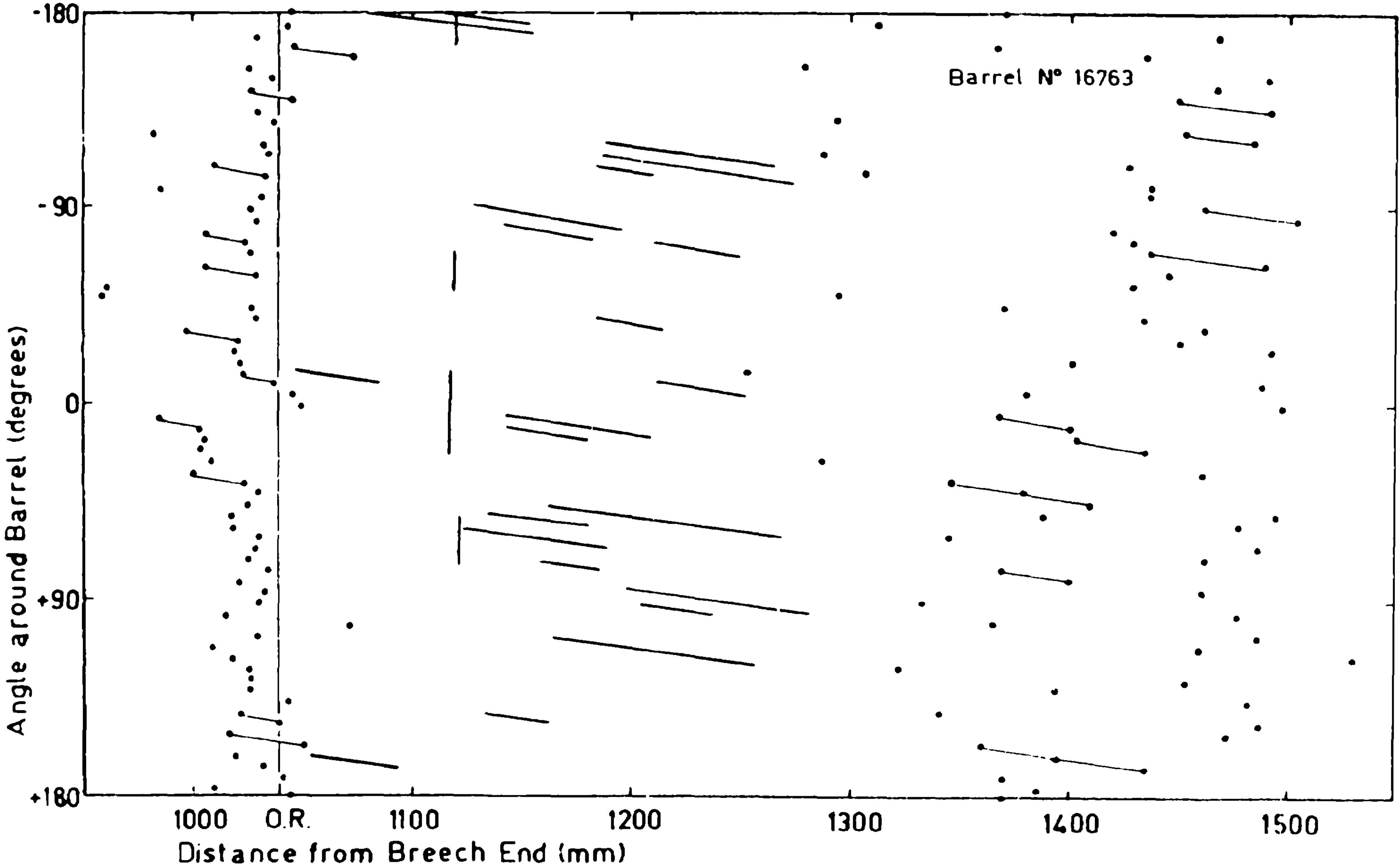

FIGURE 6. Crack map for barrel No. 16763 after 2189 rounds.

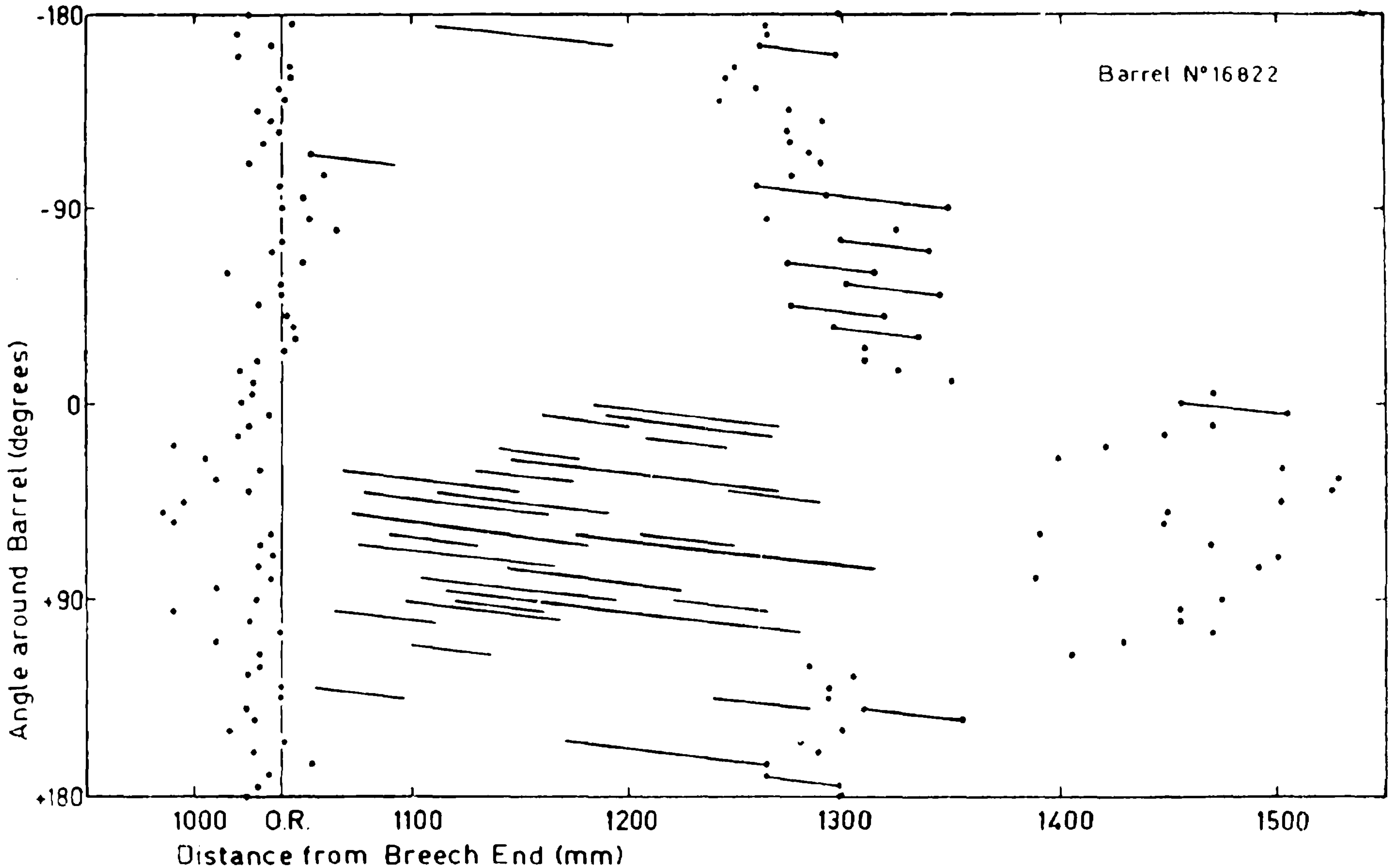

FIGURE [illegible]. Crack map for barrel No. 16822 after 2043 rounds.

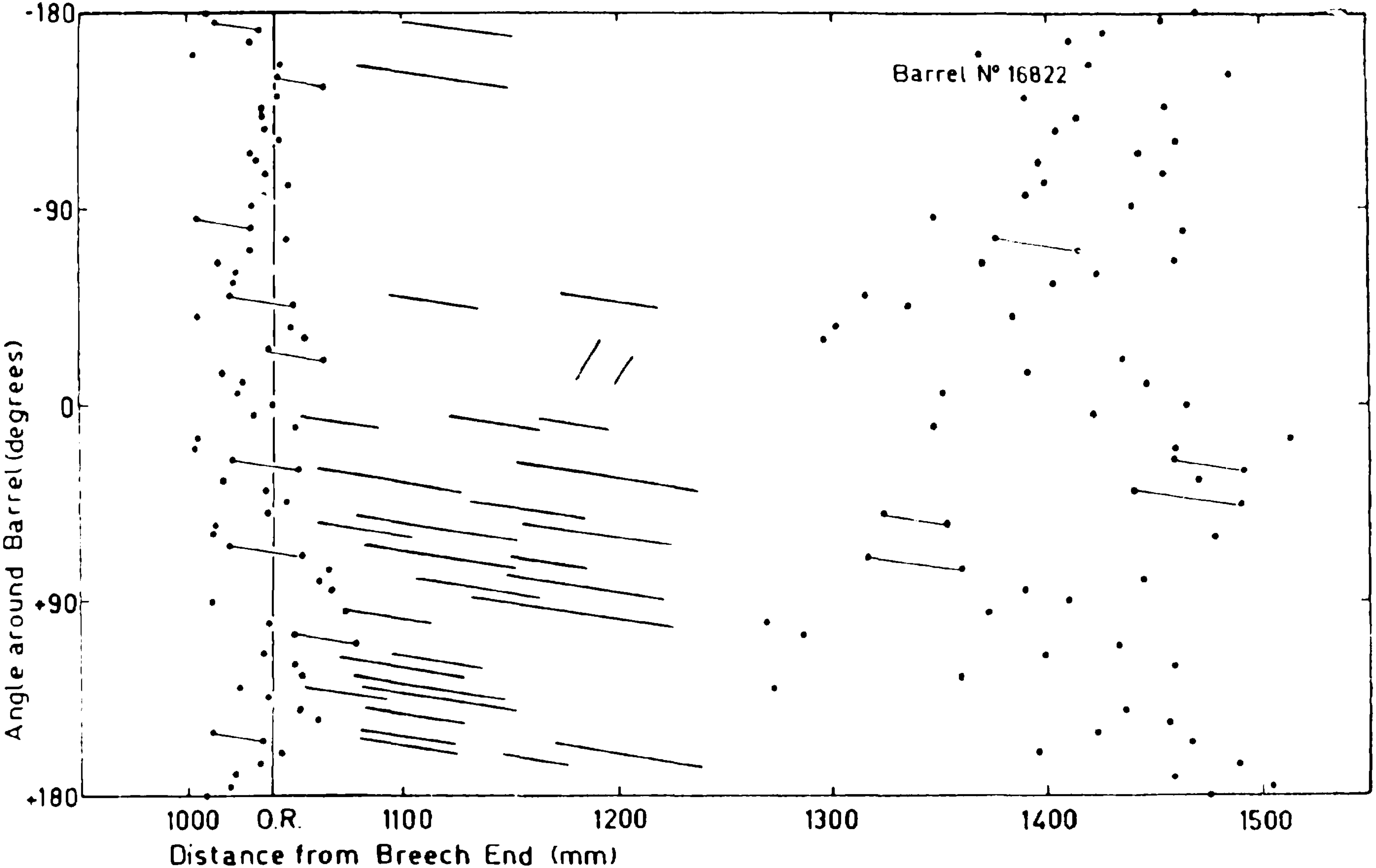

FIGURE 8 Crack map for barrel No. 16822 after 2179 rounds.

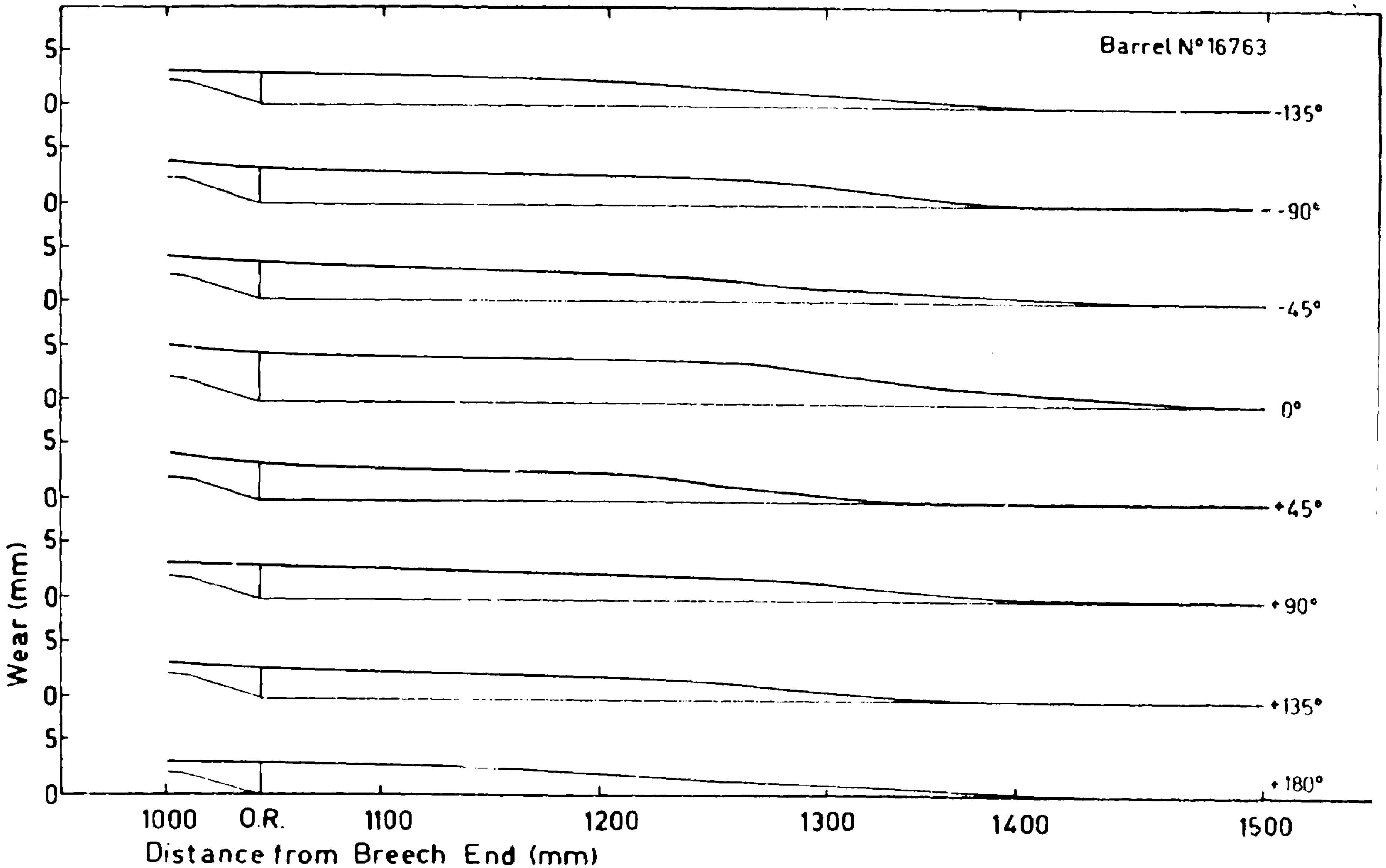

FIGURE [illegible] Erosion profiles for barrel No. 16763 after [illegible] rounds.

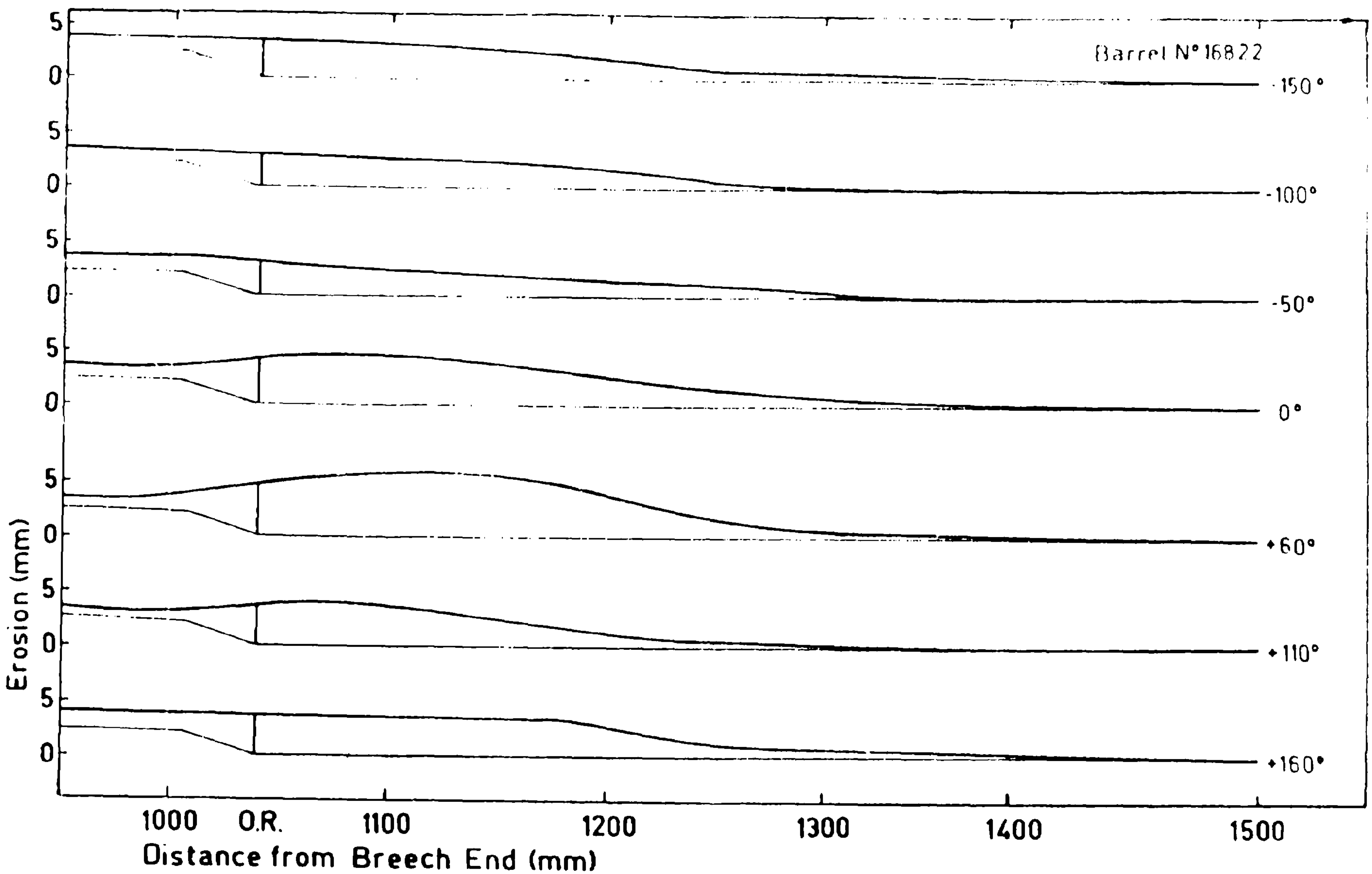

FIGURE 10 Erosion profiles for barrel No. 16822 after 2043 rounds.

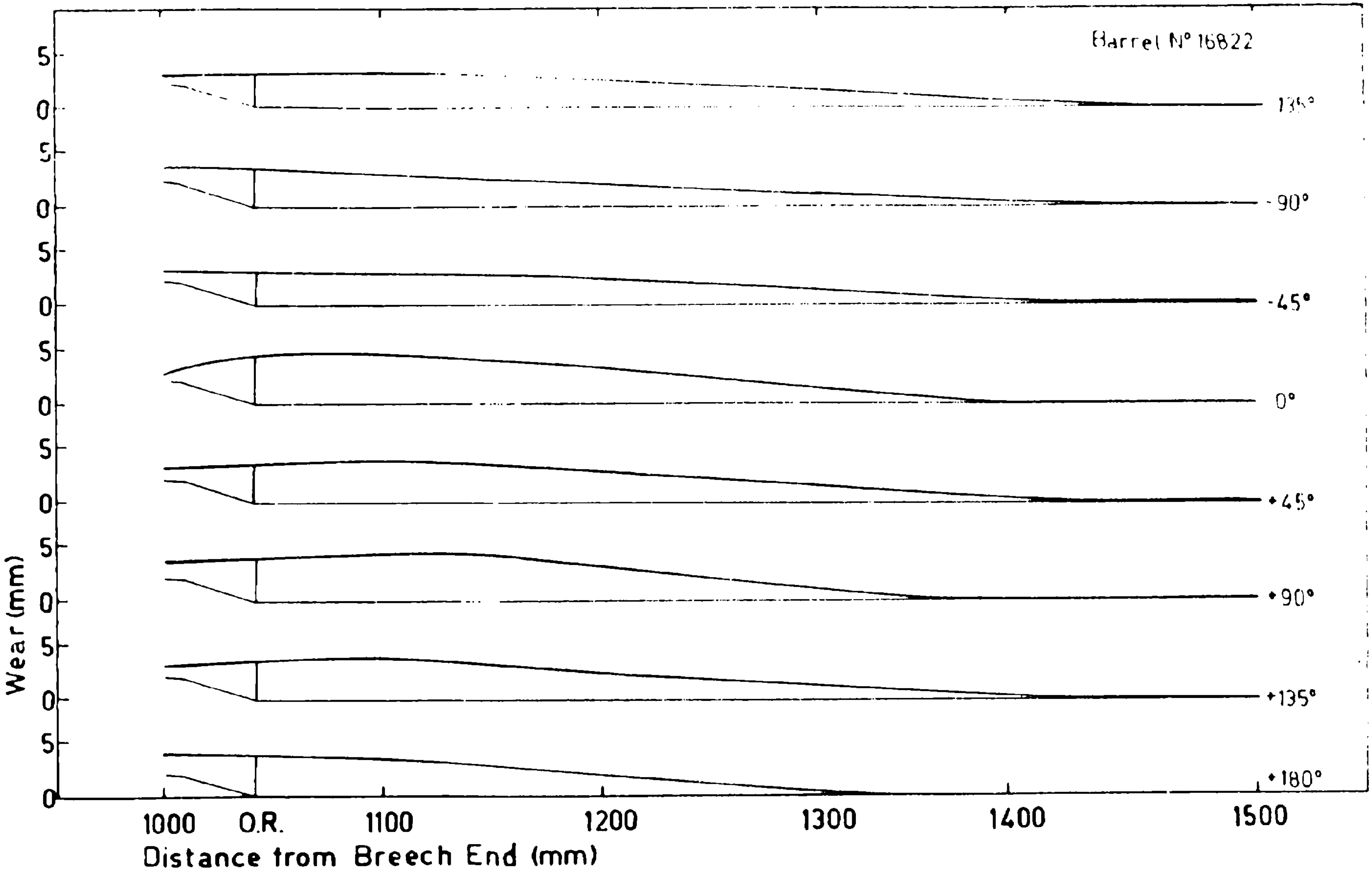

FIGURE 11 Erosion profiles for barrel No. 16822 after 2179 rounds.

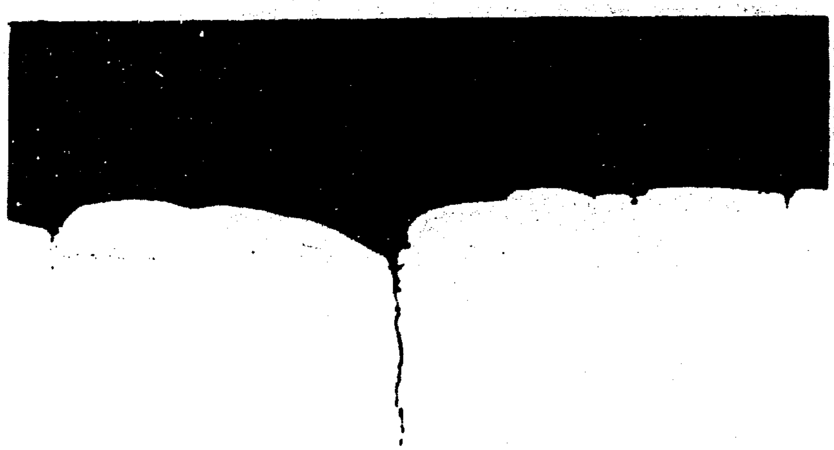

FIGURE 12   Section from barrel No. 16763 showing a crack in the wall of a 5 mm deep gutter.   (X50)

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