

Development of ACPD Technique for Short and Long Crack Measurement

Project DME11:

Stress Corrosion Cracking and
Corrosion Fatigue from Pits

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ABSTRACT

The application of the alternating current potential drop (ACPD) technique for measurement of the depth of short cracks initiated from corrosion pits has been investigated. Cylindrical specimens were pre-pitted using a NPL procedure which enables the development of essentially a single pit of controlled depth. Cracks of varying depth were then generated under uniaxial tension-tension loading. Calibration of the measured potential drop was performed using dye, beach marking and corrosion stain techniques. The effect of stress, temperature, test environment and test duration on the ACPD measurement was evaluated. Comparison with measurement of long crack behaviour in fracture mechanics specimens is made and the effectiveness of the ACPD technique for resolving the depth of short cracks from pits is quantified.

INTRODUCTION

It has been well documented that the growth behaviour of short cracks, such as those that initiate from corrosion pits, cannot be described by linear-elastic fracture mechanics (LEFM)¹⁻⁴ and hence extrapolation of long crack growth rates may not be appropriate. In view of the potential impact of short cracks on the service life of many engineering components, e.g. steam turbines, it is important to develop reliable techniques to detect such cracks and to measure their growth rate. One such technique is the alternating current potential drop (ACPD) method.⁴⁻⁶

In this report, the feasibility of using the ACPD technique for laboratory measurement of the growth rate of short cracks developing from pre-generated pits in a turbine disc steel (3% Ni) both in air and in an aqueous environment has been evaluated. The ACPD technique has also been calibrated for long cracks using conventional fracture mechanics specimens made of a turbine blade steel (12% Cr) as well as the disc steel.

The effect of stress, temperature and environmental exposure on the estimated crack depths is examined.

Alternating Current Potential Drop (ACPD)

When passing through a metal, the alternating current is not distributed uniformly through the depth of the metal, but instead it is forced to flow mainly in a thin surface layer; an effect often referred to as the “skin effect”⁴⁻⁶. This skin depth, δ , is given by:

$$\delta = (\pi \mu \sigma f)^{-\frac{1}{2}} \quad (1)$$

where μ is the magnetic permeability, σ is the electrical conductivity of the metal, and f is the operating frequency of the alternating current. At a typical frequency of 5 kHz, the skin depth is of order 0.1 mm in mild steel, 1 mm in aluminium, and 10 mm in stainless steel.

The relationship between crack size and the potential drop measured by ACPD can be determined experimentally and an empirical relationship developed. The theoretical treatment is based on the solution to Laplace’s equation. In this case, the thin skin effect permits a one-dimensional analysis yielding an expression for the crack depth, a , given by⁴:

$$a = \frac{d_{ref}}{2} \left(\frac{V_{crack}}{V_{ref}} - \frac{d_{crack}}{d_{ref}} \right) \quad (2)$$

where V_{crack} is the potential drop across the crack, V_{ref} is the potential drop measured with a reference probe adjacent to the crack, d_{crack} is the crack probe spacing and d_{ref} is the reference probe spacing.

If $d_{crack} = d_{ref} = d$, then

$$a = \frac{d}{2} \left(\frac{V_{crack} - V_{ref}}{V_{ref}} \right) \quad (3)$$

or, for cracks developed from a notch,

$$\Delta a = a - a_0 = \frac{d}{2} \left(\frac{V_{crack} - V_{ref}}{V_{ref}} - \frac{V_{crack,0} - V_{ref,0}}{V_{ref,0}} \right) \quad (4)$$

where Δa is the crack depth measured from the root of the notch, a_0 is the depth of the notch or pre-crack and $V_{crack,0}$ and $V_{ref,0}$ are the initial readings of V_{crack} and V_{ref} respectively. The validity of the above expressions relies on the following assumptions:

- The skin depth, δ , is small compared with the crack depth (typically 1:10) so that the field is then uniform everywhere on the metal and crack surface except very close to the edges of the crack. For mild steel, the minimum depth of a crack for which Equation (4) is valid is approximately 1 mm.
- The crack aspect ratio, a/l , is small, where l is the surface length of the crack in the cylindrical specimen. For a crack of 1 mm depth with an aspect ratio of 0.1, the crack length is then 10 mm.
- The crack length (l) is large compared with the ACPD probe spacing (d), ($l/d > 3$).

When the above conditions are not met, theoretical modelling may be difficult. In this case, an empirical relationship between the potential drop across a crack and the crack size can be established using experimental data. The potential drop is then measured as a function of the crack size characterised at periodic intervals by beach marking or some other method and an empirical equation obtained by curve-fitting.

EXPERIMENTAL

Specimens

The materials used in this work were a disc steel (3% NiCrMoV), cut from an ex-service steam turbine disc supplied by PowerGen, and a blade steel (12 Cr) supplied by ABB Alstom Power. The chemical compositions are listed in Table 1.

Table 1 Chemical compositions of the disc steel (3% NiCrMoV)
and blade steel (12 Cr) (mass %)

Steel	C	Si	Mn	P	S	Cr	Mo	Ni	V	N	Fe
Disc	0.30	0.28	0.45	0.017	0.013	0.69	0.27	2.89	0.091	0.21	bal
Blade	0.11	0.23	0.71	<0.009	<0.003	11.69	1.73	2.71	0.30	0.026	bal

Cylindrical specimens of the disc steel were manufactured according to ASTM E8⁷ with the longitudinal axis perpendicular to the radius of the turbine disc. The overall length was 125 mm, the shoulder diameter 16 mm, the gauge length 25.4 mm and the diameter 6.4 mm. The surface was dry ground to a 2400 SiC grit finish. The final grinding direction, and hence any grinding marks, were parallel to the length of the specimen. The fracture mechanics specimens, 30 mm in width and 15 mm in thickness, were made according to ISO 11782-2⁸.

The notch depth, as measured from the loading line, was 7.5 mm. Stress relief was conducted in vacuum for 2 hours at 580 °C for the blade steel and 625 °C for the disc steel. The mechanical properties are listed in Table 2.

Table 2 Mechanical properties of the disc steel (3% NiCrMoV)
and blade steel (12 Cr) (mass %)

Steel	Condition	T (°C)	E (GPa)	$\sigma_{0.2}$ (MPa)	UTS (MPa)	Elongation (%)
Disc	As received	23	208 ± 2	747 ± 9	882 ± 5	23 ± 1
	Stress relieved	23	206 ± 1	734 ± 4	870 ± 2	20 ± 0
	Stress relieved	90	210 ± 4	705 ± 4	827 ± 13	20 ± 0
Blade	As received	120	202 ± 2	817 ± 4	909 ± 5	24 ± 1
	Stress relieved	23	211 ± 1	885 ± 6	984 ± 1	25 ± 1
	Stress relieved	120	211 ± 5	827 ± 0	915 ± 1	22 ± 2

The choice of temperature reflects intended laboratory stress corrosion testing conditions.

Pit generation

The depths of cracks initiated from corrosion pits in the disc steel was characterised on six cylindrical specimens. A single pit on five of the specimens was generated in 0.02M $\text{Na}_2\text{B}_4\text{O}_7$ +0.010M NaCl at 23 ± 2 °C. The pits were generated under anodic galvanostatic control using the pre-pitting procedure described elsewhere⁹. Briefly, after the specimens had been immersed in the solution at open circuit for 20 minutes, an anodic current of 10 μA was applied to initiate and maintain the growth of the pit until the desired pit depth was reached. These conditions were satisfactory for growing pits of depth of up to 100 μm . If exposed for longer periods to achieve deeper pits there was a tendency for extended localised corrosion at the main pit mouth. It was found that a very small adjustment of the chloride concentration to 0.007 M NaCl was sufficient to minimise this problem.

The pit depths, a_{pit} , and surface diameters, d_{pit} , are listed in Table 3.

Table 3 The depths and surface diameters of pits from which cracks initiate

Specimen No.	1	2	3	4	5	6
a_{pit} (μm)	68	68	74	79	99	217
d_{pit} (μm)	187	255	223	210	270	305

ACPD measurement

The arrangement of ACPD probes for the tensile cylindrical specimens and the fracture mechanics specimens is shown schematically in Figure 1. Three platinum wires of 200 μm diameter were spot welded on to the specimens. The platinum wires were insulated with PTFE sleeves and the contact area between the platinum wire and the specimen was insulated with high modulus polyurethane sealant (Holdtite) which can be immersed in water at 130 °C. The distance between the two probes was 2 mm for the pre-pitted cylindrical specimens and 3 mm for the fracture mechanics specimens. The potential drop between the two wires across the crack, V_{crack} , and between the two wires outside the crack, V_{ref} , was measured using a computer controlled ACPD measurement instrument, U10 Crack Microgauge (Technology Software Consultants). It contains an alternating current supply, high gain amplifier, phase sensitive detector, low pass filter, microprocessor and interface to a remote computer for test control, data acquisition, storage and analysis. In the present work, the applied AC current was 5 A with frequency 5 kHz and the maximum range of potential drop was 2 V.

For both cylindrical tensile specimens and fracture mechanics specimens, the cracks were initiated and propagated under uniaxial tension - tension cyclic loading (sine waveform) using a servo-hydraulic fatigue machine in accordance with BS 3518¹⁰ and ISO 11782 - 2⁸. The fatigue frequency used was 25 Hz and the stress ratio was 0.1. For measurement of short crack depth, three tests were conducted on the cylindrical specimens (Specimens No. 2, 3 and 4) in air at 24 ± 1 °C and three tests (Specimens No. 1, 5 and 6) were conducted in distilled water at 90 °C. For long cracks in mechanics specimens, all tests were conducted in air at 24 ± 1 °C, unless stated otherwise. The relative humidity of the air was below 50% for all tests. It should be emphasised that all crack measurements were made under static load since this would be relevant to the intended stress corrosion cracking tests planned. Under fatigue loading at low stress ratios, crack closure may be important, which will be a function of crack depth, and could influence the calibration.

Crack size characterisation

Long cracks in fracture mechanics specimens

The depth of the long cracks in the fracture mechanics specimens (both disc and blade steel) were characterised using the beach marking technique. An initial stress intensity range of 34 MPa $\text{m}^{1/2}$ was applied to initiate cracking from the notch. Beach marks were made by reducing the stress range by more than 25% after the cracks had propagated approximately 2 mm (the beach marks were not clear when the stress range was reduced by less than 25%). The crack depth was measured using a travelling microscope with a resolution of 1 μm , on the fractured surface at both edges and at positions 0.25B, 0.5B and 0.75B, where B is the thickness of the specimen (in accordance with ISO 11782 -2)⁸. The average value of these five measurements was used. At each crack depth, the potential drop was measured under the same applied static load (for reason explained later in section on “effect of stress”) with the stress intensity factor always greater than the mean value associated with the cyclic loading to minimise any possible influence of crack closure.

Cracks initiated from pits

Characterisation of the depth of cracks initiated from pits was undertaken only for the disc steel. For tests conducted in air, cracks of depths greater than 1 mm were characterised also by beach marking. An initial stress range of 630 MPa was applied to initiate the crack from the pre-generated pit. Beach marks were made by reducing the stress range by more than 25%. At each stage, the potential drop was measured with the load held under static conditions with the stress greater than the mean value associated with the cyclic loading. The distance between consecutive beach marks were approximately 0.25 mm. For crack depths less than 1 mm, the beach markings could not be discerned with confidence. For this case, the crack depth was characterised using a dye method. Two dyes, one alcohol-based blue ink and one water-based yellow ink, were consecutively applied to each specimen to mark two consecutive depths.

For tests conducted in water, crack depths were determined by corrosion staining. After the crack had propagated to a certain depth, the specimens were left in water at 90 °C for more than 12 hours under static loading conditions (mean value of the cyclic loading). This procedure gave rise to a clearly delineated crack front. Following this, a cyclic load with the stress range reduced by 20% was then applied to allow the crack to grow. It was stopped when the crack depth reached was suitable for the next stain. 4 to 8 marks were made on each specimen.

The cracks were all elliptical in shape once they had developed to a depth of about 120% of the original pit depth. The maximum depth of crack was measured using a travelling microscope with a resolution of 1 µm with care being taken to ensure a proper reference to the surface.

Two tests were conducted to compare the dye and the corrosion stain methods. A crack was generated on a pre-pitted specimen in air and marked with the alcohol-based ink. The specimen was then immersed in aerated distilled water at 90 °C for more than 12 hours to allow the corrosion stain to form. On examination of the fracture surface, it was revealed that there was no measurable difference between the dye and the stain marks. The crack depths characterised by beach marking and by the dye technique were also in agreement.

RESULTS AND DISCUSSION

ACPD measurement calibration

1. Long cracks in fracture mechanics specimens

The relationship between the measured crack depth in the fracture mechanics specimens and the values determined theoretically from the ACPD measurements at a static load of 10 kN are shown in Figures 2 and 3. Using linear regression, the crack depth measured on the fracture surface, Δa_{actual} (**measured from the notch root**) can be expressed as:

$$\Delta a_{actual} = M \Delta a_{calculated} \quad (5)$$

where $\Delta a_{calculated}$ is the calculated crack depth from Equation (4), M is the multiplier. For disc steel, $M = 1.138 \pm 0.003$, and for blade steel 1.120 ± 0.004 , i.e.,

for disc steel:

$$\Delta a = \frac{1.138d}{2} \left(\frac{V_{crack} - V_{ref}}{V_{ref}} - \frac{V_{crack,0} - V_{ref,0}}{V_{ref,0}} \right) \quad (6)$$

and, for blade steel:

$$\Delta a = \frac{1.120d}{2} \left(\frac{V_{crack} - V_{ref}}{V_{ref}} - \frac{V_{crack,0} - V_{ref,0}}{V_{ref,0}} \right) \quad (7)$$

2. Cracks initiated from pits

The actual depths of cracks initiated from pits are compared with the calculated values from Equation (3) in Figure 4. These data include measurements at a static load of 16 kN from different temperatures and environments (at 24 °C in air, specimen nos. 2, 3 and 4, and in water at 90 °C; specimen nos. 1, 5 and 6).

It can be seen that, unlike the behaviour of long crack in fracture mechanics specimens, there is no linear correlation. This is not a surprise since the conditions for a uniform current field cannot be met due to the geometry of cracks on the cylindrical specimens particularly in the short crack regions, i.e.

- (a) the crack aspect ratio, a/l , varies as the crack depth increases and is generally greater than 0.1;
- (b) the ratio of the skin thickness (typically 0.1 mm for a magnetic steel) to the crack depth (0.08 mm to 2.6 mm) is not always greater than 0.1; and
- (c) the ratio of the crack length to the probe spacing (2 mm) is generally less than 3.

It also can be seen that the data are more scattered than for long cracks in fracture mechanics specimens, possibly due the variation in the crack aspect ratio. Nevertheless, an empirical expression for the crack depth, a_{actual} , can be derived from the polynomial fit as:

$$a_{actual} = b_1 a_c + b_2 a_c^2 + b_3 a_c^3 \quad (8)$$

where a_c is the calculated crack depth using Equation (3) and b_i are constants: $b_1 = 3.838$, $b_2 = -2.113$ and $b_3 = 0.529$.

Effect of stress

The effect of stress on the measured potential drop across a crack in the fracture mechanics specimen (blade steel) was studied to assess the possible impact of crack closure. The results are shown in Figure 5. An effect of crack closure would be expected to result in an *increase* in the potential drop with increasing load. In practice, the crack potential drop, V_{crack} , *decreased* as the applied loading increases with the effect more pronounced the deeper the crack. The reference potential, V_{ref} was unaffected as the effective stress here is not significant. The impact on the calculated crack depth is shown in Figure 6.

For an actual crack depth of 13.19 mm, the calculated values could range from 12.95 mm (at zero load) to 14.03 mm at the maximum load studied. Although the maximum variation of the calculated crack depth is less than 7% , in the load range studied, this is not insignificant. It would be advisable to conduct the ACPD calibration for a loading condition broadly similar to that used in the crack growth measurement in order to minimise uncertainty, particularly for long cracks.

This effect of stress on the measured values of potential drop has been reported previously¹¹. It has been suggested¹¹ that the change in potential drop with stress could be due to variation in the conductivity and permeability of the metal and that for magnetic materials it is the changes in permeability that gives the larger effect. This effect is related to magnetostriction where the magnetic field and the mechanical strain influence each other. Since the skin depth is given by Equation (1), the potential drop varies as $(\mu/\delta)^{1/2}$ for a given total current flow.

There was no evidence of a significant effect of crack closure on the potential drop, which is another concern for the ACPD measurement¹². There was a small increase in potential drop and apparent crack depth with increase in stress but only at the smallest loads (Figure 6). The effect of crack closure on the potential drop depends on the characteristics of the films present on the contacting surfaces and could be different during for aqueous exposure conditions. For that reason, the static stress used in calibration should always be reasonably high. In the present work,

Stress had a much less significant effect on the potential drop for the disc steel, as shown in Figure 7. The maximum variation in the calculated crack depth from potential drops is less than 3%. The reason is not clear at this stage but one possible explanation is that the effect of stress on the permeability is less significant for the disc steel.

There was no significant effect of stress for cylindrical specimens tested in air, since the areas where V_{crack} and V_{ref} are measured are under similar magnitude of stress (Figure 1 (a)). However, for a 925 μm deep crack developed in distilled water at 90 °C, an effect of crack closure was observed, as shown in Figure 8.

In the present work, the correlation between the actual and the calculated crack depth, shown in Figures 2 - 4, are based the ACPD measurements conducted under the same static loading condition at 16 kN for cracks initiated from pits. The effect of crack closure at this load is insignificant.

Effect of temperature

It can be seen from Figure 9 that V_{crack} and V_{ref} measured for short cracks have the same dependence on temperature. As a result, $(V_{\text{crack}} - V_{\text{ref}})/V_{\text{ref}}$ and hence the calculated crack depths remain constant as temperature changes, which is reflected also in Figure 4. This is of course one of the reasons for using the reference probes.

The potential drop for long cracks in fracture mechanics specimens was measured also in the temperature range of 24 °C to 120 °C. There was likewise no effect of temperature on the calculated crack depth.

Effect of environment

Figure 4 indicated that there was no difference whether the data were obtained in air (specimen nos. 2, 3 and 4) or in distilled water (specimen nos. 1, 5 and 6). This was confirmed by measuring the potential drop in air and in aerated distilled water at 25 °C, as shown in Table 4.

Table 4 The effect of environment on the ACPD crack depth measurement

Environment	T (°C)	V _{crack} (mV)	V _{ref} (mV)	a _c (μm)	a _{actual} (μm)	error (%)
air	25	7.27	6.99	150	142	5.6
distilled water	25	7.26	6.98	151	142	6.3

The long term stability of the ACPD system

There is a concern that the electronics of the ACPD system are relatively complex and that there may be difficulty in achieving the required long term stability⁸. To assess this, the potential drop was monitored over a period of time. The time variation of the calculated depths of a 6.8 mm deep crack in a fracture mechanics specimen and a 945 μm deep crack initiated from a pit (pit depth: 68 μm) is shown in Figures 10 and 11. It can be seen that the ACPD system is stable for the test duration studied and that the standard deviation is less than 1.4% for the long fracture mechanics (FM) crack and 0.4% for the short crack.

Impact of pits on crack depth measurement

A key issue in the application of ACPD for the measurement of short cracks initiated from pits is the impact of the pit itself on crack depth measurement, especially in the early stages. The data in Figure 4 are composed of crack depth measurement in specimens with different pit depths. Nevertheless, a good correlation between actual and calculated crack depths was observed.

Table 5 lists the minimum crack depths measured on four specimens, together with the depths and aspect ratios of the pits from which the cracks initiated. It should be recalled that the crack depths are measured from the surface and hence include the depths of pits. It can be seen that when cracks extended 20% to 40% of the pit depth beyond the pits, the crack depths could be measured reasonably accurately using ACPD. It was not possible to quantify the depth of a crack emerging from a pit prior to merging as a semi-elliptical defect. Although the potential drop indicated some growth, attempts to mark the position of these small embryo cracks prior to coalescence using dye or corrosion staining were not successful.

Table 5 The effect of pits on the crack depth measurement of ACPD

Pit depth (μm)	Aspect ratio	a _c (μm)	a _{actual} (μm)	error (%)	a _{crack} /a _{pit}
68	0.36	88	83	6.0	1.22

74	0.33	107	97	10.3	1.31
99	0.37	140	142	0.7	1.43
217	0.71	322	306	5.2	1.41

Crack depth measurement resolution

For cracks which are much deeper than the pit depth, the accuracy of the ACPD technique depends on the resolution of the potential drop measurement. For the system used in the present study, the resolution of the potential drop measurement was 0.1%. From Equation (8), it can be seen that the theoretical resolution for a 1 mm crack is approximately 4 μm . Even considering the measurement noise (Figure 11), the resolution would still be approximately 0.4%. However, there is some scatter in the data (Figure 4), perhaps due to some small variation in the crack aspect ratios. The average measurement error (defined as the percentage error between the actual crack depths and the calculated depths using the polynomial fit) is 6.7%.

In the present probe attachment (Figure 1 (b)), the resolution of the ACPD technique is considerably reduced for long cracks due to the presence of the long notch. The standard deviation for a 6.8 mm deep (FM) crack (exclusive of the notch) is ± 0.047 mm (Figure 10). The resolution is therefore estimated as approximately 1.4%. On the other hand, there is little scatter in the data (Figures 2 and 3) since the long cracks in the fracture mechanics specimens are through-thickness and the geometry is reasonably well defined. The average measurement error is less than 2.1% and the maximum error is less than 4%.

In addition, care must be taken in the ACPD probe attachment, as the spacing between the probes affect the slope of the calibrated curve, as well as the initial values of crack depths. In the present study, the 200 μm platinum wires were carefully spot welded on to the specimens under a microscope with a resolution of 1 μm . The variation in the initial readings of the potential drops was less than 5%.

CONCLUSIONS

1. The ACPD technique has been applied to measurement of the depth of short cracks initiated from pits on cylindrical specimens of the 3-NiCrMoV turbine disc steel in air and in aerated distilled water. Cracks of depths down to 83 μm were characterised and an empirical relationship established from polynomial fitting.
2. It was not possible to quantify the depth of a crack emerging from a pit prior to merging as a semi-elliptical defect. Although the potential drop indicated some growth, attempts to mark the position of these small embryo cracks prior to coalescence using dye or corrosion staining were not successful.
3. For long cracks in fracture mechanics specimens, a linear relationship between the theoretically calculated and the actual crack depths has been established.
4. The applied stress can have an effect on the potential drop measured by the ACPD technique. Tests in air showed an *decrease* in the potential drop in fracture mechanics specimens with increasing stress which was more significant the longer the crack. Although not a very large effect, it is recommended that calibration should be conducted

at a stress broadly similar to that for the intended application. An effect of crack closure (potential drop *increasing* with applied stress) was observed in aqueous environments at low loads.

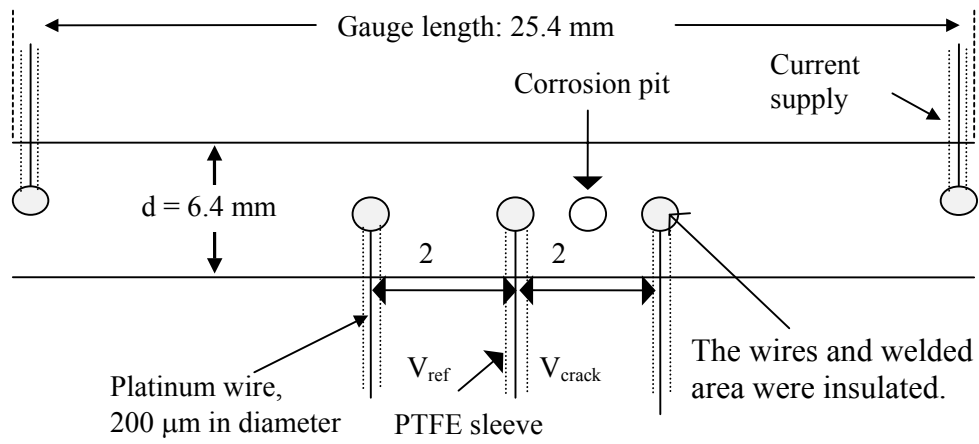
5. The resolution of the ACPD system with the present probe attachments is estimated as 0.4% for cracks initiate from pits on the cylindrical specimens and 1.4% for long cracks in mechanics fracture specimens.

ACKNOWLEDGEMENTS

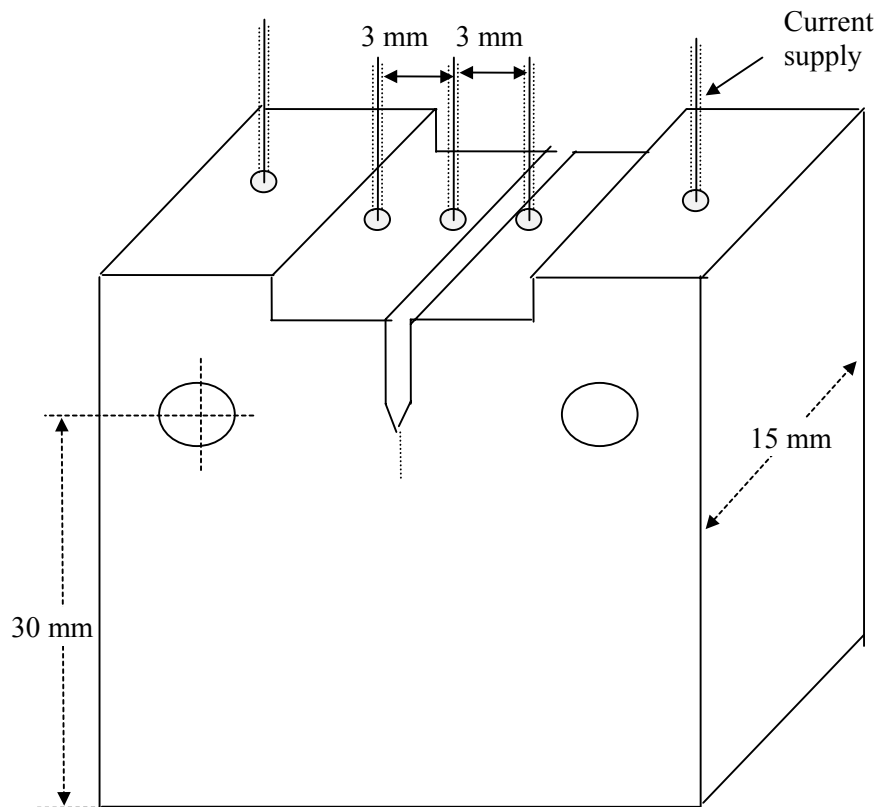
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(a) Cylindrical specimen



(b) Fracture mechanics specimen

Figure 1 Schematic diagram showing the ACPD probe attachment positions

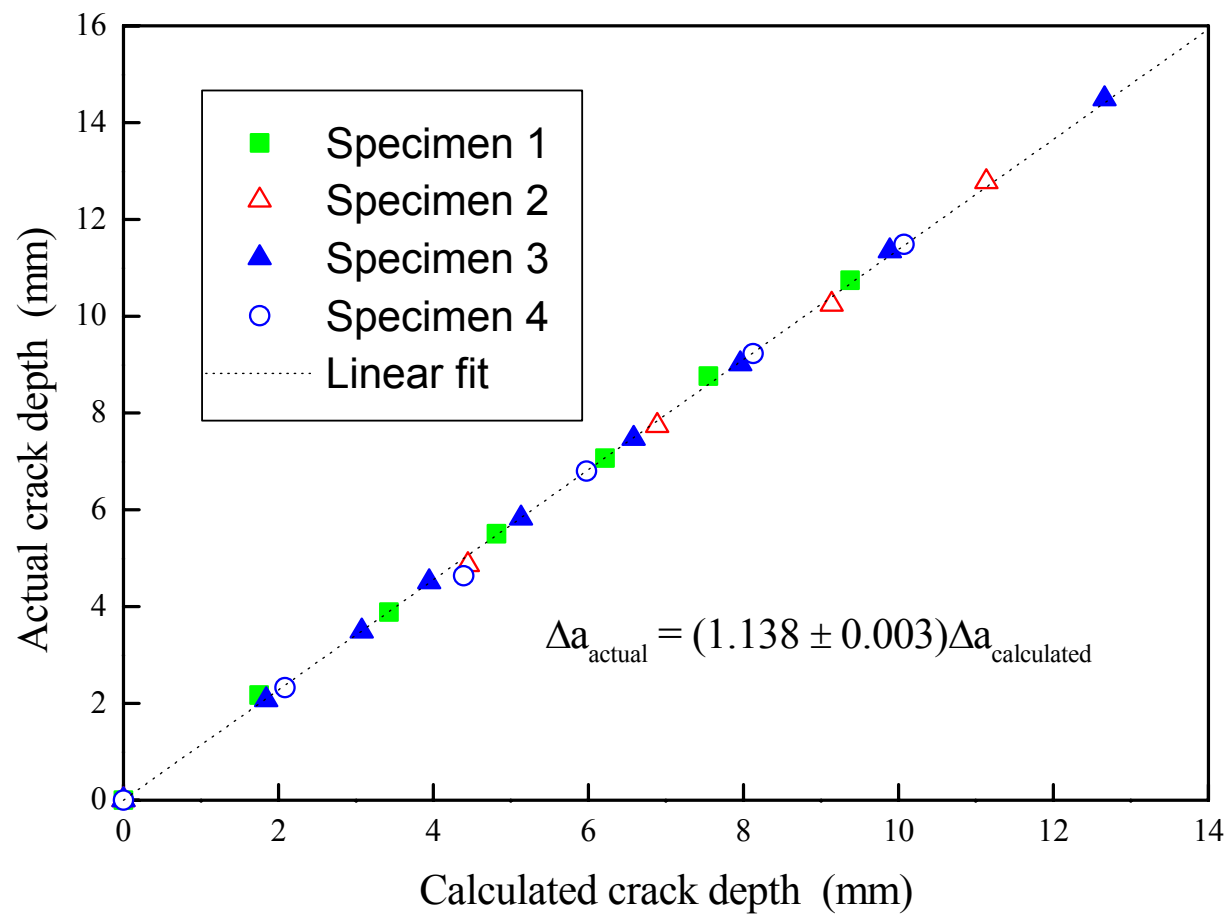


Figure 2 Comparison of the actual depths of long (FM) cracks in the disc steel with the calculated depth using Equation (3)

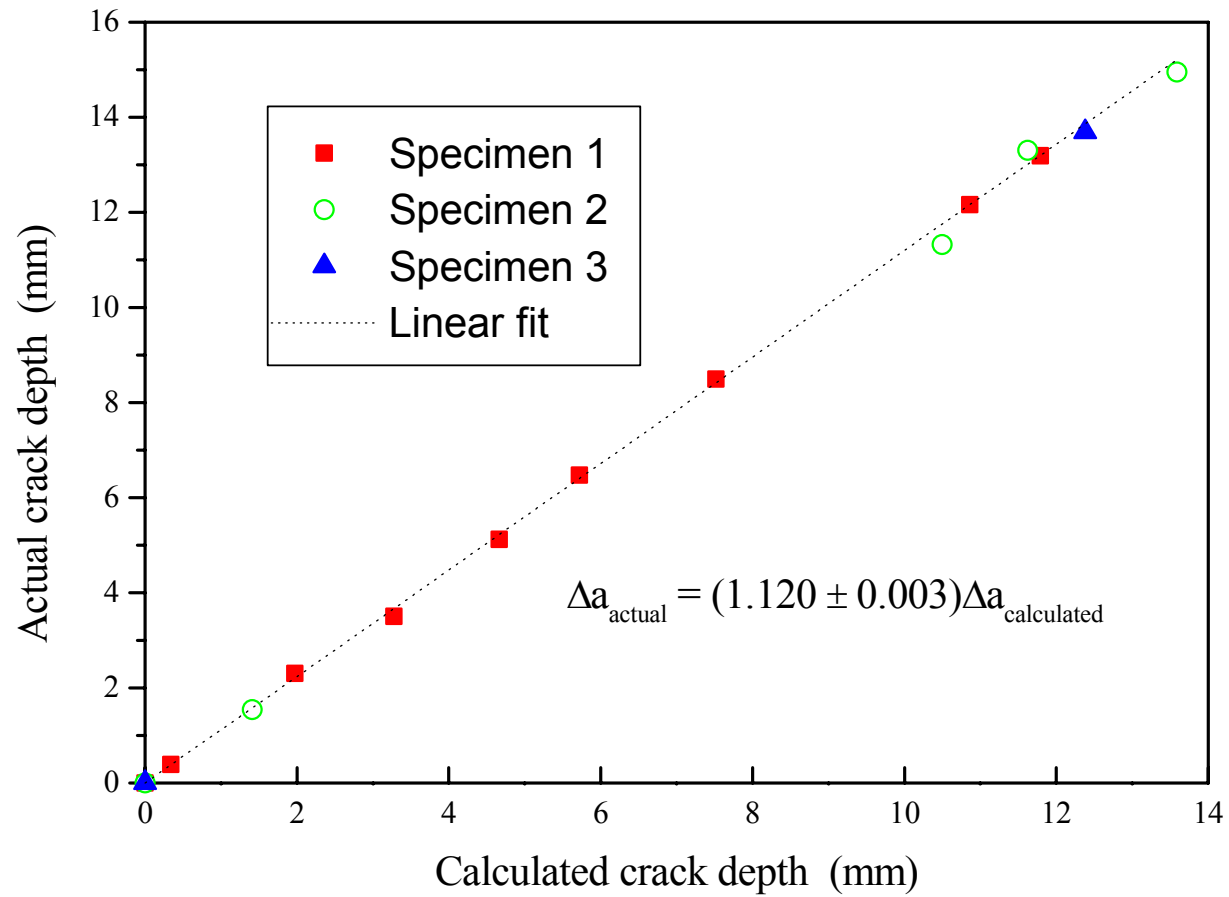


Figure 3 Comparison of the actual depths of long (FM) cracks in the disc steel with the calculated depth using Equation (3)

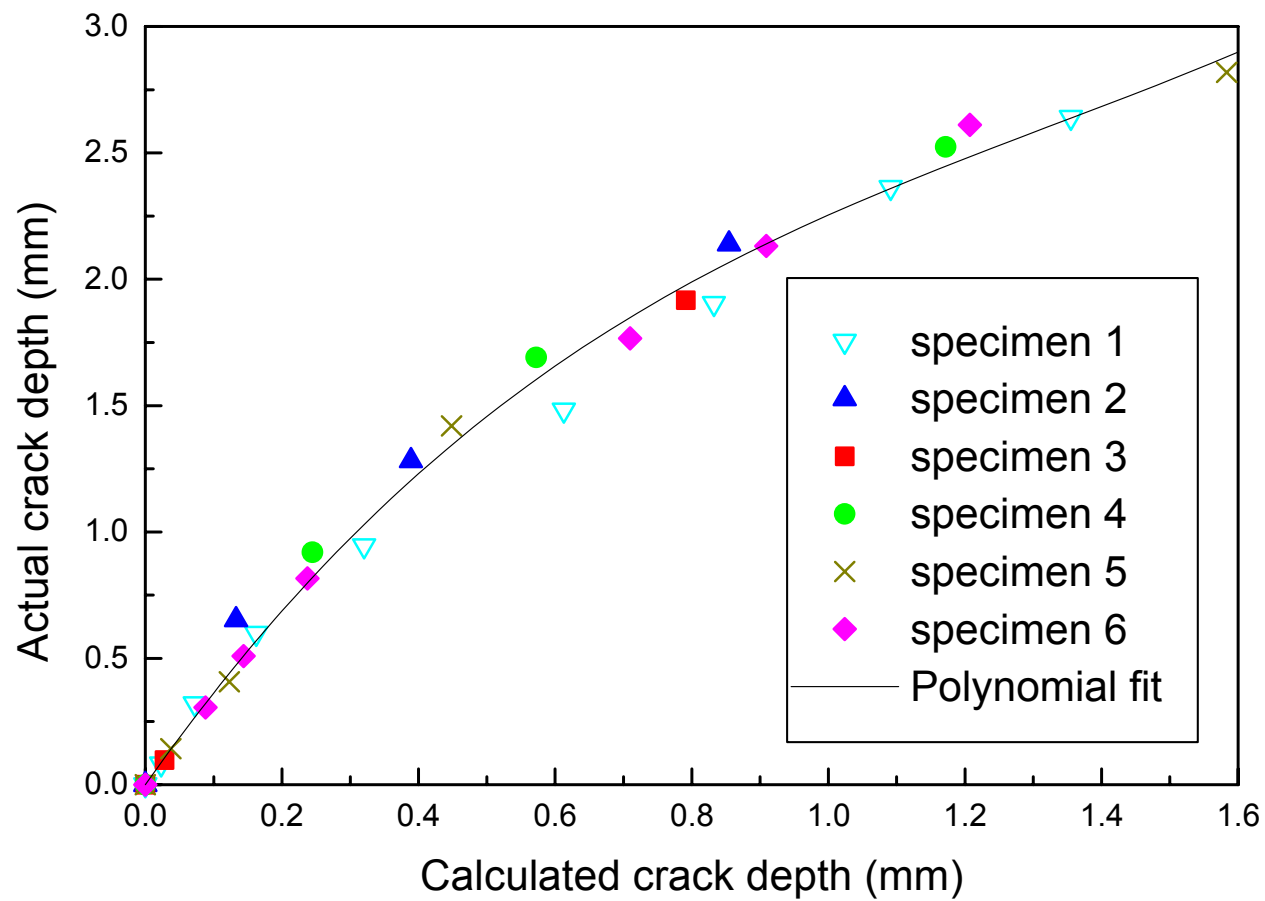


Figure 4 Comparison of the actual depths of cracks from pits in the disc steel with the calculated depth using Equation (3)

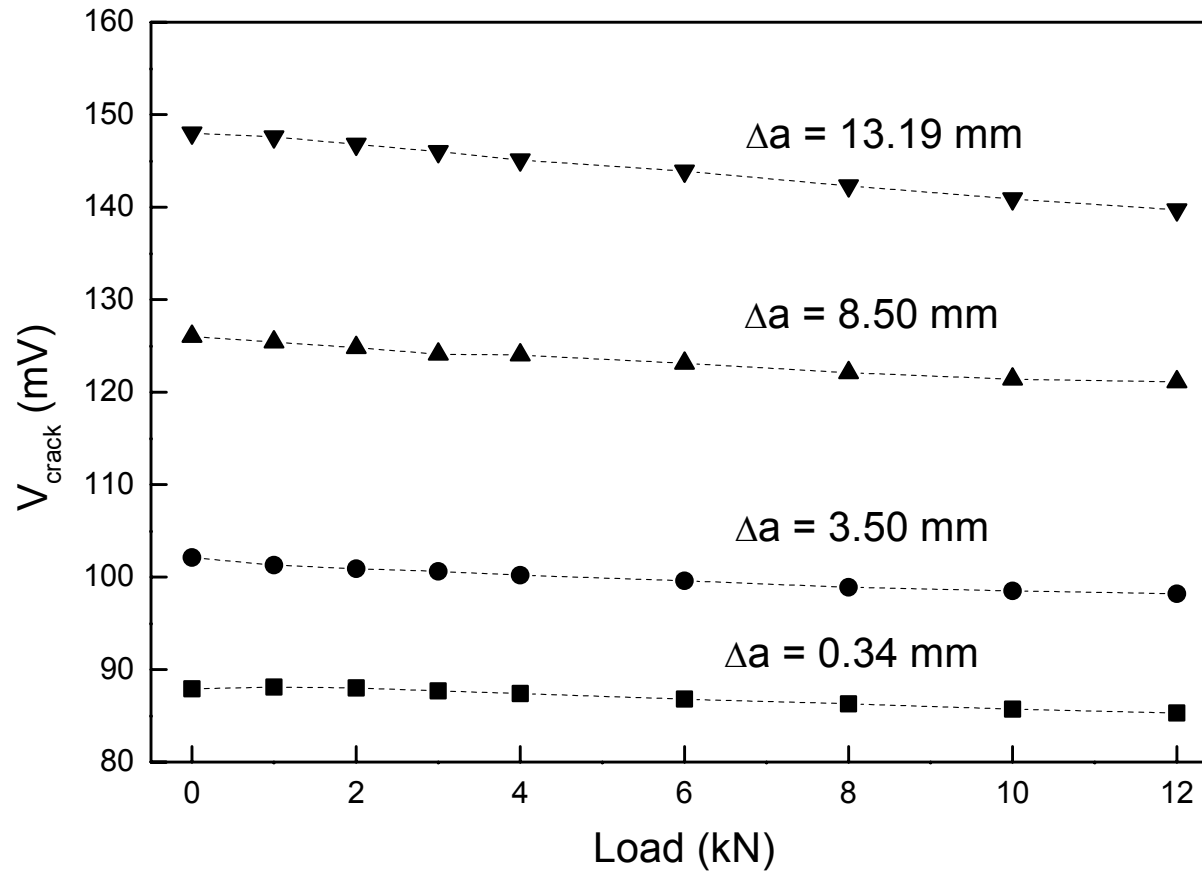


Figure 5 The effect of applied loading on the potential drop, V_{crack} , across long (FM) cracks for the blade steel. Δa is the actual crack depths measured from the notch root.

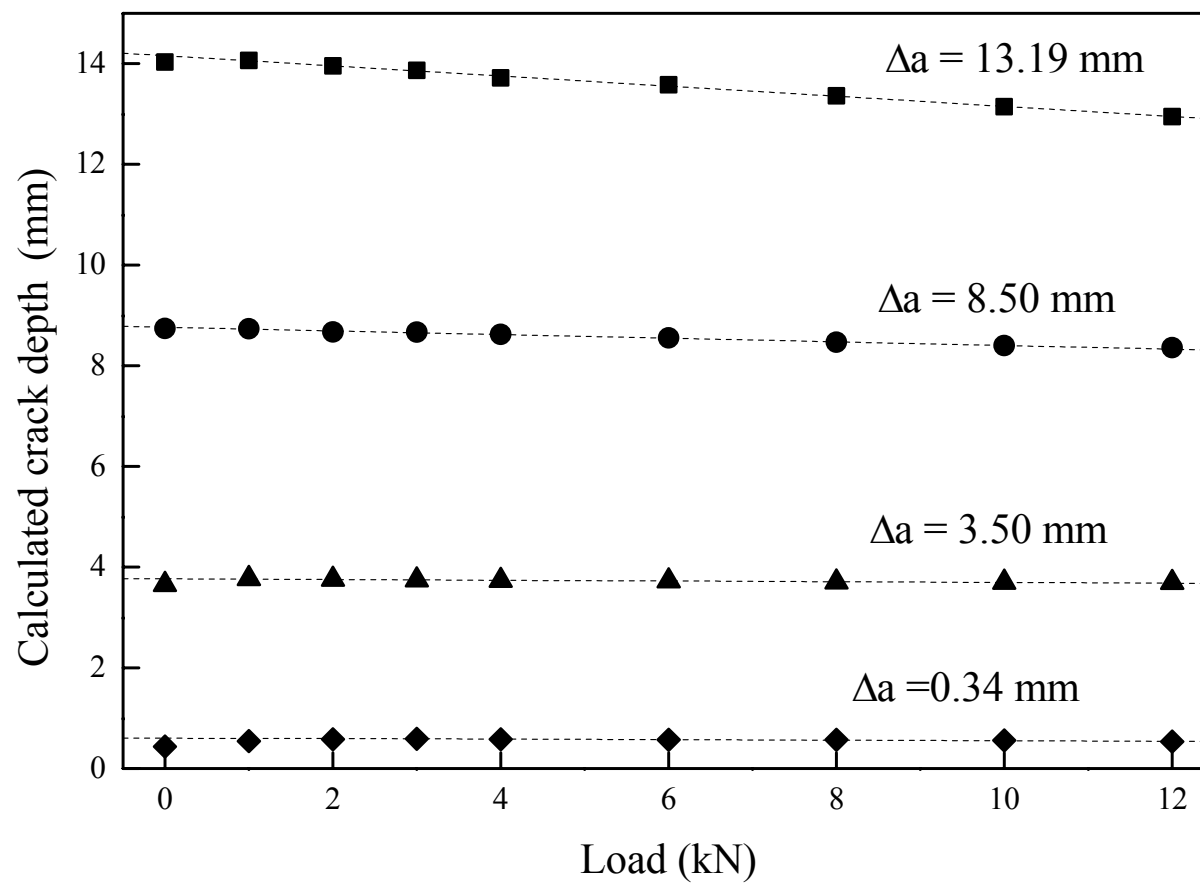


Figure 6 The effect of applied loading on the calculated crack depth for the blade steel, using Equation (7). Δa is the actual crack depths measured from the notch root.

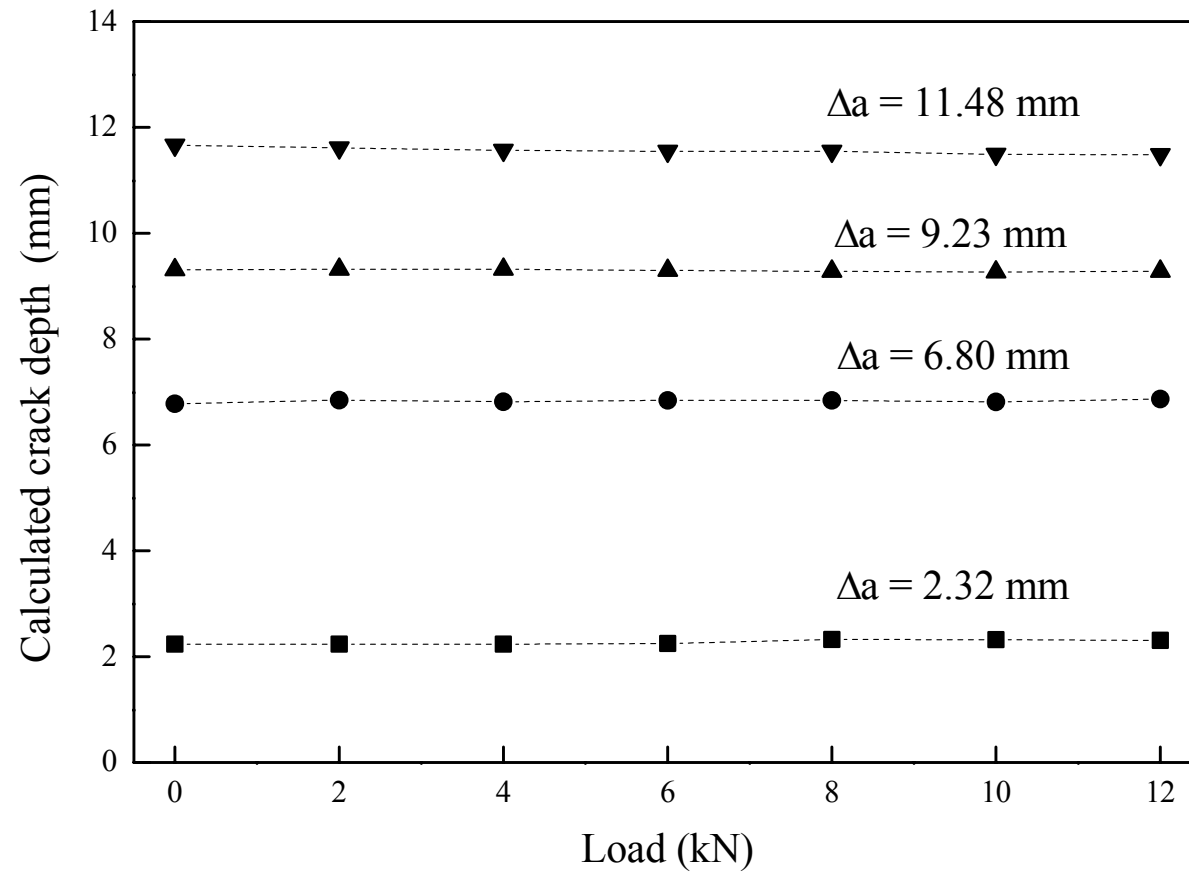


Figure 7 The effect of applied loading on the calculated crack depth for the disc steel, using Equation (6). Δa is the actual crack depths exclusive of the notch.

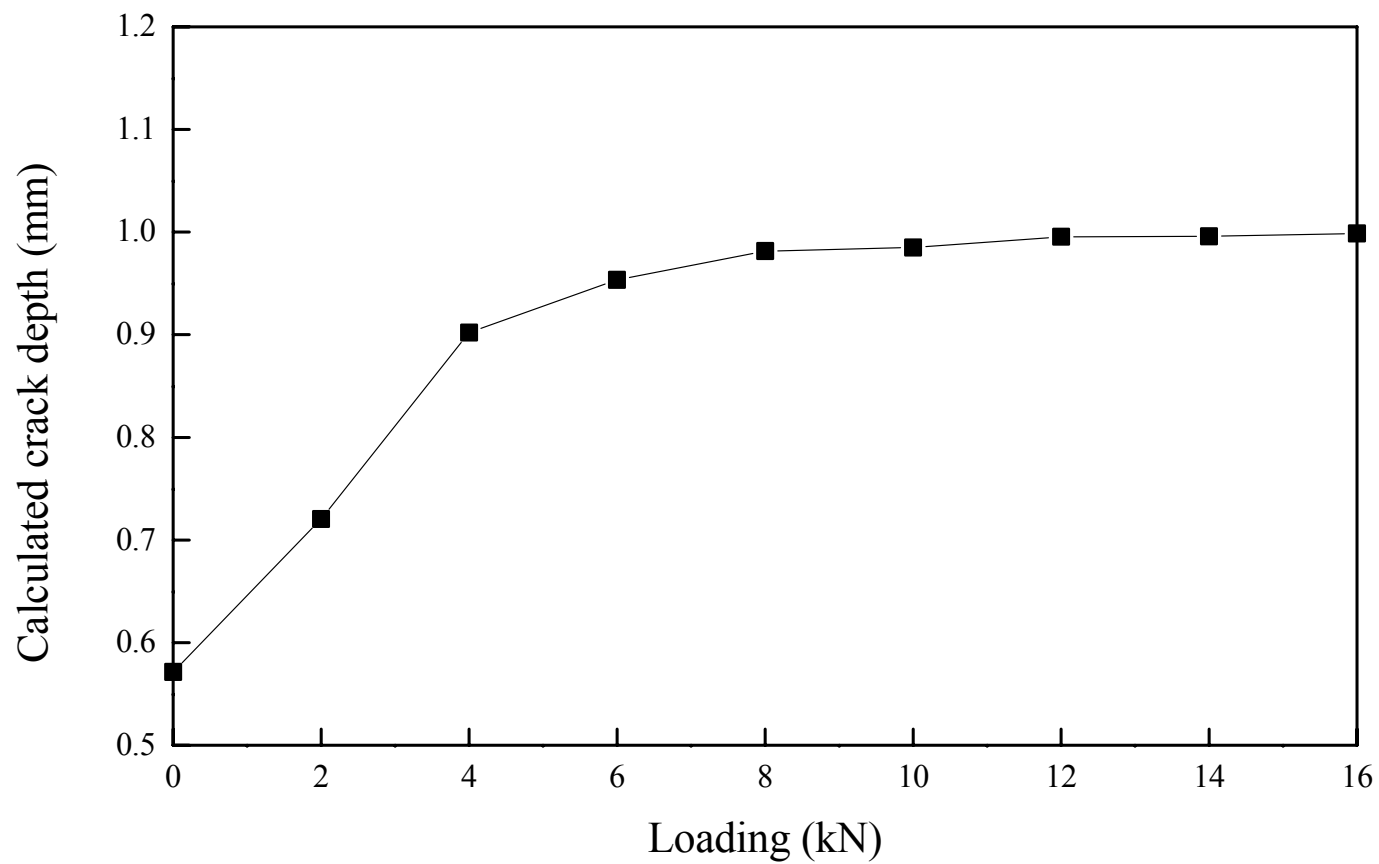


Figure 8 The effect of the crack closure on the calculated short crack depth using Equation (7) for the disc steel in distilled water at 90 °C. Actual crack depth: 945 μm .

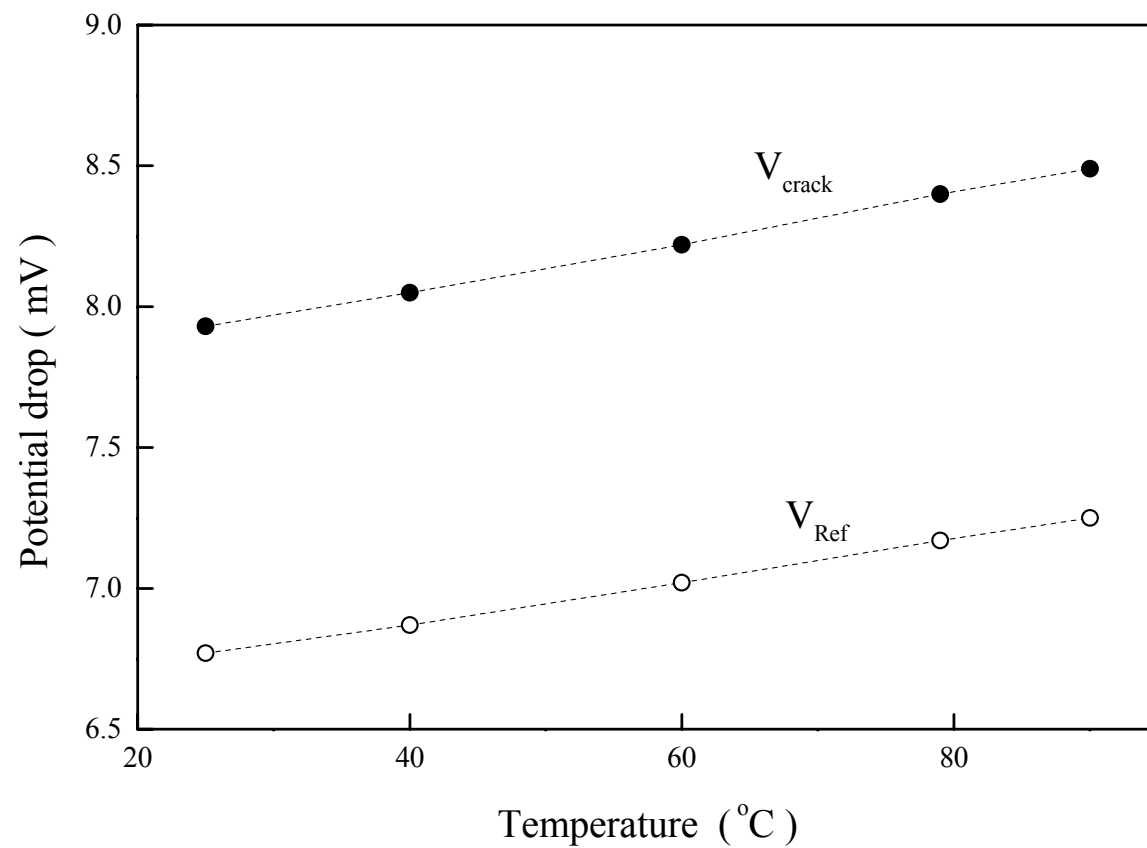


Figure 9 The effect of temperature on the potential drops on a cylindrical specimen of the disc steel in distilled water. Actual crack depth: 407 μm .

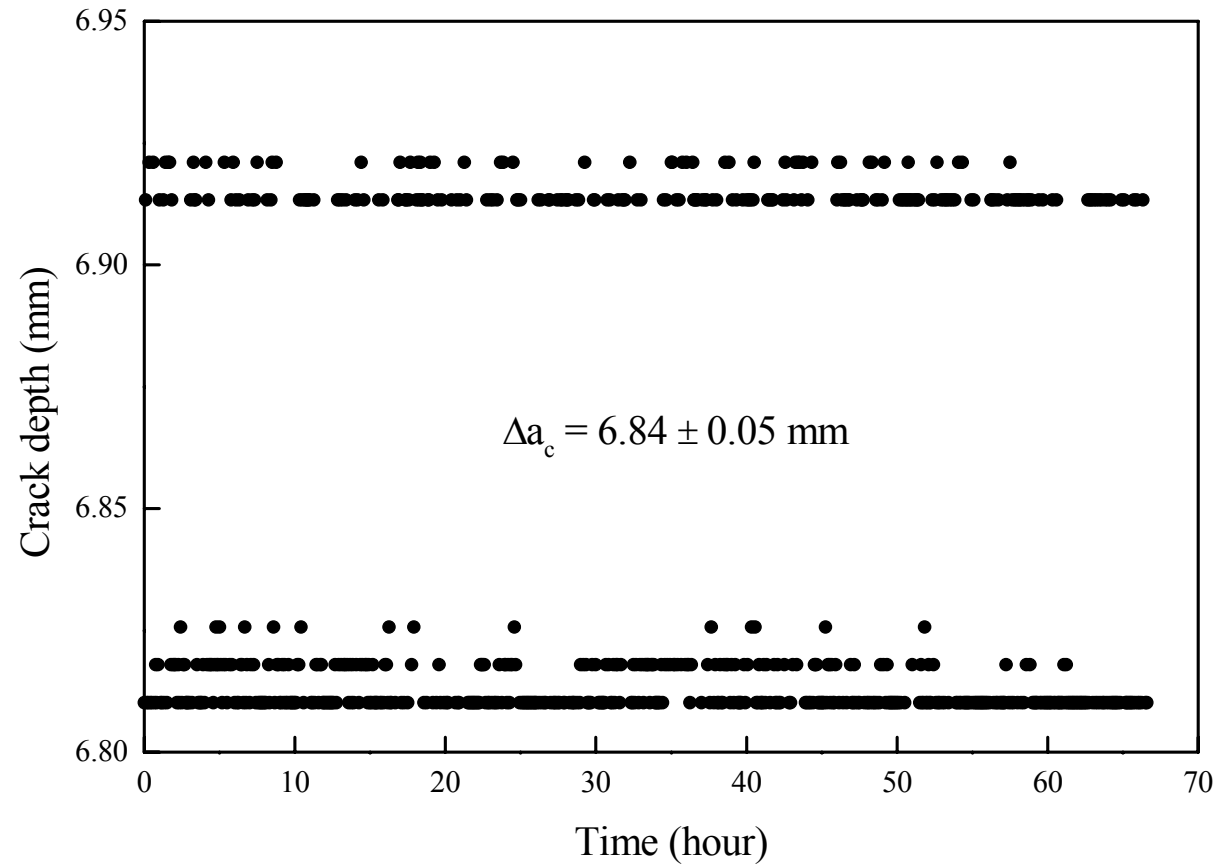


Figure 10

The dependence of calculated depth (using Equation (6)) of a long crack using a fracture mechanics specimen of the disc steel, showing the stability of ACPD system. Actual crack depth measured from the notch root: 6.80 mm.

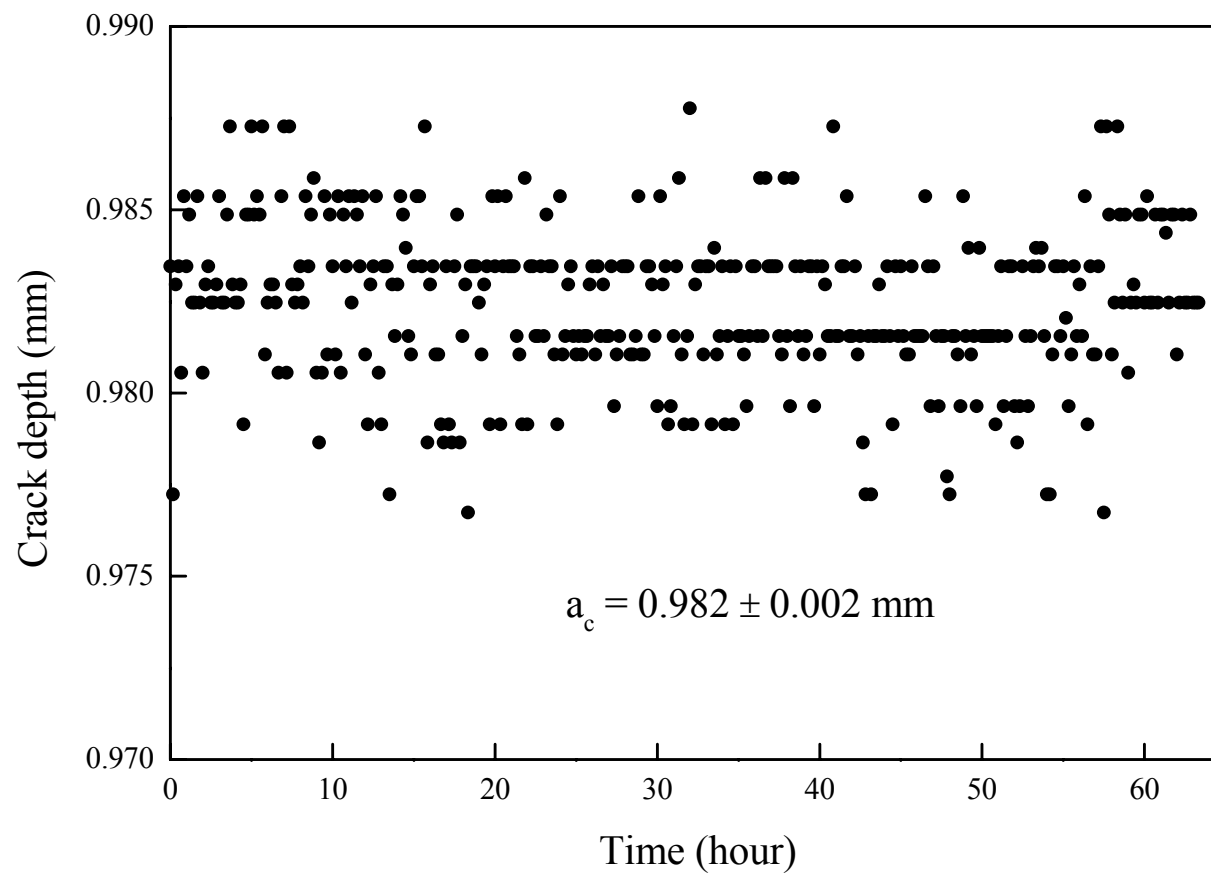


Figure 11 The dependence of calculated depth (using polynomial fit) of a short crack initiated from a pit (pit depth: 68 μm), showing the stability of ACPD system. Actual crack depth: 0.945 mm.