

**NPL REPORT
DEPC-MPE 041**

**Stress Corrosion Short Crack
Growth Measurement for A
Steam Turbine Disc Steel**

**Shengqi Zhou and
Alan Turnbull**

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Stress Corrosion Short Crack Growth Measurement for a Steam Turbine Disc Steel

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ABSTRACT

Preliminary measurements have been conducted to determine the growth rate of short stress corrosion cracks in a steam turbine disc steel in aerated 1.5 ppm Cl^- solution at 90 °C. The initial crack depths were in the range 473 μm to 672 μm . For these depths the growth rate was about the same or greater than a typical long crack growth rate. Further studies are required to establish the dependence of the growth rate on crack length at shorter crack lengths in order to test model predictions.

Keywords: Steam turbine, short crack, disc steel

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ISSN 1744-0262

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We gratefully acknowledge the financial support of the UK Department of
Trade and Industry (National Measurement System Policy Unit)

Approved on behalf of the Managing Director, NPL,
by Dr M G Gee, Knowledge Leader, Materials Performance Team
authorised by Director, Engineering and Process Control Division

CONTENTS

1. INTRODUCTION	1
2. EXPERIMENTAL	1
MATERIAL	1
SPECIMENS	2
PRE-CRACKING	3
WATER CHEMISTRY	4
DCPD MEASUREMENT SYSTEM FOR MONITORING THE CRACK GROWTH	4
TEST PROCEDURE	5
3. RESULTS AND DISCUSSION	6
CORROSION POTENTIAL MEASUREMENT	6
EFFECT OF INITIAL CRACK LENGTH ON THE GROWTH RATE OF SHORT CRACKS	6
DCPD MEASUREMENT	11
4. CONCLUSIONS	13
5. ACKNOWLEDGEMENTS	13
6. REFERENCES.....	13
7. APPENDIX A.....	15

1. INTRODUCTION

The measurement of short crack growth rate is of great interest both scientifically and technically as the growth in the short crack regime is often perceived to occupy the largest section of life of a component¹⁻⁶. There is no uniform definition of what constitutes a short crack as the growth rate for short cracks may be distinguished from long cracks for a variety of reasons including mechanical, microstructural and chemical. The growth rate of short cracks is usually greater than for long cracks (for the same mechanical driving force) under corrosion fatigue conditions¹ but there is a paucity of data for short crack growth rates under stress corrosion cracking conditions. There are two separate issues. Is there a short crack effect on crack growth rates for the same mechanical driving force? Does the K (stress intensity factor) independence of long crack growth kinetics prevail for short cracks (in other words is there a crack size dependence for short cracks at constant applied stress)? Using smooth specimens, extensive exposure tests have been conducted on a steam turbine disc steel to understand the development of stress corrosion cracks in simulated condensate environments and to provide insight into factors controlling the life of steam turbine plant. For low to medium strength steels, stress corrosion cracks have been shown to emanate from corrosion pits. Recent novel research using X-ray tomography has indicated that these cracks develop not at the base of the pit but on the pit walls somewhere near, or at, the pit mouth⁷. Such studies have provided valuable conceptual insight but quantifying the subsequent growth of these cracks is a challenge. In-situ real-time crack depth measurement for such testing conditions is not readily possible and it is necessary to rely on the adoption of pre-cracked specimens.

In this report, the testing procedures for producing nominally short precracks, direct current potential drop (DCPD) calibration and measurement, and the preliminary results for the short crack growth rate of a disc steel in a relatively severe environment (aerated 1.5 ppm Cl⁻ solution) are presented and discussed.

2. EXPERIMENTAL

MATERIAL

The material used in this work was a disc steel (3% NiCrMoV), cut from an ex-service steam turbine disc supplied by E-on. The chemical composition is listed in Table 1. As supplied, the steel had been thermally treated at 840 °C, oil quenched, followed by tempering at 590 °C and then air cooling. The microstructure of the steel was bainitic, as shown in Figure 1. The mean grain size was $26 \pm 8 \mu\text{m}$.

Table 1. Chemical composition of the 3% NiCrMoV disc steel (mass %).

C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Fe
0.30	0.28	0.45	0.017	0.013	0.69	0.27	2.89	0.091	0.21	bal

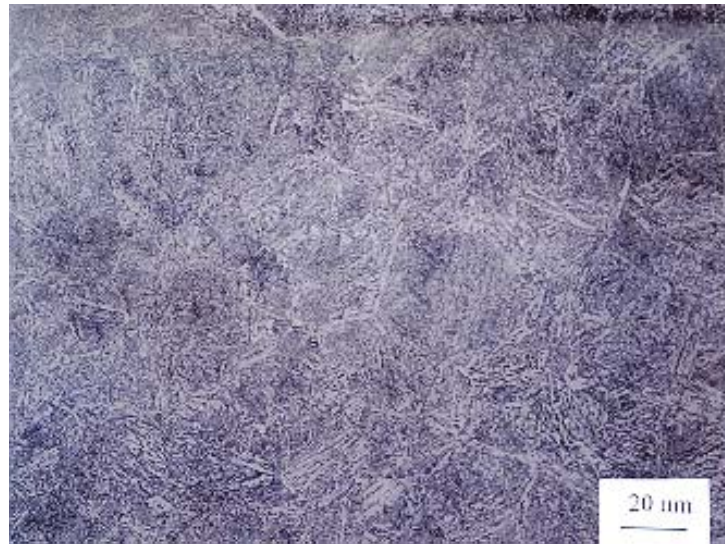


Figure 1. Microstructure of 3% NiCrMoV disc steel.

SPECIMENS

Attempts were initially made to produce a fatigue precrack from a shallow notch of about 300 μm wide and 30 μm in depth. However, a relatively high level of stress range is required to develop a precrack from such a shallow notch (the maximum stress is near to the yield stress under fatigue conditions with the stress ratio = 0.1). This is not desirable as the gross plastic deformation of the net section may then have a significant effect on the subsequent stress corrosion cracking. The alternative is to create a deep notch, precrack and then machine off the notch to leave a crack of the required length (since there is no notch, crack length and crack depth are interchangeable terms). To that aim, a relatively deep mechanical slot of 2 mm depth and 0.3 mm width was introduced by electric discharge machining in a single edge notched tensile (SENT) specimen as shown Figure 2. The gauge length was 25 mm, the initial width (w) in the gauge length before machining was 10 mm and the thickness (B) was 8 mm.

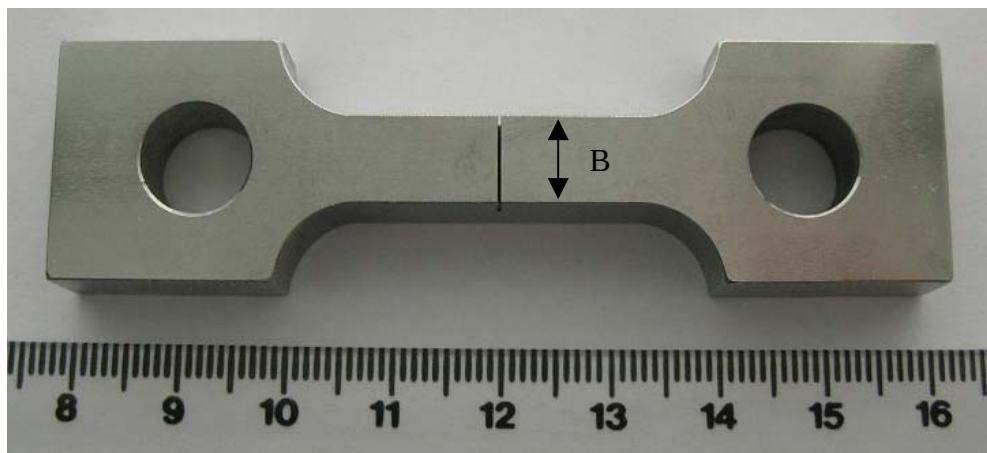


Figure 2. Photograph showing the original geometry of SENT specimen before precracking.

To avoid an uncontrolled influence of residual stress resulting from machining, all specimens, prior to fatigue precracking, had been stress-relieved in vacuum for 2 hours at 625 °C. The mechanical properties at ambient temperature and at the test temperature are listed in Table 2. The data were the average of three tests under each condition.

Table 2. Mechanical properties of the disc steel.

Condition	T /°C	E /GPa	$\sigma_{0.2}$ /MPa	UTS /MPa	Elongation /%
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

It can be seen that the stress relief had no effect on the mechanical properties. Since the specimens were cut from an ex-service disc, there was a concern that the mechanical properties might vary at the different locations of the disc. Therefore, the hardness of the steel was measured on ten randomly selected specimens. There was no significant variation in the hardness measured; the average value being 28.5 (Rockwell C), with a standard deviation of 1.5.

PRE-CRACKING

The fatigue pre-cracking was conducted by uniaxial tension-tension loading in air at ambient temperature (25 ± 2 °C) using a servo-hydraulic fatigue machine, in accordance with BS EN ISO 7539-6:2003⁸. The fatigue frequency was 110 Hz and the stress ratio was 0.1. The initial pre-cracked depth was 4 mm from the root of the notch such that the total initial crack length, a , from the surface (including the notch) was 6 mm. There were two main criteria adopted in the fatigue precracking procedure:

- The applied maximum stress should not exceed the proportional limit for the net section material. The maximum stress in this work was no greater than 145 MPa, well below the departure stress in the stress - strain curve of the disc steel.
- The applied stress range should be reduced in a stepwise fashion so that the final nominal maximum stress intensity factor would be less than 75% of the applied nominal stress intensity factor in the subsequent SCC testing. In this work, the final apparent ΔK was 9 MPa m^{1/2} ($K_{\max} = 10$ MPa m^{1/2}). The estimated size⁹ of the monotonic plastic zone size is 10 µm and the reversed plastic zone at this stress intensity factor is about 2.5 µm.

After precracking, the mechanical slot and the majority of the precrack were then ground out to leave a short crack of the required length and a final width of the specimen of about 4 mm. After grinding, the surface roughness R_a value was 0.2 µm.

WATER CHEMISTRY

All tests were conducted at 90 °C in aerated 1.5 ppm Cl^- solution made of AR grade NaCl. The environment was chosen to correlate with model predictions for pitting and cracking¹⁰⁻¹¹. The test set up in Figure 3 gives an indication of the cell arrangement and solution circulation system though not all features are shown. Aeration was achieved by bubbling air through the reservoir solution, held at 90 °C. The solution was preheated before entering the cell to minimise thermal loss in the circulation line. The test solution was refreshed weekly to limit build-up of corrosion product and conductivity change. The oxygen content and solution conductivity were monitored on line and were controlled at $1.7 \text{ ppm} \pm 0.1 \text{ ppm}$ and $5.7 \text{ }\mu\text{S/cm}$ to $9.5 \text{ }\mu\text{S/cm}$ respectively at $23 \pm 2 \text{ }^\circ\text{C}$.

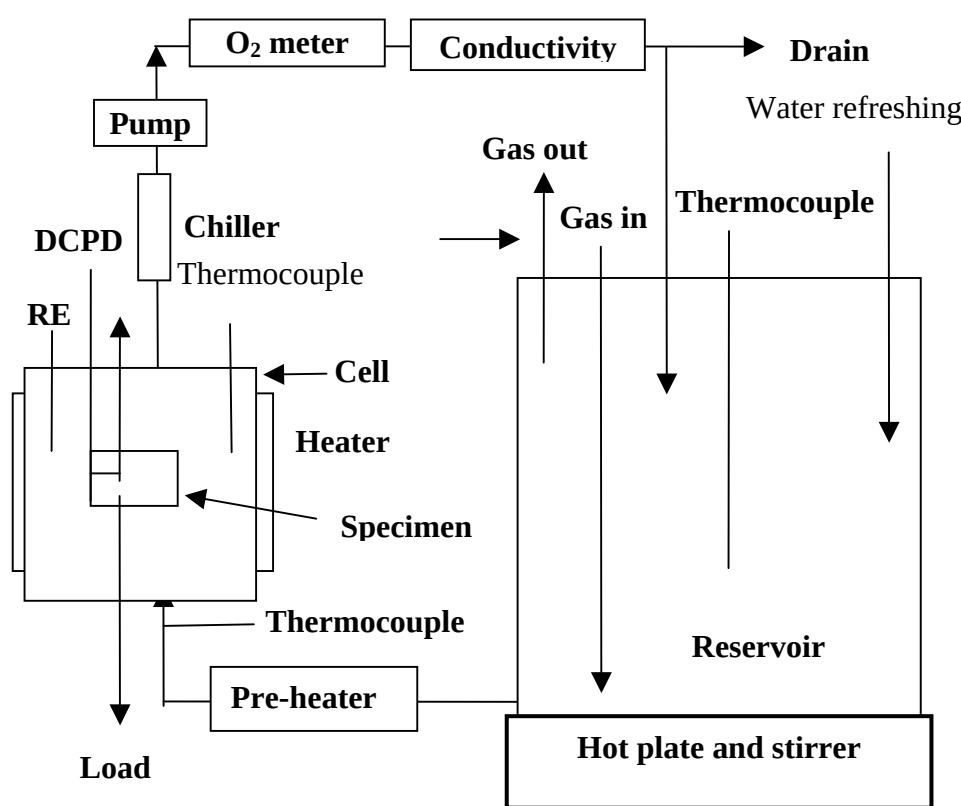


Figure 3. Recirculation loop, showing oxygen and conductivity monitoring, solution replenishment, temperature control and corrosion potential measurement.

DCPD MEASUREMENT SYSTEM FOR MONITORING THE CRACK GROWTH

Stress corrosion crack growth was monitored using a multi-channel pulsed DCPD system with high resolution and stability. The details of the system have been described elsewhere¹². The current and potential measurement leads were insulated using PEEK tubing and spot welded to the specimens. The current leads were attached to the centre in the shoulder area and the potential drop probes were attached to either side of the crack with a spacing of 3 mm (Figure 3). The spot welded area was protected with an adhesive stable in water at temperatures up to 170 °C.

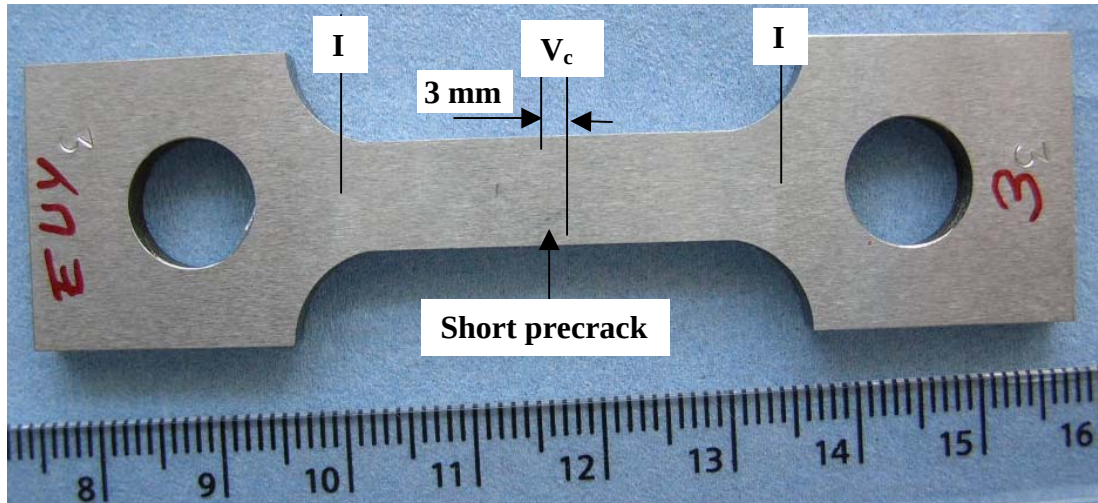


Figure 4. Photograph showing the geometry of SENT specimen after pre-cracking and the removal of the slot; also shown are the locations of the DCPD probes.

In the present study, the following parameters were chosen. A reversible direct current of 4 A was applied and 3 measurements made with both positive and negative current to obtain an average potential drop per current cycle. Since the crack growth rate is very slow in this system, the following procedure was adopted: 1000 current cycles were applied once per day over a time period of 3 hours and the data were then averaged to obtain one potential drop value per day.

To calculate the crack length, a , a calibration curve linking crack length with potential drop was obtained using a conventional foil-slitting calibration process (see appendix A). The final crack length measured on the fracture surface of the test specimen (an average of 7 measurements at different locations across the crack front) was then used to benchmark the calibration curve.

TEST PROCEDURE

Prior to testing, the specimen surface, as well as the precrack, was cleaned with high purity water, ethanol and acetone, under a small tensile stress of 100 MPa. After placing the specimens onto the constant loading machine, without applying load, the test solution was introduced and the test temperature increased gradually to 90 °C in about one hour. The load was then applied to a nominal stress (without taking into account the presence of the shallow precrack) equivalent to 75% of yield stress.

The temperature was controlled at 90 ± 1 °C and recorded hourly. The corrosion potential was measured using an external saturated calomel electrode (SCE). The reference electrode was connected to the test cell through a glass bridge filled with the test solution. The reference electrode chamber and the test cell were separated with a glass valve, which was closed except when a measurement was taken. The solution conductivity was monitored to ensure that there was no significant contamination due to diffusion of chloride from the reference electrode chamber to the test cell during the potential measurement. All potentials quoted are with reference to the saturated calomel electrode (SCE) at 25 °C.

3. RESULTS AND DISCUSSION

CORROSION POTENTIAL MEASUREMENT

The corrosion potentials of the three specimens are shown in Figure 5. It can be seen that the potential increases rapidly over a period of 150 hours initially, but then more slowly, consistent with previous measurements for self-loaded cylindrical and FM specimens¹²⁻¹³. Hence, for most of the test, the potential was effectively constant and as such the electrochemical driving force for cracking, accounting also for the crack-tip potential¹⁴, would be considered constant.

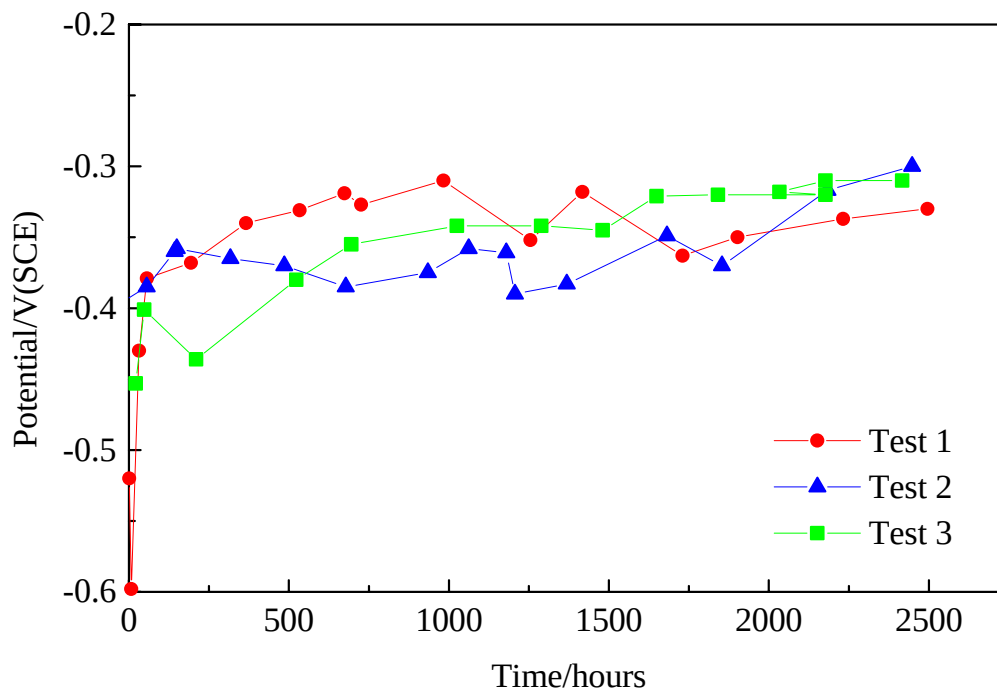


Figure 5. The variation of the corrosion potential of the disc steel in aerated 1.5 ppm Cl^- at 90 °C with time.

EFFECT OF INITIAL CRACK LENGTH ON THE GROWTH RATE OF SHORT CRACKS

On completion of testing, the specimens were off-loaded and removed from the corrosion cell. The external surface of the specimens was covered with brownish corrosion products with an adherent black film underneath when the loose corrosion deposits were removed. The specimen was cleaned with high purity water, ethanol and acetone. Pitting corrosion on the external surface was evident (Figure 6) and the pre-crack can be seen more clearly.

The specimens were then fatigue fractured. The initial and final crack lengths were measured on the fractured surface using a travelling microscope with a magnification of 100, as listed in Table 3. Since the crack front is not uniform, the data in Table 3 are

average values of the crack lengths measured at seven points evenly distributed across the whole specimen thickness.

It was somewhat surprising that the crack lengths measured on the fracture surface were so markedly different from those measured on the side surfaces (Table 3), which was the target average length in fatigue pre-cracking. Although the pre-crack front was broadly uniform (but with local variations) there appeared to be some pinning of the crack at the specimen sides such that the crack extension was reduced in that region. The pinning at the surface is not readily seen from the fractured surface because of general corrosion at the edge of the specimens. Clearly, extra care is needed in pre-cracking to achieve the desired initial average depth, combining surface crack length measurement and DCPD measurement.

Based on the initial and final crack lengths measured on the fractured surface, the corresponding stress intensity factors were calculated using the empirical equations derived from the single edge notched foil strip¹⁵. The results, together with the applied nominal stress and the stress in the net section with the presence of the crack, are also listed in Table 3. At these stress intensity factors, the monotonic plastic zone sizes were in the range 65 μm and 218 μm . Therefore, these cracks were not short at the microstructural scale, as the average grain size was about 26 μm (Figure 1).

The average crack growth rate was obtained by dividing the crack extension measured on the fracture surface by the effective crack growth time (the total test duration minus the time to crack initiation indicated by the DCPD measurement (see below), also listed in Table 3. It can be seen that the crack growth rates of two specimens with a similar initial crack length (Tests 1 and 3) are almost the same, while the crack growth rate for the specimen with a smaller initial crack length (Test 2) is much lower.

The fracture surface was examined using scanning electron microscopy (SEM) after one half of the fractured specimen was chemically cleaned using “Super Clarke’s” solution (10 g/l of 1,3-Di-n-butyl-2-thiourea (DBT) in 37.5% HCl), as shown in Figures 8 and 9. Separate tests were conducted to confirm that there is no general corrosion or pitting of the disc steel in this cleaning solution. Figure 8 shows a SEM micrograph at low magnification (20 x). It can be seen that pitting occurred on the precrack surface, with pit diameters of several hundred μm . The coalescence of pits can also be observed. There was also significant dissolution on the crack wall in the region of SCC and pitting was apparent on the fracture surface. Figure 9, taken at the SCC region, showed that the stress corrosion crack was transgranular, consistent with that observed previously in FM and smooth cylindrical specimens^{12 - 13}.

Table 3. The initial and final crack lengths, a_i and a_f , measured on the side surface and on the fractured surface, the applied stress, σ_{app} , and initial and final nominal stress intensity factors, K_i and K_f , for the measurement of the growth rate of short cracks in aerated 1.5 ppm Cl^- solution at 90 °C.

Parameters	Test 1	Test 2	Test 3
a_i measured on side surface (μm)	393	233	86
a_i measured on fractured surface (μm)	672	473	634
a_f measured on fractured surface (μm)	996	628	954
Average crack extension (μm)	324	155	320
Applied nominal stress ($\% \sigma_{0.2}$) ⁽¹⁾	75	75	75
Initial true stress ($\% \sigma_{0.2}$) ⁽²⁾	89.4	84.9	88.6
Final true stress ($\% \sigma_{0.2}$) ⁽²⁾	98.6	88.7	97.6
Nominal K_i ($MPa m^{1/2}$) ⁽³⁾	31.6	24.7	31.7
Nominal K_f ($MPa m^{1/2}$) ⁽³⁾	45.2	30.7	42.6
Effective test duration (h)	1992.1	2353.5	2016.0
Average crack growth rate (m/s)	4.5×10^{-11}	1.8×10^{-11}	4.4×10^{-11}
(1) Calculated stress without taking into account of the presence of the crack. (2) Stress at the neck section with the crack (3) K was calculated using empirical equations derived from the single edge notched strip ¹⁵ .			



Figure 6. Photograph showing pitting in the SENT specimen after testing in aerated 1.5 ppm Cl^- solution at 90 °C for 2667 h.

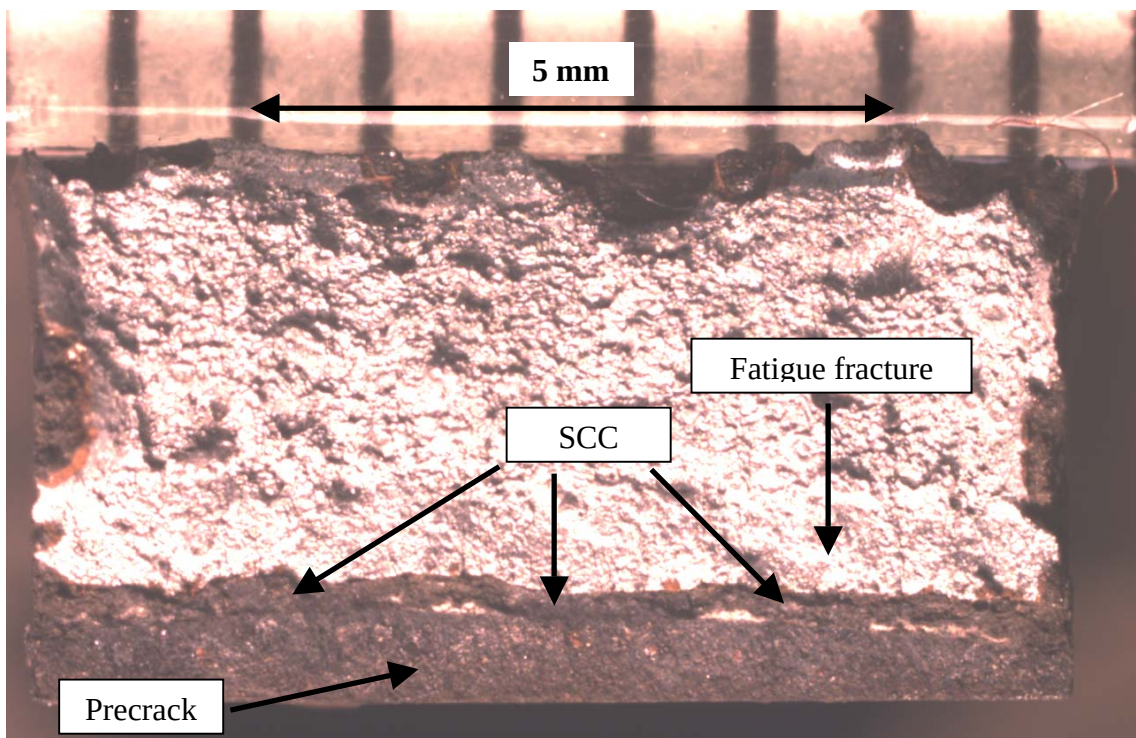


Figure 7. Fracture surface of the SENT specimen of the disc steel after testing in aerated 1.5 ppm Cl^- solution at 90 °C for 2667 h.

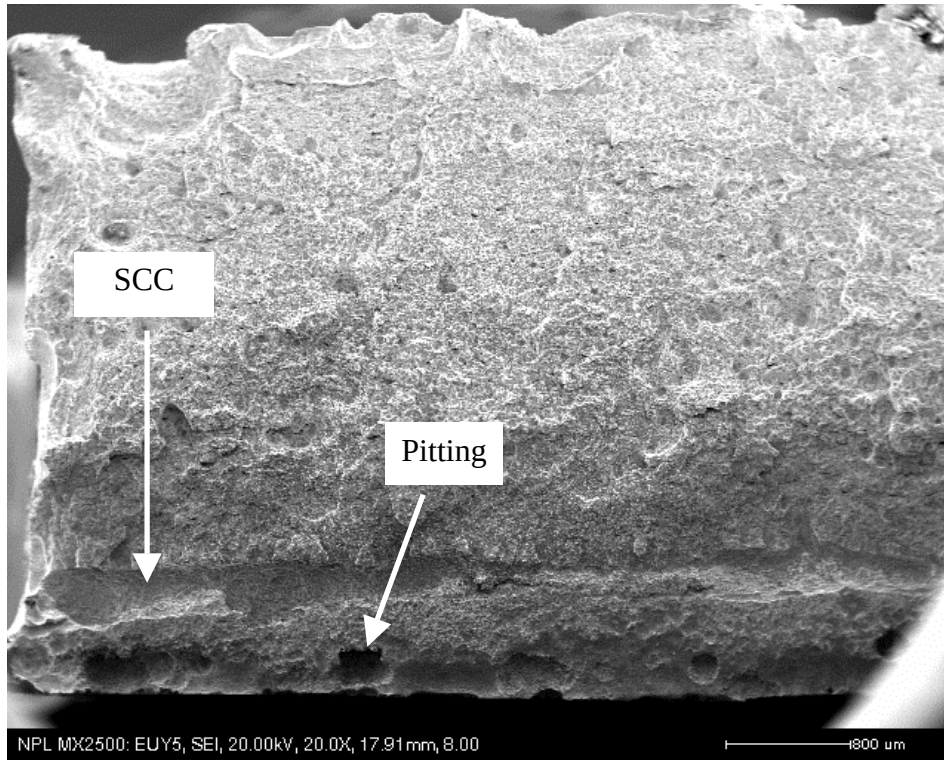


Figure 8. SEM micrograph of the fracture surface showing transgranular stress corrosion cracking (low magnification, 20X).

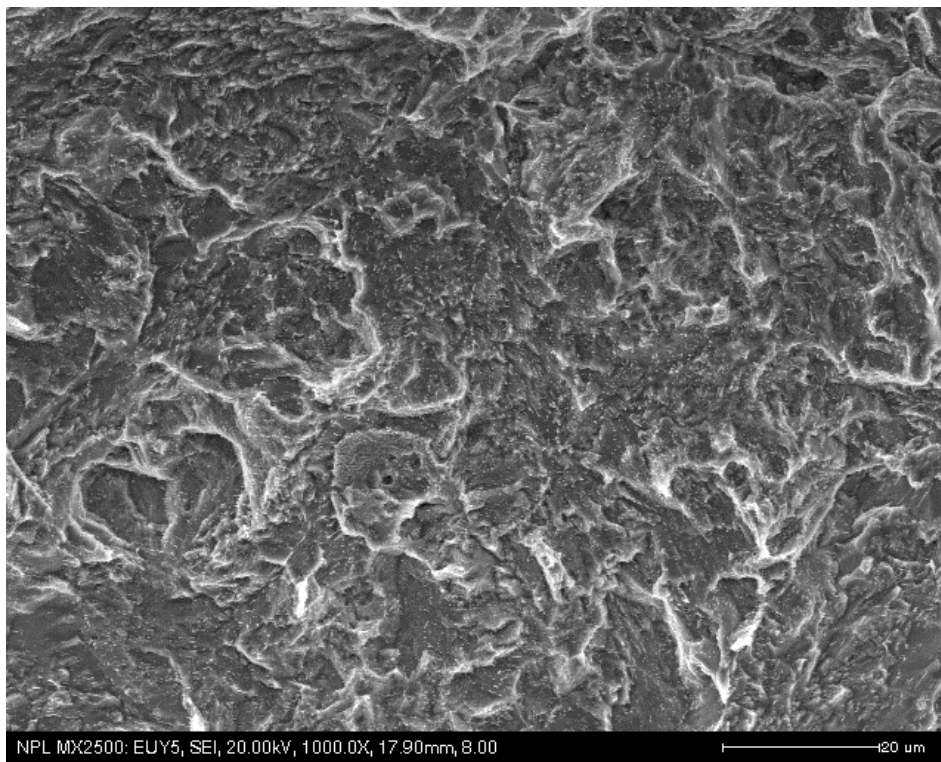


Figure 9. SEM micrograph of the fracture surface showing transgranular stress corrosion cracking.

DCPD MEASUREMENT

The crack length/depth as a function of test time was calculated from DCPD using the calibration described in Appendix A, as shown in Figure 10. It can be seen that the DCPD measurement is effective in detecting the crack initiation time. The crack initiation time of the disc steel in aerated 1.5 ppm Cl^- was less than 500 hours, except for Test 1 in which the applied stress was reduced to zero between 252 hours and 718 hours due a failure of the loading machine. There was a good agreement between the crack lengths measured on the fractured surface and those projected by the potential drop. The crack extensions for Tests 1 and 2 were 344 μm and 173 μm respectively (the DCPD measurements for Test 2 failed at 535 hours due to a probe failure). These values were 6% and 12 % greater than those measured on the fractured surface for Test 1 and 3 respectively. The small discrepancy was at least partly due to reduction in the specimen dimension resulting from general corrosion, but also probably due to the inaccuracy of the crack length measurements on the fractured surface, as the crack front was not uniform. Therefore, the crack length obtained from DCPD was not proportionally scaled down, as suggested by Gangloff et al.¹⁶.

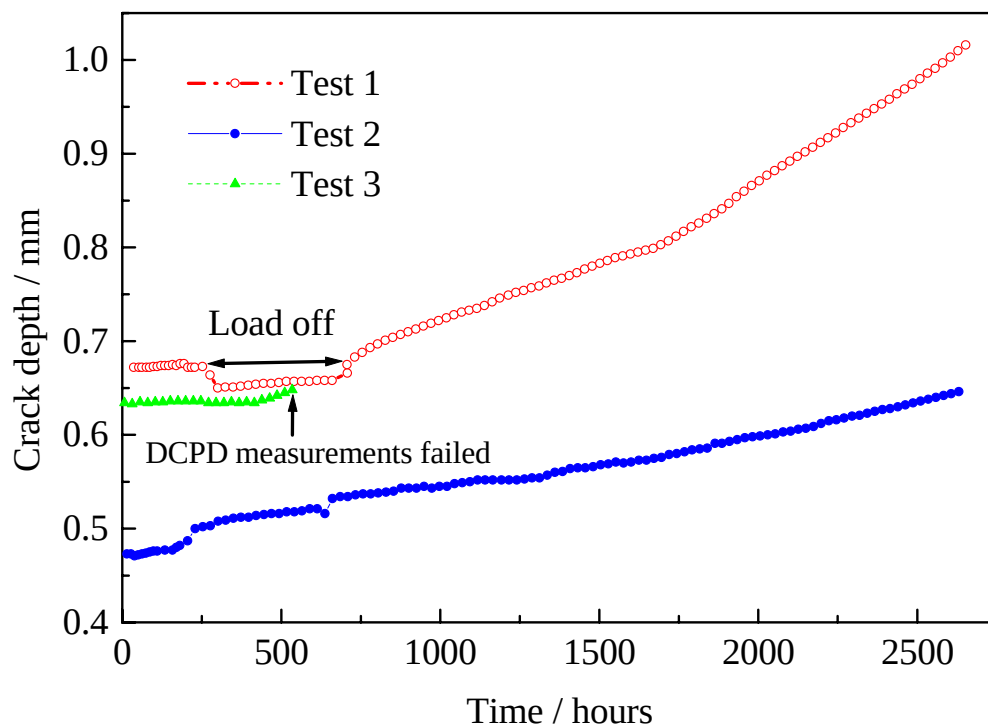


Figure 10. The variation of the crack length, derived from DCPD, with time.

The crack growth rate was estimated from the data in Figure 10 using a 20-point incremental method in which the slope of the first 20 data points was determined, the data points were advanced by one and the slope of the next 20 point determined and so on. The crack growth data as a function of stress intensity factor are shown in Figure 11 and highlight the unsteady nature of the apparent growth rate with respect to time (and hence the stress intensity factor). Despite good agreement between the overall crack extension estimated from the DCPD method and the measured crack extension on the

fracture surface it is uncertain whether this behaviour is intrinsic or reflects an artefact, perhaps due to the pitting corrosion and general corrosion observed on the fracture surface.

When the two sets of data are combined, together with the average growth rate and stress intensity factor for Test 2 in which no instantaneous crack growth rate can be obtained as the DCPD measurement failed at 535 hours, there is an indication of an increase in the crack growth rate with the increase of stress intensity factor in Figure 11. This may indeed be real but more data are required to confirm the trend. The growth rate of a long crack (greater than 6 mm) in the FM specimen was previously measured in the same environment and had a value of 2.7×10^{-11} m/s (also plotted in Figure 11), lower than the values obtained in Tests 1 and 3 but greater than that in Test 2 (Table 3). In view of this apparent lack of consistency with the long crack growth data and limited range of K it would be premature to make any strong statements about crack size effects.

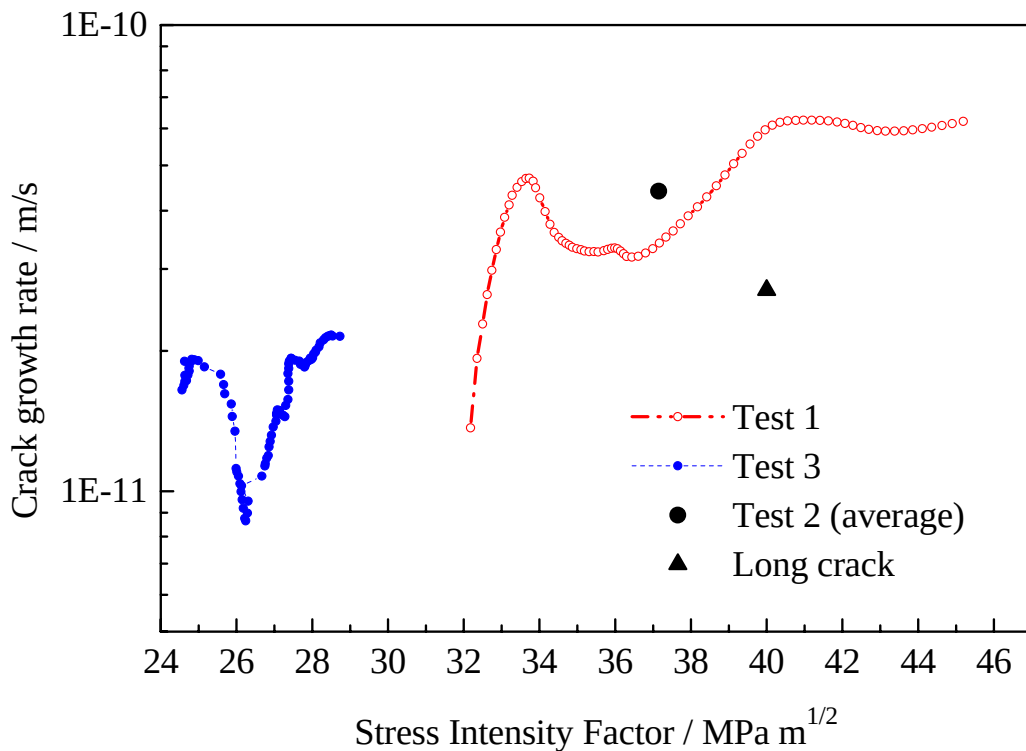


Figure 11. The variation of the crack growth rate as a function of stress intensity factor.

The model of Turnbull et al¹¹⁻¹² predicts that the crack growth rate should show a crack depth (and hence K) dependence at constant applied stress for cracks less than about 600 μm . The data generated in this study do not allow any assessment of those predictions and further work with shorter initial crack depths is required.

4. CONCLUSIONS

1. A procedure to generate short cracks in SENT specimens has been developed to ensure that the effect of fatigue loading during precracking on subsequent SCC testing is negligible and that stress corrosion cracks develop from the intended sites.
2. There was good agreement between the crack length derived from DCPD and that measured from the fractured surface.
3. When comparing trends in these short crack growth data there was an apparent crack size effect but deductions should be put on hold until further measurements with shorter initial crack lengths are undertaken and an extended range of long crack data are generated.

5. ACKNOWLEDGEMENTS

This work was conducted as part of the Materials Performance programme, a joint venture between the United Kingdom Department of Trade and Industry and an Industrial Group comprising Alstom, BNFL Magnox, British Energy, E-ON, RwenPower and Siemens.

6. REFERENCES

1. R. P. Gangloff and R. O. Ritchie in *Proceedings of Fundamentals of Deformation and Fracture, Sheffield, 1984*, ed. K.J. Miller, Cambridge University Press, Cambridge, UK, 1985, pp 529-558.
2. A. Turnbull, Environment assisted fatigue, in *Comprehensive Structural Integrity (Fracture of Materials from Nano to Macro)*, Volume 6: Environment-Assisted Fracture, Vol. Editors, J Petit and P Scott, pp 163-210, Elsevier, 2003.
3. *Small Fatigue Cracks*, Eds. R. O. Ritchie and J. Lankford, The Metallurgical Society, Inc., 1986.
4. *The Behaviour of Short Fatigue Cracks*, Eds. K. J. Miller and E. R. de los Rios, EGF Publication 1., MEP, Instn Mech Engs, London, 1986.
5. *Short Fatigue Cracks*, Eds. K. J. Miller and E. R. de los Rios, Mechanical Engineering Publications, 1992.
6. *Effect of the Environment on the Initiation of Crack Growth*, Eds. W. A. van der Sluys, R. S. Piascik and R. Zawierucha, STP 1298, ASTM, Publication, 1997.
7. B. J. Connolly, D. A Horner, S. Zhou and A. Turnbull, *Tomography Studies of Transition from Pits to Stress Corrosion Cracks*, manuscript under preparation, 2007.
8. ISO 7539-6, *Corrosion of Metal and Alloys – Stress Corrosion Cracking Testing, Part 6: Crack Propagation Testing Using Precracked Specimens*, (2003).
9. H. J. Ewalds and R. J. H. Wanhill, *Fracture Mechanics*, Edward Arnold (Publishers) Ltd, London, 1983.
10. A. Turnbull, S. Zhou and L. N. McCartney, A model to predict the evolution of pitting corrosion and the pit-to-crack transition incorporating statistically distributed parameters, *Corros. Sci.*, 48, 2084-2105, 2006.
11. A. Turnbull, L. N. McCartney and S. Zhou, Modelling of the evolution of stress corrosion cracks from corrosion pits, *Scripta Materialia*, Vol. 54, 575-578, 2006.

12. S. Zhou and A. Turnbull, Environment Assisted Cracking of Steam Turbine Disc and Blade Steels - Description of Test Procedure and Preliminary Results, NPL "A" Report, MATC 41, 2001.
13. A. Turnbull and S. Zhou, Pit to Crack Transition in Stress Corrosion Cracking of a Steam Turbine Disc Steel, Corros. Sci. 46, 1293 – 1264, 2004.
14. A. Turnbull, S. Zhou and G. Hinds, Stress Corrosion Cracking of Steam Turbine Disc Steel – Measurement Of The Crack-Tip Potential, Corrosion Science, Vol. 46, 193, 2004.
15. H. Tada, P. Paris and G. Irwin, The Stress Analysis of Cracks Handbook, Del Research Cooperation, 1975.
16. R. P. Gangloff, D. C. Slavik, R. S. Piascik and R. H. Van Stone, Direct Current Electrical Potential Measurement of the Growth of Small Cracks, in Small-Crack Test Methods, Eds. J. M. Larsen, and J. E. Allison, ASTM STP1149, Philadelphia, p.116, 1992.

7. APPENDIX A

The relationship between the direct current potential drop (DCPD) and the crack depth for the SENT specimen was calibrated using a conventional foil-slitting calibration process. As shown in Figure A1, the size of the aluminium foil was 40 times larger than that of the specimen.

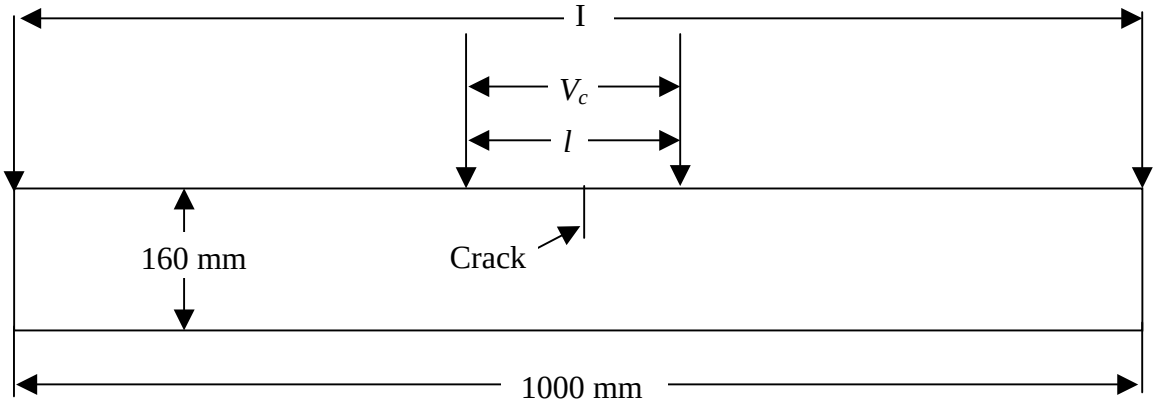


Figure A1. Schematic diagram showing the configuration of the DCPD probe attachments during calibration with aluminium foil.

The results are shown in Figure 2 and the data are best fitted with the following empirical equation:

$$\frac{a}{B} = \alpha \left[\frac{V_c}{V_0} - 1 \right]^\beta \quad (1)$$

where a is the crack length, B is the specimen thickness, V_c is the potential drop across the crack, V_0 is the initial value of the potential drop without the crack, α and β are fitting parameters.

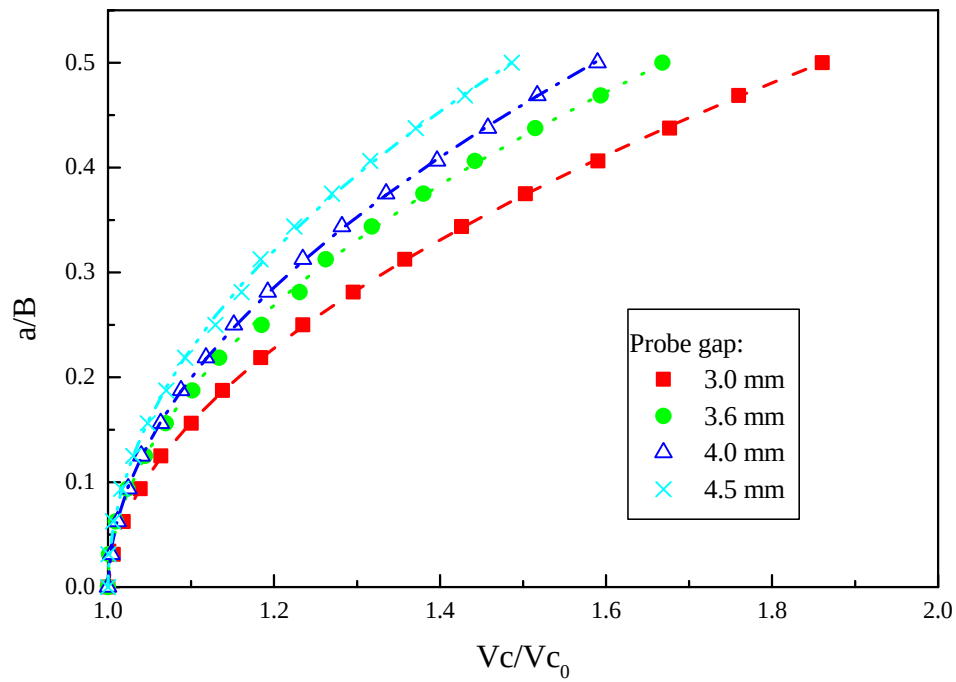


Figure A2. The ratio of crack length, a , to the specimen thickness, B , as a function of the ratio of potential drop across the crack to the initial value of the potential drop without the crack.

The values of α and β for different probe spacings, l , are listed in Table A1 from which it can be seen that α and β are strongly dependent on l . Therefore, care should be taken in attaching the wires for DCPD measurement and the crack extension derived from DCPD must be checked with that measured on the fractured surface. If the probe spacing were to depart from the set value, the following empirical equation may be used to correct the values of α and β (Figure A3):

$$\alpha = 0.129 + 0.134l \quad (2)$$

$$\beta = 0.617 - 0.025l \quad (3)$$

Table A1. Fitting parameters, α and β , at different probe spacings, l .

Probe spacing (mm)	2.0	2.5	3.0	4.0
α	0.3914	0.4651	0.5422	0.6598
β	0.5711	0.5512	0.5381	0.5194

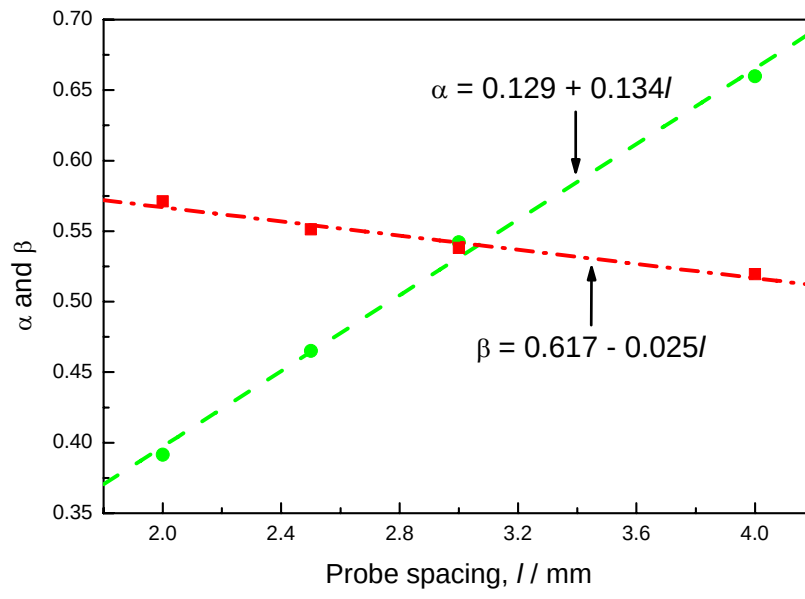


Figure A3. Fitting parameters, α and β , as a function of probe spacing, l .