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**Shengqi Zhou and Alan Turnbull**

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National Physical Laboratory | Hampton Road | Teddington | Middlesex | United Kingdom | TW11 0LW
**Switchboard** 020 8977 3222 | **NPL Helpline** 020 8943 6880 | **Fax** 020 8943 6458 | **www.npl.co.uk**

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# Pitting and Cracking of a Steam Turbine Disc Steel in Out-of-Specification Water Chemistry

Shengqi Zhou and Alan Turnbull
Engineering and Process Control Division

## ABSTRACT

Following previous long term pitting and cracking tests of a 3 NiCrMoV steam turbine disc steel, supplementary short term exposure tests have been carried out in an out-of-specification water chemistry, viz. aerated water containing 1.5 ppm $Cl^-$. The disc steel was in the form of cylindrical tensile test specimens self-loaded to 50%, 70% and 90% of $\sigma_{0.2}$. The pit growth law was evaluated to be $a_{pit} = 1.9 \times 10^{-7} t^{0.49}$. Threshold pit depths for initiation of stress corrosion cracks were determined.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW



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## INTRODUCTION

The power industry has experienced failures from environment assisted cracking (EAC) of steam turbine blades, discs and rotors. Despite worldwide effort, occasional problems still arise. The major challenge is to predict more reliably the conditions under which cracking is likely and, for those conditions, the evolution of crack size with time so that non-destructive evaluation may be used in a focused manner and informed decisions made about inspection intervals and remnant life. The difficulty is the complexity and transient nature of service conditions, and constraints in their detailed characterisation, e.g. the chemistry of the condensate formed on the turbine steel surface.

Stress corrosion cracking of the turbine discs usually results from water chemistry excursions. For example, a separate study[1] has shown that no pitting and cracking initiated from smooth cylindrical specimens under constant loading and exposed to a simulated on-load environment, viz. deaerated 300 ppb $Cl^-$ and 300 ppb $SO_4^{2-}$ at 90 °C, over a test period of 1 year. Similarly, no cracking was observed on specimens exposed to deaerated pure water at 90 °C for 22 months[2]. However, pitting and cracking were observed in aerated pure water and in aerated water containing chloride[2]. These studies were undertaken recognising that oxygen in the condensate may develop at least transiently under on-load conditions and that the inlet water chemistry for the steam generator may not be controlled within the specification[3]. In the previous investigation[2], the disc steel was loaded to 90% of the proof stress in aerated water containing 1.5 ppm $Cl^-$. Stress corrosion cracking was prevalent in all tests including the shortest duration test of 5107 h but even that test in itself was of quite long duration. It was pertinent to undertake shorter-term tests to assess the exposure period at which cracks initiated and also to investigate the effect of applied stress. This report summarises the results of these tests.

## EXPERIMENTAL

Exposure tests were conducted on self-loaded cylindrical specimens of the disc steel, 3% NiCrMoV, cut from an ex-service steam turbine disc supplied by PowerGen. The oxygen concentration and solution conductivity were monitored and controlled using a flow loop, as shown in Figure 1. The testing procedure, such as the specimen preparation, the water chemistry, temperature and corrosion potential monitoring, and the measurement of pits and cracks are described in detail elsewhere[2]. In brief, three stainless steel test cells are arranged in series and the test solution of aerated 1.5 ppm $Cl^-$ at 90 ± 1 °C recirculated from a 40 L reservoir. The test solution is refreshed weekly to limit build-up of corrosion product and conductivity change. The initial loading condition, the location in the circulation line and the exposure time of the specimens are listed in Table 1. All tests were conducted at 90 ± 1 °C.

On completion of the tests, the specimens were removed from the solutions approximately 1 hour after the heater was switched off, when the solution temperature had decreased to below 50 °C. The specimens with their loading frames were washed immediately with high purity water, ethanol and acetone. Unloading was then undertaken on a mechanical test machine. After unloading, the specimen surface was

carefully examined and photographed before and after chemical cleaning using "Super Clarke's" solution (10 g/l of 1,3-Di-n-butyl-2-thiourea (DBT) in 37.5% HCl).

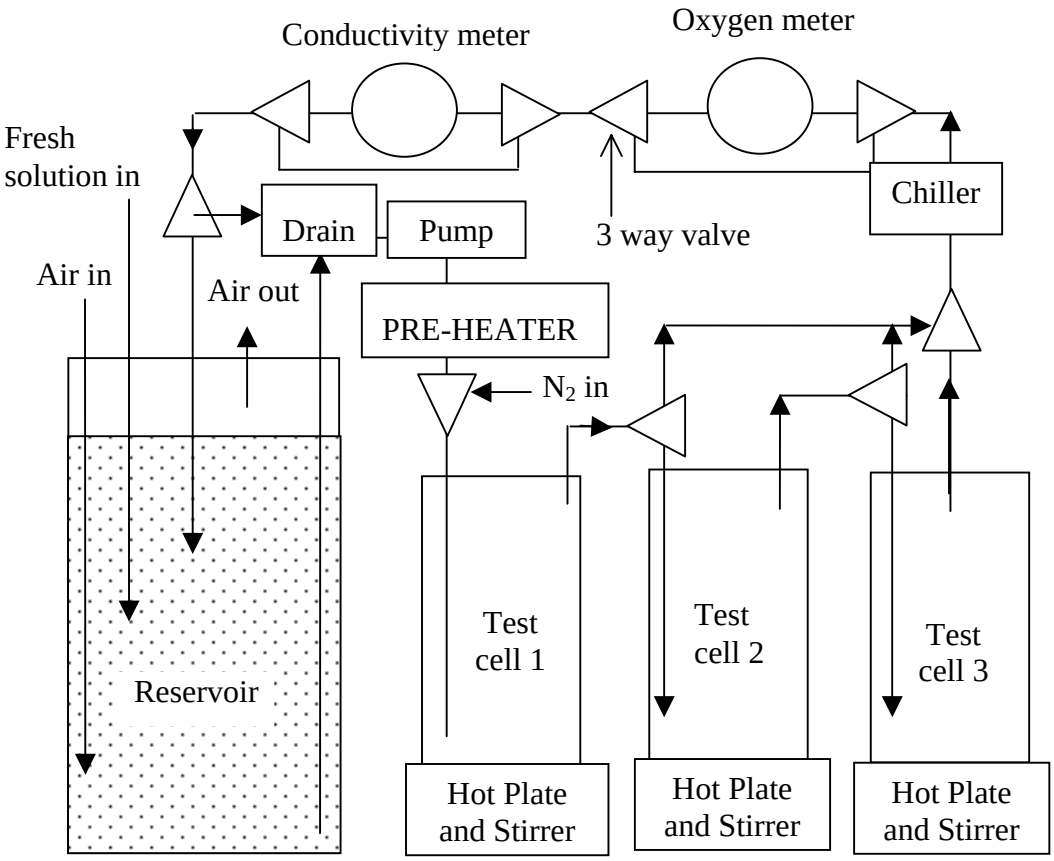


**Figure 1.** Schematic diagram of the test solution circulation loop.

**Table 1.** Details of testing conditions

| Specimen no. | Initial loading ($\%\sigma_{0.2}$) | Cell number | Exposure time /h |
|---|---|---|---|
| 35 | 90 | 3 | 171 |
| 9 | 90 | 2 | 668 |
| 18 | 90 | 1 | 2209 |
| 40 | 70 | 1 | |
| 15 | 50 | 1 | |

The depth and the surface width of the pit (the mouth of the pit was not always ideally circular) were measured using a travelling microscope (resolution 1 μm). In the latter case, the maximum width in one direction was measured and the width perpendicular to this was measured also. The average value was used later in calculating the aspect ratio.

## RESULTS AND DISCUSSION

### Surface analysis of pit and crack distribution

The surface appearance of the specimen tested for 7 days is shown in Figure 2. A large number of pits had already developed in this relatively short period.

A summary of the measurement of pit depths and observations of cracking after exposure periods of 171 h, 668 h and 2209 h is given in Table 2 (also listed in Table 2 are the results of long term exposure tests conducted previously[2], 5107 h, 7173 h and 9187 h). For specimens exposed for 2209h, the complete measurement of all pits was only taken on the specimen loaded to 90% $\sigma_{0.2}$ but not on the specimens loaded to 50% and 70% $\sigma_{0.2}$ (the measurement was extremely time consuming due to the high density of pits). Cracking was observed on specimens loaded to 90% $\sigma_{0.2}$ and tested for 668 h and 2209 h. The minimum depth of pit from which a crack initiated was 76 µm and 62 µm on specimens tested for 668 h and 2209 h respectively. However, no cracks were found on the specimen loaded to 90% $\sigma_{0.2}$ and exposed for 171 h and on the specimen loaded to 50% of $\sigma_{0.2}$ and tested for 2209 h despite pits depths up to 193 µm in the former and 493 µm at the lower stress. Cracks were observed on the specimen loaded to 70% of $\sigma_{0.2}$ and tested for 2209 h.

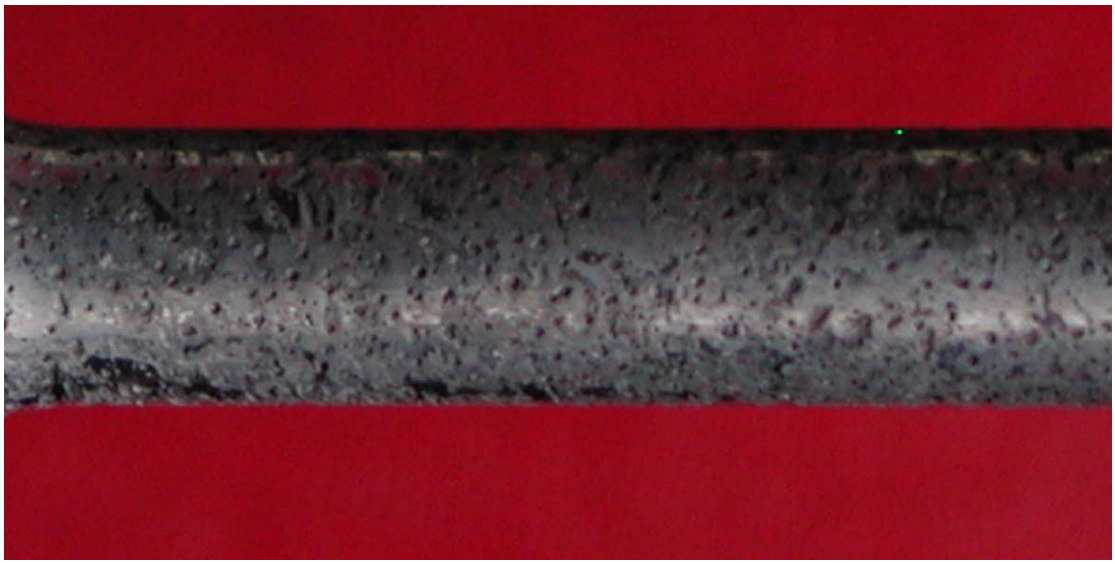

Figure 2. Surface appearance of a self-loaded cylindrical tensile specimen tested in aerated 1.5 ppm $Cl^-$ solution at 90 °C for 171 h.

**Table 2.** Pit size measurements for disc steel specimens in aerated 1.5 ppm $Cl^-$ at 90 °C (the analysed specimen surface area is 6 $cm^2$). The results for 5107 to 9187 h relate to previous work[2].

| Test time /h | Stress (% of $\sigma_{0.2}$) | Pit density /$cm^{-2}$ | Maximum pit depth /μm | Average depth of 10 deepest pits /μm | Cracking (Yes/no) | Minimum depth of pit with crack initiation /μm |
|---|---|---|---|---|---|---|
| 171 | 90 | / | 193 | 183 | No | / |
| 668 | 90 | 290 | 275 | 260 | Yes | 76 |
| 2209 | 90 | 225 | 448 | 401 | Yes | 62 |
| | 70 | / | / | / | Yes | 125 |
| | 50 | / | 494 | 391 | No | / |
| 5107 | 90 | 53.3 | 861 | 747 | Yes | 63 |
| 7173 | 90 | 42.7 | 932 | 813 | Yes | 52 |
| 9187 | 90 | 56.4 | 1117 | 936 | Yes | 53 |

The pit density in these short term tests was much higher than that measured previously in the long term tests. Although the same solution chemistry maintenance and control procedure was used in all tests and there were no significant variations in the corrosion potentials measured, there were a number of differences in the test set-up.

The previous tests were conducted in three parallel cells. In the new design, the solution was made to flow from one cell to another in series so that a better flow rate control could be achieved. Nevertheless, the recirculation rate in the new tests was 20 mL/min, the same as that used previously. The key point is that the solution in the test cells was magnetically stirred at a speed of 200 rpm in both sets of tests. Hence, flow rate or solution replenishment was not a factor.

There is a concern that the different pit densities in the two sets of tests may be related to the MnS distribution in the steel. However, as the test samples were machined at the same time and were given the same heat treatment it is unlikely that all specimens in the short term tests have the same MnS distribution but different from the longer term tests. Nevertheless, the MnS distribution in specimens from the short and long term tests is being analysed.

Another difference is that the new test cells were made of 316L stainless steels, while the previous tests were conducted in glass vessels. Although effort was made in the previous work[2] to minimise the inhibiting effect on corrosion of dissolved silicate from the glass, and the silicon content was measured below 700 ± 200 ppb (silicate species at these levels was considered to have no significant effect on the corrosion rate of mild steel in distilled water[4]), there is a small possibility that silicate from the glass might have inhibited the corrosion process.

The surface finish of specimens used in the short term tests was different from the earlier work. In the previous tests, the cylindrical specimens were ground on a lathe, transversely, to a final finish of 2400 grit. The arithmetical mean deviation of the assessed profile, $R_a$, was 0.25 ± 0.01 μm for the 2400 grit dry - ground specimens. The corresponding maximum height of the profile[5], $R_z$, was 2.63 ± 0.28 μm. The new specimens were polished on an automatic machine with 1 μm diamond polishing cloth to achieve a better repeatability. The arithmetical mean deviation of the assessed profile, $R_a$, was 0.12 ± 0.02μm. The corresponding maximum height of the profile, $R_z$, was 0.66 ± 0.10 μm. The effect of surface finishing on the pit initiation in the dilute chloride solutions needs to be further studied.

It seems unlikely that a smoother surface finish should give rise to a higher pit density, although tests are being initiated for the same set-up to resolve this. Currently, our thinking is that silicate inhibition may have been the key factor, despite the care taken to prevent any such effect.

The distribution of pit depths for the current tests is shown in Figure 3. Here, the data are expressed as the normalised distribution (the percentage of pits in a given range of pit depth over the total number of pits) in order to make sensible comparison with the previous work, which had a lower pit density. The latter results are expressed in the same form in Figure 4. Despite the different pit densities the trend for the evolution of the pit depth distribution with exposure time is fairly consistent.

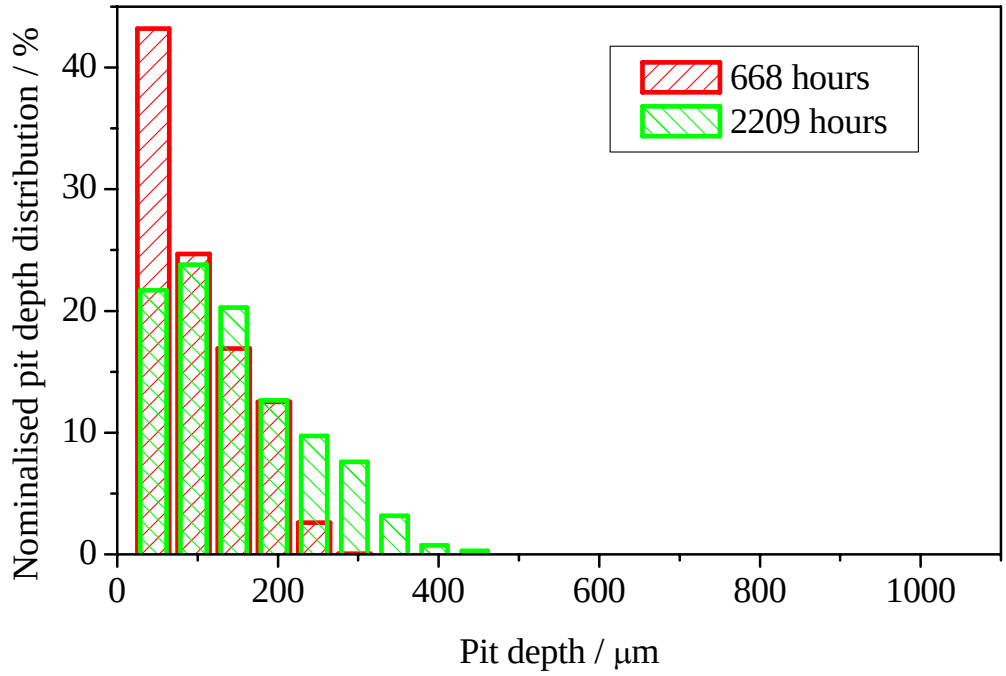


Figure 3. The normalised distribution of pit depths in the specimens tested for 668 hours and 2209 hours

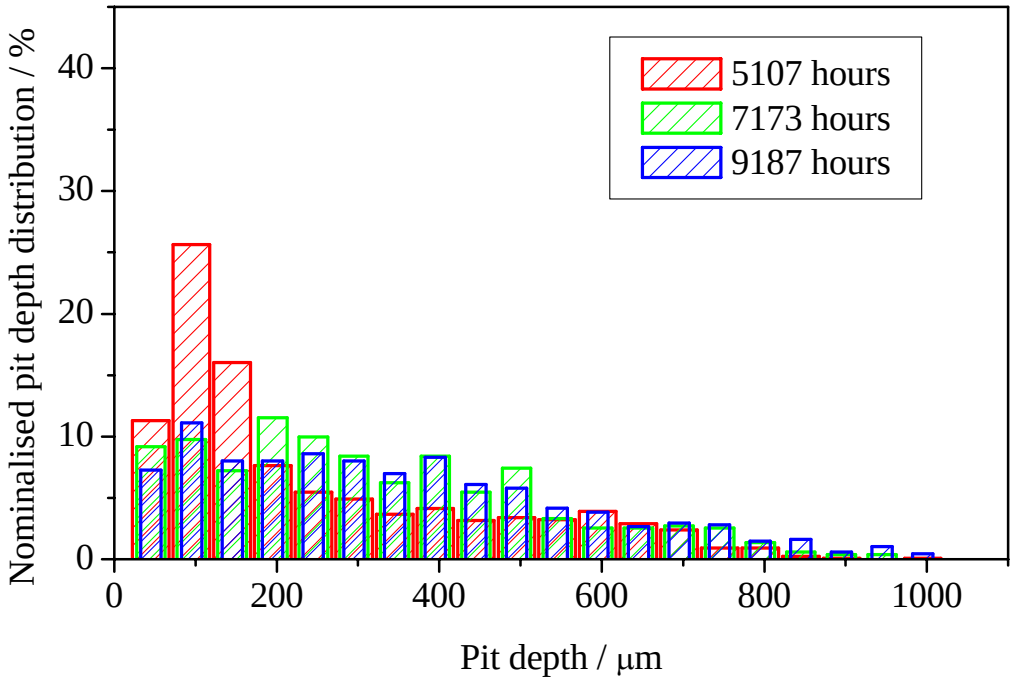


Figure 4. The normalised distribution of pit depth in the specimens tested for 5107 hours, 7173 hours and 9187 hours

**Pit growth rate**

An aim of these tests was to obtain a more accurate determination of the growth rate of pits. The average depth of the 10 deepest pits as a function of the test duration is shown in Figure 5. It can be seen that the time dependence of the pit depth is reasonably consistent in the short and long term tests and follows the same growth law. From linear regression analysis, the pit growth can be expressed by

$$a_{pit} = 1.9 \times 10^{-7} t^{0.49} \quad (1)$$

where $a_{pit}$ is the average depth of 10 deepest pits in meters, t is the time in seconds.

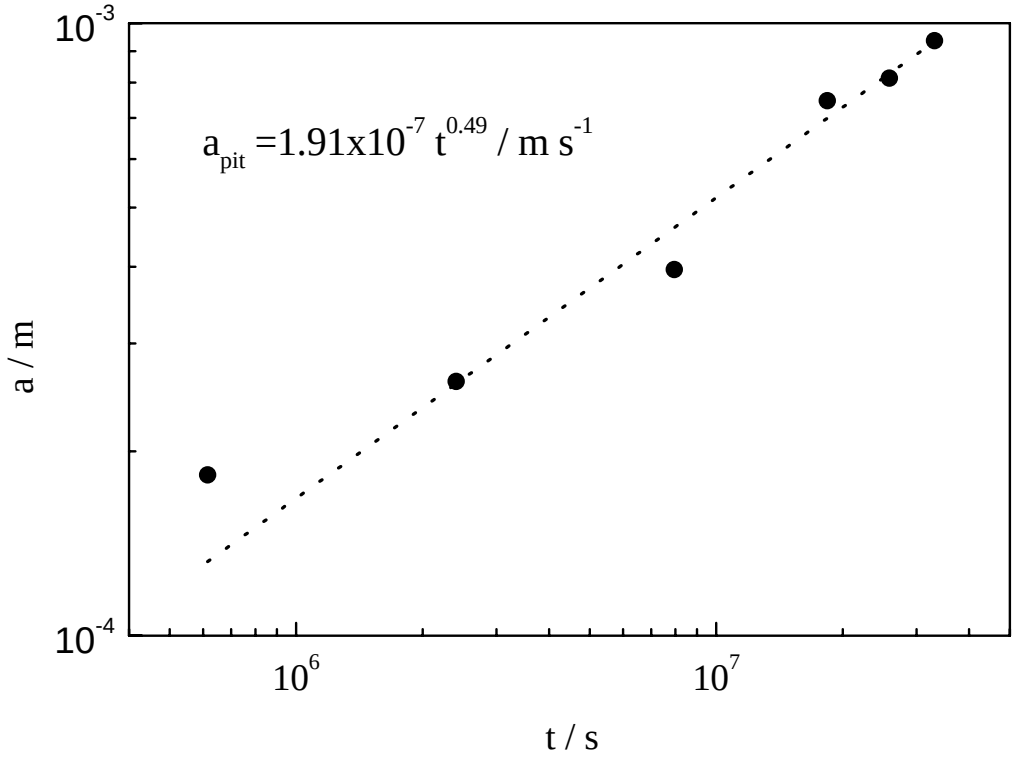


Figure 5 Time dependence of the average depth of 10 deepest pits in the disc steel tested in aerated 1.5 ppm chloride solution at 90 °C.

**Threshold stress for crack initiation**

The tests at different applied stress can be analysed to establish the dependence of the threshold pit depth for crack initiation on the applied stress, although the data were confined to an exposure period of 2209 h. It was established previously[2] that the threshold pit depth for crack initiation on specimens loaded to 90% of YS was approximately 50 μm. (it was 76 μm and 62 μm for specimens tested for 668 h and 2209 h respectively, see Table 2). For the specimen loaded to 70% $\sigma_{0.2}$ the minimum depth of pits from which crack developed was 125 μm. No cracking was found on the specimen loaded to 50% $\sigma_{0.2}$ and tested for 2209 h despite a maximum pit depth of 494 μm.

Adopting an approach for fatigue short cracks developed by El Haddad et al[6,7], the relationship between threshold stress intensity factor, $K_{ISCC}$, and the pit depth, a, can been described by:

$$K_{ISCC} = \alpha\sigma_{th}\sqrt{\pi(a + a_0)} \qquad (2)$$

where $\sigma$ is the stress and $a_0$ is a constant designed to account for short crack effects, albeit wholly empirical.

Equation (2) can be expressed as:

$$a = \frac{K_{ISCC}^{\ 2}}{\alpha^2 \pi \sigma_{th}^{\ 2}} - a_0 \qquad (3)$$

From equation (3), it can be seen that $K_{ISCC}$ and $a_0$ can be determined readily by applying linear regression analysis to a plot of a vs. $\sigma_{th}^{-2}$, as shown in Figure 6.

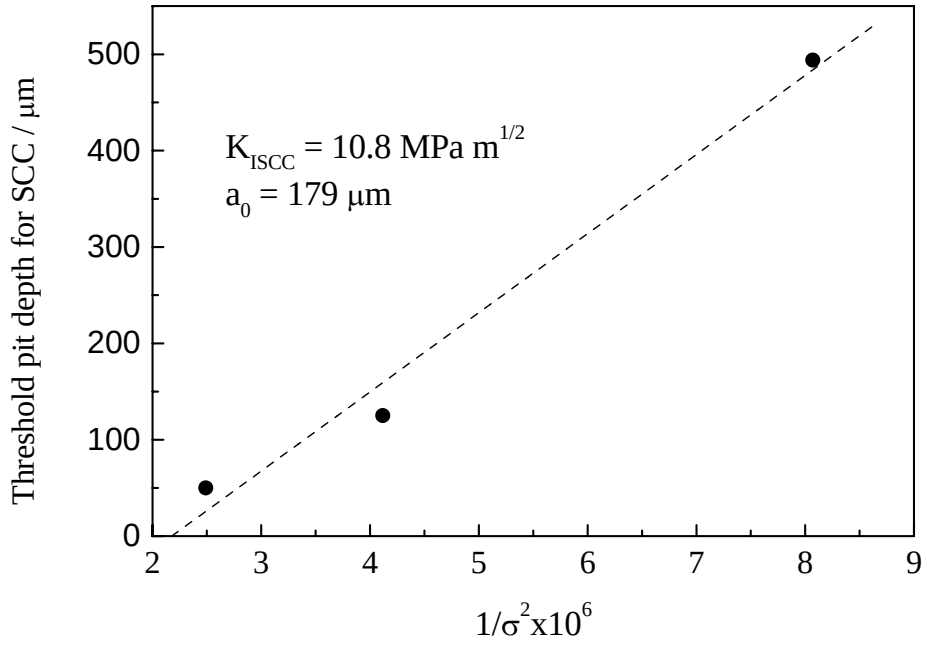


Figure 6 Dependence of threshold pit depth as a function of $1/\sigma^2$.

Assuming a value for $\alpha$ of 0.67 corresponding to a semi-circular defect, a value of 10.8 MPa m$^{1/2}$ for $K_{ISCC}$ and 179 μm for $a_0$ is estimated. This analysis is very crude but should represent a minimum for $K_{ISCC}$ in view of the uncertainty in the threshold pit depth at 50% $\sigma_{0.2}$. Nevertheless, the $K_{ISCC}$ value is of the same order, 8 MPa m$^{1/2}$ to 11 MPa m$^{1/2}$, as that determined by Lyle[8] for SCC of disc steel in contaminated water.

## CONCLUSIONS

- Combined with short and long term exposure tests, the pit growth rate in a disc steel in aerated 1.5 ppm $Cl^-$ at 90 °C has been established as follows:

$$a_{pit} = 10.9 \times 10^{-7} t^{0.49}$$

- The corresponding threshold pit depth for crack initiation was observed to be 52 μm at 90% $\sigma_{0.2}$, 125 μm at 70% $\sigma_{0.2}$ and greater than 494 μm at 50% $\sigma_{0.2}$.

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