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**Effect of Stress Transients
on the Crack Propagation
Rate in Steam Turbine Disc
Steel**

**Shengqi Zhou and Alan
Turnbull**

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Effect of Stress Transients on the Crack Propagation Rate in Steam Turbine Disc Steel

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ABSTRACT

An evaluation has been made of the effect of stress transients on the growth rate of long cracks in fracture mechanics specimens of a 3NiCrMoV steam turbine disc steel in deaerated 300 ppb Cl^- + 300 ppb SO_4^{2-} solution at 90 °C. Trapezoidal loading simulating two-shifting in service gave a high cyclic crack growth rate of about 10^{-6} m/cycle. With typically one cycle per day in service except weekends, and accounting for any stress corrosion cracking component at maximum load, a crack growth rate of 0.4 mm per year is estimated. Under constant load for the same environment no crack growth occurred at exposure times up to 9 months but an uncontrolled excursion in oxygen and chloride for just one hour was sufficient to induce crack growth with rates as high as 9.0×10^{-12} m/s.

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1 INTRODUCTION

For economic reasons, the UK power industry is now operating its 500 MW coal-fired plants on a two-shift cycle in which the turbines are on-load for 16 hours per day and off-load overnight and at weekends. The concern with ‘two-shifting’ is the impact on environment assisted cracking of the associated transients in stress, water chemistry and temperature¹. On-load, with well-controlled water chemistry, the condensate on the low-pressure turbines will be free of oxygen with chloride and sulphate levels both up to about 300 ppb. Off-load, the condensate would essentially be pure water but aerated unless there is nitrogen blanketing. The stress off-load would be zero.

Ideally, to fully simulate two-shifting in laboratory testing, the combined influence of transient stress and water chemistry would be evaluated but there are technical difficulties in synchronising the changes in the stress, temperature, and oxygen and anion (chloride and sulphate) concentrations. For the purpose of assessing the impact of transient stress on crack propagation, the environment was held constant. In previous work, using 3NiCrMoV disc steel, a very severe environment, aerated 1.5 ppm Cl solution at 90 °C², was adopted. In the present study, a more relevant environment for on-load simulation of deaerated 300 ppb Cl⁻ + 300 ppb SO₄²⁻ solution at 90 °C was used.

2 EXPERIMENTAL

Materials

The material used in this work was disc steel 3% NiCrMoV, cut from an ex-service steam turbine disc supplied by PowerGen. The chemical composition is presented in Table 1.

Table 1: Chemical composition of the disc steel (mass %)

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

Specimens

Compact tension (CT) specimens were made in accordance with ISO 7539-6⁵. The thickness (B) and width (W) were 15.0 mm and 30 mm respectively. The notch depth, as measured from the loading line, was 7.5 mm.

Stress Relief

To avoid uncontrolled influence of residual stress resulting from machining or from grinding, all specimens were stress relieved in vacuum for 2 hours at 625 °C before pre-cracking. The mechanical properties at ambient temperature and at the test temperature (90 °C) are listed in Table 2.

Table 2: Mechanical properties of the disc steel (mass %)

Condition	T (°C)	E (GPa)	$\sigma_{0.2}$ (MPa)	UTS (MPa)	Elongation (%)
As received	23	208 $\pm$ 2	747 $\pm$ 9	882 $\pm$ 5	23 $\pm$ 1
Stress relieved	23	206 $\pm$ 1	734 $\pm$ 4	870 $\pm$ 2	20 $\pm$ 0
Stress relieved	90	210 $\pm$ 4	705 $\pm$ 4	827 $\pm$ 13	20 $\pm$ 0

Pre-cracking

The specimens were fatigue pre-cracked to a depth of 6 mm from the root of the notch such that the total crack length, a , from the loading line (including the notch) was 13.5 mm. The crack length in this case refers to measurement at the surface. The pre-cracking was conducted according to ISO 7539-6⁶ with a final $K_{\max}$ of 17 MPa m^{1/2}. The fatigue frequency was 110 Hz and the stress ratio was 0.1.

Environmental Conditions

The solution was prepared from analytical grade chemicals and high purity water with initial conductivity 0.06 $\mu\text{S cm}^{-1}$ and was circulated to the test cell from a 22-litre reservoir. Three cells were arranged in series in the loop.

The solution conductivity and oxygen concentration were monitored using on-line probes. The solution in the reservoir was refreshed weekly or when the conductivity reached a specified value (5.0 $\mu\text{S/cm}$ compared to the initial value of 2.2 $\mu\text{S/cm}$). A very low oxygen level (typically below 1 ppb and always less than 10 ppb) was achieved by using stainless steel pipe, stainless steel cells, and a stainless steel dosing pump and by continually passing nitrogen into the reservoir. Fresh solution was always pre-deaerated so that the low oxygen level was maintained during solution changes. The volume flow rate through the system was 3 mL s⁻¹ (about 11 litre/hour), corresponding to a linear flow rate of 0.3 mm s⁻¹ past the specimens.

The solution was pre-heated before entering the first test cell. The temperature was maintained by heaters around each cell and controlled by thermocouples placed in each cell. Separate thermocouples were used to record the temperature near to each specimen. The test temperature was maintained at 90 $\pm$ 1 °C. In service, a temperature decrease to 70 °C overnight is expected under two-shifting conditions but for pragmatic reasons, the conservative approach of maintaining the temperature at the value on-load corresponding to the onset of condensation on the turbine disc was adopted.

Corrosion Potential Measurement

The corrosion potential in each cell was measured with respect to an external 0.01 N Ag/AgCl reference electrode specially designed with an extremely low chloride diffusion rate. 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 the measurements were being taken. The solution conductivity was monitored to ensure that there was no significant chloride contamination due to the diffusion of chloride from the reference electrode chamber to the test cell. The reference electrode remained at ambient temperature. All potentials quoted are relative to the saturated calomel electrode (SCE).

Loading waveform

In two-shifting practice, the start-up speed and the on-load period vary from station to station and depend on the type of start-up. For systems that are shut down overnight, the turbines are on-load for 16 hours per day and off-load overnight. The load will increase rapidly, reaching the operating conditions in 20 minutes to 2 hours.

However, for the laboratory study of the effect of transient loading, it is desirable to sensibly accelerate the process to maximise the number of stress cycles per day. In this case, a 20 min period was fixed for both the load rise and fall time. At zero load, not much is expected to happen so a short hold period of 20 min was adopted. The key issue is the time at maximum load. This should be long enough to exhaust the effect of any induced transient in crack-tip conditions associated with the stress transient. Holding beyond that time would seem inefficient. Previous studies⁴ suggested that the crack tip potential of the disc steel in deaerated water at 90 °C reached a reasonably stable value within 100 min after increasing the load from zero to the maximum value. Furthermore, published work of Endo et al⁶ also indicated limited influence of hold time at times greater than 1-2 hours. Therefore, testing was made initially with a 100 min hold time, with a maximum K value of $40 \text{ MPa m}^{1/2}$, giving 9 load cycles per day. Subsequently, the effect of increasing the hold time to 300 min was assessed.

In parallel with the transient load tests, two tests at constant stress intensity factors of $30 \text{ MPa m}^{1/2}$ and $40 \text{ MPa m}^{1/2}$ were undertaken.

After the specimens and test cells were fitted on the loading machine, the circulation line and the test cell were deaerated with nitrogen before the test solution was introduced.

Development of pulsed DCPD system

Stress corrosion crack growth for this system is very slow and it is appropriate to describe in detail the crack measurement system. A multi-channel pulsed direct current potential drop (DCPD) system with high resolution and stability was developed. The system is capable of monitoring eight specimens simultaneously.

To eliminate the instrument offset and the thermo-potential difference between the metal-to-metal connections the DC potential drop was measured using a reversible DC current. A positive DC current was applied and the potential across the notch mouth measured. The current, of the same magnitude, was then reversed in sign and the potential drop measured again. The average of the absolute values was then determined. The current and potential measurement leads were insulated using PEEK tubing and spot welded to the specimens. The spot welded area was protected with an adhesive stable in water at temperatures up to 170 °C.

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. For the specimens under constant load, 1000 current cycles were applied once per day over a time period of 3 hours. For the specimens under transient loading, 400 cycles were performed for each measurement, taking 75 min, as the DCPD was only measured on-load (to prevent any influence of crack closure). For both loading conditions the data were averaged to obtain one potential drop value per day.

3 RESULTS AND DISCUSSION

Corrosion Potential

The corrosion potential of the disc steel in deaerated 300 ppb Cl^- + 300 ppb SO_4^{2-} solution at 90 °C reached a stable value of -0.64 V/SCE to -0.65 V/SCE several hours after the solution was introduced into the test cell. The corrosion potential did not change with time over a period of about a year, provided the oxygen concentration was controlled below 5 ppb (see later). Furthermore, there was no apparent effect of transient loading on the corrosion potential. The corrosion potential was not disturbed by the DCPD measurement.

Crack Growth Measurement

Constant Load

The time variation of the crack length for the specimens tested under constant load at stress intensity factors of 30 $\text{MPa m}^{1/2}$ and 40 $\text{MPa m}^{1/2}$ is shown in Figure 1. There was no apparent crack growth in the latter test after 6370 h (about 9 months). Within the measurement resolution of the DCPD system, this implies that the crack growth rate, if any, was less than 1.3×10^{-13} m/s. The view was taken that perhaps activation of the crack growth might be necessary and a single trapezoidal load with a hold time of 100 min was then applied. Although there was a step-wise increase in the potential drop (perhaps due to a residual ligament failure) there was no evidence of a progressive change; i.e. there was no crack growth over the next 2000 hours. However, at 8500 h an indication of progressive crack extension, about 10 μm over 1300 h, was observed (not so obvious perhaps on the scale of Figure 1). The estimated crack growth rate assuming the extension is uniform across the crack front (rather unlikely) is 2.2×10^{-12} m/s. Based on a linear fit, the uncertainty in growth rate is about 10%.

This growth rate is very low and prolonged testing over many more months is required to ensure it is sustained. Nevertheless, it does emphasise the need for patience in this type of testing. The crack extension does not seem correlated with the single load cycle, or, if so, there is a very delayed response. Possibly, slow progressive dissolution of the crack tip exposes enough MnS to enrich the tip zone and propagation ensues locally, or there is a delay in activating intergranular cracking (the expected mode for this steel) from a transgranular fatigue precrack.

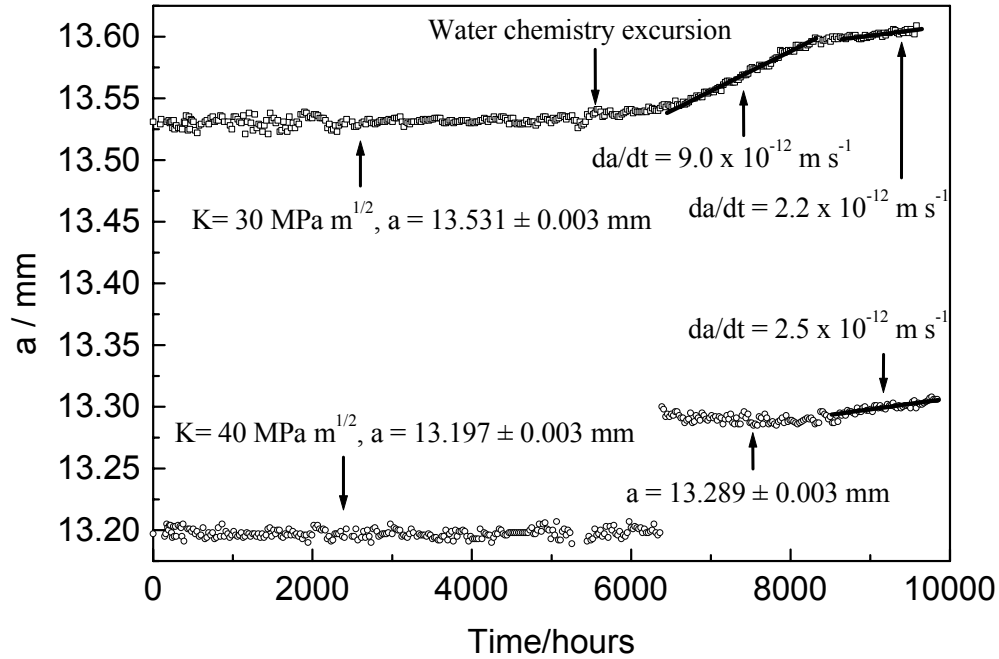


Figure 1: The time dependence of the crack length of the disc steel under constant loading corresponding to $30 \text{ MPa m}^{1/2}$ and $40 \text{ MPa m}^{1/2}$ in deaerated 300 ppb Cl^- + 300 ppb SO_4^{2-} solution at 90°C , derived from V_{crack} .

For the test with a stress intensity factor of $30 \text{ MPa m}^{1/2}$, the reference electrode used for corrosion potential measurement failed after 5465 hours. In replacing this, a short-term water chemistry excursion occurred. However, since a by-pass in the circuit was used this affected only the cell of interest. During the excursion, the oxygen concentration reached about 100 ppb and the chloride concentration reached about 10 ppm (estimated from the solution conductivity of $50 \mu\text{S/cm}$). Normal environmental conditions were restored in 1 hour. The potential was -0.52 V (SCE) on restoring the system and reached a stable value of -0.64 V (SCE) after 6 hours.

The crack growth rate shortly after the excursion was estimated to be $9.0 \times 10^{-12} \text{ m/s}$, very similar to that ($8.9 \times 10^{-12} \text{ m/s}$) in aerated 1.5 ppm Cl^- solution at 90°C , although the latter is a much more aggressive environment⁷. However, such a comparison may not be wholly appropriate, as the growth rate in aerated 1.5 ppm Cl^- solution was derived by dividing the crack extension measured on the fractured surface by the total exposure time, and hence the crack initiation time was neglected.

The unexpected feature was that the crack should continue growing despite the restoration of low oxygen conditions. However, after 3000 hours of this almost steady growth, the crack appeared to be slowing. The rate is very similar to that measured at 40 MPa $\text{m}^{1/2}$ but it is premature to place much emphasis on this. The idea of a trigger event to activate crack growth, in this case by a water chemistry excursion, such that the growth rate is then maintained has been a matter of open discussion at recent meetings. The rationale is that once sufficient crack tip dissolution occurs this generates crack tip straining which in turn stimulates further dissolution and so on in a coupled way. The puzzle is that after 100 days of nearly constant growth rate the crack should then slow down.

Published crack growth rates of disc steels in pure water and steam at about 90 °C under static loads⁸⁻¹⁰ are highly variable ranging between $3 \times 10^{-12} \text{ m s}^{-1}$ and $6 \times 10^{-11} \text{ m s}^{-1}$ with apparent inconsistencies, e.g. with respect to the effect of oxygen. Once crack growth initiated in the present study, the growth rates fell approximately within the reported range. Tests in steam at 120 °C¹¹ suggest no crack growth in the absence of oxygen and no crack growth in oxygen-containing solution at very low chloride. There is no doubt that aeration, even transiently, has a significant role as evidenced by the impact of the uncontrolled excursion in this study, though the chloride concentration was relatively high also.

Transient Loading

Two separate specimens were tested under transient loading (maximum load corresponding to 40 MPa $\text{m}^{1/2}$ in each case) and for one of those the effect of hold time was assessed.

The results for the first test, which had to be terminated early due to a electric insulation failure, are shown in Figure 2 and indicate very steady crack growth with $da/dN = 1.1 \times 10^{-6} \text{ m/cycle}$, albeit over a short crack extension (the uncertainty in growth rate is less than 2% for all tests under transient loading, estimated from the linear fits).

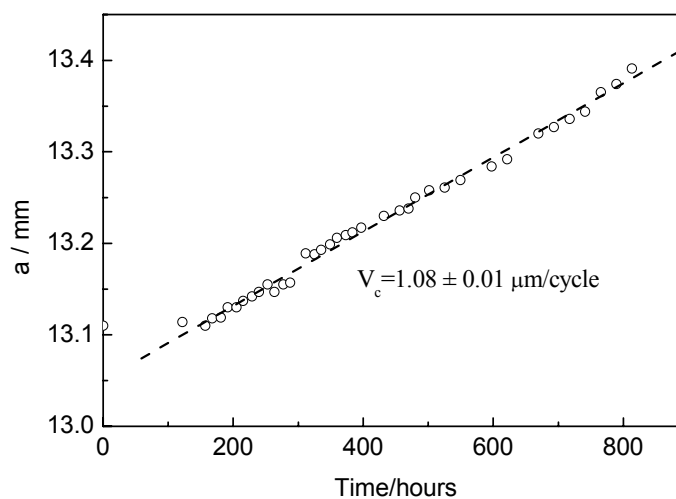


Figure 2: Crack growth rate under trapezoidal loading for turbine disc steel in deaerated 300 ppb Cl^- + 300 ppb SO_4^{2-} solution at 90 °C.

The test was repeated and the results are shown in Figure 3.

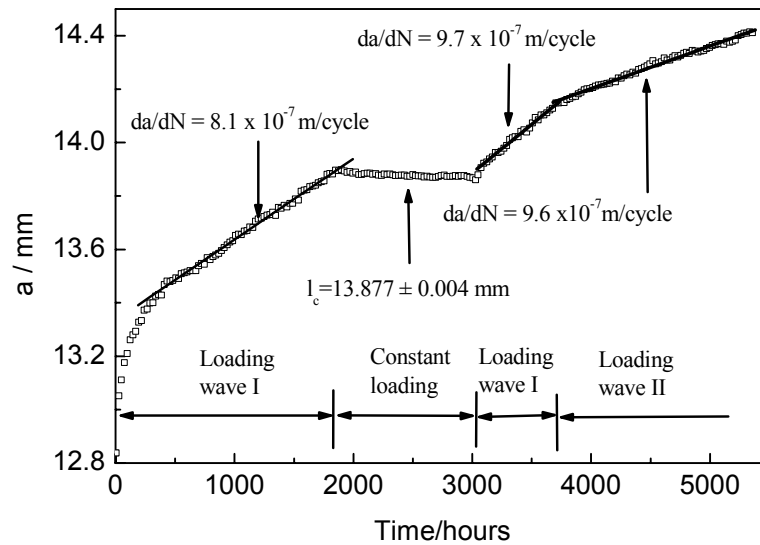


Figure 3: Crack growth rates for repeat tests under trapezoidal loading for turbine disc steel in deaerated 300 ppb Cl^- + 300 ppb SO_4^{2-} solution at 90 °C. Loading Wave I has hold time of 100 min and Loading Wave II has hold time of 300 min.

There was a difference initially, compared to the first test, with a transient growth rate period before attainment of the steady crack growth. The latter was marginally lower than in the first test. There was no obvious reason for the initial transient growth rate with indicators such as the corrosion potential and water chemistry suggesting constant behaviour.

After a period of steady crack growth, the load was held at the maximum value for about 1000 h. There was an initial slight decay of the potential drop, perhaps related in some way to corrosion product bridging. Certainly, there was no crack growth over the 1000 h hold period, consistent with the observation from applying a single transient in the constant load test described above. On recommencement of transient loading, crack growth resumed with a value similar to that before holding and similar to the first test. At 3700 h, the hold time was increased to 300 min with other loading variables unchanged. The time dependent growth rate decreased but there was no difference in the cyclic growth rate. The similarity in cyclic growth rate suggests that crack growth occurs predominantly during rising load with no discernible evidence of enhanced extension of crack growth rate during the hold period. However, this needs to be confirmed by testing with a very short or no hold period.

4 IMPLICATIONS

The ratio of chloride to sulphate concentration will vary from plant to plant. Hence, the choice in this study is necessarily a little arbitrary. Further work is required at different ratios. Published work¹¹ in steam indicates that addition of sulphate anions to chloride solutions results in only a small increase in crack growth rate. This deduction based on the authors' data at 120 °C conflicts somewhat with their conclusion.

In relation to two-shifting in practice, with just one cycle per day and off-load for the weekend, it is necessary to compute the growth induced by the cyclic loading. Within the constraints of this study, which does not account for water chemistry and oxygen transients, the crack extension would be about 10^{-6} m/day or 0.26 mm/year. The unknown feature is the impact of the oxygen and water chemistry transients on the growth rate at maximum load. There is some indication from the uncontrolled excursion in this study that crack growth under constant load could be induced with a growth rate of about 9×10^{-12} m/s. Assuming this prevails at maximum load the combined effect of the cyclic and static load components would represent about 0.39 mm/year. This is not trivial and the higher growth rate should be accounted for in determining inspection intervals. It is possible that the growth rate may be higher under cyclic loading if there is an effect of transient exposure to oxygen. However, previous measurements of the effect of transient loading in *aerated* 1.5 ppm chloride indicated a growth rate of 6.7×10^{-7} m/cycle⁷. No in-situ crack measurement was made for this test, the growth rate being calculated by dividing the crack extension by the exposure time. Nevertheless, the evidence of the present study suggests that any incubation period will be short. Thus, under transient loading conditions, the growth rate in aerated solution is not greater than in deaerated solution and may even be less. In this test with aerated 1.5 ppm chloride, the hold time was longer, 4 h and 20 min, and corrosion blunting may have been a factor

5 CONCLUSIONS

Trapezoidal loading of fracture mechanics specimens of turbine disc steel in deaerated 300 ppb Cl^- and 300 ppb SO_4^{2-} , simulating two-shifting in service, gave a high cyclic crack growth rate of about 10^{-6} m/cycle. With typically one cycle per day in service except weekends, and accounting for any stress corrosion cracking component at maximum load, a crack growth rate of about 0.4 mm per year is estimated.

Crack inspection intervals should be adjusted accordingly under two-shifting operation. With proposals for four-shifting under consideration, life expectancy will be very significantly reduced.

Unusual behaviour was experienced in tests of the disc steel under constant load in deaerated 300 ppb Cl^- + 300 ppb SO_4^{2-} . No crack growth was observed for well-controlled conditions extending to 9 months. However, in one test an uncontrolled excursion in oxygen and chloride solution lasting just 1 hour, by which time the environmental conditions had been restored to normal, induced a crack growth rate of 9.0×10^{-12} m/s, which was sustained for a further 4 months before decreasing to 2.3×10^{-12} m/s. In another test, after 9 months at constant load with no crack extension, a single trapezoidal load was applied. No crack extension was detected in the next 2.8 months after the transient load application but the crack then grew at a rate of 2.2×10^{-12} m/s.

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