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Electrochemical short crack effect in environmentally assisted cracking of a steam turbine blade steel

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ABSTRACT

Measurement has been made of the corrosion fatigue short crack growth rate in a 12Cr steam turbine blade steel subjected to low frequency trapezoidal loading in aerated and deaerated 300 ppb[1] Cl^- and 300 ppb SO_4^{2-}, simulating early condensate chemistry. No difference in growth rate compared to that for long cracks was observed in deaerated solution but significantly enhanced growth rate was obtained in aerated solution for a short crack of length less than 250 μm. Complementary stress corrosion cracking tests were conducted but to ensure crack development at modest applied stresses the environment adopted was aerated 35 ppm Cl^-, representing a severe system upset. In this case, the growth rate of the short crack was up to 20 times higher than that for a long crack (>6 mm), even though the crack length had reached 1.6 mm. An explanation for both sets of data based on the difference in potential drop between a short and long crack is expounded.

1. Introduction

A predictive approach to lifetime management based on quantifying the evolution of cracks from the earliest stage, including crack precursor development, is a major undertaking that requires development in mechanistic understanding of the controlling processes, high resolution crack growth monitoring, and modelling. The growth of cracks in the short crack regime is often perceived to occupy the largest section of life of a component but correspondingly can be the most challenging to quantify. There are no standards that guide the measurement process; simply recognition that the growth rate may be different from that for long cracks, and that the rate will be sensitive to local electrochemistry, near-surface microstructure and mechanical properties, as well as loading conditions. Furthermore, guideline documents on fracture assessment do not deal adequately with environmental effects and short crack growth. In contrast, for long cracks, standards for measuring environment assisted crack growth rates are well established [1,2], there is a wealth of data for key industrial sectors and there is a degree of confidence in their engineering application, the latter coupled with advanced monitoring and non-destructive inspection techniques.

There has been a number of investigation of fatigue short crack growth rates in air [3,4] and to a lesser extent in aqueous environments [5–15]. Differences in short and long crack growth kinetics can arise due to crack tip shielding because of fracture surface roughness, plasticity effects and deposits. In principle, the environment could have an effect on closure via the nature and extent of deposition but the more interesting issue is the extent to which the environment directly enhances the short crack growth rate in the manner articulated by Gangloff [5] in his concept of a chemical short crack effect (an electrochemical short crack effect is arguably a more generic term).

In contrast to corrosion fatigue, stress corrosion crack growth measurements in the short crack regime are not so common. An enhanced short crack growth rate was reported by Jones and Simonen [16] for Ni in 1 N H_2SO_4 but for most industrial applications there is a paucity of relevant data.

Measurement of short crack growth behaviour has been conducted primarily with fracture mechanics specimens. However, in an engineering component, cracks will emerge inherently as surface cracks (from physical defects, corrosion pits or localised deformation). Their development will depend on local microstructure, local mechanical properties, and the resolved applied and residual stress, with the significance of these varied factors dependent on the surface machining history [17]. The goal is to characterise the evolution of surface cracks in response to these near-surface variables, and to quantify the growth rate. As a precursor, corrosion fatigue and stress corrosion cracking tests have been undertaken using fracture mechanics specimens to enable comparison with long crack growth rates for nominally the same conditions; i.e. without the potentially confusing influence of near-surface mechanical and material properties. In the case of the stress

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[1] All concentrations are specified in terms of ppb or ppm where these represent respectively parts per billion or parts per million by mass.

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Table 1
Composition of FV566 blade steel (in mass%).

C	Si	Mn	P	S	Cr	Mo	Ni	V	Fe
0.11	0.23	0.71	<0.009	<0.003	11.69	1.73	2.71	0.30	bal

Table 2
Mechanical properties of FV566 steel.

T/°C	$\sigma_{0.2}$/MPa	UTS/MPa	Elongation/%
23	894	975	29
90	841	937	27

corrosion cracking studies, the results have been presented in a parallel publication [18] but have been reproduced here to provide context and support for the proposed mechanistic basis of the short crack effect.

A material of practical relevance is 12Cr steam turbine blade steel, for which much progress has been made in quantifying long crack growth rates [19–25] but there are no data for short cracks.

2. Experimental

2.1. Material and mechanical properties

The material tested was a FV566 steam turbine blade steel with composition as described in Table 1. The steel had been annealed at 1050 °C for 1 h 45 min then air-cooled, tempered at 650 °C for 4 h and air-cooled. The inclusion density was determined to be 290 cm^{-2} with average inclusion size of 3.4 µm and the microstructure was martensitic with a mean grain size of 27 ± 2 µm. The mechanical properties were measured at ambient and test temperature and are listed in Table 2.

2.2. Specimen geometry

Short crack growth rate measurements were made for a through-thickness crack in a single edge notched tensile (SENT) specimen (Fig. 1), manufactured in accordance with ISO 7539-6 [1].

The specimen gauge length was 25 mm and the other dimensions are listed in Table 3 where W is the specimen width, B the thickness, M the length of the notch, l the precrack length from the root of the notch, and the full crack length from the loading line (including the notch) to the crack tip. The notch was in the form of a mechanical slot of 2 mm depth and 0.3 mm width introduced by electric discharge machining.

Compact tension (CT) specimens were used for measurement of the growth rate of long cracks and were manufactured in accordance with ISO 7539-6 [1]. Two different sizes of specimen were used reflecting material availability issues but this would have no impact on the results. In this case a longer notch was generated with a V-shaped root.

Prior to testing all specimens were stress-relieved at 600 °C under vacuum for 2 h and vacuum cooled.

2.3. Pre-cracking

Fatigue pre-cracking of the SENT specimens, to a final length of 4 mm, was undertaken in air in accordance with ISO 7539-6 at a loading frequency of 110 Hz and with a maximum net section stress in producing the precrack no greater than 145 MPa, well below the departure stress in the stress–strain curve of the blade steel. The applied stress range was reduced in a stepwise fashion with a final ΔK (range of stress intensity factor) of about 9 MPa m$^{1/2}$ (K_{max} = 10 MPa m$^{1/2}$). The size of the monotonic plain strain plastic zone was estimated [26] to be less than 10 µm. After pre-cracking, the mechanical slot and the majority of the precrack were then ground out to leave a short crack of the required initial length and a final width of the specimen of about 4 mm. The specimen was then ultrasonically cleaned in high purity water, rinsed with ethanol and dried in acetone. The average surface roughness, Ra, was 0.2 µm as measured by contact stylus.

In an initial test, the crack length was based on surface measurement but crack curvature local to the surface caused a significant underestimate of the average crack length. Specifically, for an average initial precrack length of 536 µm (measured from the fracture surface) the surface crack length was 400 µm. This did not affect evaluation of the subsequent crack growth rate, determined using direct current potential drop (DCPD), but the crack curvature

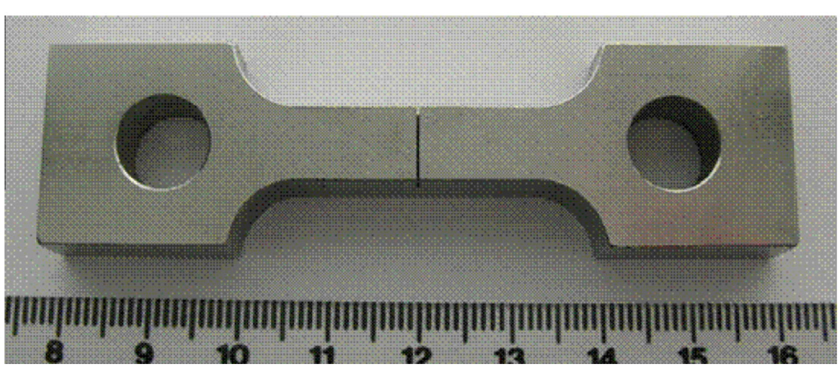

Fig. 1. SENT specimen with notch prior to pre-cracking.

Table 3
SENT and CT specimen geometries (units are mm).

Specimen type	W	B	M	l	a
SENT 1 (before grinding to remove notch and most of precrack)	10	8	2	4	6
SENT 2 (after grinding)	4	8	0	0.1 to 0.5	0.1 to 0.5
CT1	40	20	14	6.0	20
CT2	30	15	7.5	6.0	13.5