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Environmentally assisted small crack growth

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Abstract

Corrosion fatigue small crack growth rates have been determined for a 12Cr steam turbine steel in a simulated condensate solution under conditions representing repetitive turbine start-up and shut-down. Cracks were grown from a single corrosion pit generated electrochemically using the droplet technique and the crack length monitored optically and by direct current potential drop (DCPD). A comparison is made with growth rates for short and long cracks determined using fracture mechanics specimens. The enhanced crack growth rate observed for a short crack (relative to that for a long crack) but not realised for the small crack is rationalized on the basis of an electrochemical crack size effect.

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Keywords: corrosion pits, small cracks, corrosion fatigue

1. Introduction

Life prediction and intelligent plant maintenance scheduling in applications where the environment impacts on structural integrity are commonly based on long crack growth data. For long cracks, standards are in place for measuring crack growth rates and there is a degree of confidence in their laboratory and engineering application, the latter coupled with advanced non-destructive evaluation techniques. However, in the case of small cracks, there are no standards that guide the measurement process; simply recognition that the growth behaviour can be different, that the rate will be sensitive to near-surface material properties, and that the time spent in the small crack regime may have an impact on life assessment codes and inspection intervals.

In a previous publication, Turnbull et al. (2013), an evaluation was made of the viability of different techniques for measuring small crack size, and thence growth rate, for stress corrosion and corrosion fatigue cracks emanating from a corrosion pit in a 12Cr steam turbine blade steel. Several techniques were investigated including an advanced optical method for surface crack length measurement, surface crack opening displacement determination using digital image correlation, Duff and Marrow (2012), and pulsed DCPD. Of these approaches, direct optical measurement in combination with DCPD was considered the most pragmatically useful, with the inherent constraint on optical measurement associated with corrosion product build up.

Here we describe an extension of the preliminary investigation to generation of more extensive data for corrosion fatigue small crack growth rates.

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2. Experimental method

The material tested was a FV566 stainless steel (SS), often used for steam turbine blades, with composition in mass %: C 0.11; Si: 0.23; Mn: 0.71; Cr: 11.69; Mo: 1.73; Ni: 2.71; V: 0.30; P:<0.009; S:<0.003, bal: Fe. The steel had been annealed at 1050 °C for 105 min then air-cooled, tempered at 650 °C for 240 min 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 prior-austenite grain size of 27±2 µm. The 0.2% proof strength at the test temperature (90 °C) was 841 MPa and the UTS 937 MPa.

Flat dog-bone tensile specimens were manufactured from the FV566 blade steel with a gauge length of 20 mm and thickness and width both 4 mm. The surface was wet ground with P4000 silica grit paper giving an average surface roughness, R_a, of 0.1 µm. After machining and grinding, the specimens were stress relieved at 585 °C for 2 hours under vacuum.

The droplet technique, Turnbull et al. (2012), was used to develop a single corrosion pit of the desired depth (usually 50 µm for tests in air and 50 µm or 150 µm for tests in solution) in a specific location so that DCPD probes and the optical microscope could be positioned optimally (see Figure 1). The use of pit precursors to make the testing simpler is not unreasonable from an engineering perspective. Pitting requires a combination of aeration (an off-load condition) and a concentration of chloride ions in excess of the threshold for pitting, typically about 500 ppm for this steel. The latter can arise if there is transient loss of control of water chemistry or an anion concentrating mechanism, through evaporation for example. On-load, the condensate solution will be oxygen free, certainly within about 40 hours or so after start-up.

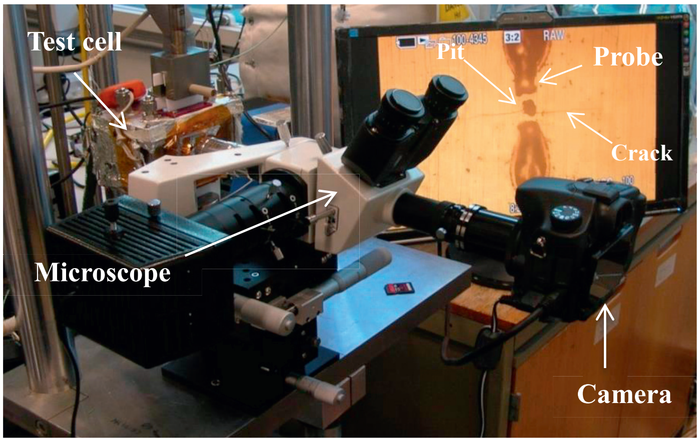

Fig. 1: Set-up for automated optical imaging of crack growing from pit. The monitor shows the DCPD probes located above and below the pit.

In previous corrosion fatigue testing of this steel for short (through-thickness crack in fracture mechanics specimen) and long crack growth measurement, Turnbull and Zhou (2012), a trapezoidal waveform was adopted with rise and fall times each of 20 min and a 100 min hold, simulating two-shifting in a steam turbine plant, albeit accelerated with respected to the hold time. However, since there was no effect on growth rate of the 100 min hold time, Turnbull and Zhou (2011), all current tests were conducted with no hold time, enabling 36 cycles per day (4×10^{-4} Hz) compared to 9 cycles per day previously. The stress ratio was 0.05 and the maximum stress about 90% of $\sigma_{0.2}$. Despite the high stress, finite element analysis showed that plastic deformation around the pit did not extend beyond a few microns and indeed plastic deformation was not discernible by electron back-scattered diffraction. The environment was aerated 300 ppb Cl^- + 300 ppb SO_4^{2-} solution at 90 °C, typical of a steam turbine condensate under normal operating conditions but with aeration ($[O_2]$ about 1.8 ppm at 90 °C) to reflect the transient retention of oxygen during start-up. The environment was circulated through a corrosion cell with a quartz glass window from a reservoir that was refreshed regularly to ensure constancy of water chemistry. The corrosion potential in each cell was measured with respect to a saturated calomel reference electrode (SCE). This electrode was held in a small reservoir containing the test solution at ambient temperature and connected to the test cell via a tube also containing the test solution. A valve isolated the reservoir except when measurement was undertaken, which was conducted on a daily basis, extending to weekly for longer term tests.

In initial testing the specimen was cyclically loaded at 4×10^{-4} Hz and observation of the surface made to detect crack development from the corrosion pit. This proved particularly ineffective as no significant crack extension was detected after considerable test duration due to the low loading frequency and perhaps a threshold number of cycles for the pit-to-crack transition. Accordingly, a loading frequency of 1 Hz was adopted to generate a precrack, with surface length typically above 100 µm before decreasing the frequency to the test value. Tests in laboratory air at 90 °C were conducted at 1 Hz with R=0.1 and a maximum stress less than 75% of $\sigma_{0.2}$. In this case, because of the higher frequency, precracking was not an issue.