Growth Rate of Short Cracks in a Steam Turbine Blade Steel

Parsons 2011

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• Introduction

• Experiment
  - Material and specimens
  - Environment control
  - Crack growth rate measurement

• Results and Discussion
  - Corrosion potential measurement
  - Growth rate of short fatigue cracks
  - Growth rate of short stress corrosion cracks

• Conclusions
Material - Blade steel FV566

1050 °C for 1 h 45 min, AC, 650 °C for 4h AC and stress relief 600 °C for 2h; martensitic, grain size: 27 ± 2 μm

Chemical compositions of the blade steel (mass %)

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ni</th>
<th>V</th>
<th>N</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>0.23</td>
<td>0.71</td>
<td>&lt;0.009</td>
<td>&lt;0.003</td>
<td>11.69</td>
<td>1.73</td>
<td>2.71</td>
<td>0.30</td>
<td>0.026</td>
<td>bal</td>
</tr>
</tbody>
</table>

Mechanical properties of the disc steel and blade steel

<table>
<thead>
<tr>
<th>Condition</th>
<th>T (°C)</th>
<th>( \sigma_{0.2} ) (MPa)</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress relieved</td>
<td>90</td>
<td>841</td>
<td>937</td>
<td>27</td>
</tr>
</tbody>
</table>
FM specimen – long crack

- W=40 mm, B=20mm
- Fatigue pre-cracked
- a = 6 mm, l = 20 mm

- Precrack was produced under load decreasing condition and the final $K_{\text{max}}$ was less than 75% of the initial value for FC and SCC test.
SENT specimen – short crack

- SENT specimen:
  - gauge length: 25 mm.
  - width (w) in the gauge length: 8 mm.
  - initial thickness (B): 10 mm.
  - mechanical slot: 2 mm x 0.3 mm
Pre-cracking

- SENT specimen:
  - Fatigue precrack of 4 mm
  - Remove the mechanical slot and ground out the precrack leave a short crack of the required length for SCC and CF testing. The final specimen thickness was about 4 mm.
Precracking

- The maximum stress in this work was no greater than 145 MPa

- The reversed plastic zone produced by precracking is about 2.5 µm

- The specimens after producing precrack was stress relieved

- For testing in air, the initial defect was produced using a sharp blade with diamond paste.
Loading waveform

Fatigue in air: sine wave, 1 Hz, R = 0.1

Fatigue in aerated and deaerated 300 ppb Cl\textsuperscript{-} + 300 ppb SO\textsubscript{4}\textsuperscript{2-} solution – simulating two shifting in service

<table>
<thead>
<tr>
<th>Loading Waveform</th>
<th>Load rising (min)</th>
<th>Load hold (min)</th>
<th>Load falling (min)</th>
<th>Load off (min)</th>
<th>Cycle /day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>100</td>
<td>20</td>
<td>20</td>
<td>9</td>
</tr>
<tr>
<td>Environments</td>
<td>Cond’ty* (μS/cm)</td>
<td>O₂**</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------------------</td>
<td>------------------</td>
<td>------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deaerated 300 ppb Cl⁻ + 300 ppb SO₄²⁻</td>
<td>1.7 – 5.0</td>
<td>&lt;1 ppb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerated 300 ppb Cl⁻ + 300 ppb SO₄²⁻</td>
<td>2.3 – 5.0</td>
<td>1.7 – 1.8 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerated 35 ppm Cl⁻</td>
<td>120 – 130</td>
<td>1.7 – 1.8 ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Measured at ambient temperature.
* *High temperature value but measured at ambient temperature.
Water Circulation Line

- **O₂ meter**
- **Conductivity**
- **Drain**
- **Gas in**
- **Gas out**
- **Water refreshing**
- **Thermocouple**
- **Reservoir**
- **Hot plate and stirrer**

Components:
- Pump
- Chiller
- Thermocouple
- Specimen
- Cell
- Pre-heater
- Load
- Hot plate and stirrer
- DCPD
- RE
Advanced crack growth rate measurement

- Pulsed DCPD

- Multi-channel (eight)
- No detectable drift over 9 months test
- Attainable uncertainty in crack size of $\pm 0.02 \ \mu m$
- Actual uncertainty depends on test conditions
Corrosion potential of FV566

In deaerated 300 ppb Cl\(^-\) + 300 ppb SO\(_4^{2-}\) (CF):

\(~ -0.6 \text{ V (SCE)}\)

In aerated 300 ppb Cl\(^-\) + 300 ppb SO\(_4^{2-}\) (CF)

\(-0.1 \text{ V (SCE) to } -0.2 \text{ V (SCE)}\)

In aerated 35 ppm Cl\(^-\) (SCC):

\(-0.1 \text{ V (SCE) to } -0.2 \text{ V (SCE)}\)
Fatigue in air

\[ a_i = 422 \, \mu m, \sigma_i = 49\% \sigma_{0.2}, \Delta K_i = 18.1 \, MPa \, m^{1/2} \]

\[ a_i = 128 \, \mu m, \sigma_i = 40\% \sigma_{0.2}, \Delta K_i = 7.6 \, MPa \, m^{1/2} \]
Fatigue growth rate in air – long and short cracks

The growth rate of short crack is slightly higher than that of long crack, probably due to crack closure effect.
Fatigue in deaerated solution

300 ppb Cl\(^{-}\) + 300 ppb SO\(_4^{2-}\), O\(_2\) < 5 ppb

- \(a_i = 416 \, \mu m, K_{max,i} = 25 \, MPa \, m^{1/2}\)
- \(a_i = 399 \, \mu m, K_{max,i} = 12 \, MPa \, m^{1/2}\)
- \(a_i = 107 \, \mu m, K_{max,i} = 8.6 \, MPa \, m^{1/2}\)
Fatigue growth rate in deaerated solution – long and short cracks

- Long crack, air: $a_i = 0.11$ mm and $a_f = 1.15$ mm
- Short crack, air: $a_i = 0.42$ mm and $a_f = 1.62$ mm
- Short crack, solution: $a_i = 0.40$ mm and $a_f = 0.70$ mm
Fatigue in aerated solution

300 ppb Cl$^-$ + 300 ppb SO$_4^{2-}$, O$_2$ $\sim$ 1.8 ppm

$a_i = 92 \, \mu$m, $K_{\text{max},i} = 12$ MPa m$^{1/2}$
Fatigue growth rate in aerated solution – long and short cracks

\[ \frac{da}{dN} / m/cycle \]

- Air, long crack, \( a_i = 6 \text{ mm} \)
- Air, short crack, \( a_i = 0.422 \text{ mm} \)
- Air, short crack, \( a_i = 0.128 \text{ mm} \)
- Solution, long crack, \( a_i = 6 \text{ mm} \)
- Solution, short crack, \( a_i = 0.092 \text{ mm} \) and \( a_f = 0.98 \text{ mm} \)

\[ \Delta K / \text{MPa m}^{1/2} \]
SCC in aerated 35 ppm Cl\(^-\) solution

- 35 ppm Cl\(^-\), ~ 1.8 ppm O\(_2\)
  - \(a_i = 237 \, \mu\text{m}, K_i = 17 \, \text{MPa m}^{1/2}\)
  - \(a_i = 278 \, \mu\text{m}, K_i = 15 \, \text{MPa m}^{1/2}\)
  - \(a_i = 536 \, \mu\text{m}, K_i = 15 \, \text{MPa m}^{1/2}\)
  - \(a_i = 130 \, \mu\text{m}, K_i = 15 \, \text{MPa m}^{1/2}\)
  - \(a_i = 157 \, \mu\text{m}, K_i = 12 \, \text{MPa m}^{1/2}\)
Stress corrosion crack growth rate in aerated 35 ppm Cl\(^{-}\) solution – long and short cracks

Long crack, \(a_i = 20.0\) mm (\(l_i = 6.0\) mm) and \(a_f = 20.3\) mm (\(l_f = 6.3\) mm)

- \(a_i = 0.24\) mm and \(a_f = 1.57\) mm
- \(a_i = 0.28\) mm and \(a_f = 1.03\) mm
- \(a_i = 0.16\) mm and \(a_f = 0.25\) mm

\(\frac{da}{dN} / \text{m/cycle} \quad \Delta K / \text{MPa m}^{1/2}\)
Fractograph of FV566 in deaerated 300 ppb Cl\(^-\) and 300 ppb SO\(_4\)^{2-}\) at 90 °C under cyclic stress

Long crack

Short crack
Fractograph of FV566 in aerated 300 ppb Cl\textsuperscript{-} and 300 ppb SO\textsubscript{4}\textsuperscript{2-} at 90 °C under cyclic stress

Long crack
Fractograph of FV566 in aerated 35 ppm Cl\textsuperscript{-} solution at 90 °C under static stress

Long crack

Short crack
Conclusions

• In air, the cyclic growth rate of short fatigue cracks is about 1.4 times higher than that of long cracks in FM specimens, probably due the crack closure effect.

• There is no significant short crack effect in deaerated and aerated 300 ppb Cl\(^-\) and 300 ppb SO\(_4\)^{2-}\), as there is no electrochemical driving force under the deaerated and the conditions and conductivity is very low so the potential drop effect in limited.

• However, in a more conducting aerated 35 ppm Cl\(^-\) solution, the short crack growth rate is about 15 to 20 times higher than that of the long crack, demonstrating the short crack effect cannot be ignored even when the length of the crack is 1.5 mm.
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