The Effect of Cathodic Protection on NNSCC Crack Growth in a Simulated Buried Pipeline Disbondment:
Paper No. 16

Ali Smith (presenter), Giuliano Malatesta, Serena Colella - Rina Consulting - Centro Sviluppo Materiali (Italy),
Hanns-Georg Schoeneich - Open Grid Europe (Germany),
Paul Roovers - Fluxys (Belgium).
Near neutral stress corrosion cracking in buried gas/oil pipelines:

- Dilute carbonate-bicarbonate ground water environment pH ≈ 5.5 – 8.5 i.e. near neutral
- NNSCC crack colony in CP shielded zone
- Electrically isolating coating

Pipeline operators encountering NNSCC need to understand the role of CP on NNSCC crack growth... will increasing CP be worse???
Some Aims.....

- Simulate the field situation with a suitable small scale laboratory crack growth method.

- Determine the NNSCC crack growth rate for different applied potentials.

- Evaluate the role of CP and possible long range H diffusion on the (shielded) crack velocity.

Motivation for EPRG project
204 To understand the effect of different CP levels on NNSCC crack propagation
Pipe material (1)

- API X60 grade pipe from early 1970s with 13.4 mm WT and OD of 914.4 mm.

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Nb</th>
<th>V</th>
<th>Ti</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.19</td>
<td>1.40</td>
<td>0.38</td>
<td>0.029</td>
<td>0.071</td>
<td>&lt;0.01</td>
<td>0.014</td>
<td>0.013</td>
</tr>
</tbody>
</table>

Pipe material (2)

- Longitudinal mechanical properties: AYS = 444 MPa, UTS = 642 MPa.

<table>
<thead>
<tr>
<th>Position</th>
<th>HV10 avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD</td>
<td>204</td>
</tr>
<tr>
<td>MID</td>
<td>199</td>
</tr>
<tr>
<td>ID</td>
<td>202</td>
</tr>
</tbody>
</table>
Experimental setup (Specimen design)

- The experimental approach was inspired by earlier Canadian published works (Uni Alberta-TransCanada-Spectra Energy).

- Flat tensile specimens machined to simulate a pre-existing shallow NNSSC surface crack:

  Epoxy coated so that only one face with notch exposed – to simulate pipe OD.

  \[ a = 2.5 \text{ mm} \quad 2c = 5 \text{ mm} \]
Experimental setup (Environment and Disbondment)

- Test cell manufactured to simulate a disbondment of 5 mm

<table>
<thead>
<tr>
<th>Solution</th>
<th>KCl (g/l)</th>
<th>NaHCO₃ (g/l)</th>
<th>CaCl₂.H₂O (g/l)</th>
<th>MgSO₄.7H₂O (g/l)</th>
<th>CaCO₃ (g/l)</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>0.0035</td>
<td>0.0195</td>
<td>0.0255</td>
<td>0.0274</td>
<td>0.0606</td>
<td>0.0075</td>
</tr>
</tbody>
</table>

Test solution fed into cell – synthetic soil solution known as “C2”

Test gas bubbled through solution during test: 5% CO₂/N₂
Experimental setup (Mechanical loading)

- A slow strain rate machine was adapted to perform cyclic loading on the precracked samples.

Fatigue loading performed to simulate pipeline pressure fluctuations

Max load was 72% of SMYS = 0.72 X 415 MPa

R value set to 0.2 after trials showed no crack growth at R = 0.6 or 0.9

Frequency was set to $6.4 \times 10^{-4}$ Hz (about $1.5 \times 10^{-6}$ /s)

Around two cycles per hour were achieved with these parameters
Experimental setup (Putting it all together....)

- Test duration max 35 days (max 1900 cycles)
- CP potential applied at “open mouth” – at top of Perspex sleeve.
- Disbondment size 5 mm = distance between sleeve and bare steel surface
- Potential at notch (crack site) located 7 cm from open mouth = open circuit value.
- pH in bulk solution and within sleeve also monitored.
Experimental setup (Finishing touches)

- To recreate field situation a flow loop was necessary to feed solution from bulk to sleeve during the tests (3.5 ml/min):

With such a setup it was possible to maintain the NN pH in the disbondment and the potential gradient stable for applied CP down to at least $-1.5 \text{V}$.
Experimental test plan

• Tests were performed for different potentials at open mouth i.e. $-1.2V_{SCE}$, $-1.5V_{SCE}$ and under open circuit i.e. OCP ($-0.75V_{SCE}$).

• Comparison tests also done in air.

• For each test condition tested 2-3 samples.

• Samples analysed via stereo microscope and SEM.

• Crack growth rates determined i.e. mm of growth in test/ number of cycles = mm/cycle.
Results: Some examples of sample appearance (1)

- Notch at 7cm from open mouth, shielded from CP
- Open mouth, CP of -1.2V versus SCE applied
Results: Some examples of sample appearance (2)
Results: Crack growth rates

<table>
<thead>
<tr>
<th>Potential $V_{SC}$</th>
<th>$(\frac{da}{dN} 90^\circ \text{ environment}) / (\frac{da}{dN} \text{ air})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.75</td>
<td>1.2</td>
</tr>
<tr>
<td>-1.20</td>
<td>19.7</td>
</tr>
<tr>
<td>-1.50</td>
<td>21.3</td>
</tr>
</tbody>
</table>
Results: Example fracture surfaces

More negative potential

-0.75\text{V}_{\text{SCE}}

4.39 \times 10^{-5} \text{ mm/cycle}

-1.2\text{V}_{\text{SCE}}

6.45 \times 10^{-4} \text{ mm/cycle}

-1.5\text{V}_{\text{SCE}}

9.14 \times 10^{-4} \text{ mm/cycle}

Increasing crack growth rate

More brittle-like fracture appearance
Discussion: Comparison with published works (1)

• Compare to IPC data [IPC2010 Paper 31436] for X65 + similar microstructure and similar flaw size in same environment.

\[ CLF = \frac{K_{\text{max}} \Delta K^2}{f^{0.1}} \]

Data for OCP condition shows very low crack growth rate—similar to air.
Discussion: Comparison with published works (2)

- Compare OCP data to literature data on compact tension specimens in same solution.

Literature data on partially coated CT shows link between $da/dN$ and distance to hydrogen generation sites.

Our data behaves like a partially coated CT.

Our specimen has smaller exposed area and crack sides not exposed.

Thus, versus an uncoated CT have little hydrogen generation and accumulation at crack tip.

Discussion: H diffusion to crack from open mouth?

- Our results showed that as potential became more negative at OM, $da/dN$ increased.
- Assuming that long range H is responsible, then diffusion distance must be overcome.

Calcs suggest up to 40% of hydrogen at open mouth position could diffuse 7 cm through steel bulk to crack site within 30 days.

Thus, a significant amount of H can reach the crack during the tests and contribute to the growth rate.
Discussion: Modelling crack growth (1)

• Crack growth model incorporating Hydrogen:

For our data $p = 1$

\[
\frac{da}{dN} = B(K_{\text{max}}\Delta K^2 f^{-0.1})^p
\]

For $pH = 6.3 = C2$ solution

\[
C_0 = 10^{-6} \frac{(5 + 10V) \times 10^{-10} \exp\left(-\frac{V}{0.03}\right)}{5 + 10V - 10^{-10} \exp\left(-\frac{V}{0.03}\right)}
\]


• Assuming that diffusion is not rate limiting we can postulate that $B$ simply depends the absorbed atomic hydrogen concentration ($C_0$) from corrosion (OCP case -0.75V) or from CP (e.g. -1.5V).

B. Lu, F. Song, M. Gao and M. Elboujdaini, NACE Corrosion (2012), paper No. 01152
Discussion: Modelling crack growth (2)

• From fitting of B values to our data and literature (imposing p = 1), can derive expression relating fitted B to hydrogen content:

\[
B = 1.03 \times 10^{-11} \ln(C_0) + 4.76 \times 10^{-11}
\]

Expression from the current work

<table>
<thead>
<tr>
<th>Solution</th>
<th>Potential versus SCE (V)</th>
<th>(C_0) (ppmw)</th>
<th>B from experiments (MPa(^{-2})m(^{-0.5})s(^{-0.1}))</th>
<th>B from equation (MPa(^{-2})m(^{-0.5})s(^{-0.1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2 (pH = 6.3)</td>
<td>-0.75 (Work of Chen et al on CT specimens )</td>
<td>0.39</td>
<td>3.86 (\times 10^{-11})</td>
<td>3.80 (\times 10^{-11})</td>
</tr>
<tr>
<td>C2 (pH = 6.3)</td>
<td>-1.2 (this work)</td>
<td>0.98</td>
<td>4.51 (\times 10^{-11})</td>
<td>4.74 (\times 10^{-11})</td>
</tr>
<tr>
<td>C2 (pH = 6.3)</td>
<td>-1.5 (this work)</td>
<td>1.36</td>
<td>5.25 (\times 10^{-11})</td>
<td>5.08 (\times 10^{-11})</td>
</tr>
</tbody>
</table>

Note that B derived from expts increases with C0- showing that B does depend on hydrogen

\[
\frac{da}{dN} = [1.03 \times 10^{-11} \ln(C_0) + 4.76 \times 10^{-11}] [K_{max} \Delta K^2 f^{-0.1}]
\]

Final model from the current work
Discussion: Modelling crack growth (3)

- Comparison of model with our data and IPC paper data (same specimen type):

Test solution is C2, pH = 6.3
Discussion: Modelling crack growth (4)

• Comparison of model with literature data (compact tension specimens):

Test solution is C2, pH = 6.3, OCP = -0.75 V_{SCE}
Discussion: Modelling crack growth (5)

- Model trends considering effect of combined loading factor and potential:

![Graph showing crack growth vs combined loading factor and potential](image)

- More negative potential gives more $C_0$ and faster crack growth
- Synergy with mechanical fatigue is evident - comparing $da/dN$ at low and high CLF.
Conclusions (1)

- Low crack growth rates (comparable to tests in air) were observed for samples tested under OCP (-0.75V_{SCE}).

- Applying CP potentials at the open mouth ( -1.2V and -1.5V_{SCE}) led to a remarkable increase in the (shielded) crack growth rate, i.e. 20 times higher than that seen in air.

- Comparison of crack growth rates with limited literature (-1.2V_{SCE}) for same specimen geometry gave good agreement, after accounting for mechanical loading factor effects.

- For the OCP case the crack growth rates were much lower than literature data from compact tension specimens.
Conclusions (2)

• This was explained to be due to differences in specimen geometry i.e. hydrogen accumulation at the crack tip was favoured for CT specimens.

• The experiments and modelling work showed that crack growth was driven by hydrogen at the crack tip in synergy with mechanical fatigue.

• The main source of hydrogen was provided by the CP at the open mouth. Diffusion calculations supported the idea of long range diffusion of hydrogen to the crack site.

• A simple model was developed from the current data with CP + literature for CT specimens under OCP:

\[
\frac{da}{dN} = [1.03 \times 10^{-11} \ln(C_0) + 4.76 \times 10^{-11}] [K_{max} \Delta K^2 f^{-0.1}]
\]
Thank you for your attention.