Fatigue and fracture of pipeline steels in high-pressure hydrogen gas (PVP2022-84757)

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• Motivation and Framework
• Materials variables
  - 3 heats of X80 with diverse microstructure
• Mechanics variables
  - Testing methods for accelerated fatigue testing
  - Effect of loading ratio (R)
  - Fracture
• Environmental variables
  - Effect of pressure
• Master Design Curve concept
Hydrogen is one method to decarbonize natural gas networks

**Transmission**
- Mostly steels
- Extensive existing network

**Distribution**
- Legacy metals
- Extensive polymer networks

HyBlend Pipeline Blending
CRADA addresses both API steels and polymer piping

This presentation focuses on steel line pipe
Hydrogen embrittlement occurs in materials under the influence of stress in hydrogen environments.

**Motivation**
With growing interest in decarbonization, hydrogen is being considered as a means to reduce carbon in energy infrastructure.

**Challenge**
Hydrogen degrades fatigue and fracture resistance of steels, and the effects on pressure vessel and line pipe steels are significant.

**Environment**
- Partial pressure
- Impurities
- Temperature

**Materials**
- Strength
- Microstructure and homogeneity

**Stress / Mechanics**
- Stress
- Defects
- Stress (pressure) cycling
- Residual stresses

Hydrogen embrittlement occurs in materials under the influence of stress in hydrogen environments.
X80 steels with a range of microstructure were tested

**Materials variables**

**Polygonal Ferrite (PF)**

**Acicular Ferrite (AF)**

Heat B
- PF – 10% AF
- Yield strength (YS) = 565 MPa

Heat E
- Fine AF
- YS = 593 MPa
- Mo additions ~0.15 wt%

Heat F
- AF – 30% PF
- YS = 552 MPa

Vintage of all 3 materials: 2000s
Testing framework: structural integrity assessment utilizing fracture mechanics-based analysis

ASME B31.12 describes rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Division 3, Article KD-10
K-control fatigue crack growth tests enable efficiency

**ASTM E647 fatigue crack growth methods using compact tension geometry**

- \(B \sim 12\text{mm} \sim (11\text{mm with side grooves})\)
- \(W \sim 26\text{ mm}\)
- C control, both K-increasing (C+) and K-decreasing (C-)
- Constant C test segments

\[
C = \left(\frac{1}{K}\right)\left(\frac{dK}{da}\right)
\]
K-increasing and K-decreasing segments show same fatigue behavior

- K-increasing and K-decreasing segments provide same da/dN-∆K response

  - As long as $K_{\text{max}}$ is restricted to moderate values
    - $K_{\text{max}} < 30 \text{ MPa m}^{1/2}$ for $R = 0.5$
    - $K_{\text{max}} < 35 \text{ MPa m}^{1/2}$ for $R = 0.7$

  - Perhaps a slight reduction in da/dN for K-decreasing from higher $K_{\text{max}}$

Outcome: For these conditions ~6X deduction in test time†

† ~3X greater C than constant load amplitude (1/3 ligament for same ∆K range), 2 values of R
Using these methods, several values of load ratio (R) can be evaluated in a single test specimen.

- In this test, three load ratios were evaluated:
  - including the influence of frequency for R = 0.7
- Unlike tests in air and general recommendations in the codes, R has an effect on \( \frac{da}{dN} \) in hydrogen.
- Higher frequency does not necessarily affect \( \frac{da}{dN} \) for low \( \Delta K \).

Outcomes:
- Influence of R should not be ignored
- Frequency can further improve testing efficiency in some cases
Fracture resistance measurements

**Mechanics variables**

- **ASTM E1820 elastic-plastic fracture measurements at the conclusion of fatigue testing**
  - Fracture resistance values are relatively consistent
  - Potential slight bias to PF microstructure

Fracture resistance values for X80 steels under different pressures:
- P = 34 bar
- P = 210 bar

<table>
<thead>
<tr>
<th>Heat</th>
<th>Fracture Resistance, $K_{JQH}$ (MPa m$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>PF-10AF</td>
</tr>
<tr>
<td>E</td>
<td>AF</td>
</tr>
<tr>
<td>F</td>
<td>AF-30PF</td>
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</tbody>
</table>

Error bars represent previously reported fracture resistance, measured at higher rate.

- B ~ 12 mm
- $B_N$ ~ 11 mm (w/side grooves)
- W ~ 26 mm
- 0.005 mm/min constant displ. DCPD
Hydrogen partial pressure has an effect on $da/dN$

- Hydrogen pressure can affect fatigue crack growth:
  - At low $\Delta K$, fatigue crack growth rate is dependent on hydrogen pressure
  - At high $\Delta K$, fatigue crack growth rate is independent of pressure

**Outcome:**
- $H_2$ partial pressure has a complicated (but predictable) influence on fatigue response
Master Design Curves bound the fatigue crack growth behavior of line pipe steel

- The effects of pressure and load ratio on fatigue crack growth are captured in conventional power law formulation:
  - At low $\Delta K$,
    \[
    \frac{da}{dN} = 7.6 \times 10^{-16} \left[\frac{1+0.4286R}{1-R}\right] \Delta K^{6.5} f^{1/2}
    \]
  - At high $\Delta K$
    \[
    \frac{da}{dN} = 1.5 \times 10^{-11} \left[\frac{1+2R}{1-R}\right] \Delta K^{3.66}
    \]

- These Master Design Curves appear to be effective for a wide range of construction steels

Outcome:
- Master Design Curves provide a simple framework to bound the fatigue crack growth of steels in gaseous $H_2$
Testing was performed for three values of $R$ and at 2 pressures for all three heats of X80

- Materials: 3 heats of X80
- Mechanics: $R = 0.1, 0.5$ and $0.7$
- Environment: 34 and 210 bar $H_2$

Outcomes:
- K-control enables testing efficiency
- All three heats of X80 perform similarly
- Influence of $R$ should not be ignored
- $H_2$ partial pressure has a complicated (but predictable) influence on fatigue response and modest effect on fracture
Thank You!

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