Hydrogen Embrittlement of Structural Steels

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Overview

Timeline
• Project start date Jan. 2007
• Project end date Sept. 2015
• Percent complete 40%

Budget
• Total project funding (to date)
  – DOE share: $700K
• FY09 Funding: $150K
• FY10 Funding: $150K

Barriers & Targets
• Pipeline Reliability/Integrity
• Safety, Codes and Standards, Permitting
• High Capital Cost and Hydrogen Embrittlement of Pipelines

Partners
• DOE Pipeline Working Group
  – Federal Labs: Sandia, Oak Ridge, Savannah River, NIST
  – Universities: Univ. of Illinois
  – Industry: Secat, industrial gas companies
  – Standards Development Organizations: ASME
Objectives/Relevance

• Why steel hydrogen pipelines?
  – Safety of steel pipelines well established (e.g., third-party damage tolerance)
  – Hydrogen pipelines safely operated under static pressure

• Demonstrate reliability/integrity of steel hydrogen pipelines for cyclic pressure
  – Address potential fatigue crack growth aided by hydrogen embrittlement

• Enable pipeline design that accommodates hydrogen embrittlement
  – Apply and optimize H₂ pipeline design code ASME B31.12
    • Emphasis in FY09-FY10 on measuring fracture thresholds and fatigue crack growth laws for X52 steel in H₂ gas
Approach

• Exploit unique capability for measuring fracture properties of steels in high-pressure $H_2$
  – Fracture properties serve as inputs into reliability/integrity assessment as specified in ASME B31.12 pipeline code
  – Milestone: Measure fatigue crack growth laws for X52 steel as function of loading frequency (75% complete)
  – Milestone: Measure fracture threshold for X52 steel as function of displacement rate (20% complete)

• Improve efficiency and reliability of test methods for steels in high-pressure $H_2$
  – Provide feedback to standards development organizations (e.g., ASME) through DOE Pipeline Working Group
Reliability/integrity assessment framework in ASME B31.12 requires fracture data in H₂

- Two fracture properties in H₂ needed
  - Fatigue crack growth law
  - Fracture threshold

- Reliability/assessment framework accommodates H₂ embrittlement
Fracture data in H₂ measured using specialized laboratory capability

Fracture threshold

Fatigue crack growth

d\alpha/dN = C[\Delta K]^m
Measured fracture properties of technologically relevant steel: API 5L X52

- Tested same X52 steel from DOE Pipeline Working Group tensile property round robin
  - Stakeholders (e.g., ASME) expressed interest in X52 steel

- Tensile properties
  - Yield strength: 62 ksi (428 MPa)
  - Ultimate tensile strength: 70 ksi (483 MPa)
Accomplishment: Measured baseline fatigue crack growth law for X52 steel in 21 MPa H₂.

- Results reveal transitions in da/dN vs ΔK trend that must be captured for measurements in H₂.
Accomplishment:

Measurement of fatigue crack growth laws must consider effects of frequency

- Tests at 1 Hz yield non-conservative data at high crack growth rates
- Frequency selected must balance test efficiency (i.e., duration) and data reliability
- Results can help optimize test methods referenced in H₂ pipeline standard ASME B31.12
Fatigue crack growth laws can be used to evaluate reliability/integrity of X52 H₂ pipelines.

- Life assessment framework in B31.12 allows limiting number of pressure cycles to be established.

\[ \Delta K = \Delta p [f(a, t, R_o, R_i)] \]
Collaborations

- DOE Pipeline Working Group (PWG)
  - Participants funded by DOE H₂ Program
    • Federal Labs: Sandia, Oak Ridge, Savannah River
    • Universities: Univ. of Illinois
    • Industry: Secat
  - Participants not funded by DOE H₂ Program
    • Federal Labs: NIST
    • Industry: energy and industrial gas companies
    • Standards Development Organizations: ASME
  - PWG meets up to 2 times/year for participants to report results and receive feedback
  - Activities coordinated among PWG participants
    • Example: Sandia and NIST coordinating testing of X52 steel in H₂
Future Work

Remainder of FY10

• Complete measurements of $da/dN$ vs frequency for X52 steel in $H_2$ at lower fatigue crack growth rates
• Measure fracture threshold ($K_{IH}$) for X52 steel in $H_2$ as a function of displacement rate
• Measure fatigue crack growth law for X52 steel seam weld in $H_2$

FY11

• Develop test methods for measuring the fracture properties of pipeline steel girth welds in $H_2$
• Measure the fatigue crack growth law for pipeline steel girth welds in $H_2$
Summary

• Measured fatigue crack growth laws allow evaluation of reliability/integrity of steel H₂ pipelines for cyclic pressure
  – Hydrogen embrittlement accommodated by measuring fracture properties in H₂ following ASME B31.12 pipeline design standard

• Measurements on X52 steel in H₂ show that fatigue crack growth rates depend on load-cycle frequency
  – Results can help optimize test methods in standards, i.e., enhancing test efficiency without compromising data reliability