Enabling Hydrogen Embrittlement Modeling of Structural Steels

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Overview

Timeline
- Project start date Jan. 2007
- Project end date Sept. 2015
- Percent complete 15%

Barriers & Targets
- Barriers addressed
  - High Capital Cost and Hydrogen Embrittlement of Pipelines
  - Storage Tank Materials and Costs

Budget
- Total project funding (through FY08)
  - DOE share: $384K
- FY07 Funding: $184K
- FY08 Funding: $200K

Partners
- DOE Pipeline Working Group
  - Sandia National Lab
  - Oak Ridge National Lab
  - Savannah River National Lab
  - CTC
  - NIST
  - Industrial gas companies
  - ASME
Objectives

- Enable application of structural integrity models to steel hydrogen pipelines
  - Models can demonstrate that hydrogen embrittlement can be accommodated and pipeline safety margins can be quantified

- Enable development of micromechanics models of hydrogen embrittlement in pipeline steels
  - Micromechanics models are essential for understanding the fundamentals of hydrogen transport and embrittlement in steels
• Measure cracking kinetics and thresholds of X100 steel under static loading in hydrogen gas pressures from 7 to 140 MPa (FY08 Q1; complete)

• Measure fatigue crack propagation rates of X100 steel in hydrogen gas over the pressure range 7 to 140 MPa (FY08 Q3; in progress)
Approach

• Measure properties of pipeline steels in high-pressure $\text{H}_2$ gas using fracture mechanics methods
  – Thresholds for sustained-load cracking
  – Fatigue crack growth rates under cyclic loading

• Assess suitability of steels by using measured properties as inputs into structural integrity models
  – Materials are qualified for service if pipeline meets performance criteria, e.g., number of allowable pressure cycles

• Identify and measure fundamental parameters in mechanistic models of hydrogen embrittlement
Materials testing motivated by design method

- Article KD-10 in ASME BPV Code Section VIII, Div. 3
  - Applies to $H_2$ pressure vessels and pipelines
  - Design method identifies two $H_2$-assisted failure modes: fatigue crack growth and sustained-load cracking
- Requires materials data in high-pressure hydrogen gas for fracture mechanics-based structural integrity models
Testing of X100 line pipe steel

- Yield strength
  - 96 ksi (662 MPa) in longitudinal (L) orientation
  - 114 ksi (787 MPa) in circumferential (C) orientation
Measurement of sustained-load cracking thresholds

- Specimen loaded to $K_o > K_{TH}$ using bolt while contained in glove box (Ar with ~1 ppm O$_2$)
- Loaded specimen exposed to H$_2$, crack extends after incubation time
- Crack arrests at $K=K_{TH}$
Results show hydrogen embrittlement in X100 steel

X100 (air)

X100 (100 MPa H₂ gas)
• Calculate critical crack depth, $a_c$, for X100 hydrogen pipeline operating at $p = 21$ MPa pressure
  – assume axial flaw with infinite length
  – hoop stress $\sigma_h = 260$ MPa (37% SMYS)
  – measured $K_{TH} = 85$ MPa-m$^{1/2}$ in 21 MPa H$_2$ gas
  – $a_c = 0.6$ cm ($a_c/t = 0.45$)

Model shows that pipeline can safely tolerate deep flaw
Incubation time for crack extension depends on $K_o$ and $H_2$ pressure

Procedures for measuring sustained-load cracking thresholds should not prescribe arbitrary test durations
Crack branching may account for absence of crack extension at low $K_0$.

Issues that compromise measurement of conservative properties must be identified.
Microscopy evidence provides insight into hydrogen embrittlement

X100 in 100 MPa H₂ gas: crack profile

X100 in 21 MPa H₂ gas: fracture surface

• Initial evidence suggests transgranular microcracks form in ferrite with limited plasticity
  – Results provide information for development of micromechanics models
System for measuring fatigue crack growth rates in H₂ gas

- Pressure vessel designed to contain H₂ gas up to 20 kpsi (138 MPa)
- Challenges in testing and system design
  - leak rates at dynamic seals
  - accurate load measurement
  - effect of high-pressure H₂ gas on instrumentation
- Fatigue crack growth data serve as inputs to structural integrity models
Future Work

Remainder of FY08

• Determine solution for leaks at sliding seals in system for measuring fatigue crack growth rates in hydrogen gas
• Measure fatigue crack growth rates of X100 in hydrogen gas

FY09

• Emphasize testing of low-strength steels such as X42 and X52
  - Includes base metal and welds
  - Measure fracture toughness, sustained-load cracking thresholds, and fatigue crack growth rates in hydrogen gas
Summary

• Completed measurements of cracking thresholds for X100 steel as a function of H$_2$ gas pressure
  – Structural integrity model shows that pipeline fabricated from X100 could tolerate deep flaws
  – Testing results demonstrate that procedures must be defined to ensure conservative properties are measured

• Microscopy evidence suggests that hydrogen embrittlement proceeds by transgranular fracture across the ferrite phase
  – Such evidence provides important information for the development of micromechanics models of hydrogen embrittlement