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%

Budget

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

Barriers & Targets

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

Partners

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

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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

Milestones

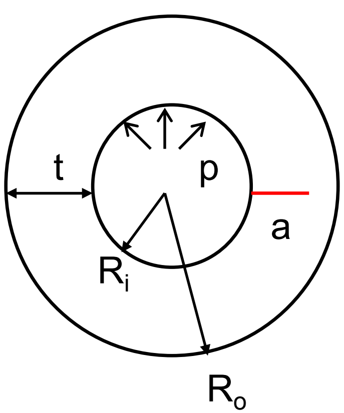
- Measure cracking kinetics and thresholds of X100 steel under static loading in hydrogen gas pressures from 7 to 140 MPa (FY08 Q1; complete)
- Measure fatigue crack propagation rates of X100 steel in hydrogen gas over the pressure range 7 to 140 MPa (FY08 Q3; in progress)

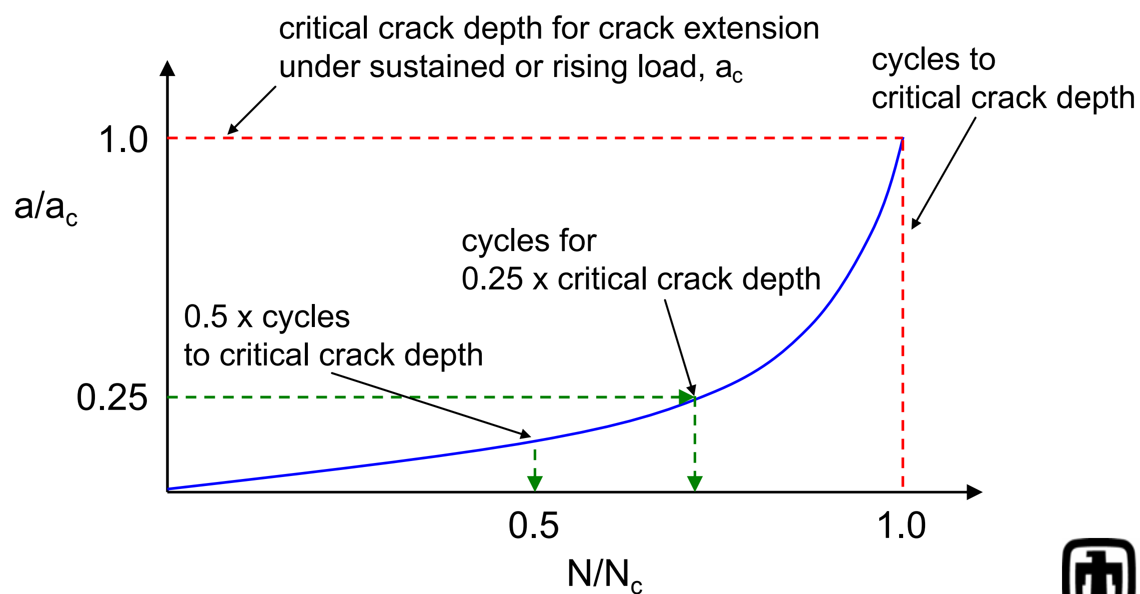
Approach

- Measure properties of pipeline steels in high-pressure 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 critieria, 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





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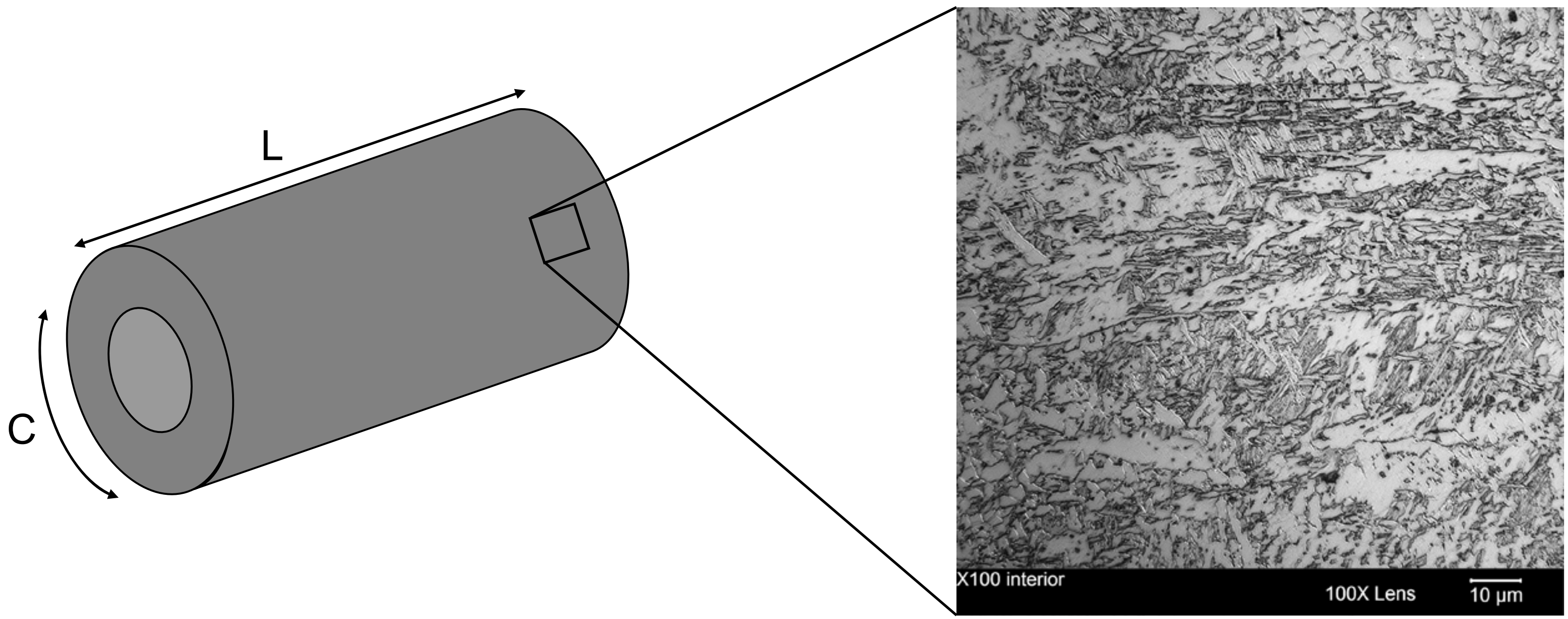
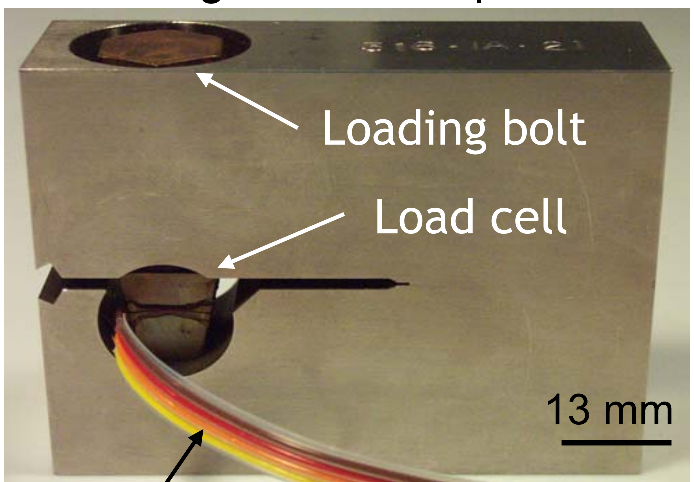
Testing of X100 line pipe steel

- Yield strength
  - 96 ksi (662 MPa) in longitudinal (L) orientation
  - 114 ksi (787 MPa) in circumferential (C) orientation

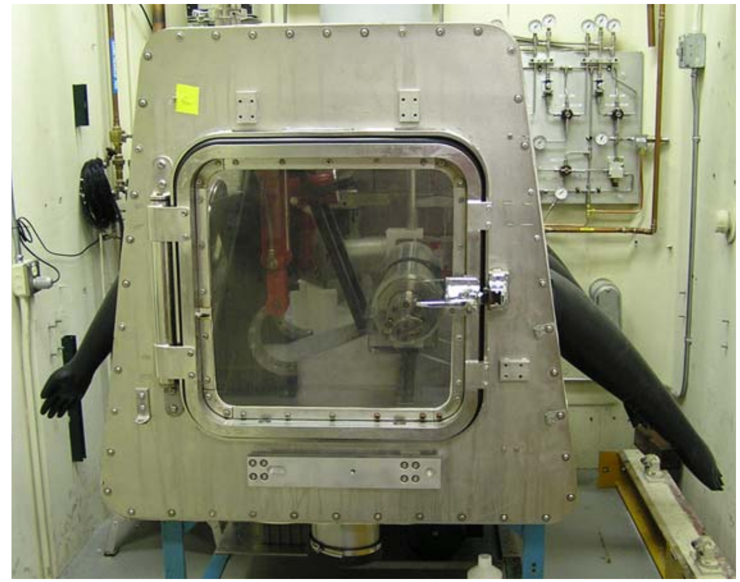


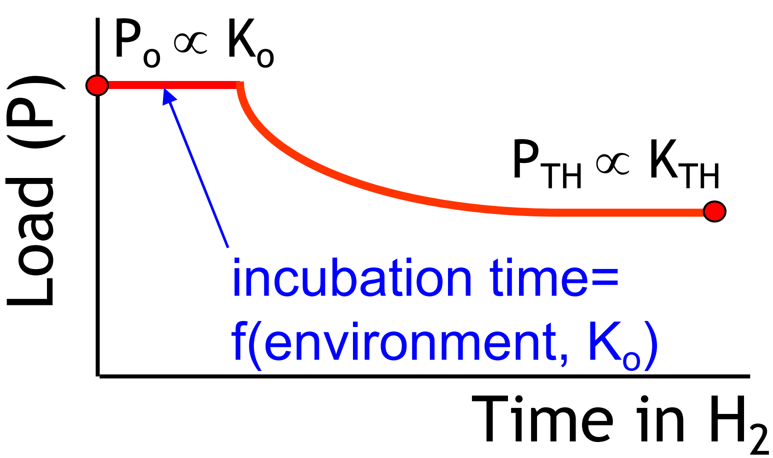
Measurement of sustained-load cracking thresholds

wedge opening load (WOL) cracking threshold specimen



strain gage leads (Excitation and DAQ)





- 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 $K = K_{TH}$

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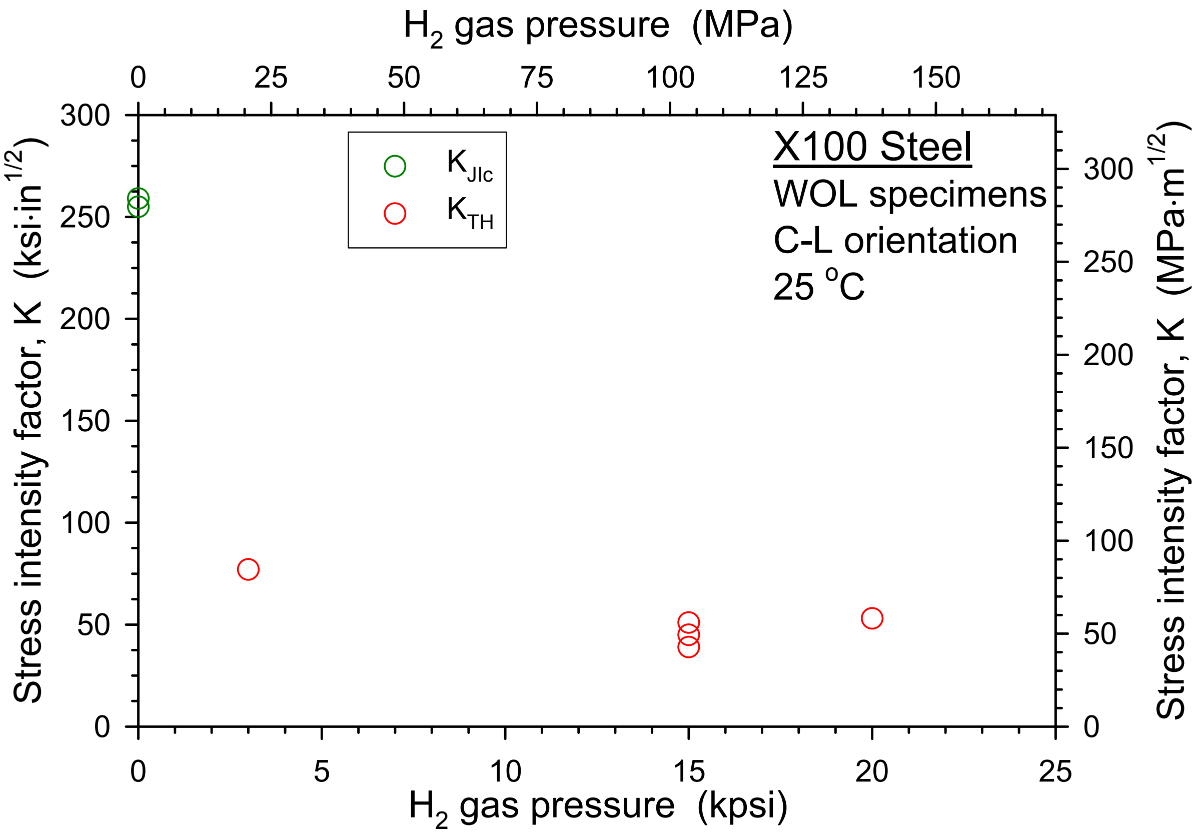
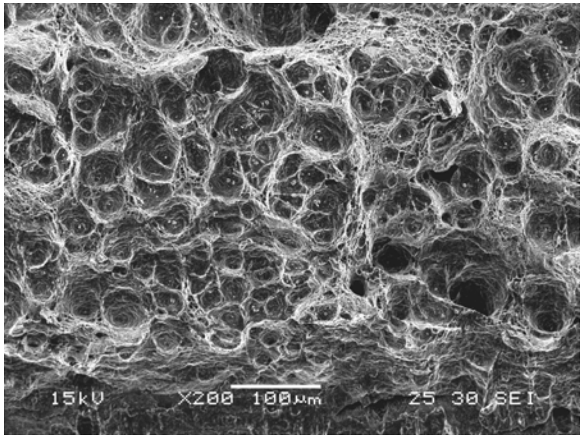
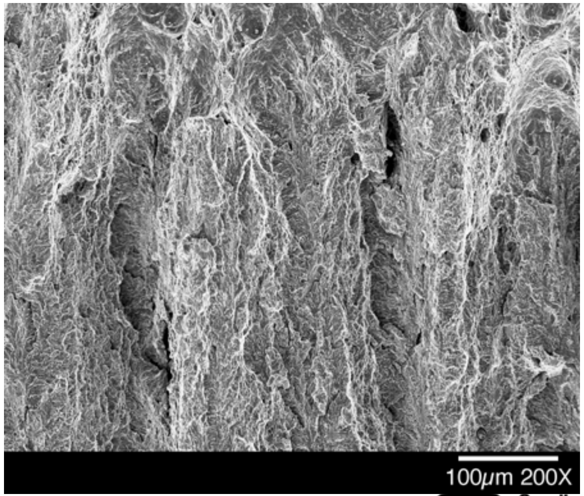
Results show hydrogen embrittlement in X100 steel



X100 (air)



X100 (100 MPa H_2 gas)



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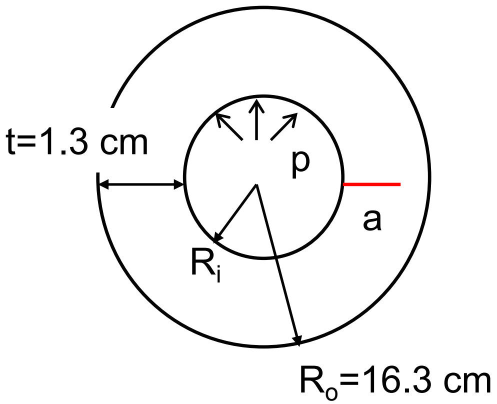
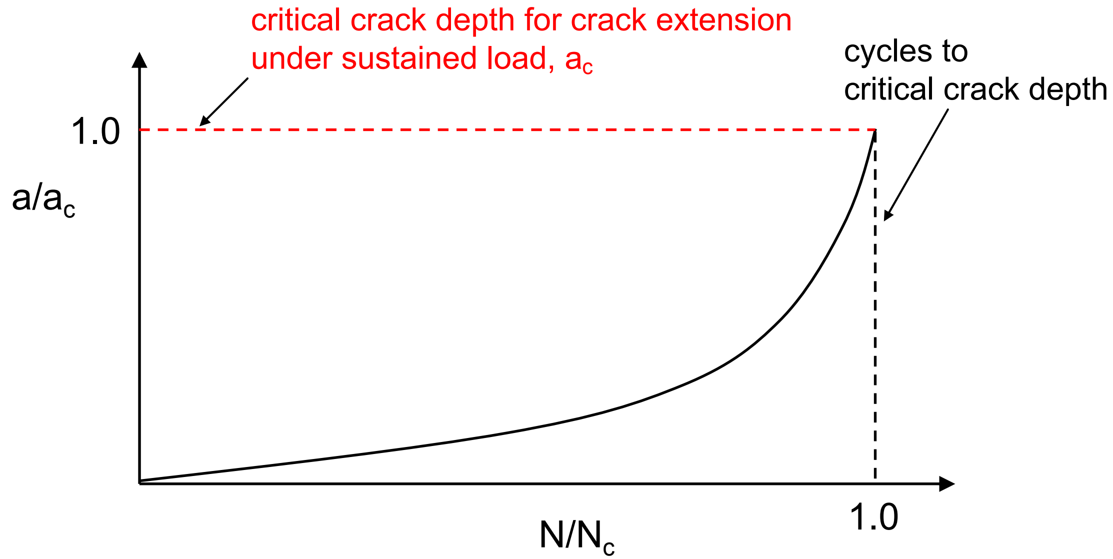
Measured properties assessed from structural integrity model





- Calculate critical crack depth, a_c, for X100 hydrogen pipeline operating at p = 21 MPa pressure
  - assume axial flaw with infinite length
  - hoop stress σ_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

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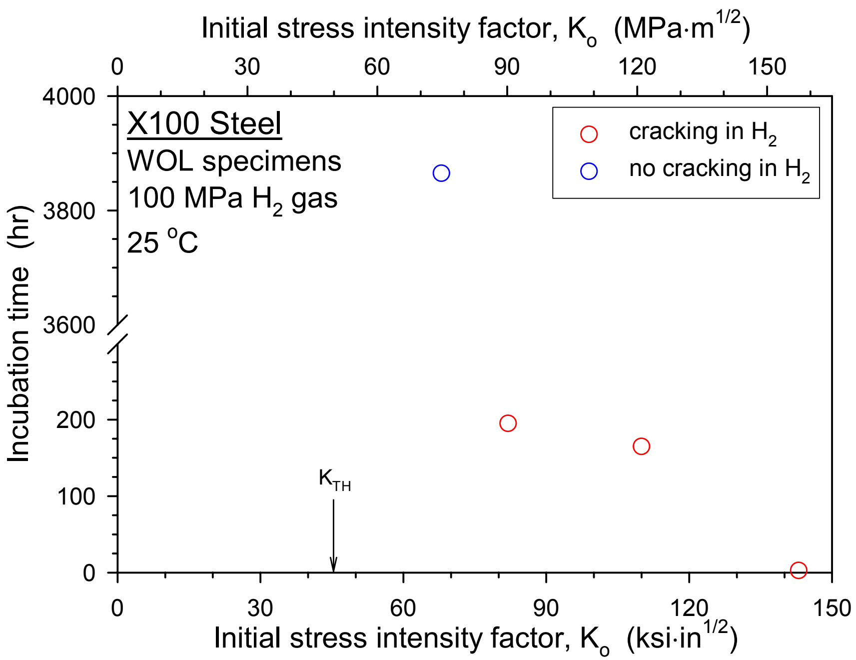
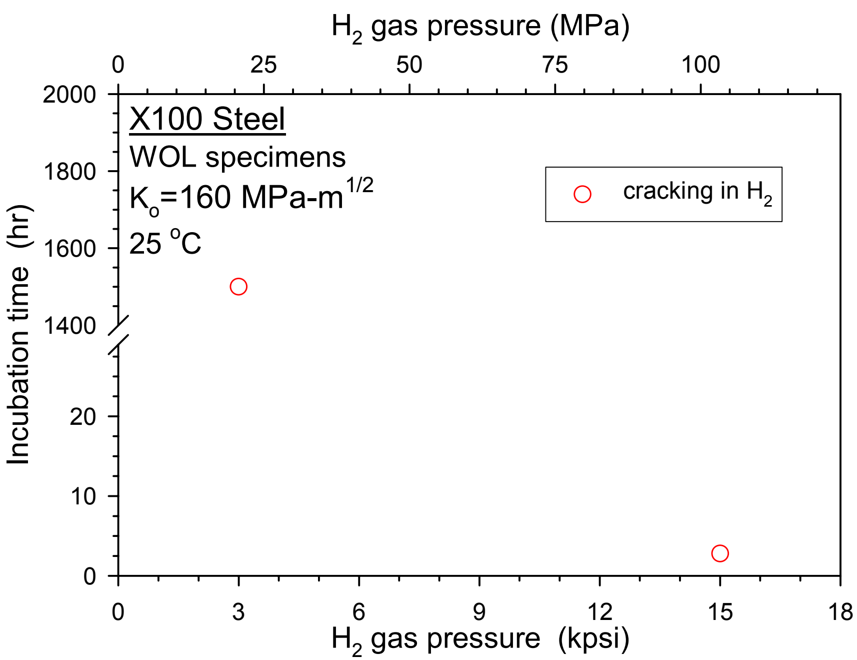
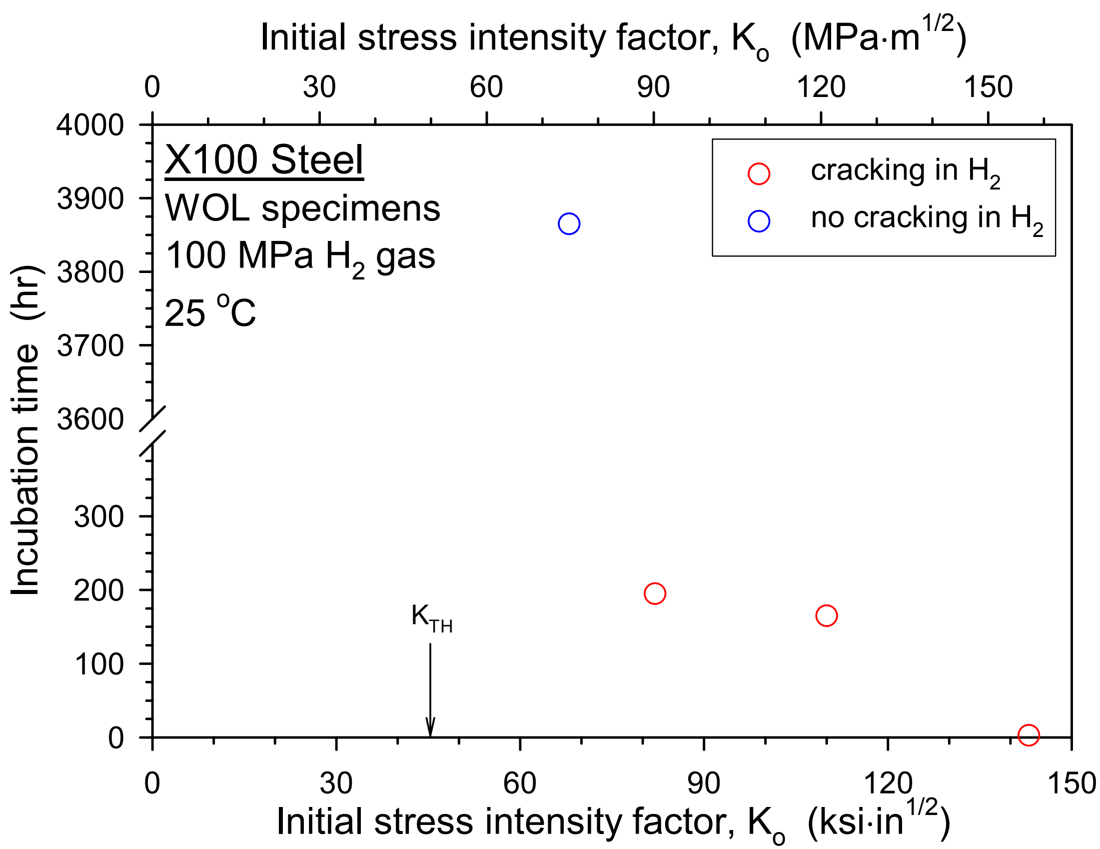
Incubation time for crack extension depends on K_o and H_2 pressure



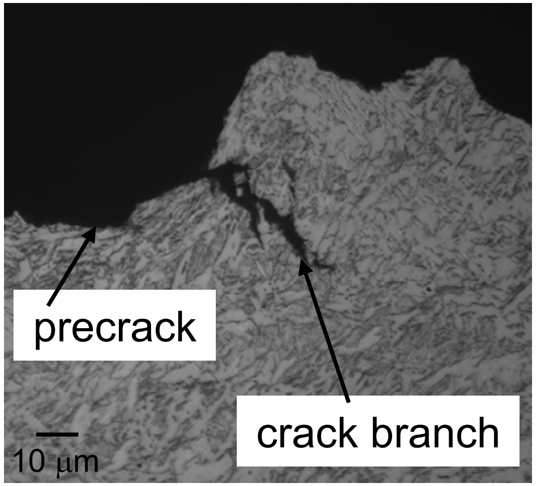


Procedures for measuring sustained-load cracking thresholds should not prescribe arbitrary test durations

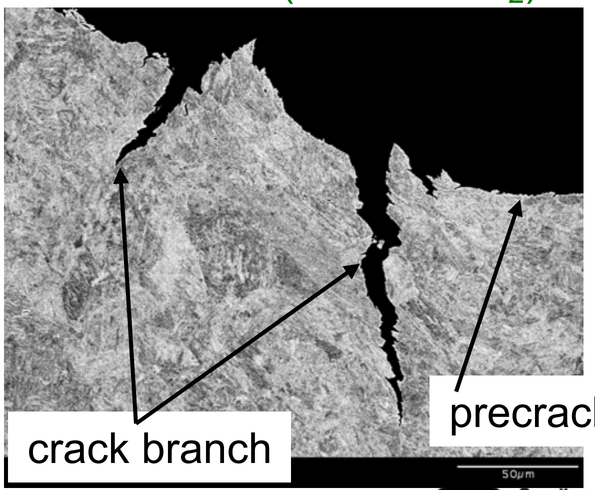
Crack branching may account for absence of crack extension at low K_o



X100 (100 MPa H_2)



SA 372 Gr. J (100 MPa H_2)



Issues that compromise measurement of conservative properties must be identified

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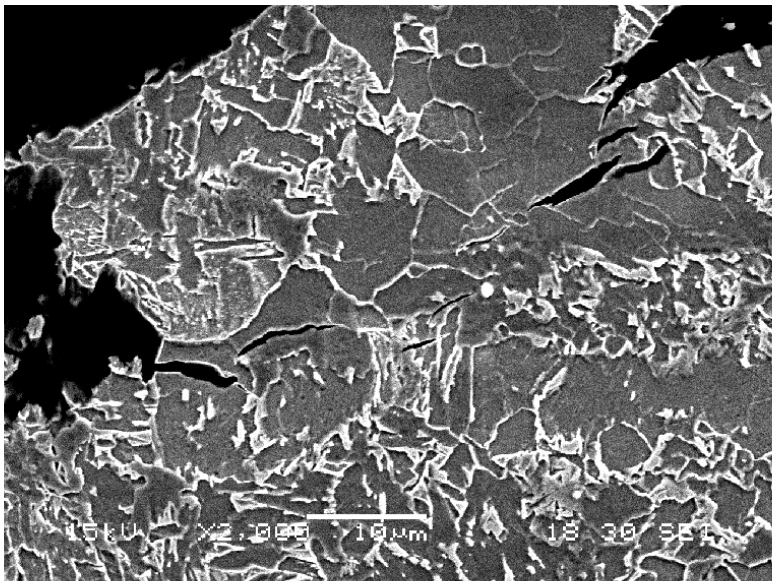
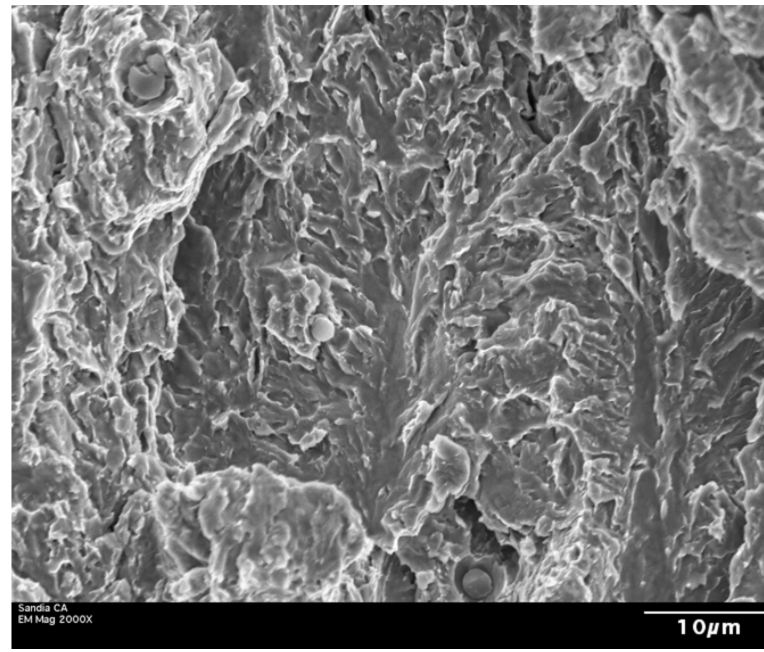
Microscopy evidence provides insight into hydrogen embrittlement

X100 in 100 MPa H_2 gas:
crack profile



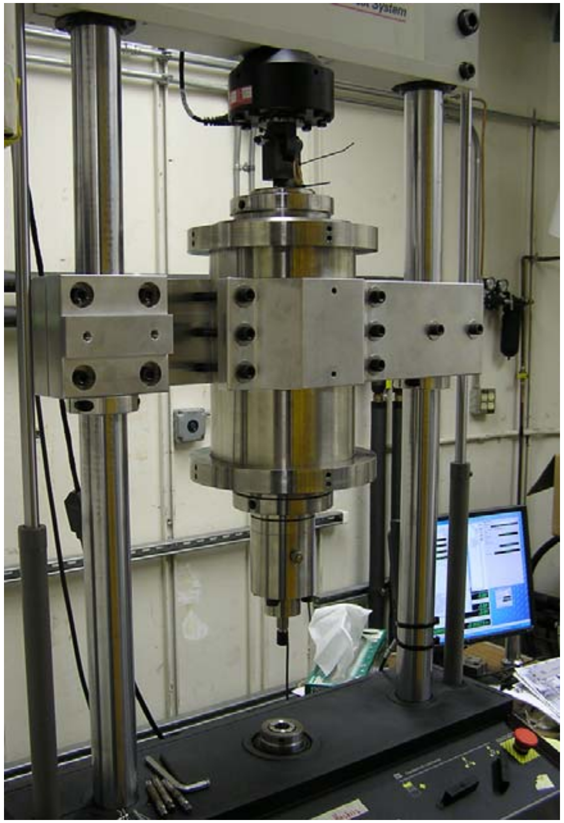
X100 in 21 MPa H_2 gas:
fracture surface



- 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 H_2 gas

vessel on mechanical test frame



- Pressure vessel designed to contain H_2 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 H_2 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