DOE Hydrogen Program

Hydrogen Embrittlement of Structural Steels

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Sandia National Laboratories

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Overview

Timeline

- Project start date Jan. 2007
- Project end date Oct. 2011*
- Percent complete 50%

Budget

- Total project funding (to date)
  - DOE share: $900K
- FY10 Funding: $150K
- FY11 Funding: $200K

*Project continuation and direction determined annually by DOE

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, ExxonMobil
  - Standards Development Organizations: ASME

Objectives/Relevance

- Why steel hydrogen pipelines?
  – Safety of steel pipelines well understood (e.g., third-party damage tolerance, vulnerability of welds)
  – 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, *particularly in welds*
- Enable pipeline design that accommodates hydrogen embrittlement
  – Ensure relevance to pipeline design code ASME B31.12
- FY10-FY11: measure fracture thresholds and fatigue crack growth laws for X52 steel in H_2 gas, emphasizing welds

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Approach

- Apply 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 fracture thresholds for X52 steel base metal and seam weld (75% complete)
  - Milestone: Measure fatigue crack growth laws for X52 steel base metal and seam weld (75% complete)
    - Evaluate effect of load-cycle frequency on measurements
- Emphasize pipeline steels and their welds identified by stakeholders as high priority
  - Provide feedback to stakeholders through DOE Pipeline Working Group

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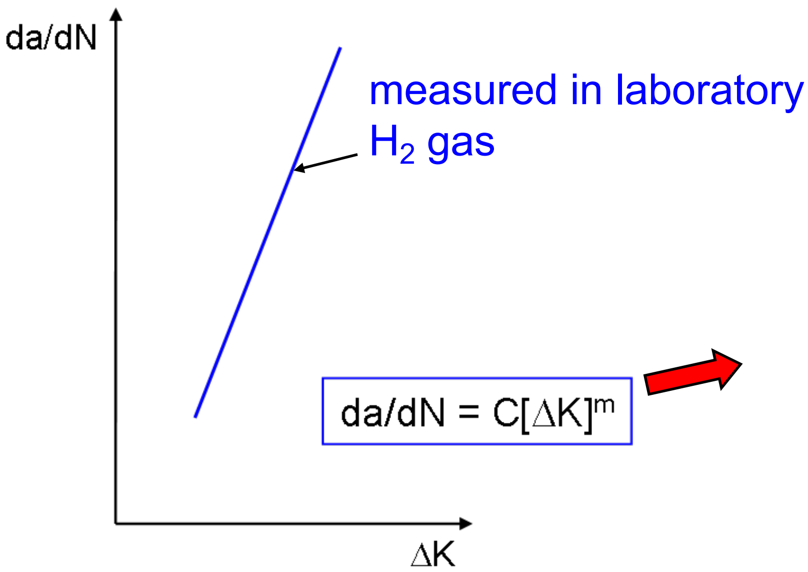
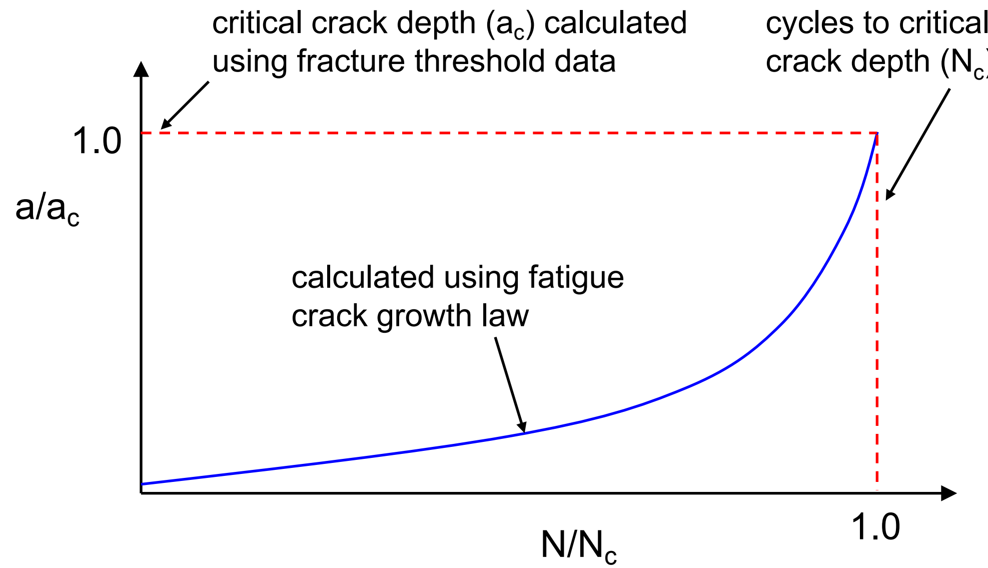
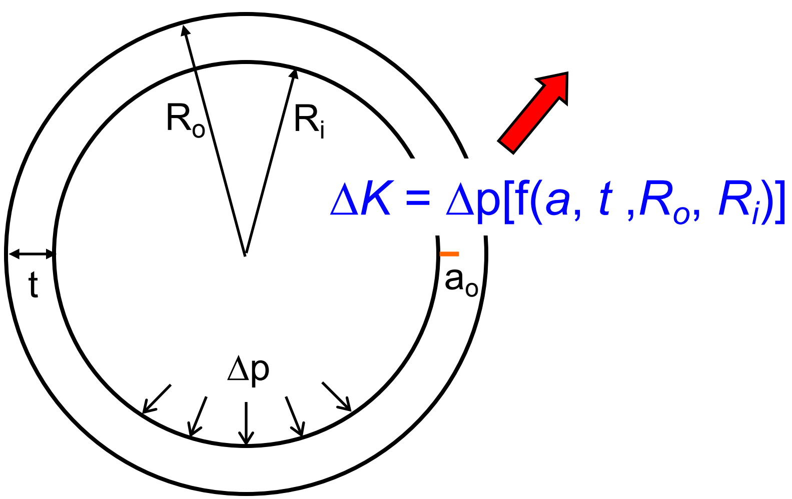
Reliability/integrity assessment framework in ASME B31.12 requires fracture data in H_2







- Two fracture properties in H_2 needed
  - Fatigue crack growth law
  - Fracture threshold
- Reliability/assessment framework accommodates H_2 embrittlement

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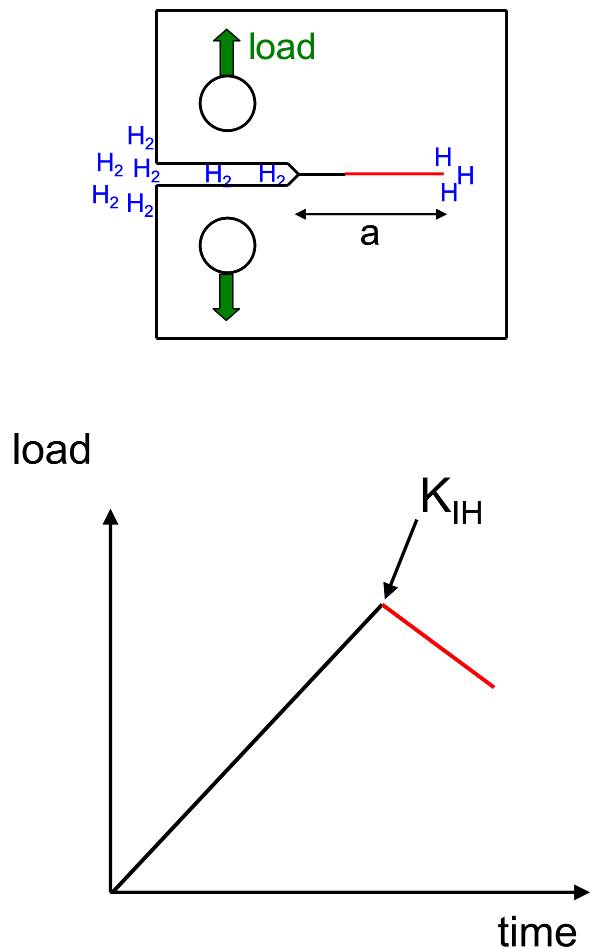
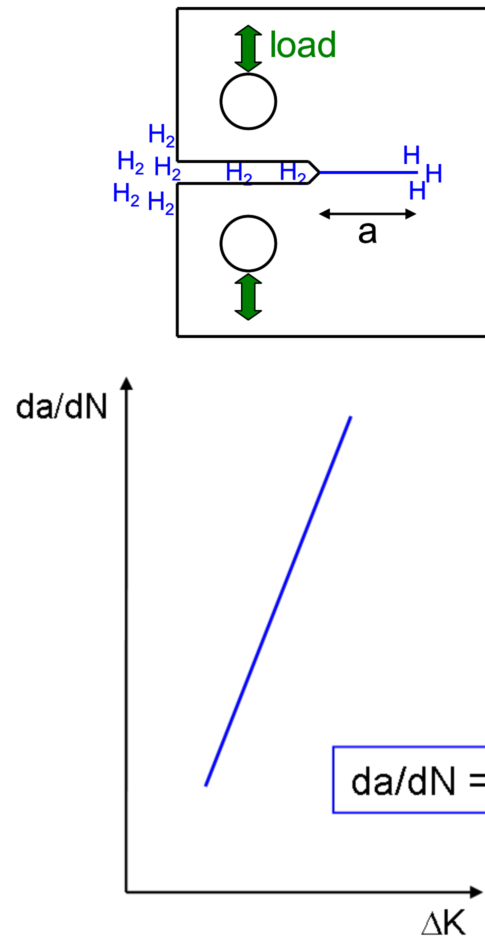
Fracture data in H_2 measured using specialized laboratory capability

Fracture threshold



Fatigue crack growth



$$da/dN = C[\Delta K]^m$$

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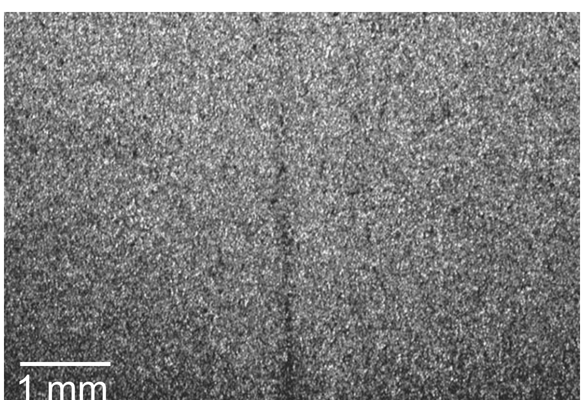
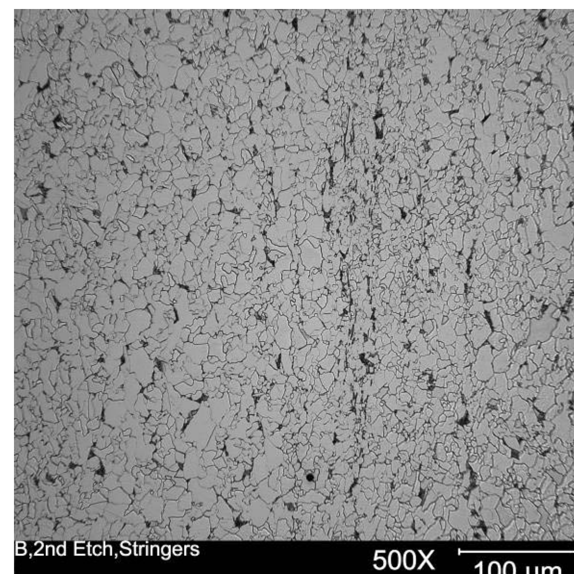
Measured fracture properties of technologically relevant steel: API 5L X52

- Tested same X52 steel from DOE Pipeline Working Group tensile property round robin
  - Stakeholders expressed interest in X52 steel
- Tensile properties
  - Yield strength: 62 ksi (428 MPa)
  - Ultimate tensile strength: 70 ksi (483 MPa)

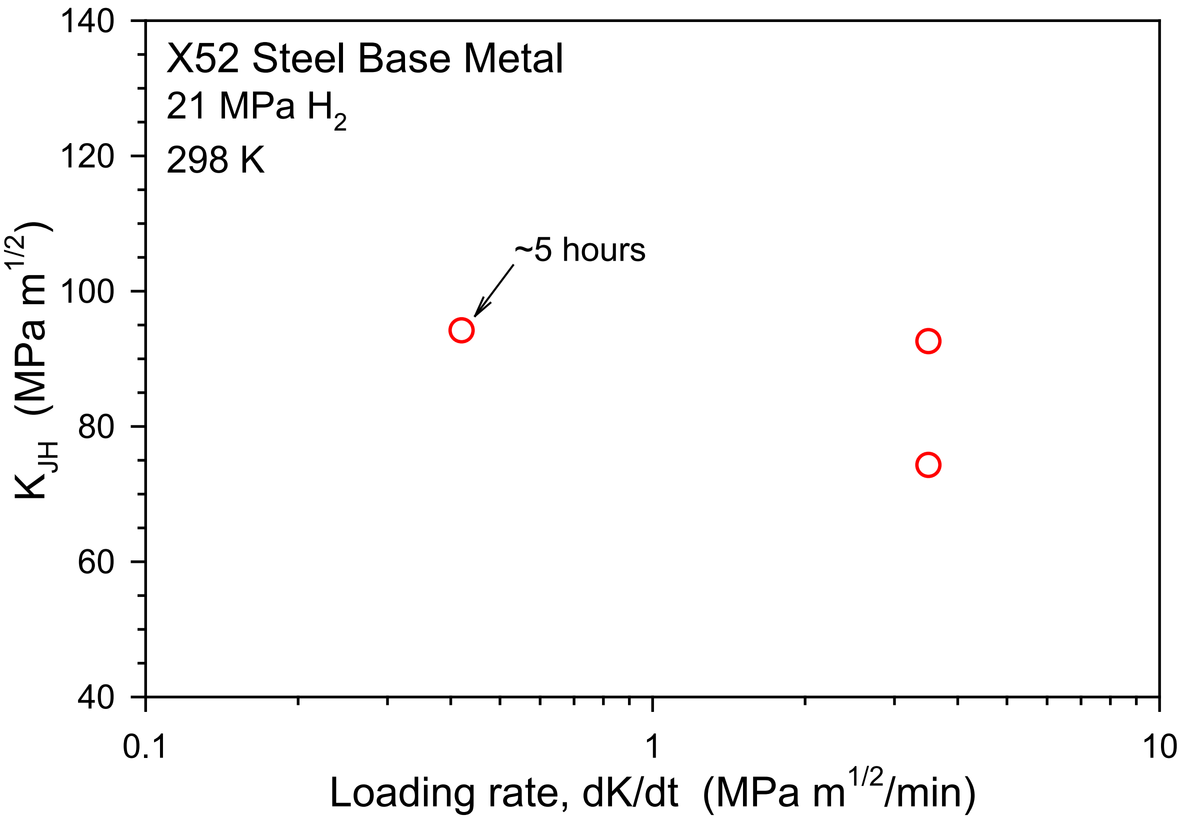


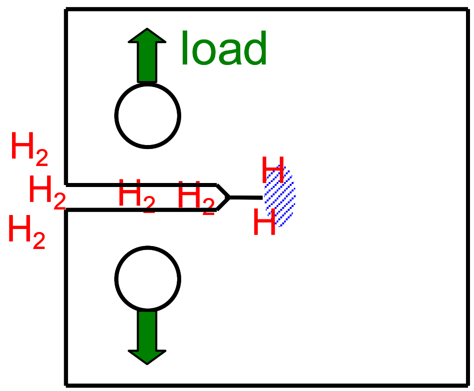
base metal



Accomplishment:

Crack initiation thresholds measured for X52 in H_2 as function of loading rate





- Loading rate must be selected to balance test efficiency and data reliability
- Fracture threshold values ~80-100 MPa $m^{1/2}$ favorable for pipeline reliability/integrity

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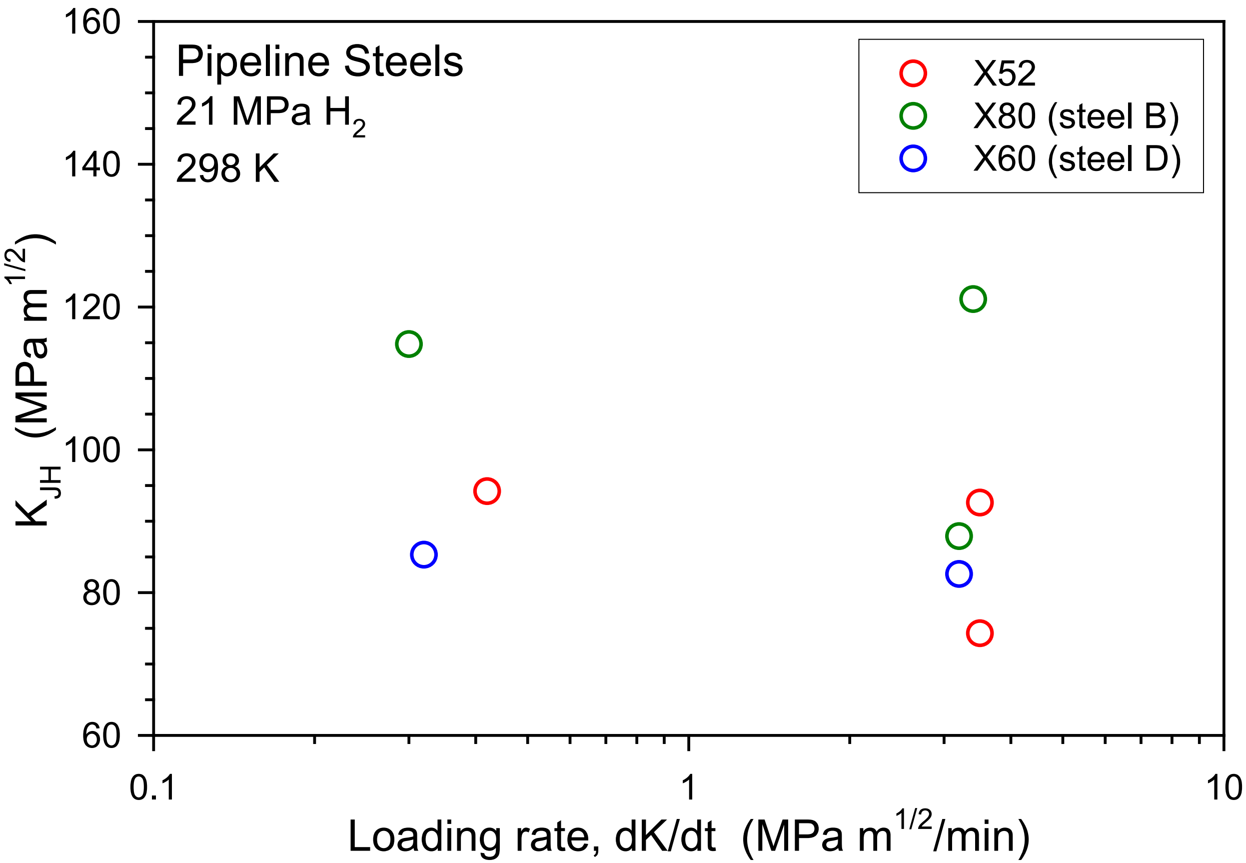
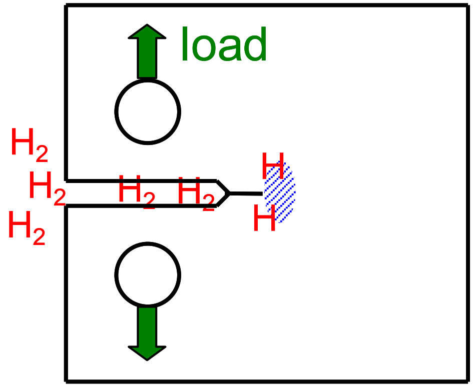
Crack initiation thresholds similar for three different pipeline steels

X60 and X80 data: *C. San Marchi et al., ASME PVP2010-25825, 2010*





- Measurements for three steels conducted by participants in Pipeline Working Group

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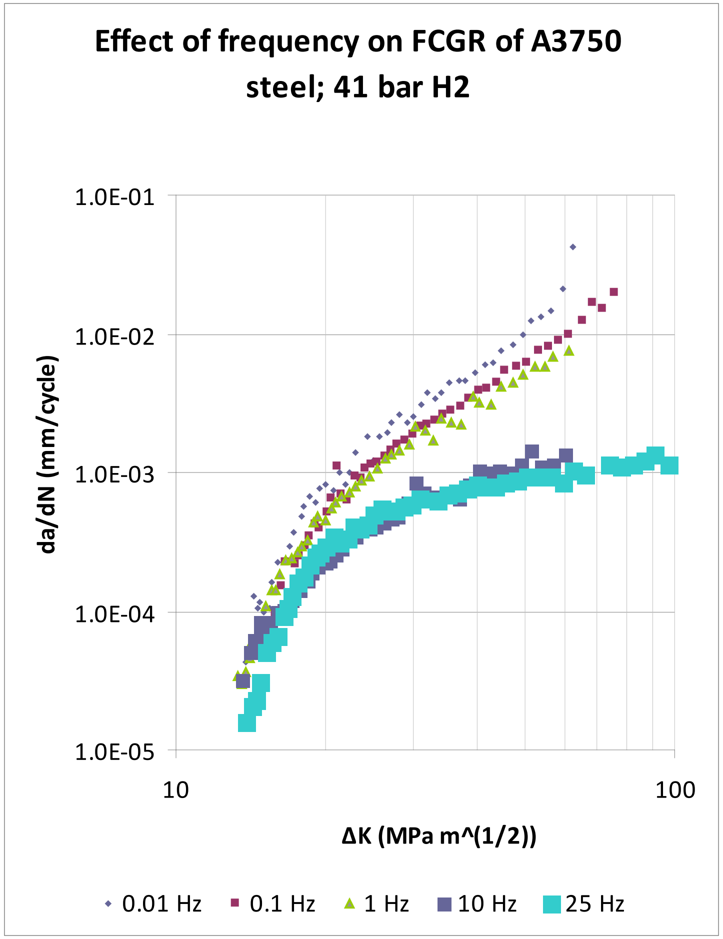
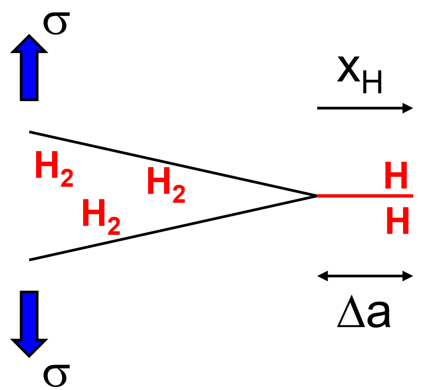
Measurement of fatigue crack growth laws must consider effects of frequency

A.H. Priest, British Steel, EHC-(1)42-012-81UK(H), 1983



Condition for H penetration to affect crack growth:



$x_H = (Dt)^{1/2}$

$\Delta a < x_H = (Dt)^{1/2}$

$\Delta a < (D/f)^{1/2}$

$$f \leq \frac{D}{(da/dN)^2}$$

- Frequency effects most pronounced at high da/dN

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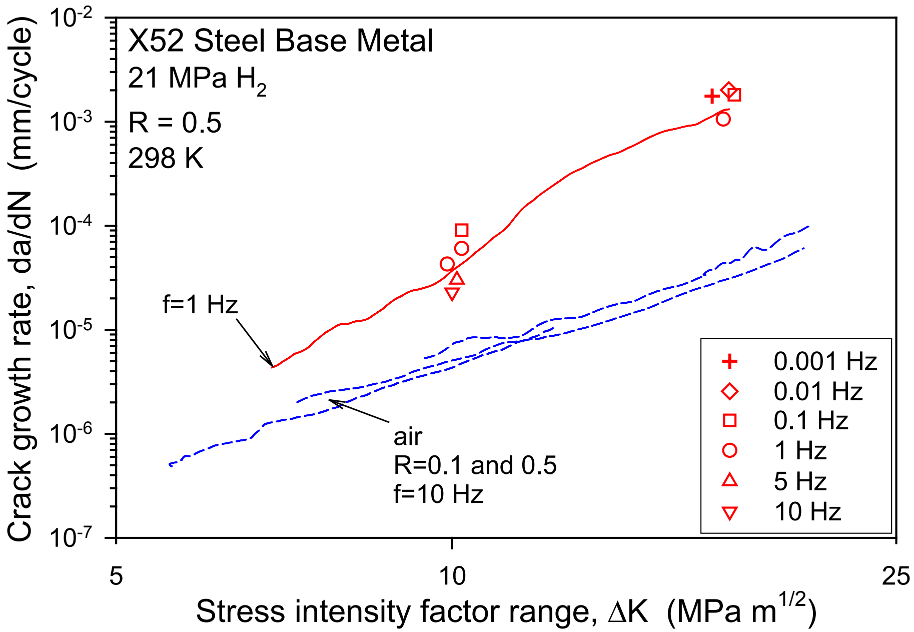
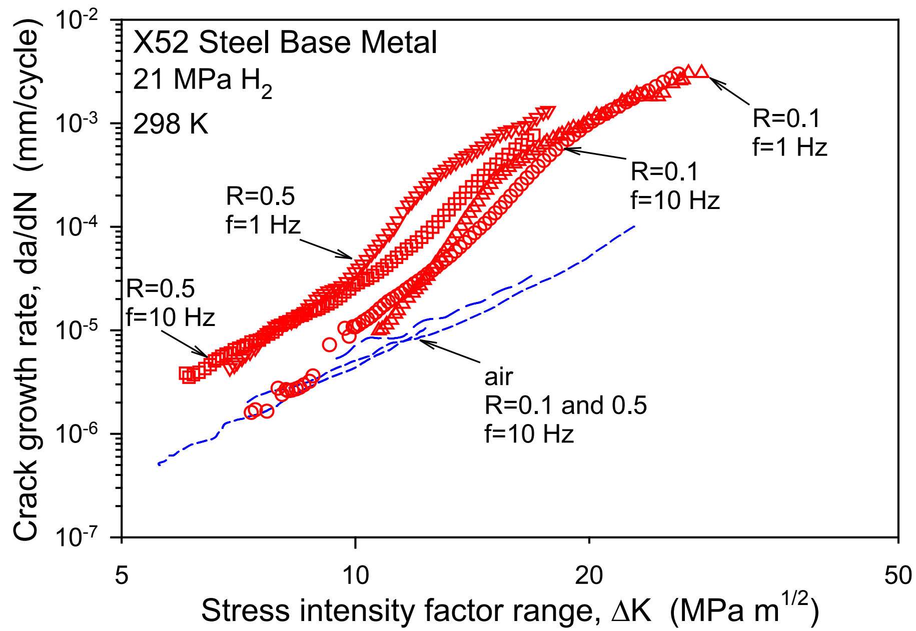
Accomplishment:

Measured effects of frequency on fatigue crack growth laws for X52 base metal

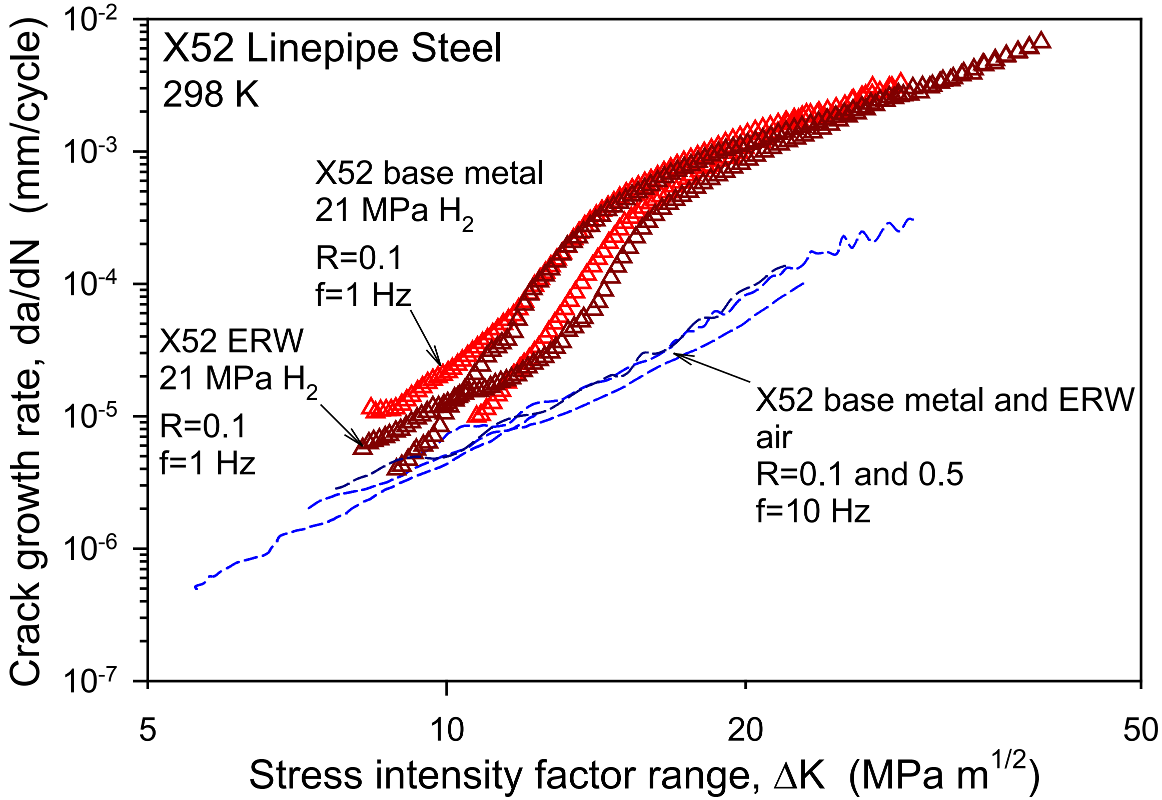




- Tests at higher frequency (> 1 Hz) yield non-conservative data at high crack growth rates
- Frequency selected must balance test efficiency (i.e., duration) and data reliability
  - Tests for comparing different materials (e.g., base metal *vs* welds) conducted at 1 Hz

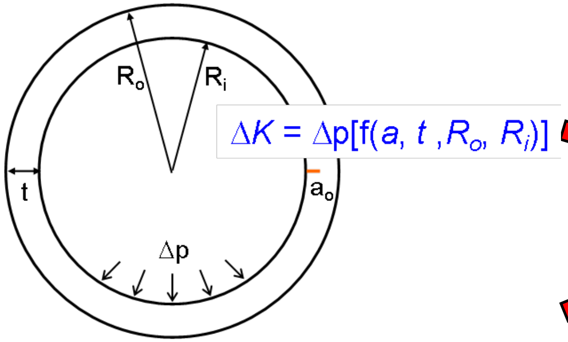
Accomplishment:

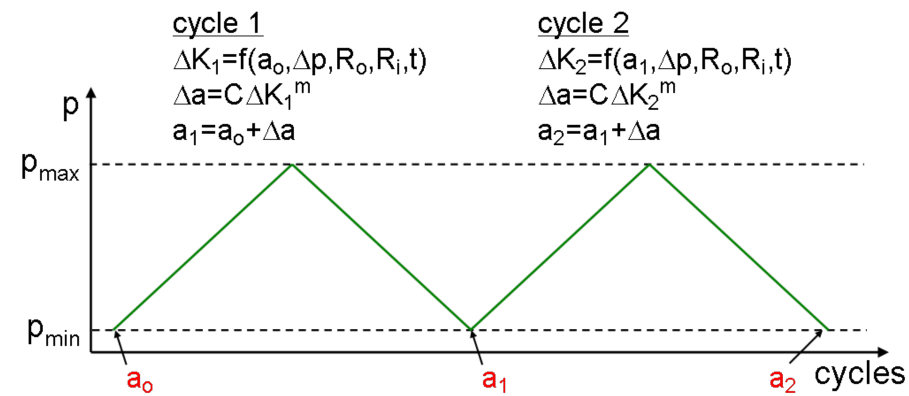
Measured fatigue crack growth laws for X52 steel base metal and ERW (seam weld)

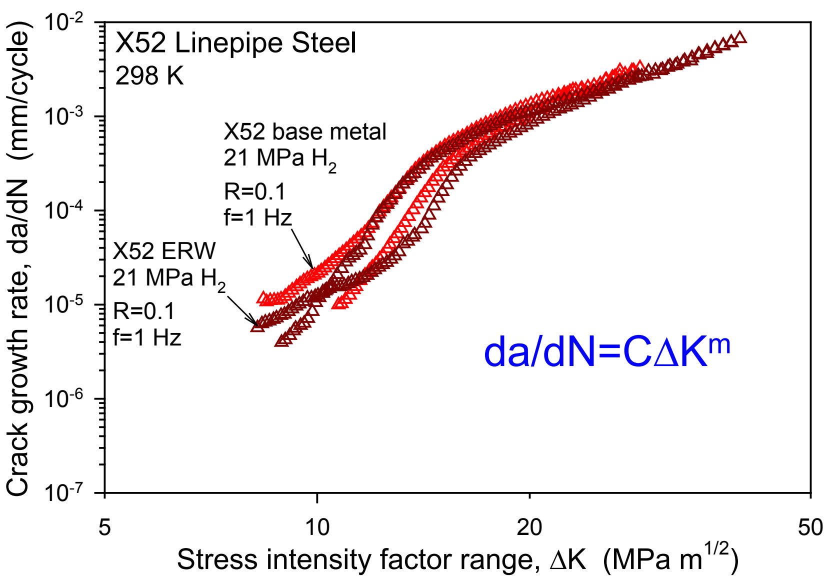


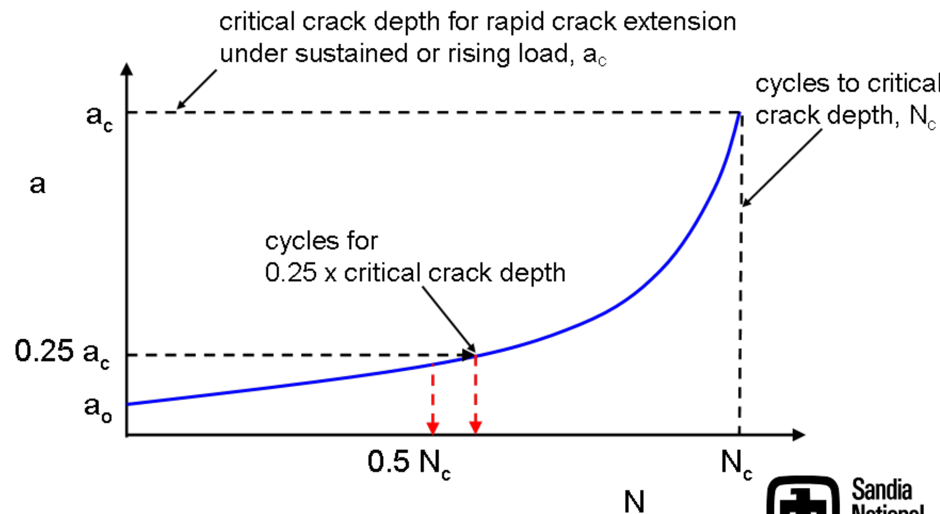
- Fatigue crack growth laws for X52 base metal and ERW similar in H_2
- Notable variability in data from replicate tests for both base metal and ERW in H_2

Fatigue crack growth laws can be used to evaluate reliability/integrity of X52 H_2 pipelines









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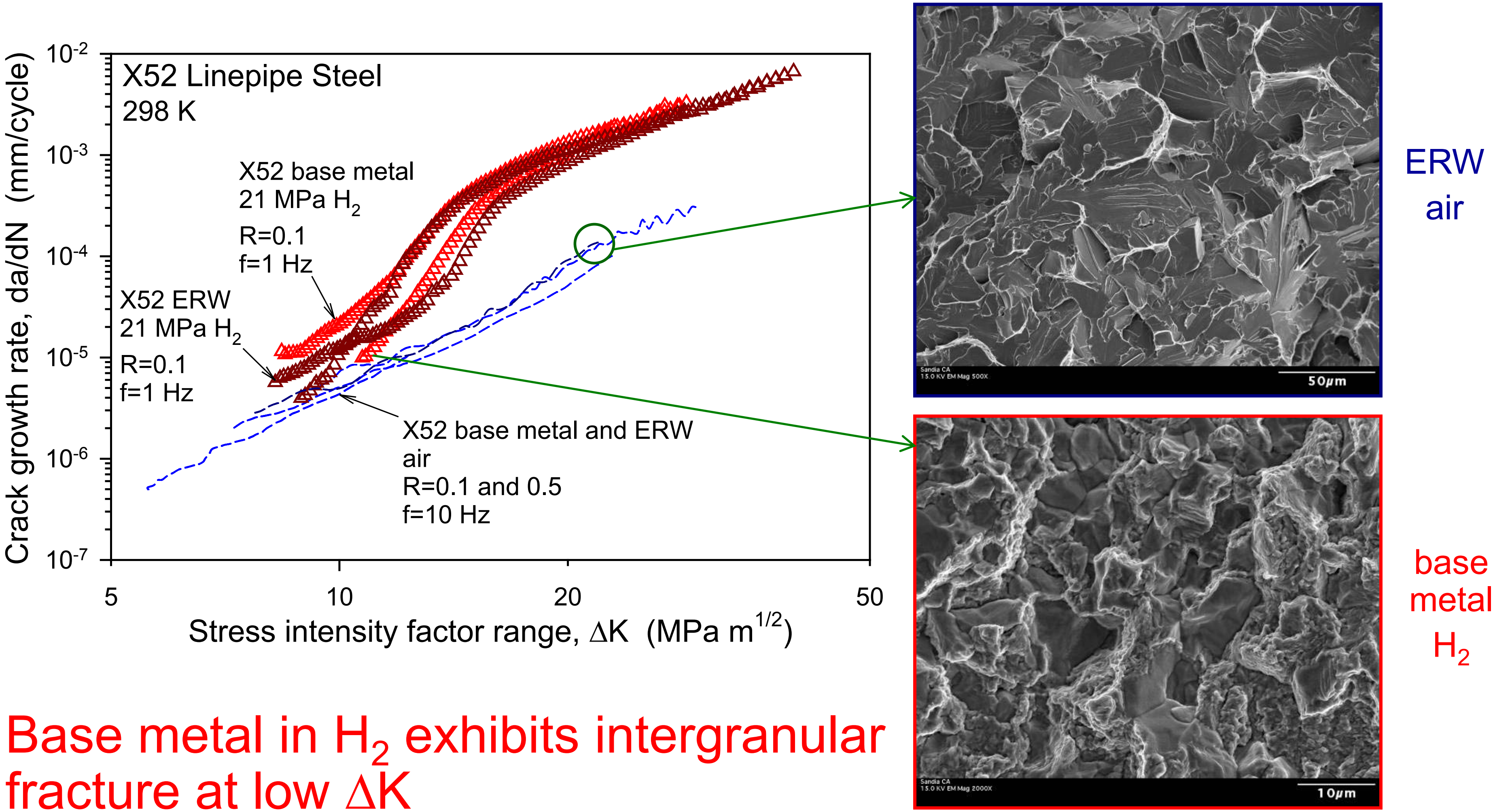
Accomplishment:

Examined fracture surfaces from fatigue crack growth specimens



- Base metal in H_2 exhibits intergranular fracture at low ΔK
- ERW in air (R=0.5) exhibits unstable fracture at K_{max}~40 MPa $m^{1/2}$ → cleavage

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Collaborations

- DOE Pipeline Working Group (PWG)
  - Participants funded by DOE FCT Program
    - Federal Labs: Sandia, Oak Ridge, Savannah River
    - Universities: Univ. of Illinois
    - Industry: Secat
  - Participants not funded by DOE FCT Program
    - Federal Labs: NIST
    - Industry: industrial gas companies, ExxonMobil
    - Standards Development Organizations: ASME
  - Extent of collaborations include:
    - PWG meetings (up to 2 times/year) for participants to report results and receive feedback
    - Leveraging resources for testing (e.g., Secat-Sandia)
    - Supplying materials (e.g., ExxonMobil-Sandia)
    - Coordinating testing (e.g., NIST-Sandia)

Proposed Future Work

Remainder of FY11

- Expand evaluation of X52 seam weld to understand implication of cleavage fracture
- Determine threshold level of O_2 to inhibit accelerated fatigue crack growth of X52 steel in 21 MPa H_2 gas
- Measure fatigue crack growth law of girth weld fusion zone in H_2 gas

FY12

- Measure fatigue crack growth law of girth weld heat-affected zone (HAZ) in H_2 gas
- Evaluate effects of load-cycle frequency on O_2 inhibition of H_2-accelerated fatigue crack growth

Summary

- Measured fracture thresholds and fatigue crack growth laws allow evaluation of reliability/integrity of steel H_2 pipelines
  - Hydrogen embrittlement accommodated by measuring fracture properties in H_2 following ASME B31.12 design standard

- Measurements on X52 steel reveal the following trends:
  - Fracture thresholds of base metal in H_2 (~80-100 MPa $m^{1/2}$) are favorable for pipeline reliability/integrity
  - Fatigue crack growth laws for base metal and seam weld are similar in H_2
  - Unstable cleavage fracture observed in seam weld at K_{max} ~ 40 MPa $m^{1/2}$ during fatigue crack growth testing in air