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Enabling Hydrogen Embrittlement Modeling of Structural Steels

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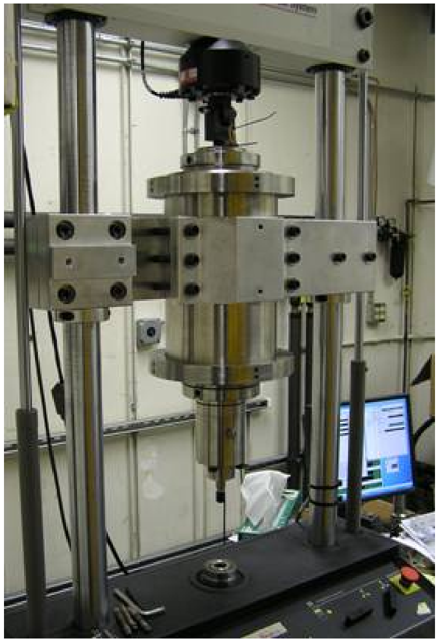


Hydrogen embrittlement of steels can be managed provided fracture properties are measured under relevant mechanical and environmental conditions. These fracture property measurements enable the implementation of both fundamental mechanistic models as well as structure lifetime models.

Project Overview:

- Provide fracture properties for pipeline steels in H_2 gas to enable implementation of hydrogen embrittlement and structural integrity models

Technical Targets (2017):

- $490k/mile capital cost for transmission pipelines
- $190k/mile capital cost for distribution pipelines
- Hydrogen delivery cost below $1.00/gge
- High reliability
- Low hydrogen permeation

Technical Approach:

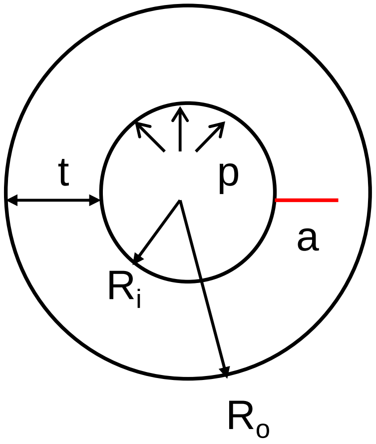
- Measure properties of pipeline steels in high-pressure H_2 gas using fracture mechanics methods
  - fatigue crack growth rates under cyclic loading
  - thresholds for sustained-load crack growth
- Assess measured properties by predicting steel pipeline lifetime using structural integrity models
- Identify and measure fundamental parameters in mechanistic models of hydrogen embrittlement
  - thermal desorption spectroscopy (TDS) gives interaction energy between H and steel defects

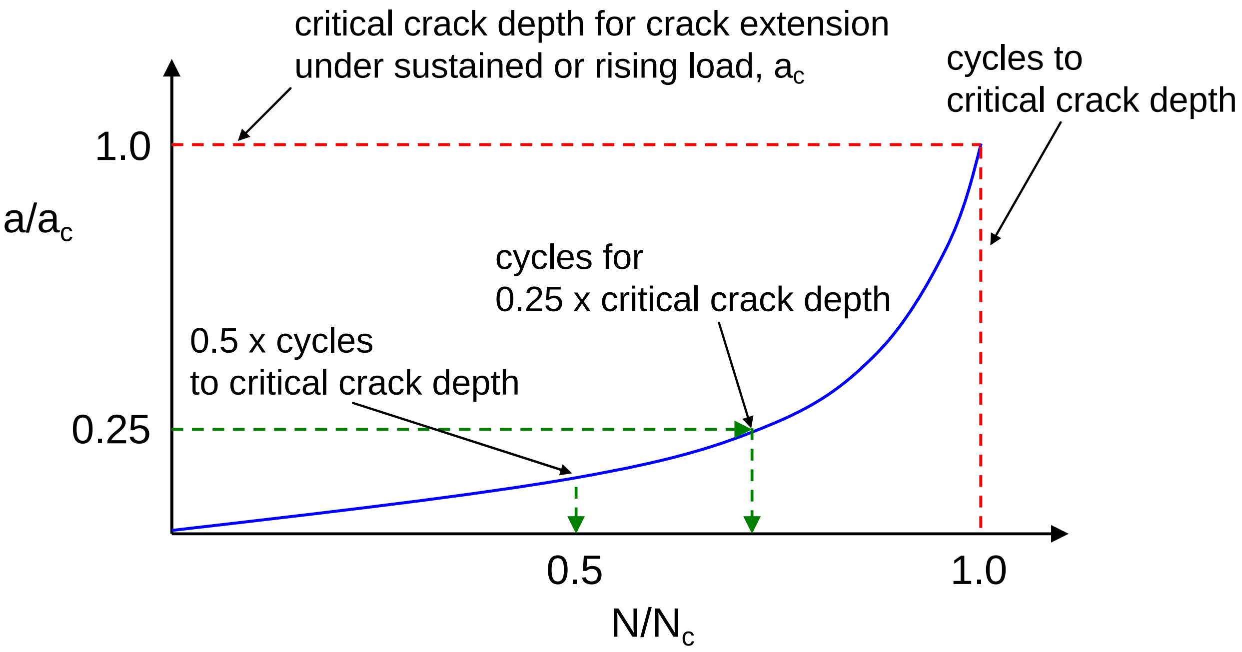
Impact:

Hydrogen embrittlement can be accommodated and steel pipeline safety margins can be *quantified* through measurement of fracture mechanics properties coupled with structural integrity and mechanistic models

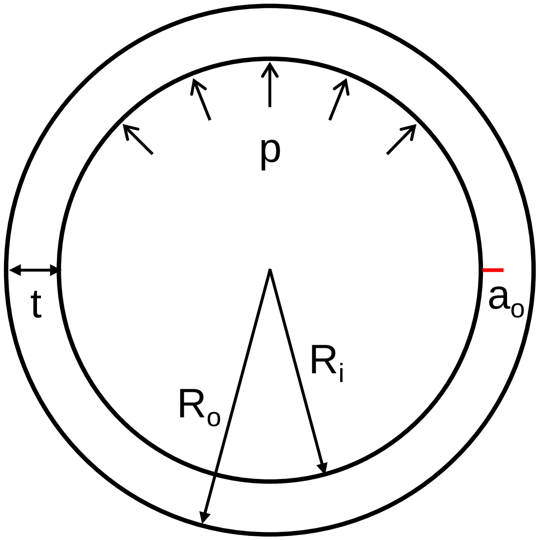
Materials testing motivated by design method

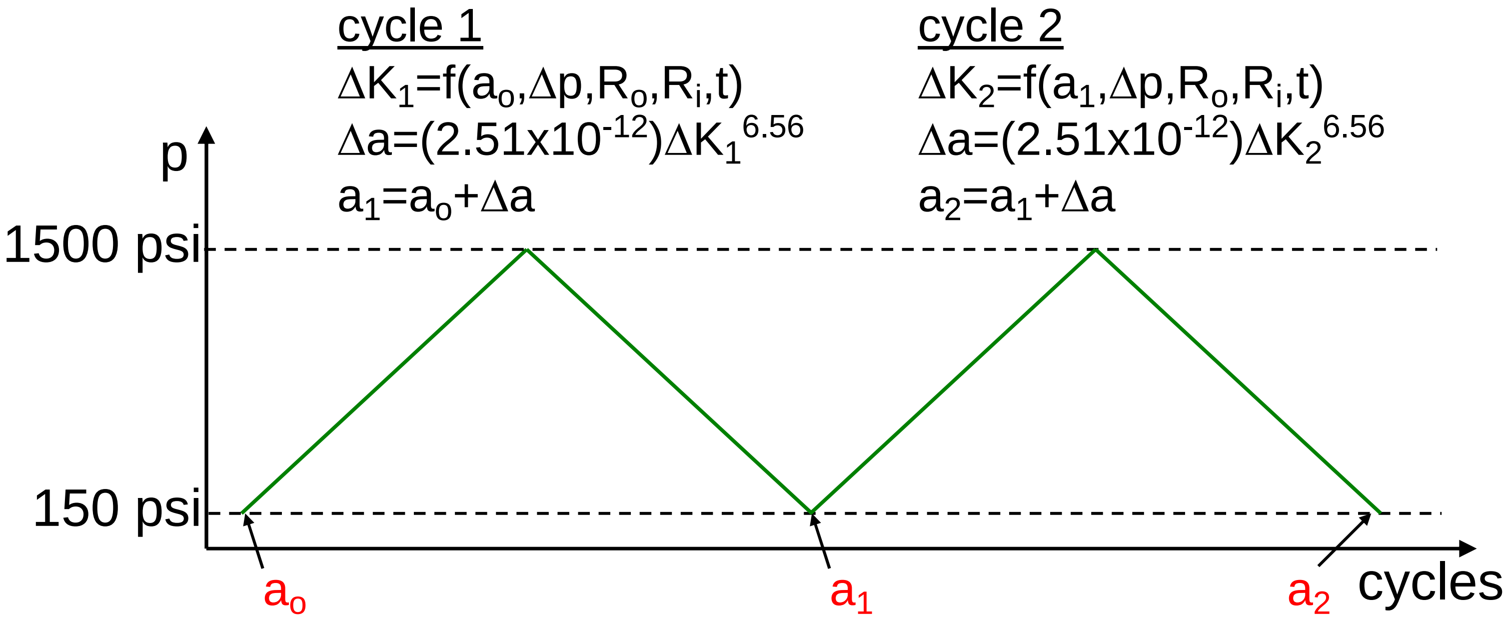
- Article KD-10 in ASME BPV Code Section VIII, Div. 3
  - applies to H_2 pressure vessels and pipelines
  - design method identifies two H_2-assisted failure modes: fatigue crack growth and sustained-load cracking
- Requires materials data in high-pressure hydrogen gas for fracture mechanics-based structural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





Calculate number of pressure cycles to reach critical crack depth for three cases





cycle 1

$\Delta K_1 = f(a_o, \Delta p, R_o, R_i, t)$

$\Delta a = (2.51 \times 10^{-12}) \Delta K_1^{6.56}$

$a_1 = a_o + \Delta a$

cycle 2

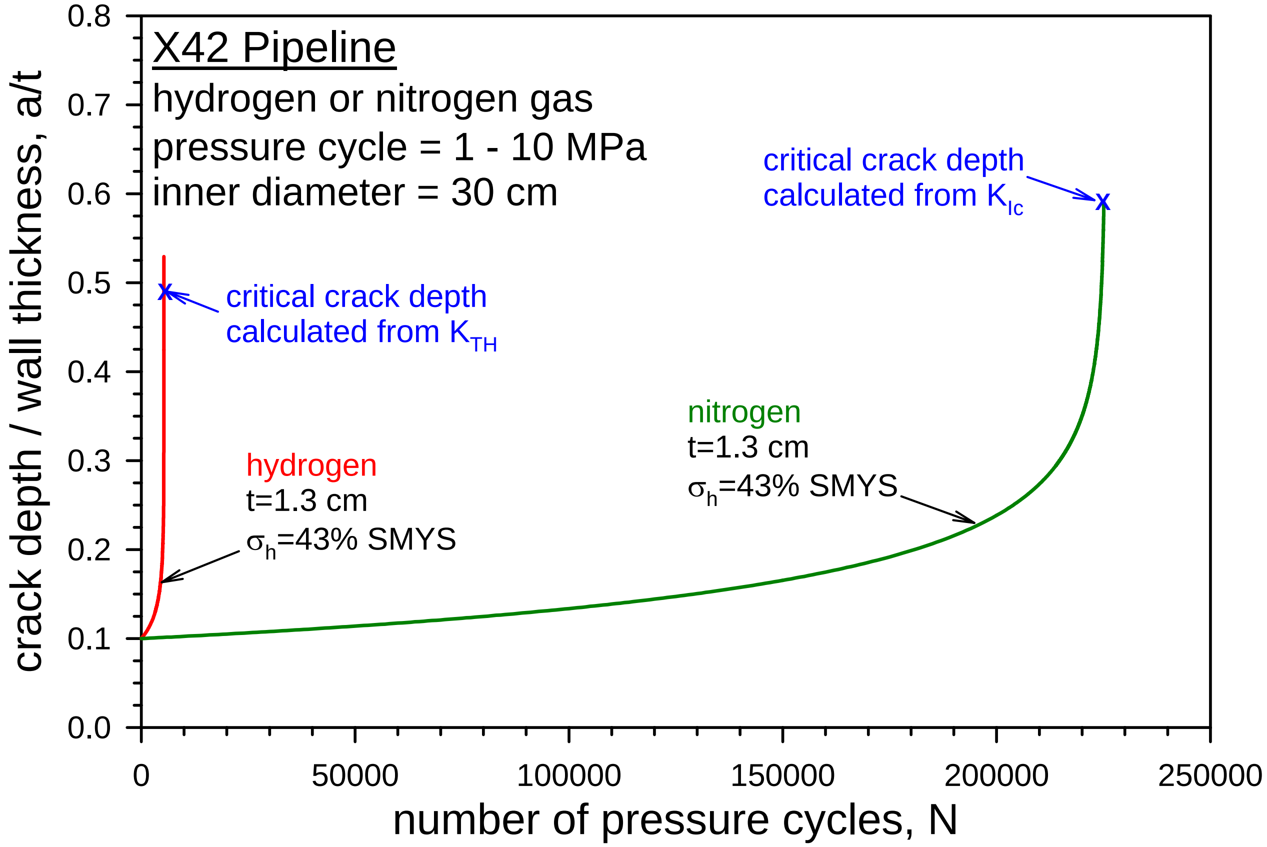
$\Delta K_2 = f(a_1, \Delta p, R_o, R_i, t)$

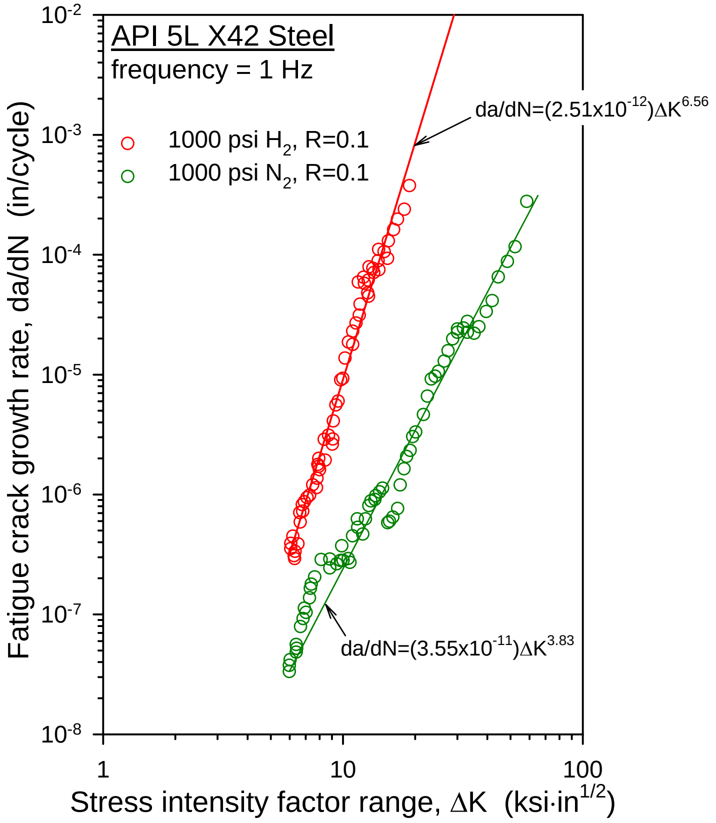
$\Delta a = (2.51 \times 10^{-12}) \Delta K_2^{6.56}$

$a_2 = a_1 + \Delta a$

- Case 1: t=0.330 in (σ_h=65% SMYS) and a_o/t=0.10
- Case 2: t=0.500 in (σ_h=43% SMYS) and a_o/t=0.10
- Case 3: t=0.500 in (σ_h=43% SMYS) and a_o/t=0.05

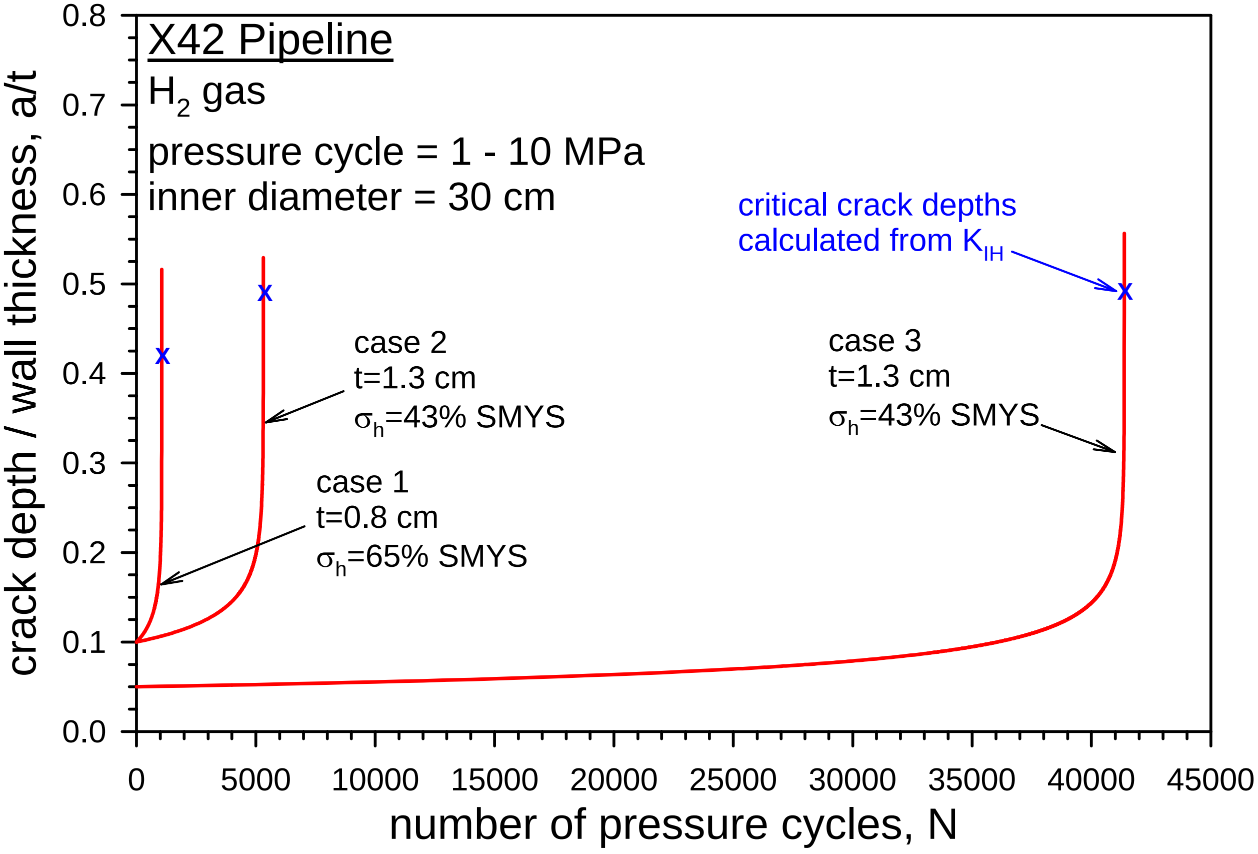
Number of pressure cycles *vs* crack depth relationships: H_2 compared to inert gas

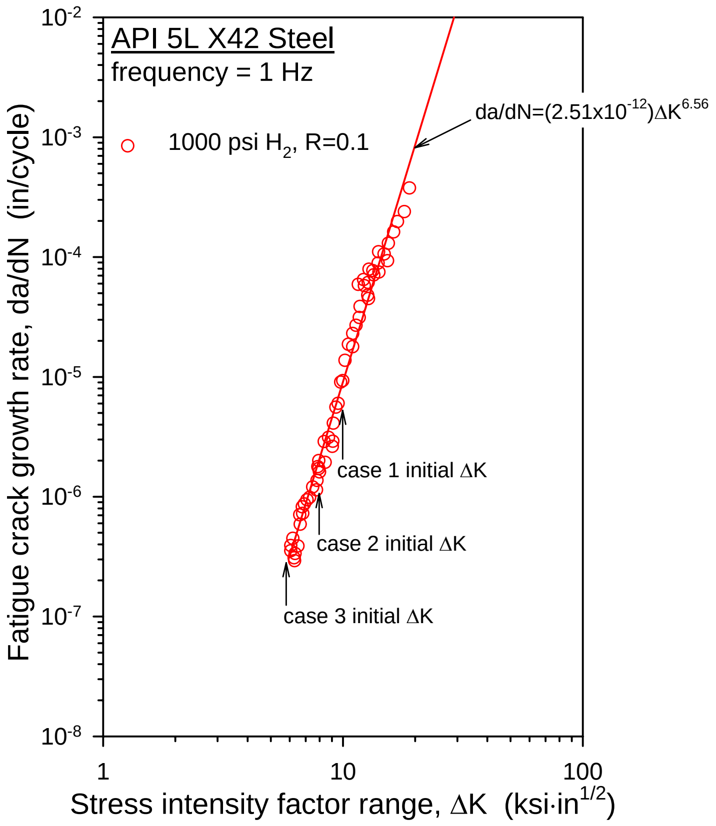




Hydrogen embrittlement results in *reduced* number of pressure cycles to reach critical crack depth

Number of pressure cycles *vs* crack depth calculated for three cases





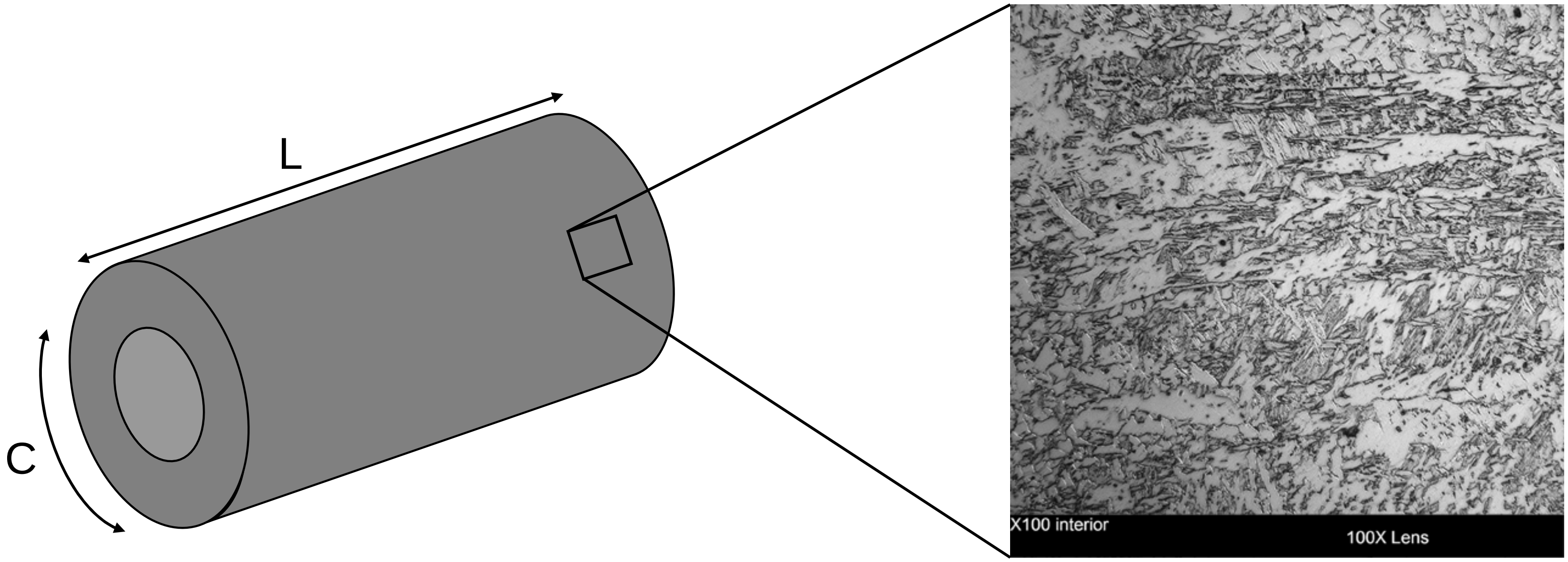
- Lifetime depends on *both* material data and structural design
- Hydrogen embrittlement can be accommodated and *safety margins can be quantified*

Hydrogen embrittlement of X100 line pipe steel

- Alloy composition

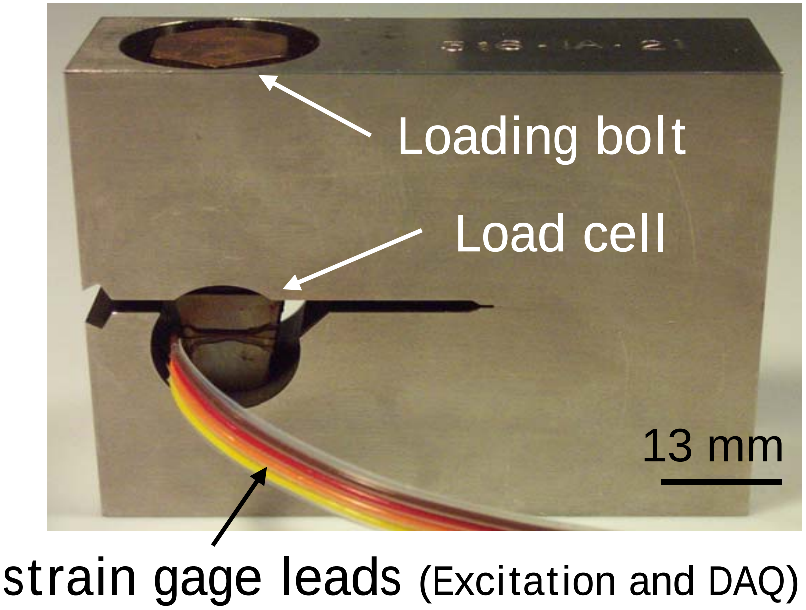
C	Mn	Si	P	S	Nb	Ti	V	Ni	Cu	Mo	Cr
0.073	1.86	0.11	0.009	<0.002	0.04	0.01	<0.005	0.48	0.27	0.17	0.02

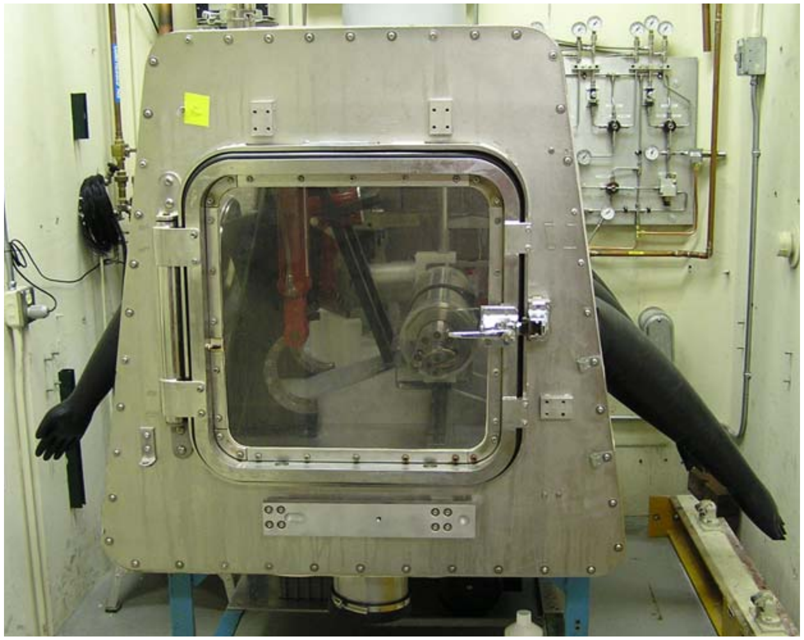
- Yield strength
  - 96 ksi (662 MPa) in longitudinal (L) orientation
  - 114 ksi (787 MPa) in circumferential (C) orientation

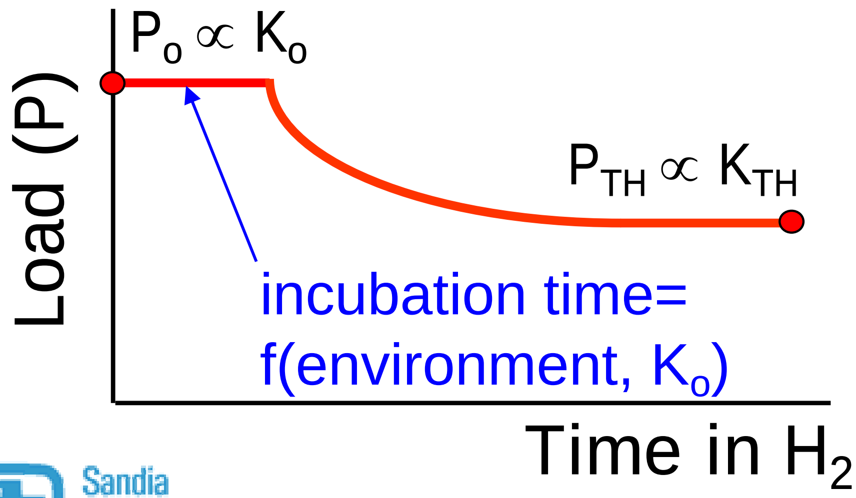


Measurement of sustained-load cracking thresholds

wedge opening load (WOL) cracking threshold specimen

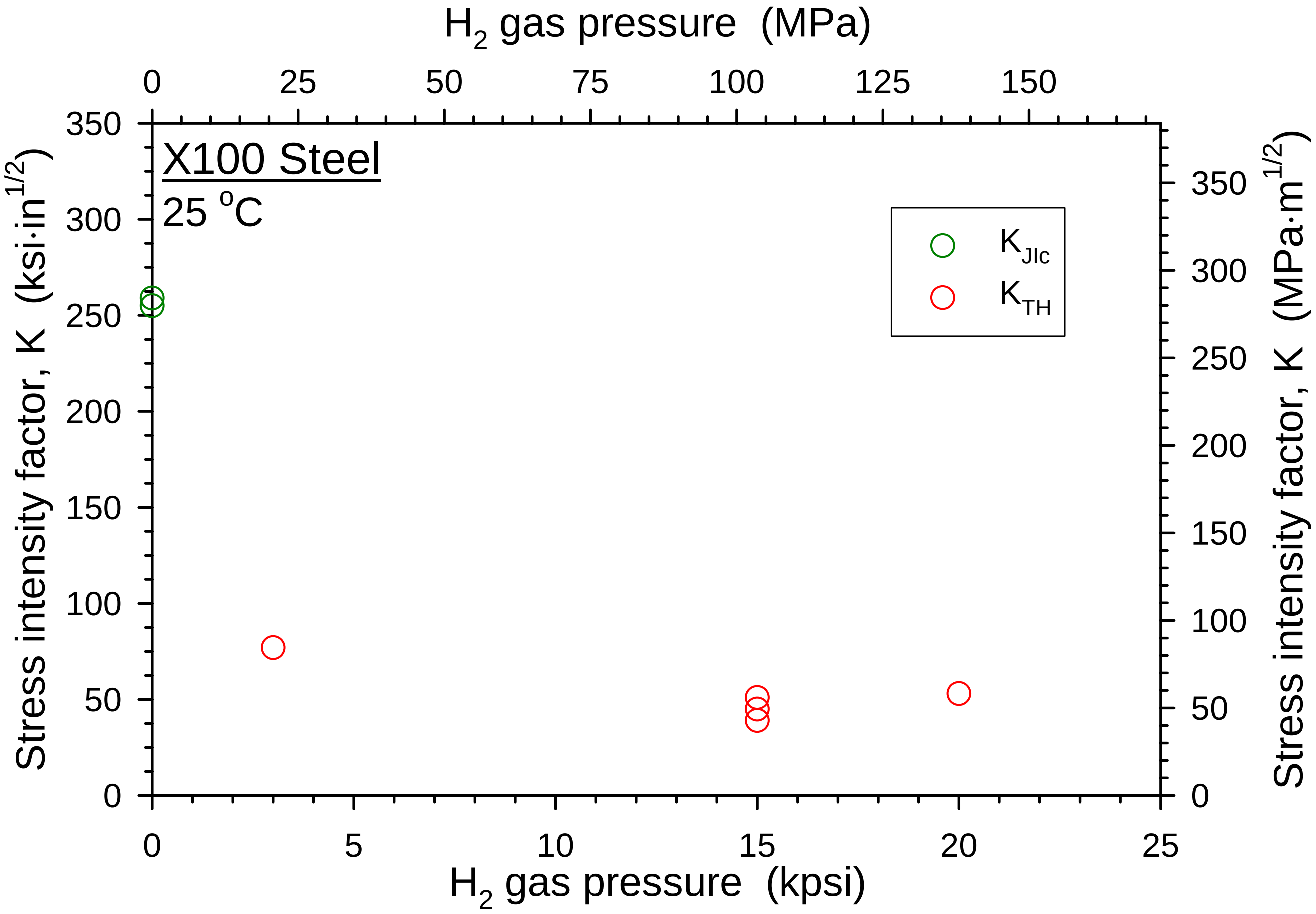




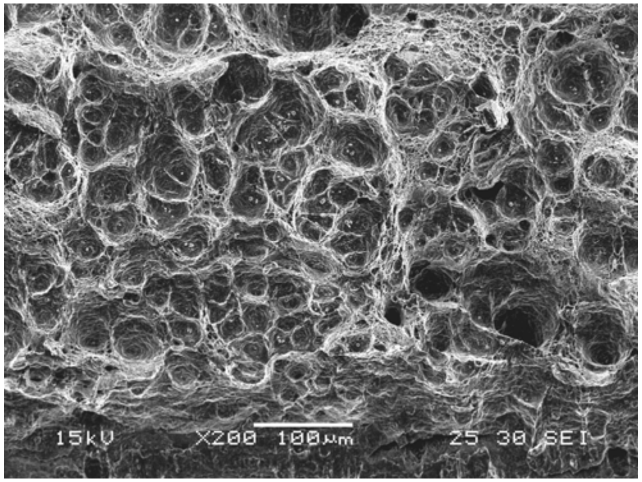


- Specimen loaded to $K_o > K_{TH}$ using bolt while contained in glove box (Ar with ~1 ppm O_2)
- Loaded specimen exposed to H_2, crack extends after incubation time
- Crack arrests at $K = K_{TH}$

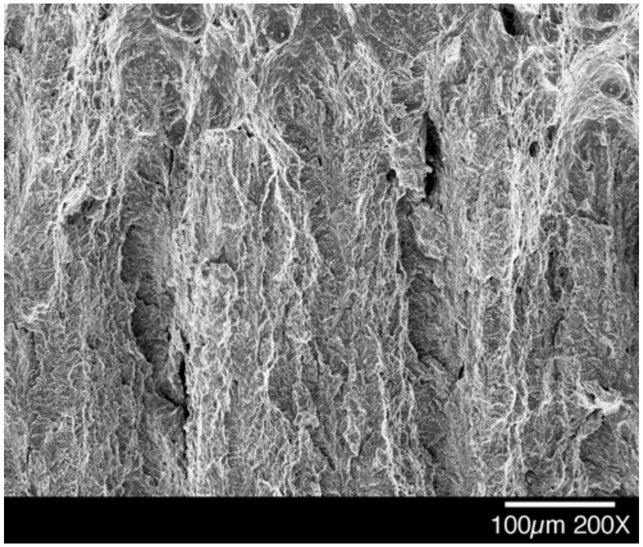
High-pressure H_2 gas severely degrades crack propagation resistance of X100 steel



X100 in air



X100 in 15 kpsi H_2 gas



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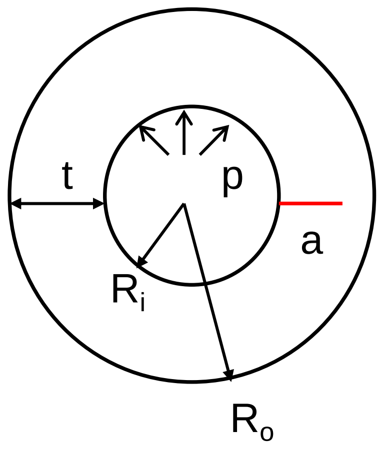
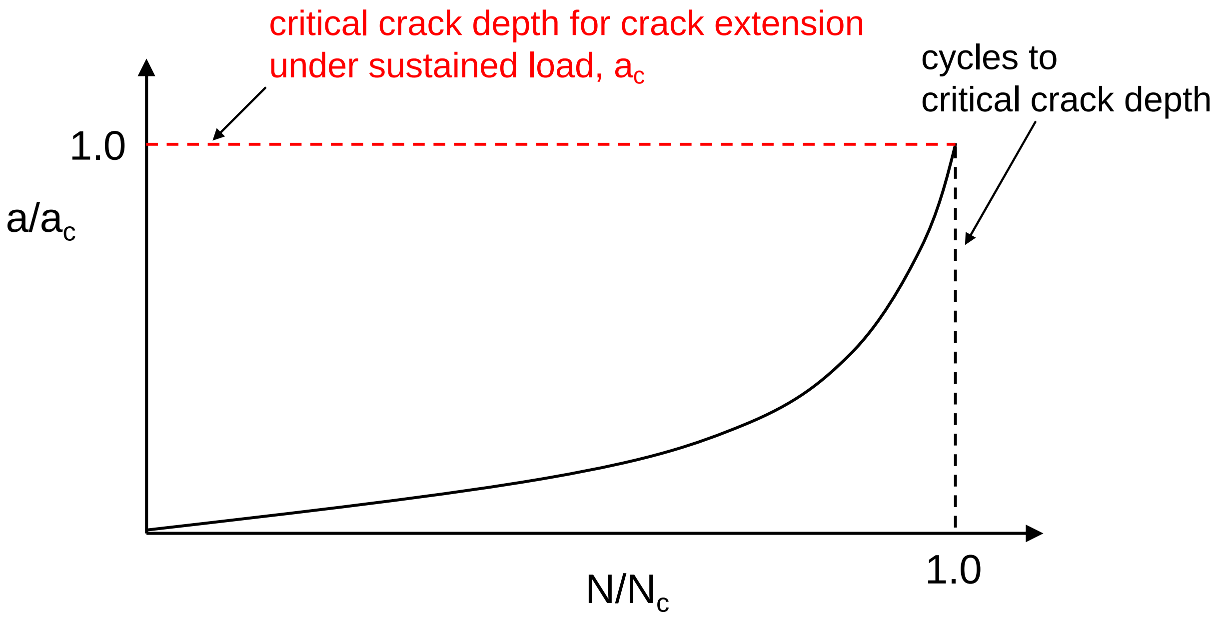
Implication of sustained-load cracking thresholds assessed from structural design model



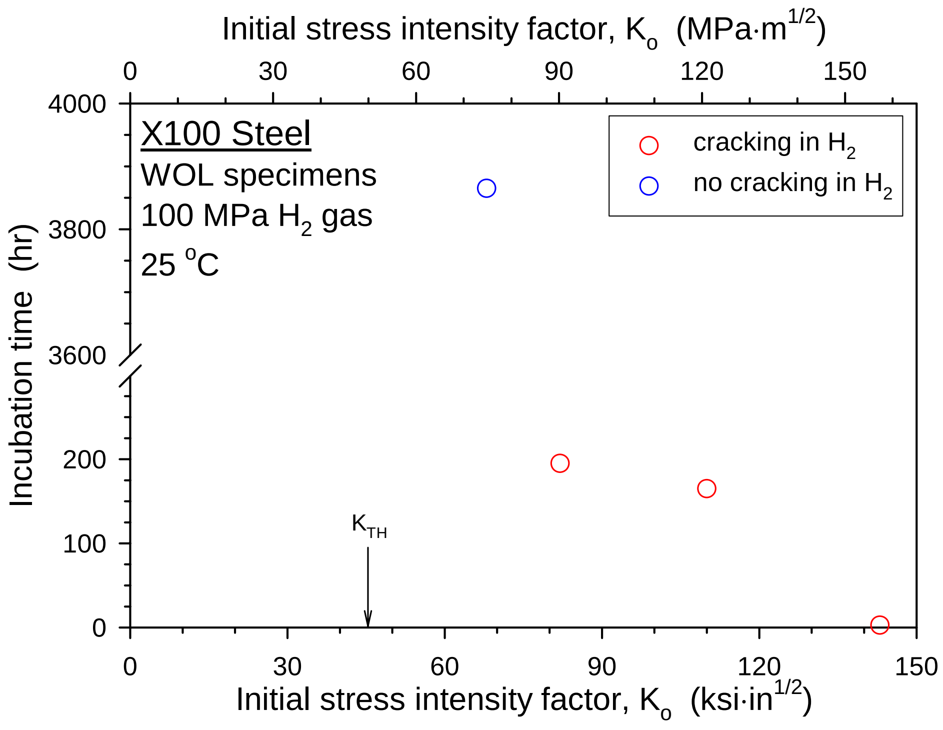


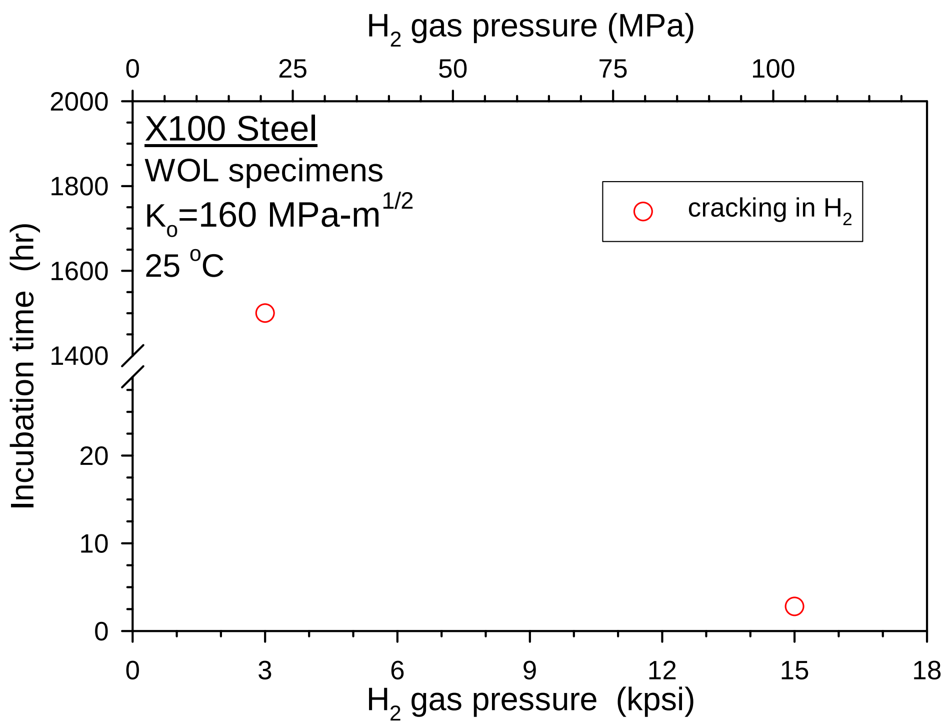
critical crack depth for crack extension under sustained load, a_c

cycles to critical crack depth

- Calculate critical crack depth, a_c, for X100 hydrogen pipeline operating at p = 21 MPa pressure
  - assume axial flaw with infinite length
  - assume R_i = 15 cm, t = 1.3 cm
  - 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)

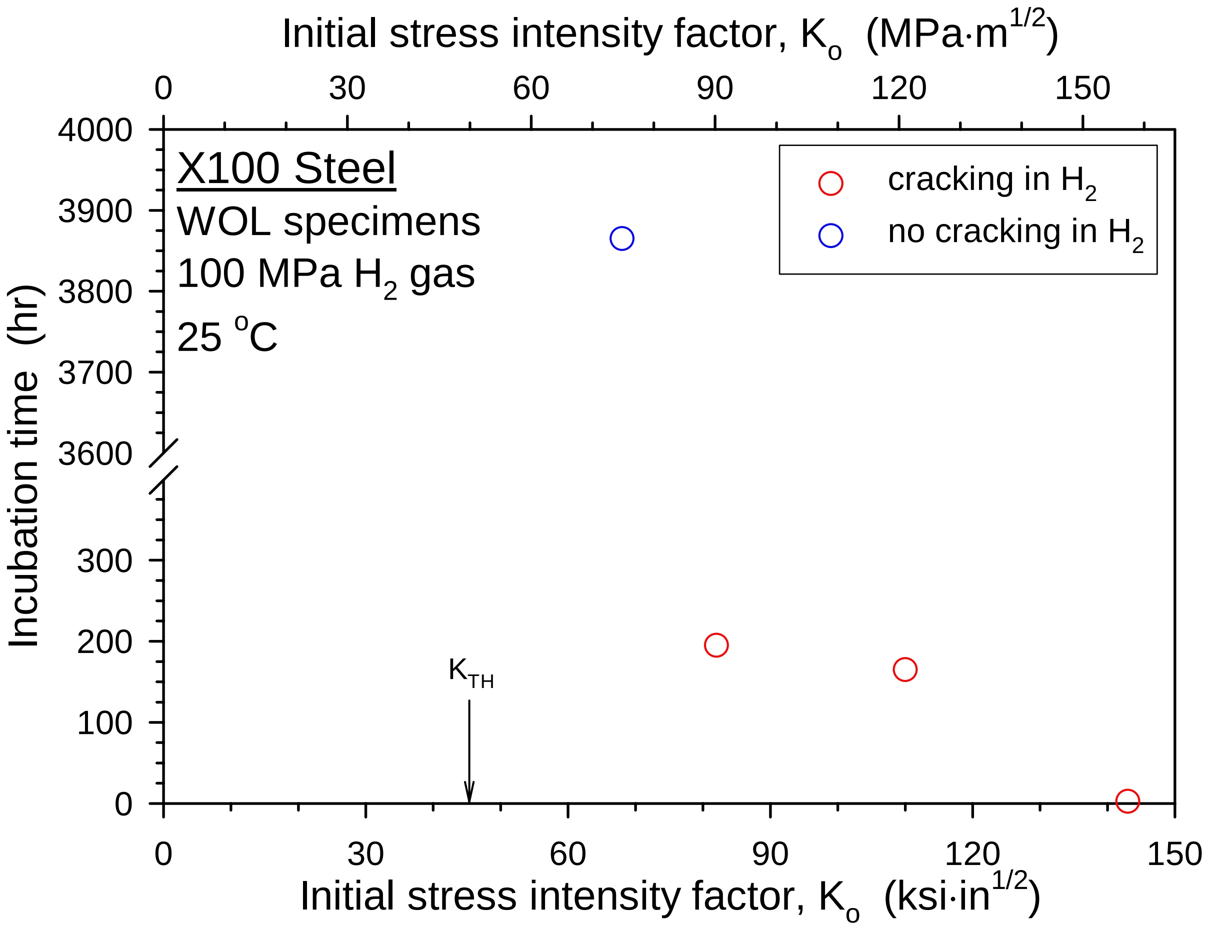
Incubation time for crack extension depends on K_o and hydrogen gas pressure

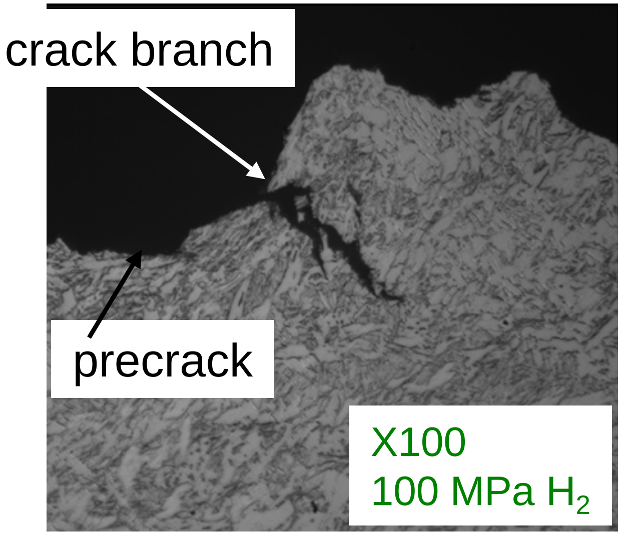


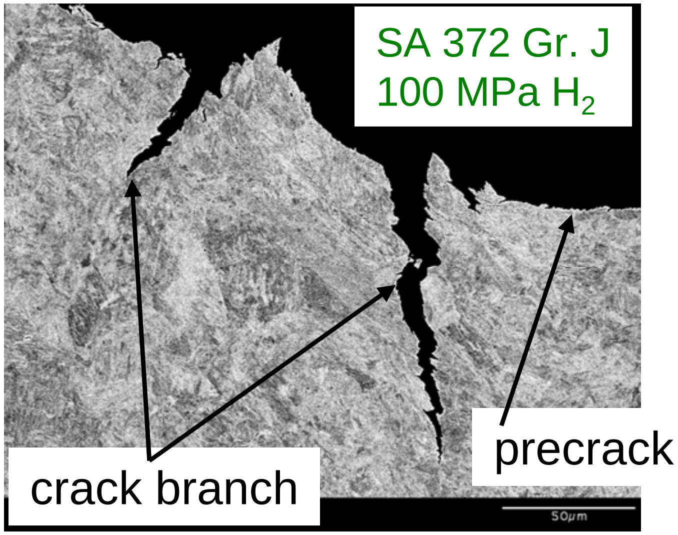


Procedures for measuring sustained-load cracking thresholds should not prescribe arbitrary test durations

Crack branching may account for absence of H_2-assisted crack extension at low K_o

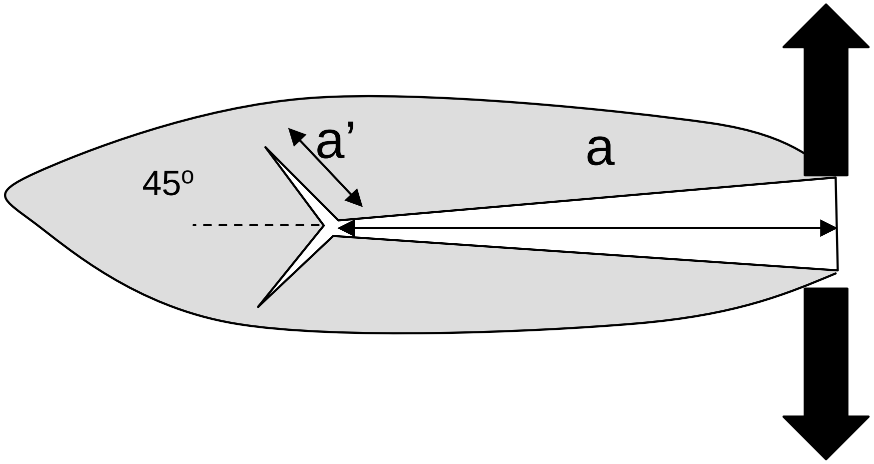






Crack branching shields “applied” K

Example for symmetrical branched crack with a’/a =0.01: K_{local}/K_{app}=.662
(Vitek, *Int. J. Fracture*, 1977)



- K_{local} is the “local” stress intensity factor driving branched crack
- K_{app} is the remote applied stress intensity factor, not accounting for branching
- K_{local}/K_{app}=0.662 implies that the stress intensity factor driving each crack branch may be much less than the intended K_{app}
- $K_{local} > K_{TH}$ for crack to propagate, regardless of K_{app}

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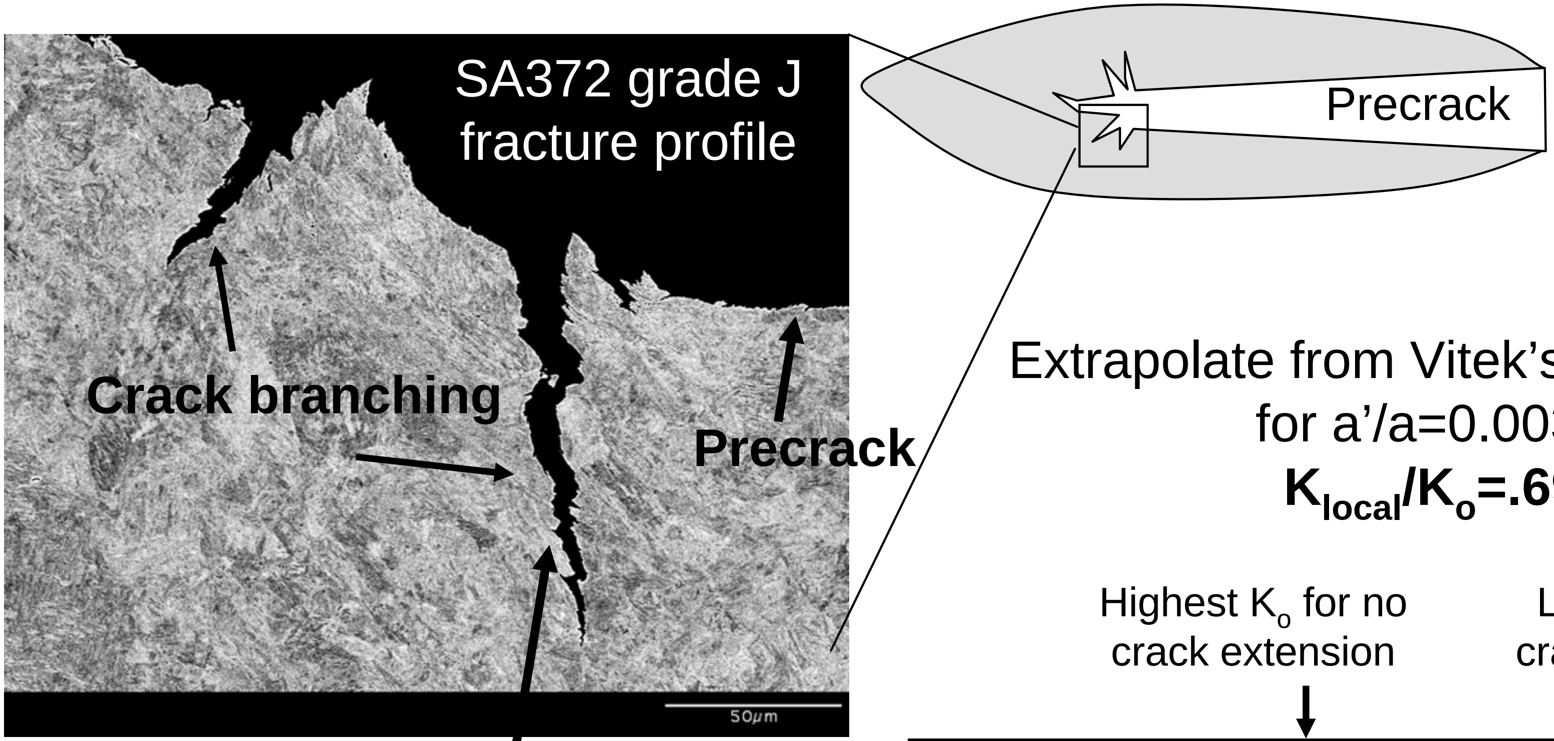
Applied K_o to cause cracking is consistent with branch shielding effects



a=31mm
a'=~.1mm

a'/a=.0033

Extrapolate from Vitek's calculations for a'/a=0.0033

K_{local}/K_o=.69

Highest K_o for no crack extension

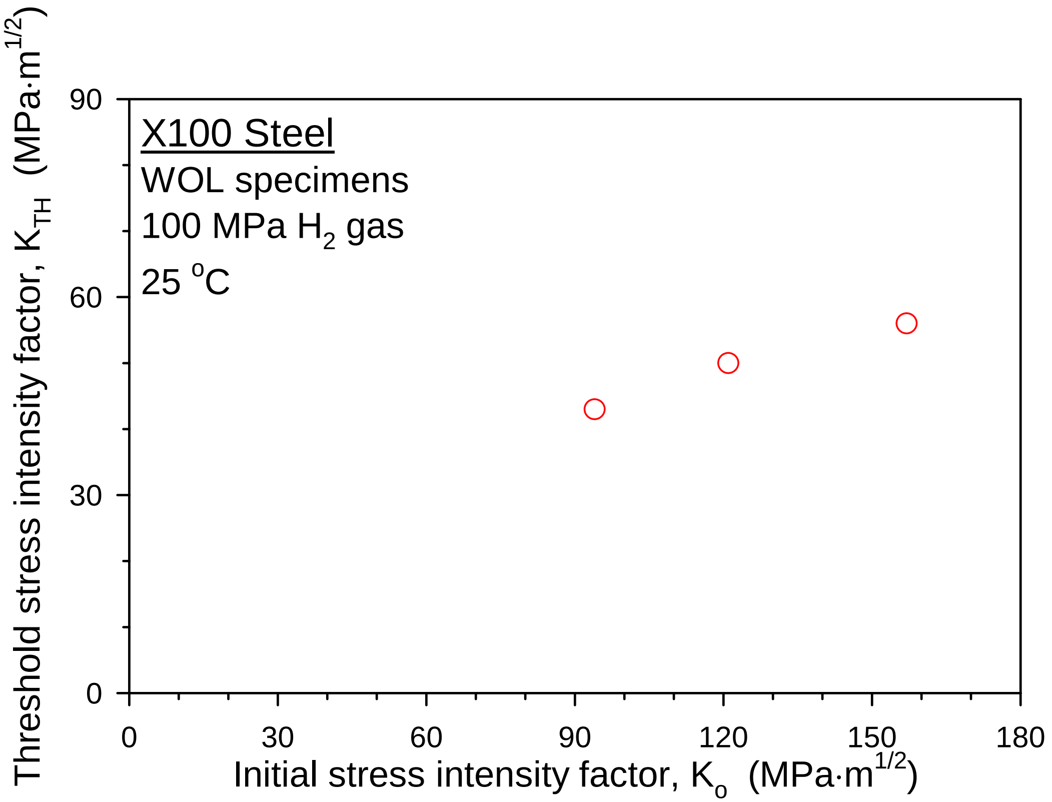
Lowest K_o for crack extension

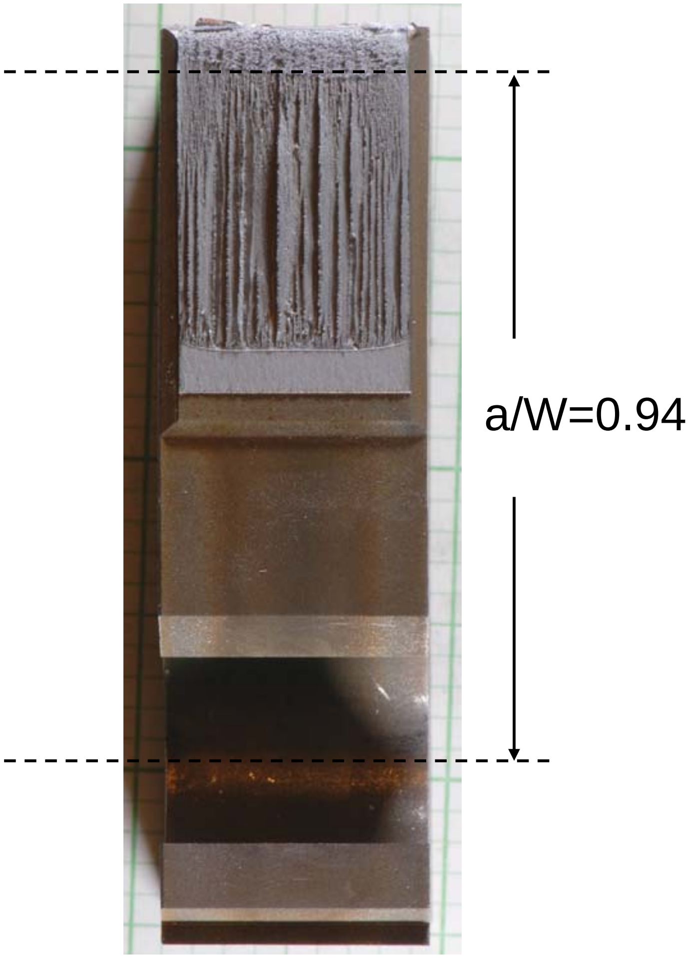
3AAX	$0.62 < K_{th}/K_o < 0.70$
3T	$0.52 < K_{th}/K_o < 0.60$
SA372 grade J	$0.70 < K_{th}/K_o < 0.76$
X100	$0.53 < K_{th}/K_o < 0.67$

→ $K_o > \sim 1.5(K_{TH})$ for $K_{local} > K_{TH}$ ←

K_{local} at crack branch must exceed K_{TH} for crack to propagate

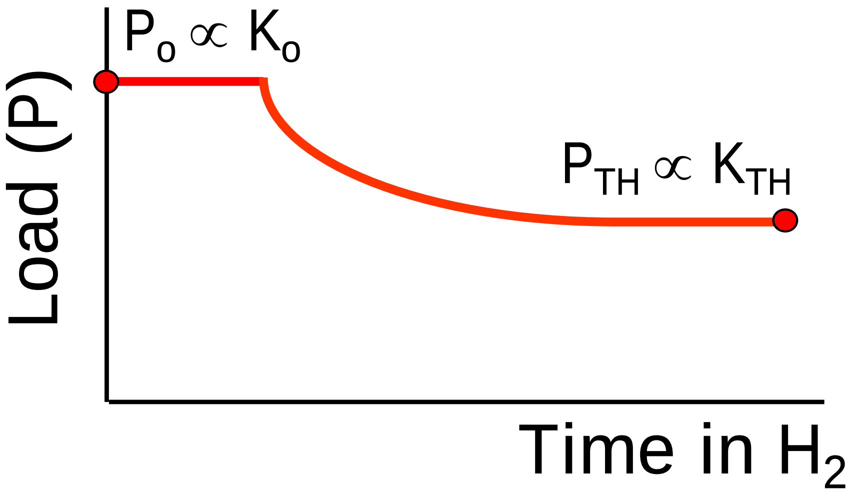
Measured K_{TH} values depend on K_o



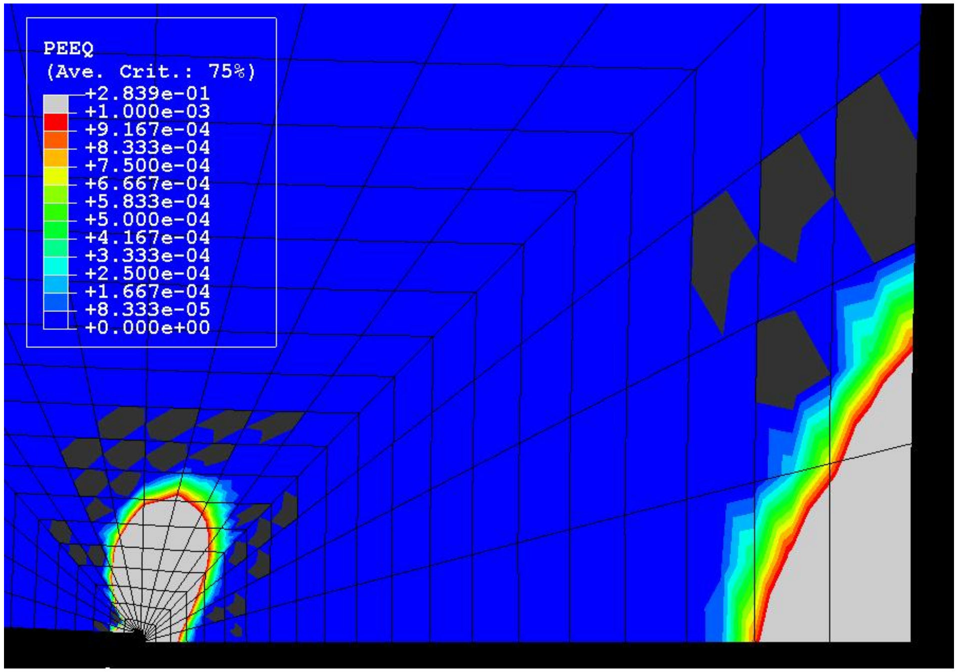


Does proximity of arrested crack to back face of specimen affect K_{TH} measurement?

Mechanics of propagating crack may account for relationship between K_o and K_{TH}



$a/W = 0.941$

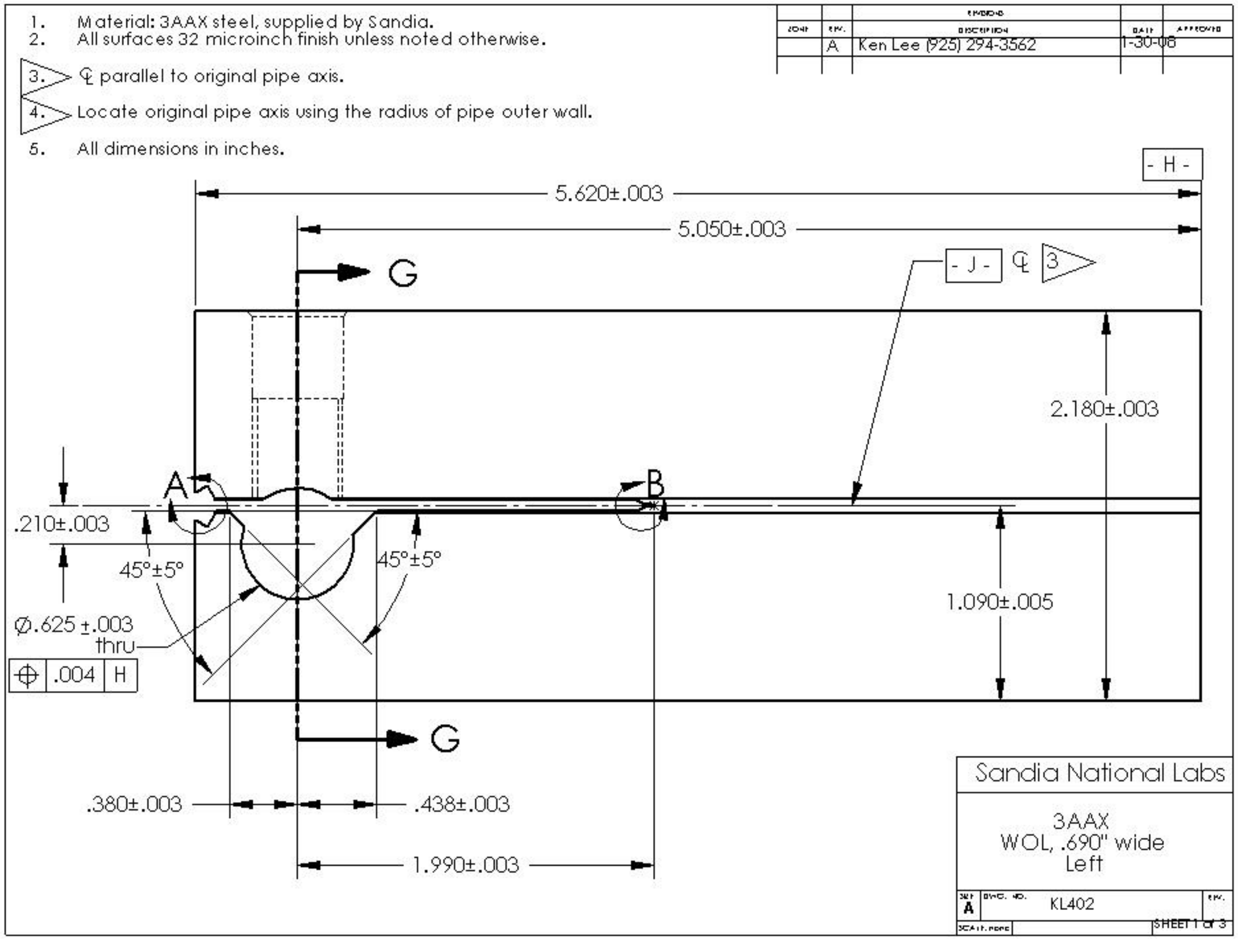


Calculations by M. Dadfarnia and P. Sofronis

Do decreasing K and back-face deformation affect mechanical conditions at tip of long crack?

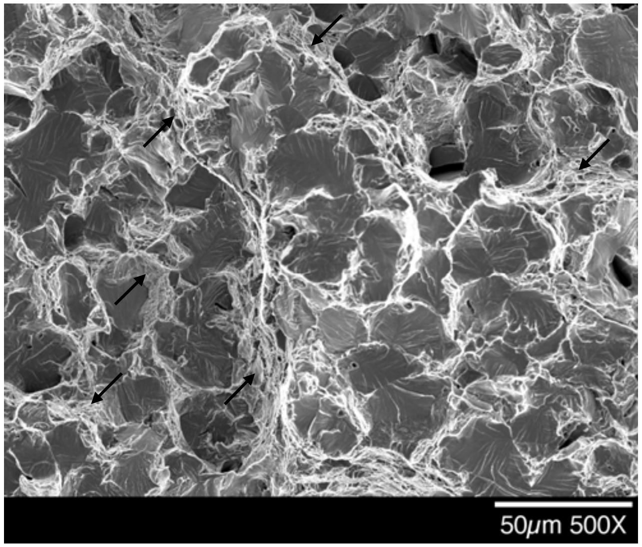
New specimen designed to eliminate effect of K_o

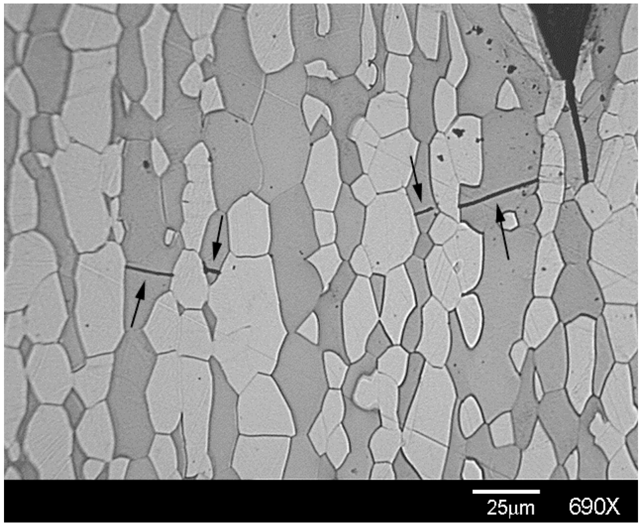
- Increase aspect ratio of WOL specimen to resemble double-cantilever beam (DCB) specimen
  - mitigate back-face deformation
  - increased ligament accommodates more crack extension



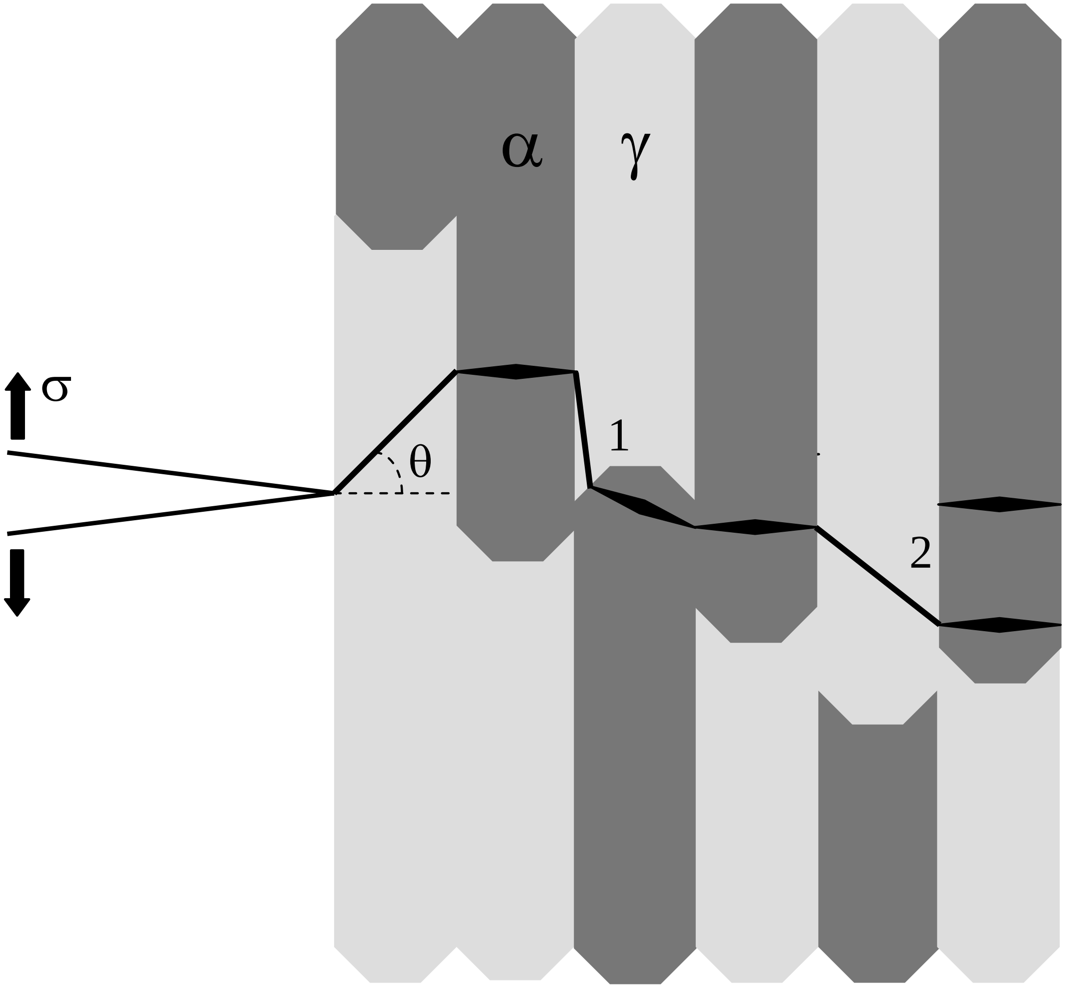
1. Material: 3AAX steel, supplied by Sandia.
2. All surfaces 32 microinch finish unless noted otherwise.
3. ℄ parallel to original pipe axis.
4. Locate original pipe axis using the radius of pipe outer wall.
5. All dimensions in inches.

Physical models of fracture must be established to enable mechanistic hydrogen embrittlement models



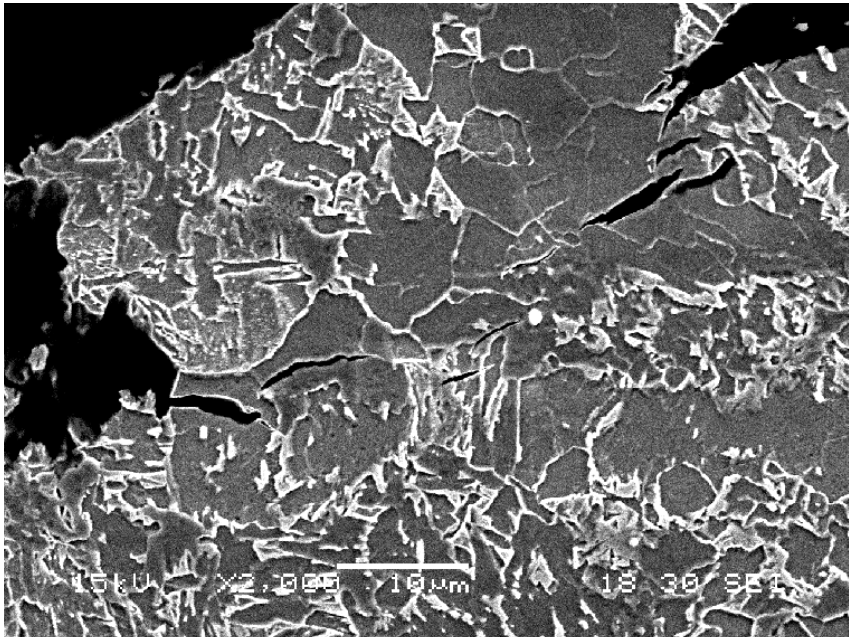


Example: hydrogen-assisted fracture in duplex stainless steel

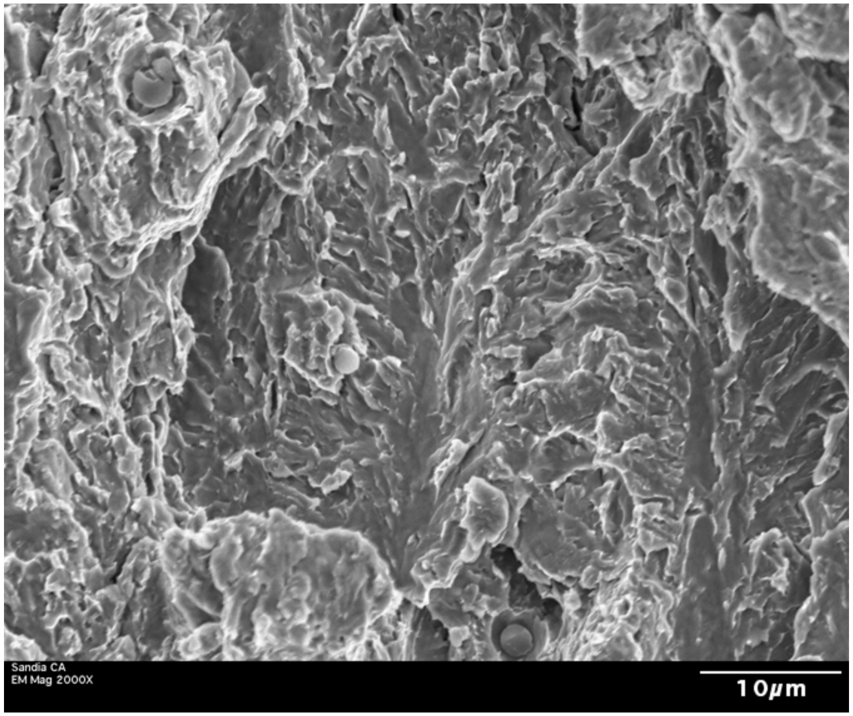


Microscopy evidence used to develop physical model for hydrogen-assisted fracture in X100

X100 in 100 MPa H_2 gas:
crack profile

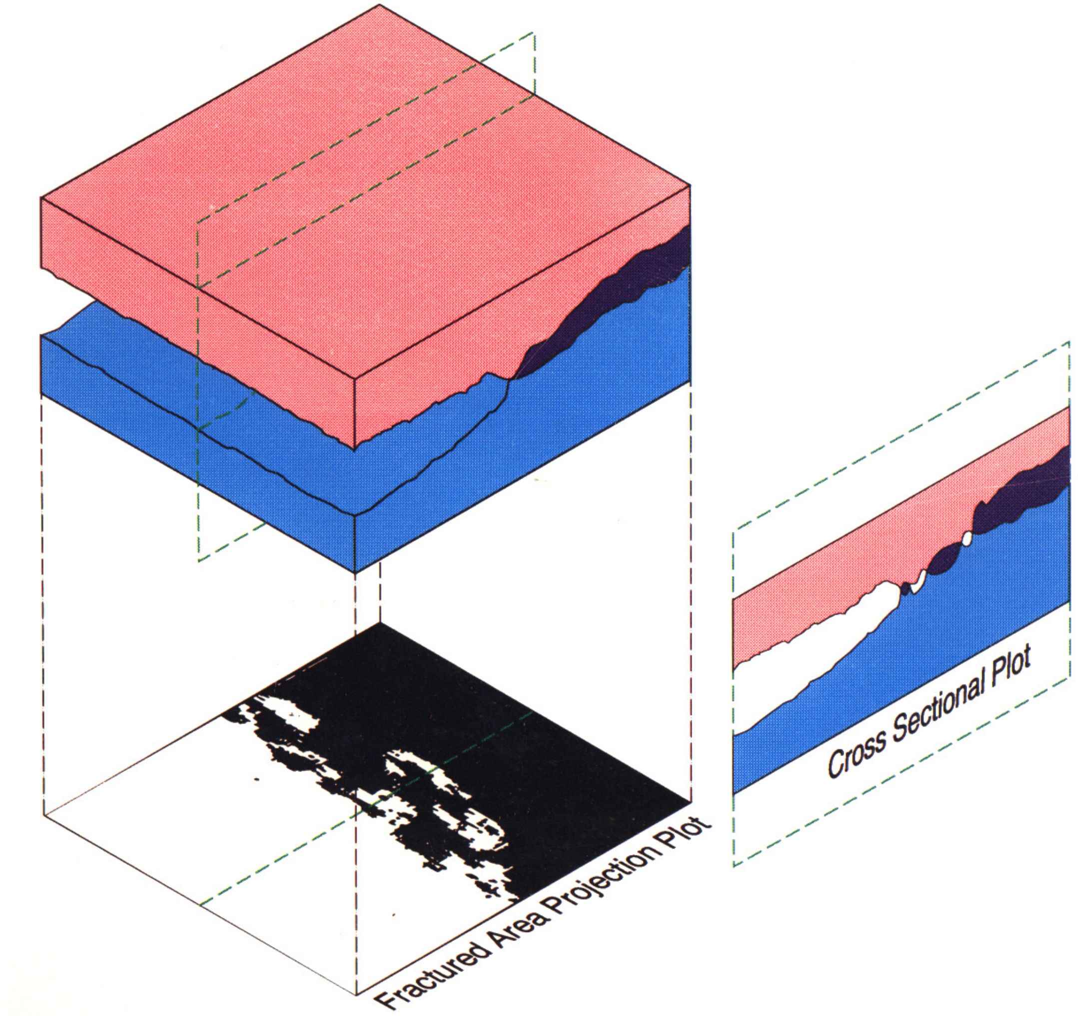


X100 in 21 MPa H_2 gas:
fracture surface



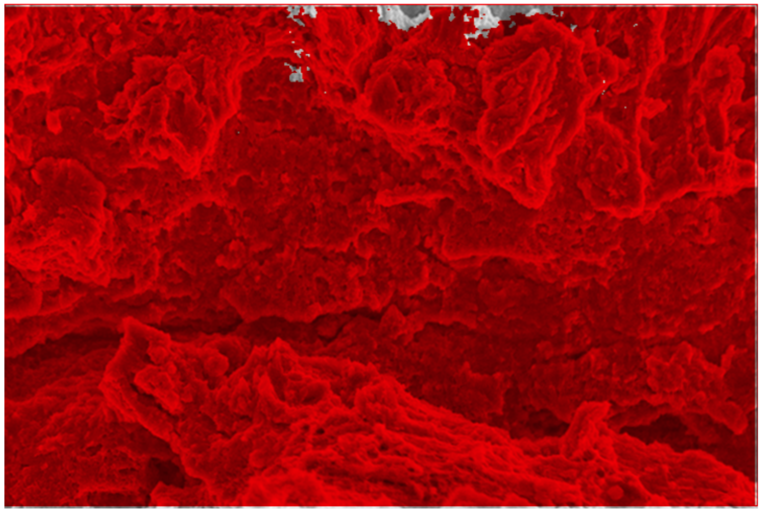
Initial evidence suggests crack propagation involves cleavage fracture in ferrite

FRASTA Operation and Results

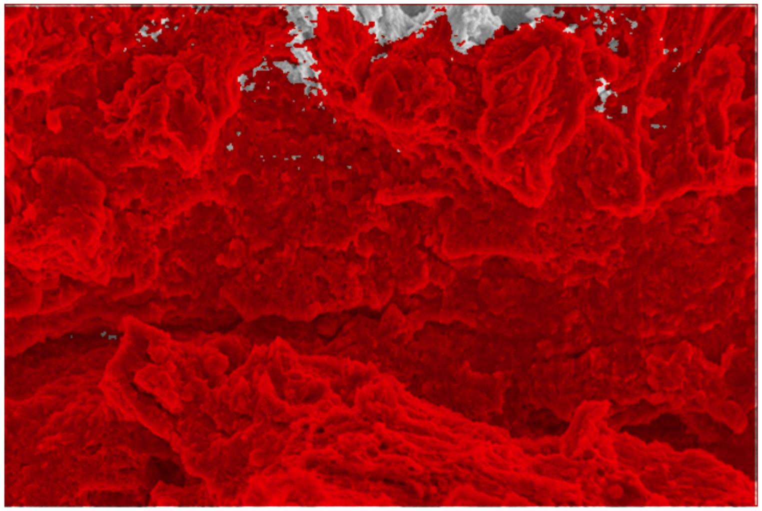


- Fractured Area Projection Plots (FAPPs)
- Cross-sectional Plots (XSPs)
- Fracture Progression Curve (FPC)

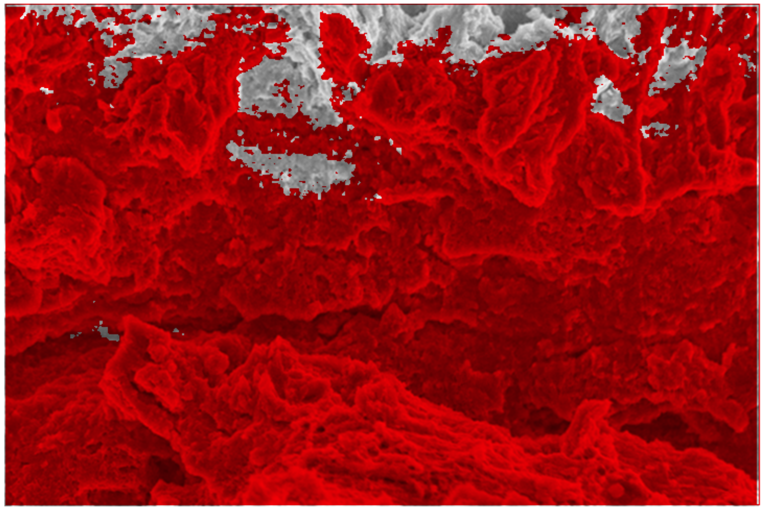
Superposition of FAPPs over SEM (1) (Higher Magnification)



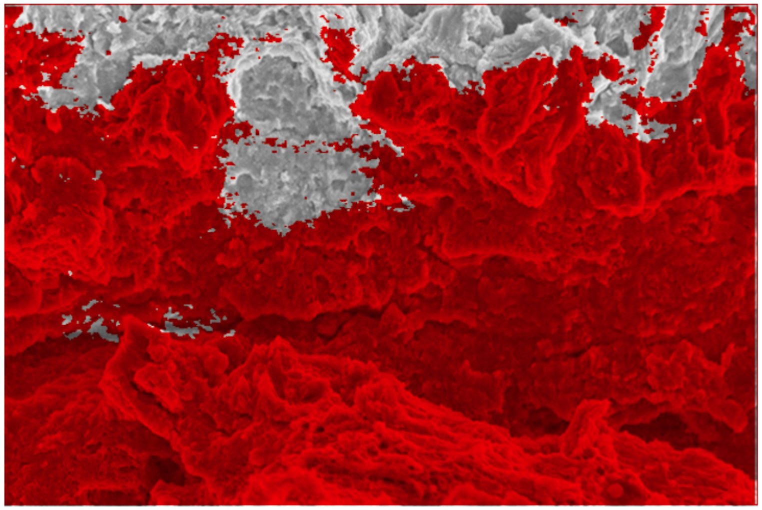
(a) FAPP at 0.320



(b) FAPP at 0.340



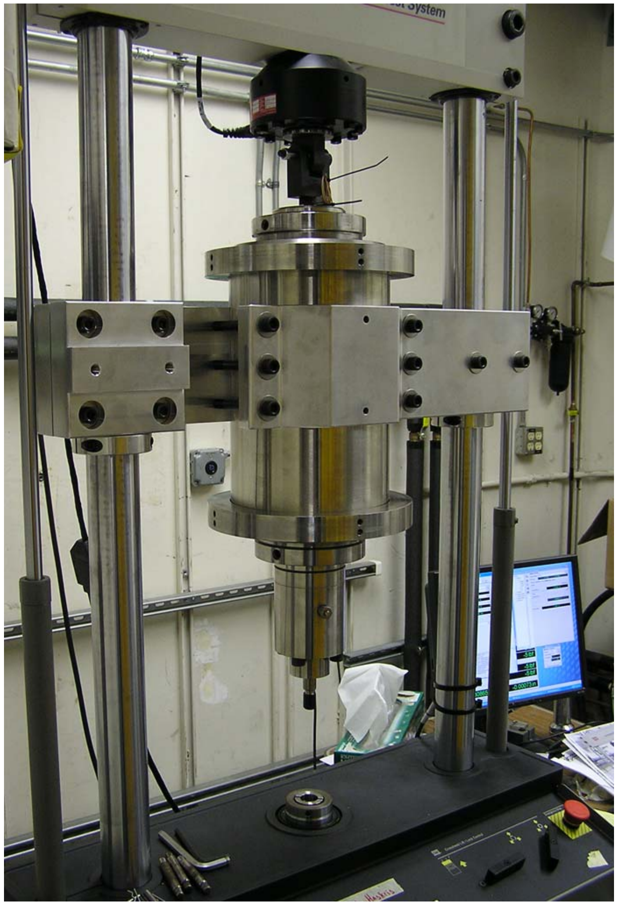
(c) FAPPat 0.360



(d) FAPP at 0.380

System for measuring fatigue crack growth rates in high-pressure 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
  - accurate load measurement
  - effect of high-pressure H_2 gas on instrumentation
  - leak rates at dynamic seals
- Materials data serve as inputs for ASME design methodology in Article KD-10

Summary

- Structural integrity models for hydrogen pipelines require two sets of material data
  - sustained-load cracking thresholds
  - fatigue crack growth rates
- *Conservative* measurements of material properties are needed to ensure reliable safety factors
  - identify variables that affect measurements
- Mechanistic models of hydrogen embrittlement must be based on detailed physical models of fracture