Mechanical Properties of Structural Steels in Hydrogen

B.P. Somerday, K.A. Nibur, C. San Marchi, and M. Yip
Sandia National Laboratories
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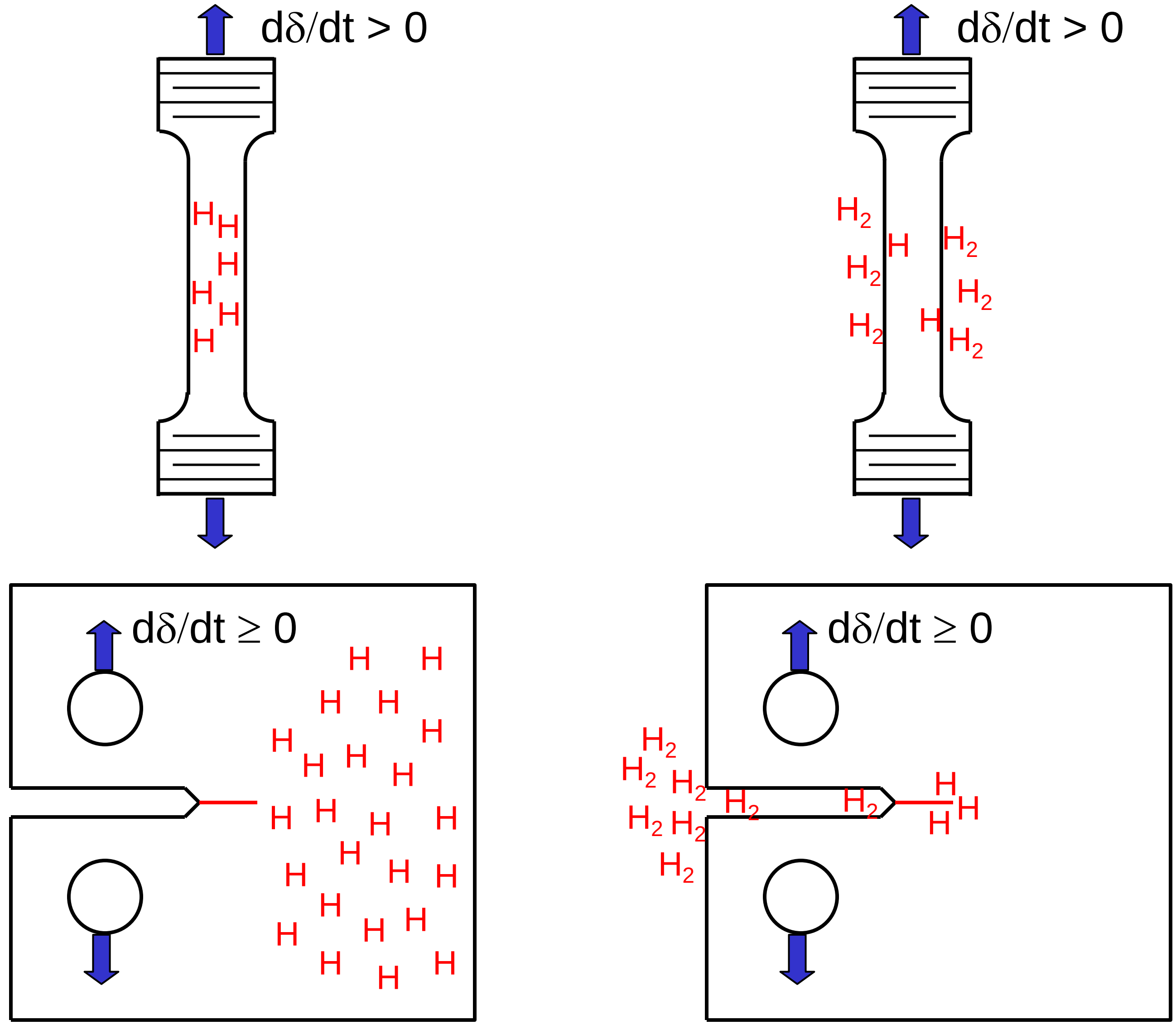
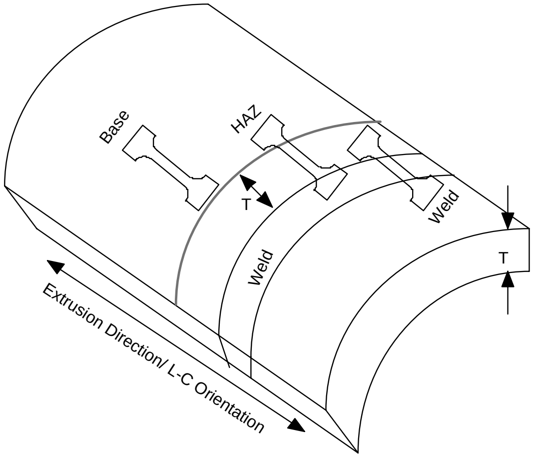
Methods for measuring mechanical properties of structural steels in hydrogen

strength of materials:
σ_{UTS}, σ_{YS}, ε_f, RA

fracture mechanics:
K_{IH}, K_{TH}



Tensile Testing Carbon Steel in H_2



- Alloys: 106 Grade B
- Multi-pass SMAW w/out stress relief
- Specimens machined in 3 conditions: Base metal, Weld and HAZ
- Orientation: L-C
- Atmosphere: 10.3 MPa H_2, ambient pressure Air
- Strain Rate: 10^{-4} /sec
- # of samples per matrix point: 6
- Argon purge followed by H_2 pressurization
- Soak (30 min.) at pressure
- Test to failure

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Tensile Properties

- Mechanical Properties

		Average Properties							
		0.2%Yield (MPa)	Dev.	UTS (MPa)	Dev.	Elong. at failure	Dev.	Reduction of Area (%)	Dev.
Base	Air	355.3	15.8	484.6	8.6	0.29	0.04	68.6	1.5
	H_2	357.1	32.9	486.4	17.8	0.19	0.04	30.8	5.0
Weld	Air	343.0	20.0	490.4	9.0	0.28	0.01	74.9	2.2
	H_2	350.0	16.1	480.9	12.0	0.21	0.02	30.5	6.4
HAZ	Air	349.3	20.8	482.3	7.6	0.27	0.04	71.0	1.7
	H_2	338.2	18.5	475.5	9.6	0.19	0.04	30.4	6.8

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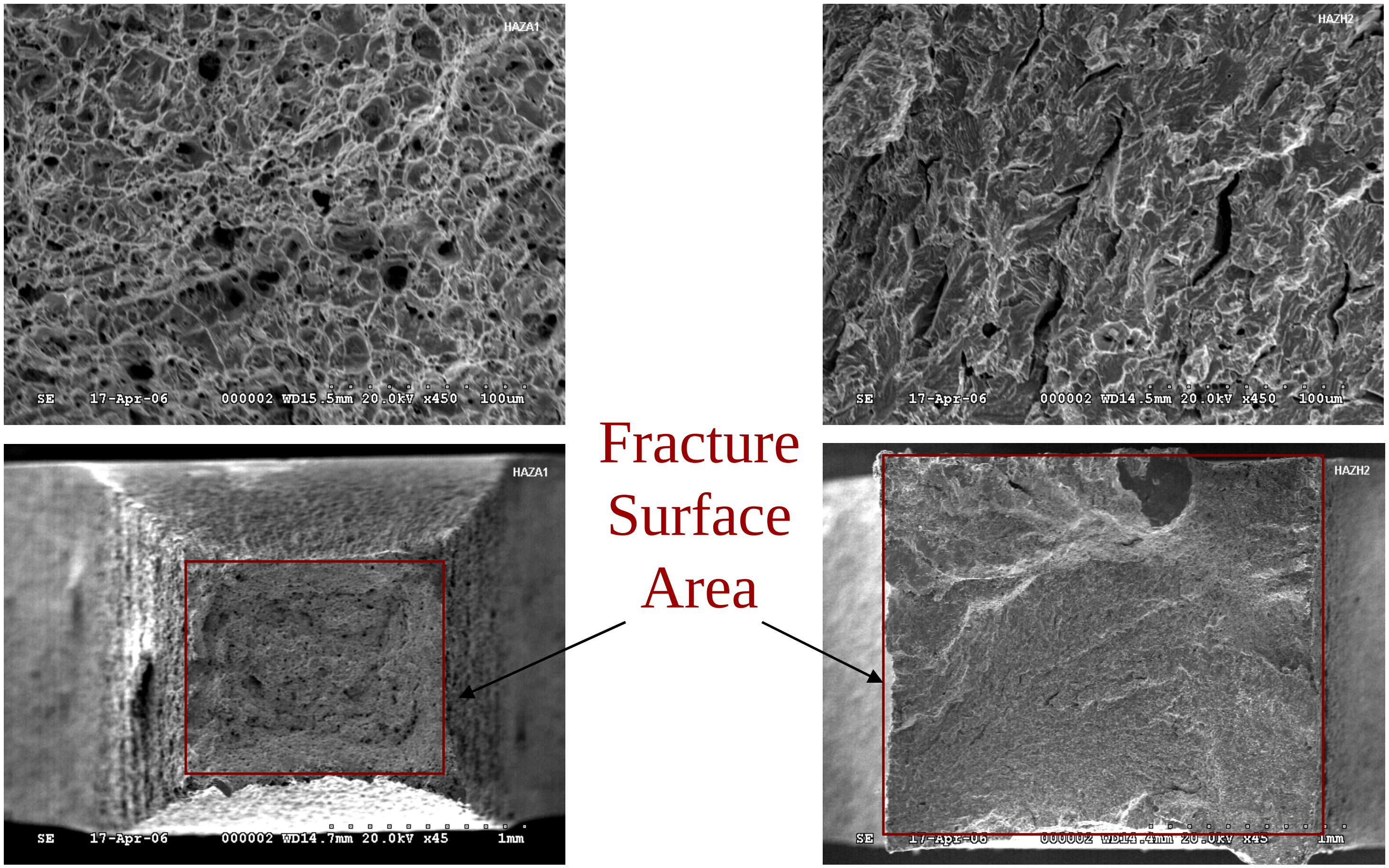
Fractography



Air **Hydrogen**

HAZ Samples

Reduction of Area reduced when tested in hydrogen

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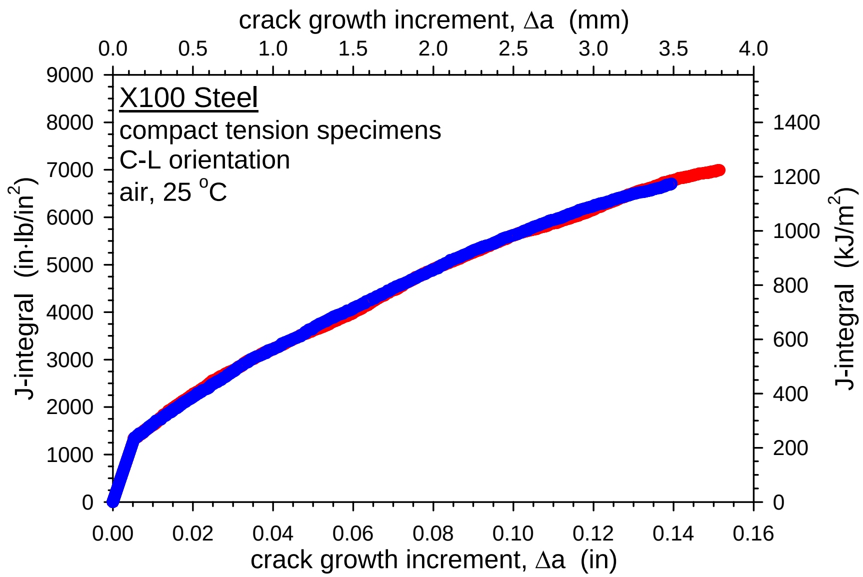
Crack propagation resistance of X100 steel

- Alloy composition

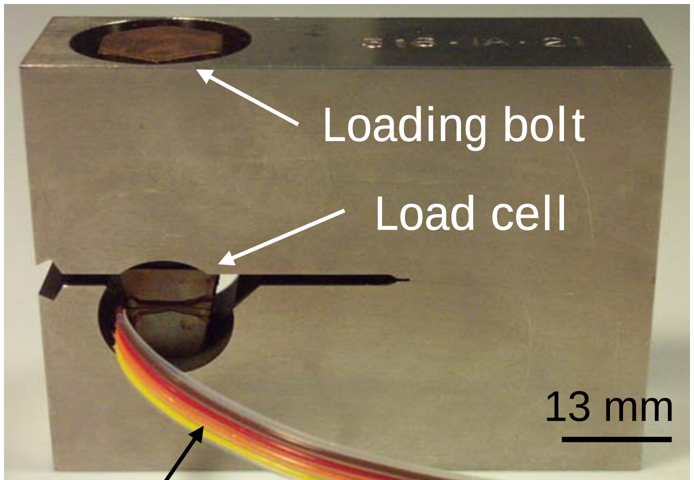
C	Mn	Si	P	S	Ti	V	Ni	Cu	Mo	Cr
0.073	1.86	0.11	0.009	<0.002	0.01	<0.005	0.48	0.27	0.17	0.02

- Yield strength
  - 96 ksi (662 MPa) in longitudinal orientation
  - 114 ksi (787 MPa) in circumferential orientation
- Crack growth resistance curves in air

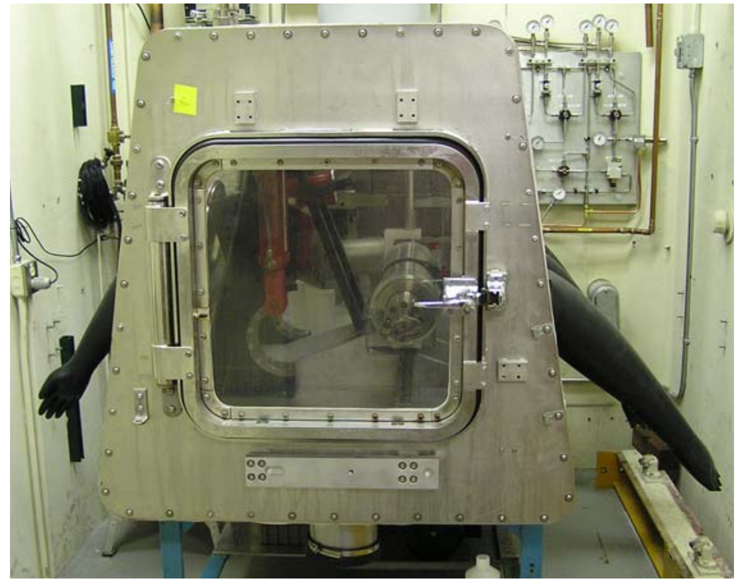


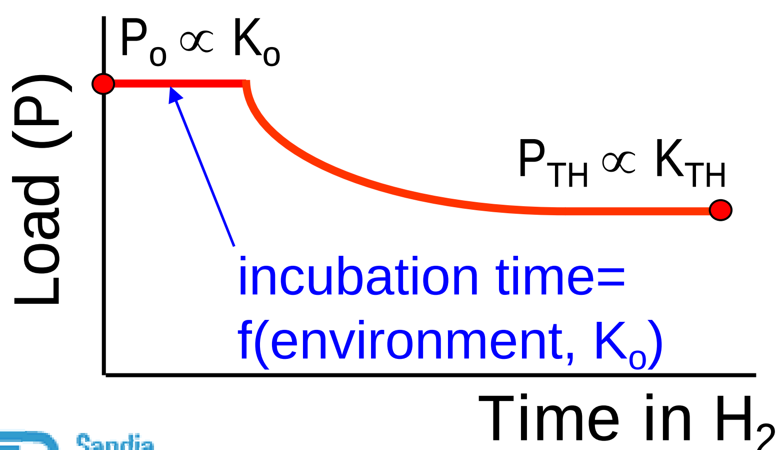
Measurement of sustained-load cracking thresholds

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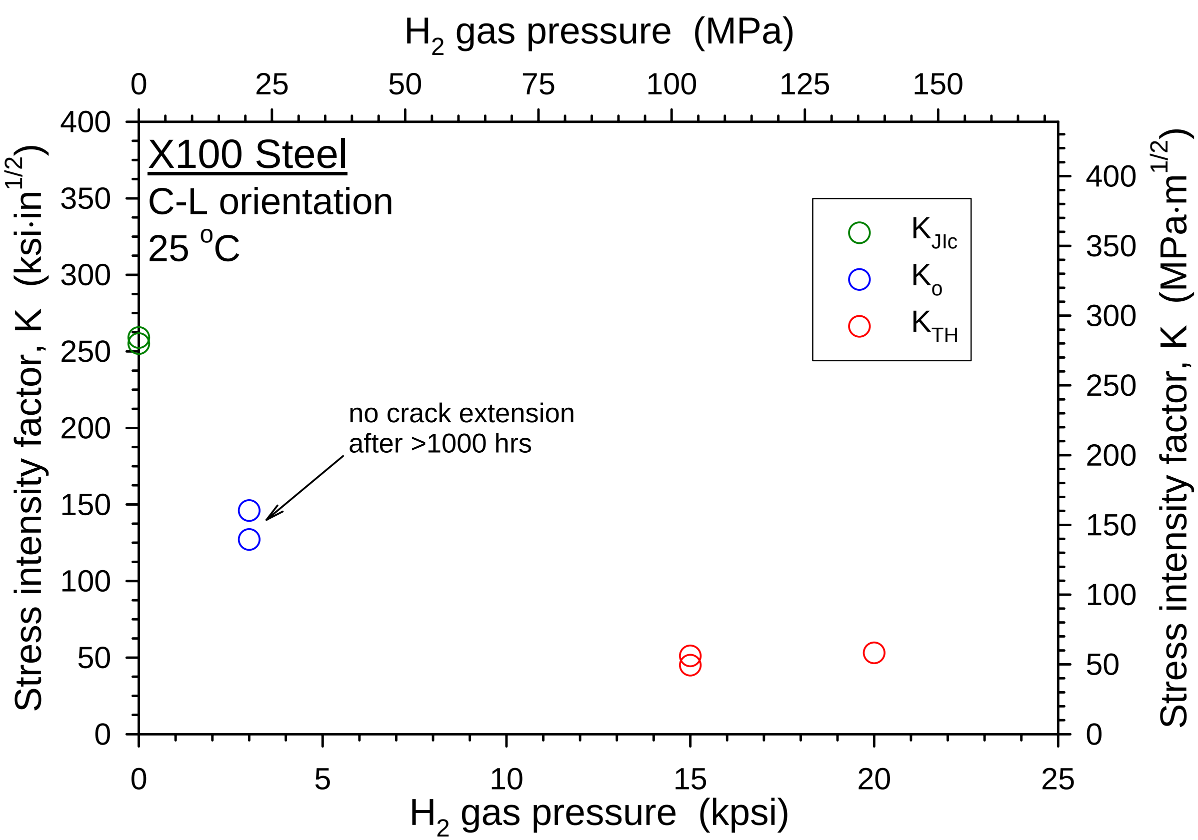
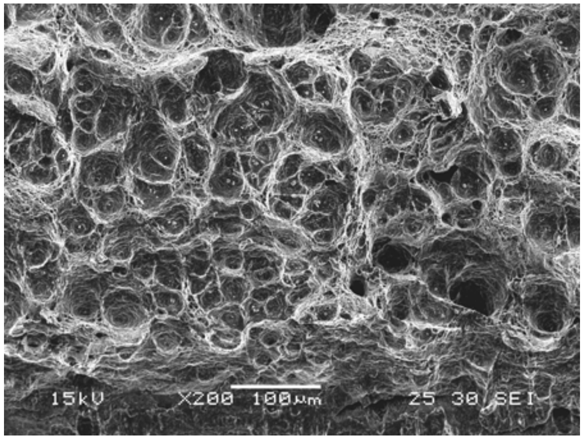
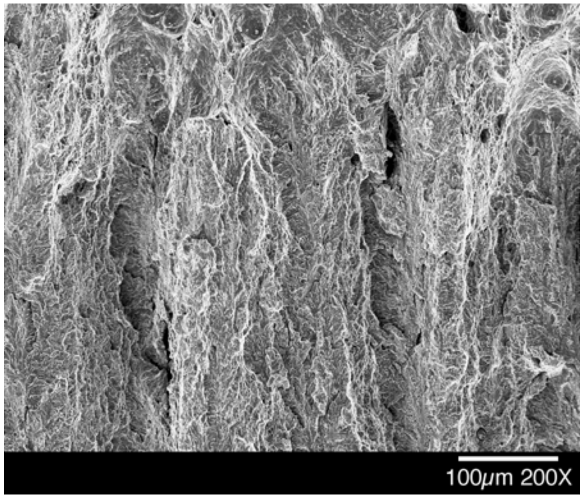
High-pressure H_2 gas severely degrades crack propagation resistance of X100 steel



X100 in air



X100 in 15 kpsi H_2 gas



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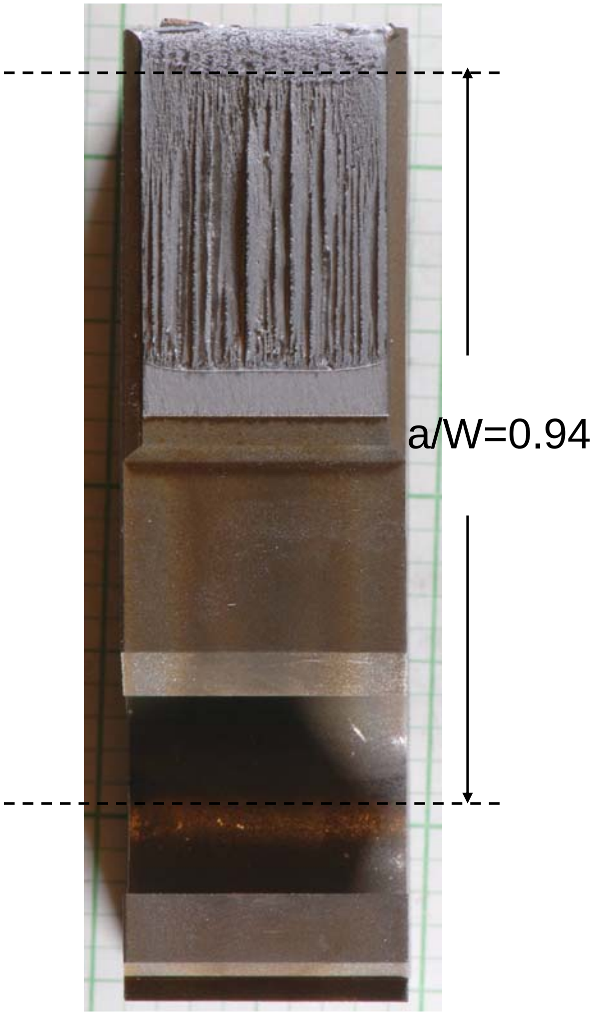
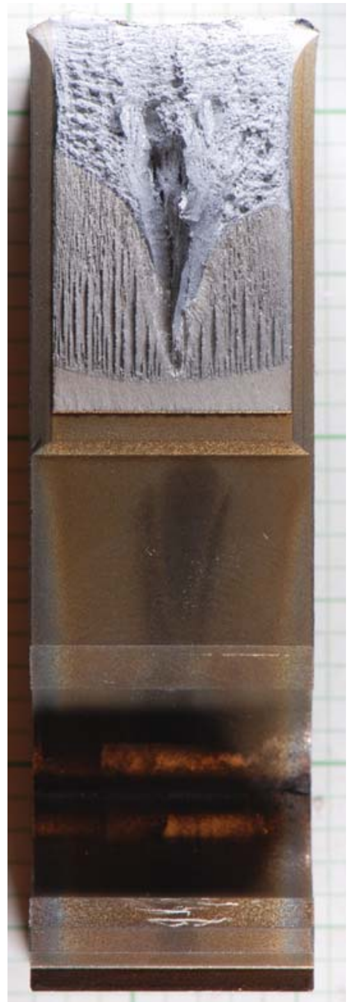
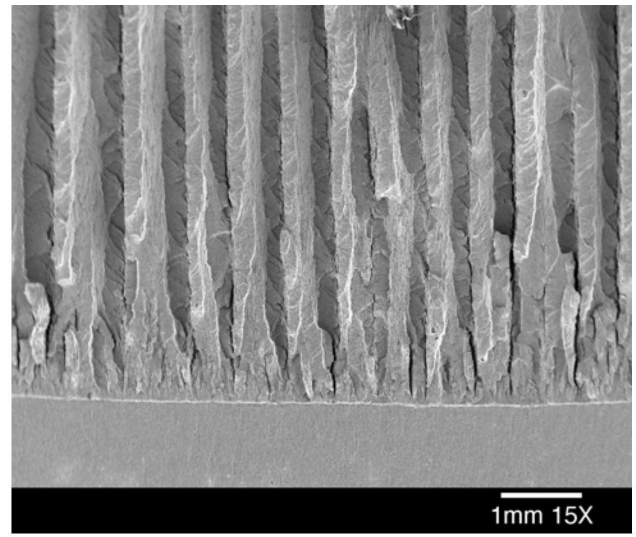
Images of fracture surfaces from X100 tested in H_2 show long crack lengths and delaminations





H_2-assisted crack extension from precrack



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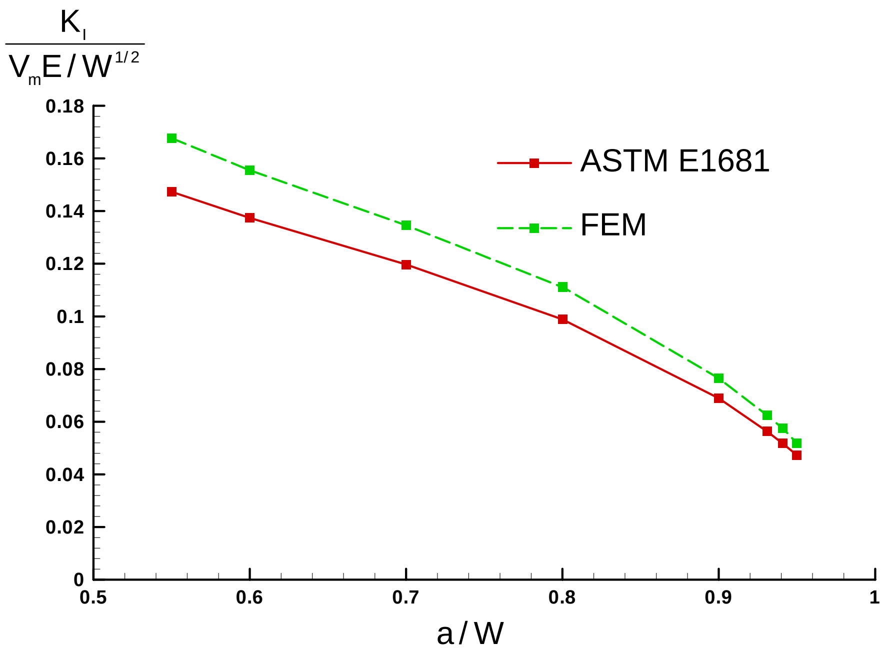
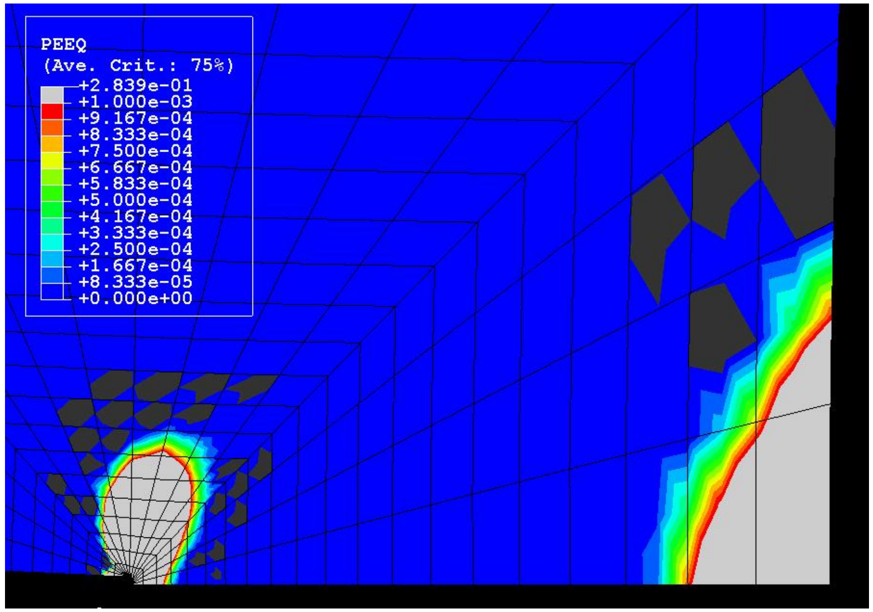
FEM calculations verify K solution and demonstrate K dominance for long cracks in WOL specimen



$a/W = 0.941$



ASTM E1681: $K_I = 57.5\,\mathrm{MPa}\sqrt{m}$

FEM elastic: $K_I = 63.8\,\mathrm{MPa}\sqrt{m}$

FEM plastic: $J = 16.0\,\mathrm{kJ/m^2}$

$$K_{IJ} = \sqrt{\frac{JE}{1-\nu^2}} \qquad K_{IJ} = 62.2\,\mathrm{MPa}\sqrt{m}$$

Calculations by M. Dadfarnia and P. Sofronis

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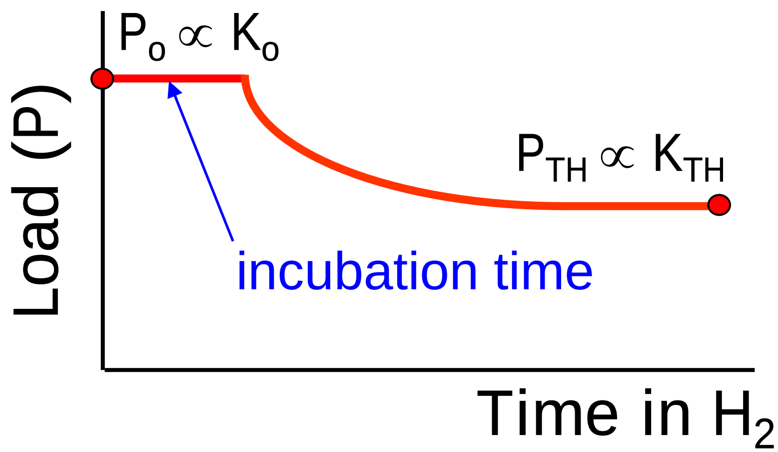
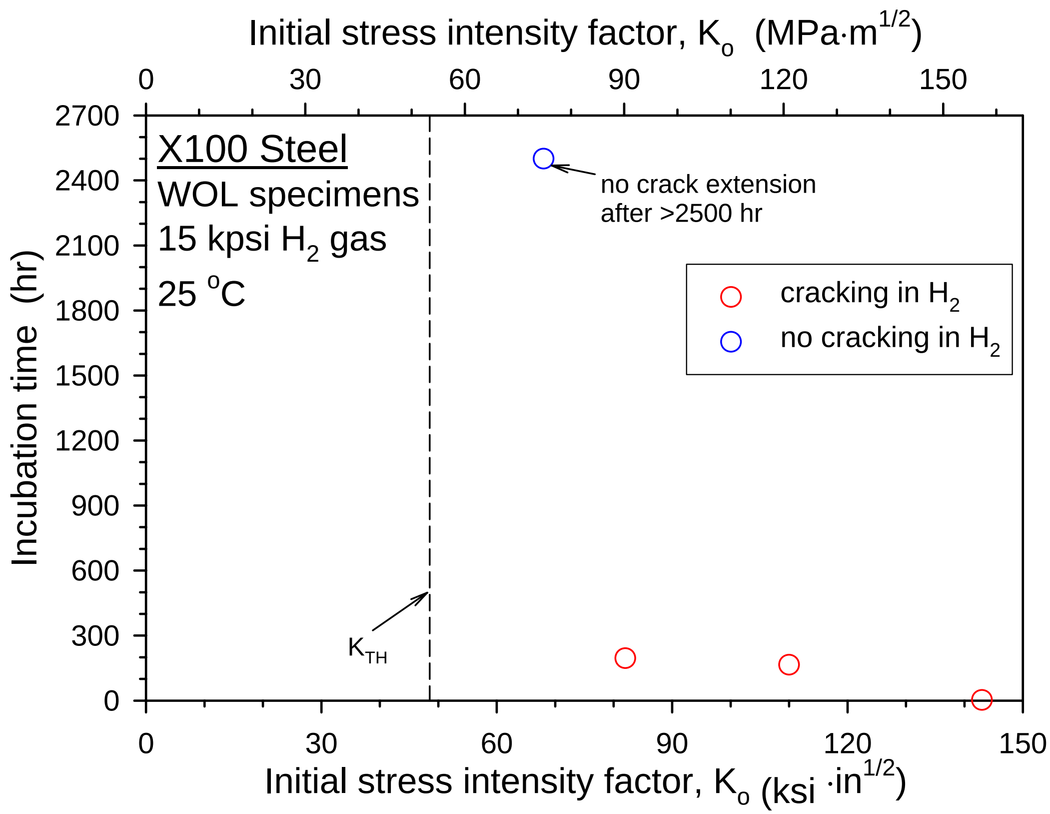
Incubation time for crack extension depends on K_o





Measurement of sustained-load cracking threshold in H_2 cannot be assured unless crack propagates

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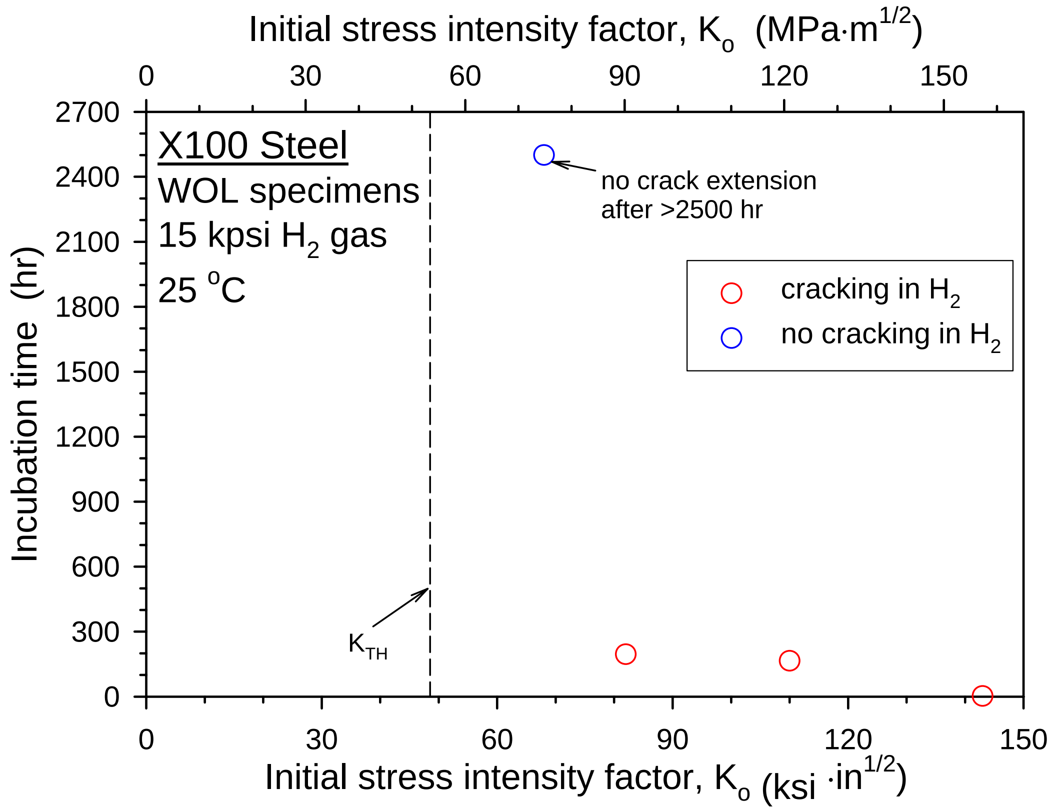
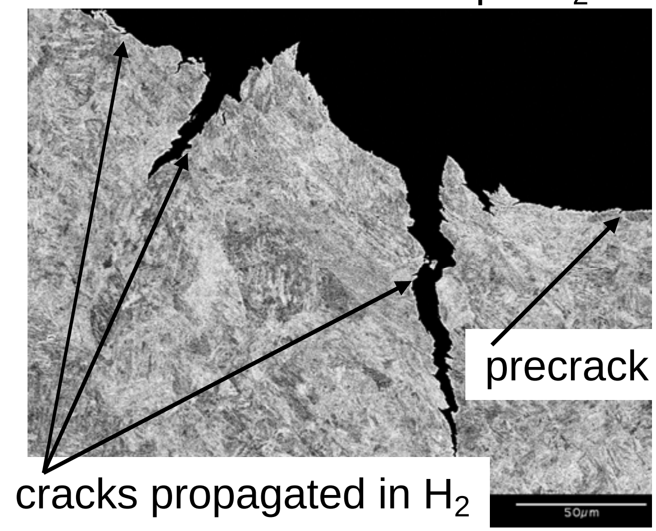
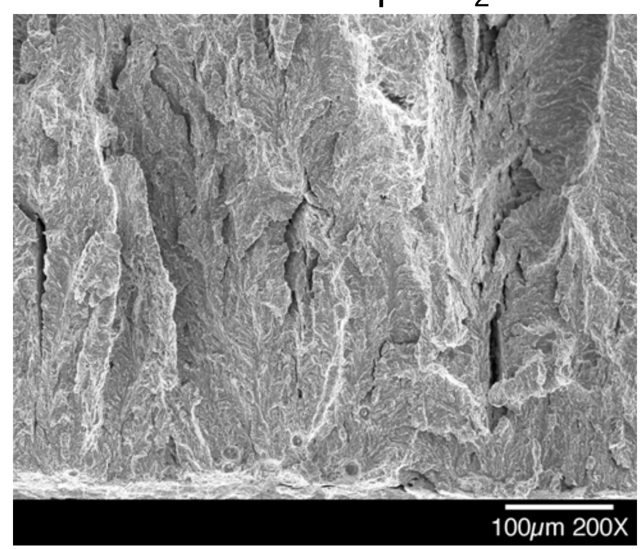
Crack branching may account for no crack extension in specimens with $K_o > K_{TH}$



SA 372 Gr. J in 15 kpsi H_2



X100 in 15 kpsi H_2



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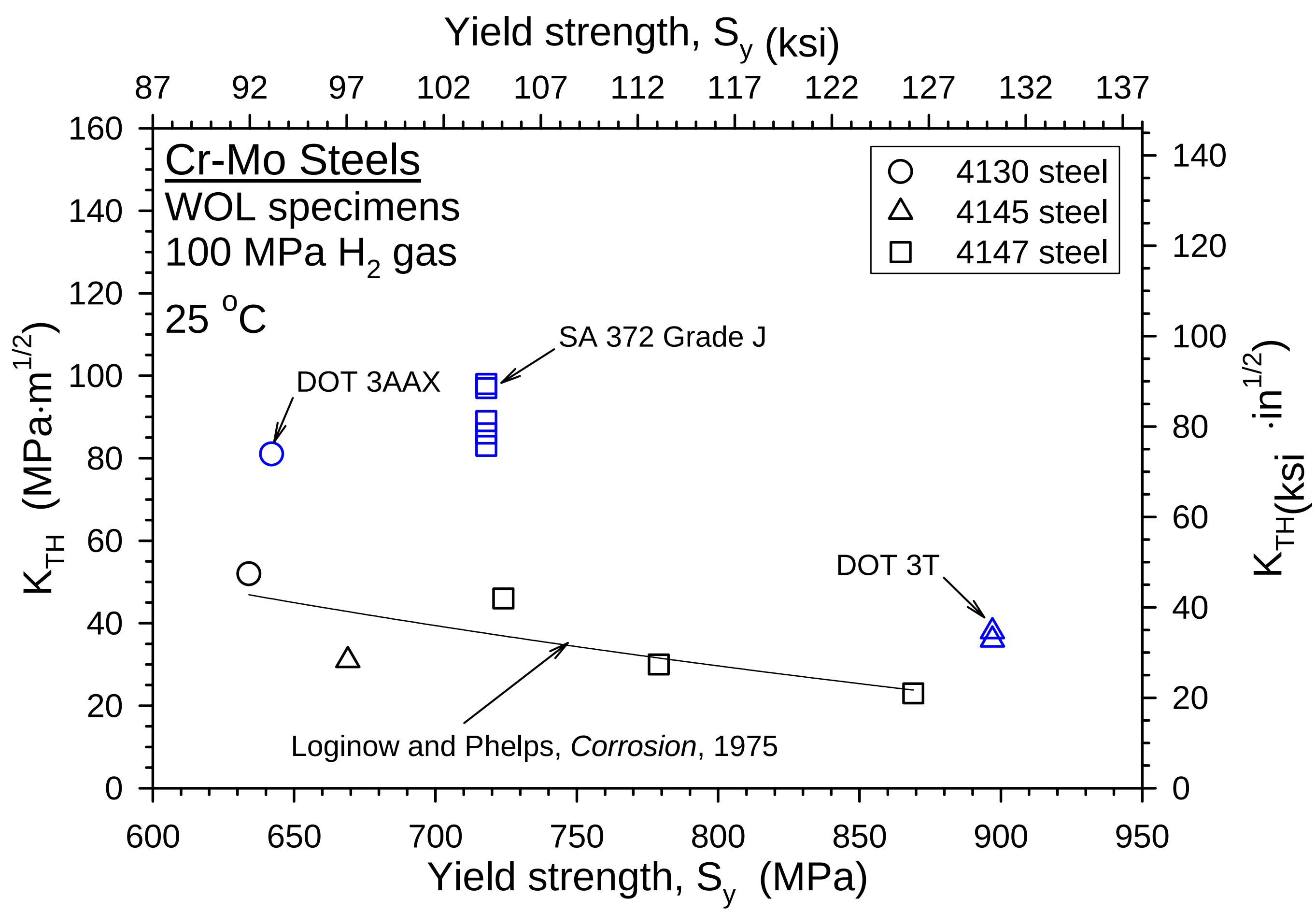
Low-alloy steels for pressure vessels: sustained-load cracking thresholds in H_2 gas



Thresholds in modern Cr-Mo steels are higher than thresholds in older steels

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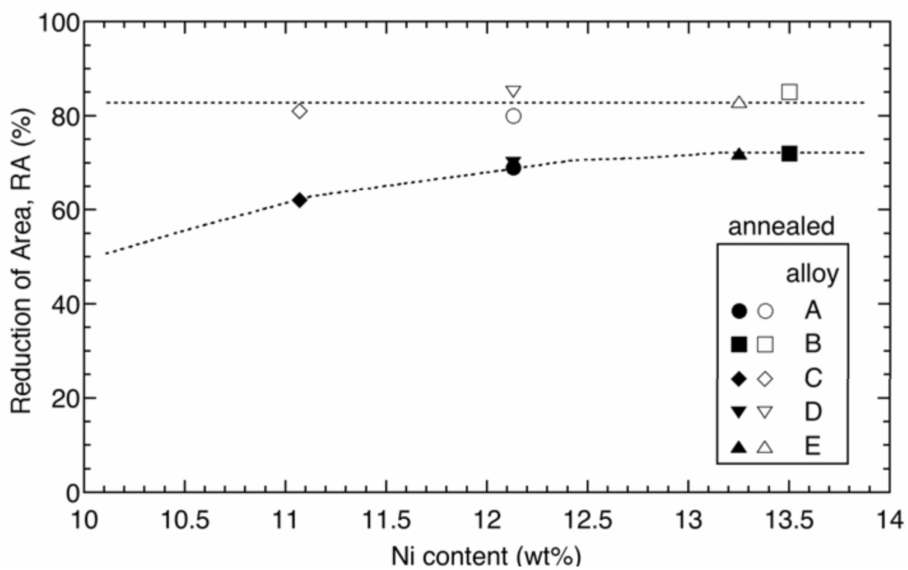
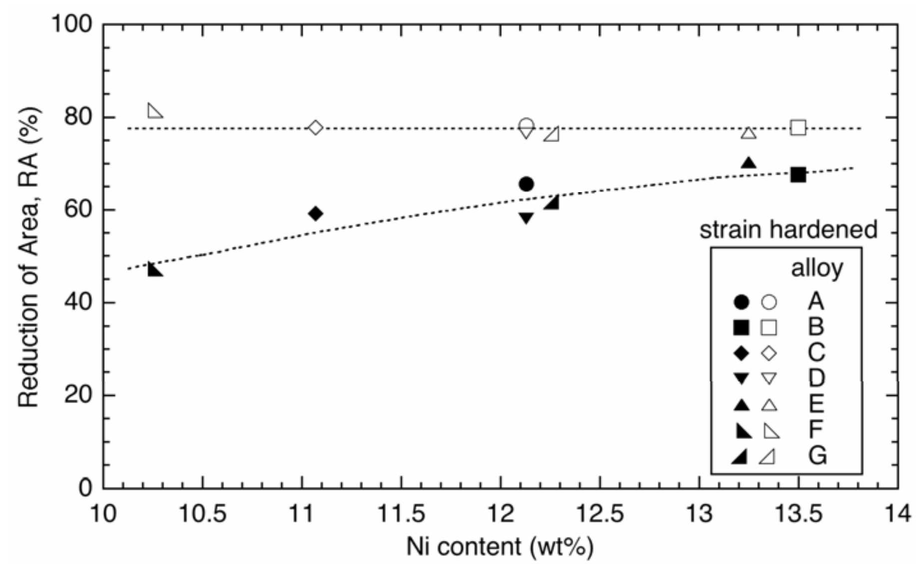
Stainless steels for piping: tensile fracture results for specimens precharged in hydrogen gas

316 stainless steels with ~140 wppm hydrogen





Tensile fracture resistance of H-precharged specimens is sensitive to nickel content but not strain hardening

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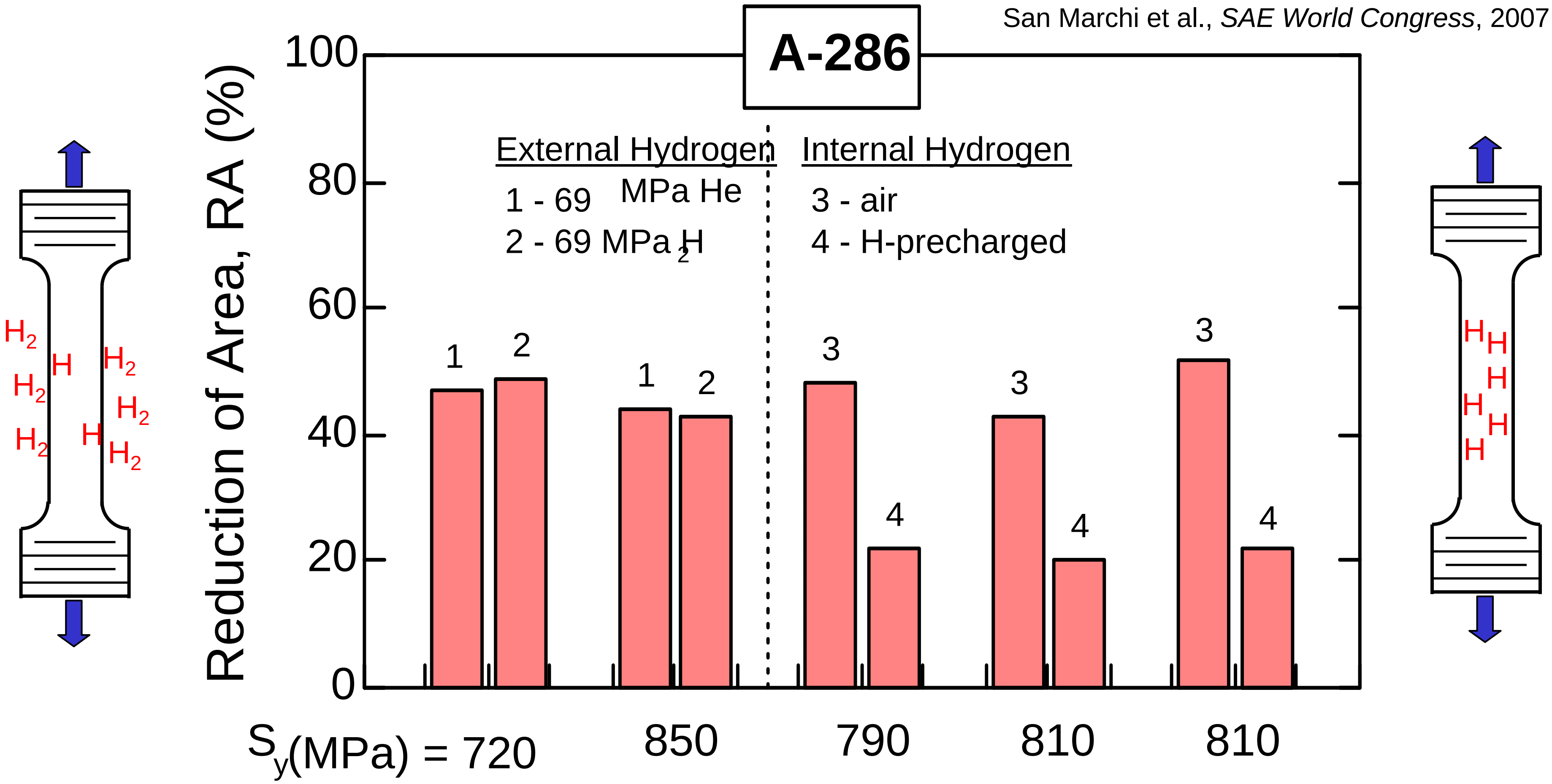
Stainless steels tested in hydrogen gas *vs* precharged show different tensile fracture behavior

San Marchi et al., *SAE World Congress*, 2007



Stable stainless steels may not exhibit loss in RA when strained in H_2 due to limited H uptake

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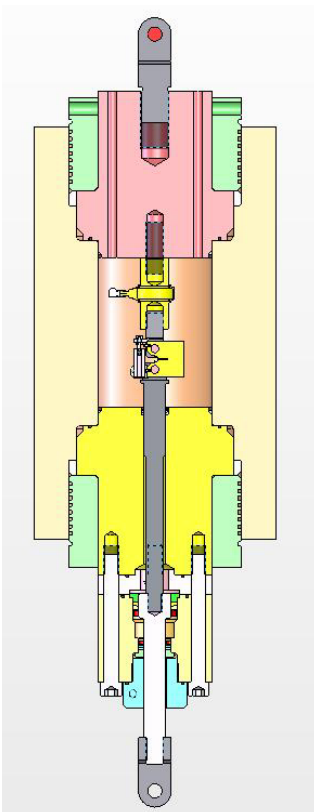
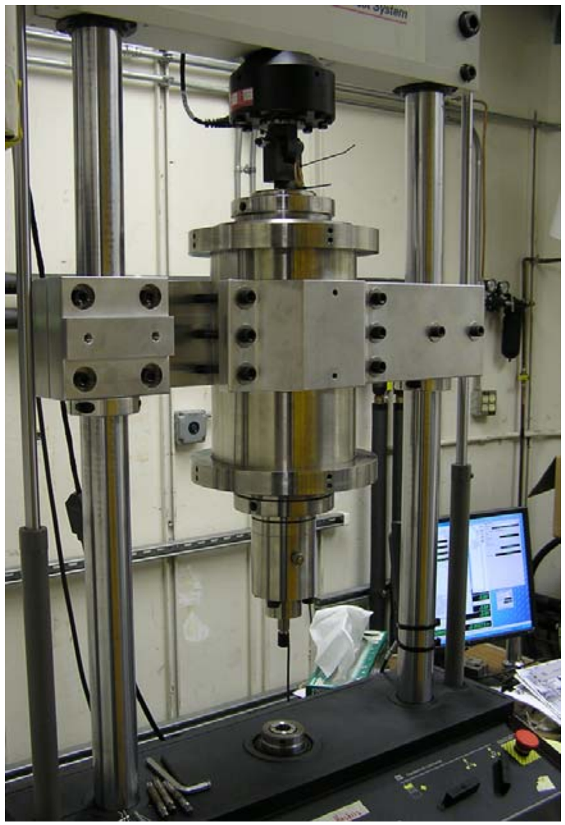
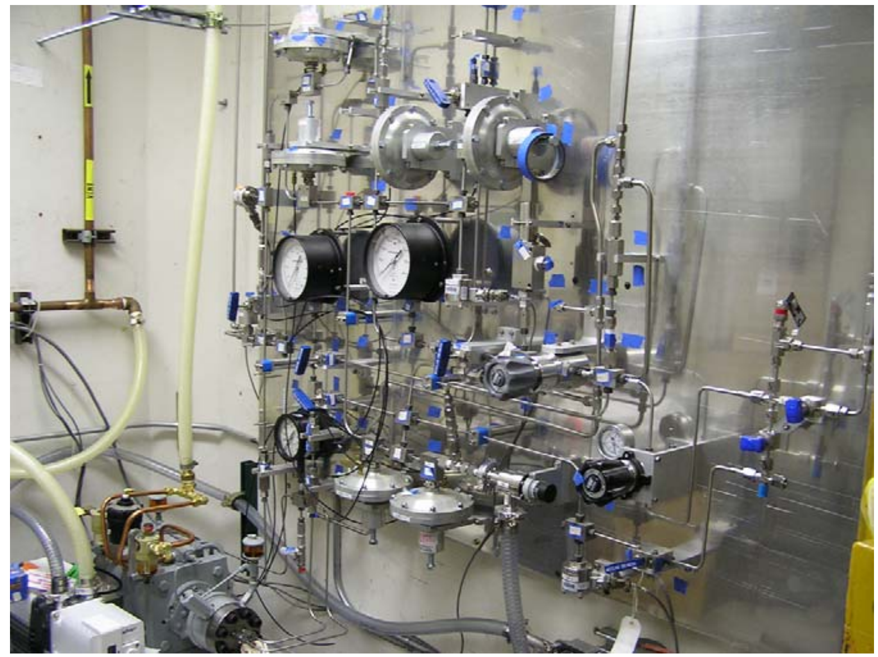
System for measuring fatigue crack growth in high-pressure H_2 nearly complete



vessel on mechanical test frame



gas manifold



- Pressure vessel can contain H_2 gas up to 20 kpsi (138 MPa)

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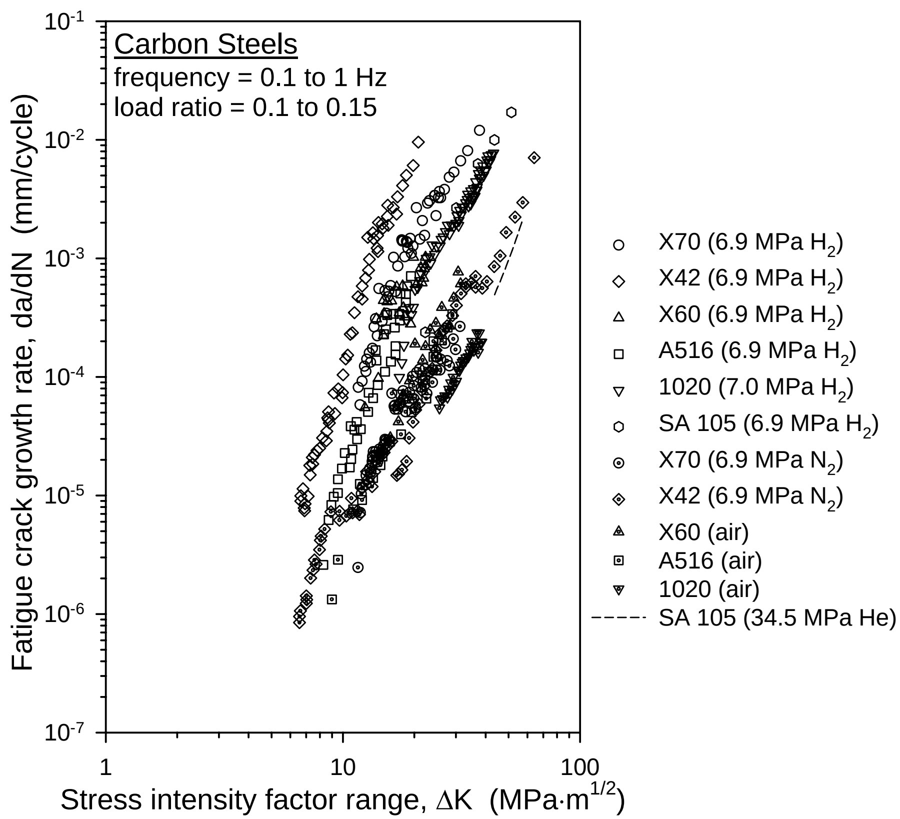
What is metric for qualifying steels for H_2 pipelines?

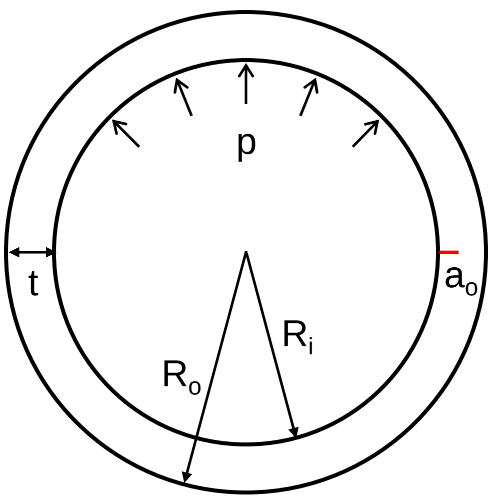
Tech. Ref. Hydrogen Compatibility of Materials,
www.ca.sandia.gov/matlsTechRef



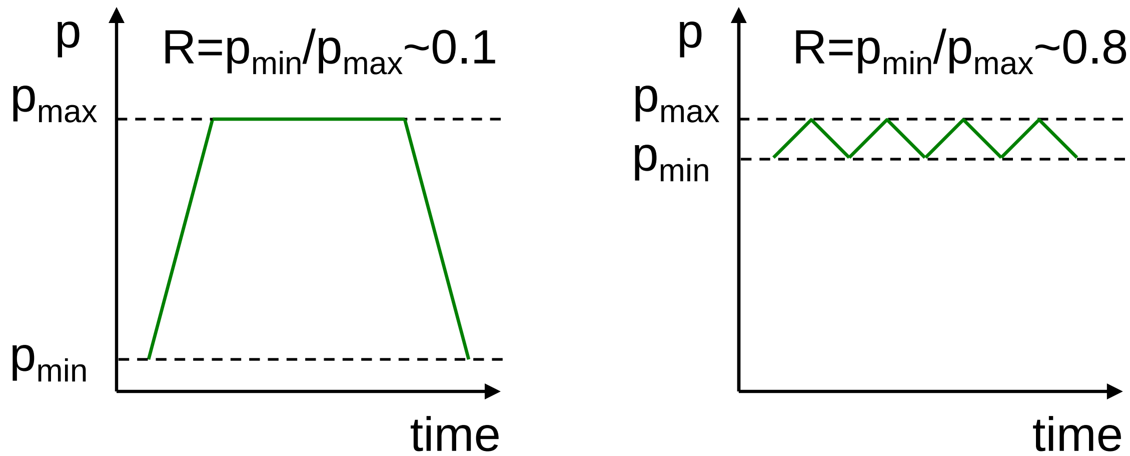
- Fatigue crack growth rates in H_2 greater than growth rates in air or inert gas
- Fatigue crack growth rates in H_2 vary by factor of 10

What is acceptable fatigue crack growth rate?

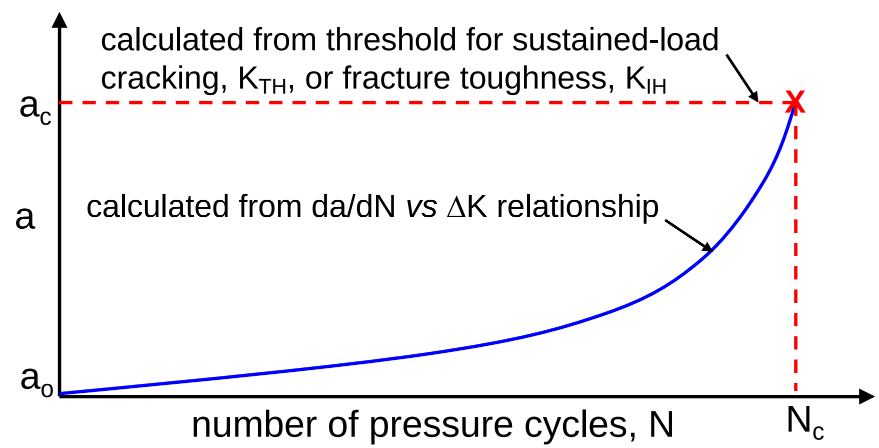
Assess fatigue crack growth data by conducting fracture mechanics analysis of pipeline



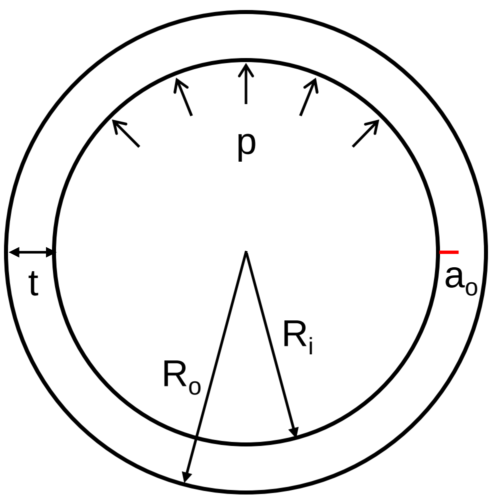
- Assume pipeline subjected to pressure cycling



- Calculate number of pressure cycles for crack to reach critical depth



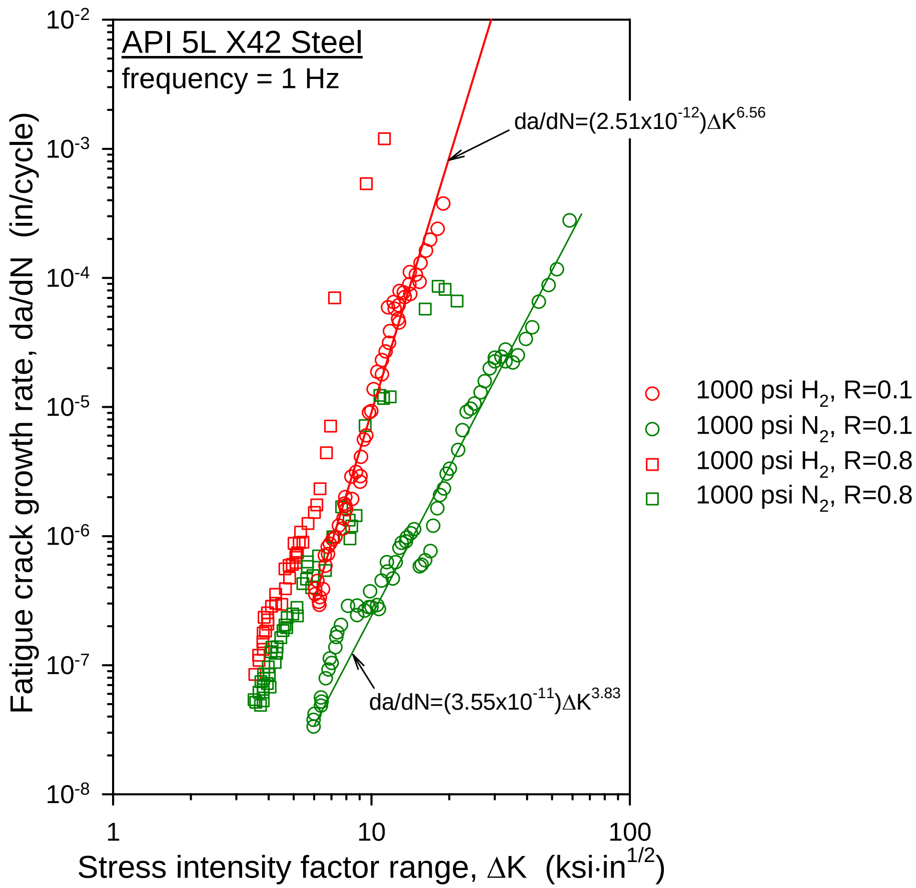
Assume steel, dimensions, and maximum pressure are similar to current H_2 pipelines



- Data for Air Products H_2 pipelines
  (ASME, *Hydrogen Standardization Interim Report*, 2005)
  - API 5L X42 steel, manufactured with ERW
  - Inner radius, R_i = 6.0 in
  - Wall thickness, t, from 0.219 to 0.500 in
- Maximum operating pressure, p = 1500 psi
- Assume existing defect with depth a_o and length parallel to pipeline axis
  - Simulates defect along manufacturing (seam) weld

Select appropriate material property data

Cialone et al., *Met Trans A*, 1985



- Need da/dN *vs* ΔK for X42 ERW in 1500 psi H_2 gas
  - assume data for 1000 psi H_2 gas representative
  - assume data for weld and base metal are similar
- Need da/dN *vs* ΔK at relevant R ratio and frequency
  - pressure cycling parameters for pipeline unknown
  - use data at R=0.1 and frequency=1 Hz
- Need fracture toughness for X42 ERW in 1500 psi H_2 gas
  - K_{IH}=44 ksi·in$^{1/2}$ for weld HAZ in 1000 psi H_2

    (Cialone et al., *ASTM STP 962*, 1988)

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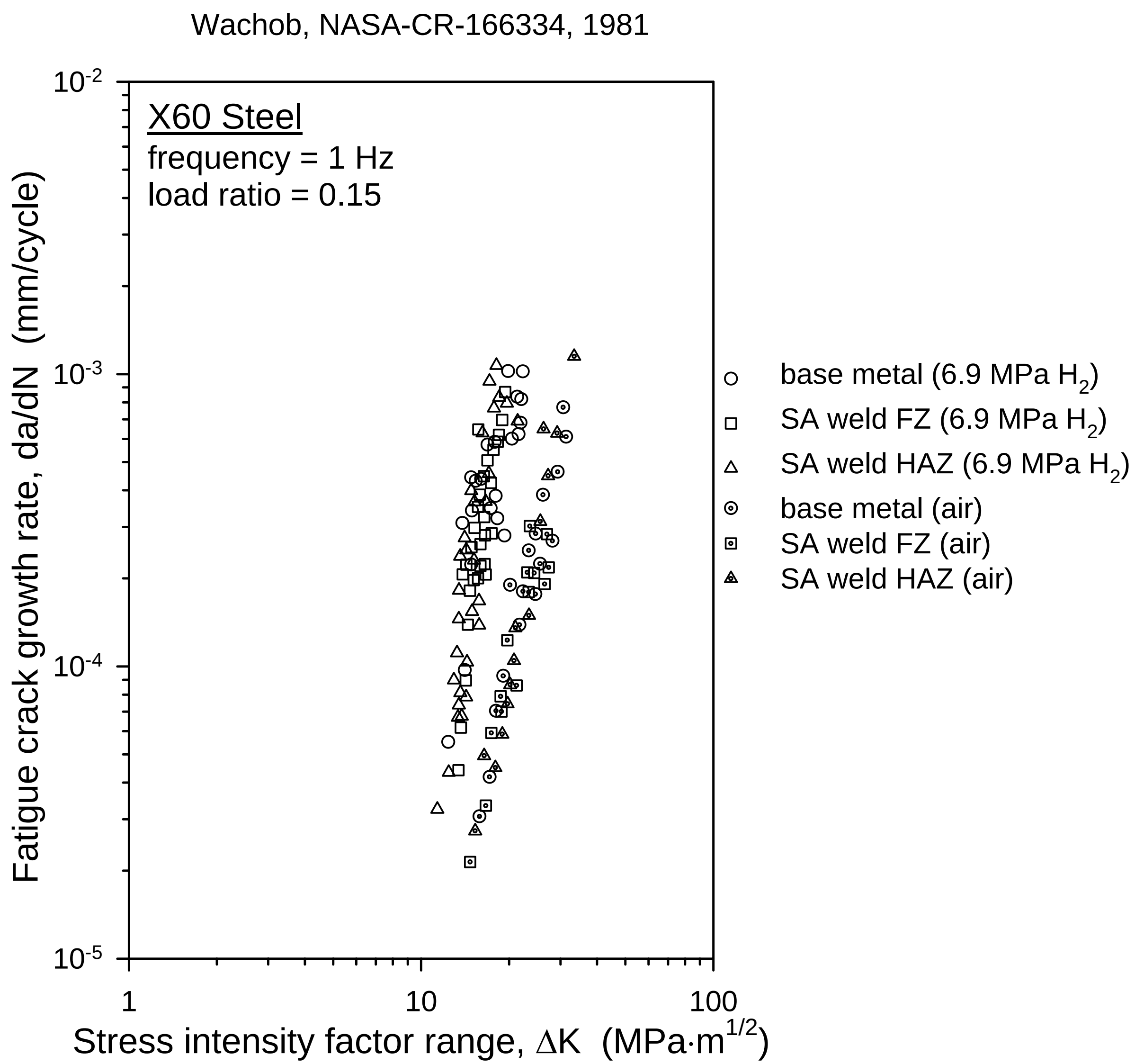
Fatigue crack growth rates similar in base metal, fusion zone, and HAZ for X60 steel



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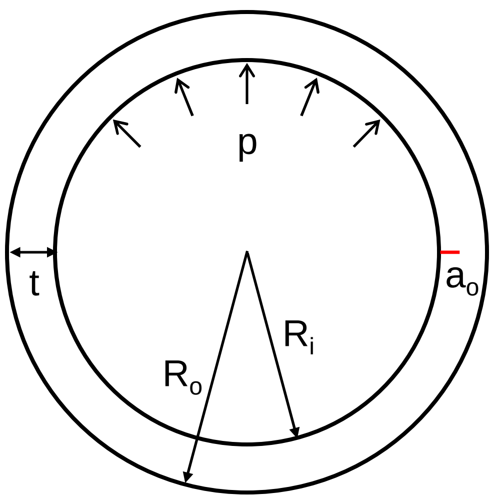
Calculate number of pressure cycles to reach critical crack depth for three cases



<u>cycle 1</u>

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

$\Delta a = (2.51\times10^{-12})\Delta K_1^{6.56}$

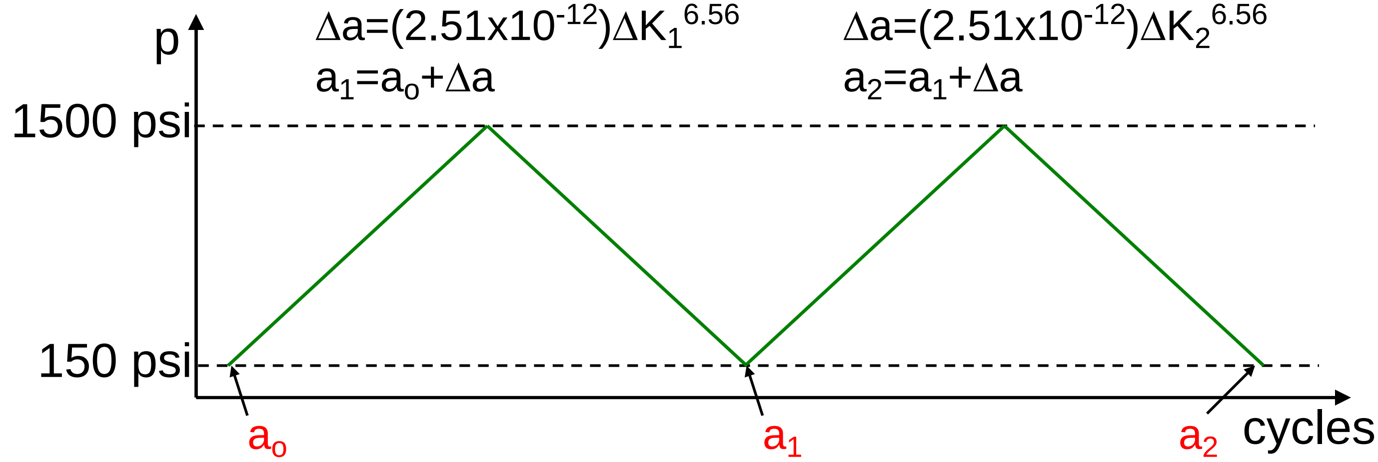
$a_1 = a_o + \Delta a$

<u>cycle 2</u>

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

$\Delta a = (2.51\times10^{-12})\Delta K_2^{6.56}$

$a_2 = a_1 + \Delta a$



- 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

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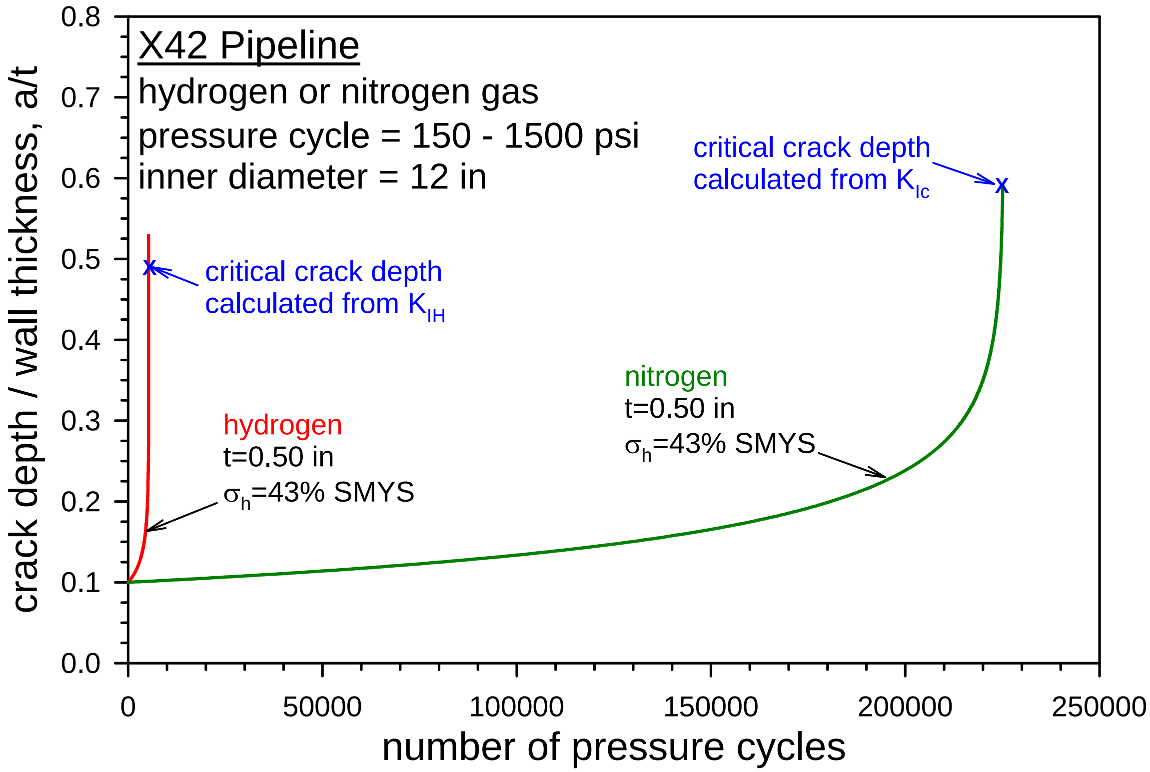
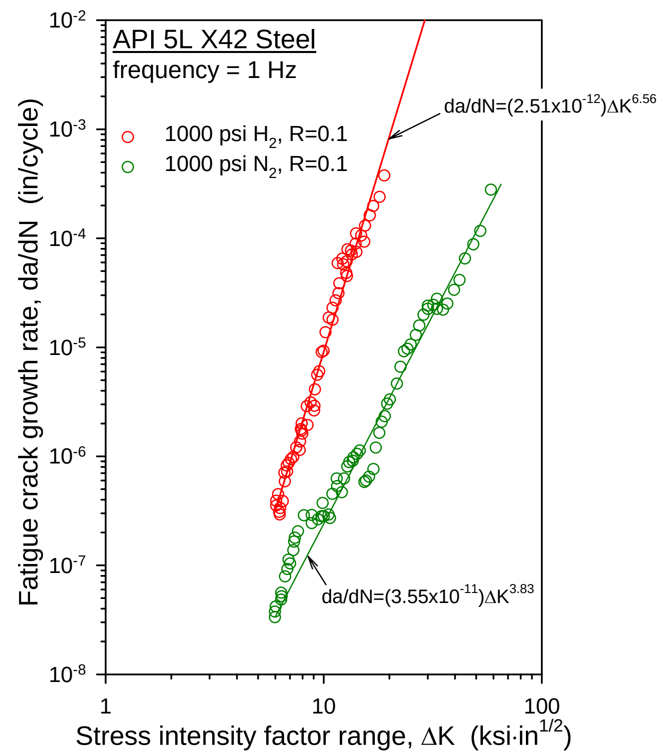
Number of pressure cycles *vs* crack depth relationships: H_2 compared to inert gas





Number of cycles to critical crack depth reduced by about factor of 40 in H_2 compared to inert gas

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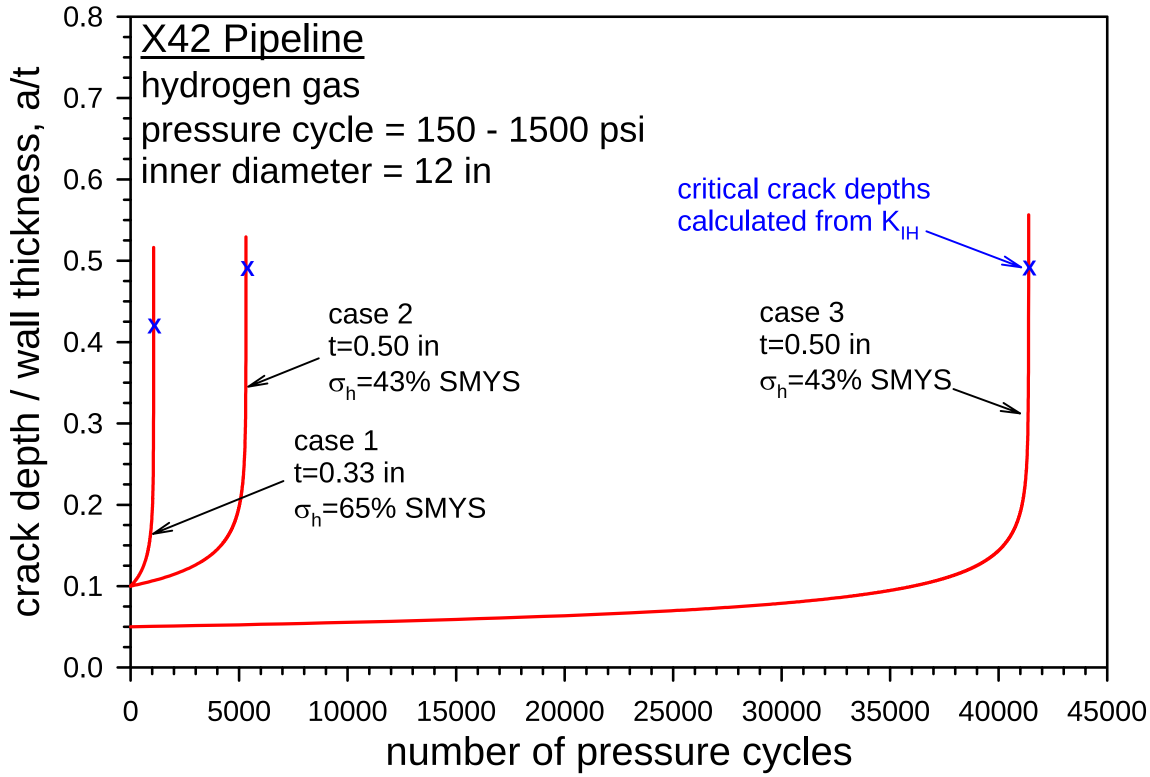
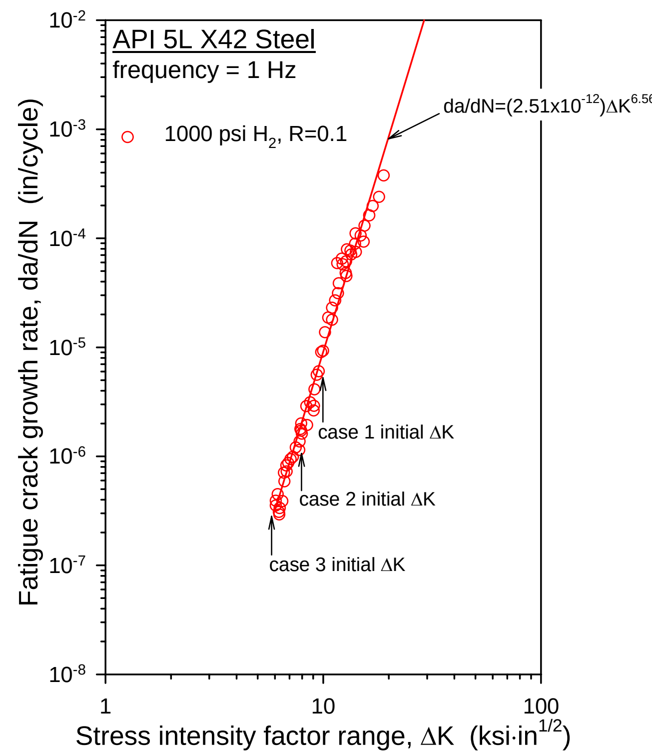
Number of pressure cycles *vs* crack depth relationships in H_2 for varying dimensions





Number of cycles to critical crack depth is sensitive to applied stress and initial crack depth

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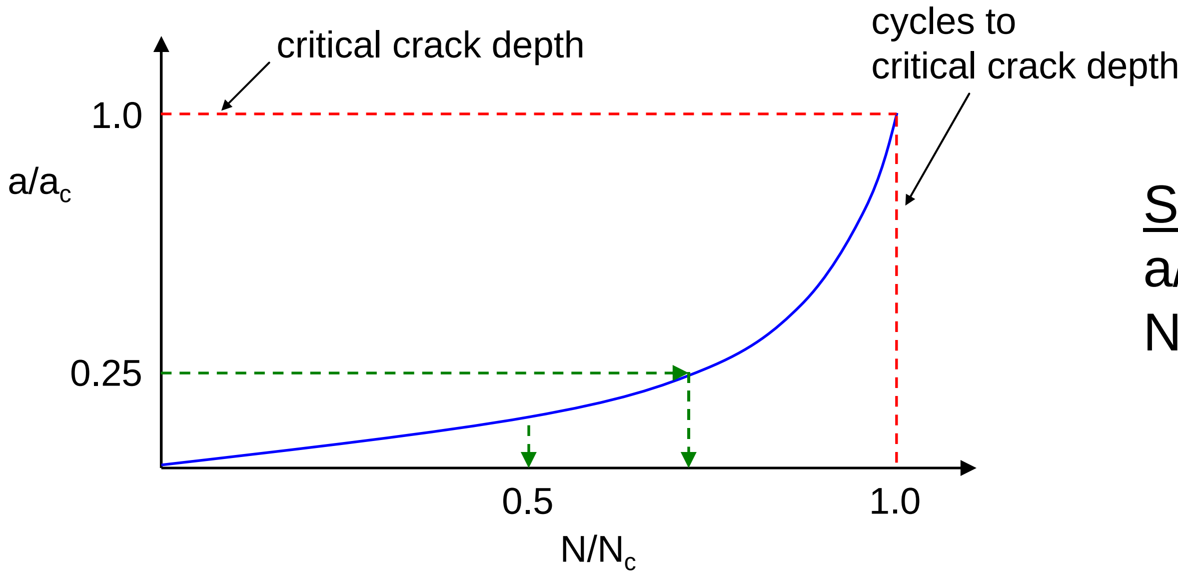
ASME applies safety factors on critical crack depth and number of cycles to critical crack depth

M.D. Rana et al., *ASME PVP*, 2007



Safety factors:

$a/a_c = 0.25$

$N/N_c = 0.5$

Environment	t (in)	σ_h	a_o/t	cycles to $0.25 \times a_c$	$0.5 \times N_c$
H_2	0.330	65% SMYS	0.10	170	535
H_2	0.500	43% SMYS	0.10	2,735	2,660
H_2	0.500	43% SMYS	0.05	38,790	20,690
inert	0.500	43% SMYS	0.10	125,260	112,545

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Lifetime of steel hydrogen pipeline depends on both material properties and structural design

- Fatigue crack growth law
  - $da/dN = C\Delta K^n$ in stage II
- Fracture toughness or threshold for sustained-load cracking
  - does not significantly affect cycles to critical crack depth
- Wall thickness
  - affects stress (ΔK)
- Initial crack depth
  - depends on detection limit of NDE
- Operating pressure
  - affects stress (ΔK) and material properties

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Fatigue crack growth rates depend on load cycle profile

Walter and Chandler, *Effect of Hydrogen on Behavior of Materials*, 1976