SAND2005-7700C

Hydrogen-Assisted Fracture of Ferritic Steels for High-Pressure Gas Storage and Delivery Applications

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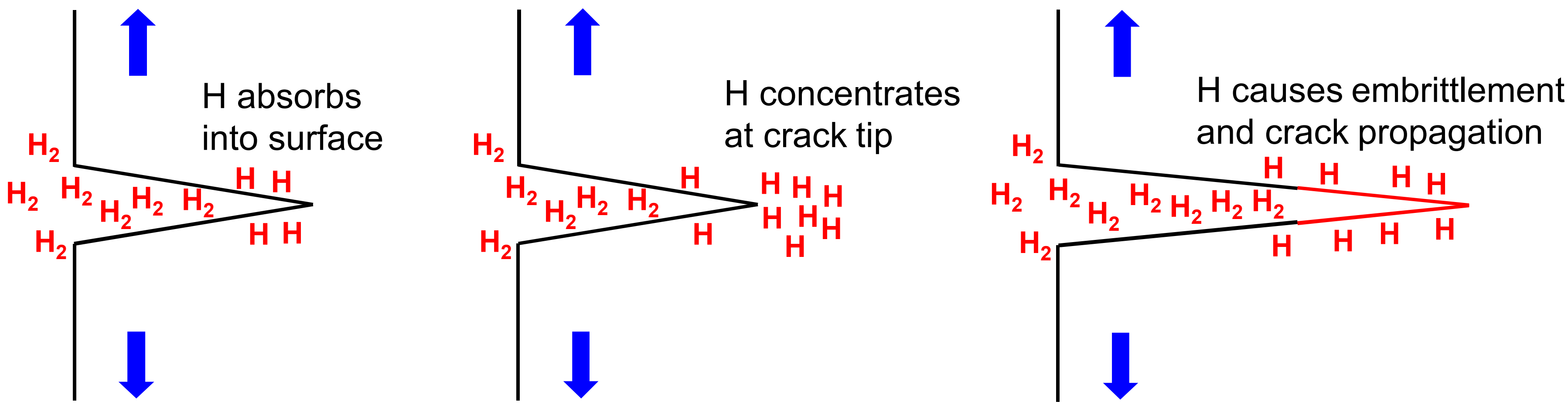
Materials Science & Technology 9/27/05

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Why is hydrogen such a concern?

Hydrogen can find and extend defects that may be undetectable by normal means

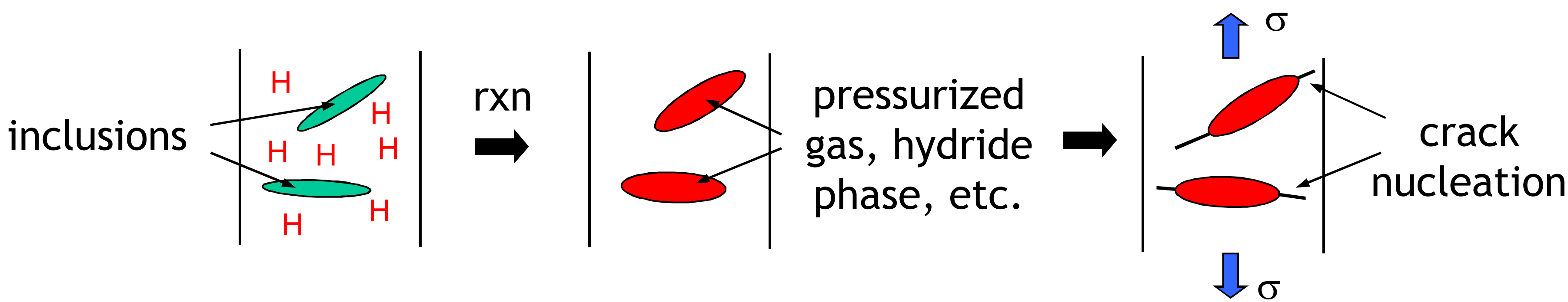
Plans for the Hydrogen Economy involve storage of H_2 at pressures up to 15,000 psi (or above?)



Unlike other gases (e.g., N_2), atomic hydrogen dissolves into metals and causes embrittlement

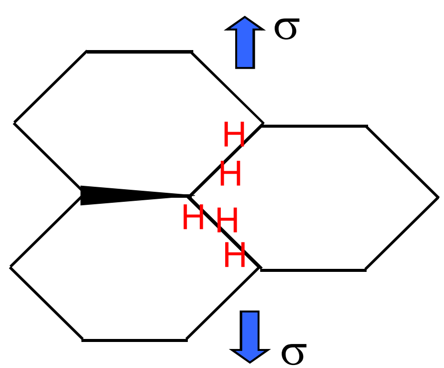
Hydrogen-assisted fracture in metals

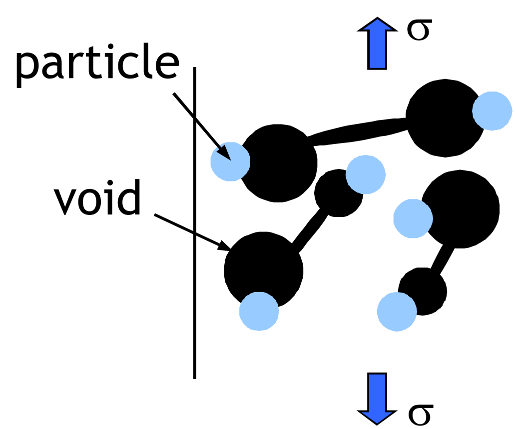
Hydrogen attack: chemical reaction of hydrogen with microstructural features



Hydrogen solute effects: hydrogen enhanced failure of interfaces, or hydrogen-enhanced deformation mechanisms

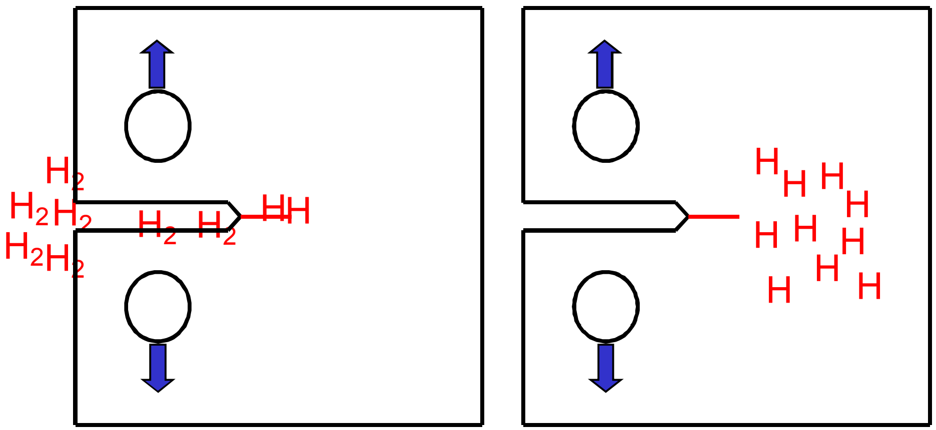
hydrogen accumulation at interfaces affects strength of interface (grain boundaries, second phases, inclusions)



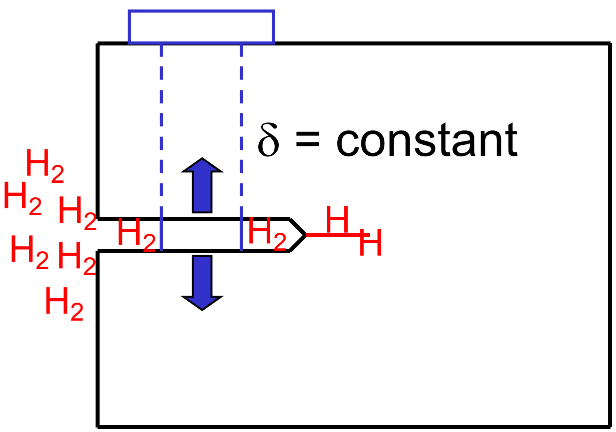


hydrogen enhanced shear localization

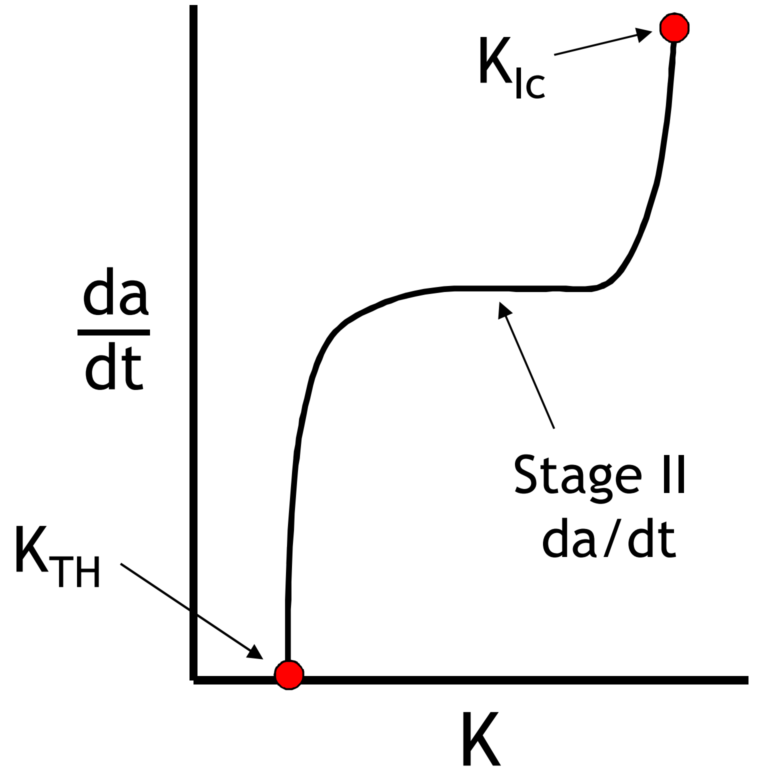
Quantify with fracture mechanics



Compact tension

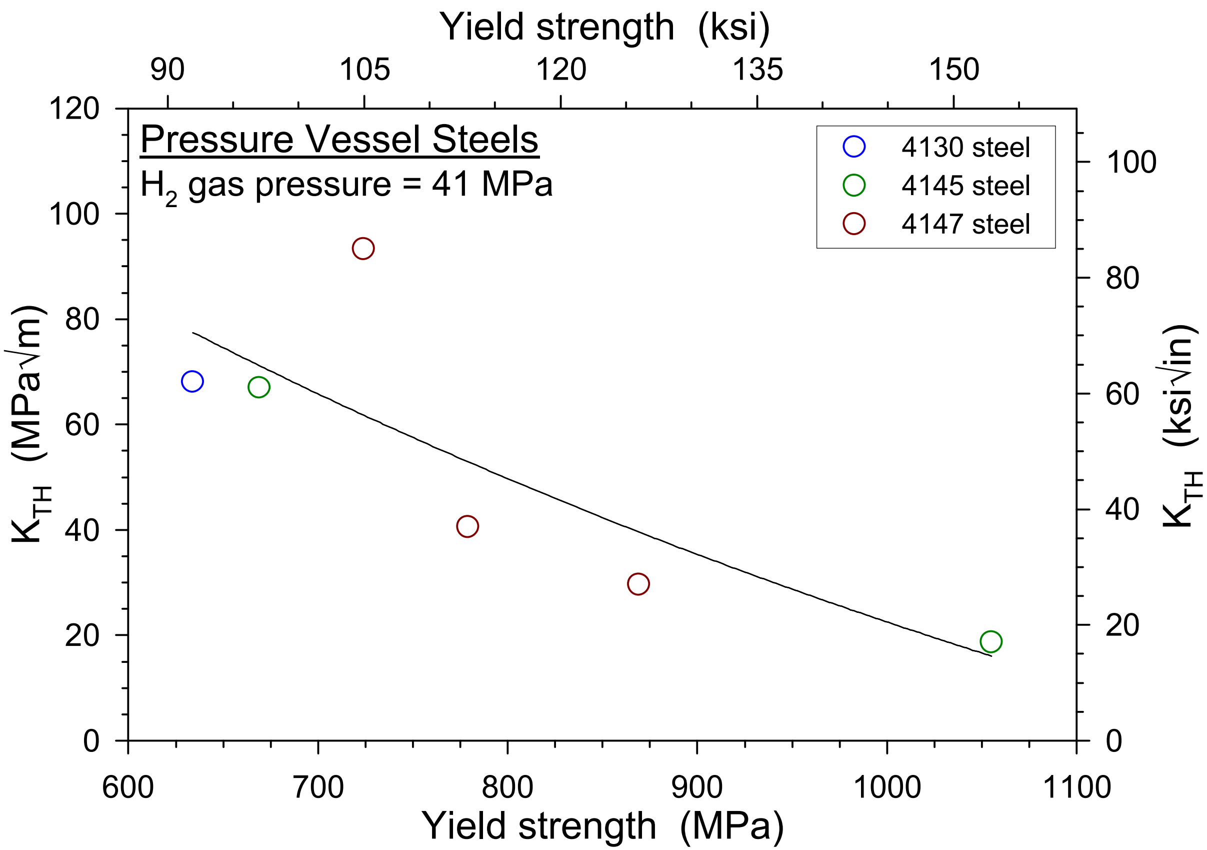


Wedge-opening load

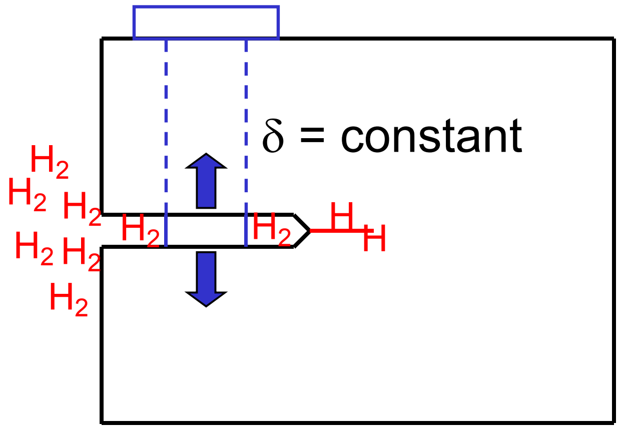


Data acquired while controlling environmental and mechanical variables

Effect of yield strength

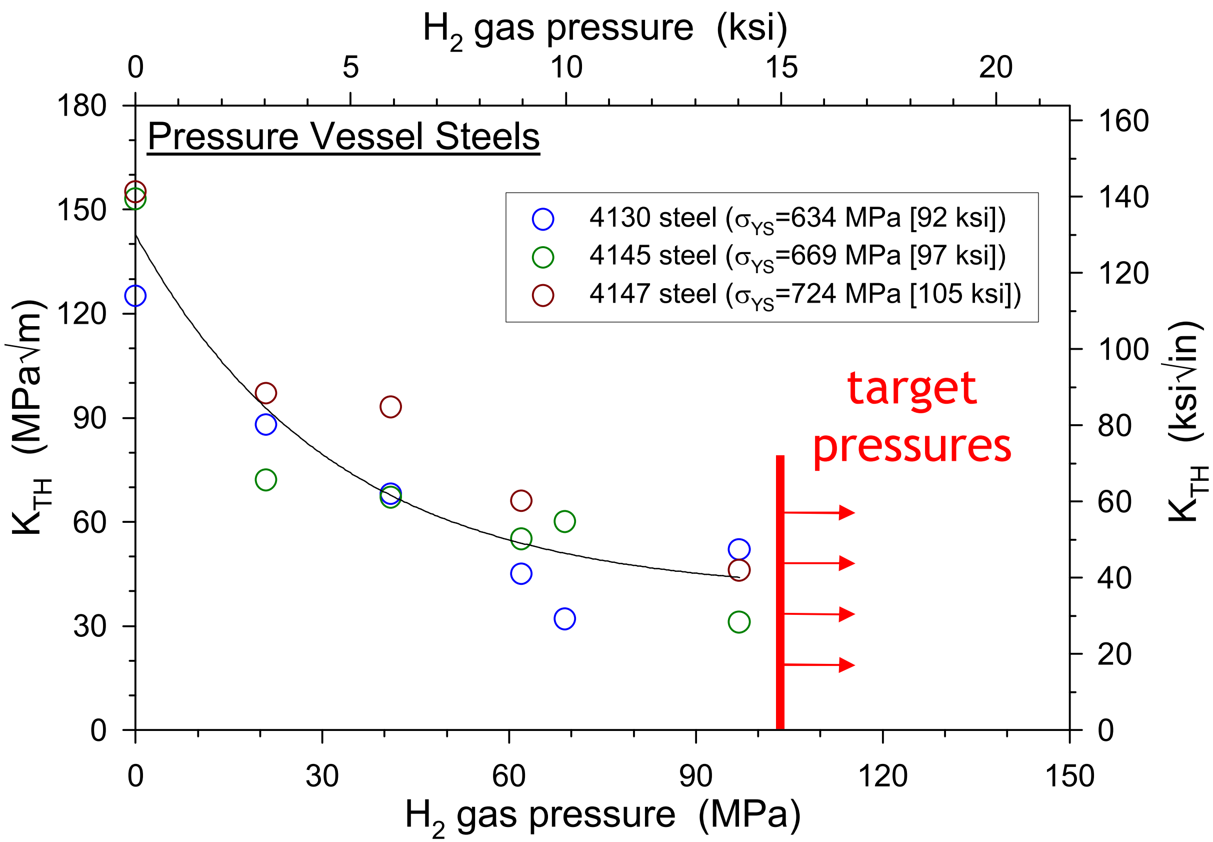


Loginow and Phelps, Corrosion, 1975



K_{TH} ↓ as σ_Y ↑ for similar steels

Effect of gas pressure



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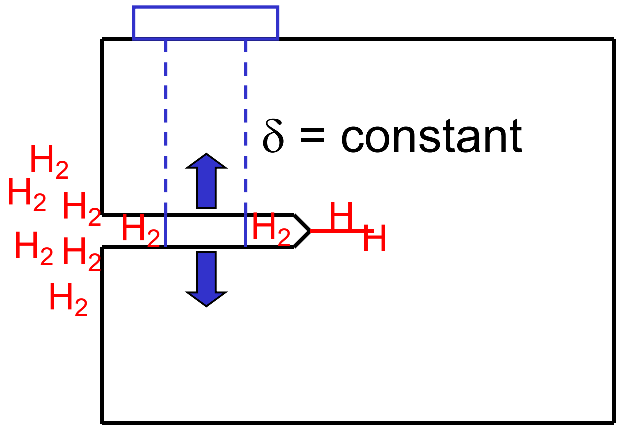
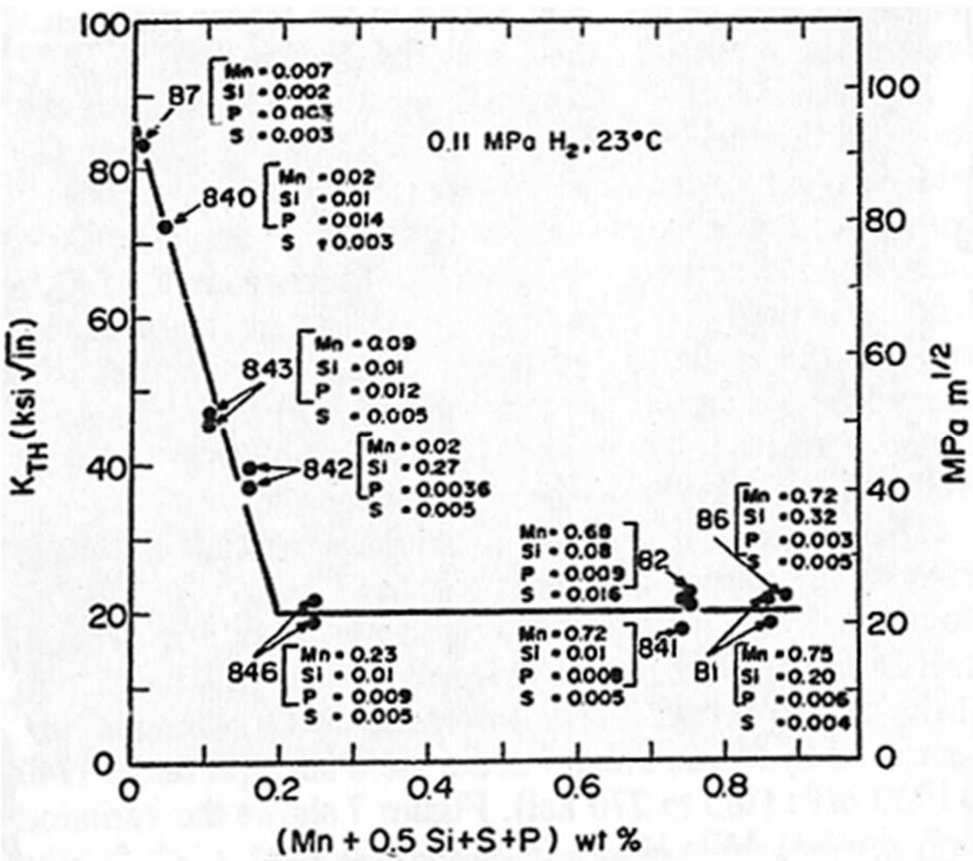


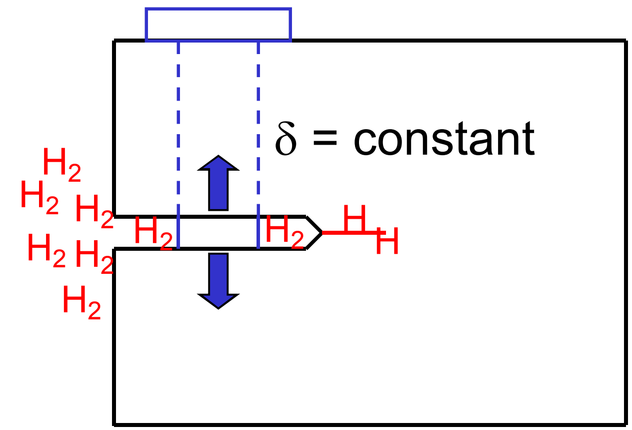
K_{TH} ↓ as P_{H_2} ↑ for similar steels

Effect of composition

4340 σ_Y = 1450 MPa (210 ksi)



N. Bandyopadhyay et al., ***Metallurgical Transactions A****, 1983*



K_{TH} can be strongly dependent on alloying element (Mn, Si) and impurity (P, S) concentrations

Lessons learned from data survey

Full characterization of hydrogen effects on materials of construction must include:

- Microstructure effects
- Temperature effects
- Gas purity and pressure effects
- Loading effects such as fatigue, sustained load cracking responses, and mixed mode behavior

Many important intersections of variables have *not* been systematically studied ⇒

- Effects of composition at high P_{H_2}
- Many effects in, e.g. 4340, at lower yield strengths

Testing of AISI 4340

Currently testing two compositions:

(wt%)	C	Cr	Ni	Mo	Mn	Si	P	S
Air-melt	0.41	0.82	1.71	0.21	0.75	0.22	0.012	0.007
Vac-melt	0.42	0.85	1.82	0.27	0.83	0.29	0.005	0.001

Variables:

Strength level: 600 to 870 MPa

Temperature: room temperature to -50^{o}C

Gas pressure: 40 to 140 MPa

can lower P, S levels lead to ↑ K_{TH}, at low strengths and high gas pressures, even with normal Mn, Si?

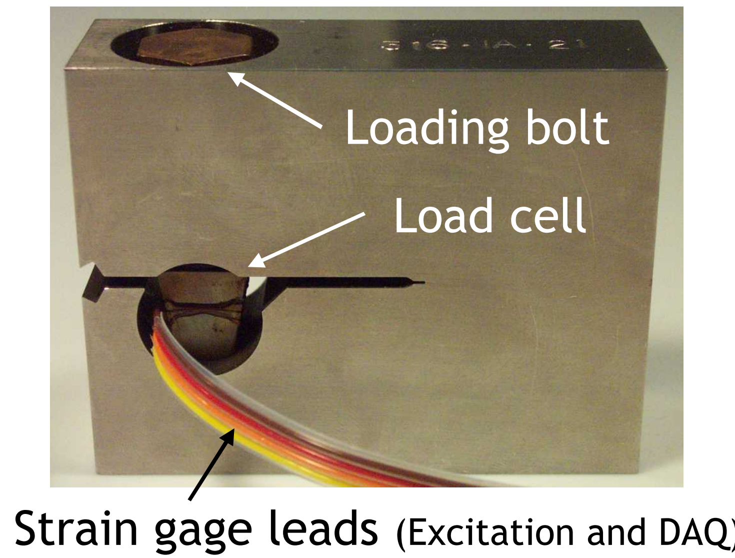
Instrumented WOL specimens

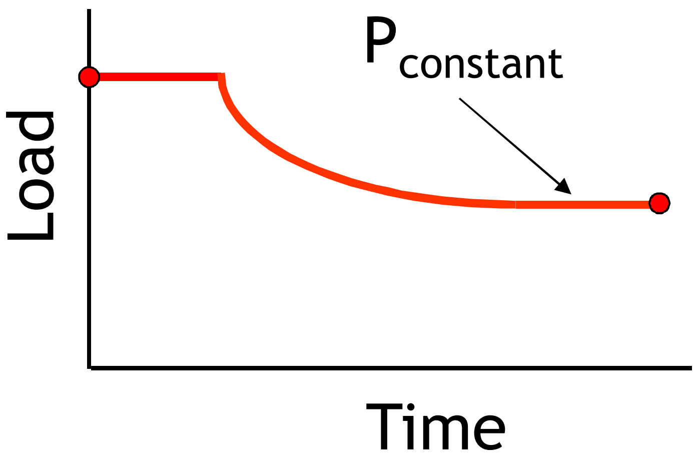
Constant displacement using instrumented load cell

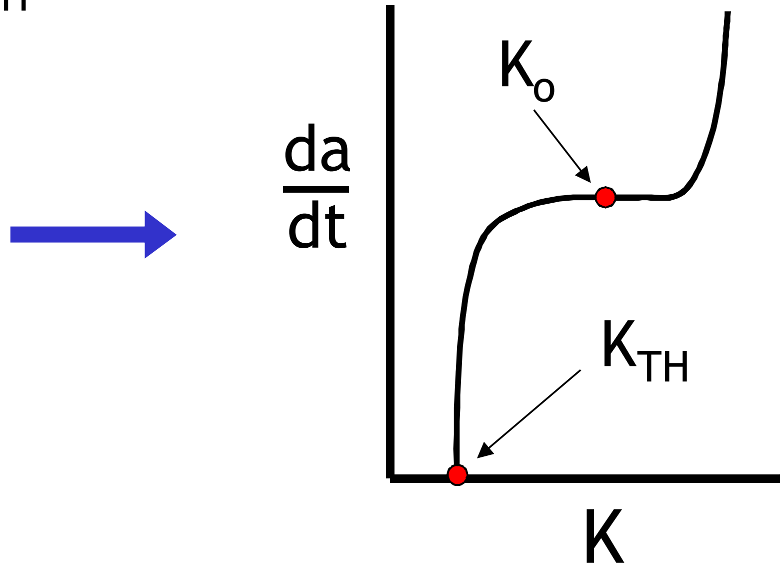
Samples bolted to $K_{Ic} > K_o > K_{TH}$

Strain gages supply load vs. time: crack advance → load drop

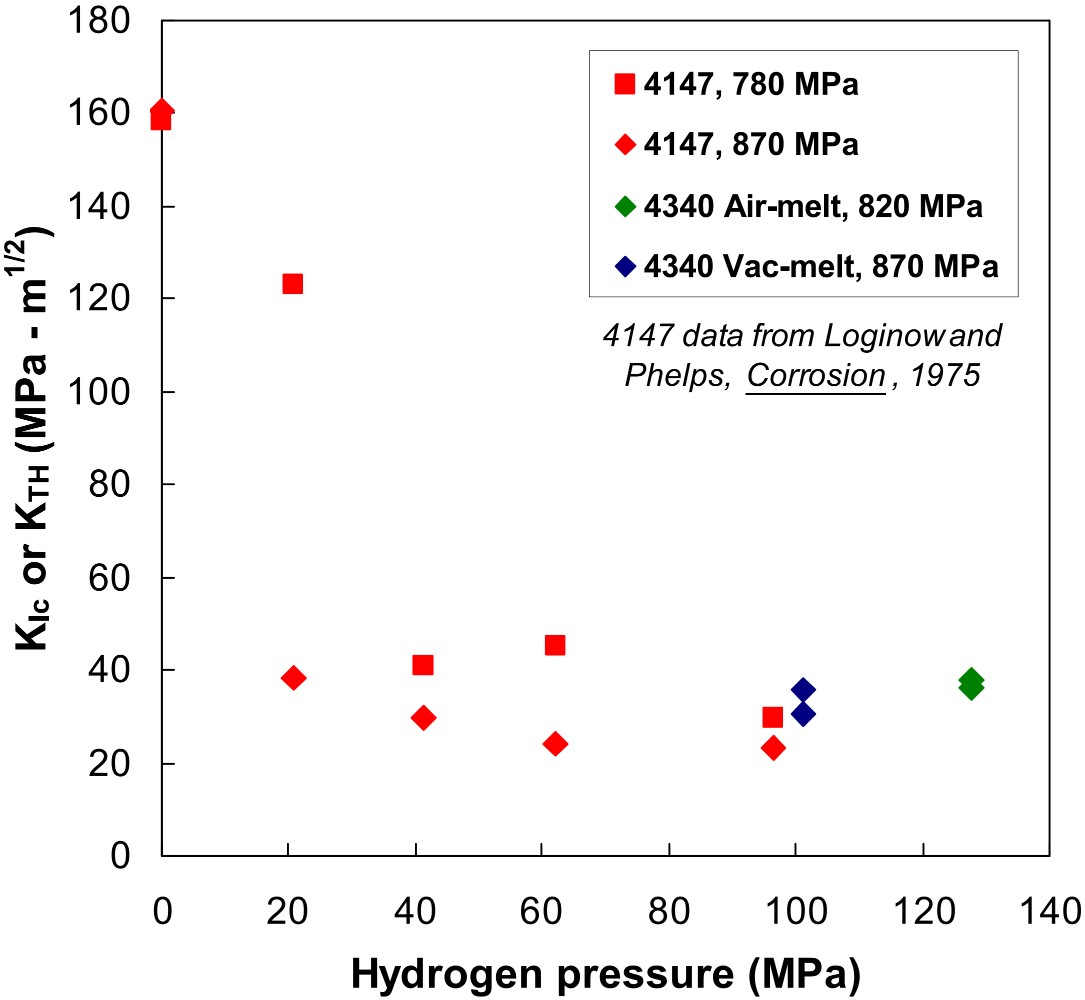
Crack arrests when $K = K_{TH}$







Threshold K values



AM-1: 38 MPa-m$^{1/2}$

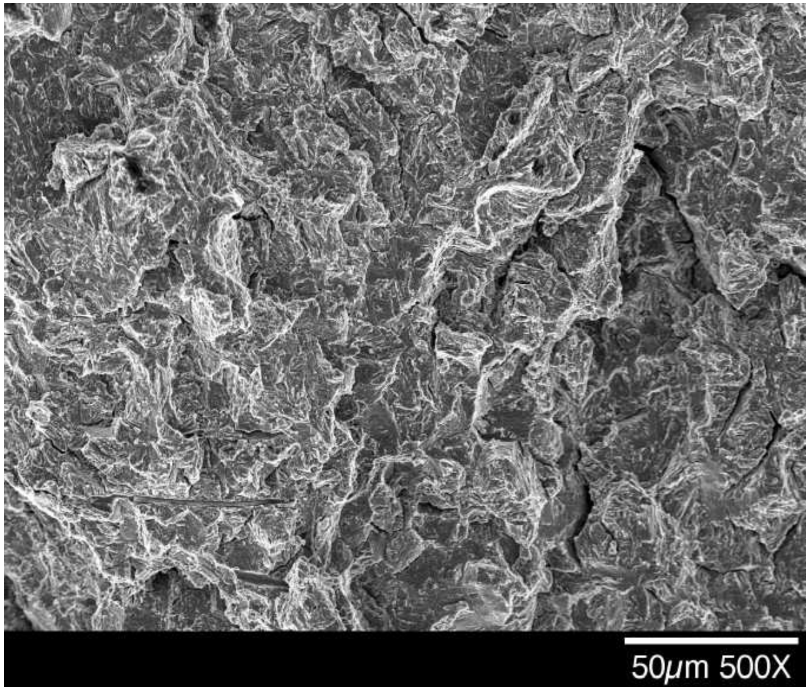
AM-2: 36 MPa-m$^{1/2}$

VM-1: 30 MPa-m$^{1/2}$

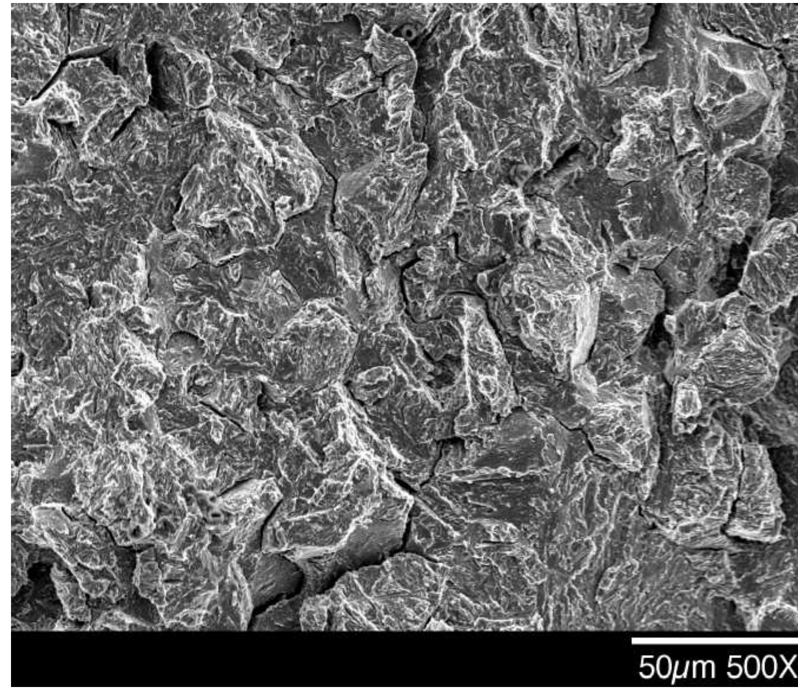
VM-2: 36 MPa-m$^{1/2}$

Not a large increase in K_{TH} with low P, S (relative to similar steels)

Fractographs



Air-melt



Vacuum-melt

Some intergranular character, but cleavage also evident ⇒ yield strength

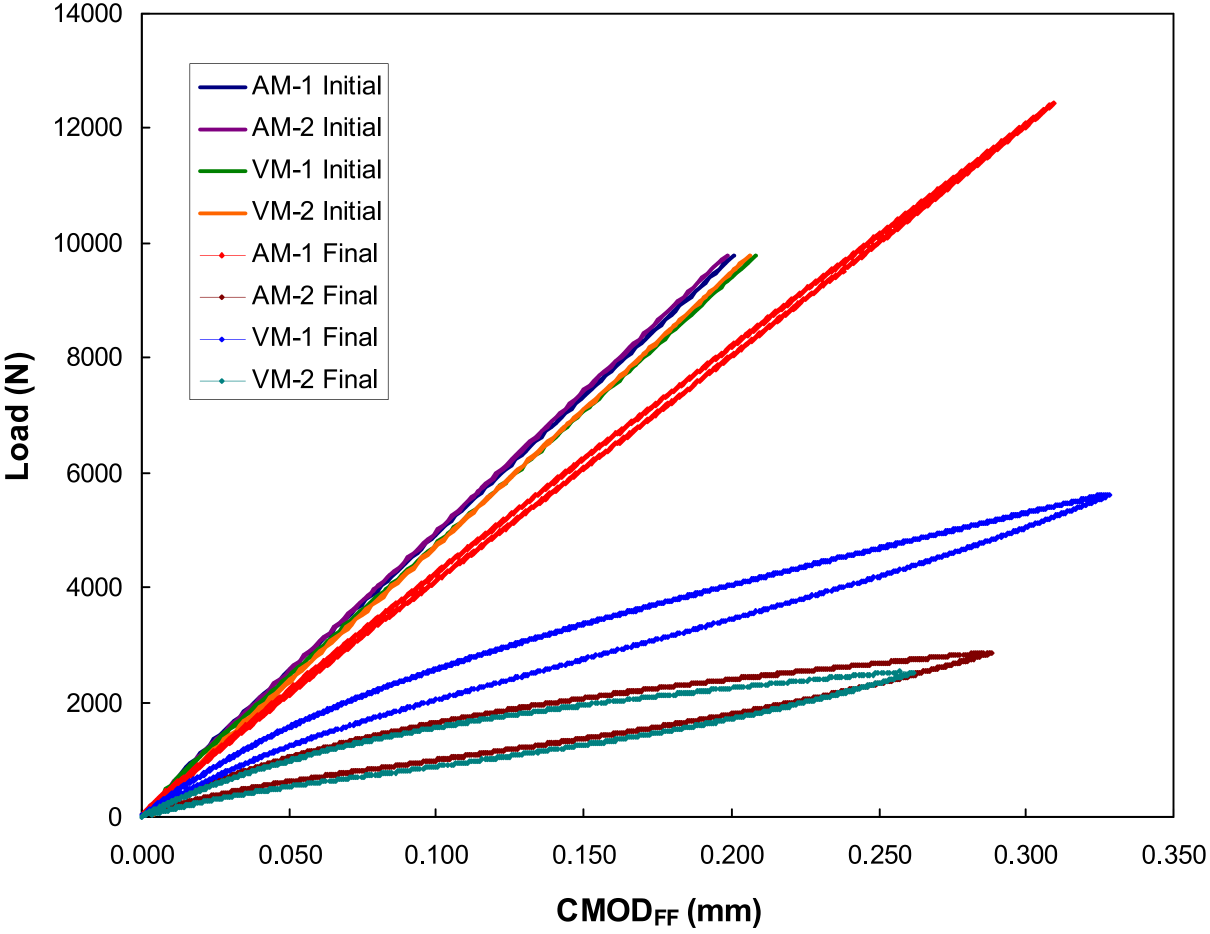
Discrepancy with stress intensity?

Post-test procedure: unbolt WOL with crack-mouth clip gage in place, reload to same displacement to measure final loads

K_{LL} based only on final loads are too high:

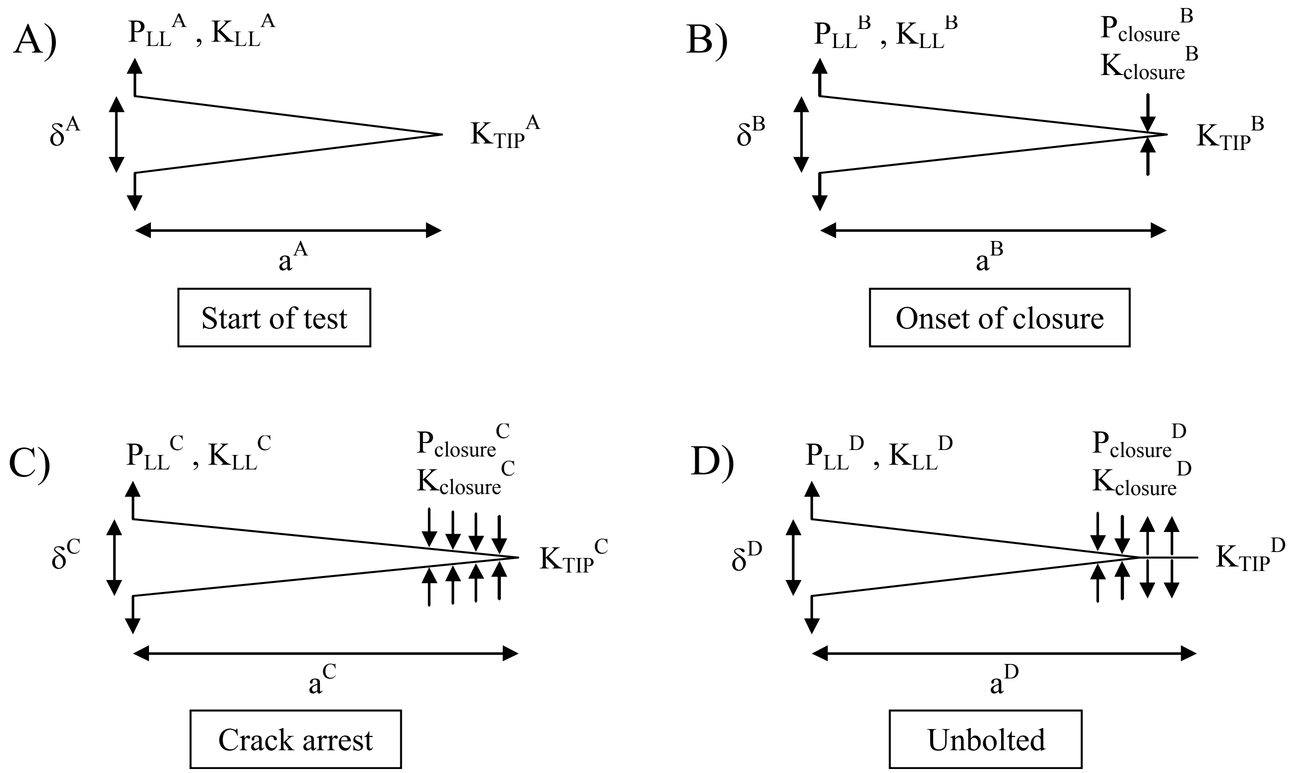
	$(a/W)_o$	K_o ($MPa\text{-}m^{1/2}$)	$(a/W)_f$	$K_{LL}{}^f$ ($MPa\text{-}m^{1/2}$)
AM-1	0.56	40	0.60	**36**
AM-2	0.55	61	0.86	**44**
VM-1	0.57	43	0.80	**46**
VM-2	0.56	61	0.89	**56**

Compliance measurements



Non-linear compliance traces, with hysteresis: evidence of closure effects

Evolution of K during fracture



Key question: how to quantify $K_{closure}$ at crack arrest, based on measured quantities

Calculating $K_{closure}$

FF displacement at arrest has 2 components: $\delta_{P\text{-}LL}$ from the load on LL, and $\delta_{closure}$ from the closure loads $\Rightarrow$ $\delta^{FF} = \delta_{P(LL)} + \delta_{closure}$

We know δ^{FF} from initial bolting (rigid bolt)

We calculate $\delta_{P(LL)}$ using the measured final load and the WOL compliance relationship

We then know $\delta_{closure}$, which arises from $P_{closure}$ $\Rightarrow$ is the nature of $P_{closure}$ important?

Conclusions

Considerable work remains to explore relevant intersections of variables

Commercial 4340 has K_{TH} values between 30 and 40 MPa-$m^{1/2}$ at low strength and high P_{H2} $\Rightarrow$ minimal increase w/ low P, S

Closure effects must be considered!!