The Relationship Between Crack-Tip Strain and Subcritical Cracking Thresholds for Steels in High-Pressure Hydrogen Gas

SAND2012-0254C

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Joint HYDROGENIUS and I^{2}CNER International Workshop
on Hydrogen-Materials Interactions
February 2, 2012
Fukuoka, Japan

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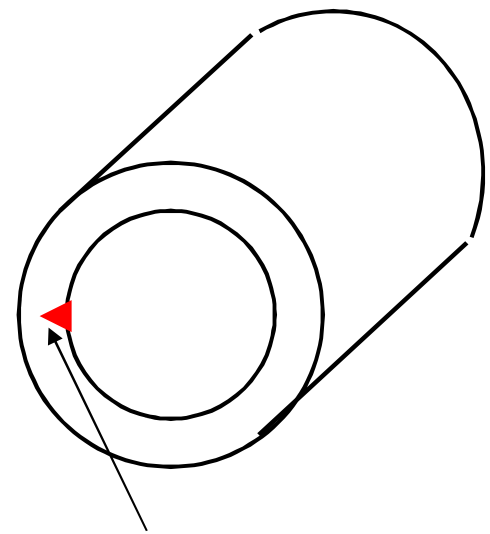
Subcritical cracking threshold (K_{TH}) measurement methods needed for H_2 pressure systems

- New applications are considering low-strength, low-alloy steels for flaw tolerant designs
  - Pressure vessels, pipelines
    - Hydrogen gas pressure up to 100 MPa
  - Designs require fracture and fatigue properties

- Conservative and reliable methods for measuring cracking threshold (K_{TH}) needed for low strength steel in H_2



K_{TH} is stress intensity factor above which subcritical crack growth proceeds under quasi-static loading

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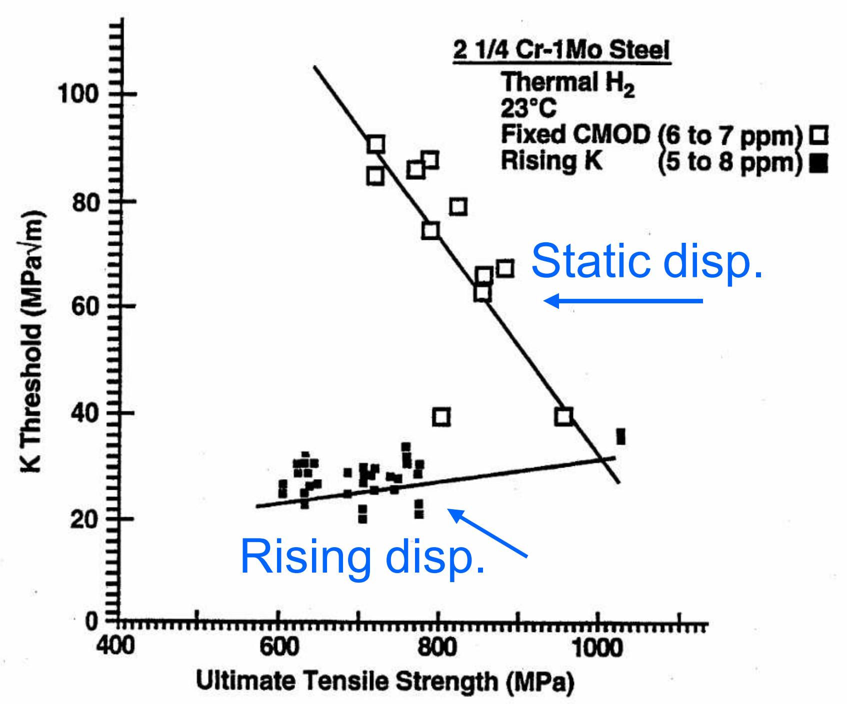
K_{TH} testing originates from stress-corrosion cracking methods

- Higher strength alloys with lower K_{TH}
- Slow environment assisted cracking kinetics
  - Favors static tests which do not impede EAC kinetics
- Ex: Bolt load compact specimen (WOL)
  - Developed and accepted into ASTM E1681 based on successful results from high-strength alloys with low fracture threshold values
  - Consequences of applying this type of test method to lower strength steels not thoroughly explored
- Literature reports suggest thresholds from constant displacement tests may be non-conservative for lower strength steels (σ_y <~1000 MPa)



Gangloff, *Comprehensive Structural Integrity*, Vol. 6, (2003), pp. 31-101.

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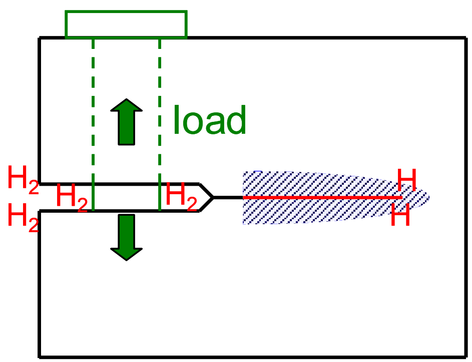
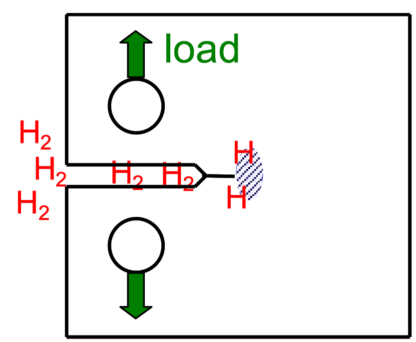
Objectives

- Evaluate and compare constant displacement and rising displacement test methods
  - Tests conducted in 100 MPa hydrogen gas
- Explain differences between these test methods in a crack tip mechanics framework
- Goal: Demonstrate that constant displacement tests do not measure the same physical property as rising displacement tests when the fracture mechanism is strain controlled
  - this difference can be explained by considering the crack tip strain fields





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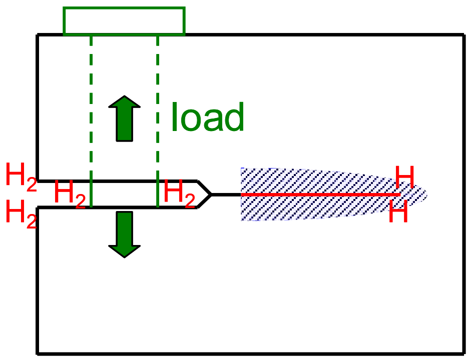
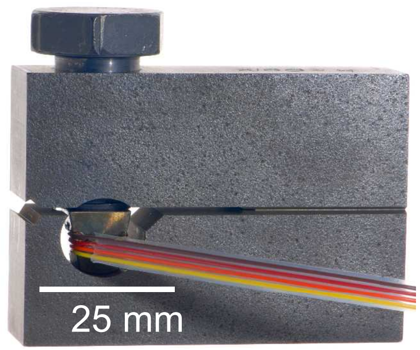
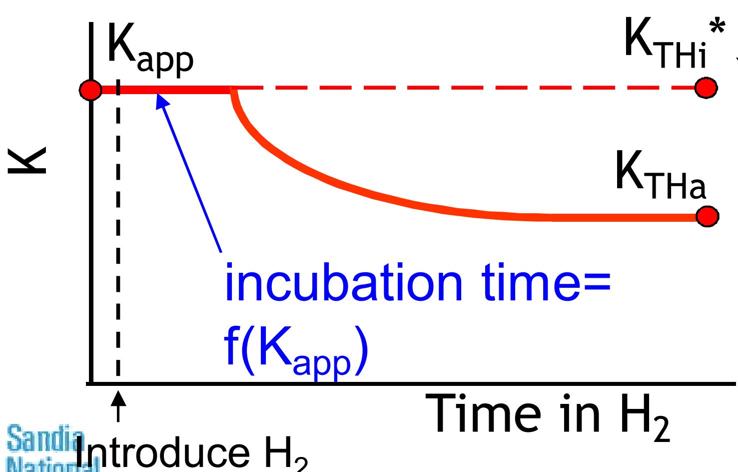
Two methods for measuring K_{TH} evaluated

Constant Displacement

- K_{THa} - measured at *crack arrest*
- ASTM E1681





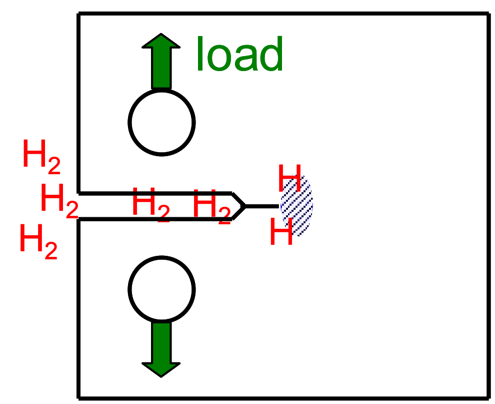


Note: K_{THi}^{*} non-conservative see SAND 2010-4633

Rising Displacement

- K_{THi} - measured at *crack initiation*
- Use elastic-plastic J-Integral (ASTM E1820)

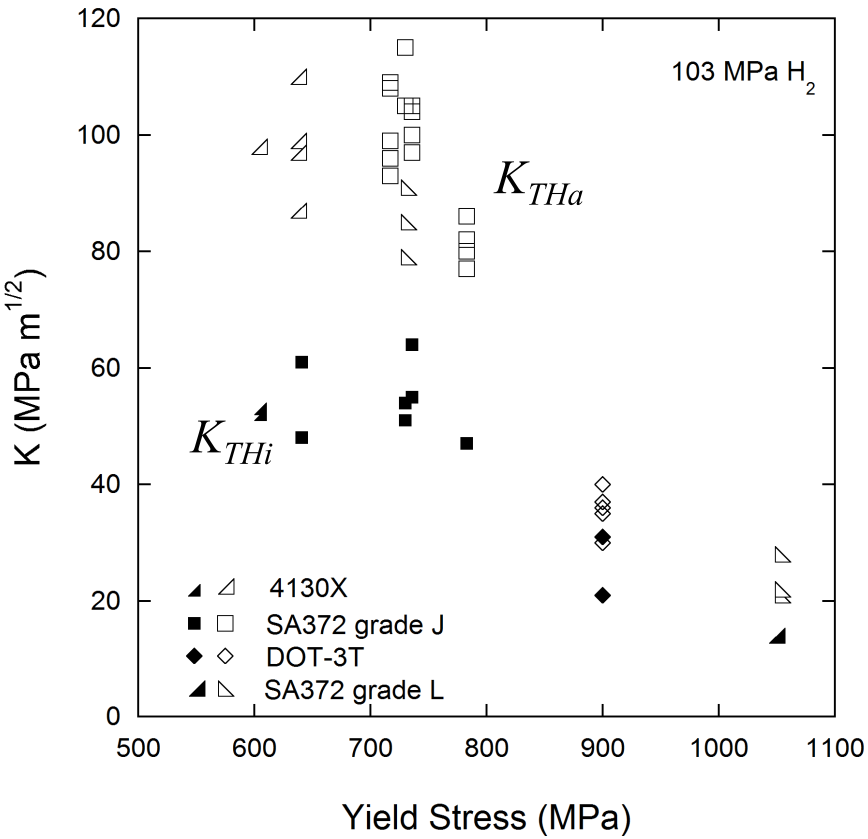
$$K_{THi} = \sqrt{J_{Ic} E'}$$



Comparison of arrest and initiation thresholds

Differences: $K_{THa} > K_{THi}$

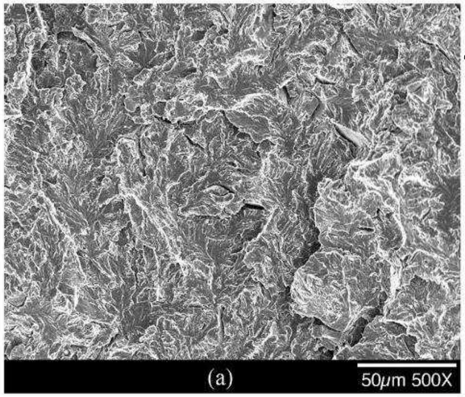
- Note: FEA demonstrates K-dominance at K_{THa} (SAND2010-4633)



Similarities:

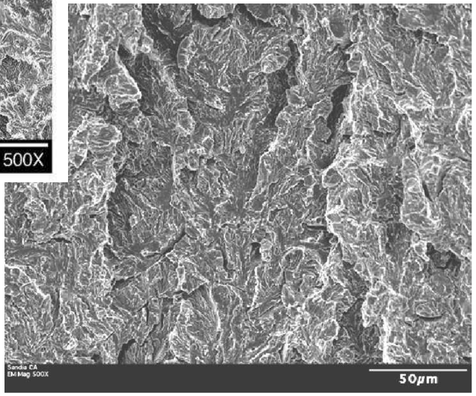
- Both thresholds increase with decreasing strength
- Fracture surface appearance suggest fracture mechanism is the same

4130X, 103 MPa H_2



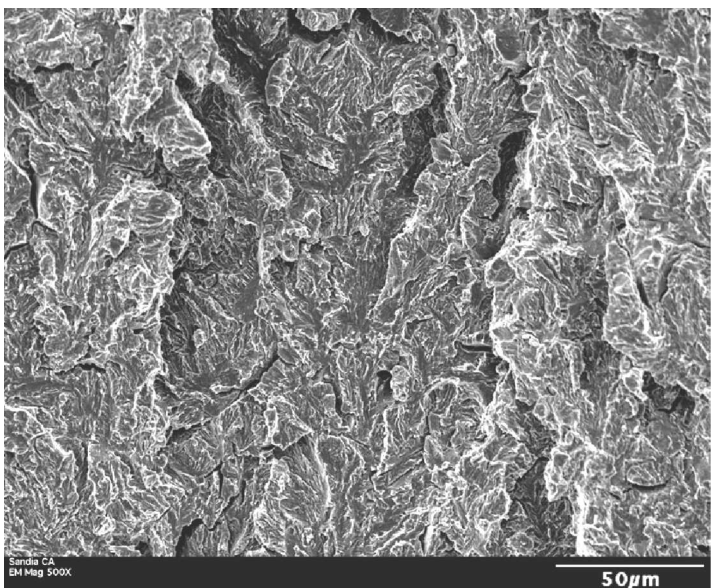
arrest threshold

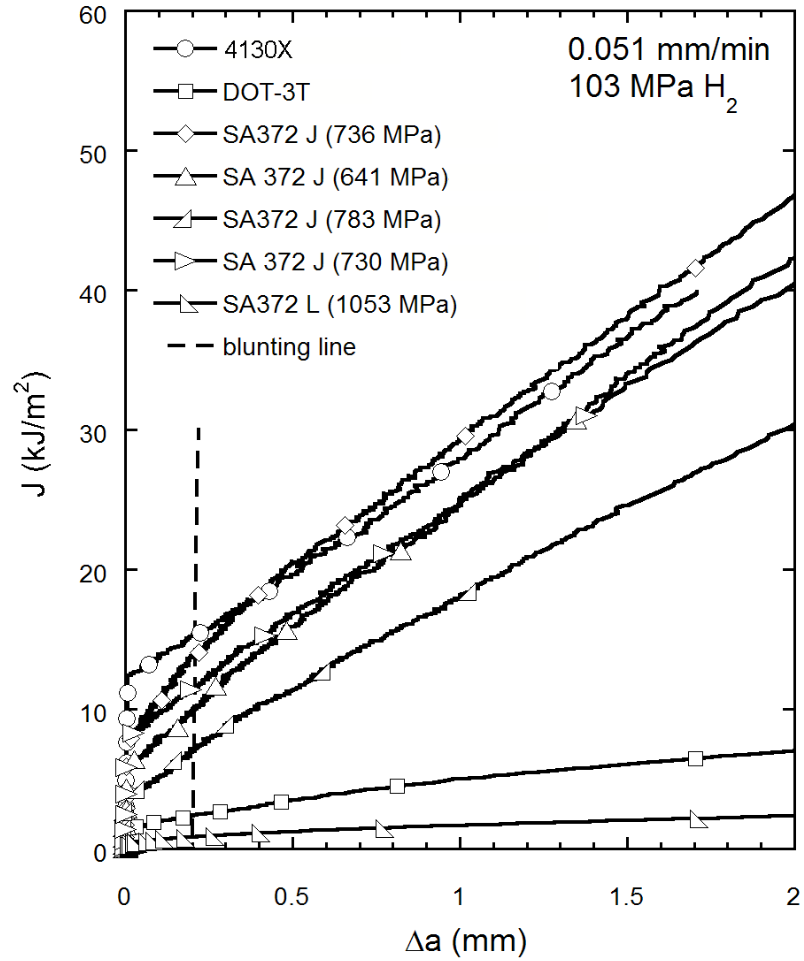
initiation threshold



Fracture mechanism is strain controlled

- Fracture surface plasticity
- R-curve
- Consensus in the literature
  - e.g. Takeda and McMahon, *Met Trans A*, 1981





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Stationary crack tip strain field provides relationship between K_{THi} and fracture strain

- Strain decays ahead of **stationary** crack tip ∝ 1/r (HRR singularity)

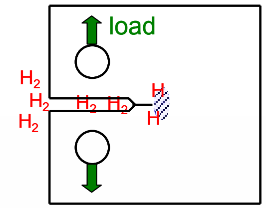
$$\varepsilon_{ij} \approx k\left(\frac{J}{\sigma_0 r}\right)$$

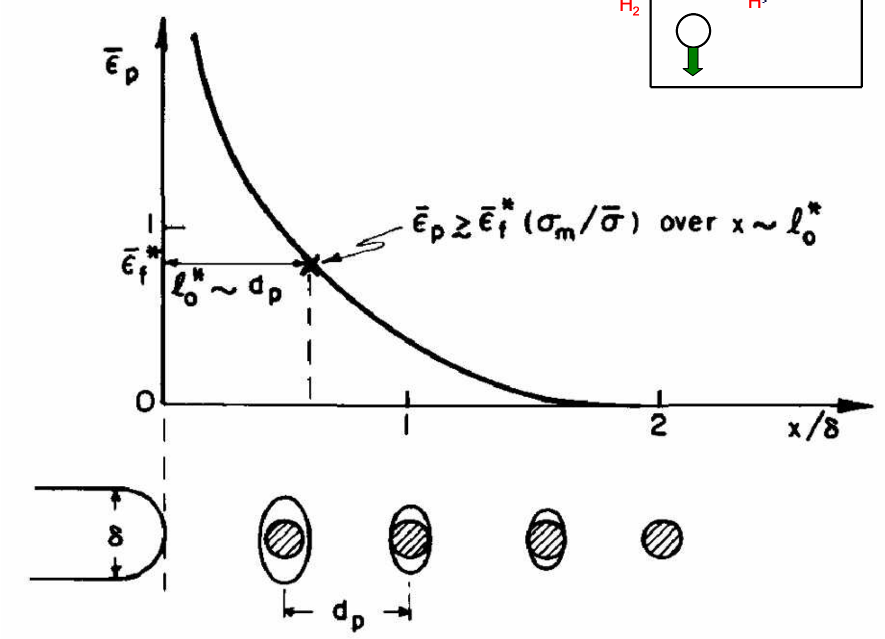
- Stress intensity factor is related to strain, ε, at distance, *r*, from crack tip:

$$K_{THi} \approx C\sqrt{E\sigma_0 l^* \varepsilon_f^H}$$

$$K_{THi} \approx \sigma_0 \sqrt{l^*}\sqrt{\frac{\varepsilon_f^H}{\varepsilon_0}}$$

*l** is a critical distance from crack tip





Ritchie and Thompson, *Met Trans*, 1985

•Analogous relationship for K_{THa} needs to be developed

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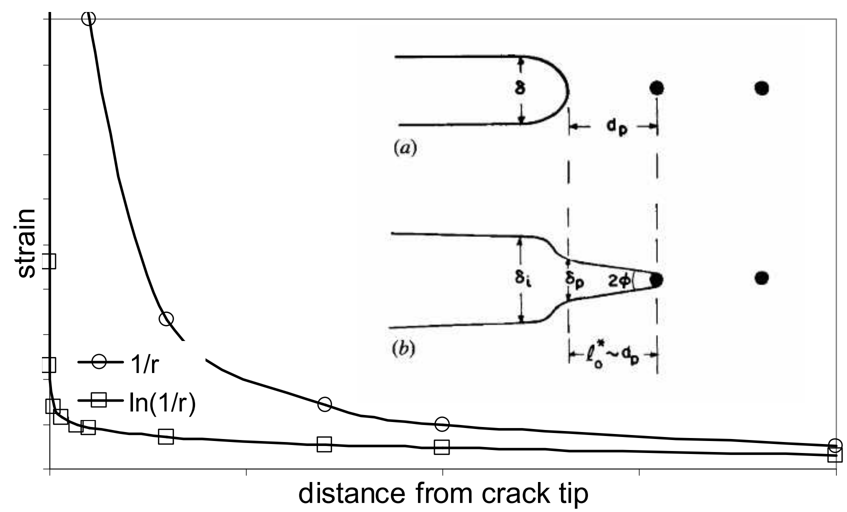
Strain field associated with propagating crack is relevant to arrest threshold

- Region of elastic unloading occurs in wake of **propagating** crack

- Leads to weakening of strain singularity
  - Strains decay ahead of propagating crack ∝ ln(1/r)

$$\gamma^{p} \approx \frac{M}{\sigma_0}\frac{dJ}{da} + \frac{1.88(5-4\upsilon)\sigma_0}{2E}\ln\left(\frac{J}{r}\right)$$



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Rice *et al*, *ASTM STP700*, 1980

Analytical expression for propagating crack strain field developed for R-curve behavior

- Strain field for propagating crack

$$\gamma^{p} \approx \frac{M}{\sigma_0}\frac{dJ}{da} + \frac{1.88(5-4\upsilon)\sigma_0}{2E}\ln\left(\frac{J}{r}\right)$$

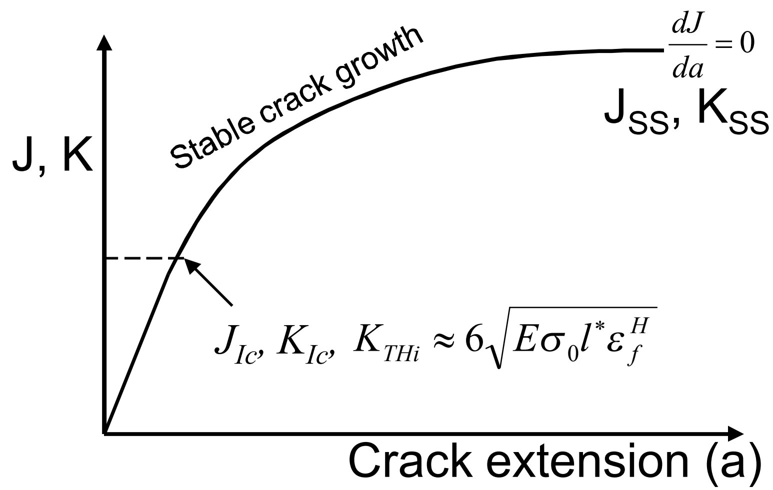
- Criterion for continued crack extension

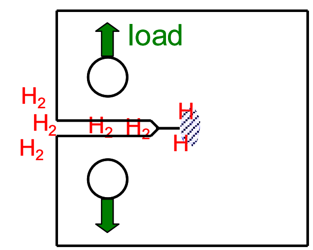
$$\gamma_f^{p} \approx \frac{M}{\sigma_0}\frac{dJ}{da} + \frac{1.88(5-4\upsilon)\sigma_0}{2E}\ln\left(\frac{J}{l^*}\right)$$

Fracture strain

$$J = K^2 / E'$$

$$\gamma_f^{p} \approx \frac{M}{\sigma_0}\frac{dJ}{da} + \frac{1.88(5-4\upsilon)\sigma_0}{2E}\ln\left(\frac{K^2}{El^*}\right)$$





Two-term field with ln(1/r) singularity presumed to represent strains for propagating crack under *decreasing* K

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Strain field for propagating crack provides relationship between K_{THa} and fracture strain

- Assume limiting case: strain represented by ln(1/r) term

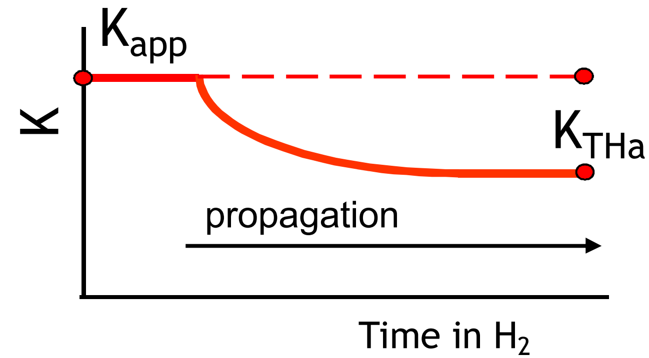
- When $K_{app} > K_{THa}$

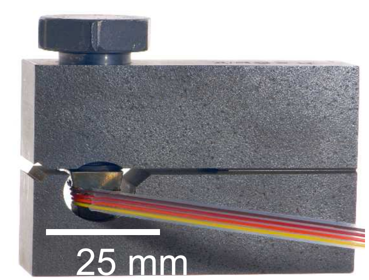
$$\gamma_f^p < \frac{1.88(5-4\upsilon)\sigma_0}{2E}\ln\left(\frac{K^2}{El^*}\right)$$

- When $K_{app} = K_{THa}$

$$\gamma_f^p = \frac{1.88(5-4\upsilon)\sigma_0}{2E}\ln\left(\frac{K_{THa}^2}{El^*}\right)$$

$$K_{THa} \approx \sigma_0\sqrt{l^*}\exp\left(\frac{\varepsilon_f^H}{\varepsilon_0}\right)$$





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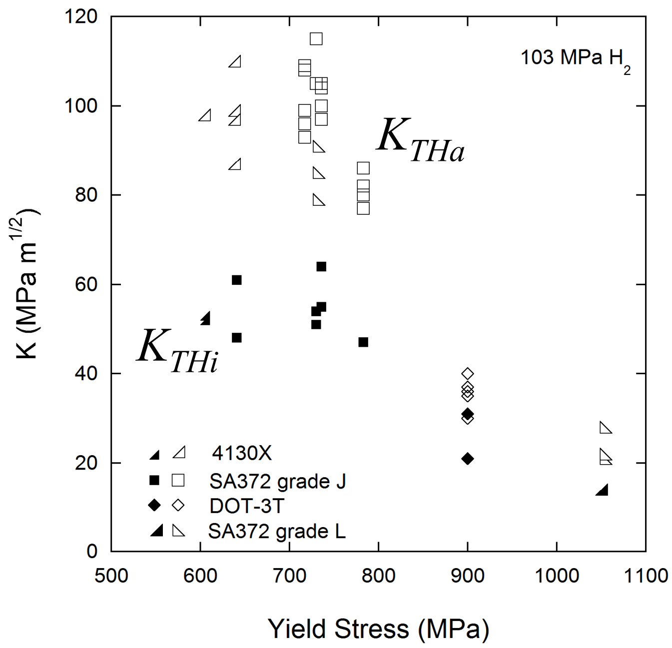
Crack tip mechanics-based models support $K_{THa} > K_{THi}$ for strain controlled fracture

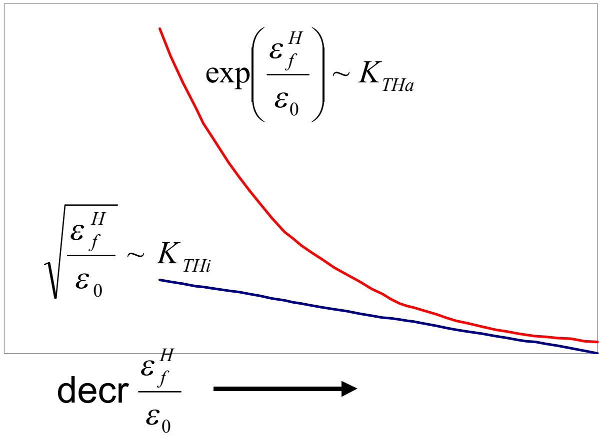
- If fracture involves plasticity, e.g. $\varepsilon^H_f > \varepsilon_0$
  - K_{THa} must be greater than K_{THi}

$$K_{THa} \approx \sigma_0 \sqrt{l^*} \exp\left(\frac{\varepsilon_f^H}{\varepsilon_0}\right)$$

$$K_{THi} \approx \sigma_0 \sqrt{l^*} \sqrt{\frac{\varepsilon_f^H}{\varepsilon_0}}$$

K_{THa}, K_{THi} equivalent only when fracture ductility is small





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Conclusions

- Subcritical cracking thresholds measured using constant displacement test methods (K_{THa}) are greater than those measured using rising displacement methods (K_{THi})
- Hydrogen-assisted subcritical cracking of low- to moderate-strength pressure vessel steels occurs via strain controlled mechanisms
- Weaker strain singularity of propagating crack (~ln(1/r)) compared to stationary crack (~1/r) can account for arrest thresholds (K_{THa}) exceeding initiation thresholds (K_{THi})