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Fracture and fatigue of commercial grade API pipeline steels in gaseous hydrogen

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Motivation

- Materials/System Selection
  - Microstructure of pipelines steels varies depending on strength level and era of manufacture
  - Need to assess performance of existing pipelines for hydrogen service as well as new pipeline steels for hydrogen service
- Engineering Requirements
  - Testing requirements in ASME Code for Pressure Piping, B31.12 Hydrogen Piping and Pipelines
    - Refers to ASME BPVC, Section VIII, Division 3, Article KD-10: Special Requirements for Vessels in High-Pressure Gaseous Hydrogen Transport and Storage Service
  - Article KD-10 requires two sets of engineering data, which are measured in gaseous hydrogen
    - Fracture mechanics properties (K_{IH})
    - Fatigue crack growth rates (da/dN)
- Science-based Engineering
  - Develop robust testing methodologies
  - Understand hydrogen-metal interactions to aid materials selection for hydrogen service

Pipeline steels being tested

Designation	Grade	Vintage (approx)	Microstructure
B	X80	2000	Ferrite / Acicular Ferrite
D	X60 HIC	2000	Polygonal Ferrite (Pearlite ~5%)
E	X70/X80	2000	Ferrite / Acicular Ferrite (microalloyed with Mo)
F	X70/X80	2000	Ferrite / Acicular Ferrite
J	X52	1990 2000	Ferrite – Pearlite (~5%)

All steels tested as skelp; except alloy J, which is from pipe.

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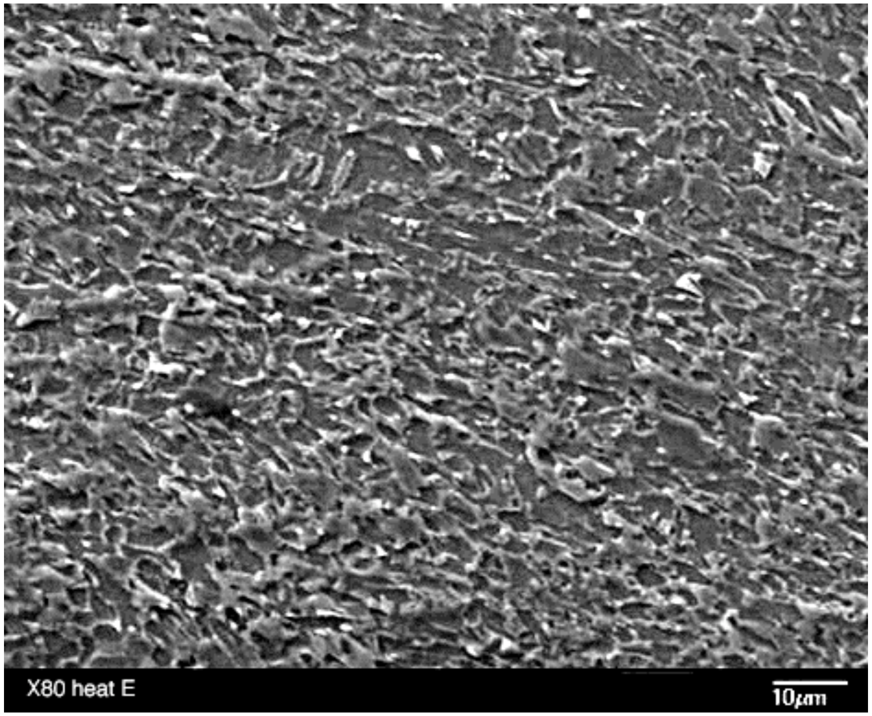
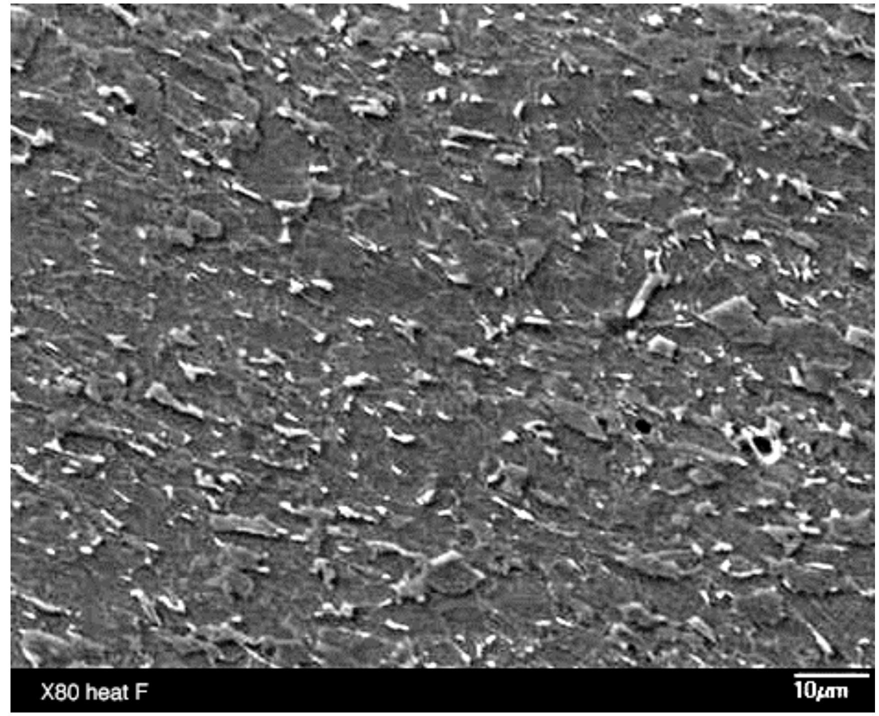
Microstructure



X80 (alloy E)
Mo additions ~0.15 wt%
Fine Acicular Ferrite
Yield strength: 593 MPa



X80 (alloy F)
Acicular Ferrite w/
30% polygonal ferrite
Yield strength: 552 MPa

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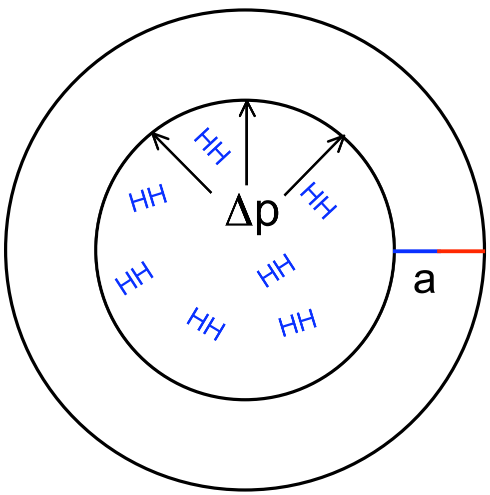
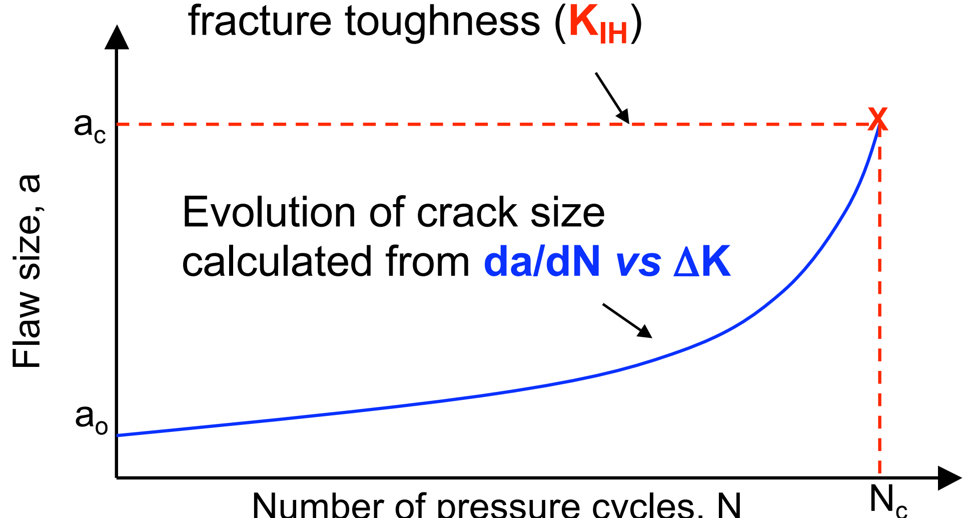
Article KD-10 provides design method for Hydrogen containing pressure vessels

- Initial flaw assumed (a_o)
- Crack propagates in fatigue at rate determined by measured crack growth rate (da/dN)
- At critical crack length (a_c), fracture resistance (K_{IH}) is exceeded and crack propagation is unstable





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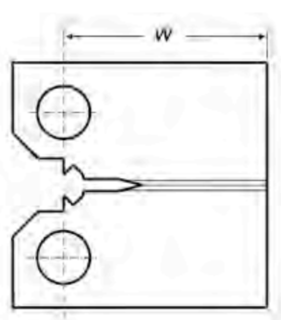
Fracture mechanics tests were conducted in gaseous hydrogen at pressure of 21 MPa

- Fatigue crack growth: da/dN
  - ASTM E647, constant load amplitude
- Fracture resistance: K_{IH}
  - ASTM E1820, elastic-plastic analysis using J-R curve determination

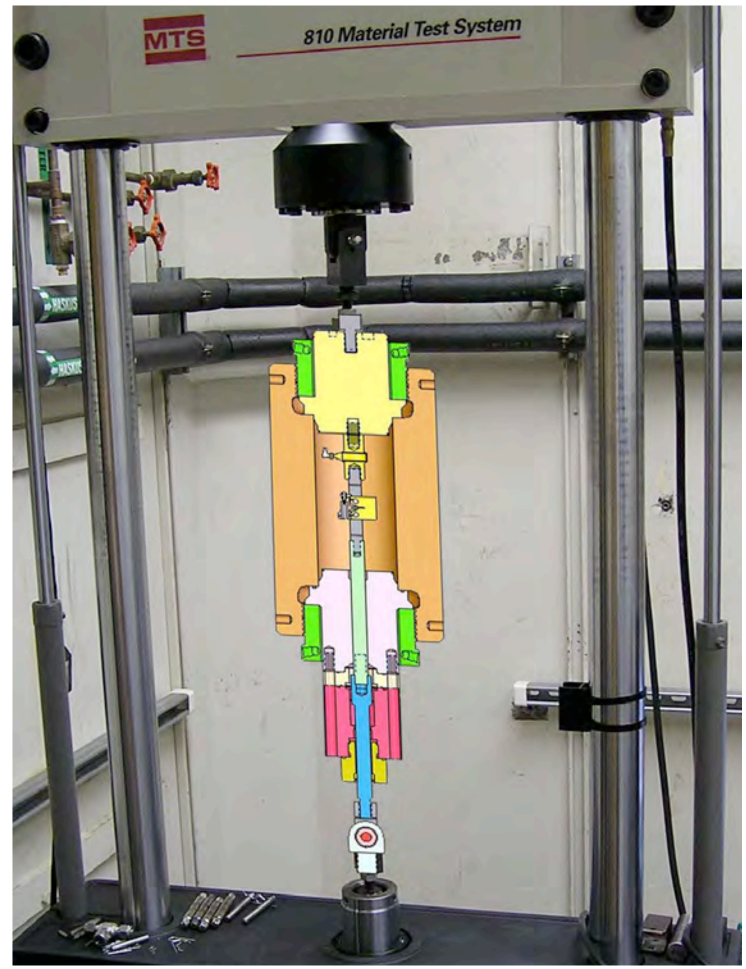
Steel plate

Rolling direction

Fracture/fatigue specimens



W = 26.4 mm
B = 12.7 mm



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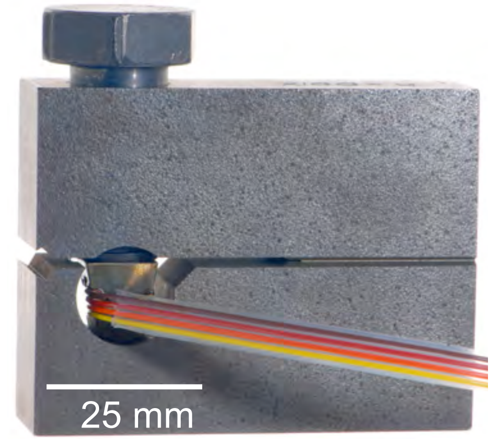
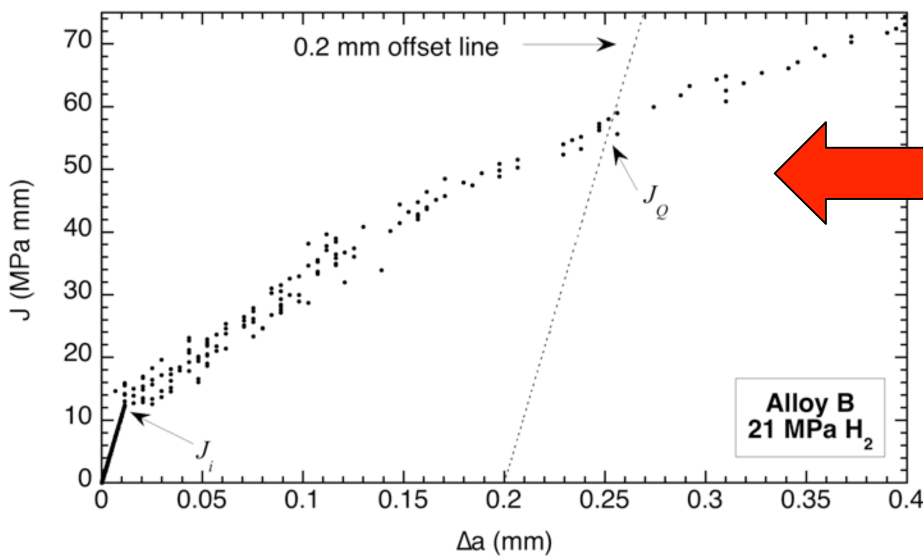
Crack extension could not be initiated in constant displacement tests

- Article KD-10 refers to test procedure in ASTM E1681
- Crack extension could not be achieved in bolt-loaded (constant displacement) specimens of steels with yield strength less than 550 MPa following ASTM E1681 in gaseous hydrogen at pressure of 103 MPa





JR-curve construction was used to evaluate fracture toughness (ASTM E1820)

- monotonic loading
- potential difference method

$$K_J = \sqrt{\frac{JE}{(1-\nu^2)}}$$

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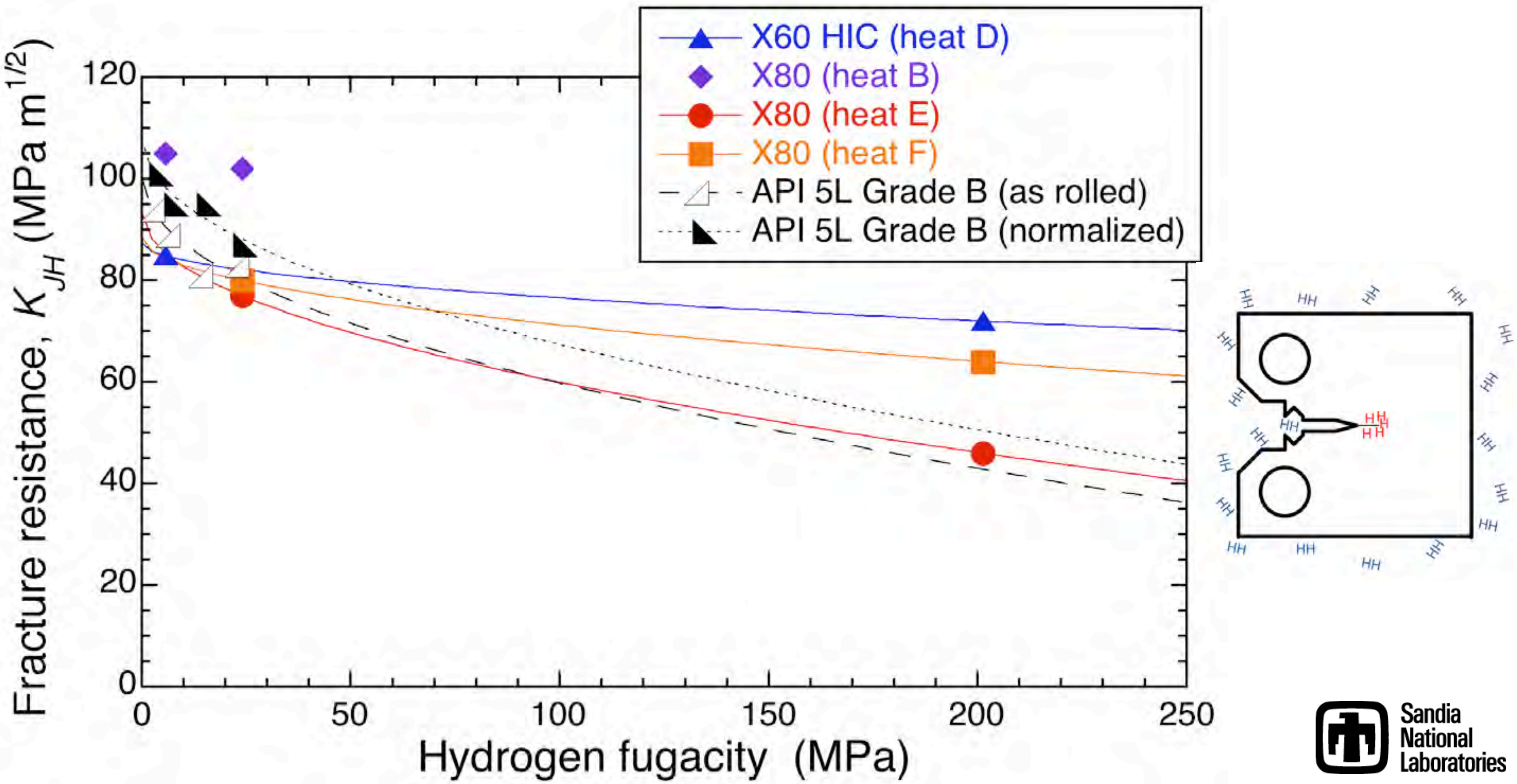
Fracture resistance in gaseous hydrogen depends on pressure

- Curves represent empirical fit assuming square root dependence on fugacity ($K \propto f^{1/2}$)
- API 5L Grade B: data from literature



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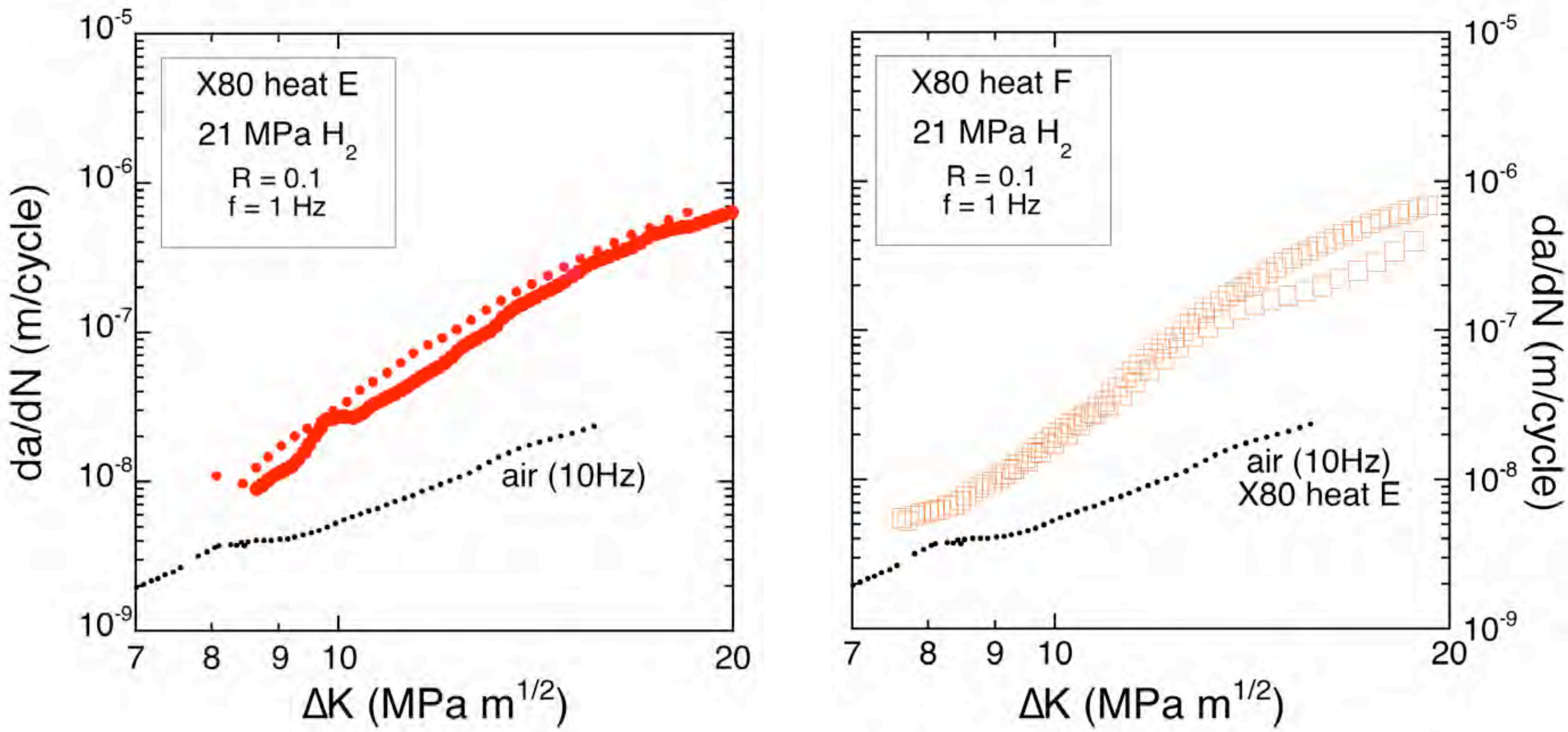
Fatigue crack growth is strongly affected by gaseous hydrogen



At "high" ΔK (>15 MPa $m^{1/2}$): $(da/dN)_H \geq 10 \times (da/dN)_{air}$

At "low" ΔK (<7 MPa $m^{1/2}$): $(da/dN)_H \Rightarrow (da/dN)_{air}$

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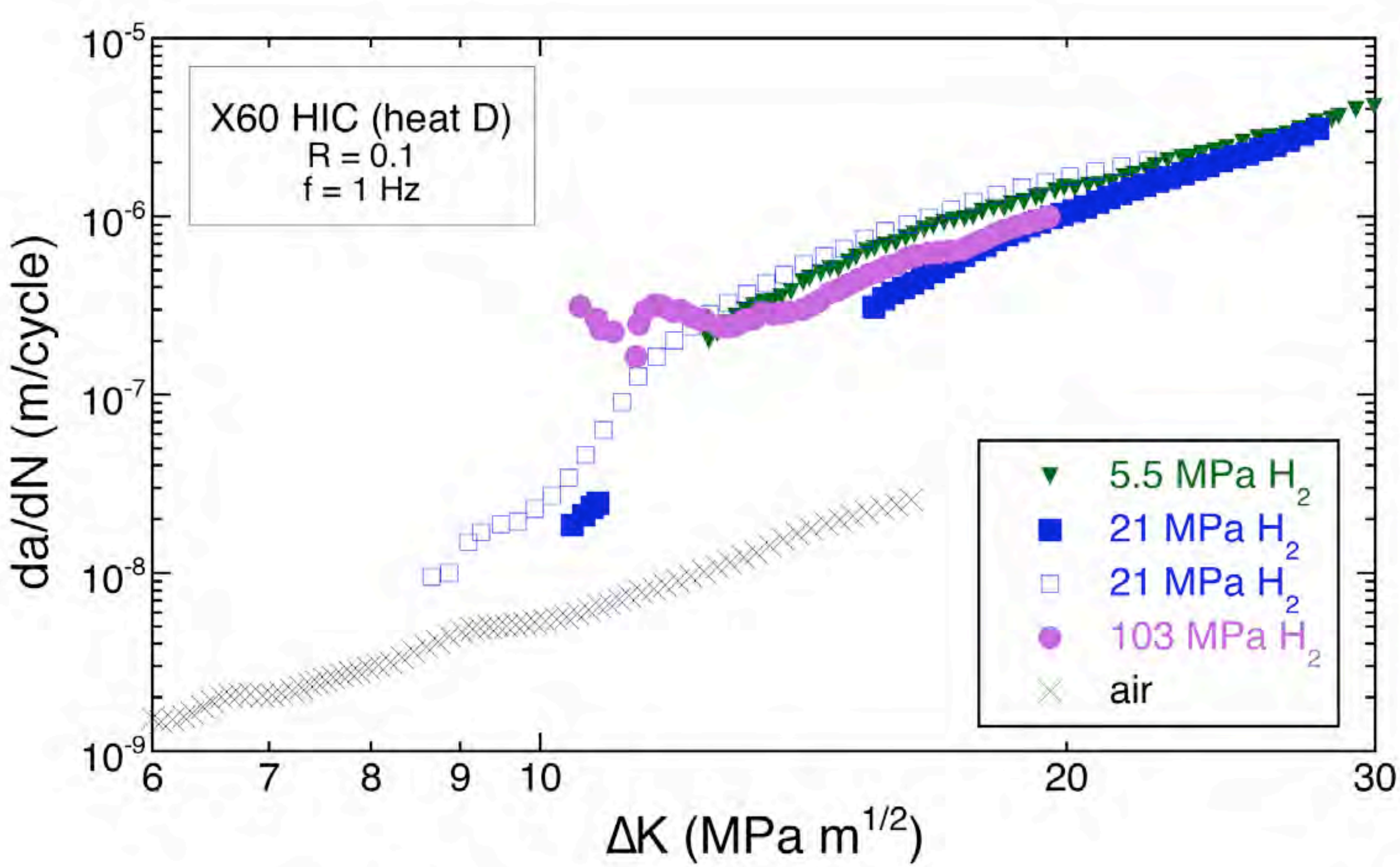
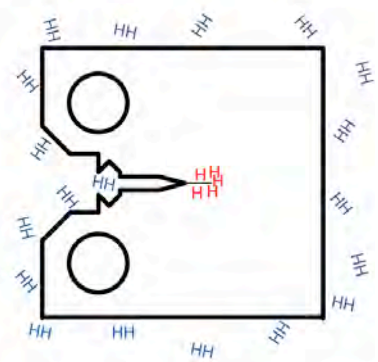
Fatigue crack growth in gaseous hydrogen does not depend on pressure

- Additional testing is necessary to clarify trends for fatigue crack growth at “low” ΔK in high pressure gaseous hydrogen





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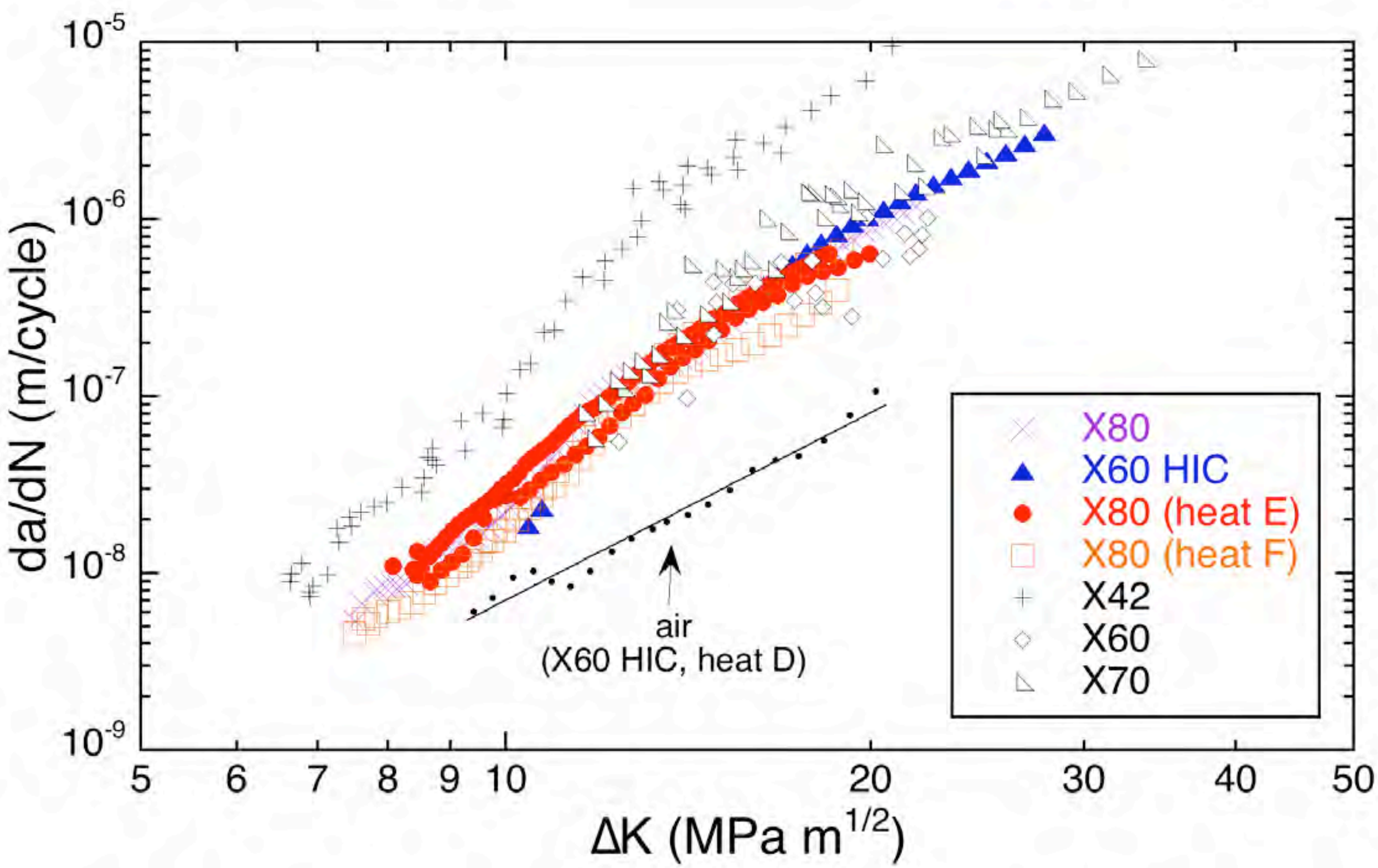
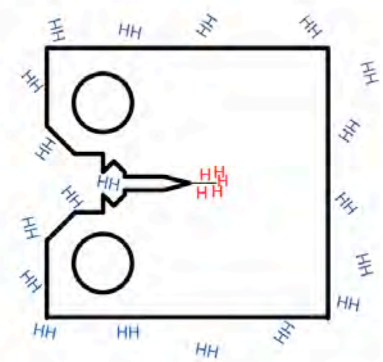
Trends for fatigue crack growth are consistent for a range of pipeline steels

Fatigue crack growth rates in gaseous hydrogen (~20 MPa pressure) appear to be consistent for a broad range of pipeline steels





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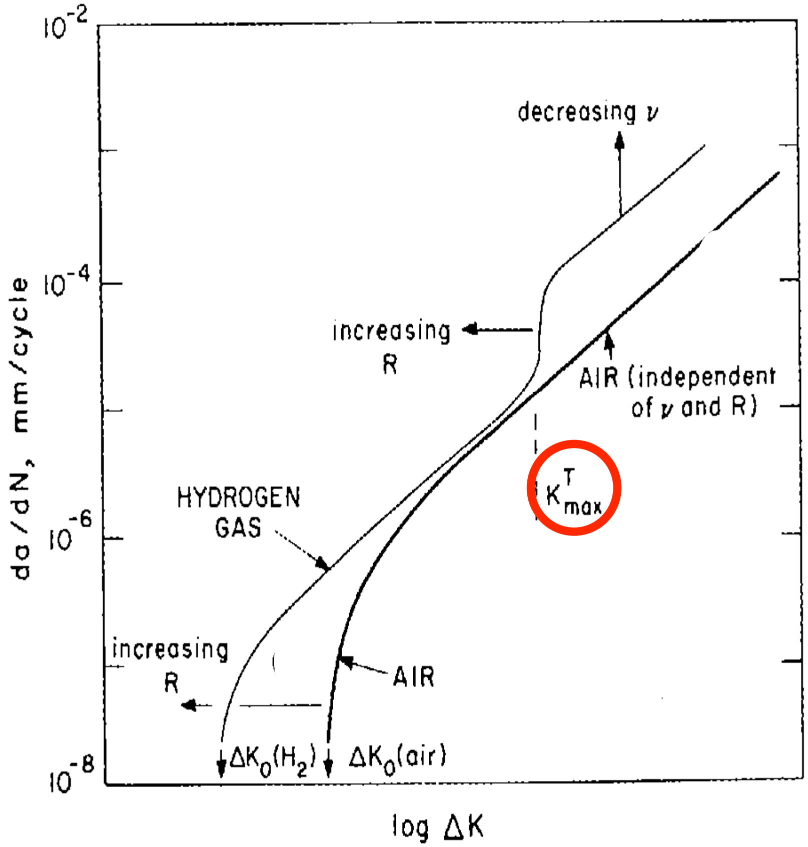
Fatigue crack growth results are consistent with previous studies



After: Suresh and Ritchie *Metal Science* 16 (1982) p.529

- Fatigue crack growth in gaseous hydrogen cannot be idealized as simple power law
- Hydrogen-assisted crack growth is "triggered" at some critical stress intensity factor called K^T_{max}
- K^T_{max} < 15 MPa m$^{1/2}$ for low-strength carbon steels in gaseous hydrogen at pressure greater than 5 MPa
- More work is necessary to characterize transition region

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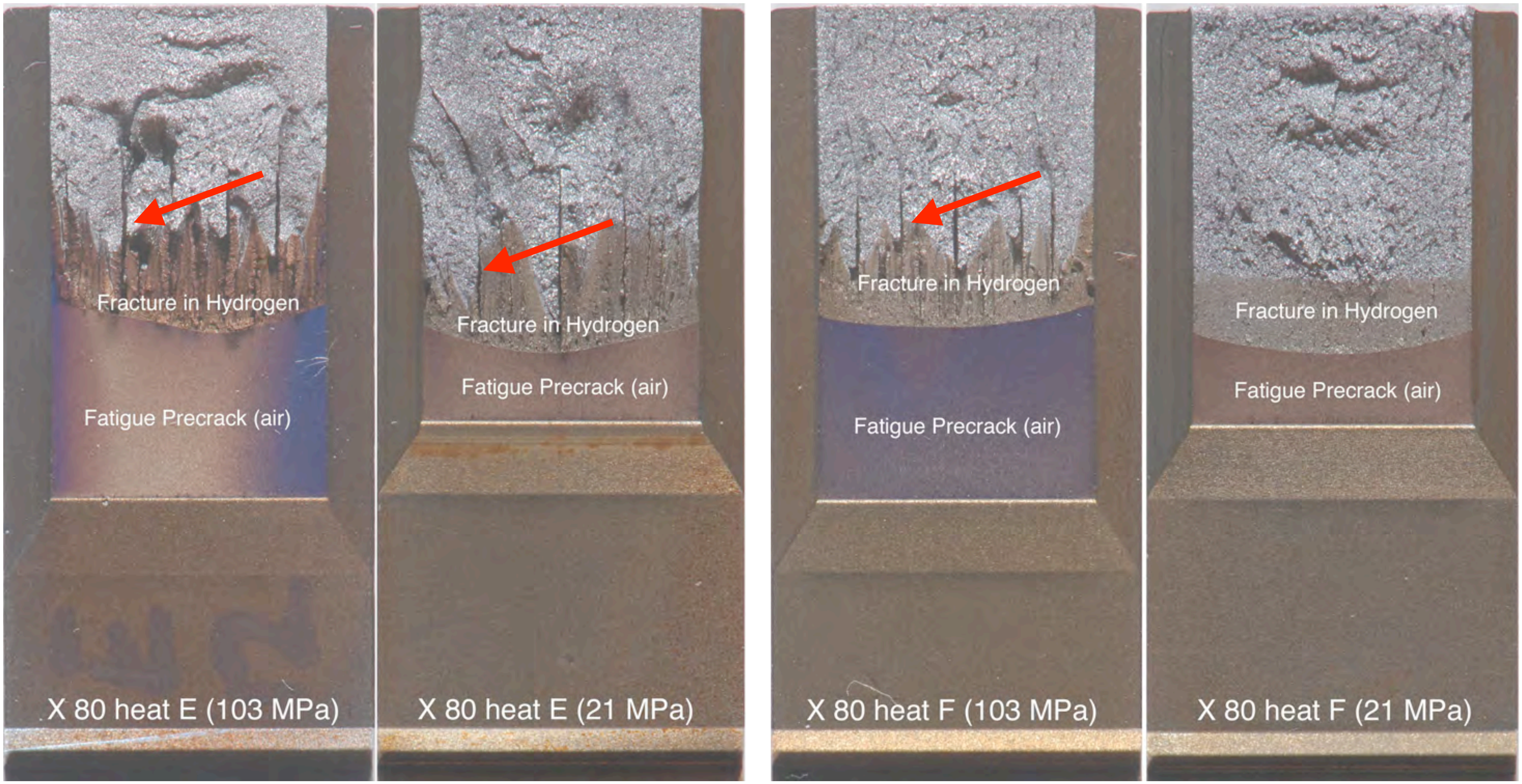
Delamination is promoted in high-pressure hydrogen, at high stress



Delamination is not observed in fatigue (low stress)

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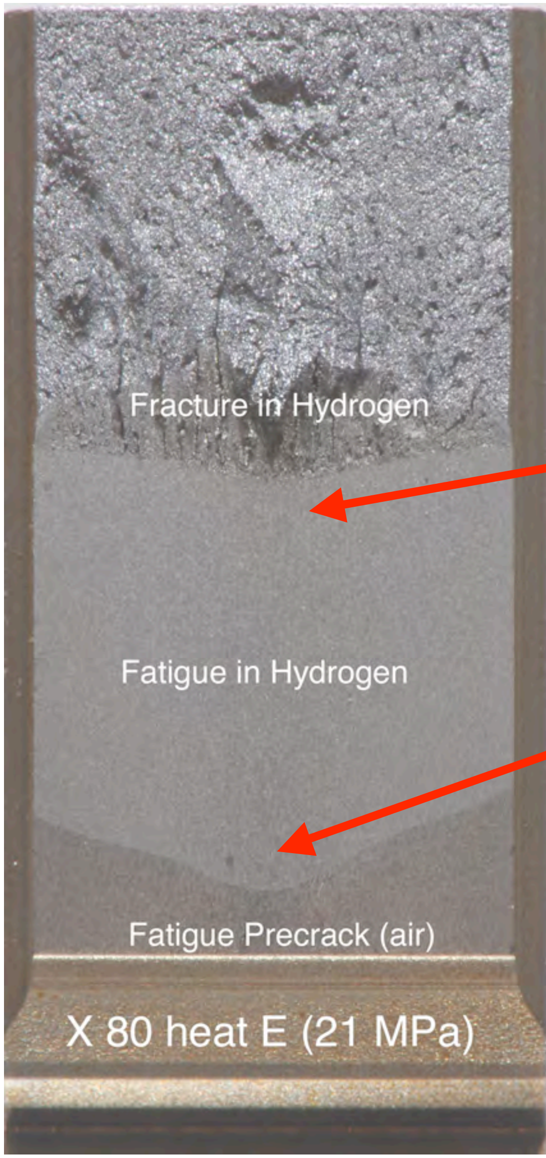
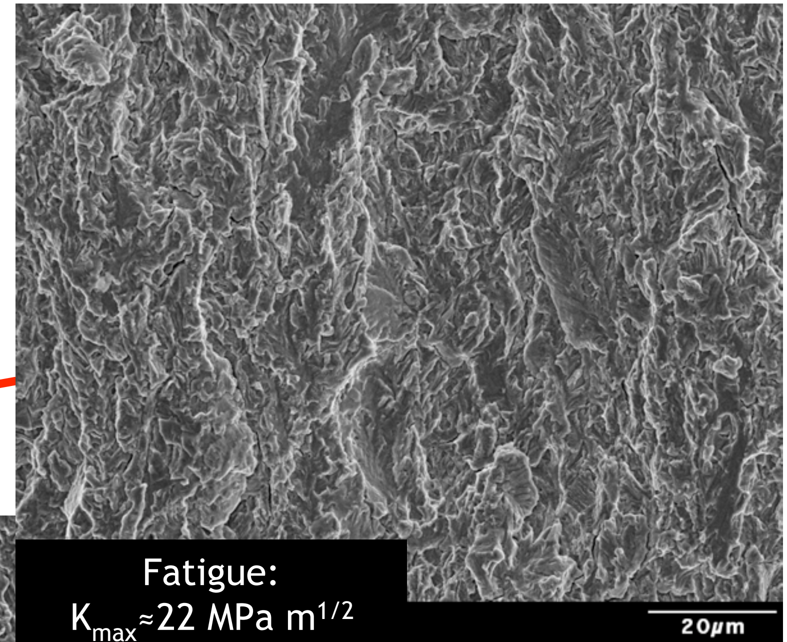
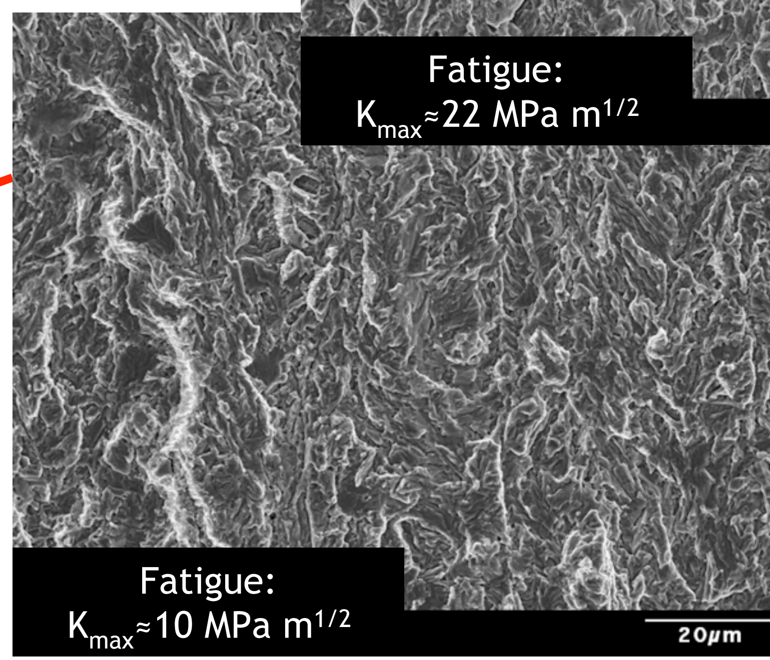
Fatigue fracture surface in hydrogen is not a strong function of $K_{max} > K^{T}_{max}$



More secondary cracking and flat features at higher K_{max}



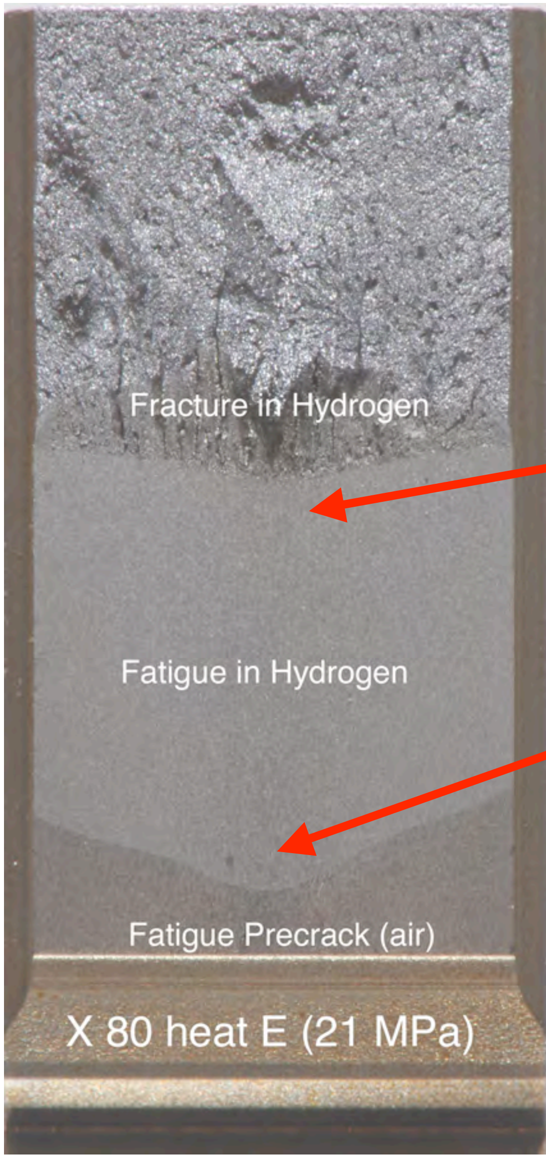


Alloy E

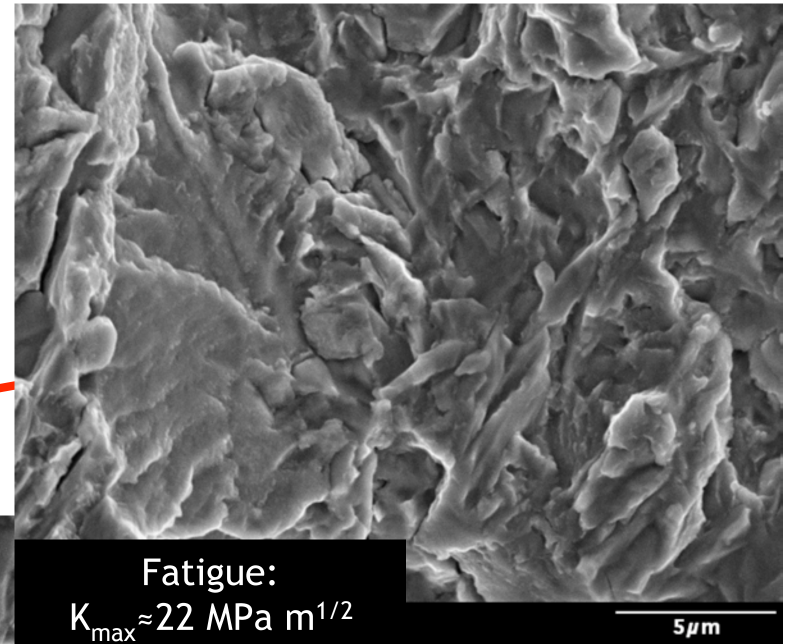
21 MPa H_2

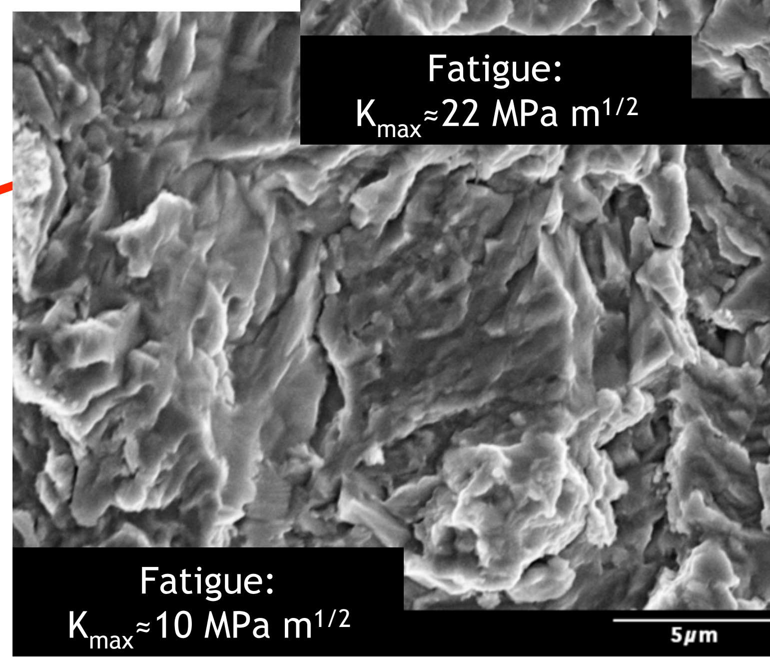
R=0.1

Fatigue fracture surface in hydrogen varies as a function of K_{max}



More secondary cracking and flat features at higher K_{max}





Alloy E

21 MPa H_2

R=0.1

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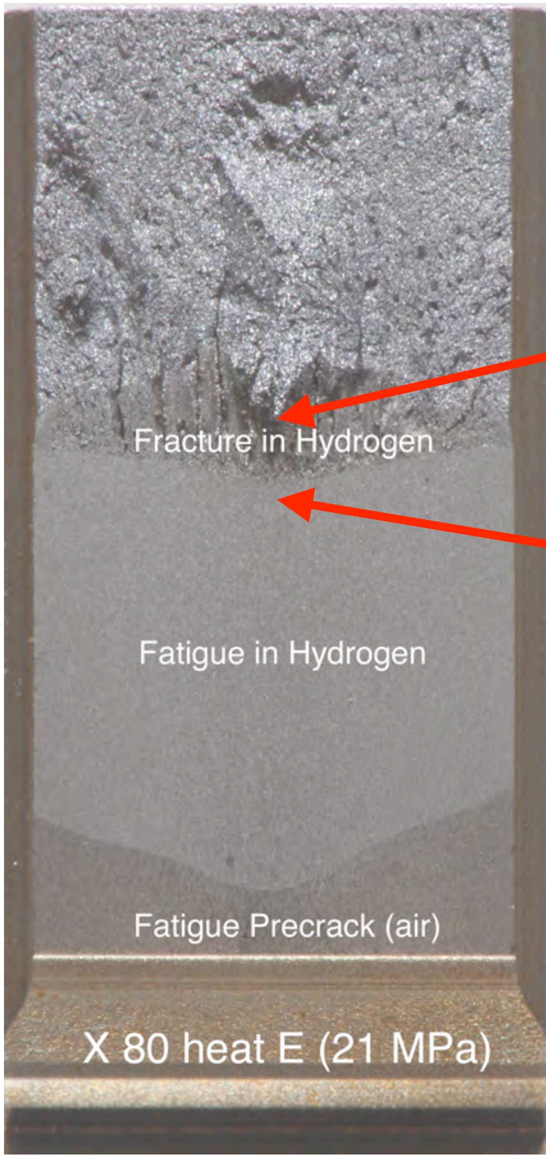
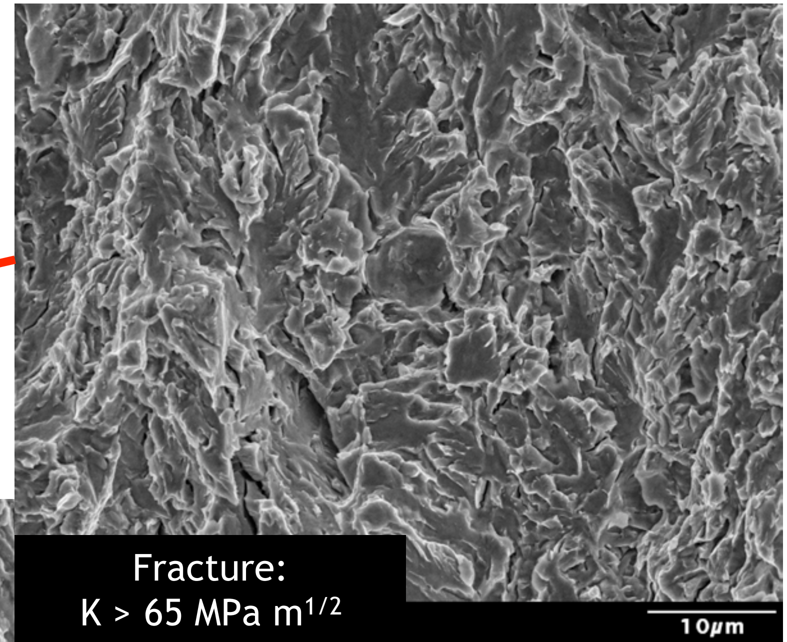
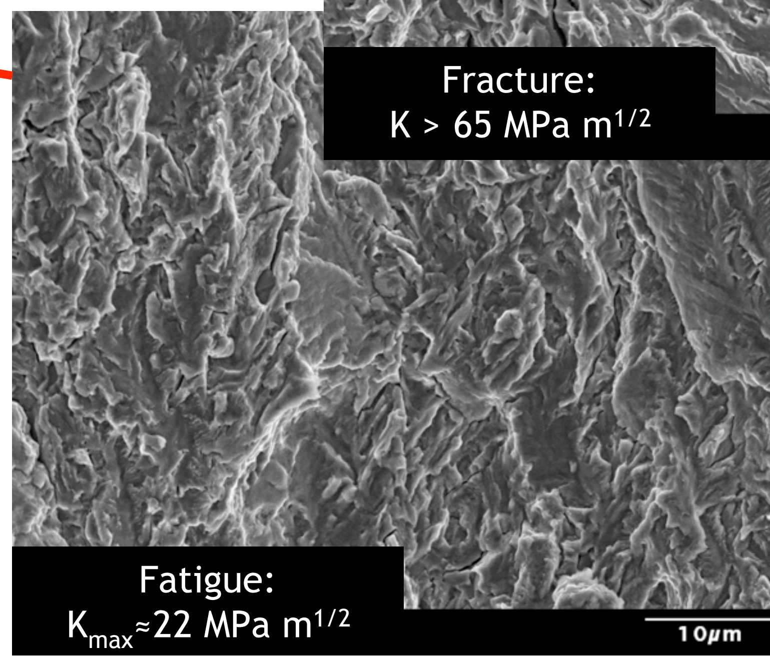
Fracture surface in fatigue at high K_{max} is similar to fracture under rising load







Alloy E

21 MPa H_2

R=0.1

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Summary

Determination of fracture resistance and fatigue crack growth rates of pipeline steels in gaseous hydrogen are motivated by ASME B31.12 code

- Fracture toughness according to BPVC VIII.3 KD-10 could not be determined
- Elastic-plastic fracture analysis of a range of pipeline steels
  - fracture resistance: K_{JH} = 80-100 MPa $m^{1/2}$
  - Hydrogen gas pressure ~5 to 25 MPa
  - Low fracture resistance at higher pressure
- Fatigue crack growth is accelerated by a factor of 10 at high ΔK, but converges with air data at low ΔK
- Fatigue crack growth rates appear less sensitive to alloy and hydrogen pressure than fracture resistance
  - At "high" ΔK, crack growth rates are not dependent on pressure in the range of 5 to 100 MPa