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Effects of Testing Rate on Hydrogen-Assisted Fracture of Ferritic Steels

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HyBlend
U.S. DEPARTMENT OF ENERGY

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Pipeline Blending CRADA

Objective - Provide scientific framework that enables blending of hydrogen into NG infrastructure

4 national laboratories

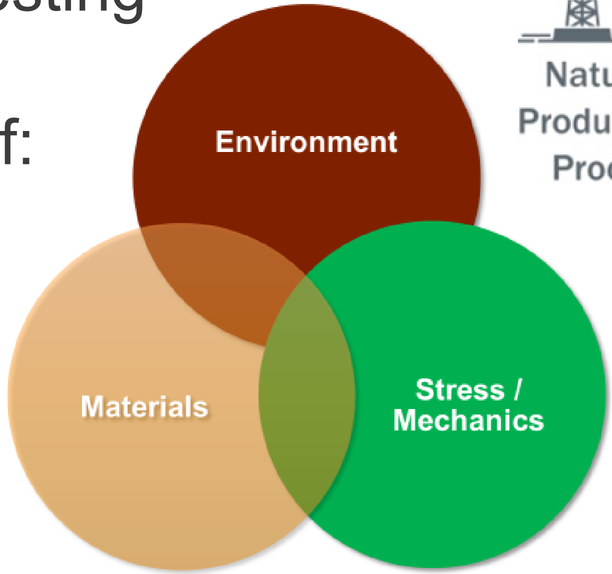
26 total industry, academia, and consortium partners

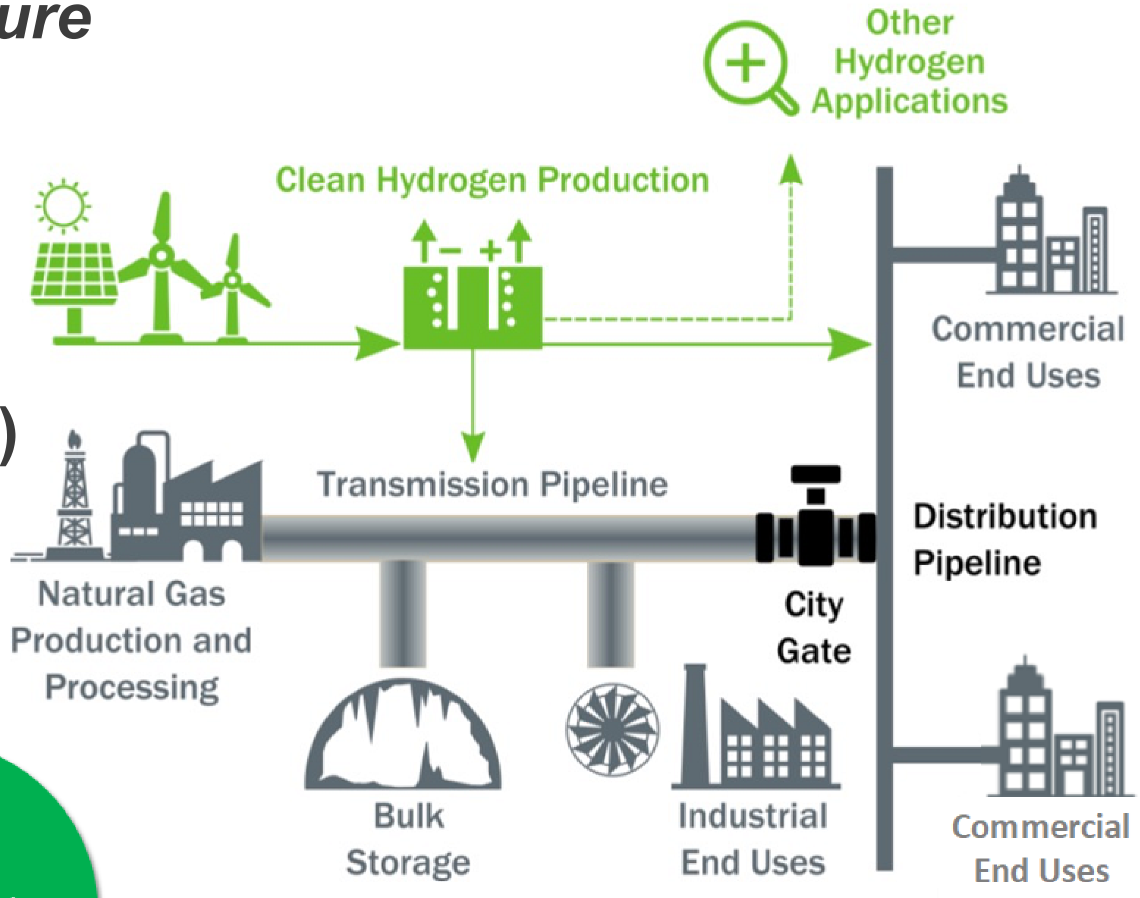
Structural Materials Task: Metals (Sandia)

→ Fatigue and Fracture Testing of Vintage pipe / welds

→ Understand influence of:

- Pressure
- Microstructure
- Rate / Frequency
- Strength



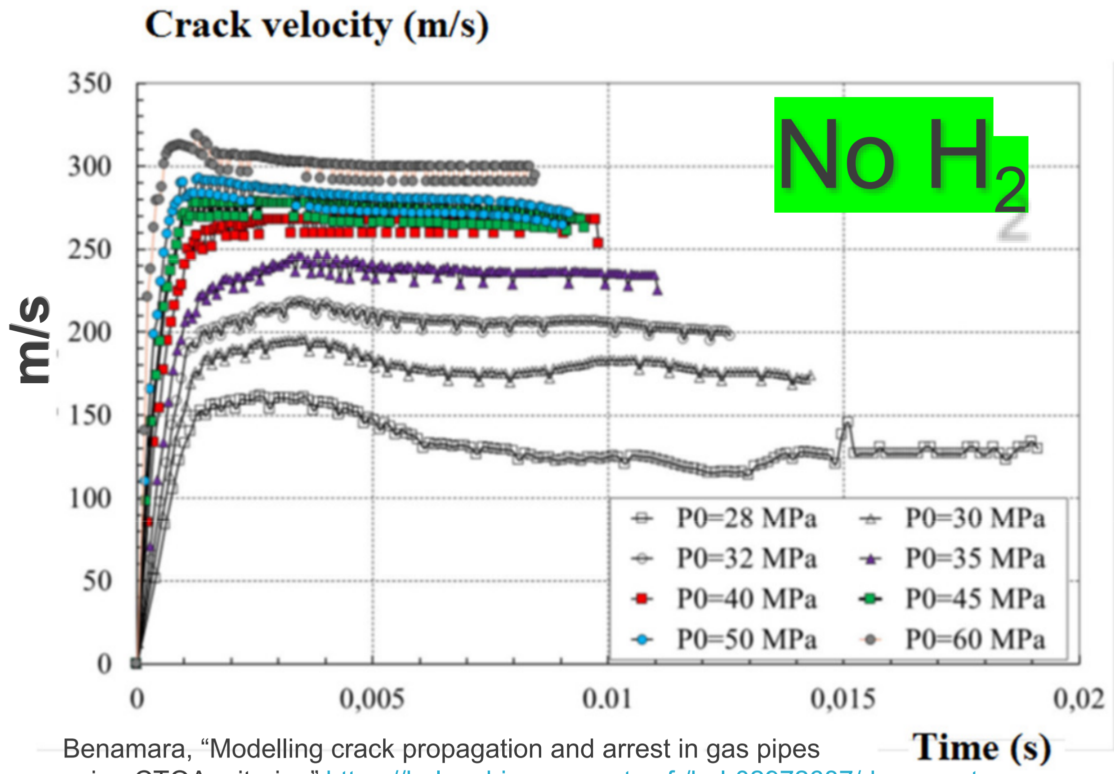


Oct 2021 – Sept 2023 (2 yr project)

Research Question: Does hydrogen have an influence on fracture resistance at fast testing rates?

→ Fracture along a seam weld of pipe can be rapid (>100 m/s)

https://www.ogj.com/general-interest/companies/article/17232192/fullscale-burst-crackarrest-testing-vets-x120-line-pipe

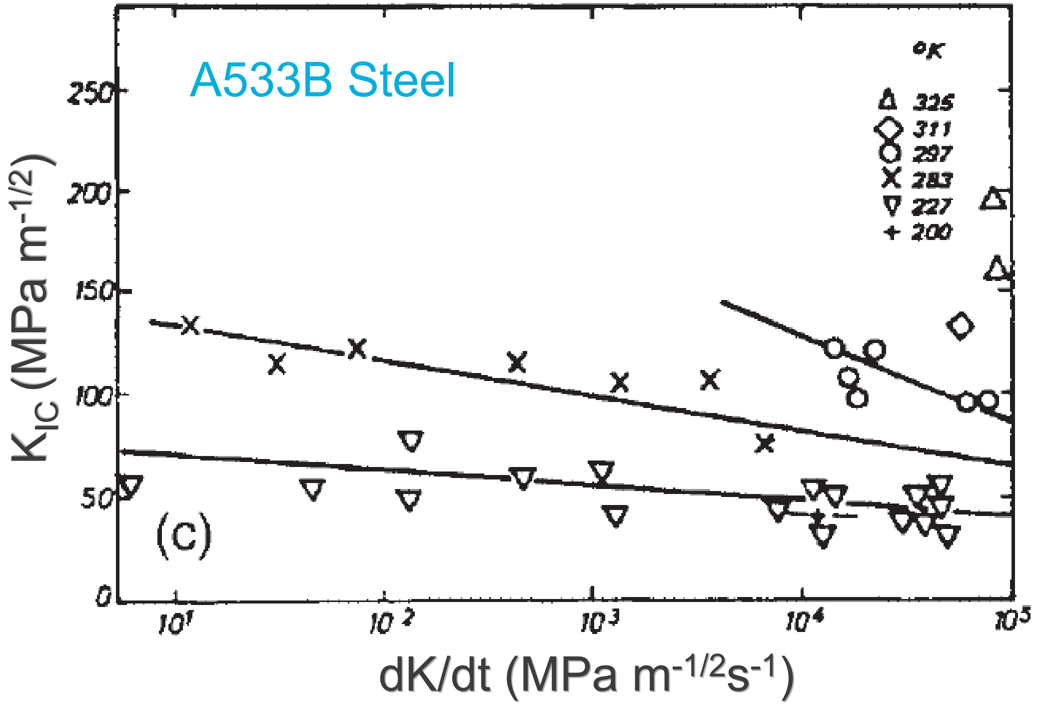


Benamara, "Modelling crack propagation and arrest in gas pipes using CTOA criterion" https://hal.archives-ouvertes.fr/hal-02972687/document

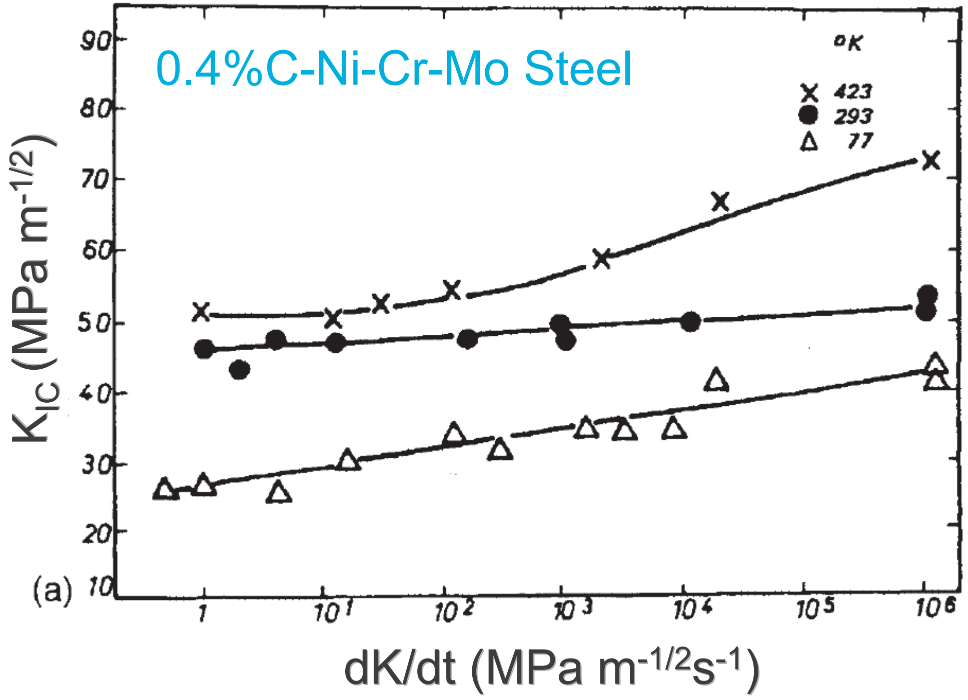
Conventional fracture toughness testing is performed at slow quasi-static rates → Limited data at *fast* rates in H_2

In absence of H_2, testing rate can influence fracture toughness

K_{IC} can ↓ as dK/dt ↑



K_{IC} can ↑ as dK/dt ↑



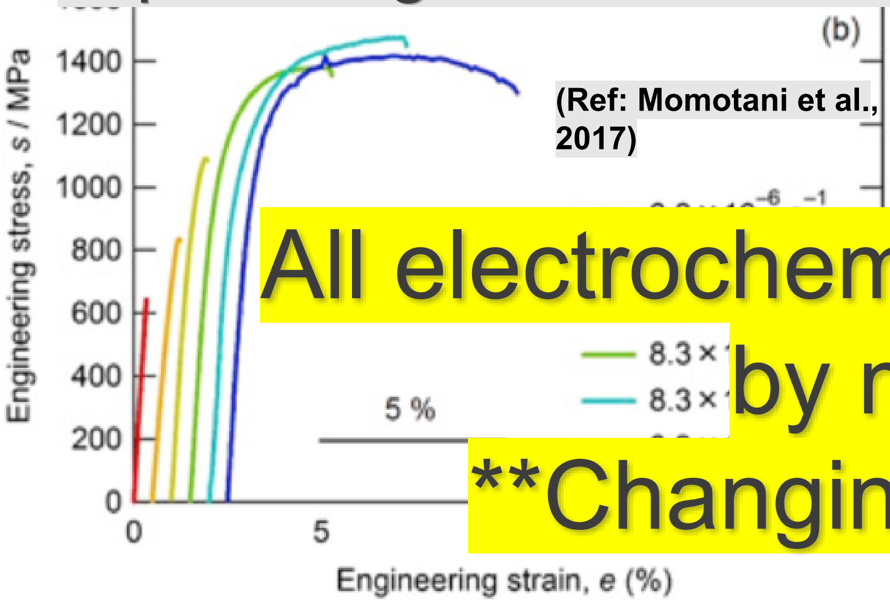
Will hydrogen influence this trend?

Ref: Wiesner and MacGillivray, 2000

Conventional thinking with H_2…

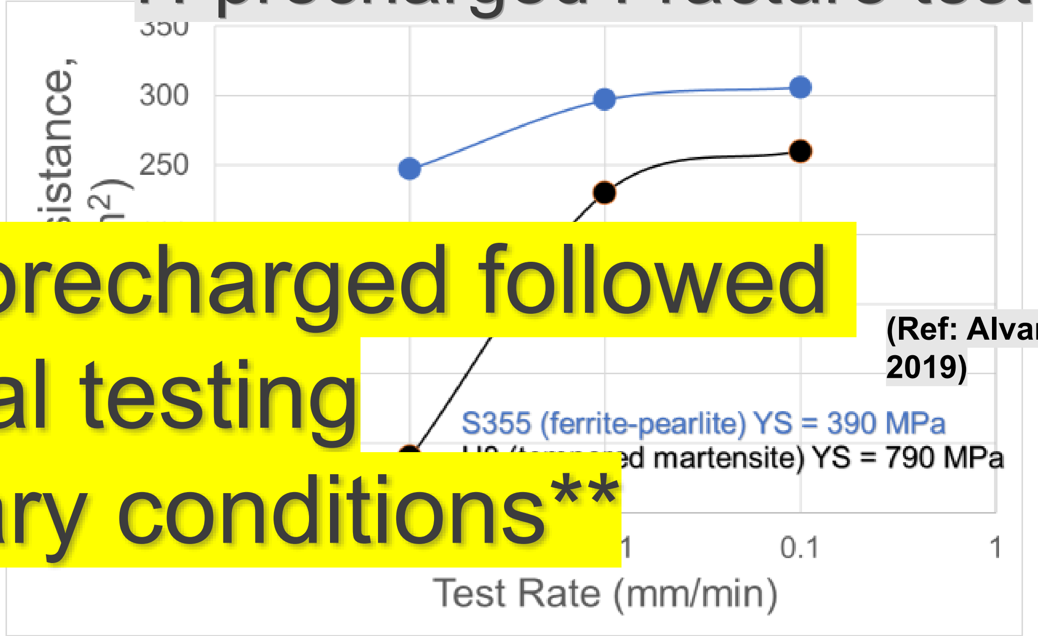
Faster testing rates → Limited Hydrogen diffusion / accumulation → Mitigates / eliminates hydrogen embrittlement

H-precharged Tensile test



(Ref: Momotani et al., 2017)

H-precharged Fracture test



(Ref: Alvarez et al., 2019)

All electrochemically H-precharged followed by mechanical testing

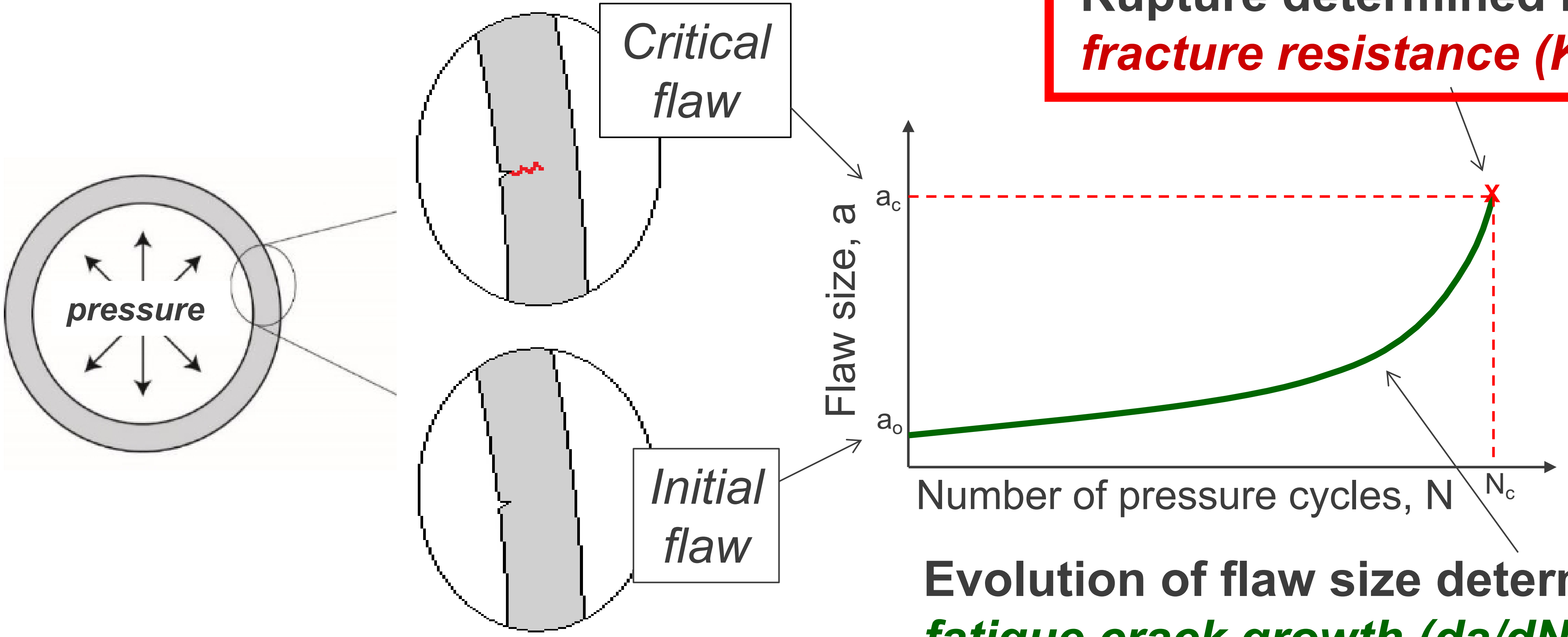
Changing boundary conditions

As strain rate ↑, effects of hydrogen ↓
For hydrogen precharged low-carbon martensite

Rate effects still apparent
→ Less rate dependence on low strength steel than high strength steel

Fracture Testing in gaseous H_2

Testing motivation: structural integrity assessment utilizing fracture mechanics-based analysis

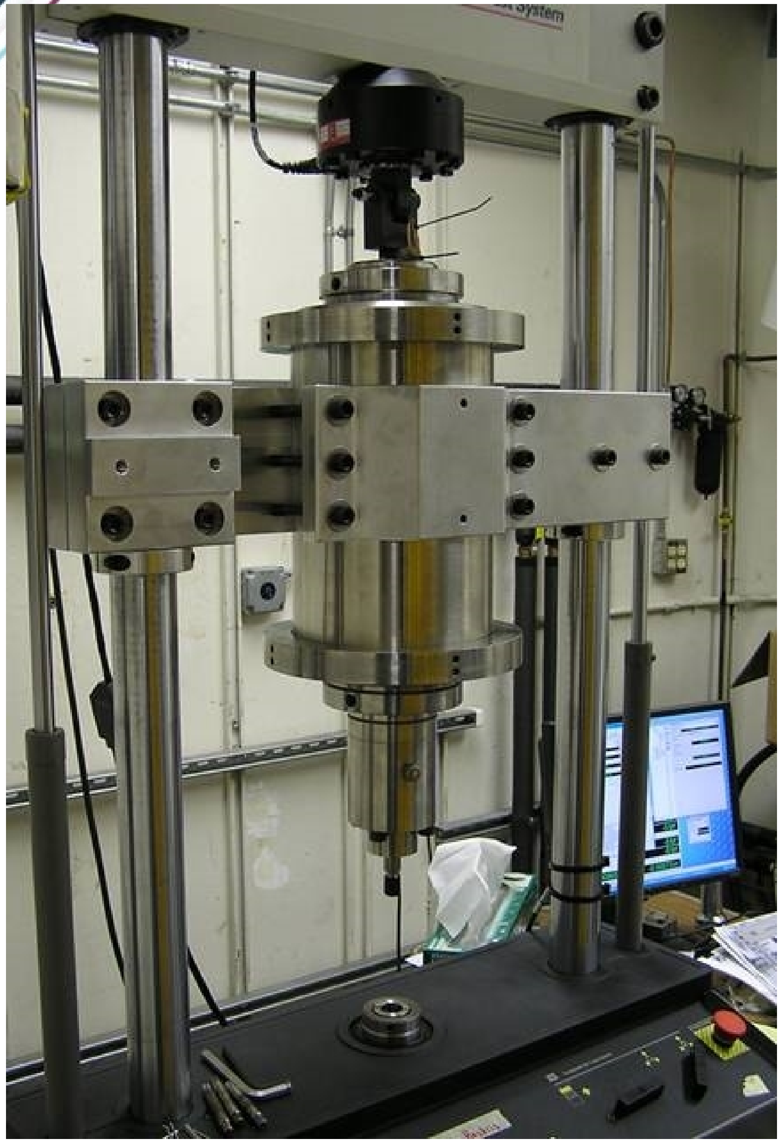


Rupture determined by *fracture resistance (K_{IC})*

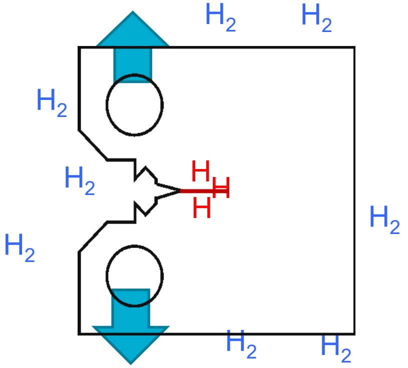
Evolution of flaw size determined by *fatigue crack growth (da/dN - ΔK data)*

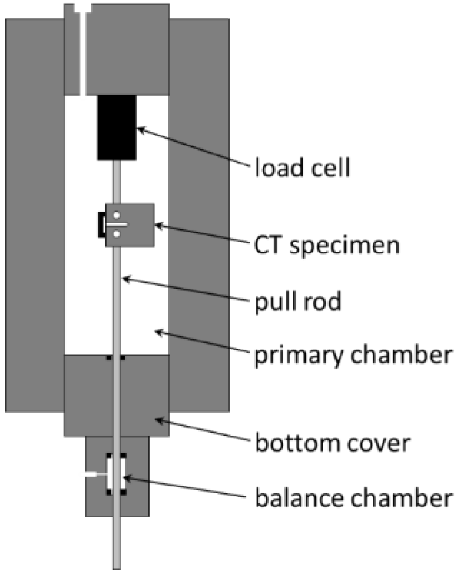
ASME B31.12 describes rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Division 3, Article KD-10

Fatigue and Fracture Testing at Hydrogen Effects on Materials Lab



Compact Tension (C(T))





Instrumentation
- Internal Load cell
- Clip gauge
- Direct Current Potential Difference (DCPD)

Fatigue: ASTM E647
- Load ratios (R) 0.1 to 0.8
- Frequency: 0.01 → 10 Hz
- Constant load or K-control

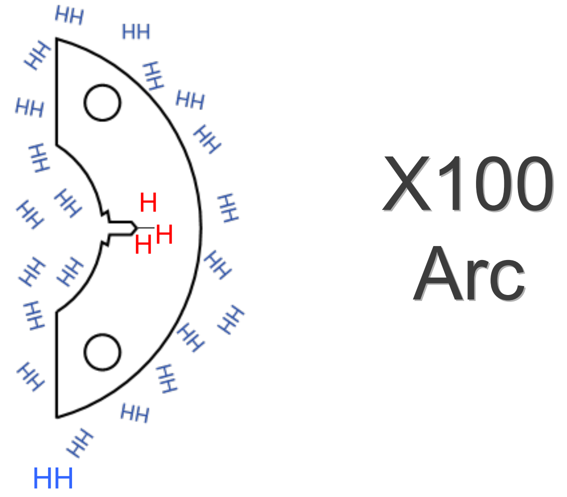
Fracture: ASTM E1820 (Elastic-Plastic)

Environment
- Air
- Pure H_2
- Gas blends, e.g. N_2 – 3%H_2
- Gas impurity mixtures:

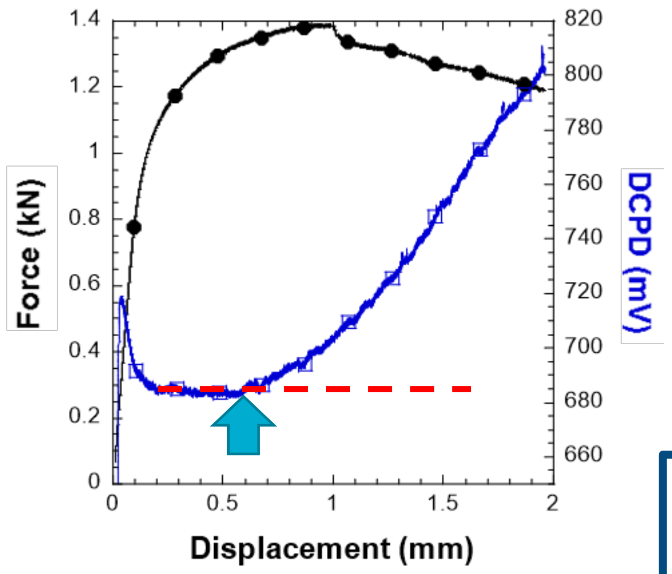
  e.g. H_2 + 10-1000 ppm O_2

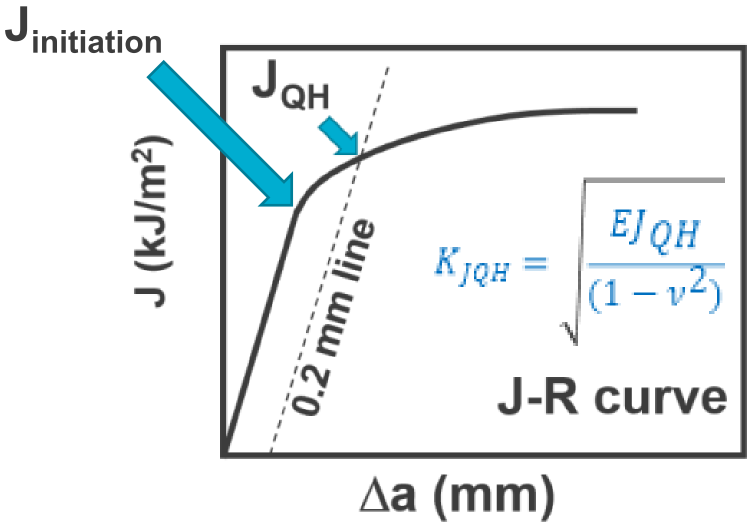
Two pipeline materials were examined

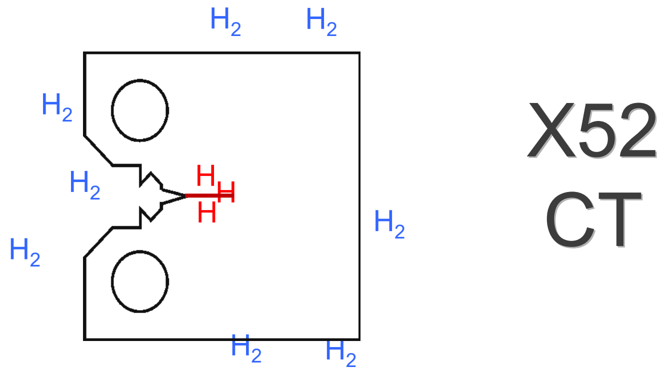
Grade	YS (MPa)	Year	Composition in wt. %								
			C	Si	Mn	P	S	V	Nb	Ti	B
X100	910	2000s	0.085	0.26	1.69	0.013	<0.001	-	0.047	0.017	0.0015
X52	490	1962	0.293	0.02	1.17	0.016	0.016	<0.002	<0.005	<0.002	<0.0005



- ASTM E1820 elastic-plastic fracture test (J-R curve)
- Fracture Displacement Rates:
  - 0.005 → 5 mm/min

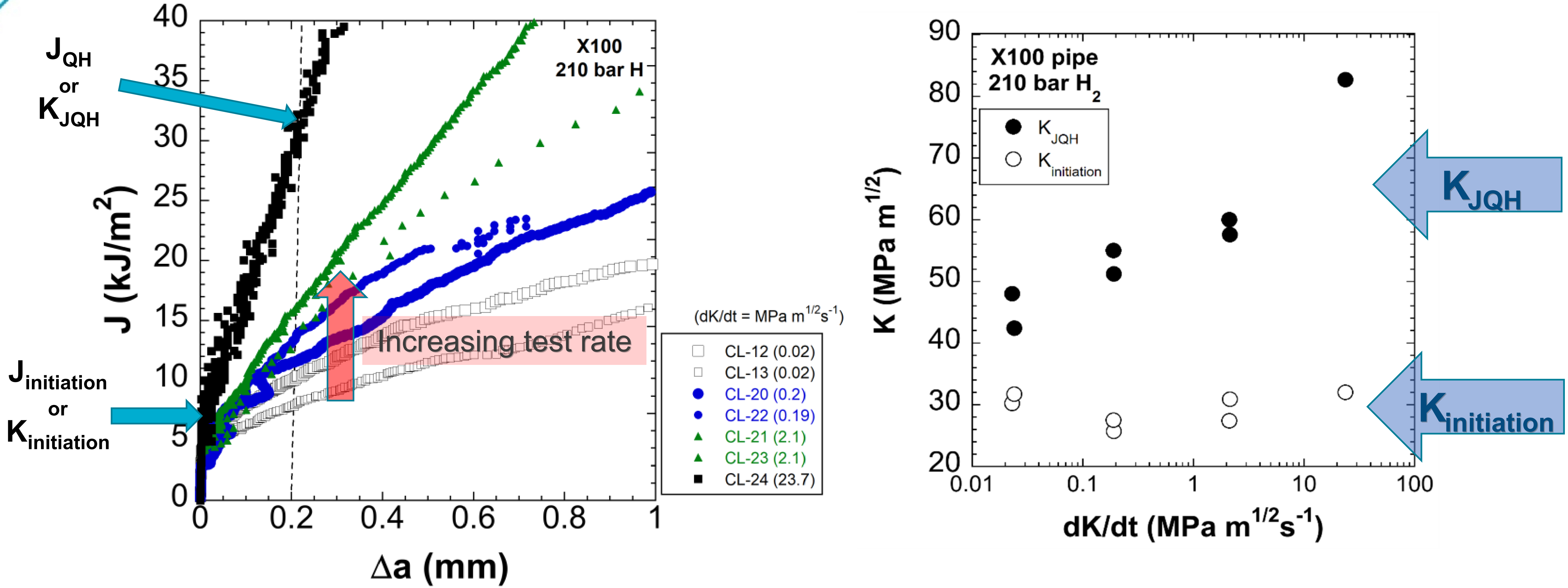






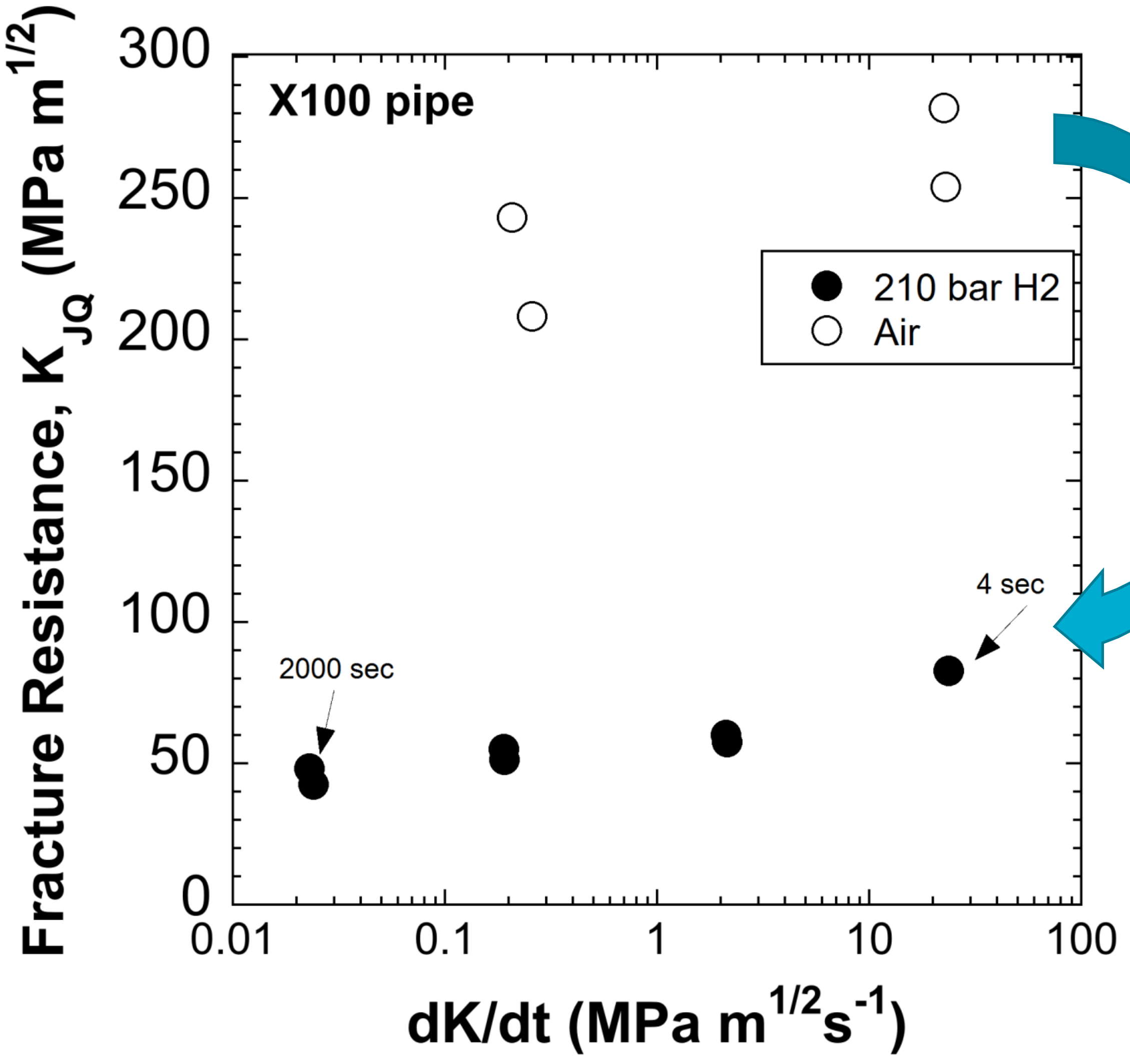
Determined fracture initiation ($J_{initiation}$) and fracture resistance (J_{QH}) from J-R curves → converted to K

Tearing modulus is clearly influenced by testing rate



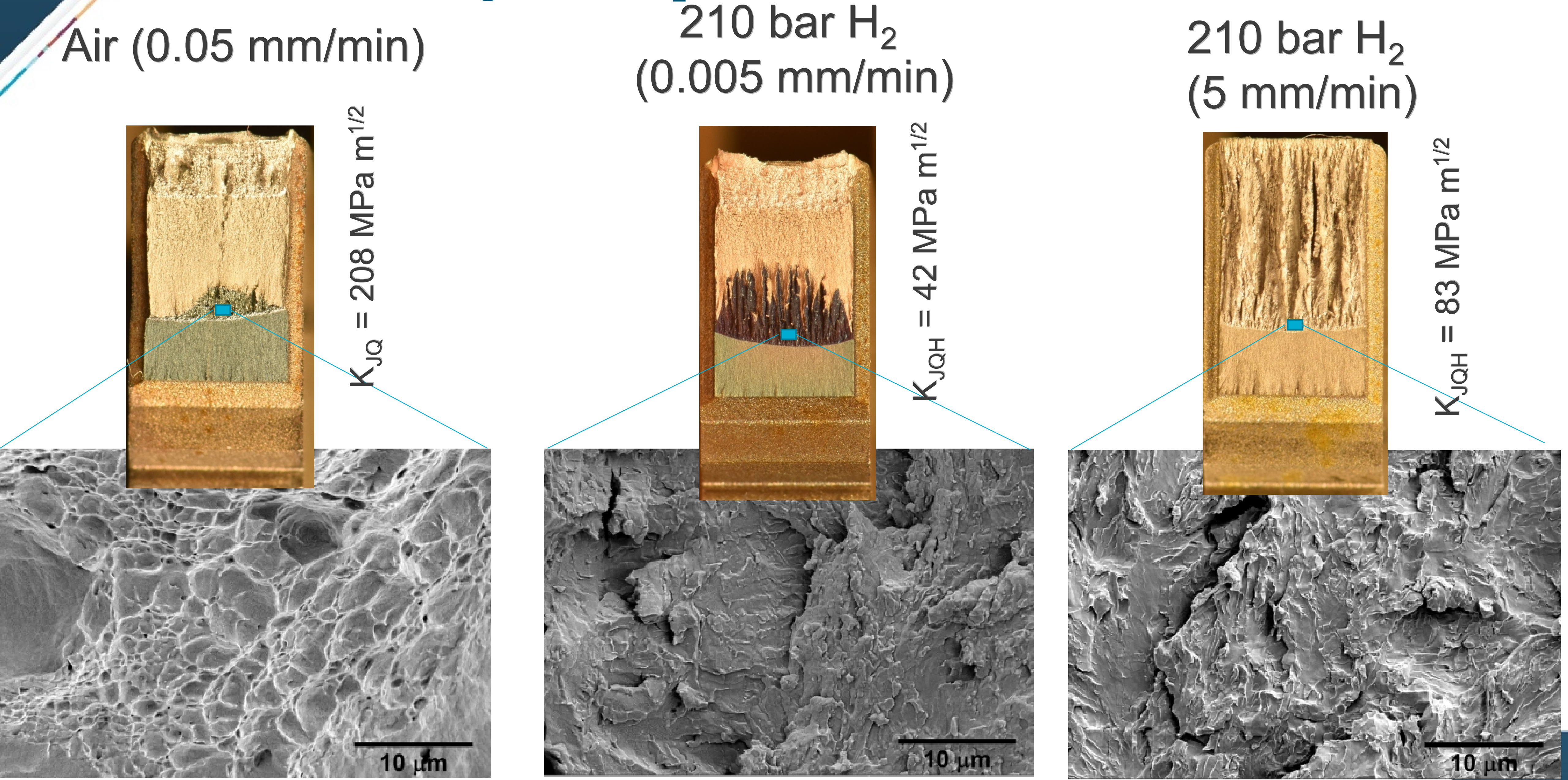
X100 fracture resistance (K_{JQH}) was rate-dependent
→ $K_{initiation}$ was less sensitive to rate

Even at high loading rates, effects of hydrogen cannot be ignored

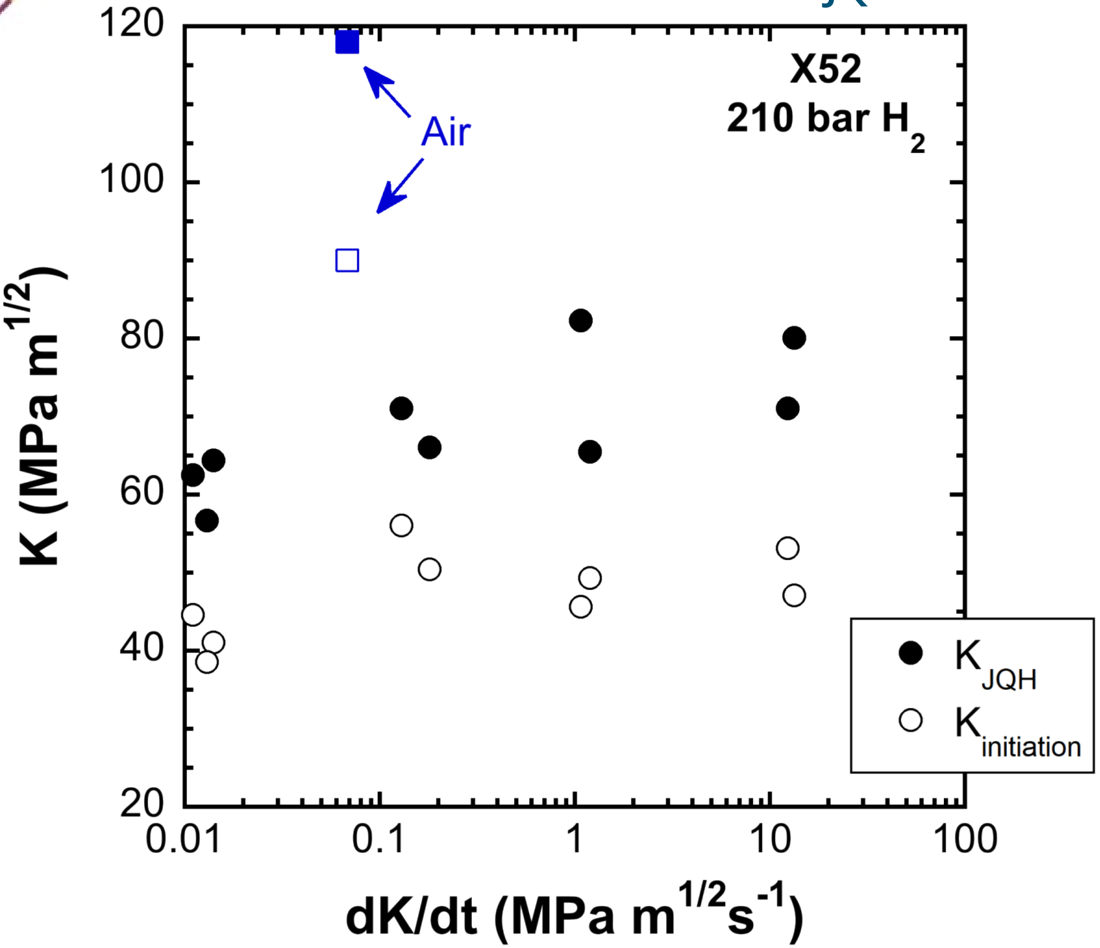


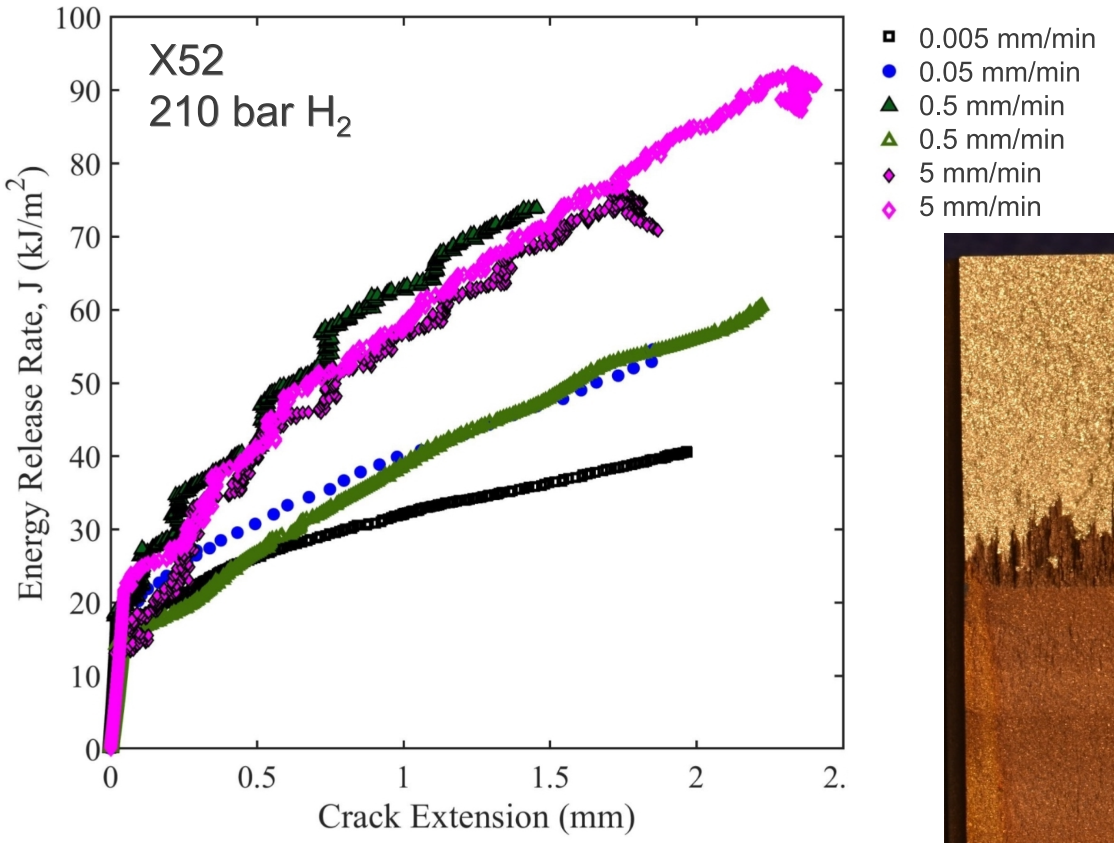
Significant difference due to H_2

Fracture surfaces still exhibit quasi-cleavage fracture at all rates when tested in gaseous H_2



X52 showed more variability for $K_{initiation}$ and K_{JQH} → Small increase in K_{JQH} with dK/dt





Variability might be due to:
→ Inclusions
→ Smaller difference between air and H_2 fracture toughness

Summary

Two pipeline steels (X52 and X100) were subjected to fracture testing in 210 bar H_2 at different testing rates

X100

- Increased K_{JQH} at faster testing rates
- Negligible change in fracture initiation ($K_{initiation}$) with testing rate

X52

- Small increase in K_{JQH} at faster testing rates
- Fracture initiation ($K_{initiation}$) exhibited more variability

Hydrogen still influences fracture even at fast testing rates & should not be ignored

<u>Gaps Remaining:</u>

- Influence of delaminations on fracture toughness
- Role of inclusions in crack initiation

Thank you for your attention!

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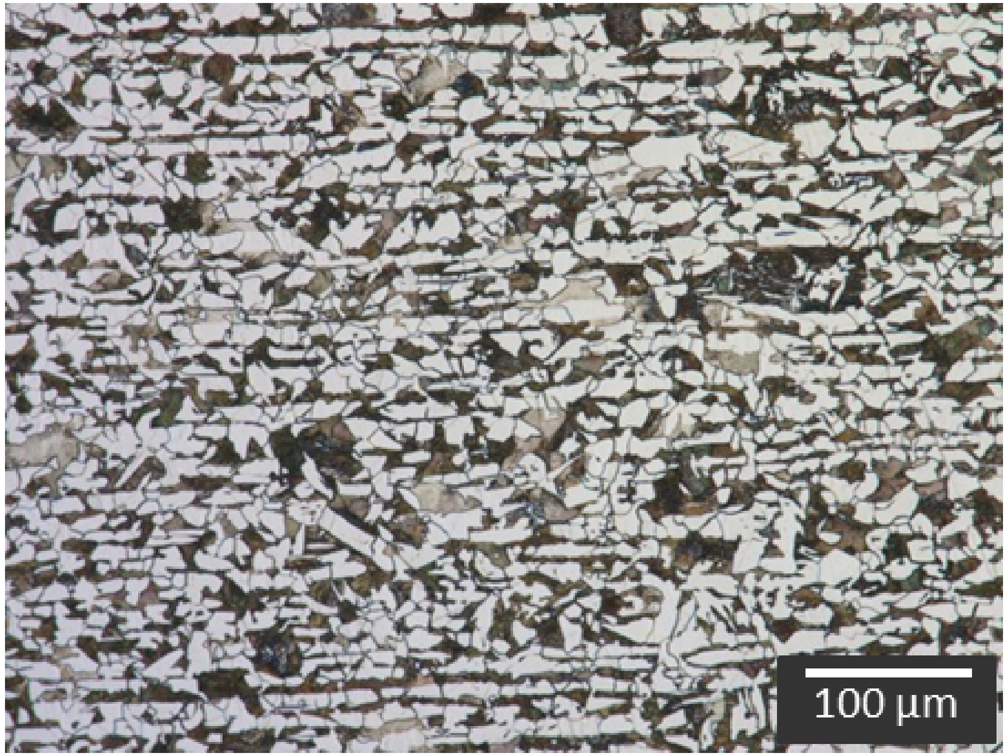
Microstructures

X52 – Ferrite/Pearlite



X100 – Acicular Ferrite/Bainite