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Fatigue and fracture of pipeline steels in high-pressure hydrogen gas (PVP2022-84757)

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H-Mat Hydrogen Materials Compatibility Consortium

HyBlend U.S. DEPARTMENT OF ENERGY

SAND2022-XXXX PE

Outline

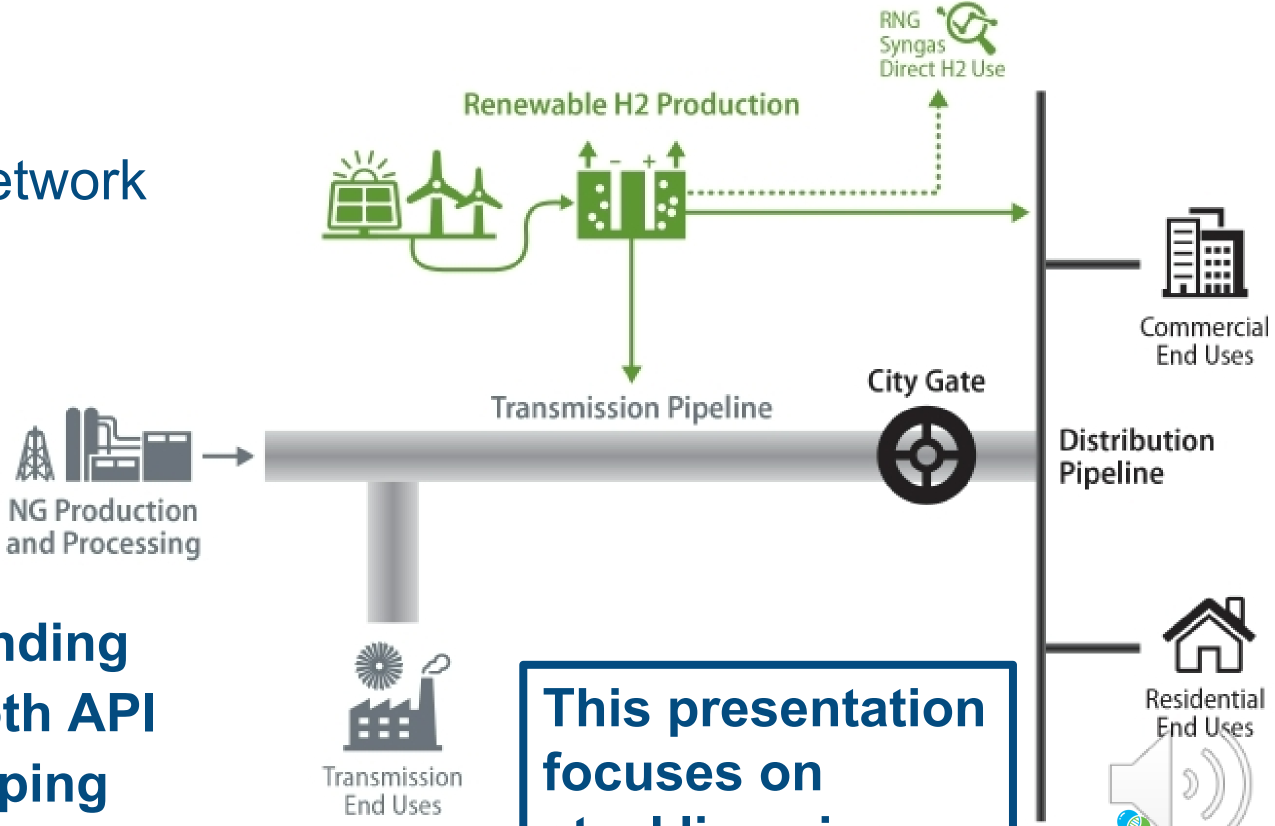
- Motivation and Framework
- Materials variables
  - 3 heats of X80 with diverse microstructure
- Mechanics variables
  - Testing methods for accelerated fatigue testing
  - Effect of loading ratio (R)
  - Fracture
- Environmental variables
  - Effect of pressure
- Master Design Curve concept

Hydrogen is one method to decarbonize natural gas networks

Transmission
- Mostly steels
- Extensive existing network

Distribution
- Legacy metals
- Extensive polymer networks

HyBlend Pipeline Blending CRADA addresses both API steels and polymer piping



This presentation focuses on steel line pipe

Motivation

With growing interest in decarbonization, hydrogen is being considered as a means to reduce carbon in energy infrastructure

Challenge

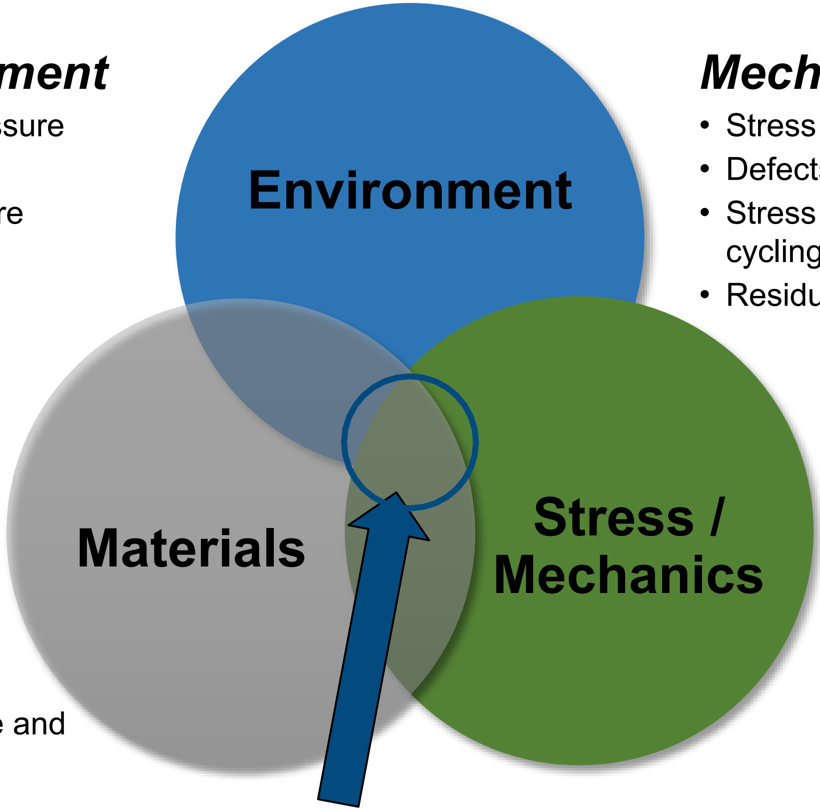
Hydrogen degrades fatigue and fracture resistance of steels, and the effects on pressure vessel and line pipe steels are significant

Environment

- Partial pressure
- Impurities
- Temperature

Mechanics

- Stress
- Defects
- Stress (pressure) cycling
- Residual stresses



Materials

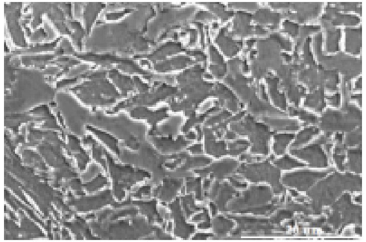
- Strength
- Microstructure and homogeneity

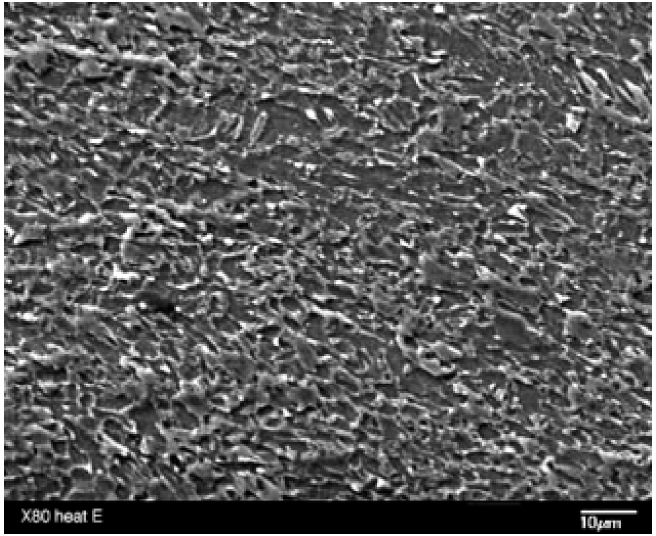
*Hydrogen embrittlement occurs in **materials** under the influence of **stress** in hydrogen **environments***

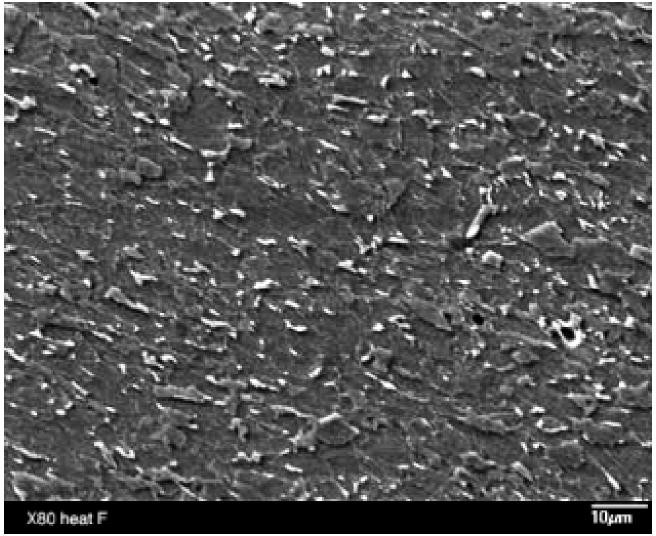
X80 steels with a range of microstructure were tested

Materials variables

Polygonal Ferrite (PF)
Acicular Ferrite (AF)







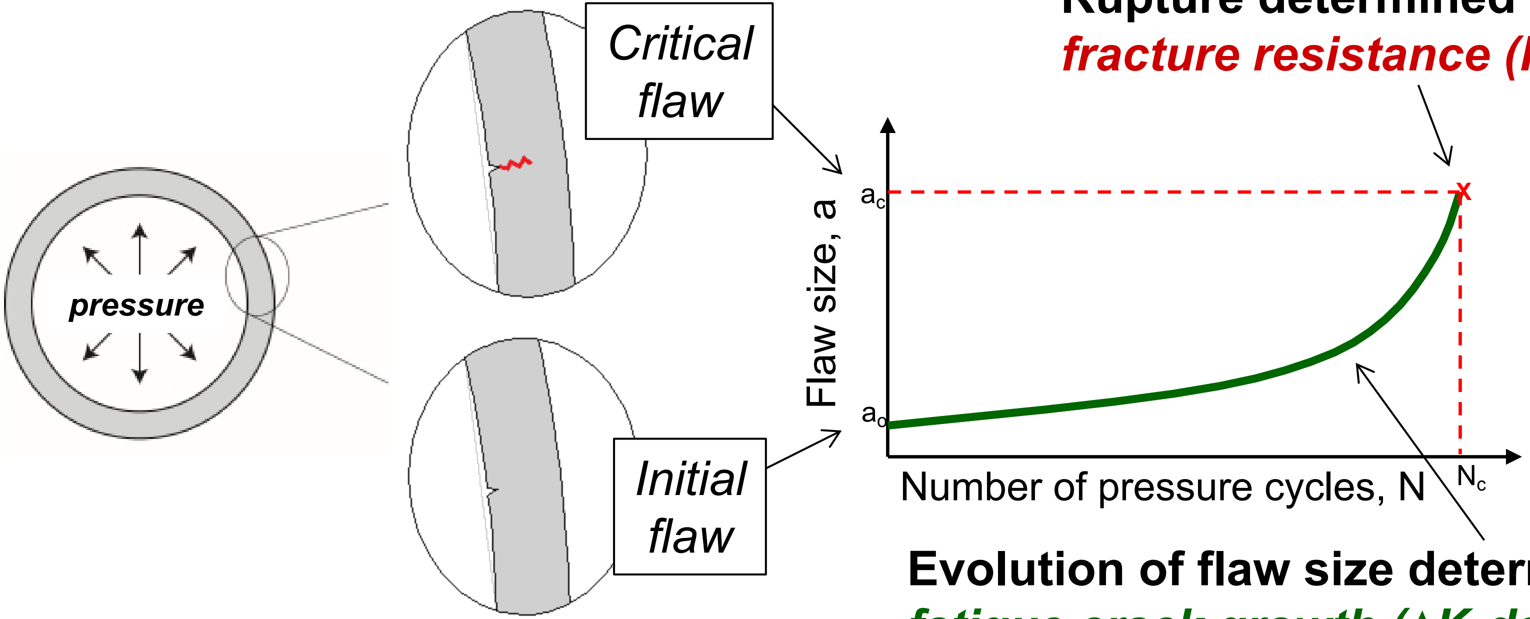
Heat B
PF – 10% AF
Yield strength
(YS) = 565 MPa

Heat E
Fine AF
YS = 593 MPa
Mo additions ~0.15 wt%

Heat F
AF – 30% PF
YS = 552 MPa

Vintage of all 3 materials: 2000s

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



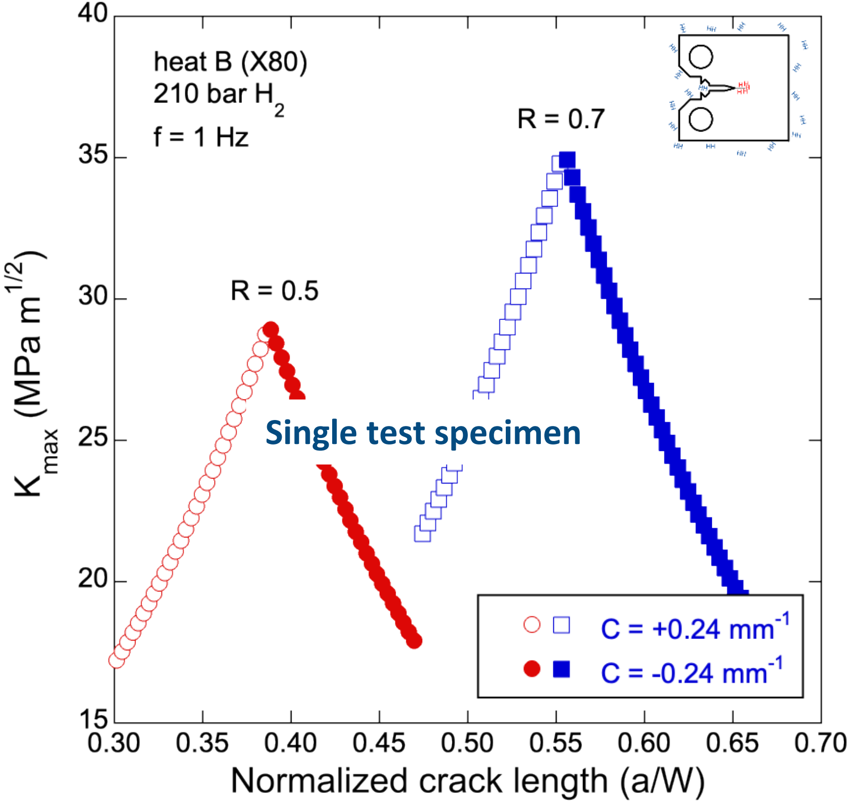
Rupture determined by *fracture resistance (K_{IC})*

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

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

K-control fatigue crack growth tests enable efficiency

Mechanics variables



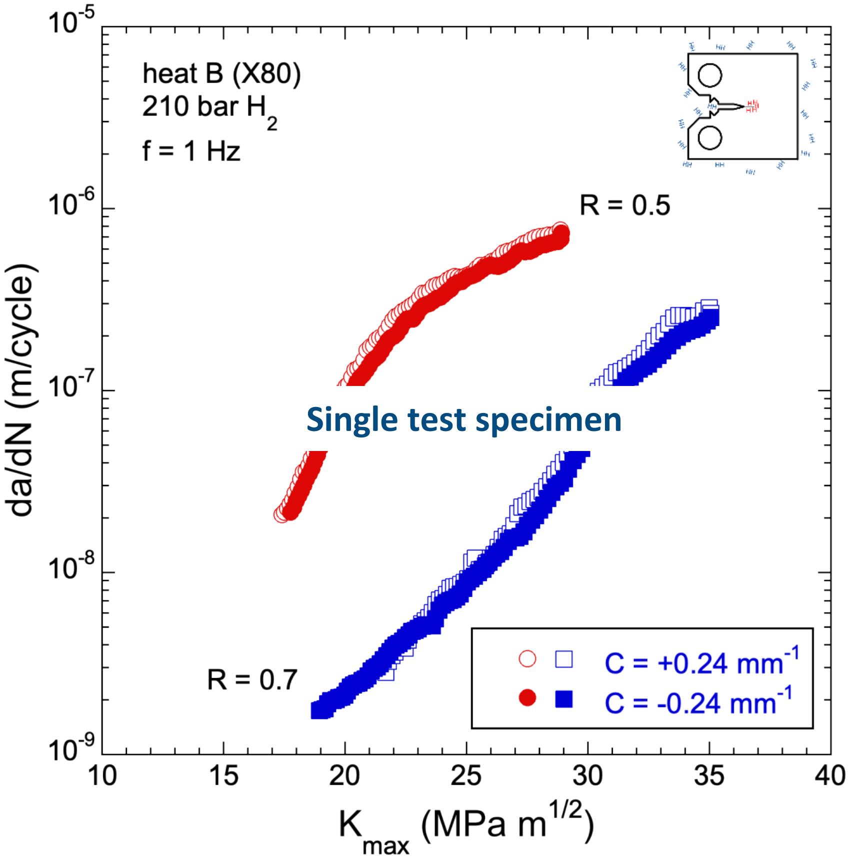
ASTM E647 fatigue crack growth methods using compact tension geometry

- B ~ 12mm (~11mm w/ side grooves)
- W ~ 26 mm
- C control, both K-increasing (C+) and K-decreasing (C-)
- Constant C test segments

$$C = \left(\frac{1}{K}\right)\left(\frac{dK}{da}\right)$$

K-increasing and K-decreasing segments show same fatigue behavior

Mechanics variables



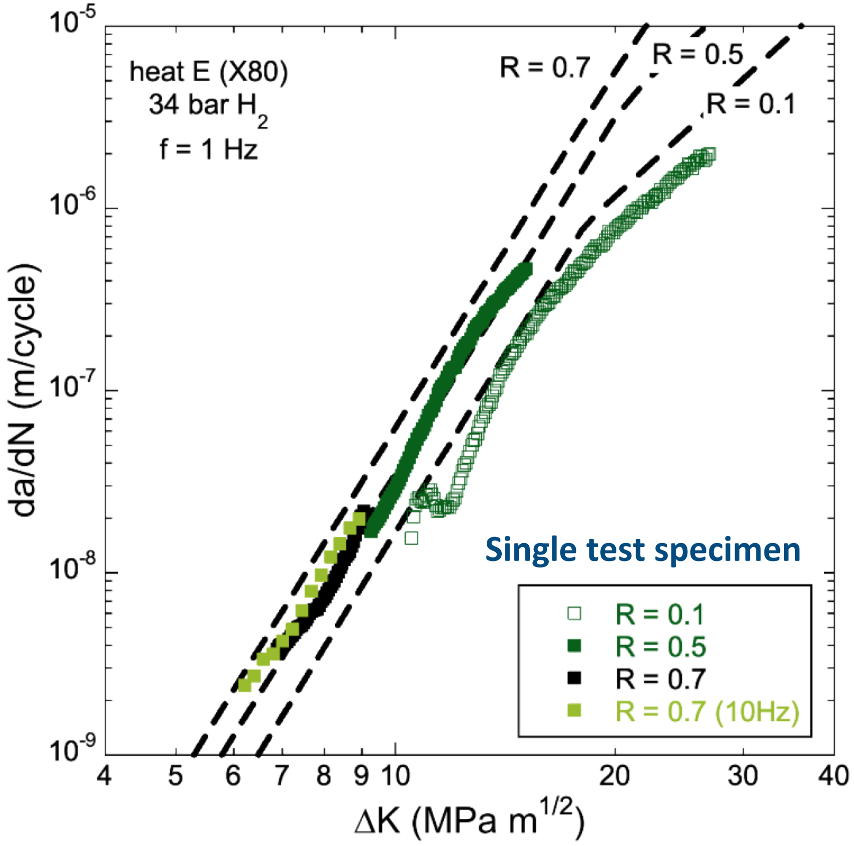
- **K-increasing and K-decreasing segments provide same da/dN-ΔK response**
  - **As long as K_{max} is restricted to moderate values**
    - **K_{max} < 30 MPa $m^{1/2}$ for R = 0.5**
    - **K_{max} < 35 MPa $m^{1/2}$ for R = 0.7**
  - **Perhaps a slight reduction in da/dN for K-decreasing from higher K_{max}**

<u>Outcome</u>: For these conditions ~6X deduction in test time†

† ~3X greater C than constant load amplitude (~1/3 ligament for same ΔK range), 2 values of R

Using these methods, several values of load ratio (R) can be evaluated in a single test specimen

Mechanics variables

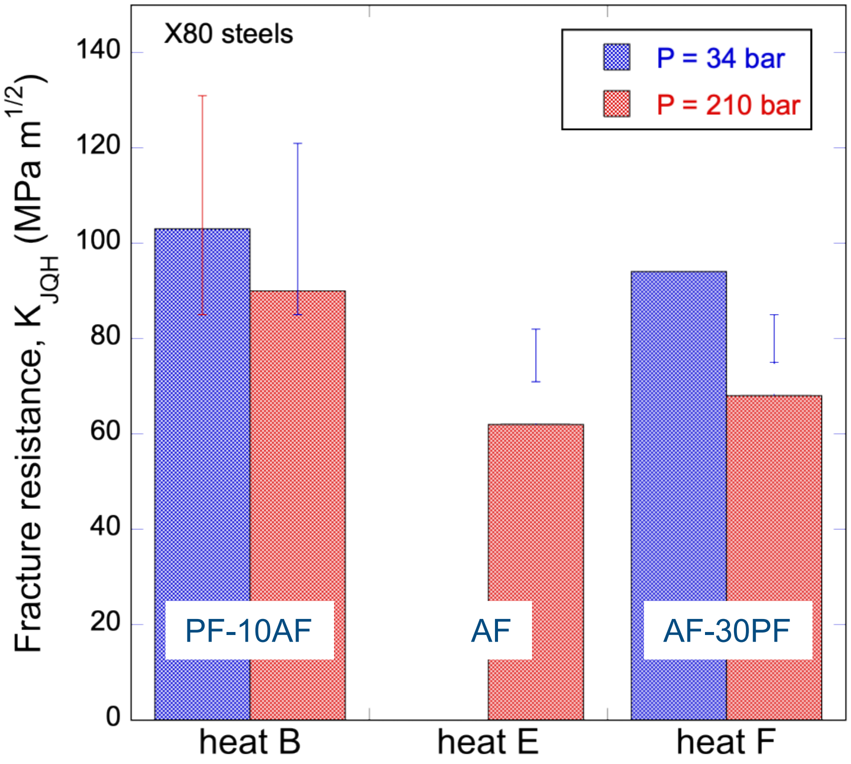


- **In this test, three load ratios were evaluated**
  - **including the influence of frequency for R = 0.7**
- **Unlike tests in air and general recommendations in the codes, R has an effect on da/dN in hydrogen**
- **Higher frequency does not necessarily affect da/dN for low ΔK**

Outcomes:
- **Influence of R should not be ignored**
- **Frequency can further improve testing efficiency in some cases**

Fracture resistance measurements

Mechanics variables

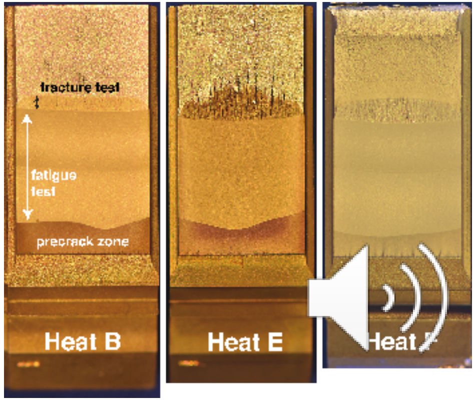


Error bars represent previously reported fracture resistance, measured at higher rate

ASTM E1820 elastic-plastic fracture measurements at the conclusion of fatigue testing

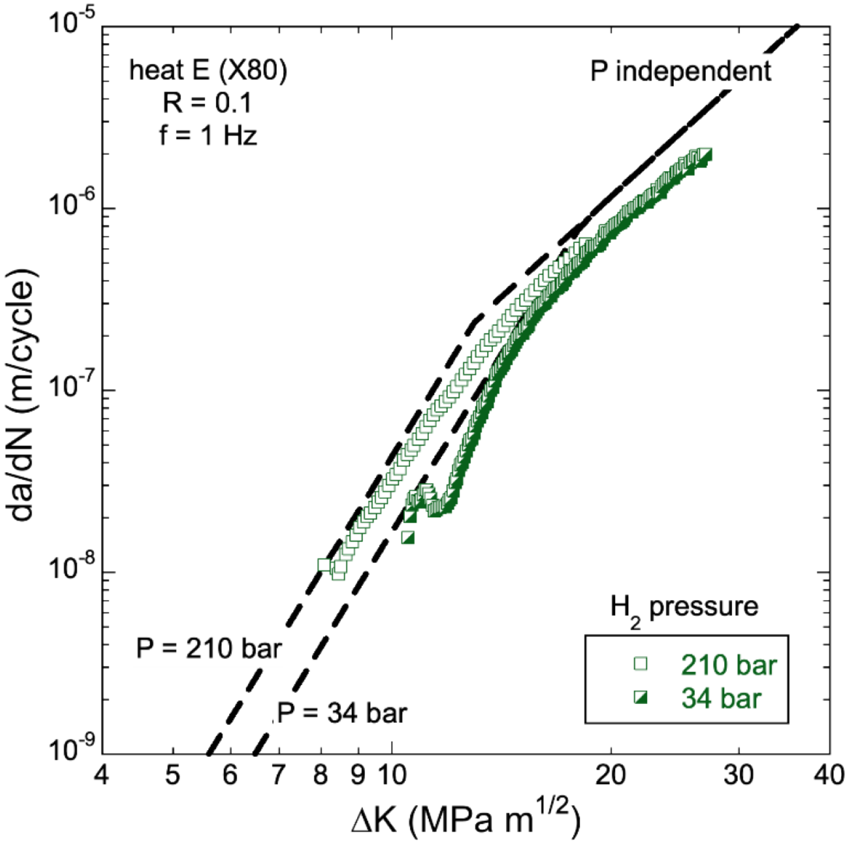
- **Fracture resistance values are relatively consistent**
- **Potential slight bias to PF microstructure**

B ~ 12 mm
B_N ~ 11 mm (w/side grooves)
W ~ 26 mm
0.005 mm/min constant displ.
DCPD



Hydrogen partial pressure has an effect on da/dN

Environmental variables

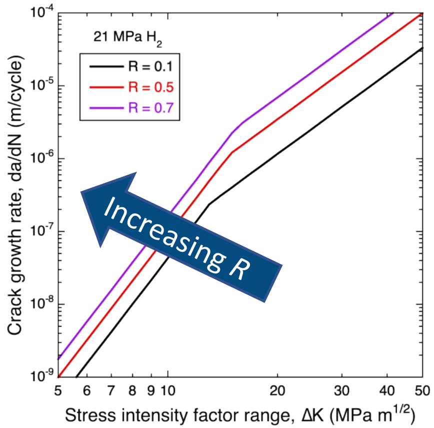


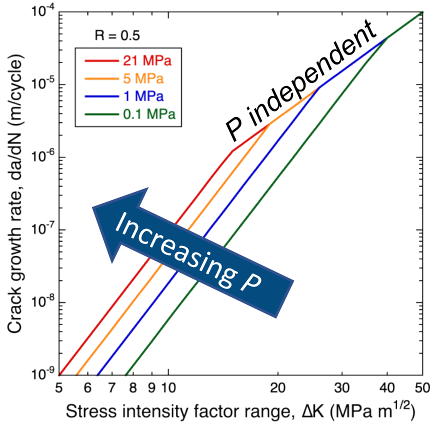
- **Hydrogen pressure can affect fatigue crack growth:**
  - **At low ΔK, fatigue crack growth rate is dependent on hydrogen pressure**
  - **At high ΔK, fatigue crack growth rate is independent of pressure**

<u>Outcome</u>:

- **H_2 partial pressure has a complicated (but predictable) influence on fatigue response**

Master Design Curves bound the fatigue crack growth behavior of line pipe steel





- **The effects of pressure and load ratio on fatigue crack growth are captured in conventional power law formulation :**
  - **At low ΔK,** $$\frac{da}{dN} = 7.6x10^{-16}\left[\frac{1+0.4286R}{1-R}\right]\Delta K^{6.5} f^{1/2}$$
  - **At high ΔK** $$\frac{da}{dN} = 1.5x10^{-11}\left[\frac{1+2R}{1-R}\right]\Delta K^{3.66}$$

ΔK (MPa $m^{1/2}$)
f (bar) – fugacity
da/dN (m/cycle)

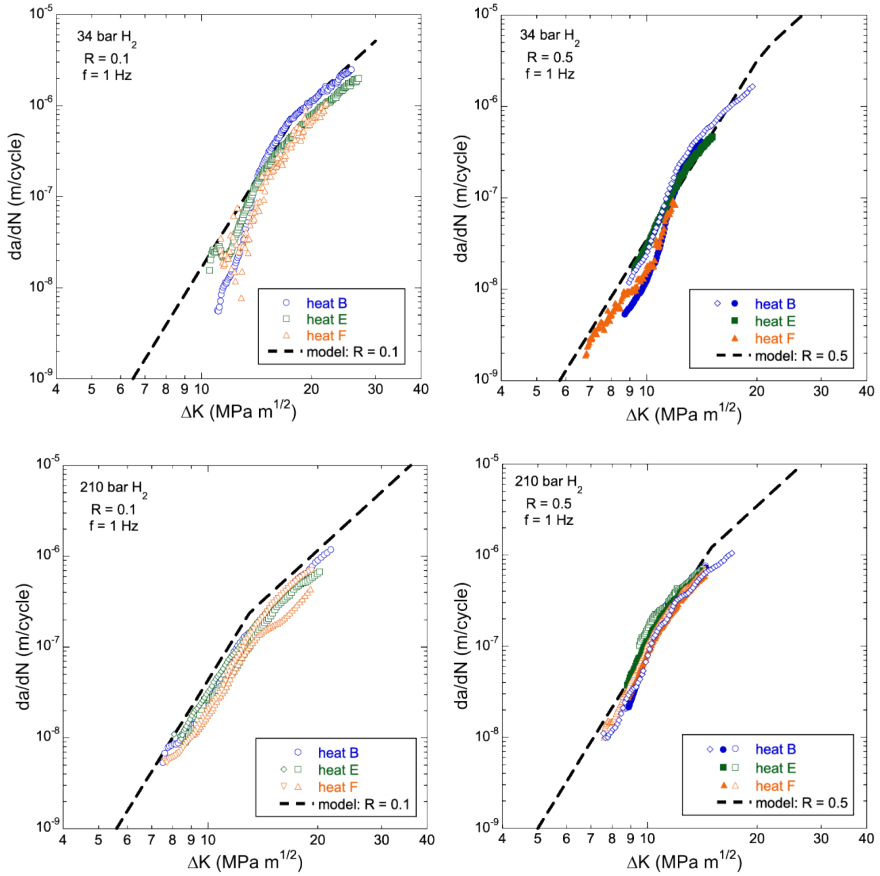
- **These Master Design Curves appear to be effective for a wide range of construction steels**

Ref: San Marchi et al, PVP2019-93803

<u>Outcome</u>:

- **Master Design Curves provide a simple framework to bound the fatigue crack growth of steels in gaseous H_2**

Summary



- **Testing was performed for three values of R and at 2 pressures for all three heats of X80**
  - ***Materials*: 3 heats of X80**
  - ***Mechanics*: R = 0.1, 0.5 and 0.7**
  - ***Environment*: 34 and 210 bar H_2**

Outcomes:

- **K-control enables testing efficiency**
- **All three heats of X80 perform similarly**
- **Influence of R should not be ignored**
- **H_2 partial pressure has a complicated (but predictable) influence on fatigue response and modest effect on fracture**

Thank You!

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https://h-mat.org/

https://www.sandia.gov/matlsTechRef/

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