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Hydrogen assisted fatigue crack growth

Optimization of Fatigue Test Methods

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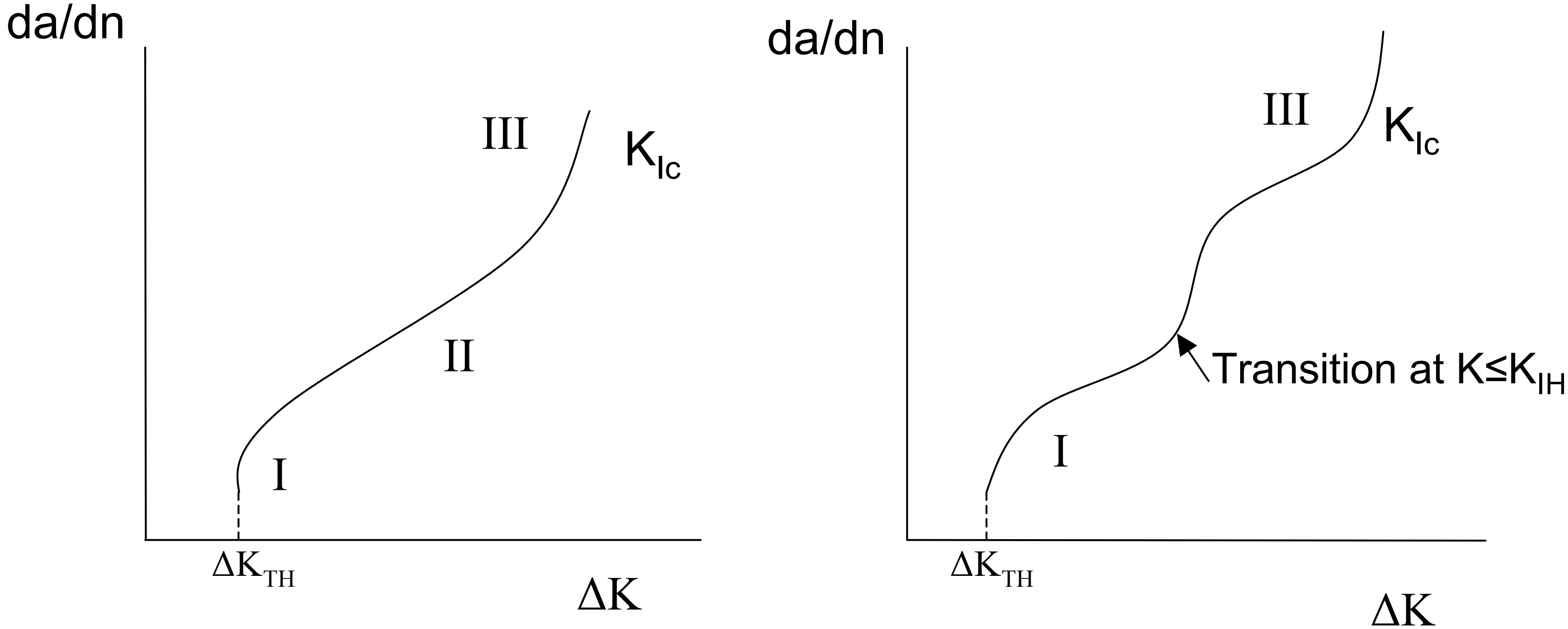
Fatigue crack growth laws in H_2 are expected to be complex

- FCGR does not follow simple Paris law relationship in gaseous hydrogen
  - Testing should identify important transitions
- FCGR in H_2 depends on cyclic load frequency and load ratio, R, (K_{min}/K_{max})
- Need to balance test efficiency with data reliability

Fatigue crack growth behavior in hydrogen differs from behavior in air

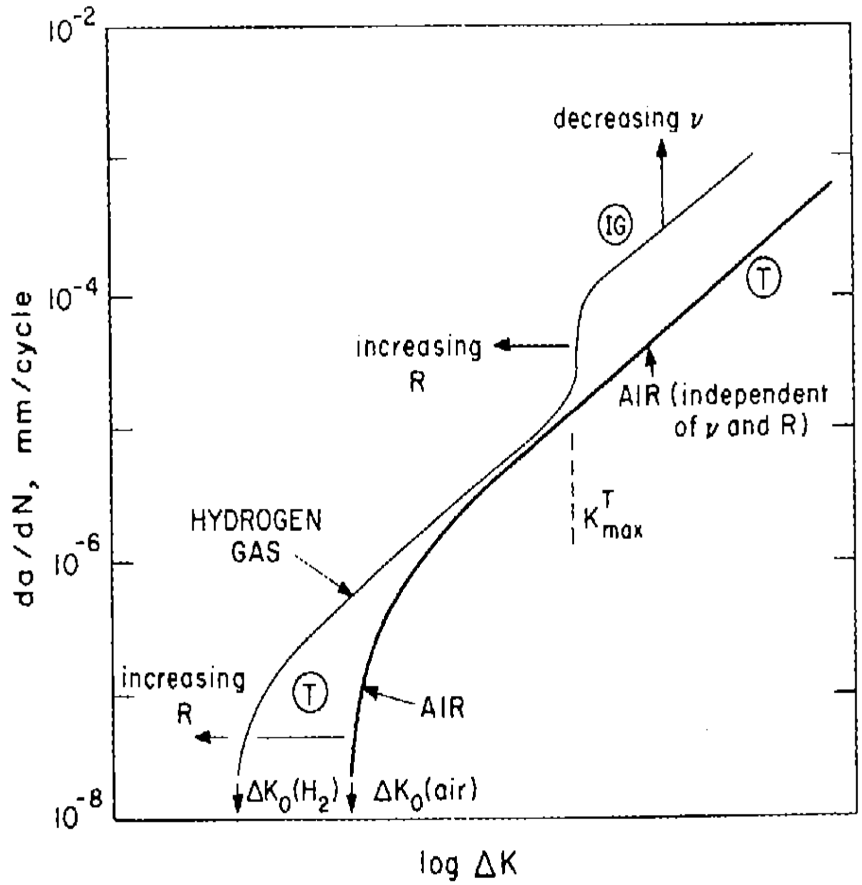
- I – Threshold region
- II – Power law growth region $da/dn = C\Delta K^m$
- III – K_{max} approaches K_{Ic}

- H_2 may promote monotonic fracture mechanisms at moderate ΔK



Many variables affect fatigue crack growth in hydrogen

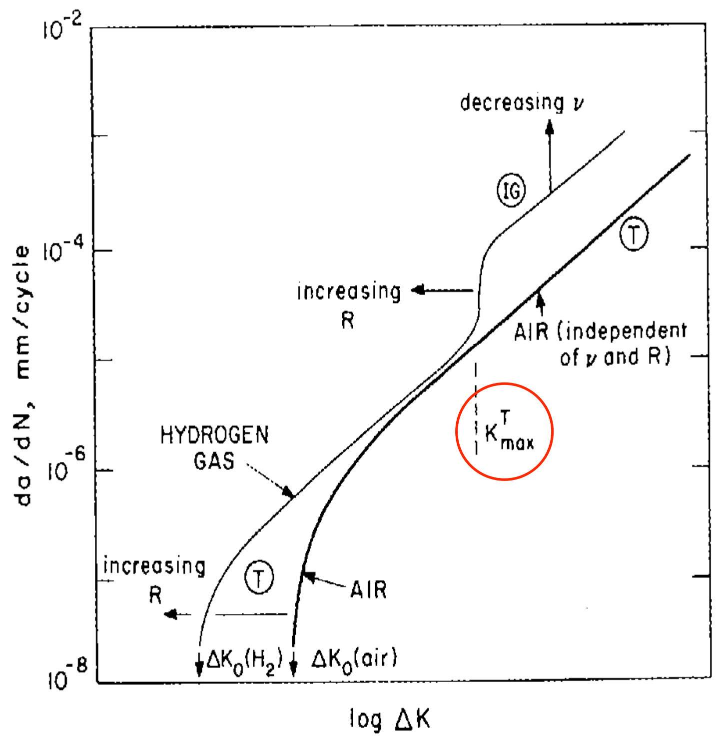
- Cycle frequency (ν)
- R-ratio (K_{min}/K_{max})
- Waveform
- H_2 gas pressure
- Fatigue threshold (ΔK_o) varies with environment-induced closure

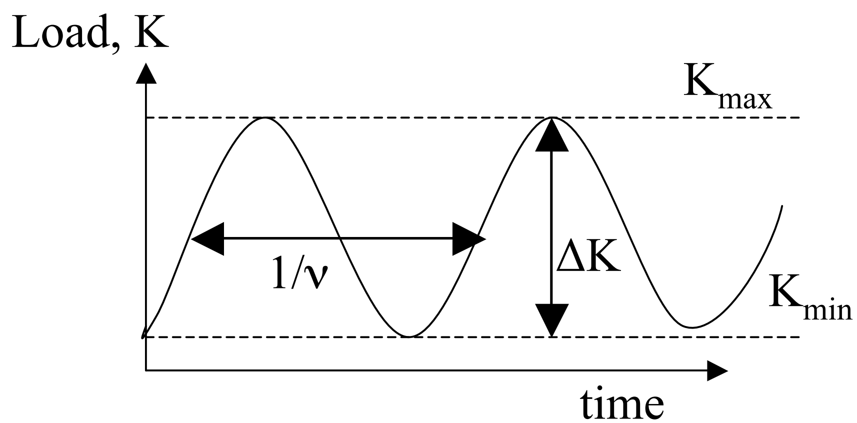


Suresh and Ritchie *<u>Metal Science</u>* *1982*

Hydrogen effects on fatigue above K^T_{max} are dependant on testing variables

Suresh and Ritchie, Metal Science, 1982





$$R = \frac{K_{min}}{K_{max}}$$

$$\Delta K = (1 - R)K_{max}$$

- $K^T_{max} < K_{JH}$
- Fatigue crack growth laws must be measured over wide range of ΔK

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Measured fracture properties technologically relevant steels

- X52 ERW linepipe steel
  - σ_Y: 62 ksi (428 MPa); UTS: 70 ksi (483 MPa)
- X60 HIC grade linepipe steel
  - σ_Y: 63 ksi (434 MPa); UTS: 70 ksi (483 MPa)
- X80 linepipe steel
  - σ_Y: 82 ksi (565 MPa); UTS: 87ksi (600 MPa)

- 4130X pressure vessel steel
  - Commercially produced test ring
  - σ_Y: 88 ksi (607 MPa); UTS: 111 ksi (765 MPa)

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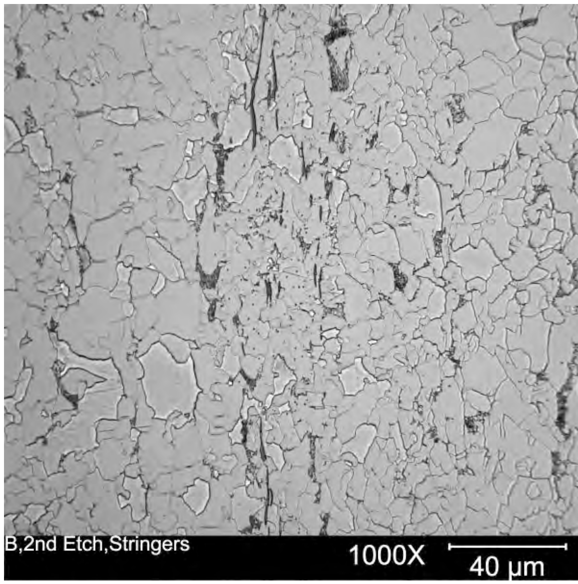
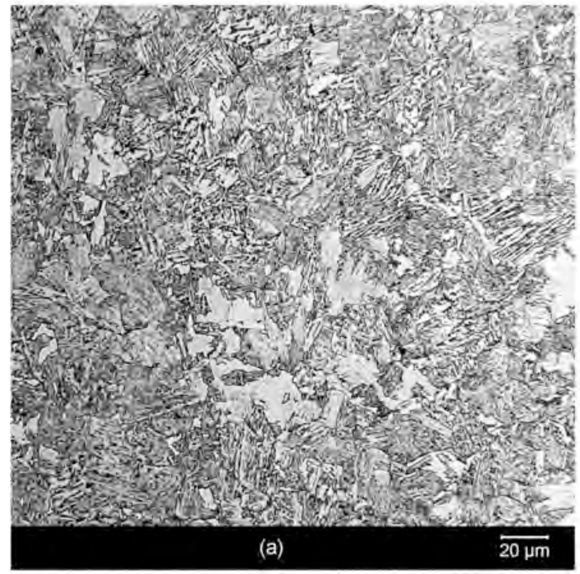
Fatigue data from two classes of steels

X52 base metal has
ferrite/pearlite microstructure



4130X is tempered martensite
with bainite and pearlite



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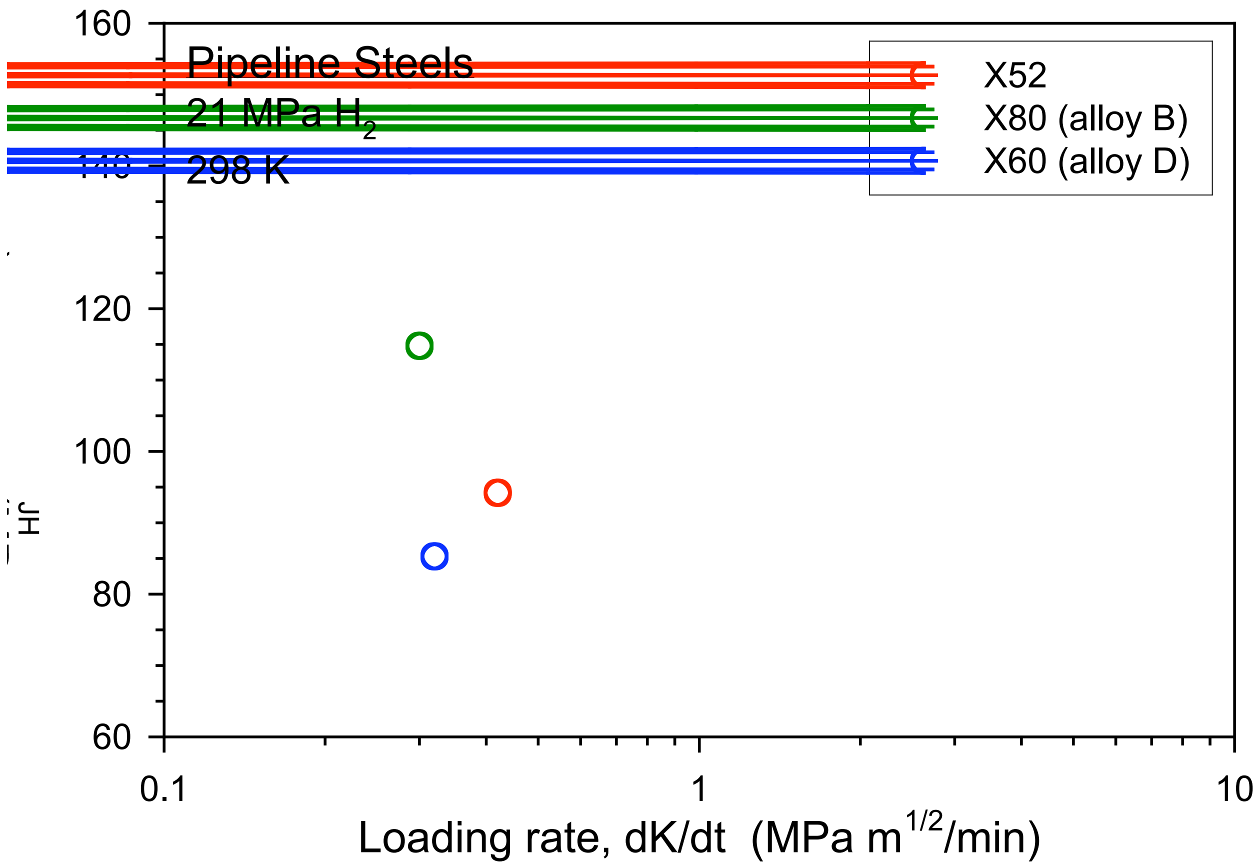
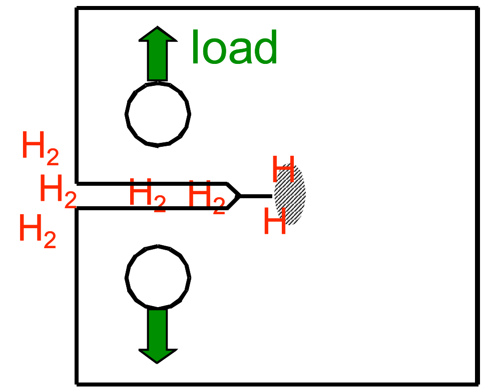
Crack initiation thresholds similar for three pipeline steels

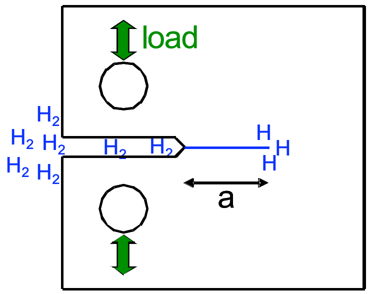
X60 and X80 data: *C. San Marchi et al., ASME PVP2010-25825, 2010*

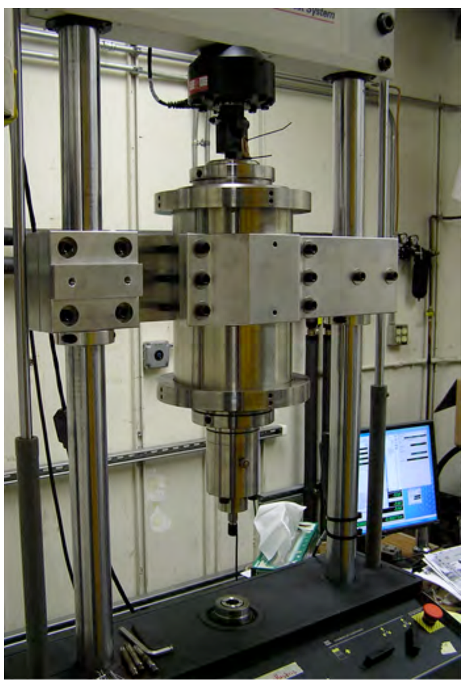




- No effect of loading rate from 0.3 to 3 MPa $m^{1/2}$/minute

Fatigue crack growth measured in H_2





- Load-control testing employs internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT
- Triangular load-cycle waveform applied
- Measured crack growth rate (da/dN) vs. stress-intensity factor range (ΔK)
  - 99.9999% H_2, pressure=3 kpsi (21 MPa) for X52, 45 MPa for 4130X
  - Evaluated effects of load-cycle frequency and R ratio (K_{min}/K_{max})

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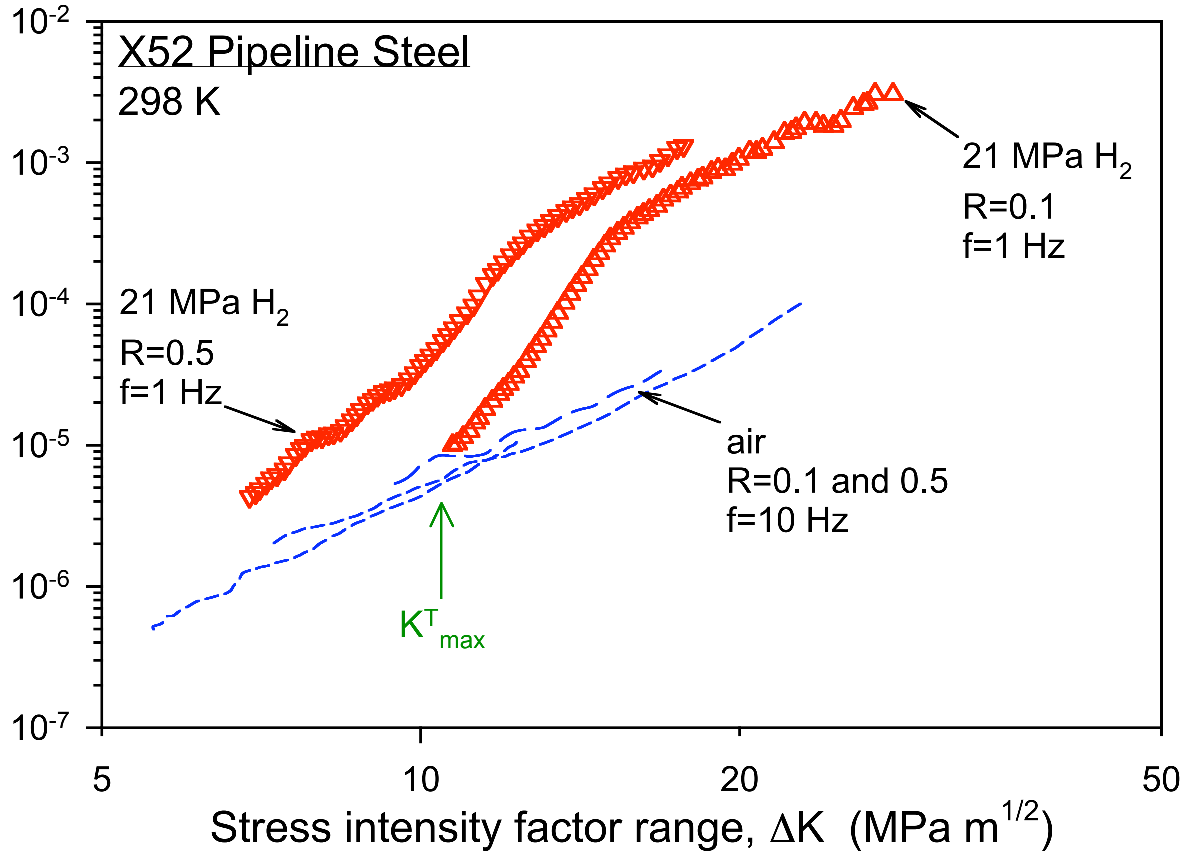
Measured baseline fatigue crack growth law for X52 steel in 21 MPa H_2



K^T_{max} ~ 10 MPa m$^{1/2}$

K_{JH} ~ 90 MPa m$^{1/2}$

- Results reveal transitions in da/dN *vs* ΔK trend that must be captured for measurements in H_2

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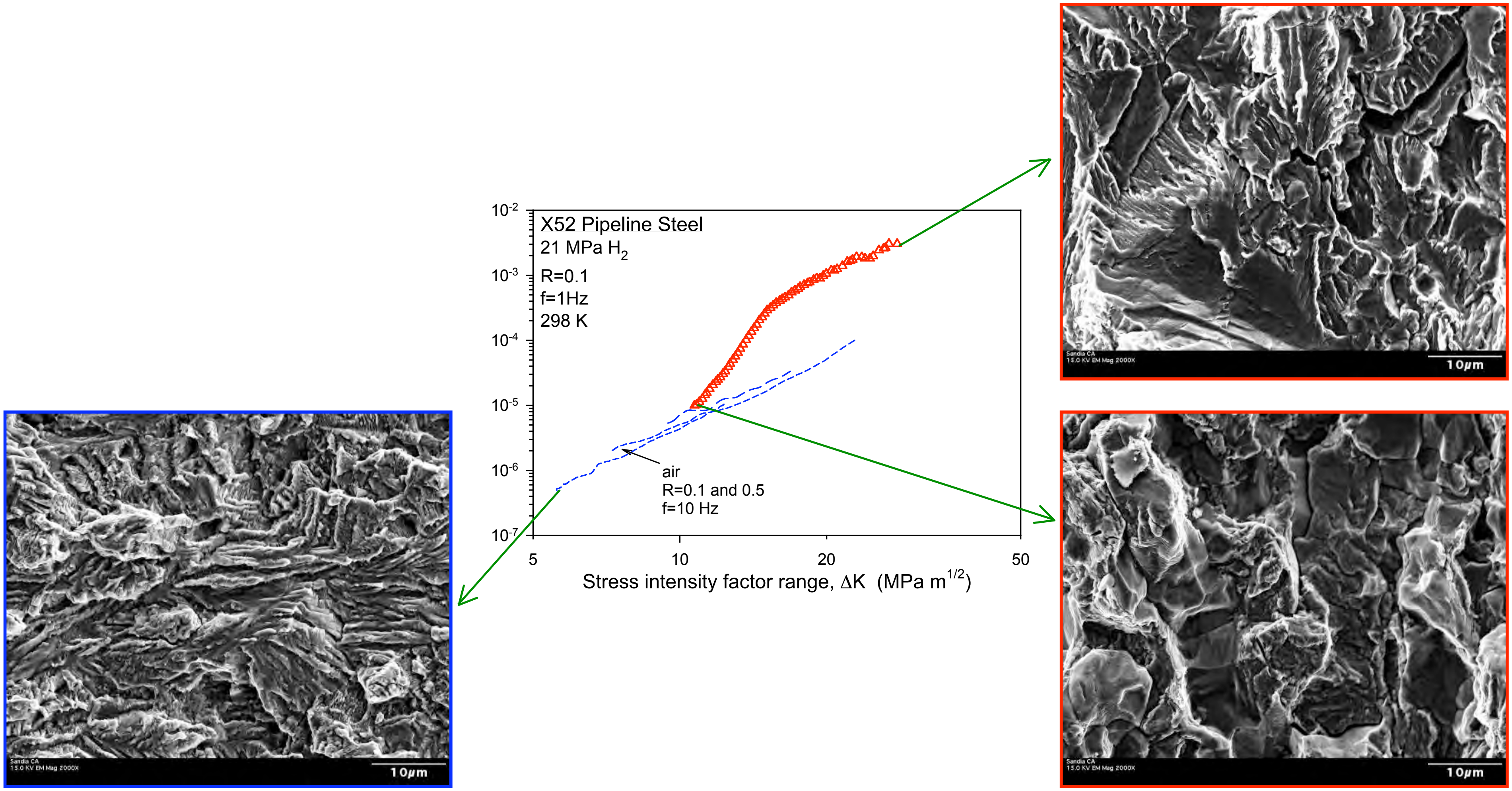
Hydrogen-assisted fracture mode evolves as a function of ΔK



- Hydrogen-assisted fatigue crack growth transitions from intergranular to transgranular mode

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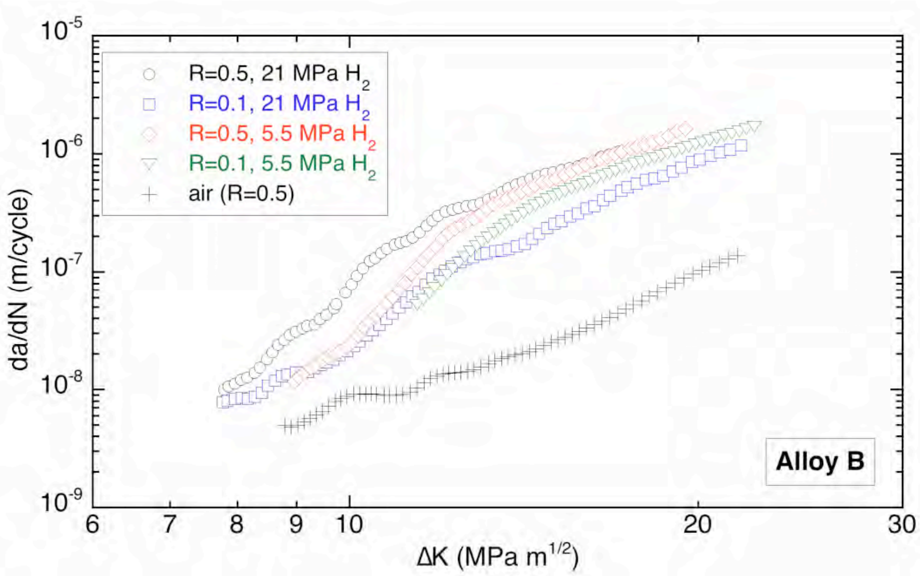
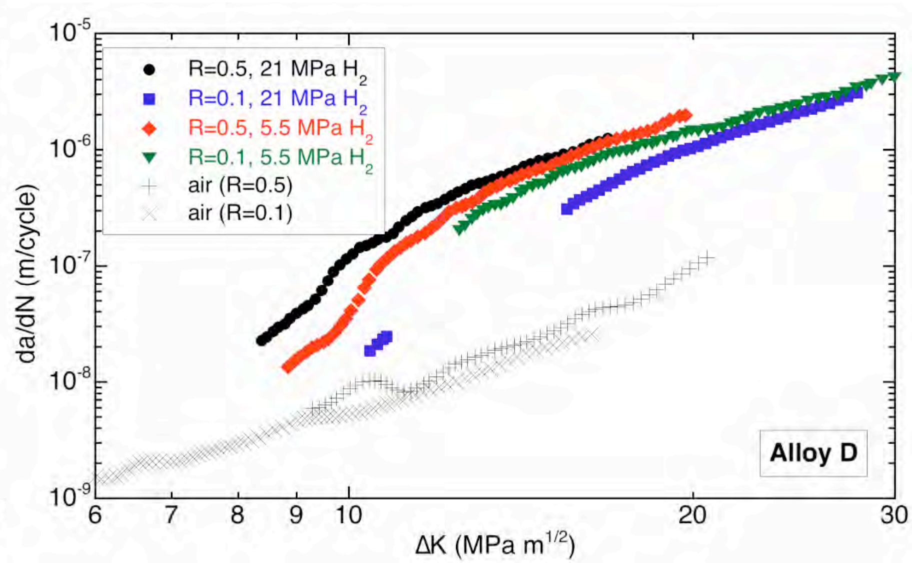
Hydrogen gas pressure affects fatigue





- Increasing H_2 pressure from 5.5 Mpa to 21 MPa <u>does not</u> significantly affect crack growth rates
  - Replicate results may reveal subtle trends

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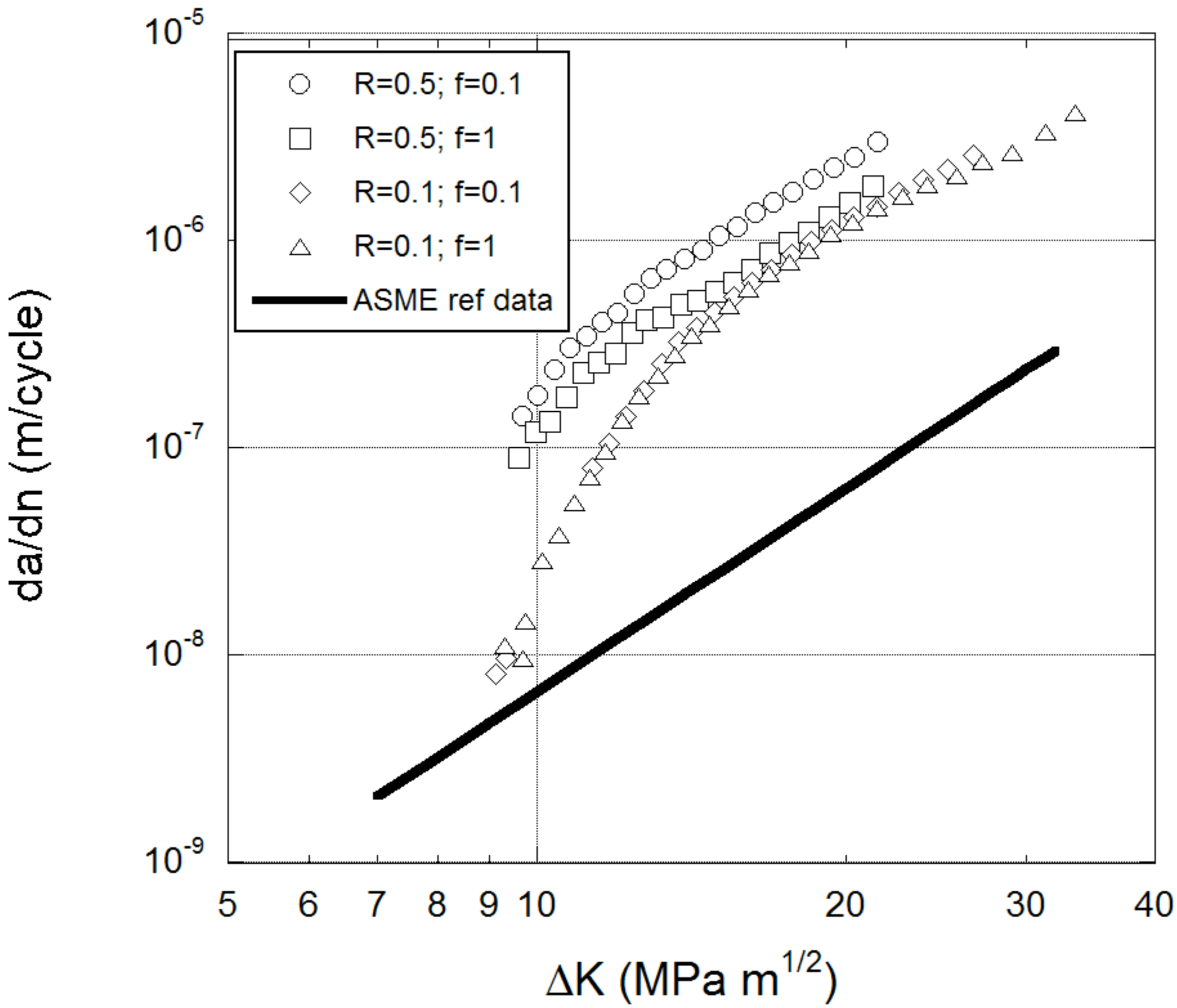
No significant effect of frequency observed for 0.1 and 1 Hz in 4130X



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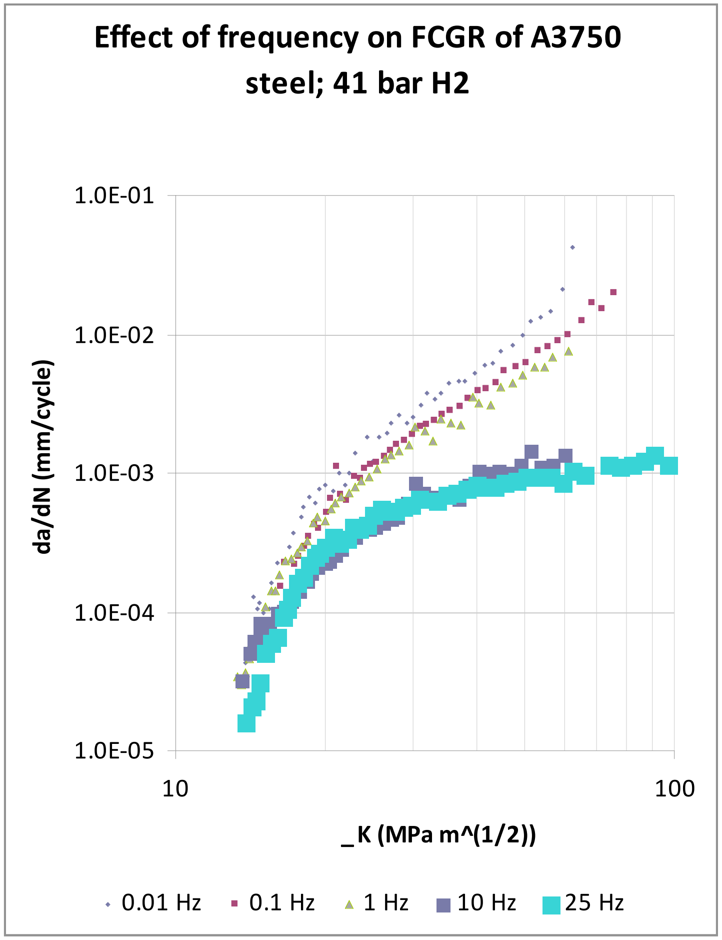
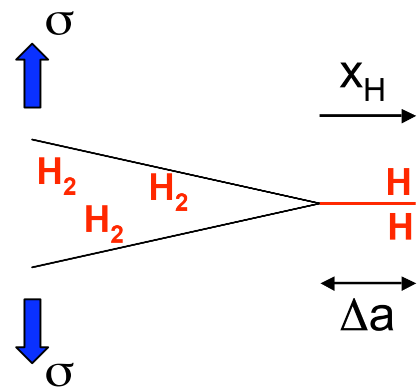
Frequency effects most pronounced at high da/dN

A.H. Priest, British Steel, EHC-(1)42-012-81UK(H), 1983





$$x_H = (Dt)^{1/2}$$

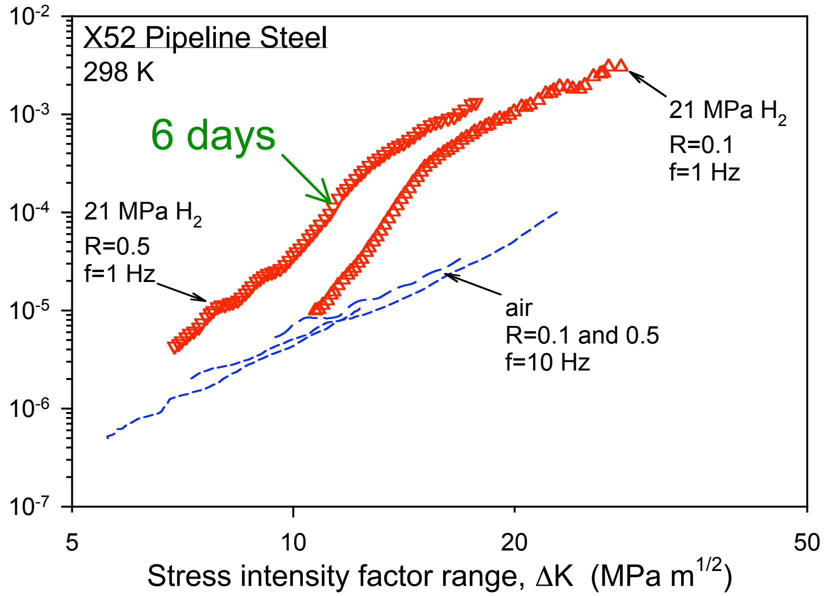
$$\Delta a = x_H = (Dt)^{1/2}$$

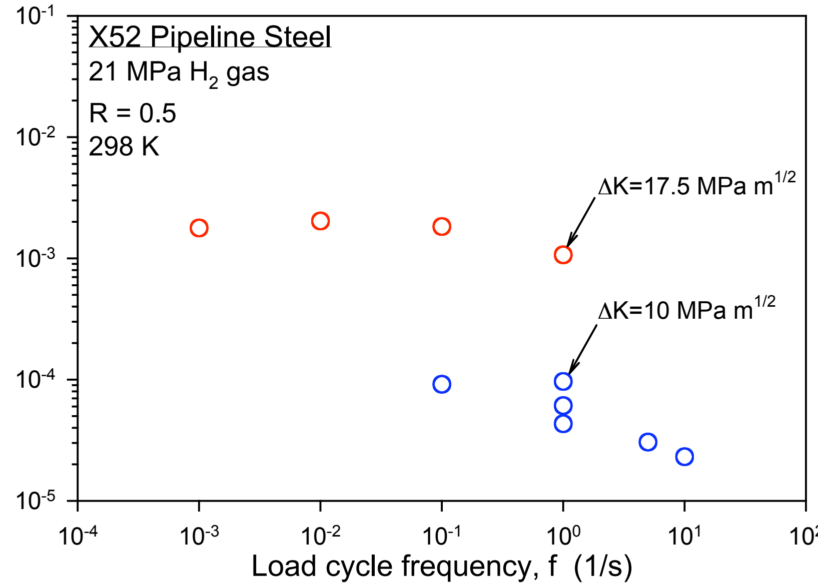
$$\Delta a = (D/f)^{1/2}$$

$$f = \frac{D}{(da/dN)^2}$$

- Most studies of frequency effects on H_2-assisted fatigue crack growth conducted at high ΔK

Measurement of fatigue crack growth laws must consider effects of frequency





- Tests at higher frequency may be non-conservative at high crack growth rates
- Frequency selected must balance test efficiency (i.e., duration) and data reliability
- Higher frequency testing may be conservative at low crack growth rates

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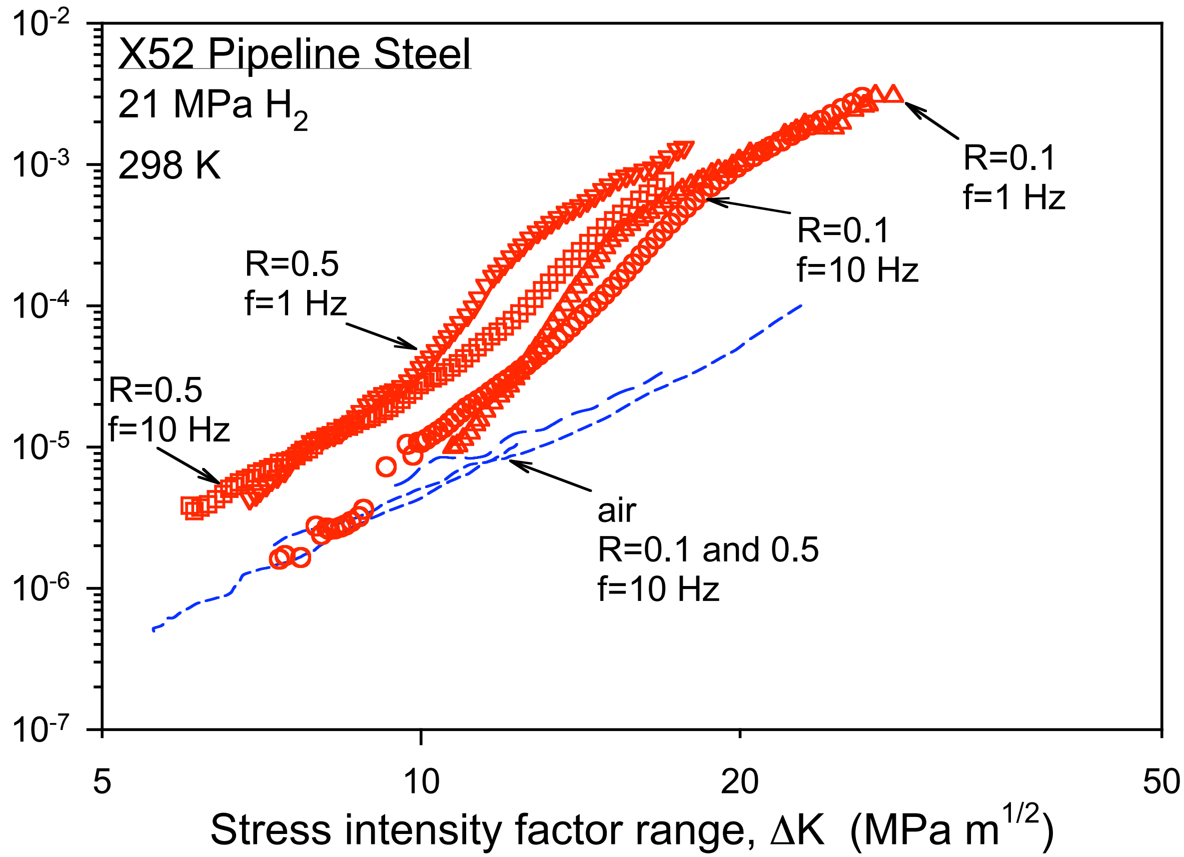
Effects of load-cycle frequency may be more complex at low ΔK



- Frequency may affect K^T_{max} as well as da/dN

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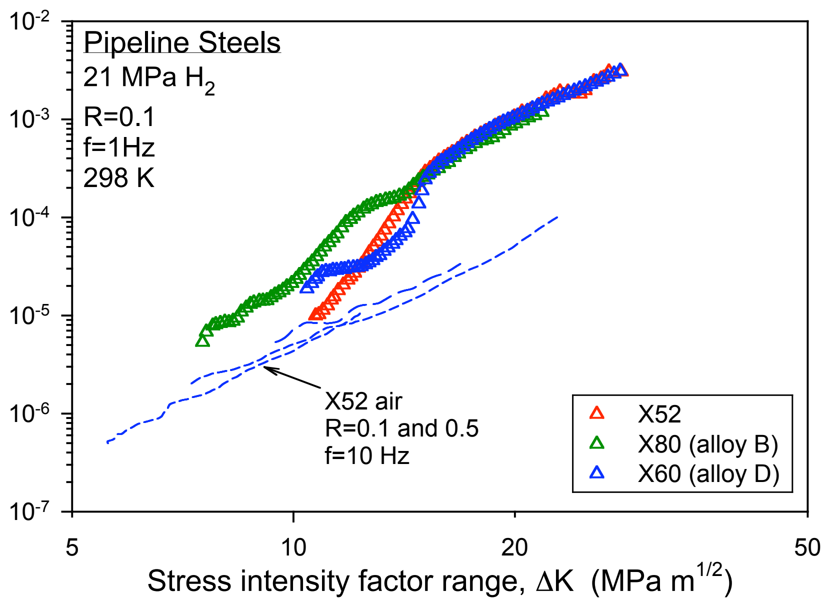
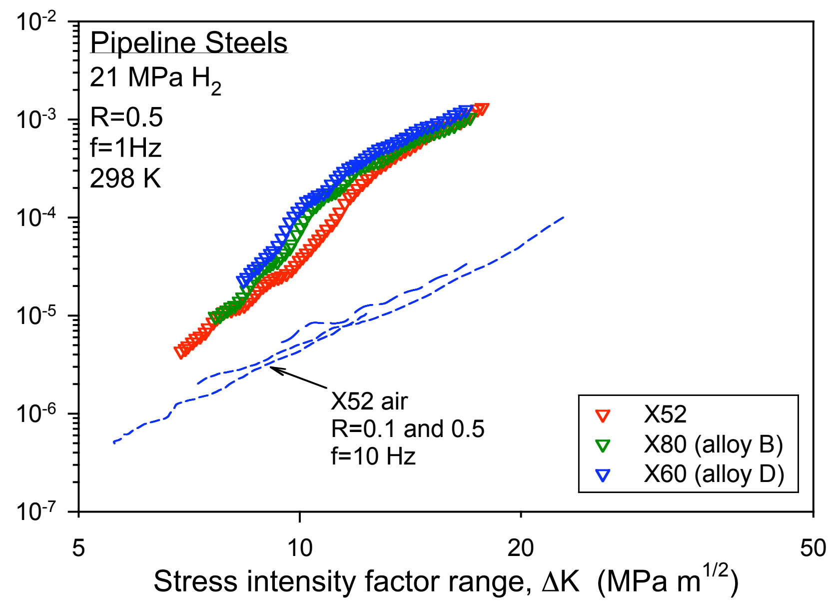
Fatigue crack growth rates in H_2 similar for three different pipeline steels

X60 and X80 data: *C. San Marchi et al., ASME PVP2010-25825, 2010*





- More disparity noted for tests at R=0.1 but replicate results are needed

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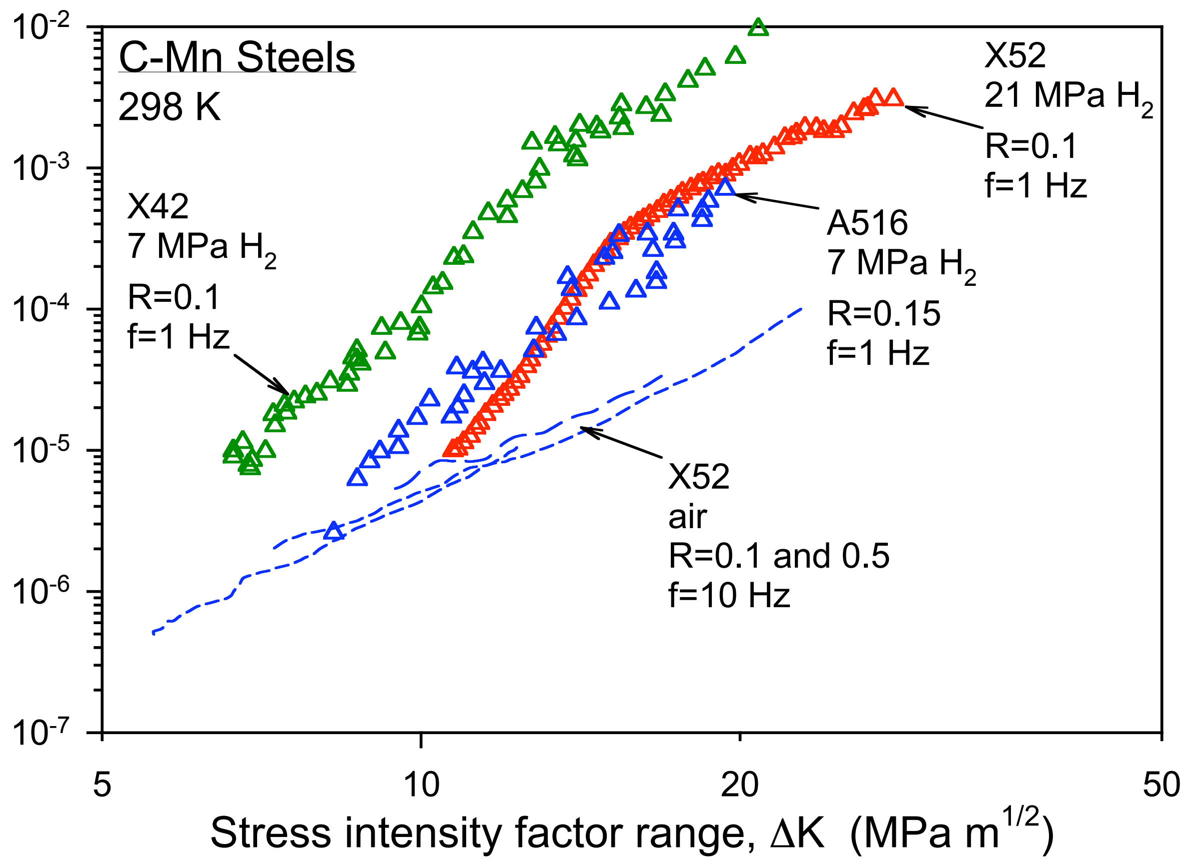
Fatigue crack growth data for X52 in H_2 compare favorably with results from literature

X42 data: *H.J. Cialone and J.H. Holbrook, Met. Trans. A, 1985*
A516 data: *H.F. Wachob and H.G. Nelson, Hydrogen Effects in Metals, 1981*



- Elevated da/dN for X42 steel may be due to severely banded ferrite/pearlite microstructure

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Conclusions

- Fatigue laws in gaseous hydrogen are not accurately described by single Paris law relationship
- Fatigue testing should identify transitions (e.g. K^T_{max})
- Fatigue may not be markedly alter by hydrogen below K^T_{max}
- Higher testing frequency may yield conservative results at low ΔK (i.e. small da/dn), but may be non-conservative at high ΔK
- K_{max} is as important as, or more important than, ΔK in controlling fatigue crack growth rates

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