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Gaseous Hydrogen-Assisted Fatigue Crack Growth in X52 Linepipe Steel

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DOE Hydrogen Program

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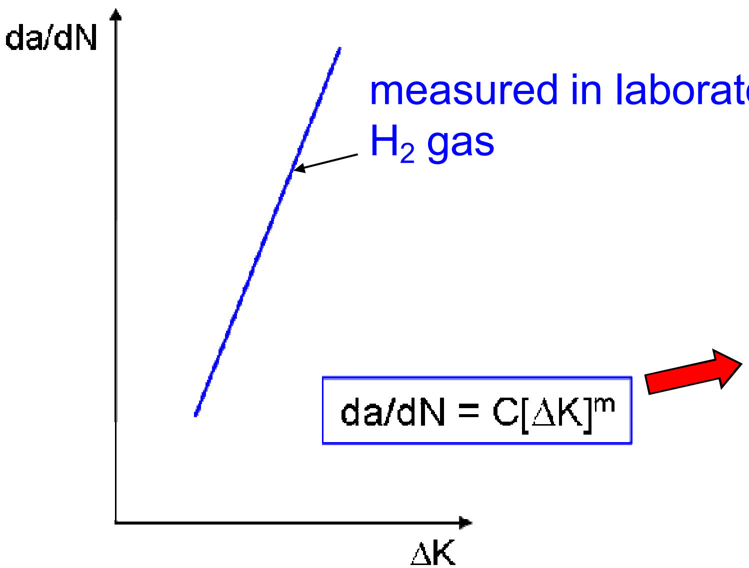
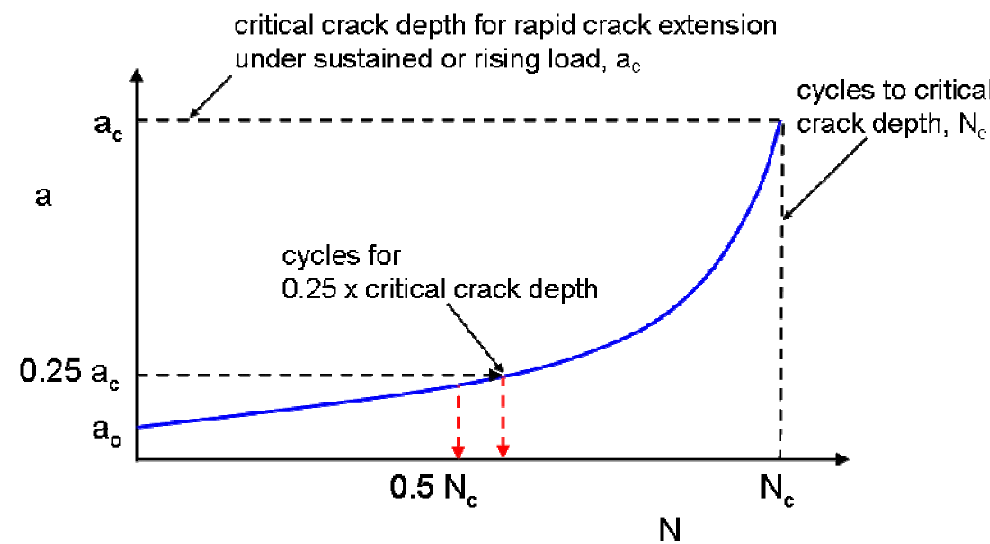
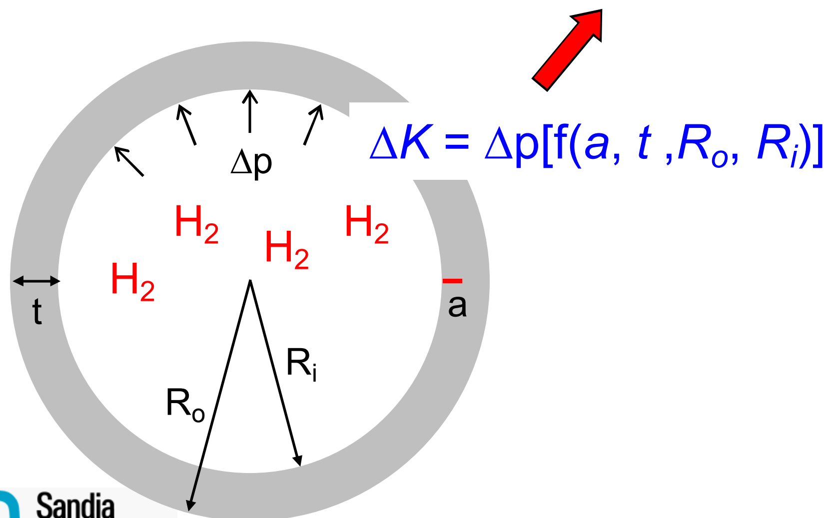
Background and Objectives

- Operating conditions for future H_2 pipelines may involve more extensive *pressure cycling*
  - Current H_2 pipelines operate under *static pressure*
- Enable pipeline structural integrity management that accommodates/mitigates H_2-assisted fatigue crack growth
  - Optimize fatigue crack growth test methods referenced in H_2 pipeline design code ASME B31.12
  - Identify pipeline steel microstructures most vulnerable to H_2-assisted fatigue crack growth, e.g., welds
  - Explore mechanisms for retarding H_2-assisted fatigue crack growth, e.g., trace additives to H_2 gas

Structural integrity assessment framework in ASME B31.12 requires fracture data in H_2







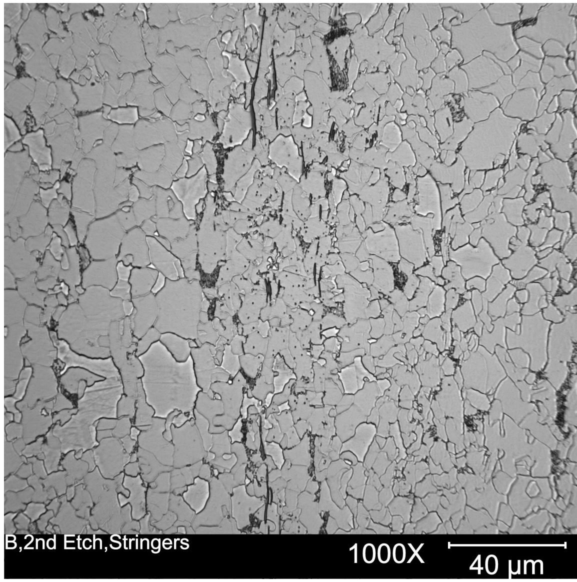
- Two fracture properties in H_2 needed
  - Fatigue crack growth law
  - Fracture threshold
- Integrity management framework accommodates H_2 embrittlement

Measured fracture properties of technologically relevant steel: API 5L X52 (PSL 2)

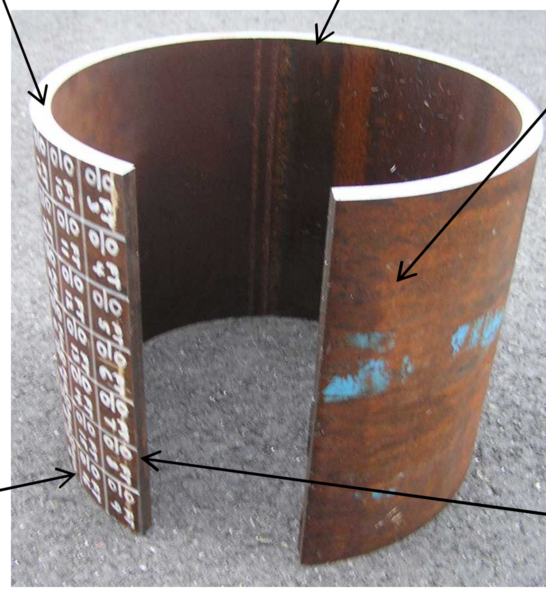
- X52 steel from ERW linepipe
  - 12.75 in OD x 0.5 in WT (324 mm x 12.7 mm)
- Tensile properties
  - Yield strength: 62 ksi (428 MPa)
  - Ultimate tensile strength: 70 ksi (483 MPa)
- Alloy composition

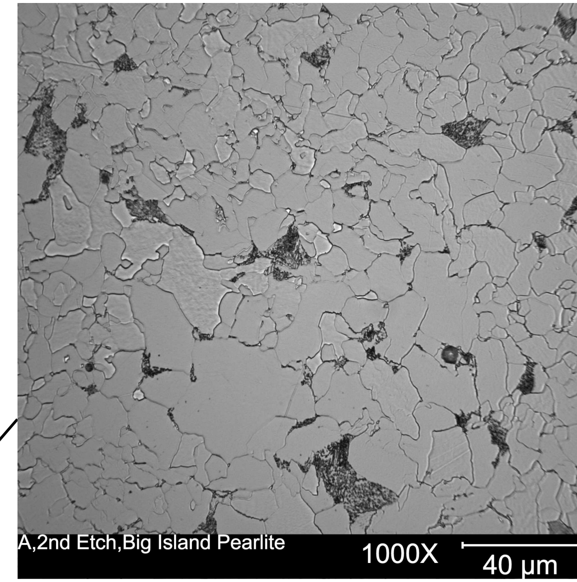
C	Mn	P	S	Si	Cu	Ni	Cr	V	Nb	Al	CE
0.06	0.87	0.011	0.006	0.12	0.03	0.02	0.03	0.002	0.03	0.034	0.11

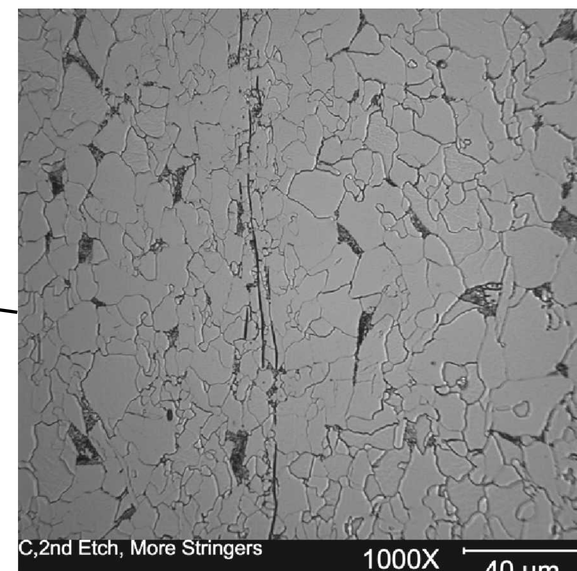
X52 base metal has ferrite/pearlite microstructure



ERW seam







Compact tension specimens extracted from 7 to 9 o’clock locations

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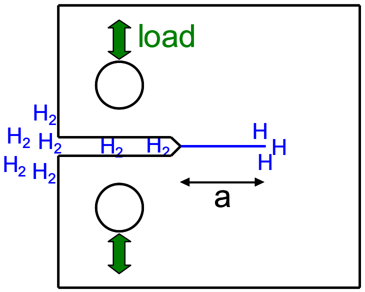
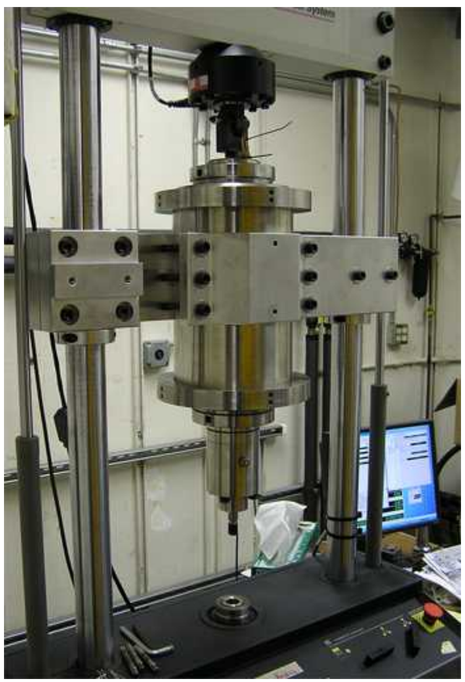
Fatigue crack growth relationships (da/dN vs. ΔK) measured in high-pressure H_2





- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude (increasing ΔK)
- Environment
  - Primary supply gas: 99.9999% H_2
  - Other supply gases: H_2 with 10-1000 ppm O_2
  - Pressure = 3,000 psi (21 MPa)
  - Room temperature

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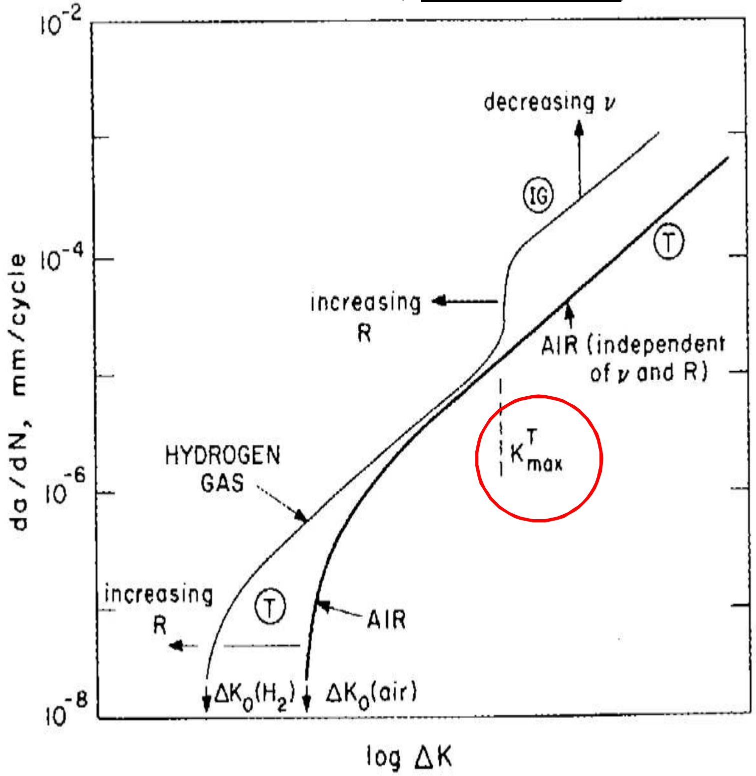
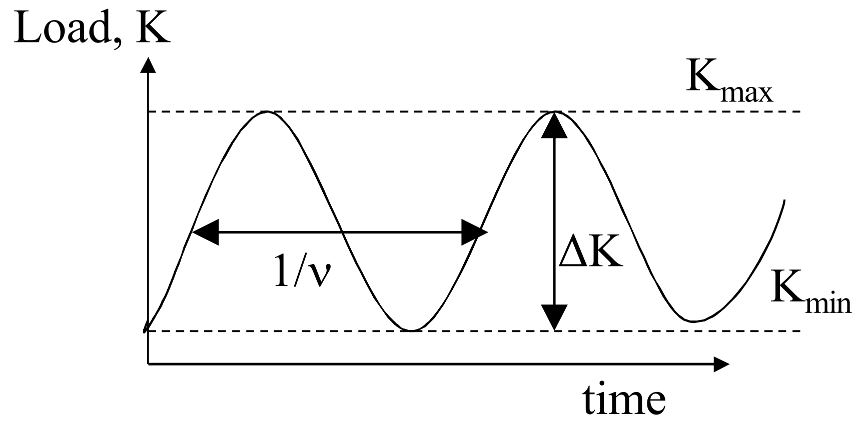
Fatigue crack growth relationships for pipeline steels in H_2 expected to be complex

Suresh and Ritchie, Metal Science, 1982





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

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

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

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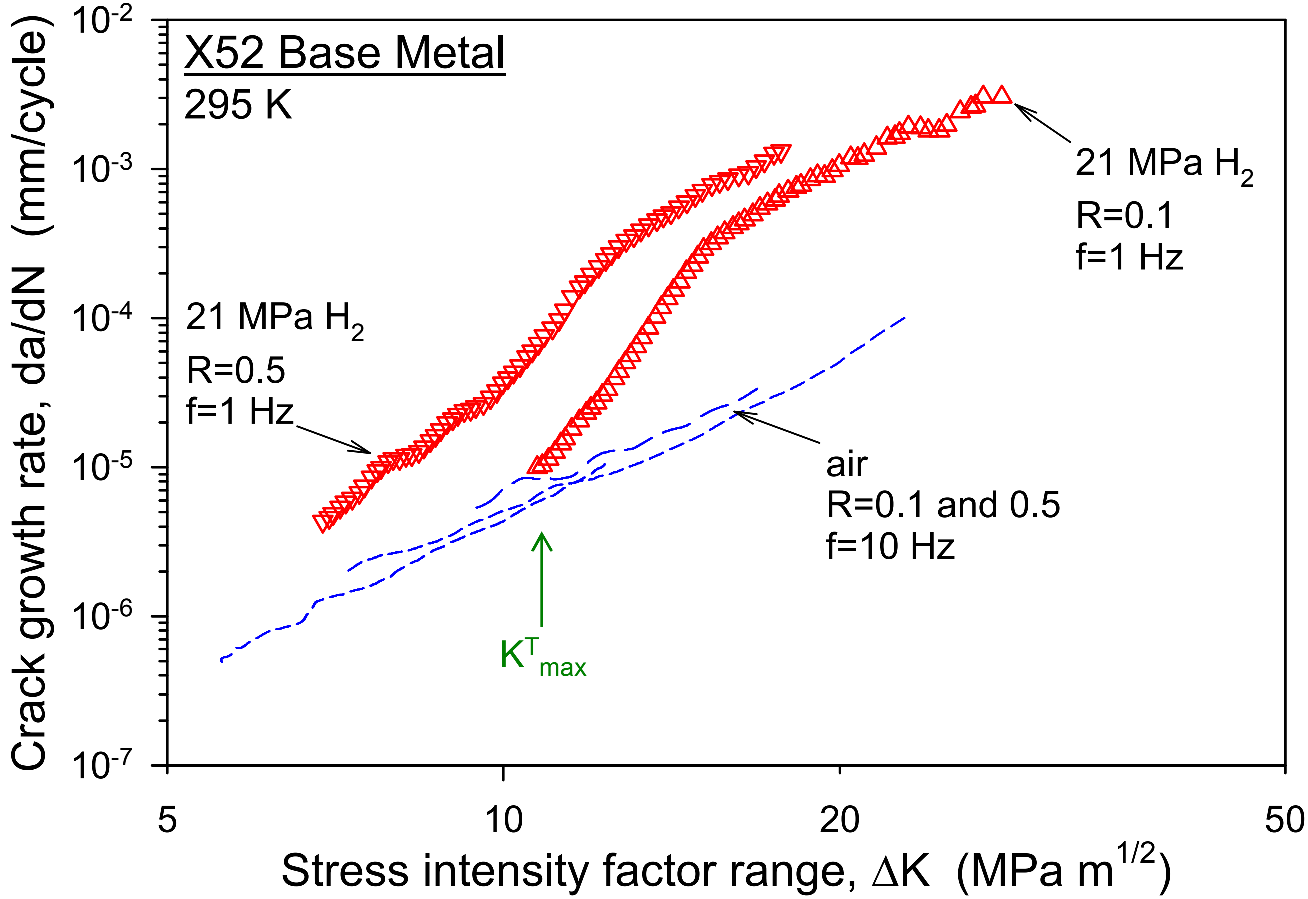
Measured baseline fatigue crack growth relationships for X52 base metal in 21 MPa H_2



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

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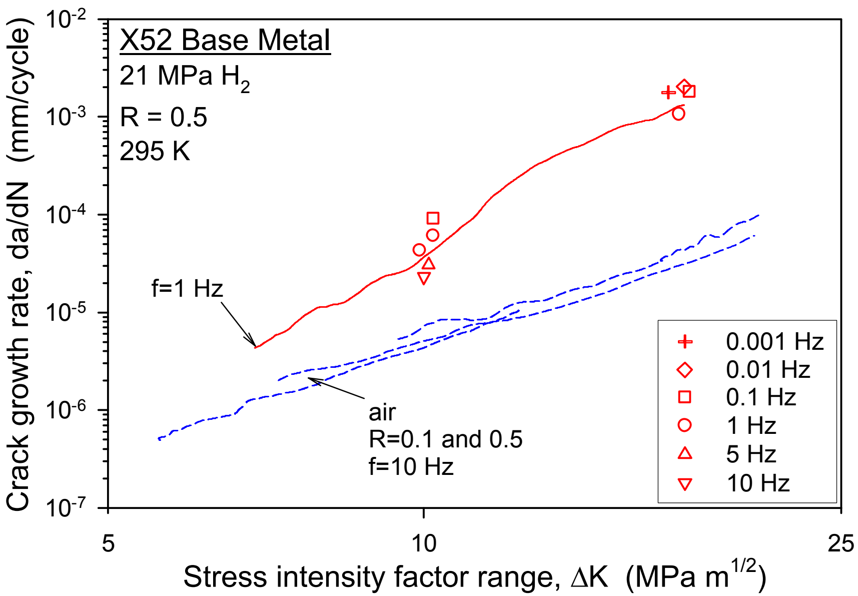
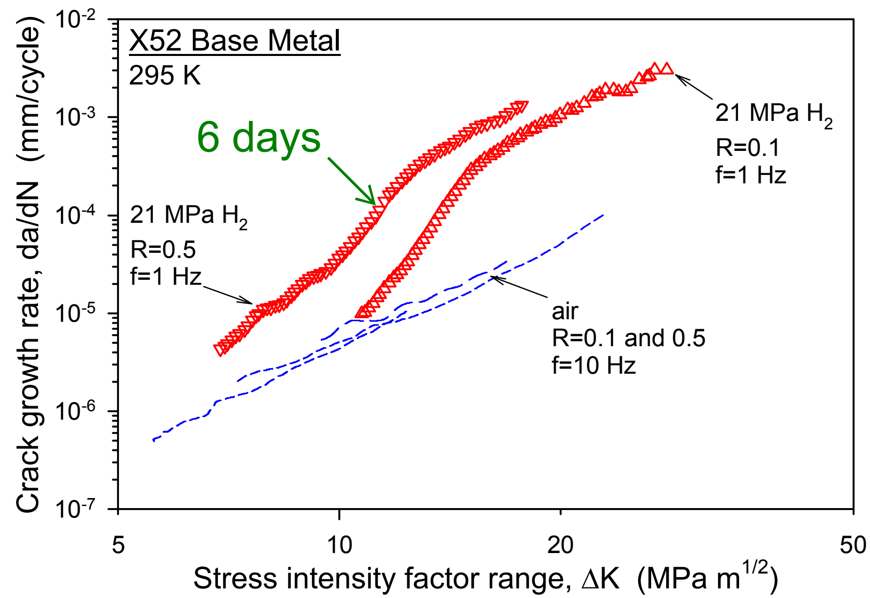
Measurement of fatigue crack growth relationships must consider effects of frequency





- Tests at low frequency are conservative, but capturing all transitions is time consuming
- Measuring relationship only at high da/dN may lead to overly conservative extrapolation at low ΔK
- Correcting da/dN relationship with constant-ΔK points may balance test efficiency and data reliability

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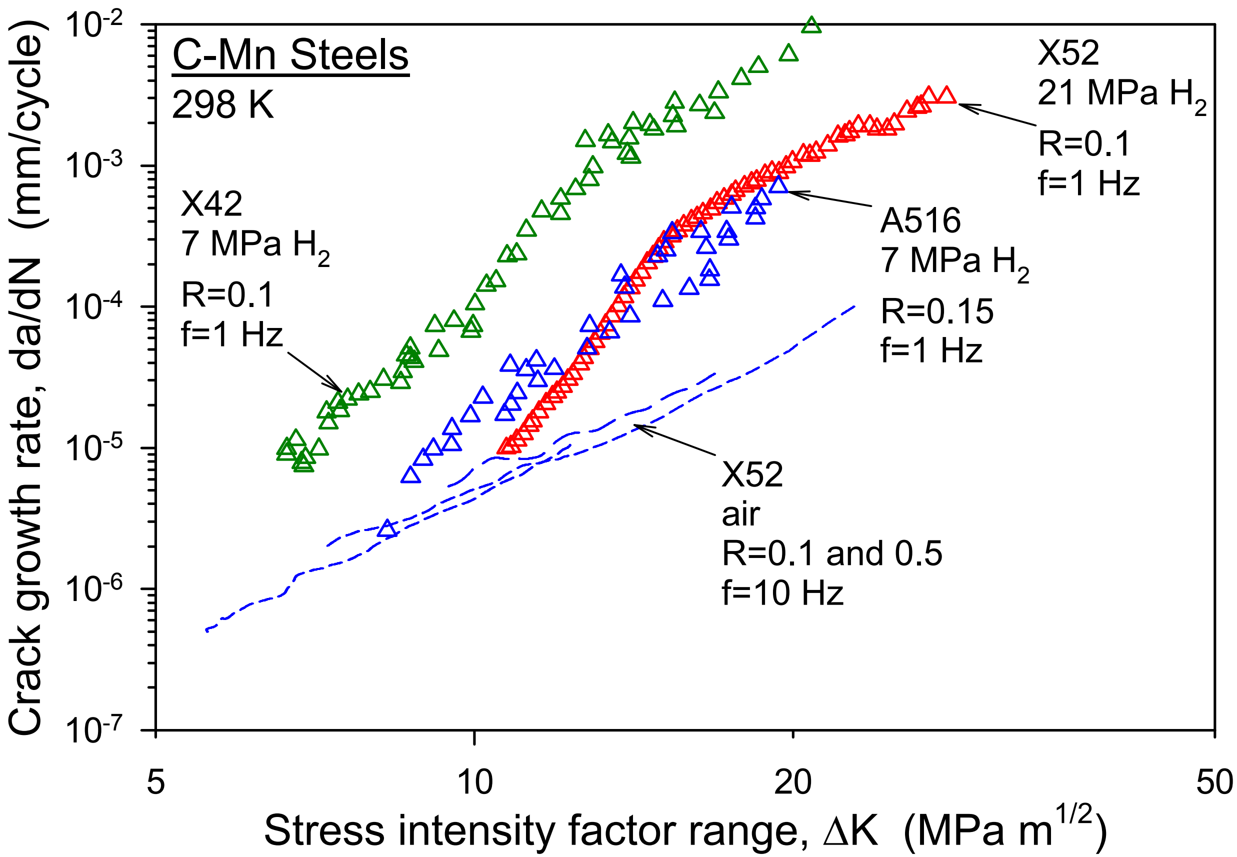
Fatigue crack growth data for X52 in H_2 compare favorably with results from literature

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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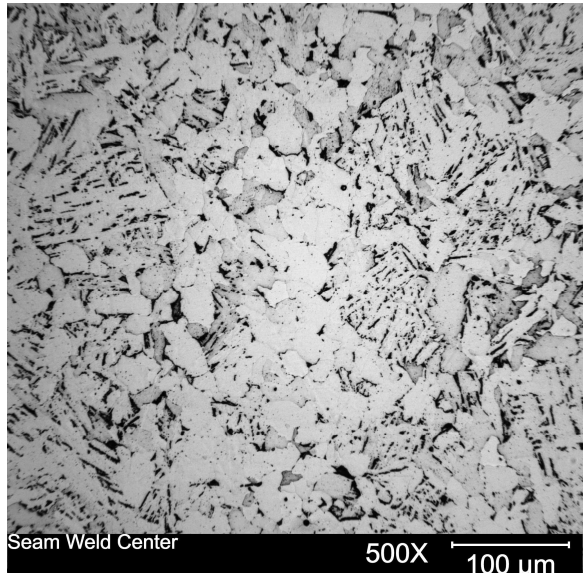
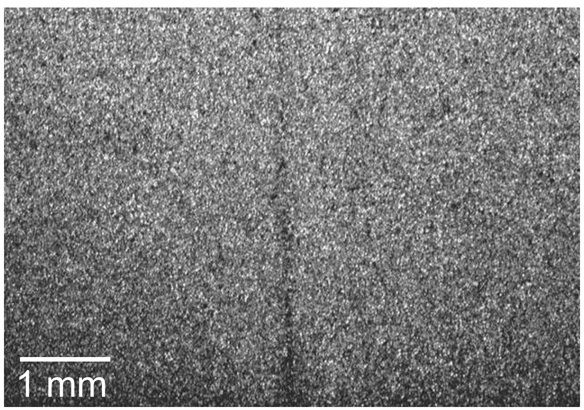
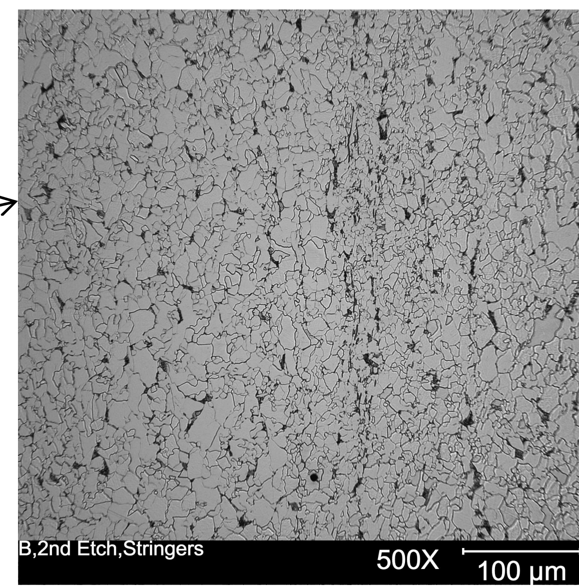
Fatigue crack growth relationships measured for ERW at bond line



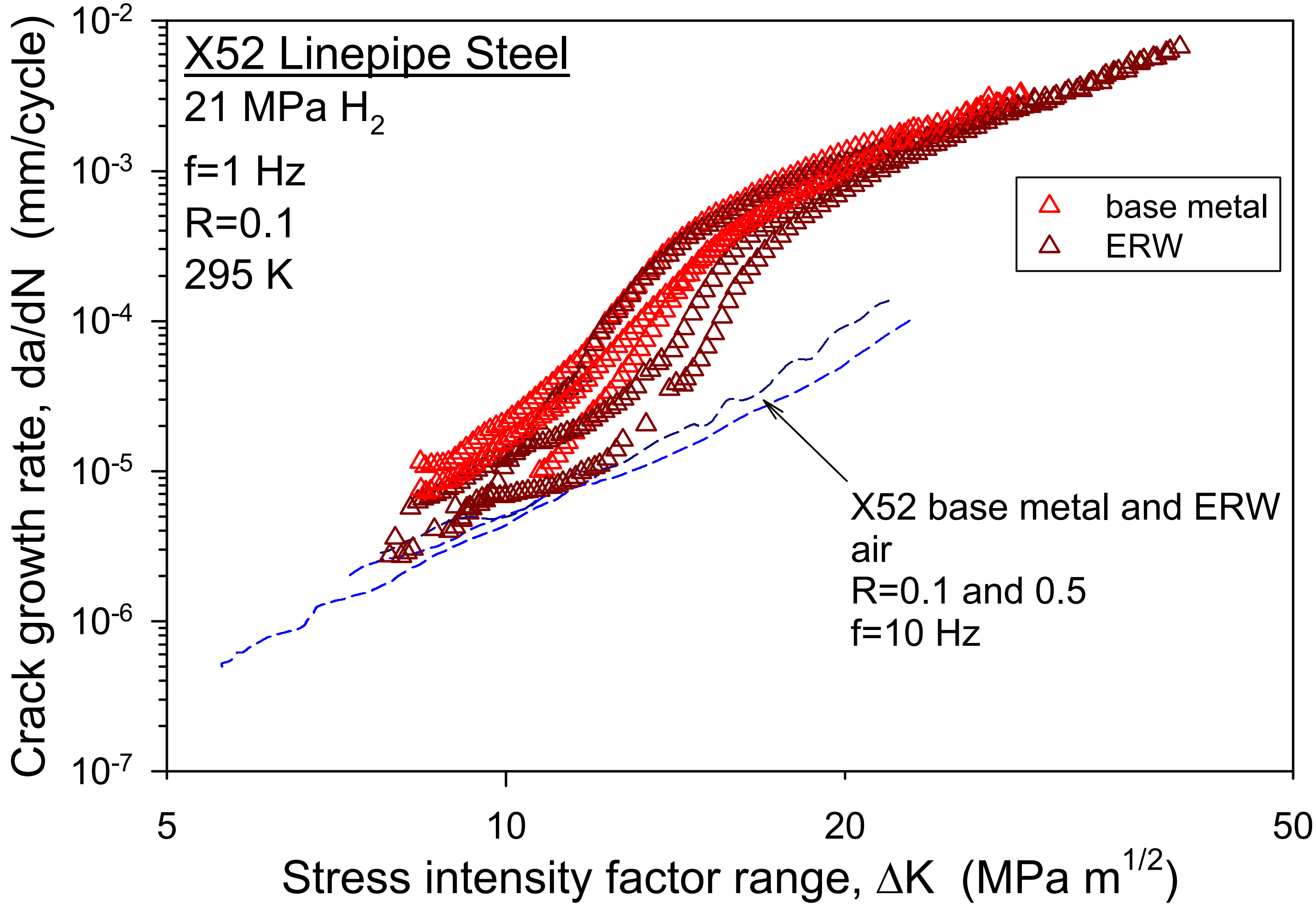
ERW seam



base metal

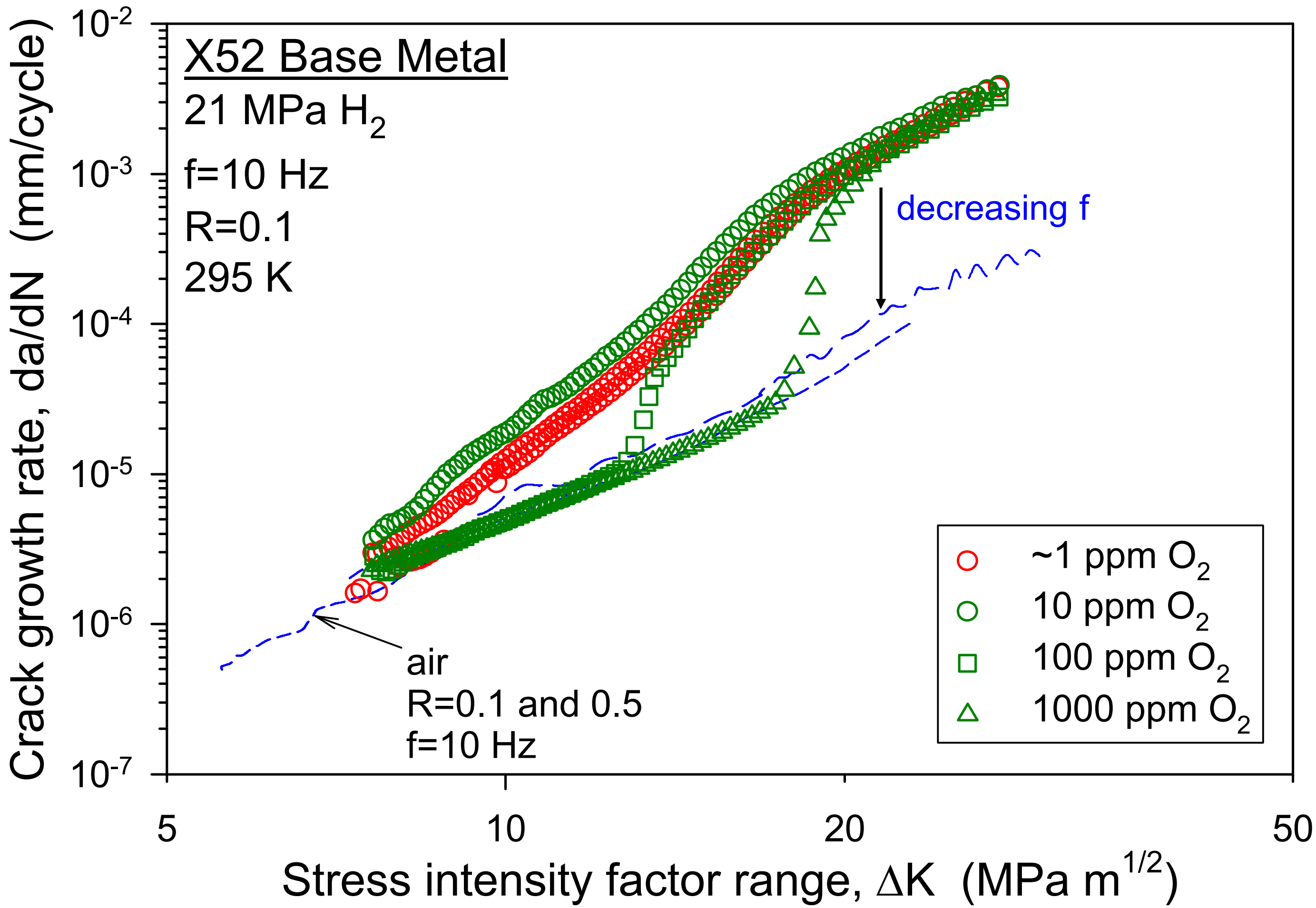


H_2-assisted fatigue crack growth rates similar in ERW and base metal



- Notable variability in data from replicate tests for both ERW and base metal in H_2

Trace O_2 additions to H_2 gas affect onset of hydrogen-accelerated fatigue crack growth



- Onset of accelerated fatigue crack growth affected by load-cycle frequency

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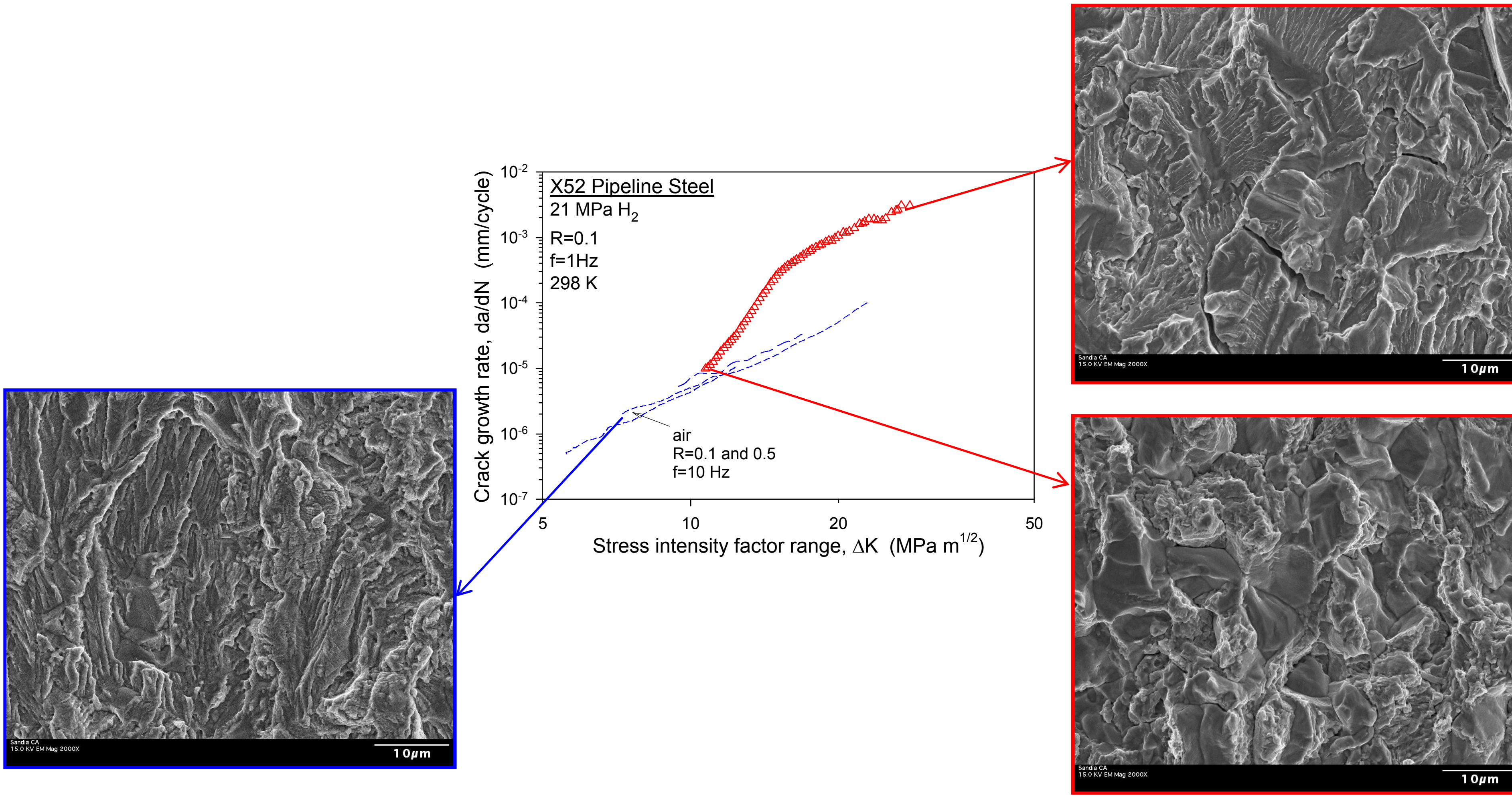
Hydrogen-assisted fracture mode evolves as a function of ΔK



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

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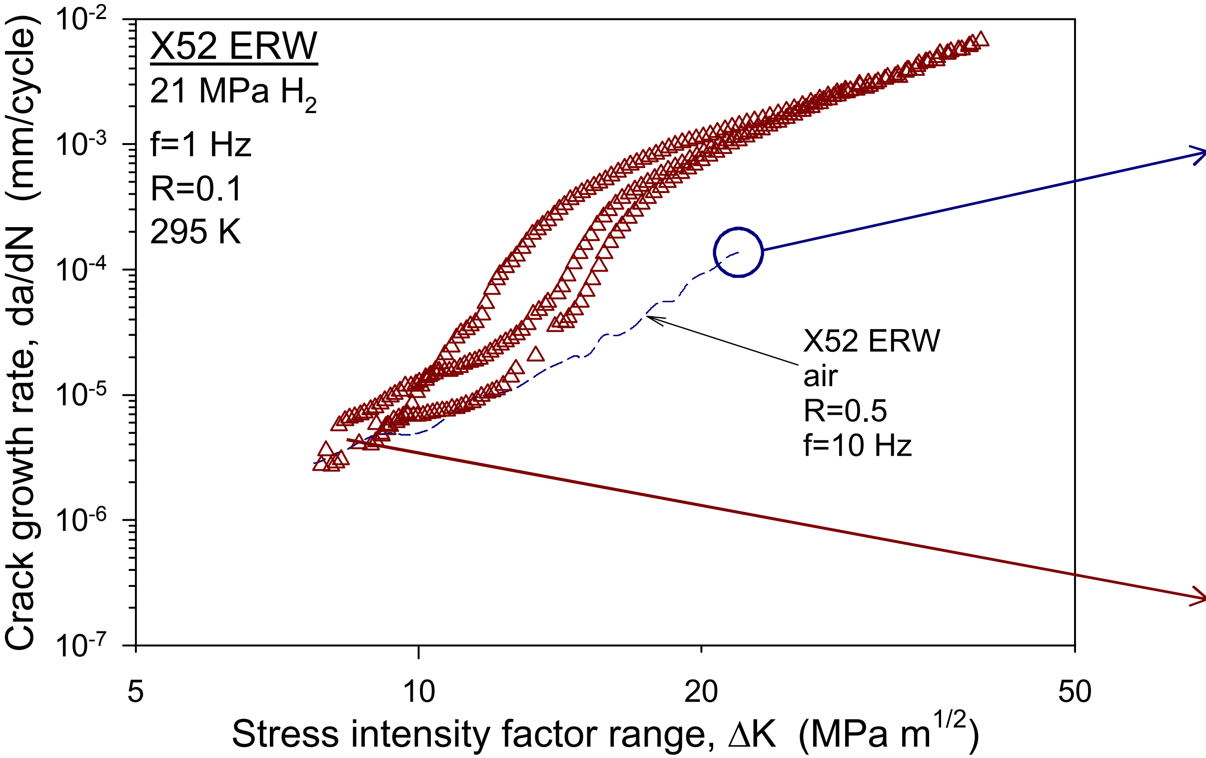
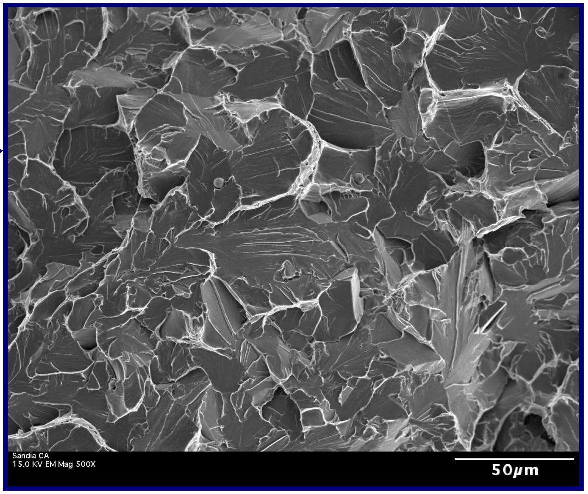
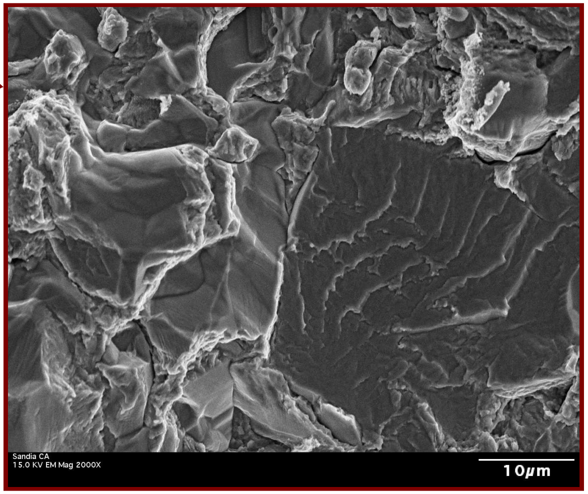
ERW exhibits differences in fracture characteristics compared to base metal







- Mixed intergranular/transgranular fracture for ERW in H_2 at low ΔK
- ERW in air (R=0.5) exhibits unstable fracture at K_{max}~40 MPa $m^{1/2}$ → cleavage

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Summary

- Fatigue crack growth relationships (da/dN vs. ΔK) for X52 steel exhibit transition points in H_2
  - Need efficient test method that captures transitions without compromising data reliability
- Fatigue crack growth relationships for X52 base metal and ERW are similar in H_2
- Trace O_2 additions to H_2 gas retard hydrogen-accelerated fatigue crack growth
- Results enable accommodation/mitigation of H_2-assisted fatigue crack growth in hydrogen pipelines