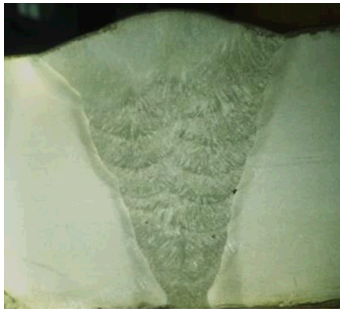
SAND2016-1604C

Accelerated Fatigue Crack Growth in Pipeline Steels and Their Welds in High Pressure Hydrogen Gas



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  - Brendan Davis
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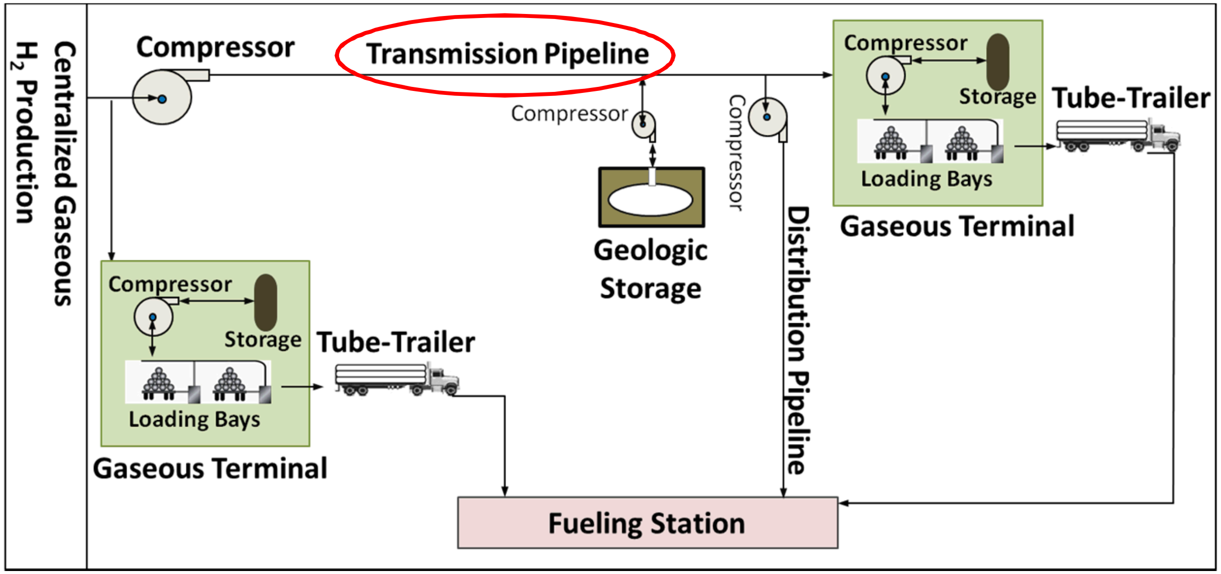
- Federal Labs: ORNL, NIST
- Academia: International Institute for Carbon-Neutral Energy Research (I^2CNER)
- Industry: ExxonMobil
- Standards Development Organizations: ASME

Structural materials are central focus for cost reduction and reliability of H_2 fuel infrastructure

Gaseous Delivery Pathways



Liquid Delivery Pathway

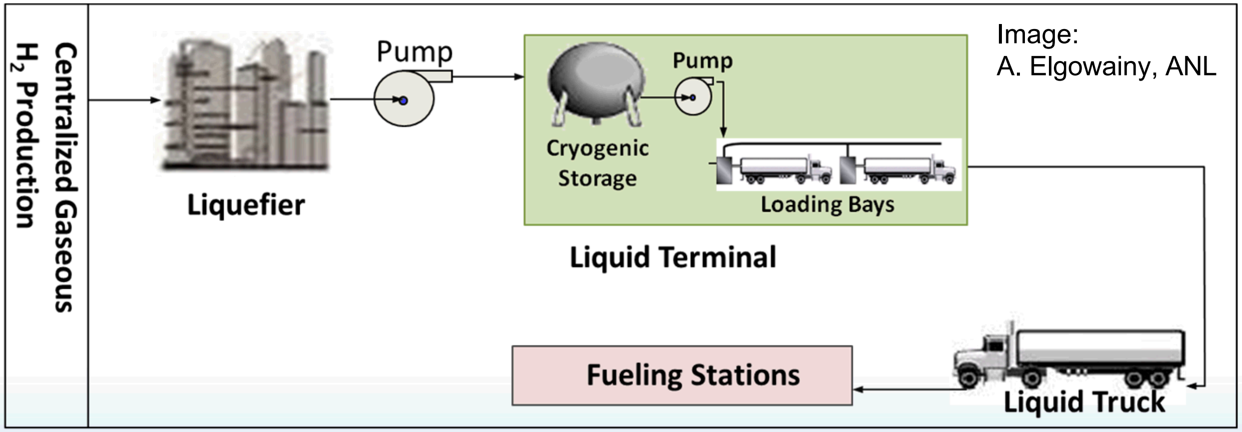


Image: A. Elgowainy, ANL

Hydrogen embrittlement recognized as potential reliability issue for steel H_2 pipelines

Background: Pipeline Installation & Operation

X52 or X65 Line Pipe (i.e. base metal)

Microstructure of base metal affects crack growth rates

Welding to join or repair pipe

Welds may be more susceptible to embrittlement

Daily pressure fluctuations can result in fatigue loading which can affect embrittlement

Can gas impurities mitigate embrittlement effect?

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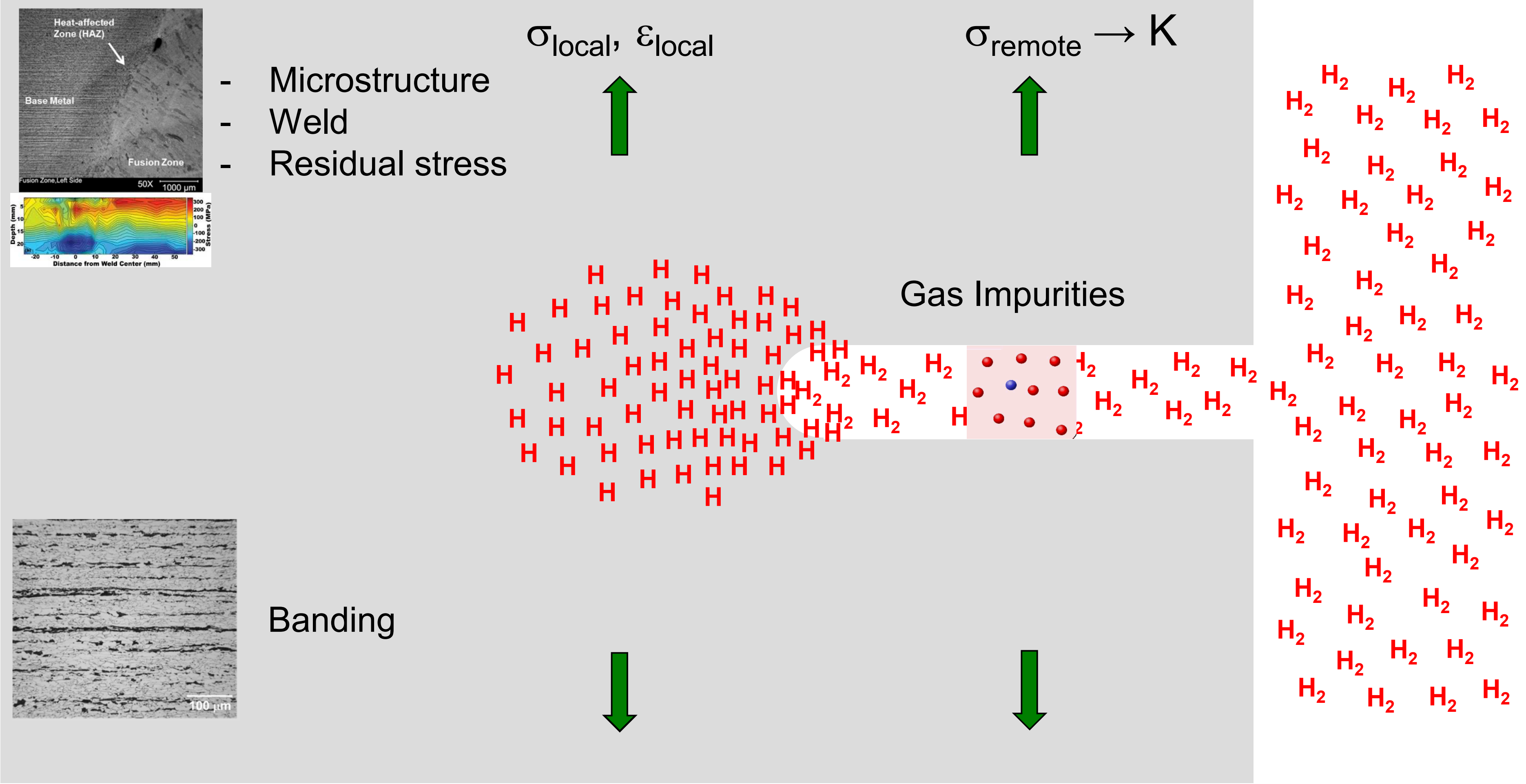
H_2 – assisted cracking is multi-element phenomenon



σ_{local}, ε_{local}

$\sigma_{remote} \rightarrow K$

- Microstructure
- Weld
- Residual stress

Gas Impurities

Banding

Hydrogen-assisted cracking trends depend on microstructure, stress, and hydrogen uptake, but may be dominated by one variable.

Objectives/Relevance

Why should steel hydrogen pipelines be used?

- Operation of steel pipelines, and resistance to 3rd party damage is well-understood
  - Hydrogen pipelines function safely under *constant pressure* load
  - 1,500 miles of steel hydrogen pipelines already in use in the U.S.

Project Purpose:

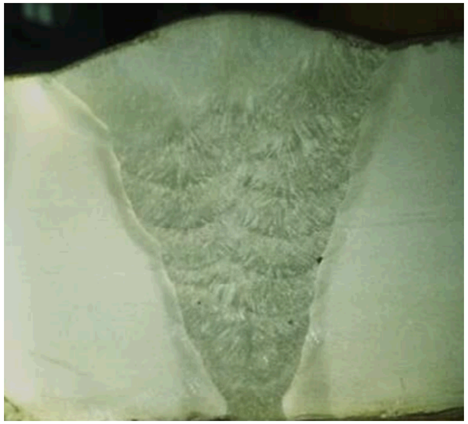
- Assess steel pipeline performance under conditions expected in mature hydrogen market
  - Determine resistance of **base metal and welds to *fluctuating* loads**
  - Experimental data and analysis can guide the **optimization of design codes and standards** to lower pipeline cost while maintaining reliability
  - Establish **models that predict pipeline behavior as a function of microstructure** to guide future developments of novel steels

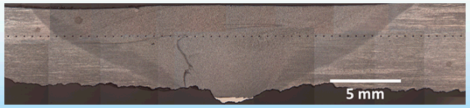
Research on hydrogen embrittlement will enable risk-informed design of lower cost hydrogen pipelines.

Approach: Base Metal and Welds

- Apply core capability (HEML) to measure fatigue crack growth in steels in high-pressure H_2 gas
  - Industrially relevant pipeline grades
  - Representative service environment
  - Fatigue crack growth data will be the basis for requirements of the ASME B31.12 code

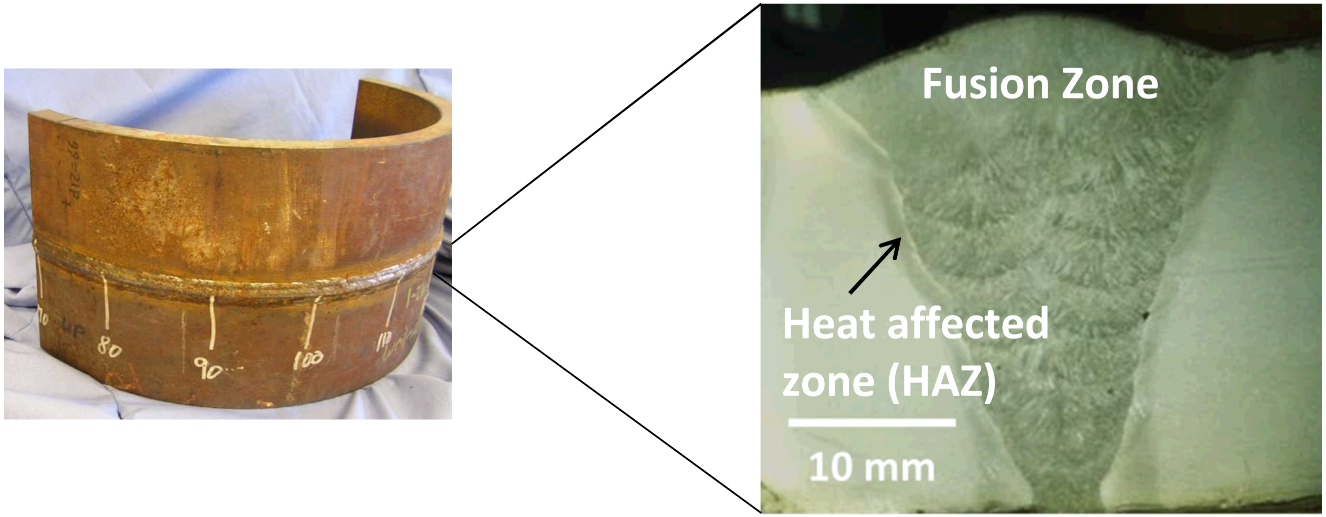
- Assess variables that influence hydrogen embrittlement in pipeline steels
  - Welds
  - Microstructural banding
  - Gas impurities





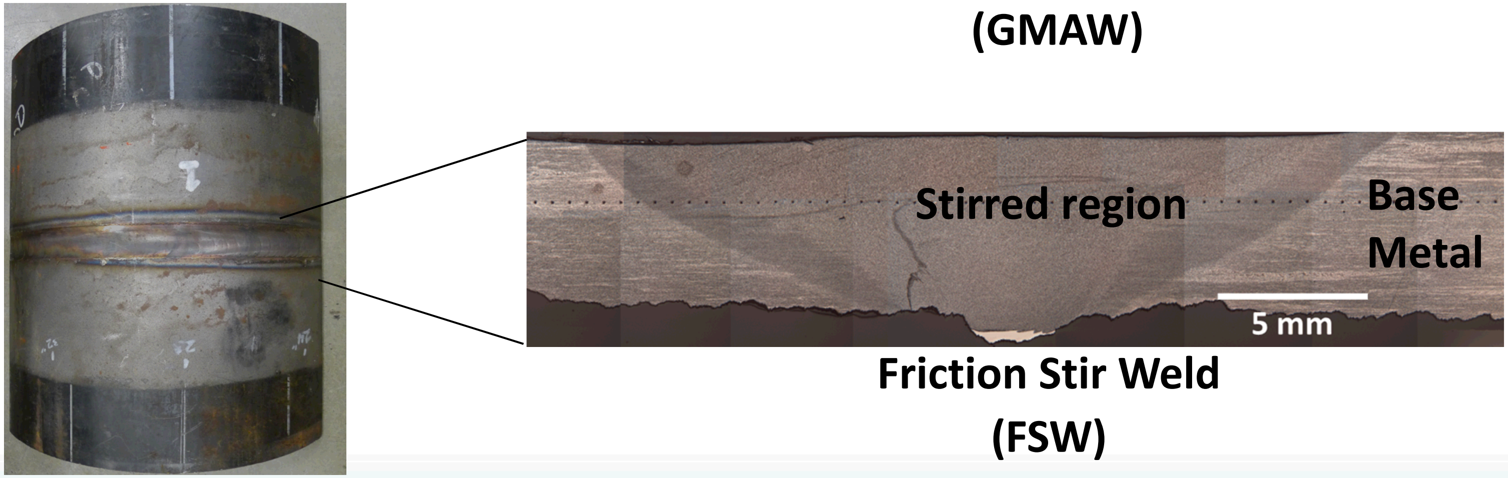
Approach: Base Metal and Welds

X65



Gas metal arc weld (GMAW)

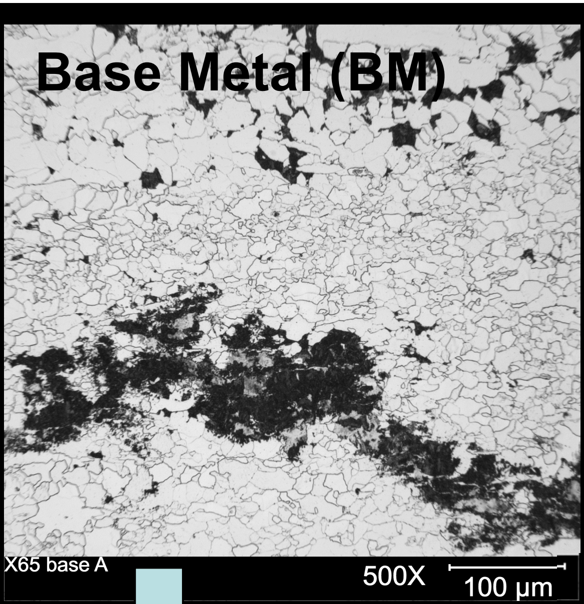
X52

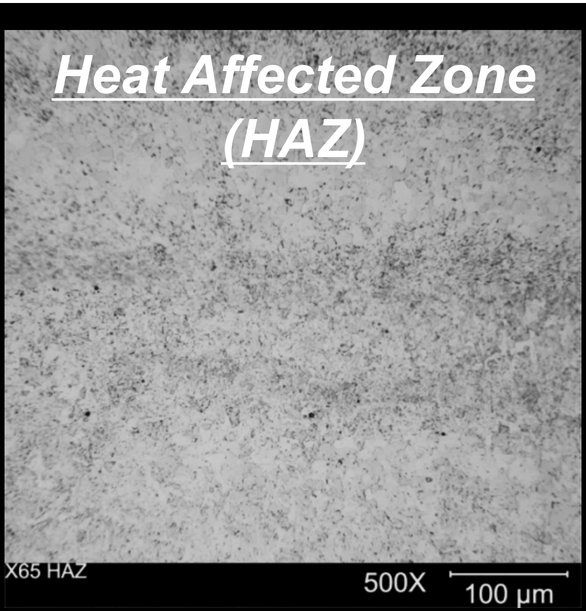


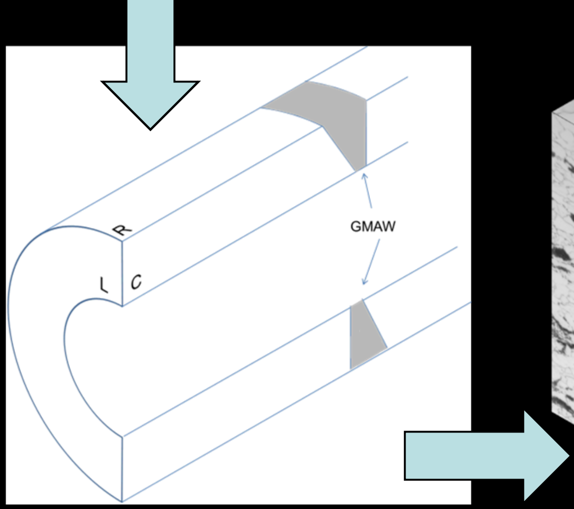
Friction Stir Weld (FSW)

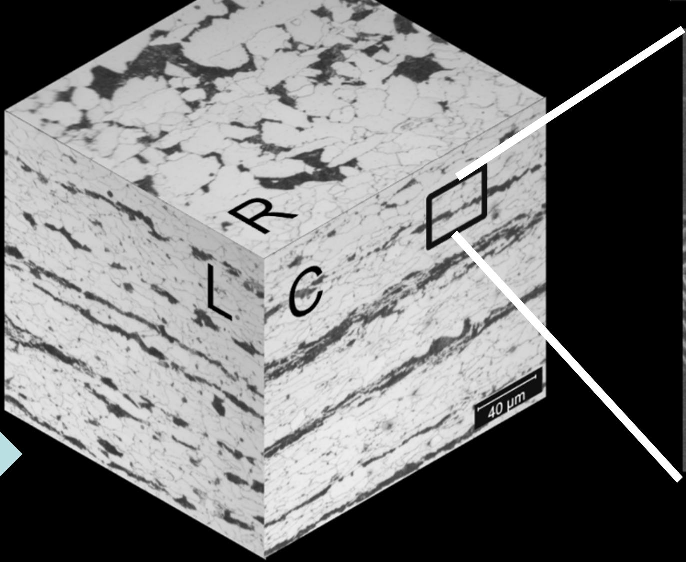
Welding process generates different microstructures and stresses than the base metal.

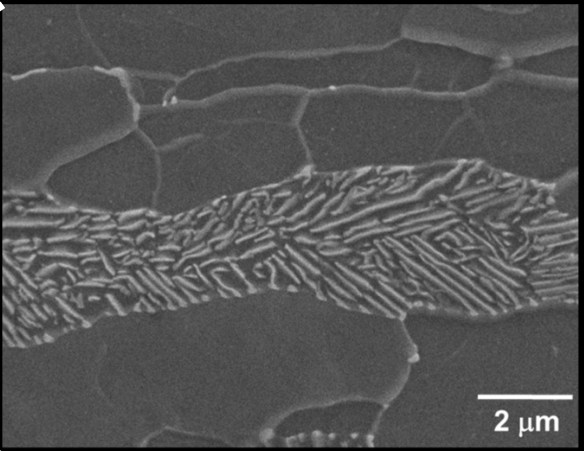
Approach: X65 Base Metal and Welds





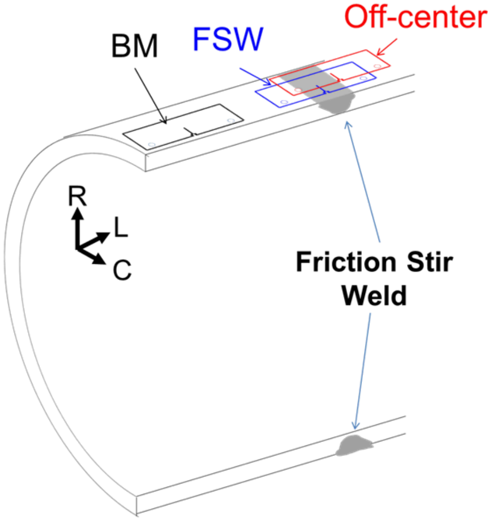


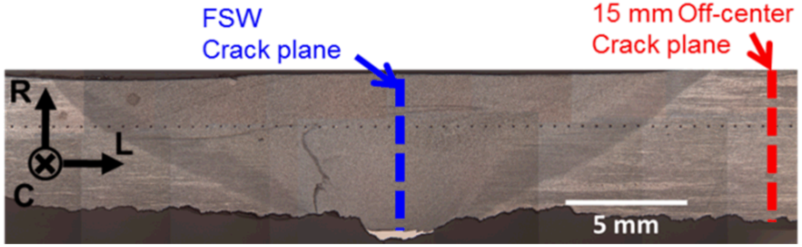




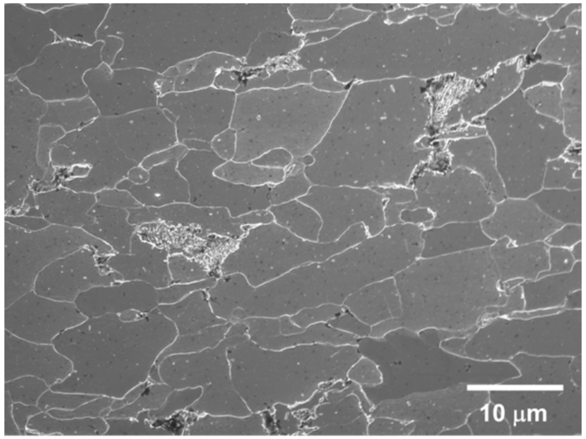
Experimentation completed on base metal, fusion zones, and heat affected zones for X65 steel.

Approach: X52 Friction Stir Welds (FSW)

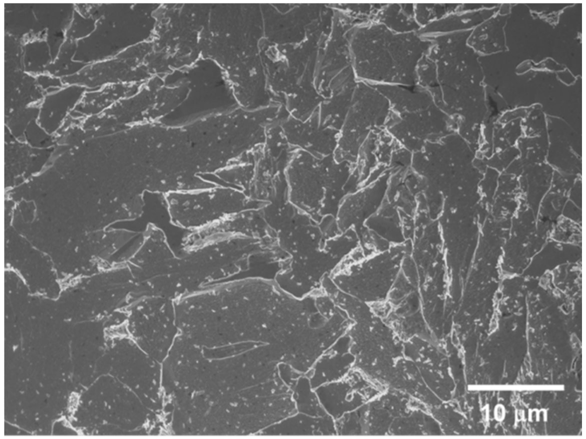




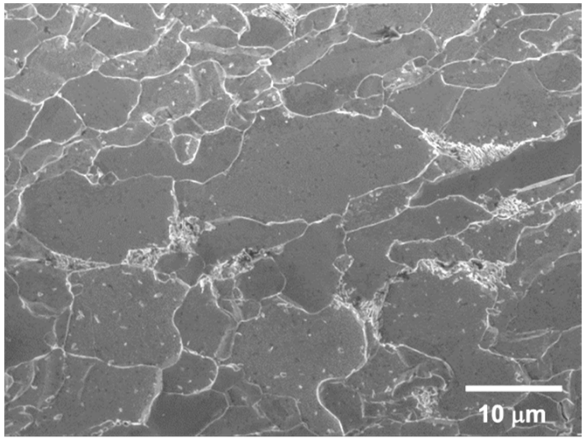
BM



FSW



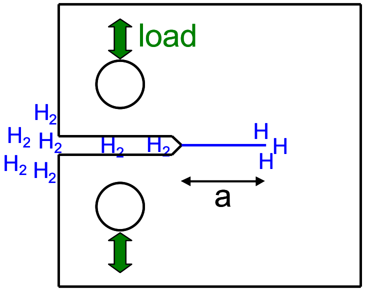
Off-Center



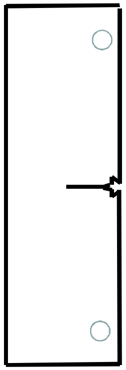
Two different regions of FSW were analyzed to account for potential differences in microstructure.

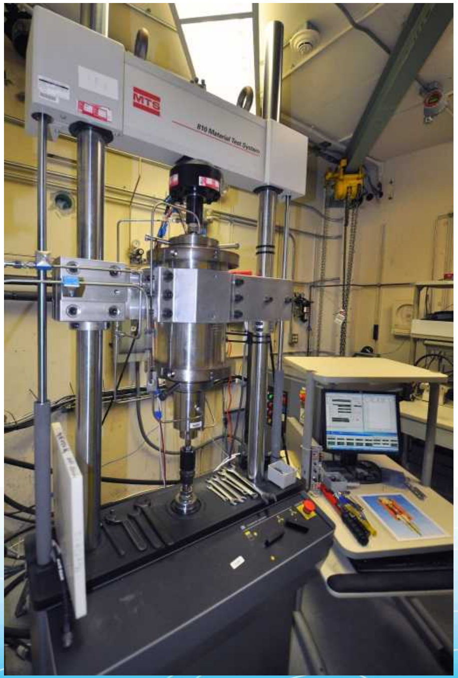
Approach: Fatigue crack growth laws measured in service environment, i.e. high-pressure H_2 gas

Compact Tension (C(T))



ESE(T)

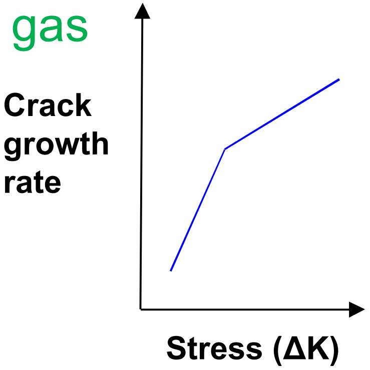




- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT or clip gauge
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude
  - $R = \frac{P_{min}}{P_{max}} = 0.5$ $freq = 1\ Hz$
- Environment
  - Supply gas: 99.9999% H_2
  - Pressure = 21 MPa (3 ksi)
  - Room temperature

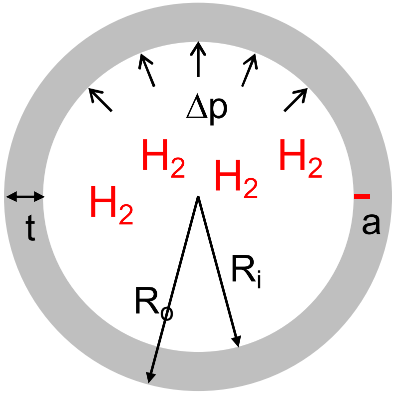
Approach: Optimization of Design

Experimentation: measurements in H_2 gas

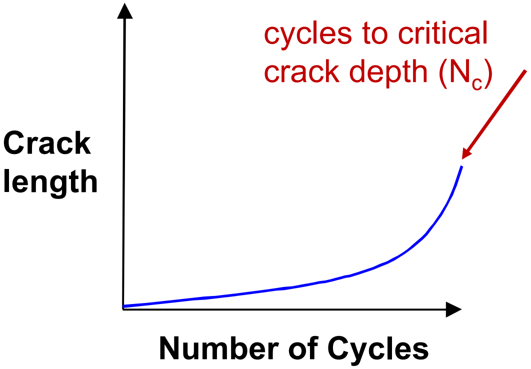


Fracture Mechanics Analysis

$$\Delta K = \Delta p[f(a, t, R_o, R_i)]$$



Assuming steel thickness, calculate:



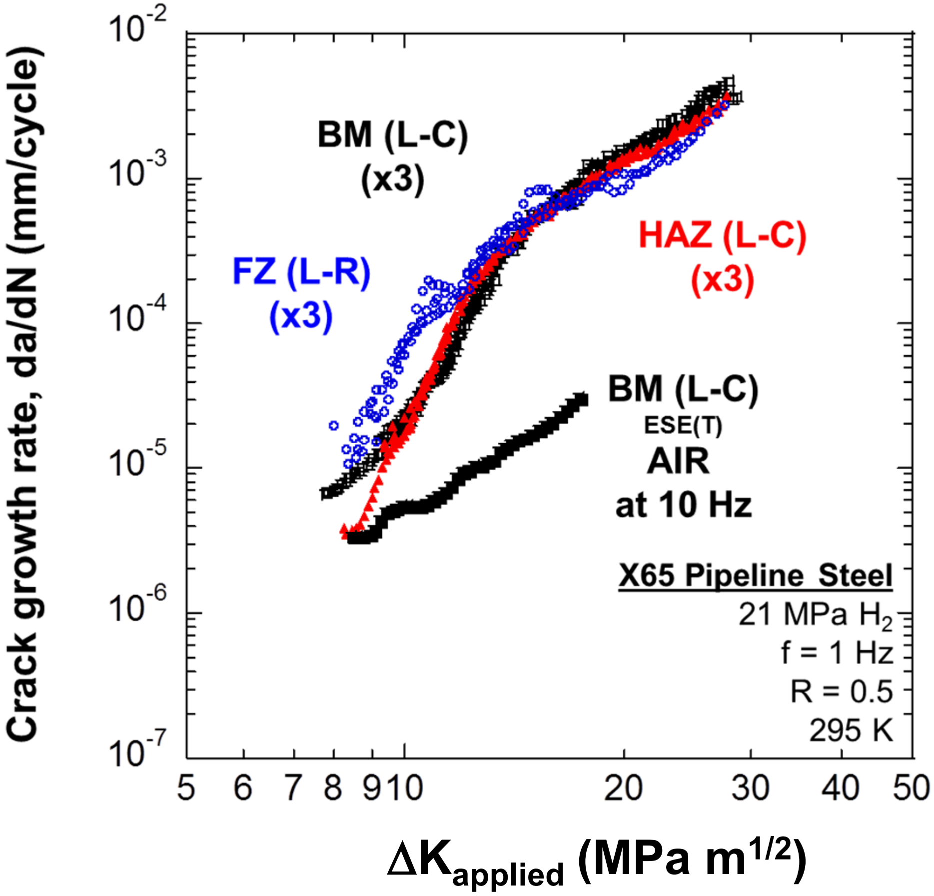
cycles to critical crack depth (N_c)

Design Analysis

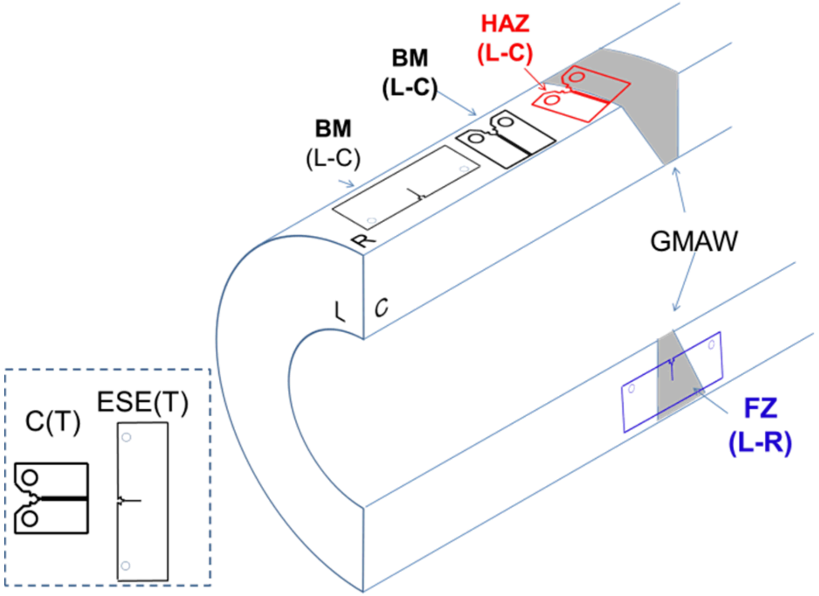
Is steel pipeline life sufficient given expected service conditions, and ASME code requirements (life = 0.5 N_c)?

Fracture mechanics analysis to characterize steel reliability in H_2 gas.

Results: X65 Gas Metal Arc Weld (GMAW)



J. Ronevich & B. Somerday, *Materials Performance and Characterization*, 2015, in press.

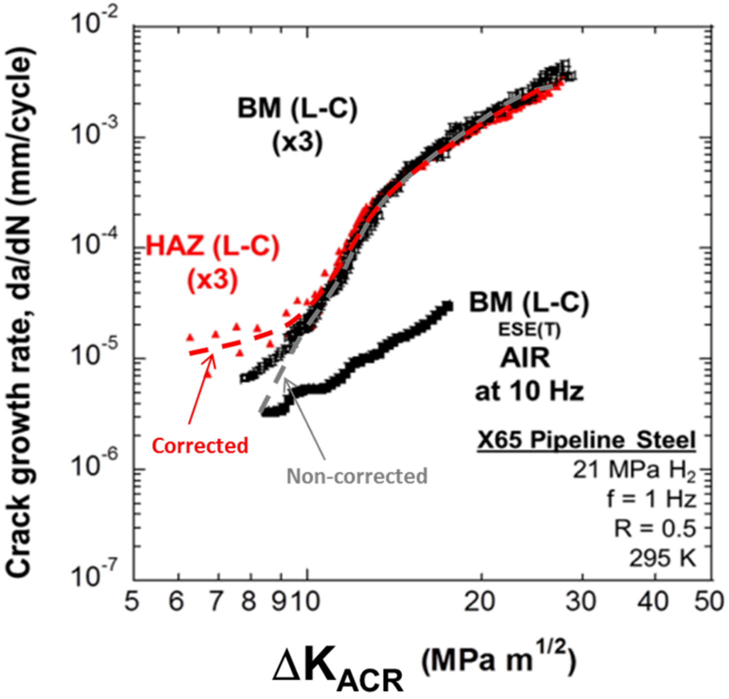


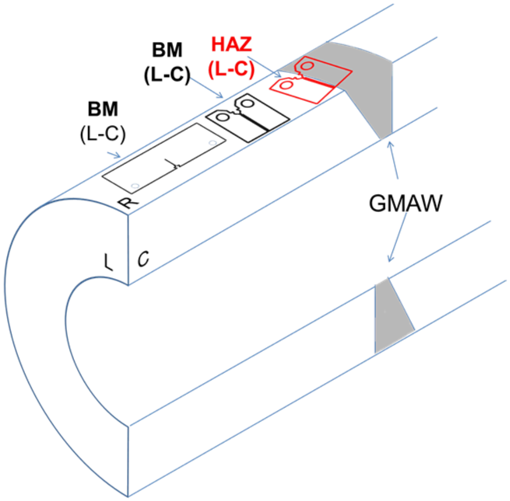
- Triplicate tests revealed repeatable results
- Results did not account for “residual stress” resulting from welding

Must perform analysis to account for contribution of residual stress to driving force, ΔK.

Results: X65 Gas Metal Arc Weld (GMAW)

Analysis to account for residual stress in driving force leads to more reliable da/dN vs. ΔK curves.

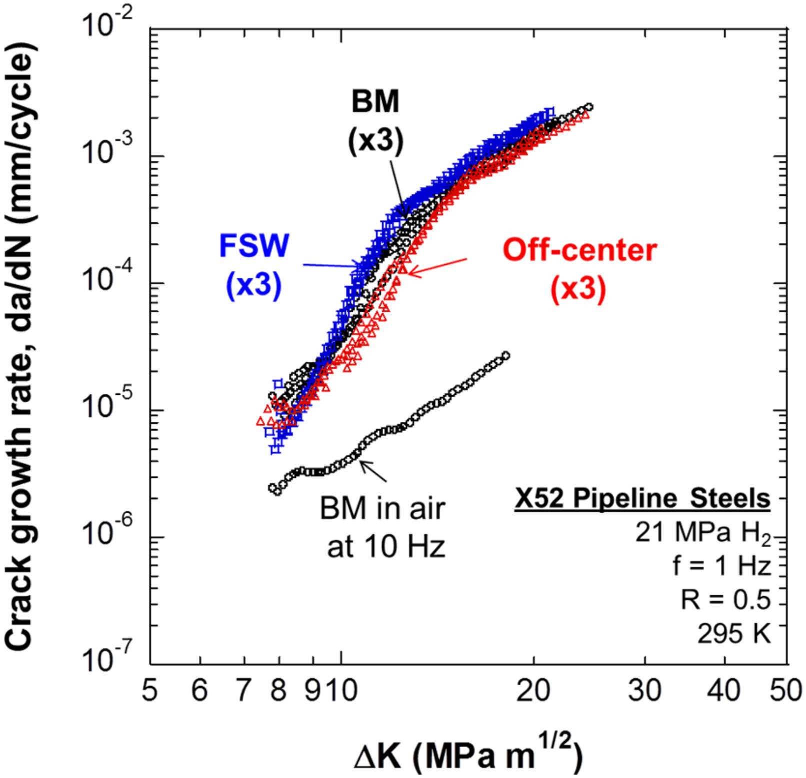


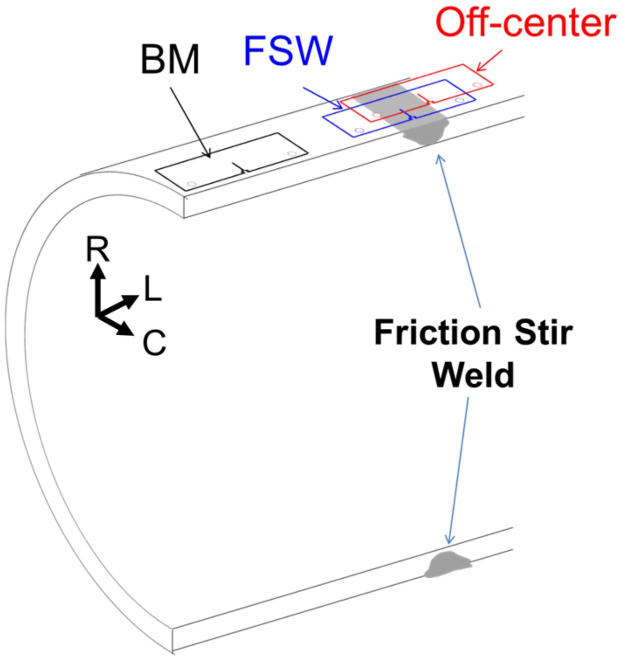


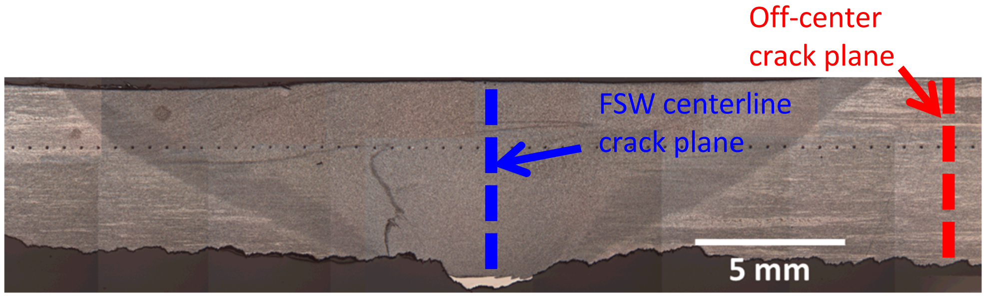
- Corrections show faster crack growth at lower ΔK than previously determined.

X65: Crack growth faster in weld heat affected zone than in base metal.

Results: X52 Friction Stir Welds (FSW)



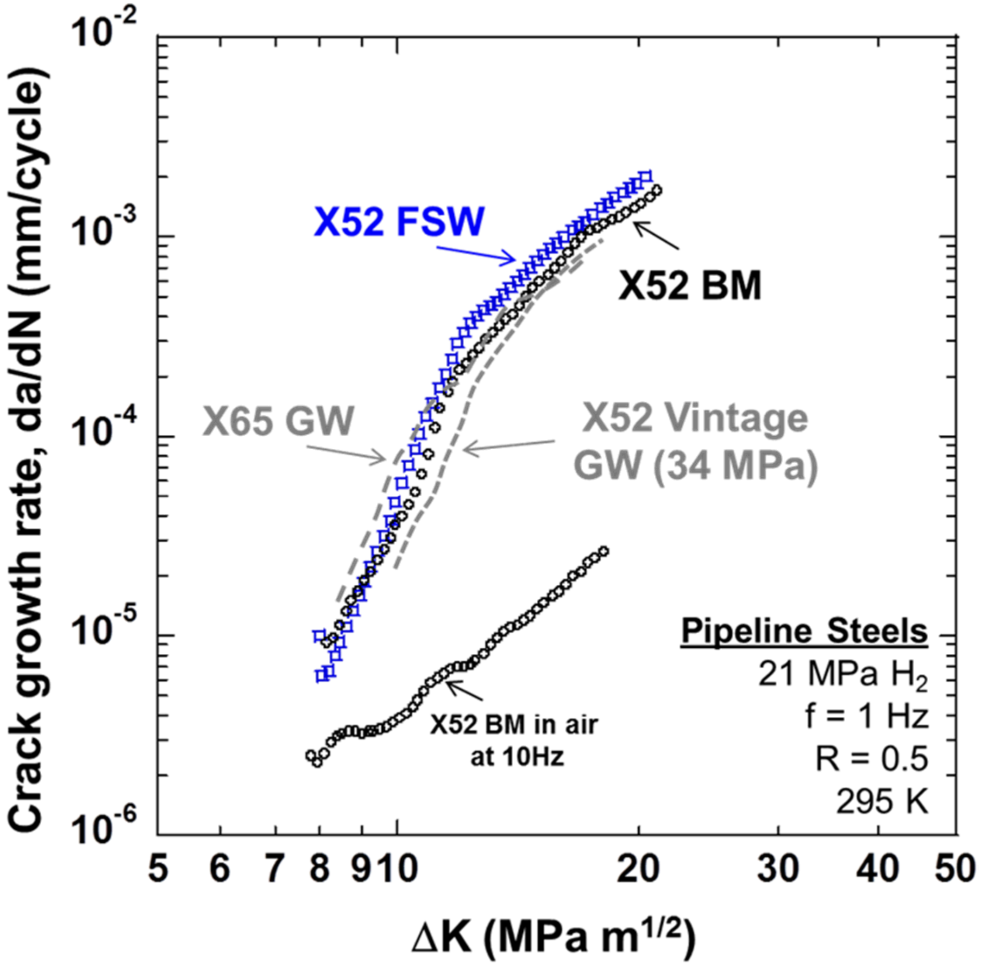




- Crack growth rate measurements in FSW are repeatable (triplicate results obtained)

X52: crack growth faster in center of FSW than in base metal, and faster in base metal than in off-center position.

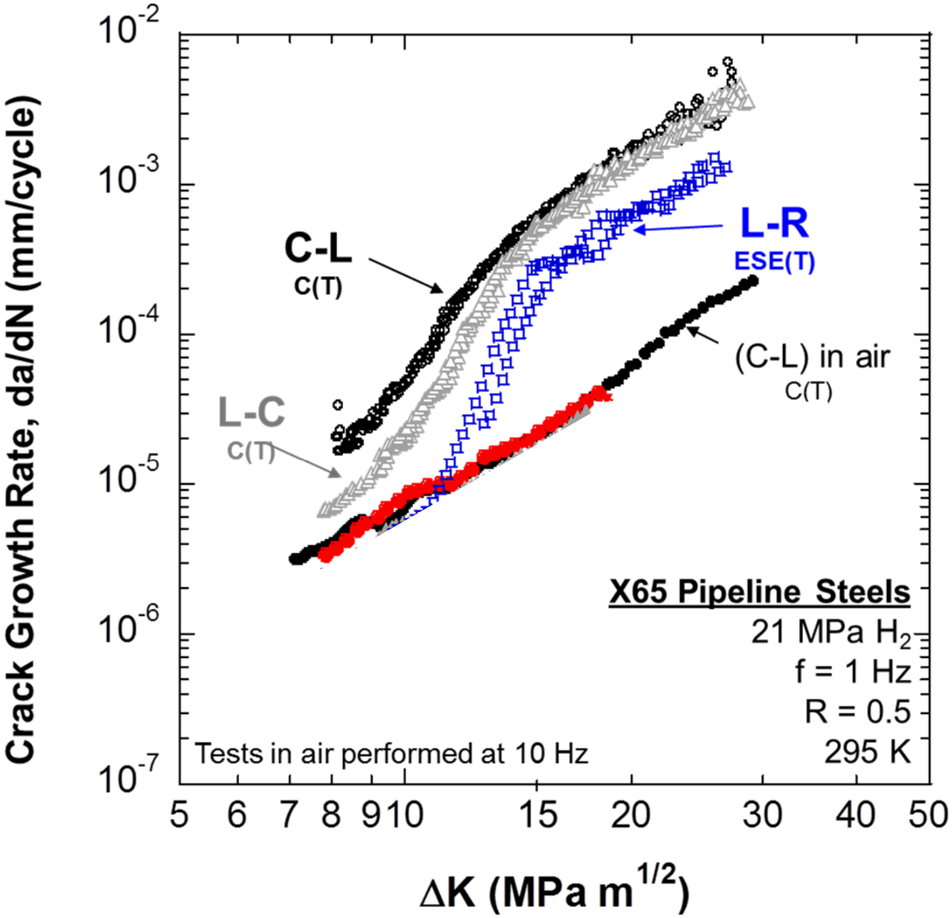
Conclusions: Welds



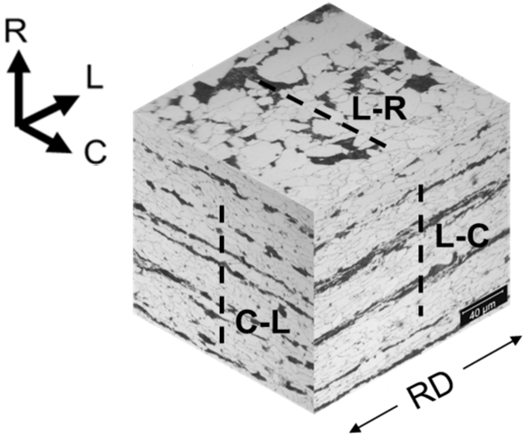
*X52 Vintage GW is work from NIST [Slifka *et al.* PVP2015]

Friction stir welds and conventional gas metal arc welds exhibit similar crack growth rates in hydrogen.

Results: Microstructural Banding



J. Ronevich et al., *Int. J. Fatigue*, 2015.



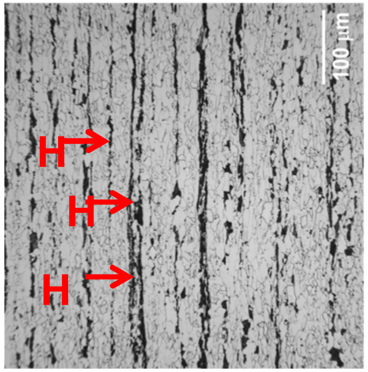
Data obtained compared to data from other specimen orientations:

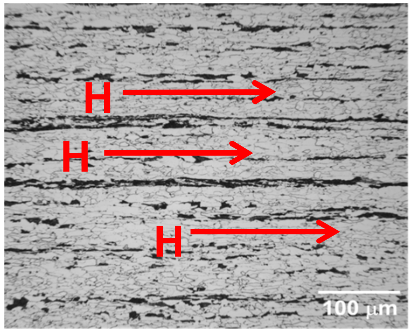
- Cracks in L-C and C-L direction encounter consistent microstructure (primarily ferrite), and had similar crack growth rates
- Cracks in in L-R direction encountered alternating bands of ferrite-pearlite, and grew much more slowly.

Bands of pearlite significantly slow crack growth.

Conclusions: Microstructural Banding

Hydrogen diffusion in L-R orientation vs. C-L orientation





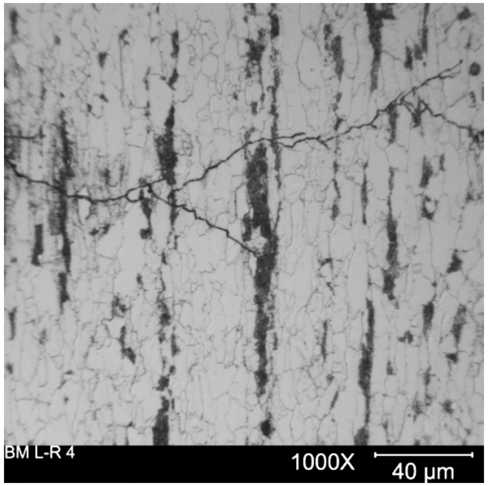
L-R

Hydrogen diffusivity <u>across</u> banded structure

<

C-L

Hydrogen diffusivity <u>along</u> banded structure



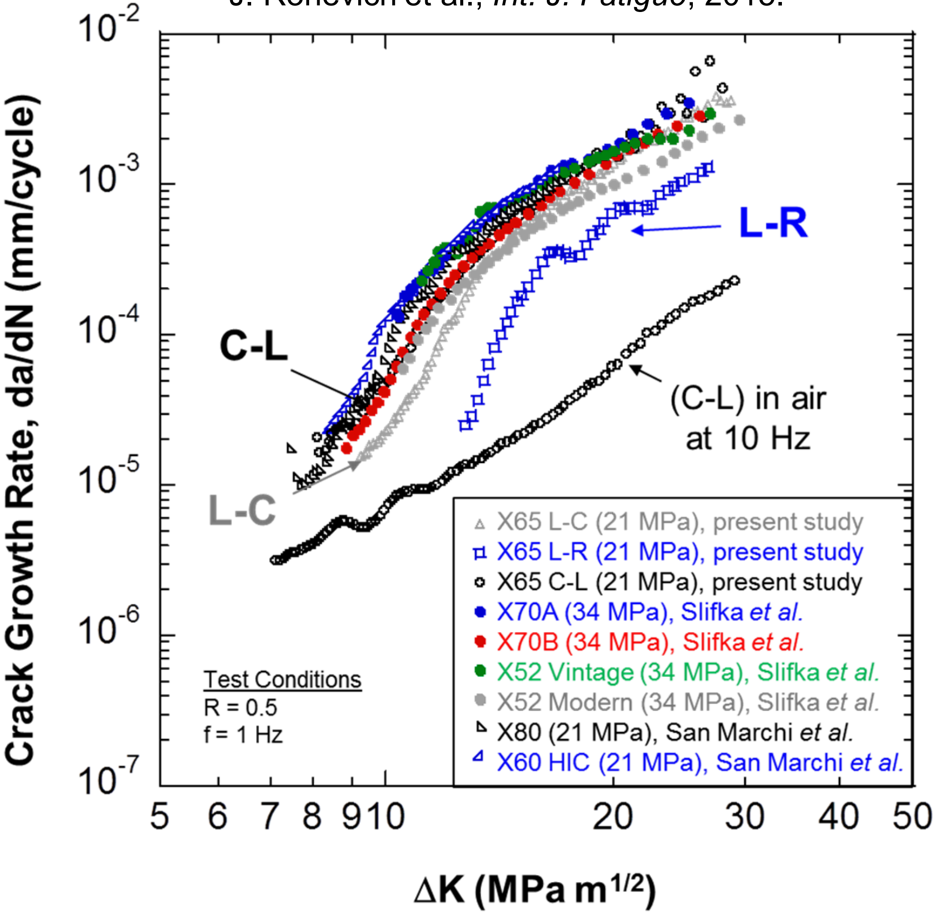
Crack-tip branching in L-R orientation

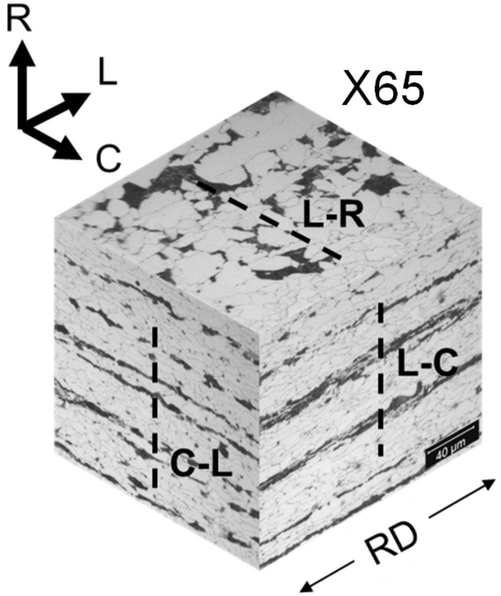
Slower rates of crack growth perpendicular to pearlite bands may be because:

1) ***hydrogen diffusion is slower, and***
2) ***Hard pearlite results in crack branching (which reduces driving force).***

Conclusions: Microstructural Banding

J. Ronevich et al., *Int. J. Fatigue*, 2015.

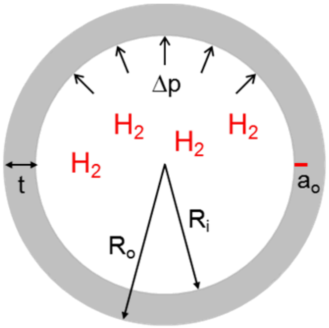




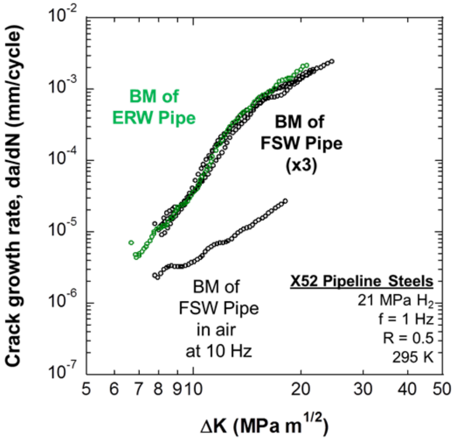
References:
X60 and X80 data:
San Marchi et al., ASME PVP, 2010
X52 and X70 data:
Slifka et al., ASME PVP, 2014
Drexler et al., Proceedings of SteelyHydrogen, 2014

Examining multiple pipeline steels demonstrates that most pronounced microstructure effect is banded ferrite-pearlite in L-R orientation

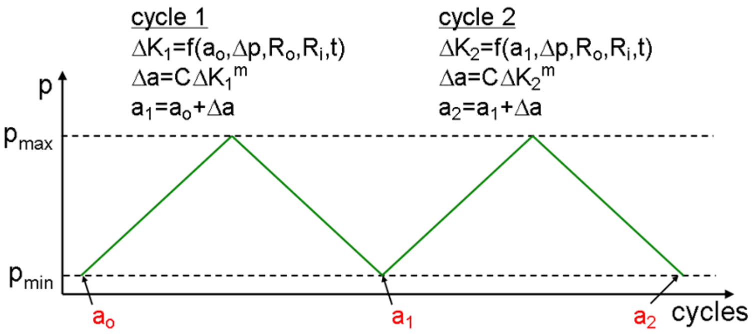
Measured fatigue crack growth laws can be applied to calculate minimum wall thickness for steel H_2 pipelines

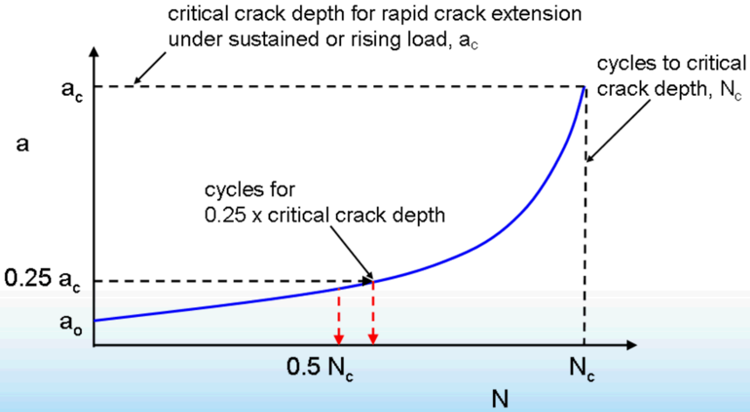


$\Delta K = \Delta p[f(a, t, R_o, R_i)]$



$da/dN = C\Delta K^m$





- ASME fatigue life calculation: structural analysis + fatigue crack growth law
- Inputs:
  - pressure cycle range (Δp)
  - initial flaw depth (a_o)
  - pipe outer diameter ($2R_o$)
  - fatigue crack growth law ($da/dN=C\Delta K^m$)
- ***Goal:*** Calculate wall thickness (t) required to attain fatigue life of $0.5N_c$

Do wall thickness premiums need to be applied?

	H_2 Pipeline Wall Thickness Necessary*	
Pressure cycle (psi)	Initial flaw depth: 3% wall thickness	Initial flaw depth: 5% wall thickness
1500 to 3000	**0.62 in (15.7 mm)**	**0.81 in (20.7 mm)**
300 to 3000	1.37 in (34.9 mm)	1.83 in (46.5 mm)

*Thickness determined by $0.5N_c$, in which N_c = 73,000 cycles
($0.5N_c$ = 36,500 cycles = 50 yr at 2 cycles/day)

- Natural Gas pipeline thickness necessary calculated based on ASME B31.8

Thickness: 0.96 in (24.4 mm)

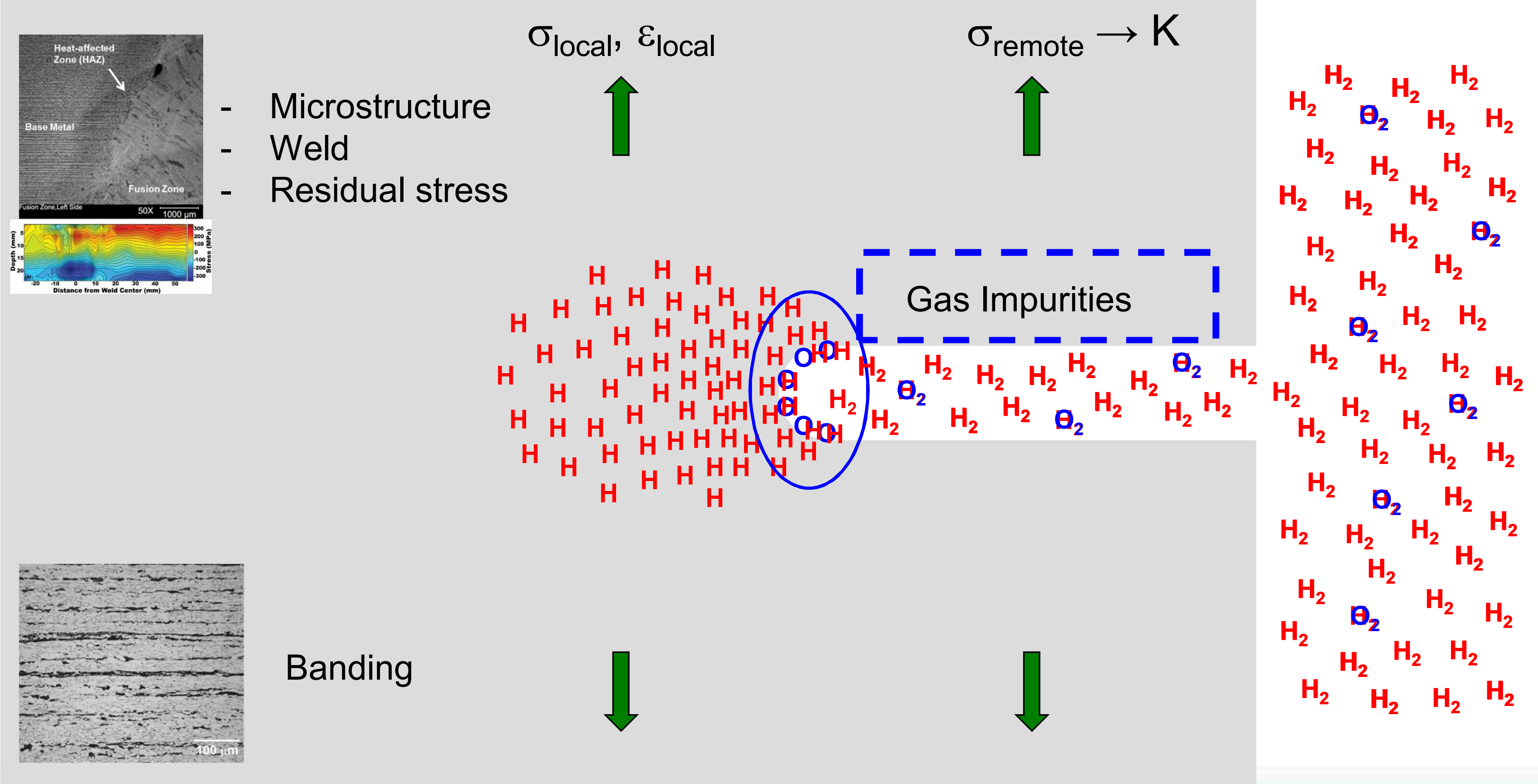
$$P = \frac{2St}{D} FET$$

P = design pressure = 21 MPa
S = SMYS = 52 ksi (X52)
t = thickness
D = outside diameter = 24 in.
F= design factor = 0.72 (Class 1)
E = longitudinal joint factor = 1
T = temp derating factor = 1

H_2 pipelines may not require a thickness premium relative to current natural gas codes.

H_2-assisted cracking is multi-element phenomenon

Trends may be dominated by one element



σ_{local}, ε_{local}

$\sigma_{remote} \rightarrow K$

- Microstructure
- Weld
- Residual stress

Banding

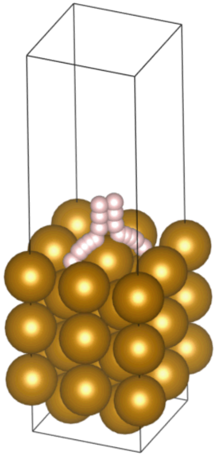
Gas Impurities

Hydrogen uptake retarded by oxygen adsorption on crack-tip surface

Related Research: Embrittlement Mitigation

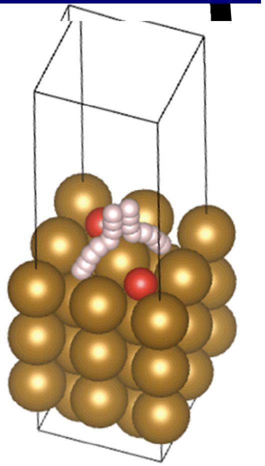
Potential energy surface scan for H_2 approaching Fe(100) surface

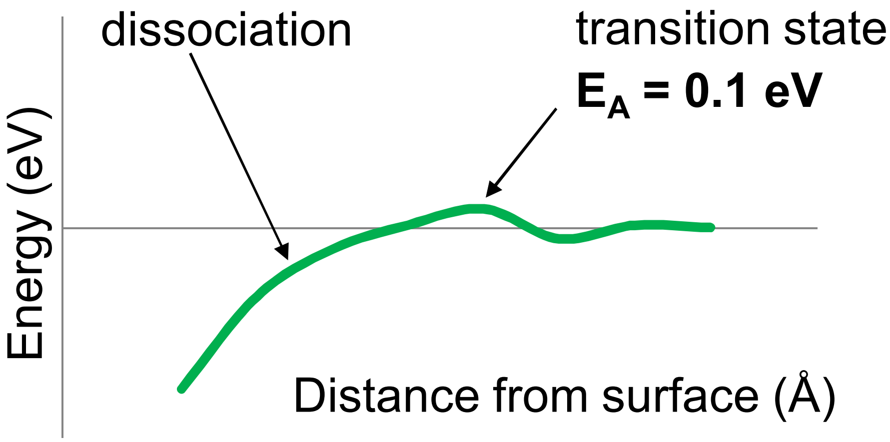
H_2 molecule approaches directly on top Fe atom

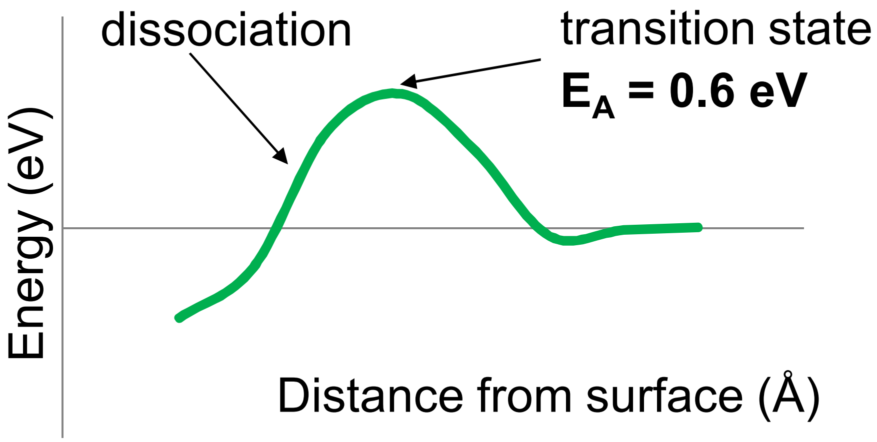


Potential energy surface scan for H_2 approaching Fe(100) surface with preadsorbed O atoms

H_2 molecule approaches directly on top Fe atom



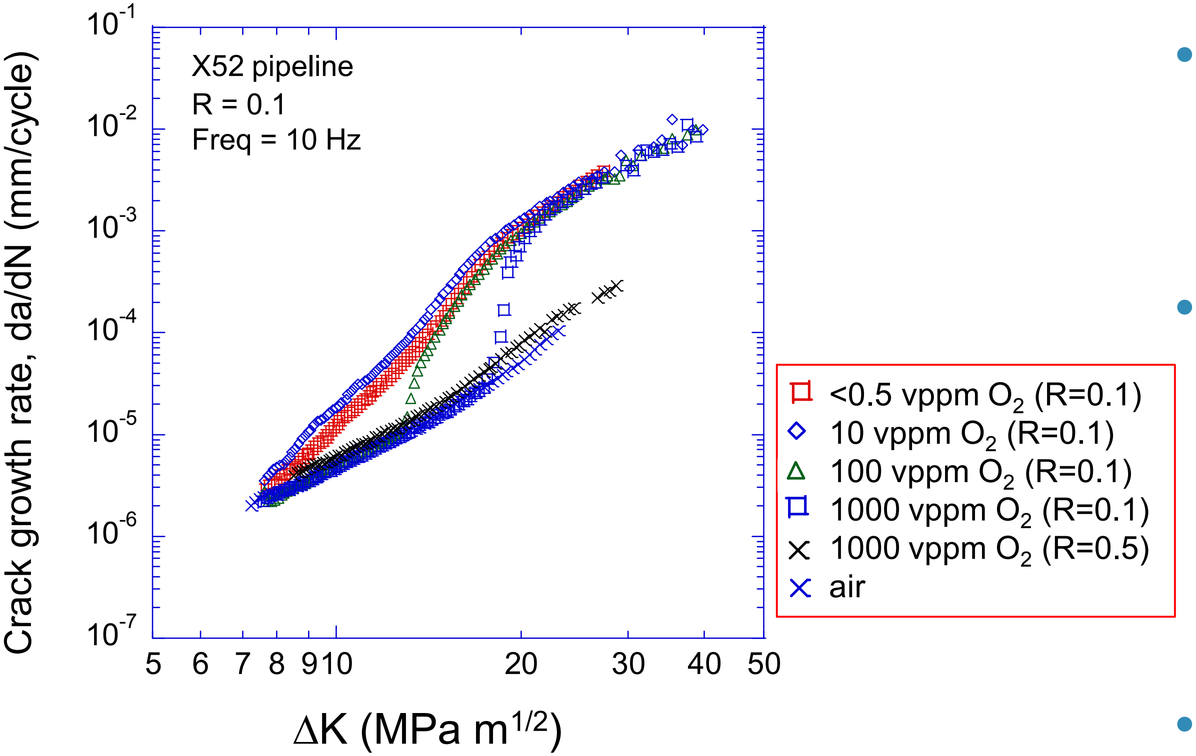




Staykov et al., *Int J Quantum Chemistry*, 2014

DFT simulations show that pre-adsorbed oxygen inhibits H_2 dissociation.

Related Research: Embrittlement Mitigation



B.P. Somerday et al., *Acta Mater*, 2013

- At lower ΔK, crack growth rates in H_2 environments same as rates in air
- At R=0.1, hydrogen-accelerated crack growth observed at higher ΔK
  - da/dN at onset of hydrogen-accelerated crack growth depends on O_2 concentration
- At R=0.5, hydrogen-accelerated crack growth not observed

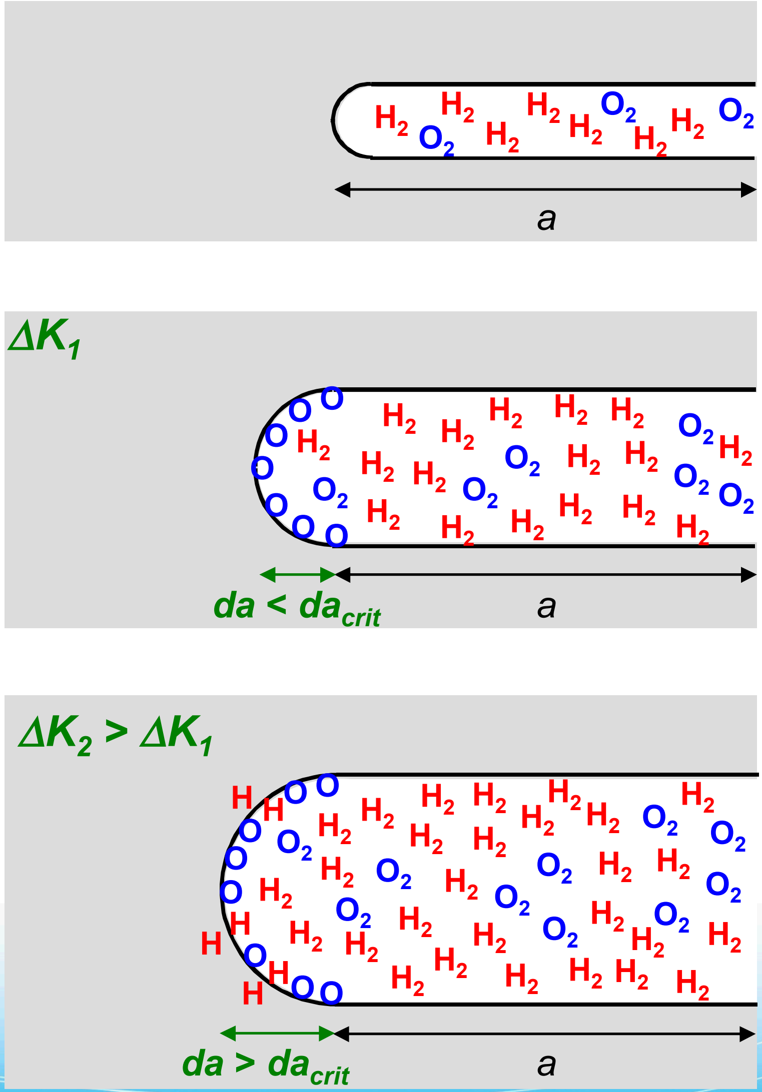
Mitigation depends on several variables: O_2 conc, R-ratio, da/dN, and load cycle frequency.

Related Research: Modeling H2 Embrittlement with Oxygen Impurities

B. Somerday et al., *Acta Mater*, 2013

Assumptions

- Initial inert-environment crack growth modeled by blunting-resharpening
- Oxygen out-competes hydrogen for adsorption sites on freshly exposed crack-tip surface
- Extent of oxygen adsorption depends on crack-tip area, proportional to crack-growth increment (*da*)
  - when *da* < da_{crit}, crack tip *fully passivated* by oxygen
  - when *da* > da_{crit}, crack tip *not fully passivated* → H uptake



Developed model that relates oxygen adsorption to hydrogen uptake.

Model developed based on idealized crack geometry and diffusion-limited oxygen adsorption

- *Goal:* quantify amount of adsorbed oxygen (n) during load-cycle time (Δt)
- *Key assumption: adsorption rate-limited by O_2 diffusion in crack channel*
  - constant crack-channel height (h) during diffusion
  - steady state p_{O2} profile
- Model foundation: oxygen delivered to crack tip ($Jh\Delta t$) = oxygen adsorbed on crack tip ($S\theta\pi\Delta a$)

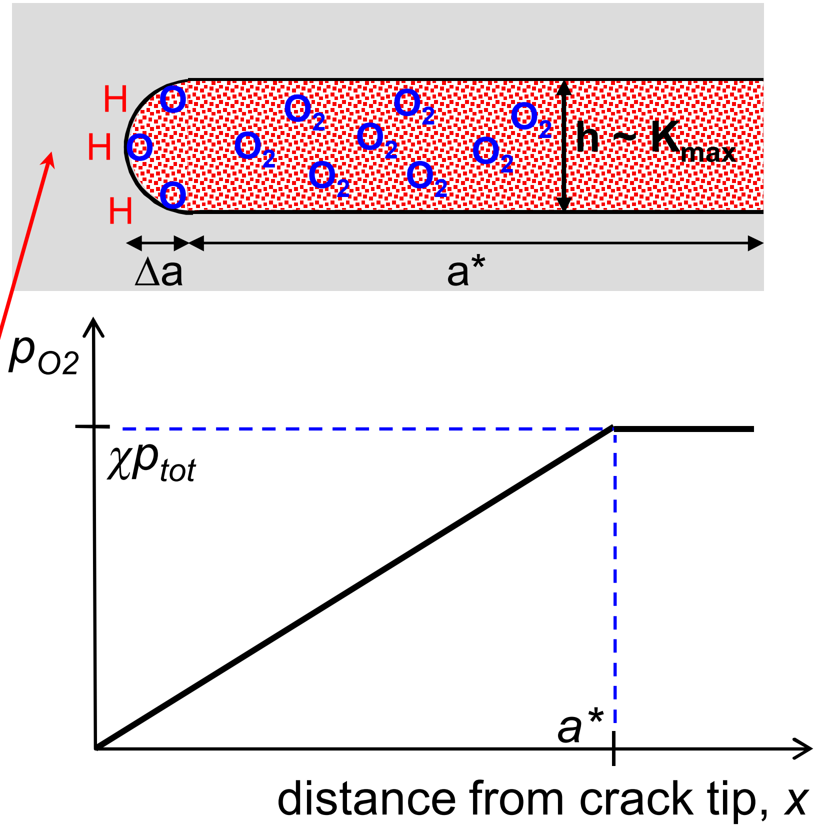
$$J = \text{flux} = D\frac{\chi p_{tot}}{R_g T a^*}$$

$$h = \text{channel height} = 0.6(1-v^2)\frac{\sigma_0}{E}\left(\frac{\Delta K}{\sigma_0(1-R)}\right)^2$$

$$\Delta t = 1/f$$

$$\theta = \text{oxygen coverage} \qquad S = \text{surface site density}$$

Somerday et al., *Acta Mater*, 2013



H uptake and accelerated crack growth when $\theta = \theta_{crit}$

$$\theta = \frac{0.3\chi D p_{tot}(1-v^2)}{\Delta a f \pi S R_g T E \sigma_0}\left(\frac{\Delta K}{\sqrt{a^*}(1-R)}\right)^2$$

Summary

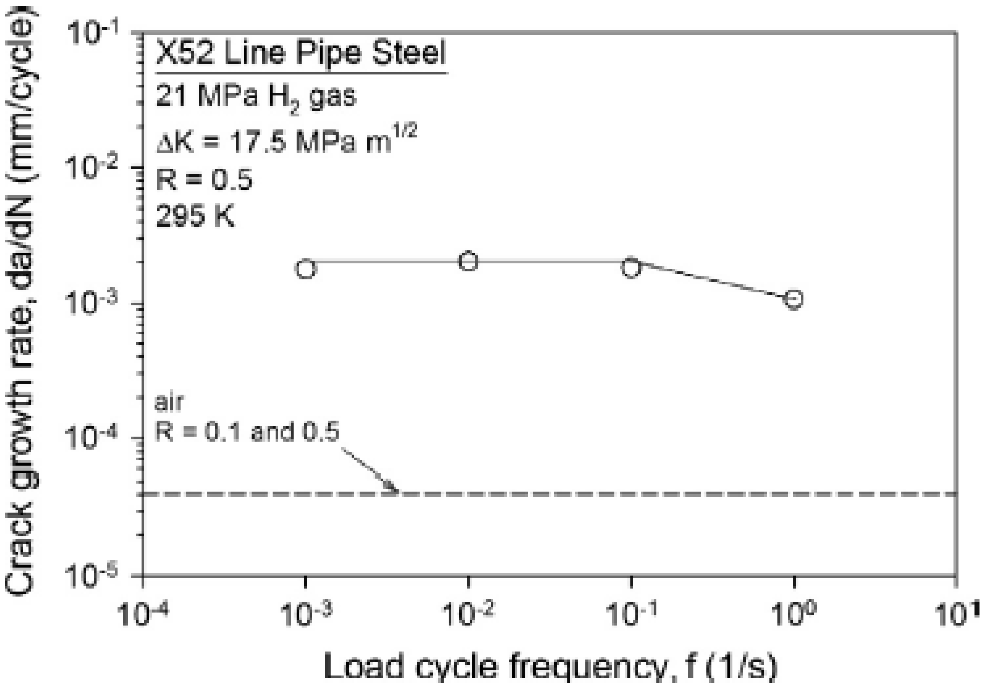
- Base Metal:
  - Resistance to hydrogen assisted fatigue depends on microstructure, not just strength.
- Welds:
  - Friction stir welds and gas metal arc welds have similar resistance to hydrogen embrittlement
    - Friction stir welding is often an economical alternative
  - Welds have slightly faster crack growth than base metal
- Design Codes:
  - Thickness premiums on hydrogen pipelines may be over-conservative
- Embrittlement mitigation:
  - Low levels (ppm) of gas species such as O_2 can enhance safety margins for steel H_2 pipelines

Back-up Slides

Remaining Challenges and Barriers

- Establish data-informed safety factors for steel H_2 pipelines, particularly for high-strength steels (e.g. X80 or X100)
  - Realistic safety factors can lower cost of steel H_2 pipelines
- Reduce testing burden for qualifying steel base metal and welds for H_2 pipelines by developing microstructure-performance (i.e., fatigue crack growth behavior in H_2 gas) relationships
  - Microstructure-performance relationships are foundation for predictive, physics-based model of H_2-accelerated fatigue crack growth

Hydrogen accelerated fatigue crack growth rates are similar over several orders of magnitude in frequency



B. Somerday et al., *Acta Mater*, 2013