Measurement of Fatigue Crack Growth Relationships for Steel Pipeline Welds in High-Pressure Hydrogen Gas

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Motivation: Assess reliability of steel H_2 pipelines

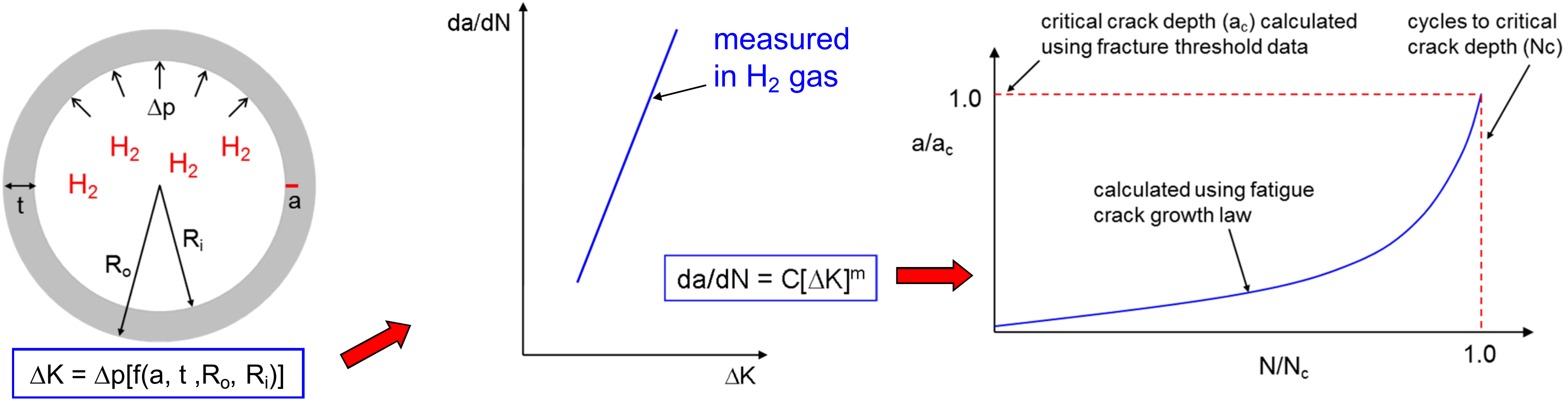
- Why use hydrogen in *steel* pipelines?
  - Large knowledge base of steel pipelines and issues (third party damage, welds)
  - H_2 pipelines operated safely under *static* pressure

- How will steel pipelines behave in ***cyclic*** pressure applications?
  - Demonstrate reliability/integrity of steel hydrogen pipelines for *cyclic* pressure applications
  - Address potential fatigue crack growth aided by hydrogen embrittlement, particularly in ***welds***
  - Relevance to H_2 pipeline code ASME B31.12

Objectives

- Measure fatigue crack growth relationships for relevant pipeline steels in H_2 gas, comparing girth weld, heat-affected zone and base metal
  - What variables govern H_2-accelerated crack growth?
  - Are welds more sensitive than base metal?

- Provide experimental component to develop damage-tolerant life prediction models



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

measured in H_2 gas

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

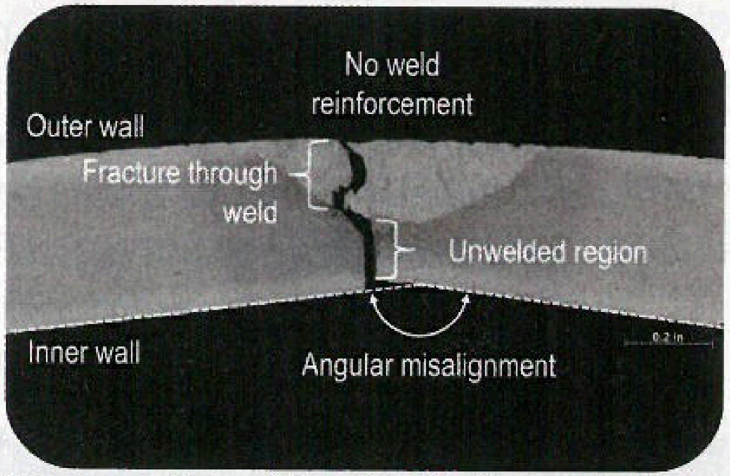
critical crack depth (a_c) calculated using fracture threshold data

cycles to critical crack depth (Nc)

calculated using fatigue crack growth law

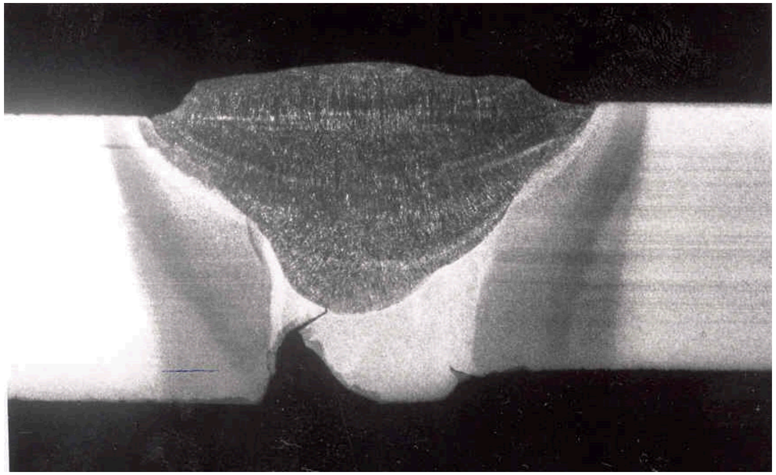
Structural integrity of welds in hydrogen is primary focus

F. Richards, Adv Mat & Processes, 2013



Cross section of longitudinal seam in the pup where the rupture initiated.

I. Alliat, NATURALHY EC project, 2007



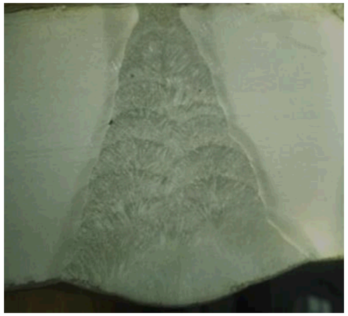
- Welding can create defects, increasing probability of crack growth in these regions
- Are weld microstructures (fusion zone, heat-affected zone) more susceptible to H_2-assisted fatigue crack growth?

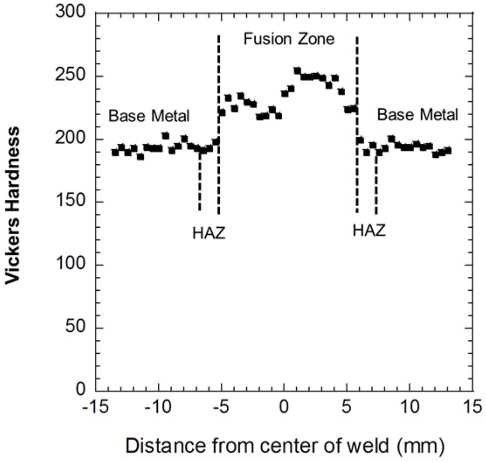
Material Tested: API 5L X65 steel with GMAW

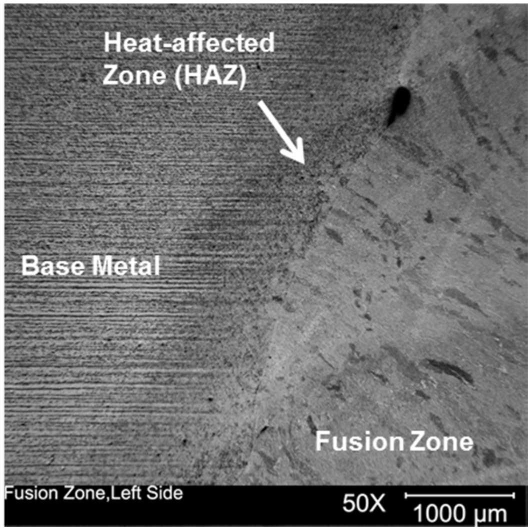
Gas Metal Arc Weld (GMAW)

508 mm OD / 25.4 mm thickness

Material	YS (MPa)	UTS (MPa)
Base Material	478	564
GMAW	591	662



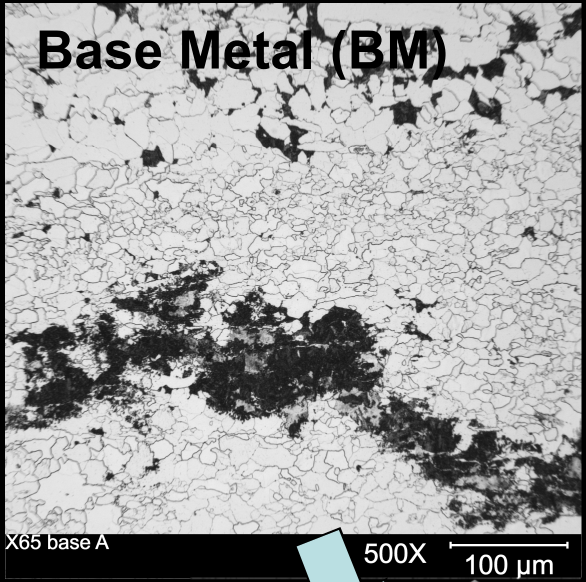




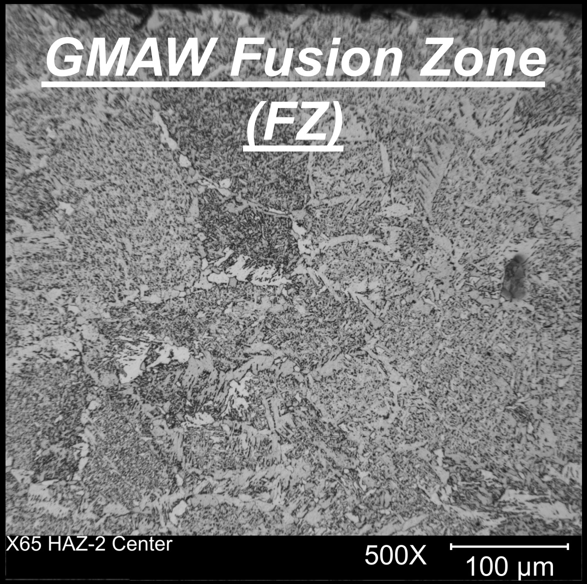
Base Metal Chemical Composition (wt %)

C	Mn	P	S	B	Si	Cu	Ni	Nb	Ti
0.08	1.53	0.01	0.001	0.002	0.32	0.024	0.038	0.039	0.002

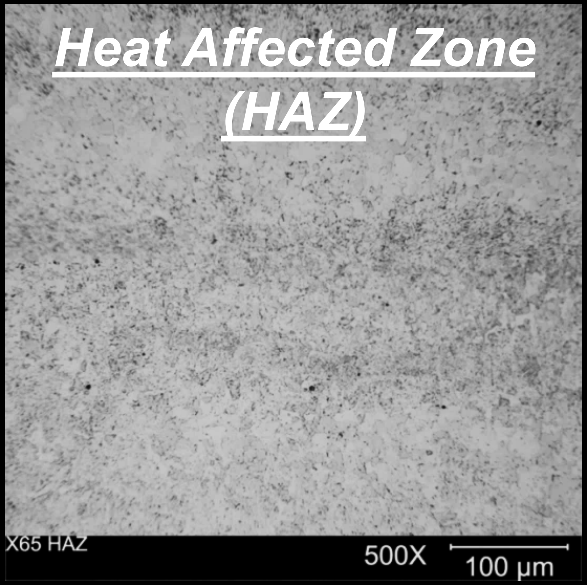
Microstructure of X65



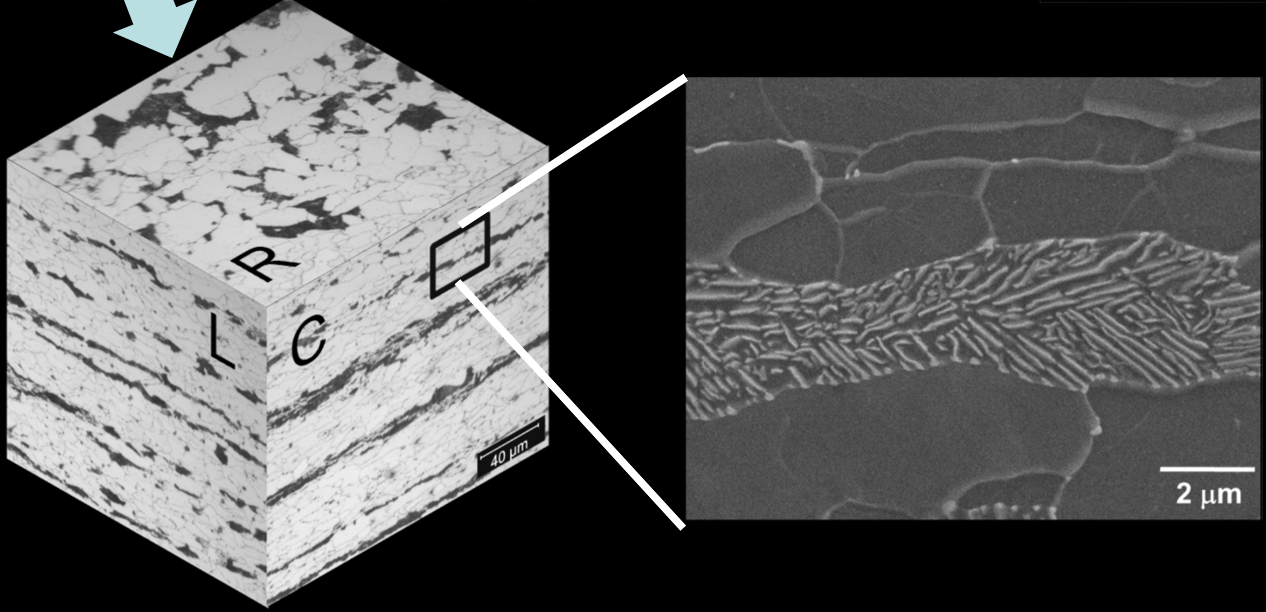
Base Metal (BM)



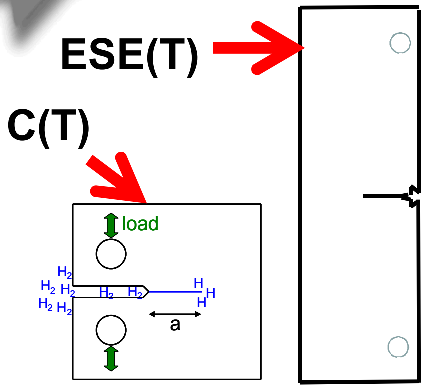
GMAW Fusion Zone (FZ)



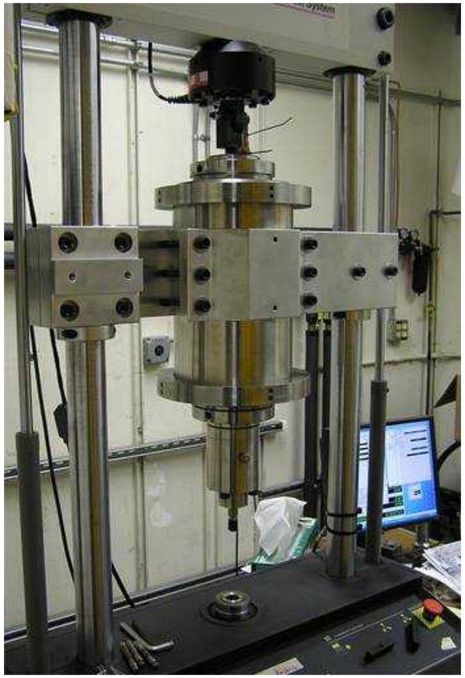
Heat Affected Zone (HAZ)



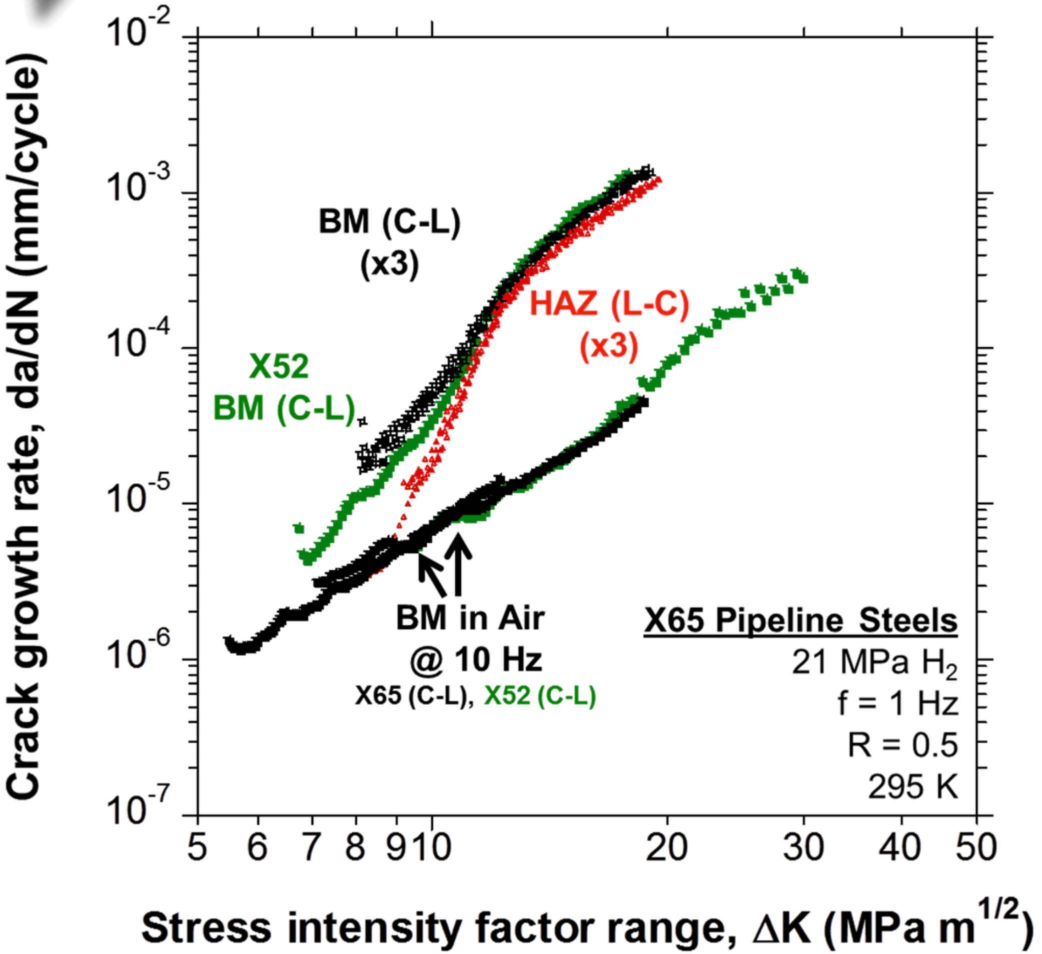
Measure fatigue crack growth in high-pressure H_2

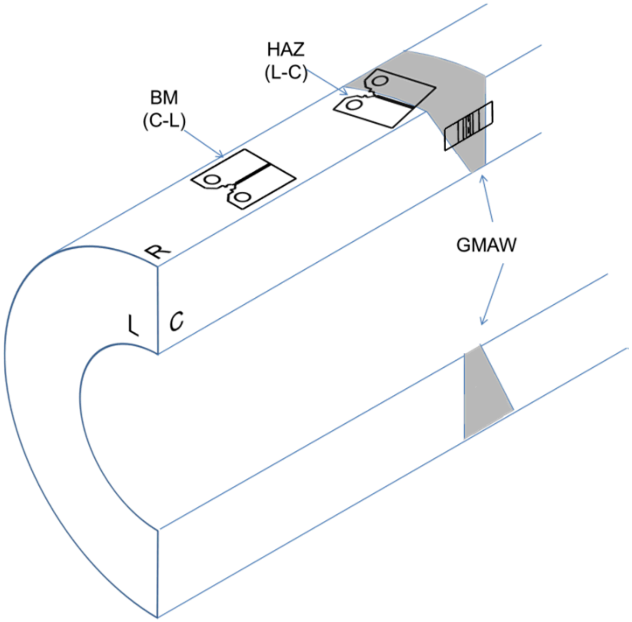


- Specimen Geometry
  - 12.7 or 6.4 mm Compact Tension, C(T)
  - 4.7 mm thick Eccentrically loaded single edge notched tension, ESE(T)
- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT or clip gage
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude (increasing ΔK)
  - R-ratio → 0.5
- Environment
  - Primary supply gas: 99.9999% H_2
  - Pressure = 3,000 psi (21 MPa)
  - Room temperature (295 K)

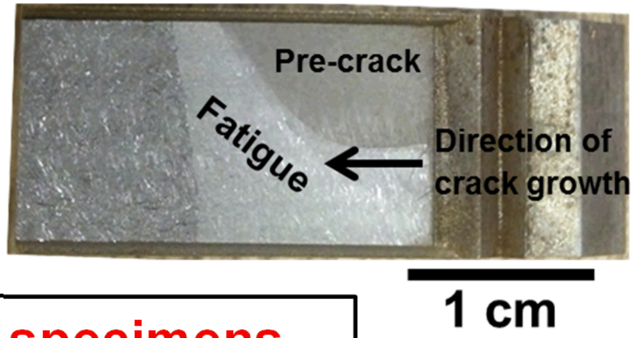


X65 HAZ exhibited lower crack growth rates than BM at low ΔK values





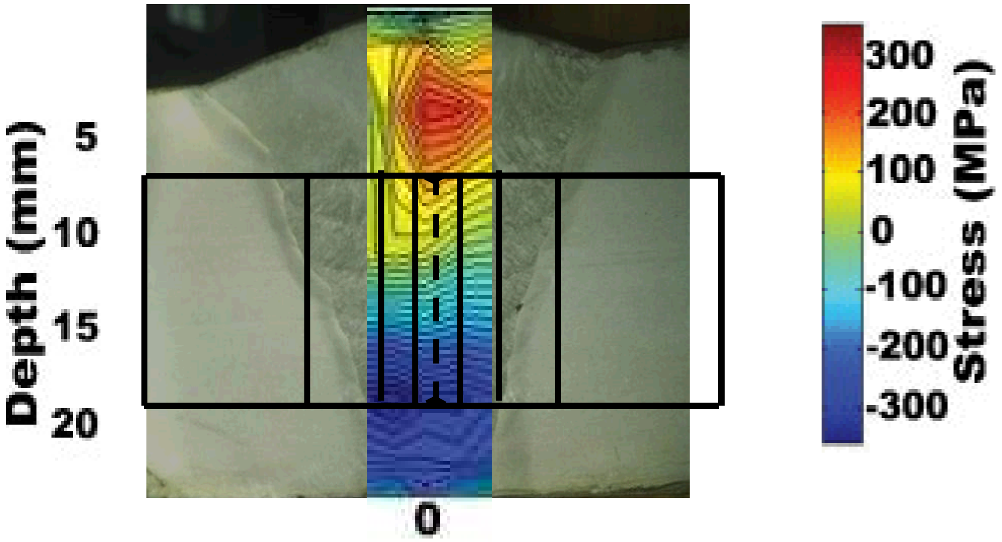
Results from fusion zone specimen not valid due to non-uniform pre-crack front

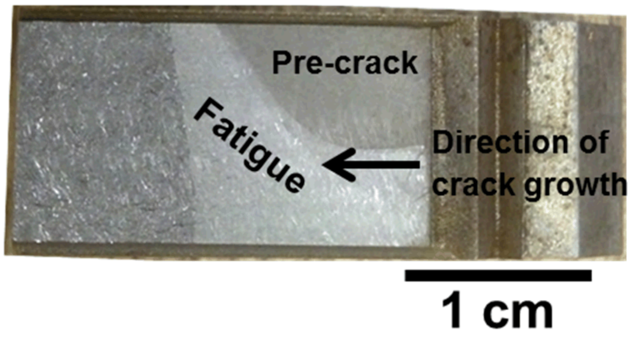


Non-uniformity of crack front in FZ C(T) specimens necessitated modified procedure

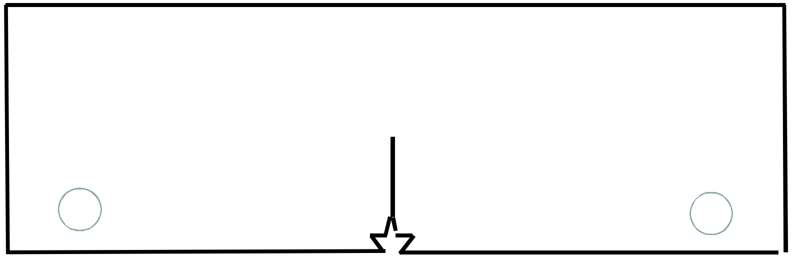
Gradient of Residual Stress Across Crack Plane in Fusion Zone

- **In C(T) specimens, compressive and tensile stress across crack front in C-L orientation**



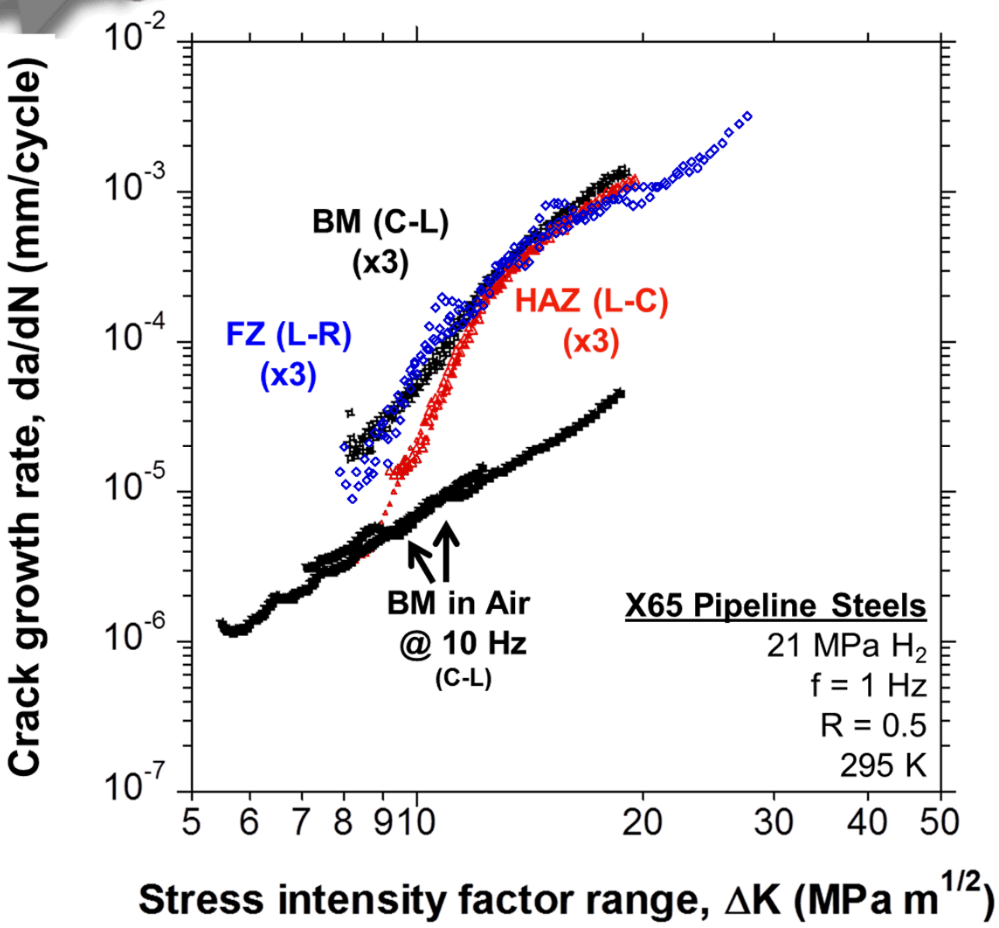


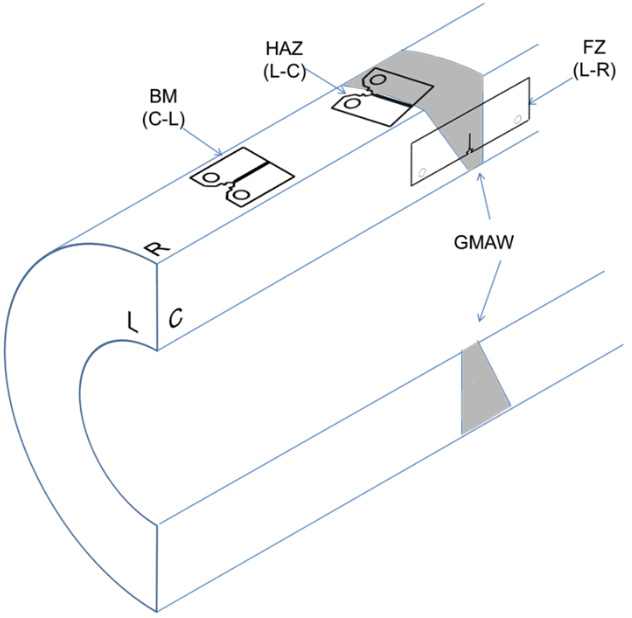
- Possible explanation for non-uniform precrack front
- Necessitate alternative geometry



(Neeraj, T. 2011)

Reproducible da/dN vs. ΔK curves for BM, FZ, and HAZ

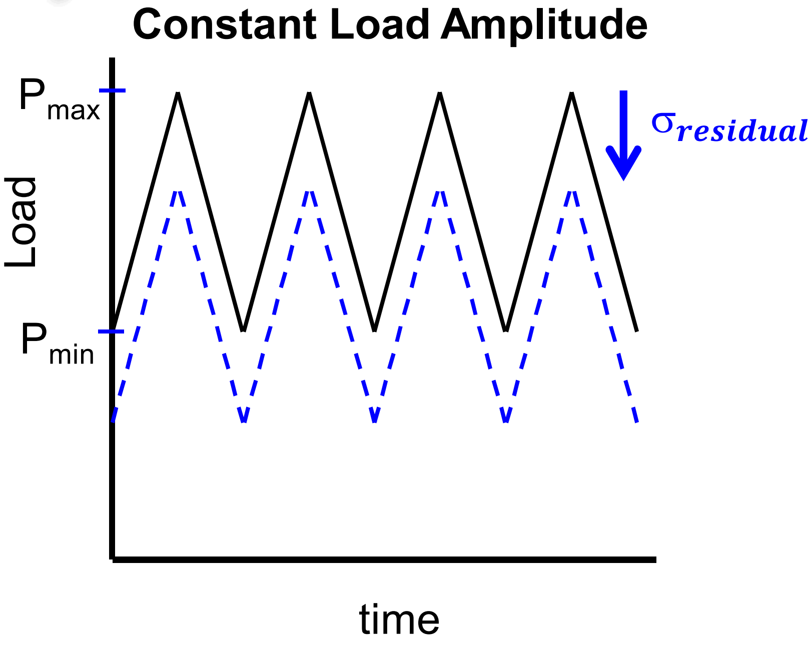




- Similar FCGR in Fusion zone and Base Metal

Why do we observe lower FCGR in HAZ as compared to FZ and BM?

Can residual stress reduce observed FCGR?

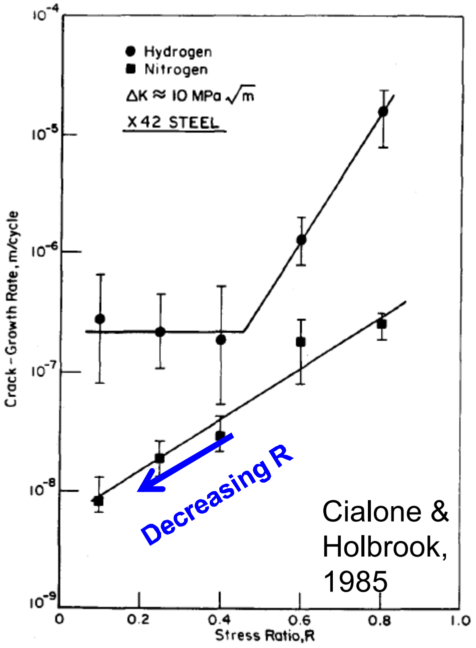


$$\frac{P_{min}}{P_{max}} = R = 0.5$$

$K = f(a, P)$, so P ~ K with $\Delta a = 0$

Effects of compressive residual stress

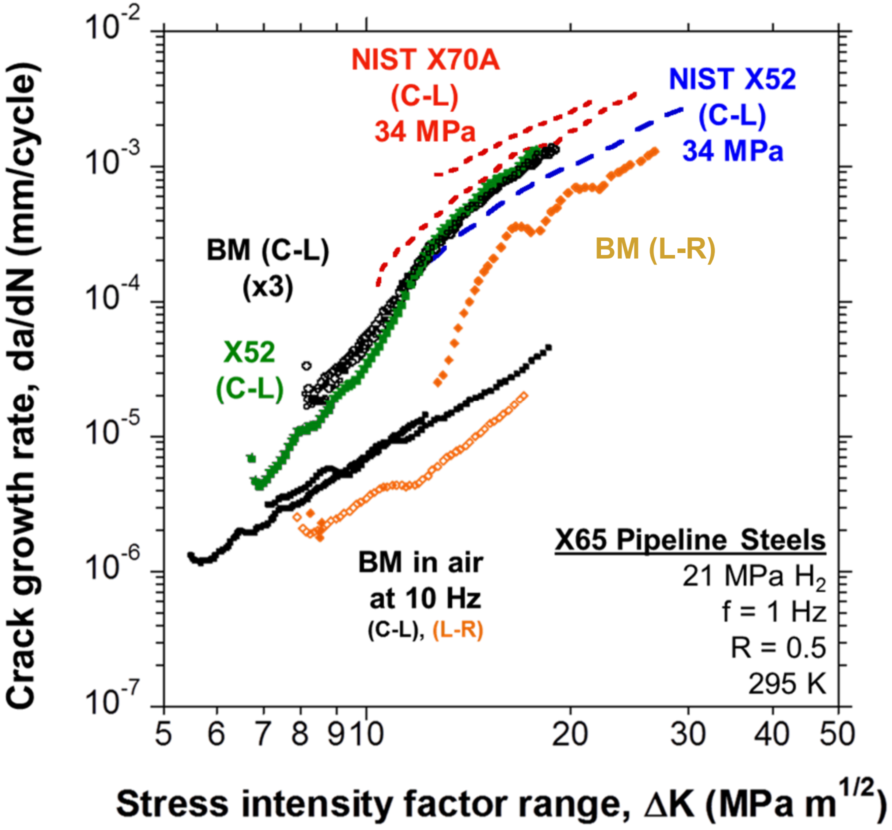
- Equal reduction of K_{max} and K_{min} assuming no crack closure
  → No effect on ΔK
- Decrease in R-ratio
- Reduction of K_{max} could affect onset of hydrogen accelerated FCG (i.e. K^T_{max})

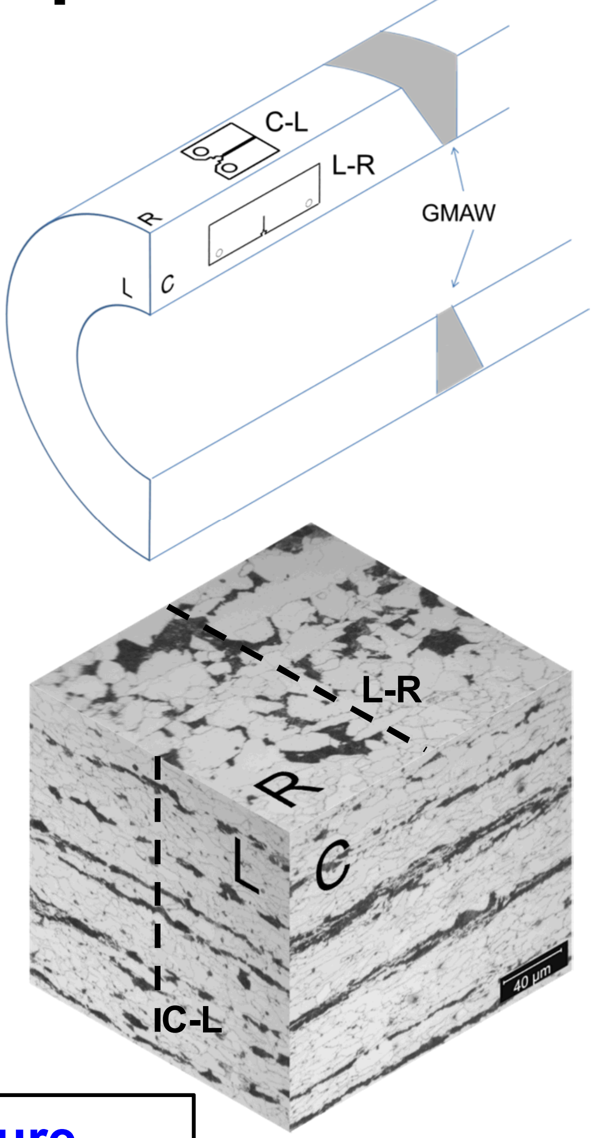


Cialone & Holbrook, 1985

Separating effects of $\sigma_{residual}$ and microstructure will improve comparison between welds and base metal FCGR

Fatigue crack growth rates in base metal depend on specimen orientation

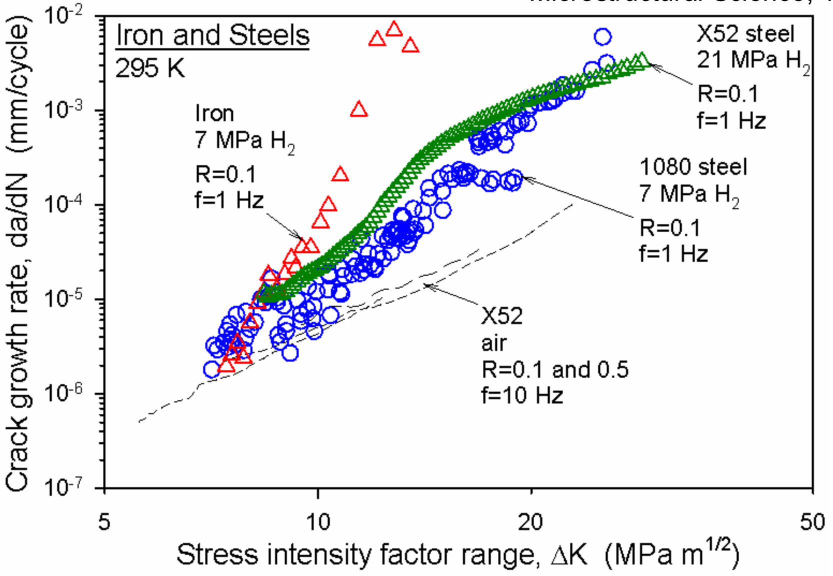




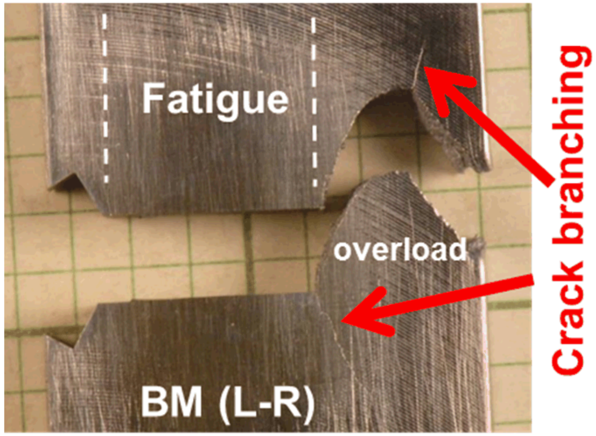
Does banded ferrite-pearlite microstructure reduce crack growth rates in L-R orientation?

Previous results show that H_2-assisted crack growth lower in pearlite compared to ferrite

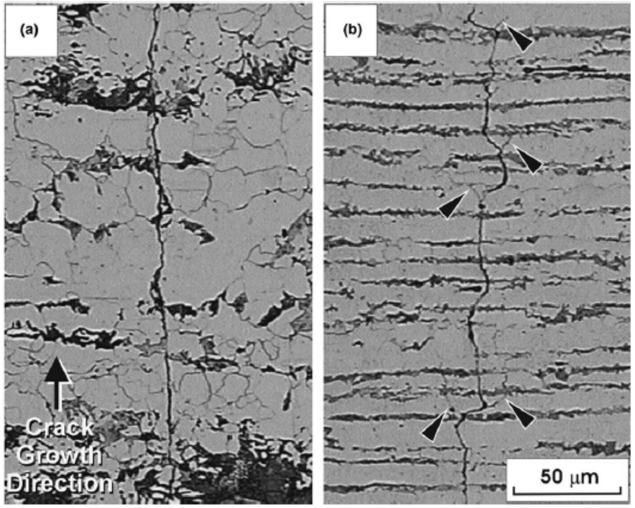
H. Cialone and J. Holbrook, *Microstructural Science*, 1987



- 100% pearlitic microstructure exhibits lower FCGR



A. Korda *et al.*, Scripta Materialia, 2006.



- More crack branching observed in banded microstructure (reduces near tip ΔK)
- Lower FCGR in banded orientation

Banded pearlite appears to be more resistance to fatigue, reducing FCGR

Summary

- Measured reproducible fatigue crack growth relationships in X65 Base Metal, fusion zone, and HAZ in H_2
    - FZ and BM exhibited similar FCG
    - HAZ is no more susceptible to hydrogen than BM or FZ
- Residual stresses in the fusion zone suppressed crack growth which necessitated modifying orientation
- Are residual stresses contributing to lower FCGR in HAZ and FZ?
- Banded ferrite-pearlite microstructure appears to reduce crack growth rates in L-R orientation
- Constant ΔK tests will be performed to evaluate residual stress and microstructural effects

Acknowledgements / References

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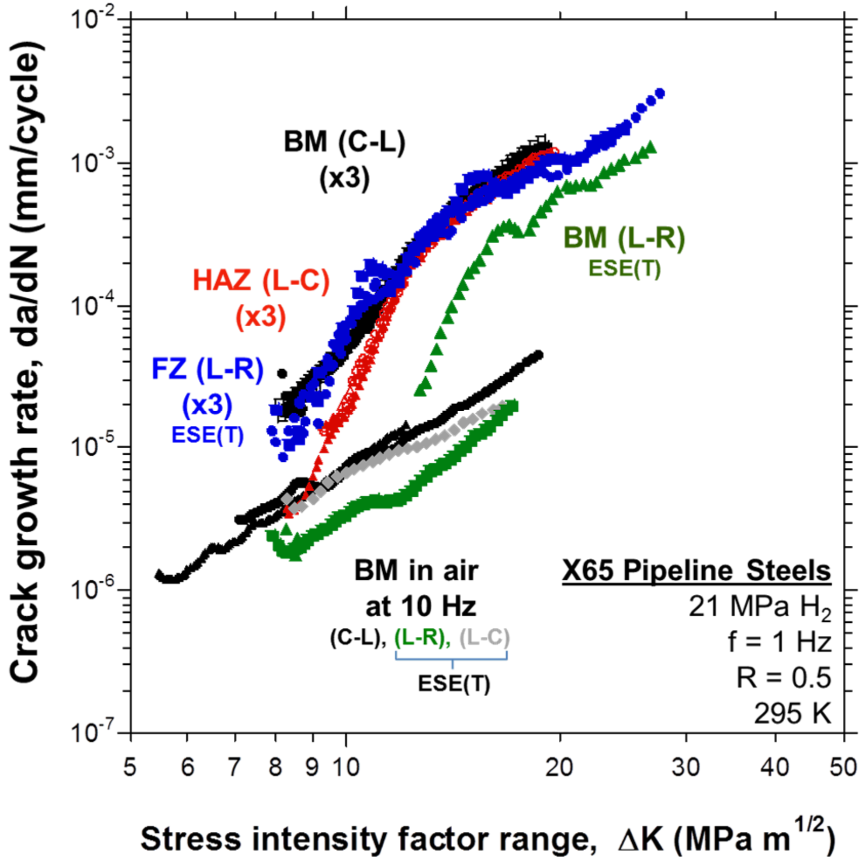
[2] Suresh, S. and Ritchie, R.O. “Mechanistic dissimilarities between environmentally influenced fatigue-crack propagation at near-threshold and higher growth rates in lower strength steels,” *Metal Science*, vol. 16, 1982, pp. 529-538.

[3] Cialone, H.J. and Holbrook, J.H. “Effects of gaseous hydrogen on fatigue crack growth in pipeline steel.” *Metallurgical Transactions A,* vol. 16A, 1985, pp. 115-122.

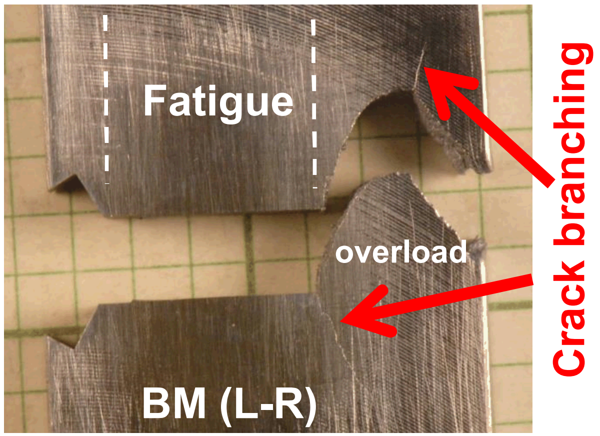
[4] Cialone, H.J. and Holbrook, J.H. “Microstructure and fractographic features of hydrogen-accelerated fatigue crack growth in steels” in Microstructural Science Vol. 14, Eds. M.R. Louthan, I. LeMay, and G.F. Vander Voort, ASM, Metals Park, OH, (1987) pp. 407-422.

[5] Korda, A.A., Mutoh, Y., Miyashita, Y., Sadasue, T., Mannan, S.L., "In situ observation of fatigue crack retardation in banded ferrite-pearlite microstructure due to crack branching," *Scripta Materialia,* vol. 54, pp. 1835-1840, 2006.

Extra



Crack growth rate, da/dN (mm/cycle)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
5
6
7
8
9
10
20
30
40
50
Stress intensity factor range, ΔK (MPa m$^{1/2}$)
BM (C-L)
(x3)
HAZ (L-C)
(x3)
FZ (L-R)
(x3)
ESE(T)
BM (L-R)
ESE(T)
BM in air
at 10 Hz
(C-L), (L-R), (L-C)
ESE(T)
X65 Pipeline Steels
21 MPa H_2
f = 1 Hz
R = 0.5
295 K



Fatigue
overload
BM (L-R)
Crack branching