

Hydrogen Embrittlement of Pipeline Steels in Base Metal and Welds

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Objectives/Relevance

- Why should steel hydrogen pipelines be used?
 - Safety of steel pipelines is well understood (e.g., third-party damage tolerance, vulnerability of welds)
 - Hydrogen pipelines are safely operated under constant pressure

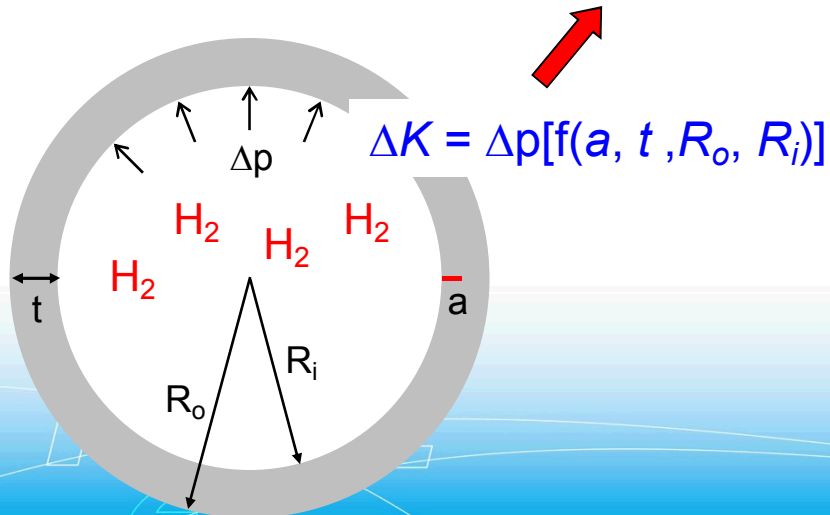
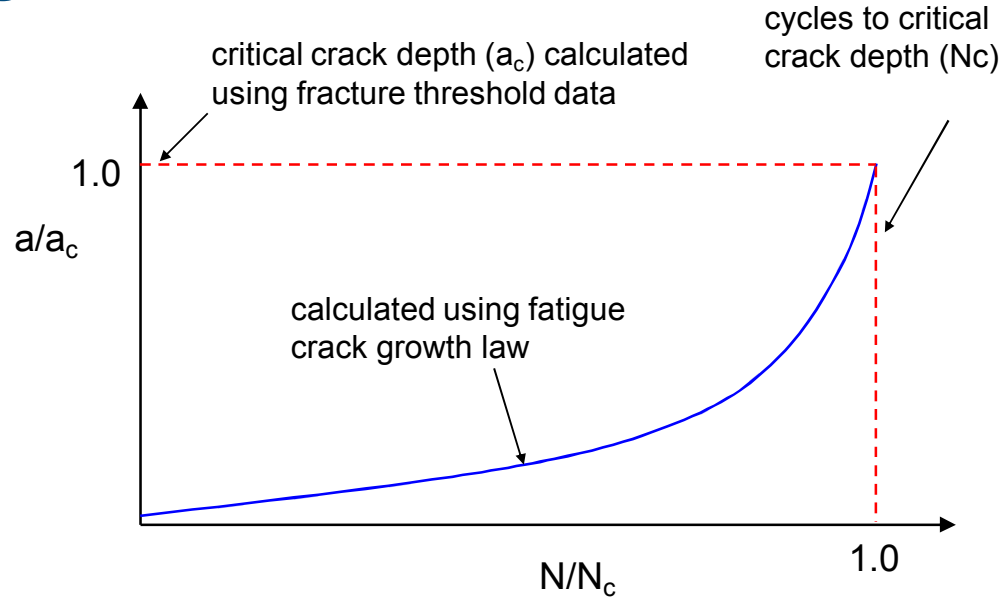
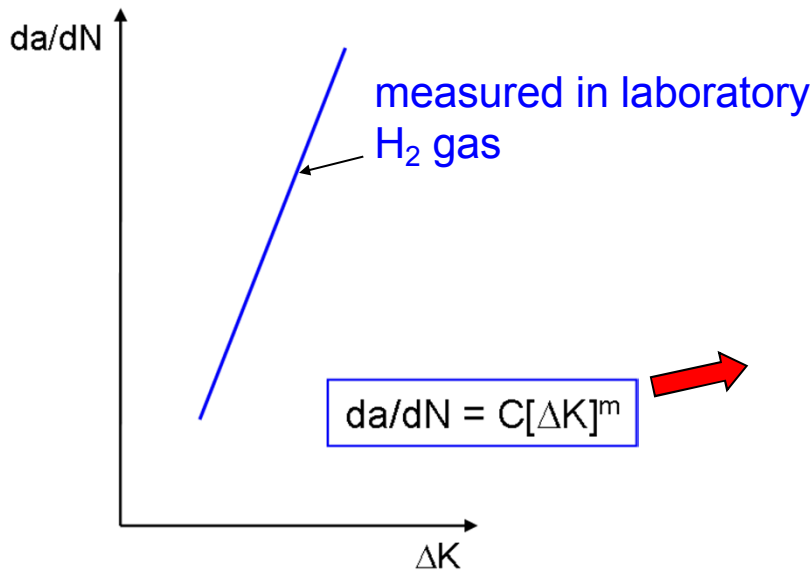
Project purpose is to:

- Demonstrate reliability/integrity of steel hydrogen pipelines for *cyclic pressure* applications
 - Address potential fatigue crack growth aided by hydrogen embrittlement, particularly in welds
- Answer specific questions about steel hydrogen pipelines
 - Are welds more susceptible to H₂-accelerated fatigue crack growth compared to base metal?
 - Can microstructure-performance relationships be established to enable steel qualification for hydrogen pipelines?
- FY14-15 tasks
 - Measure fatigue crack growth laws in H₂ gas for pipeline steel
 - Girth Welds
 - Friction Stir Welds

Approach

- Apply core capability to measure fatigue crack growth relationships for steels in high-pressure H₂ gas
 - Fatigue crack growth relationships serve as inputs into reliability/integrity assessment as specified in ASME B31.12 code
 - Milestone: Complete triplicate measurements (in each material region, i.e., base metal, fusion zone, heat affected zone) to establish reliable fatigue crack growth relationships for X65 girth weld in 21 MPa hydrogen gas. (complete)
 - Milestone: Complete triplicate measurements in X52 friction stir weld in 21 MPa hydrogen gas. (in-progress)
- Pipeline steels and their welds were identified by stakeholders as a high priority
 - Provide feedback to stakeholders (e.g., Delivery Tech Team, ASME) through project meetings and workshops, publications

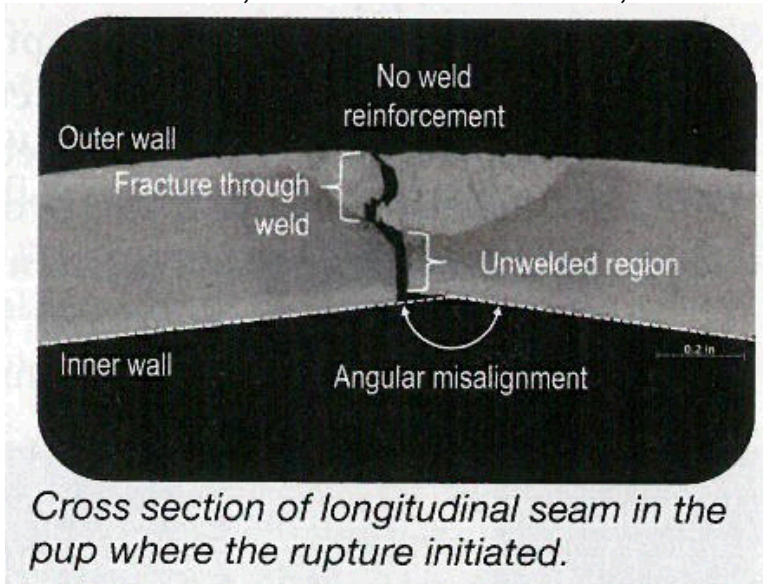
Reliability/integrity assessment framework in ASME B31.12 requires fracture data in H₂ gas



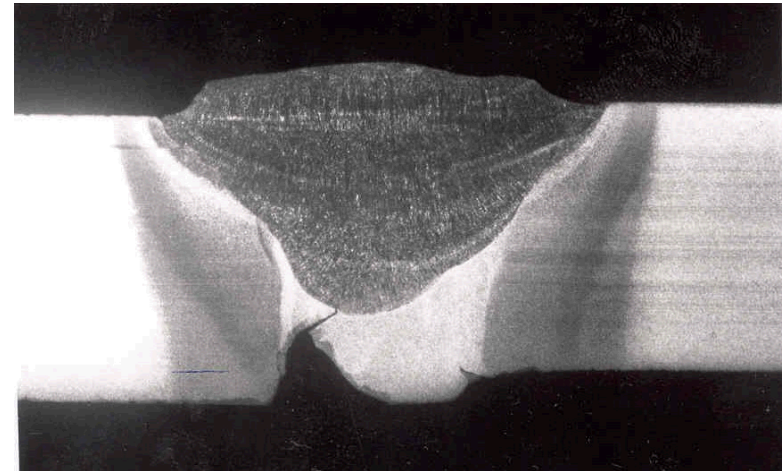
- Two fracture properties in H₂ needed
 - Fatigue crack growth law
 - Fracture threshold
- Reliability/assessment framework accommodates H₂ embrittlement

Reliability/integrity of steel hydrogen pipelines may be controlled by welds

F. Richards, *Adv Mat & Processes*, 2013



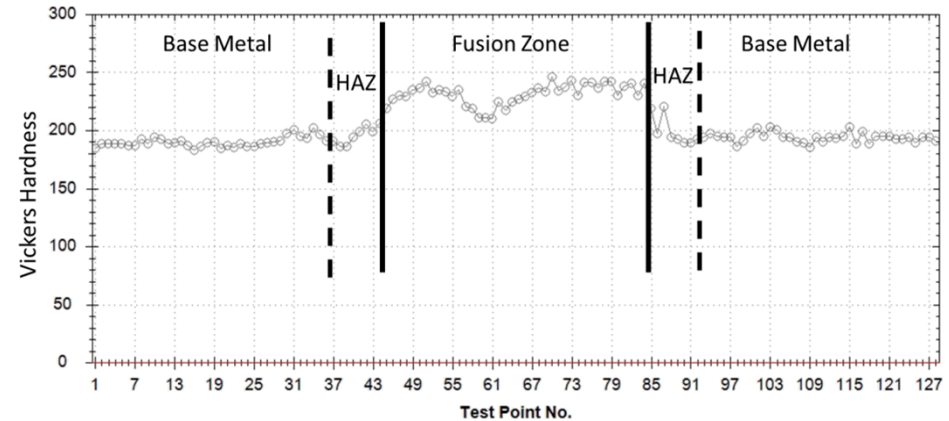
I. Alliat, NATURALHY EC project, 2007



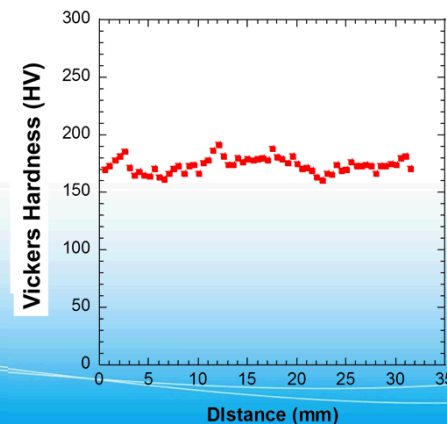
- Welding can create defects, increasing probability of crack growth in these regions
- Are weld microstructures (fusion zone, heat-affected zone) more susceptible to hydrogen embrittlement?

Gas Metal Arc Weld and Friction Stir Weld were investigated in this study

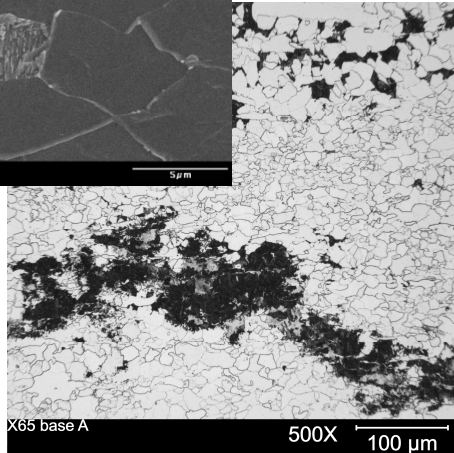
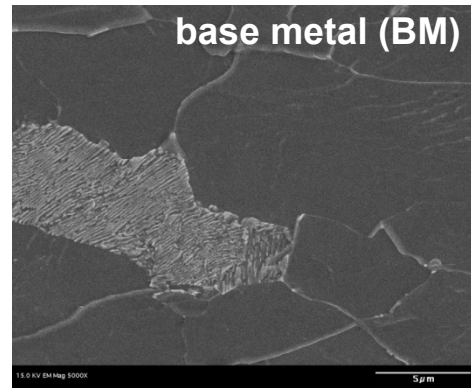
X65 Girth Weld Pipeline Steel (from ExxonMobil)



X52 Friction Stir Weld (from ORNL)



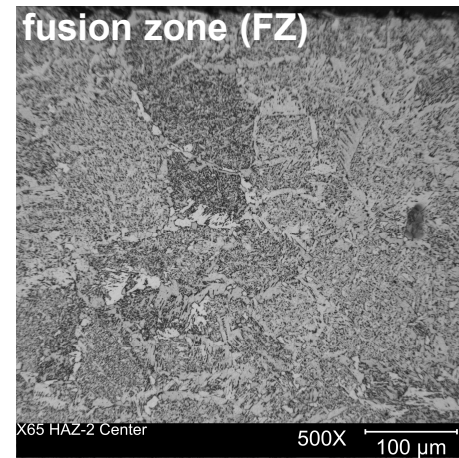
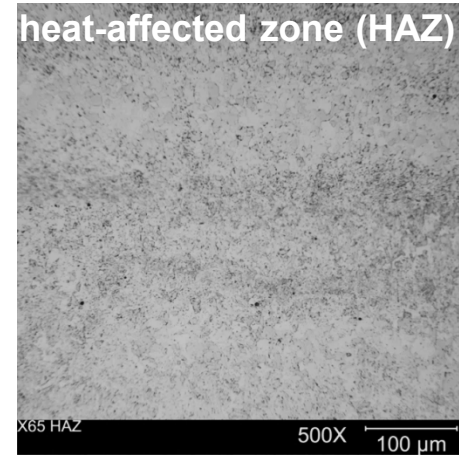
Fatigue crack growth measurements performed on API 5L X65 pipe with GMAW



Gas metal arc weld (GMAW)



508 mm OD x 25.4 mm WT

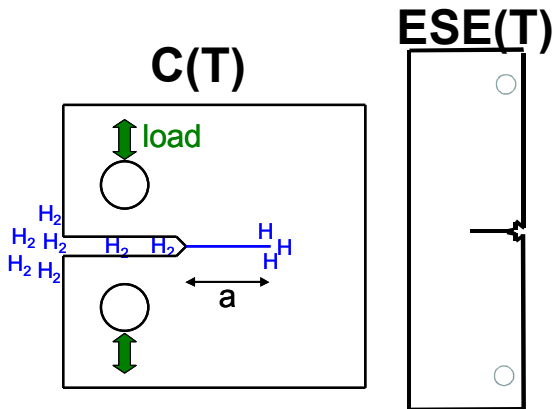


- Base metal tensile properties
 - Yield strength: 478 MPa (69 ksi)
 - Ultimate tensile strength: 564 MPa (82 ksi)

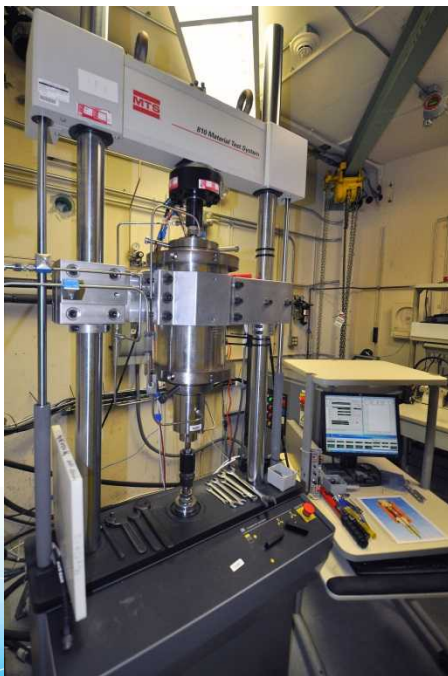
- Base metal composition

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

Fatigue crack growth relationships measured in high-pressure H₂ gas

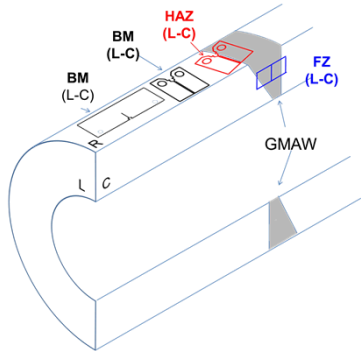
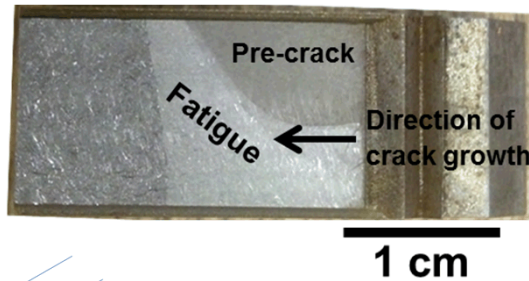


- **Material**
 - X65 base metal and GMAW
- **Instrumentation**
 - Internal load cell in feedback loop
 - Crack-opening displacement measured internally using LVDT
 - Crack length calculated from compliance
- **Mechanical loading**
 - Triangular load-cycle waveform
 - Constant load amplitude
- **Environment**
 - Supply gas: 99.9999% H₂
 - Pressure = 21 MPa (3,000 psi)
 - Room temperature

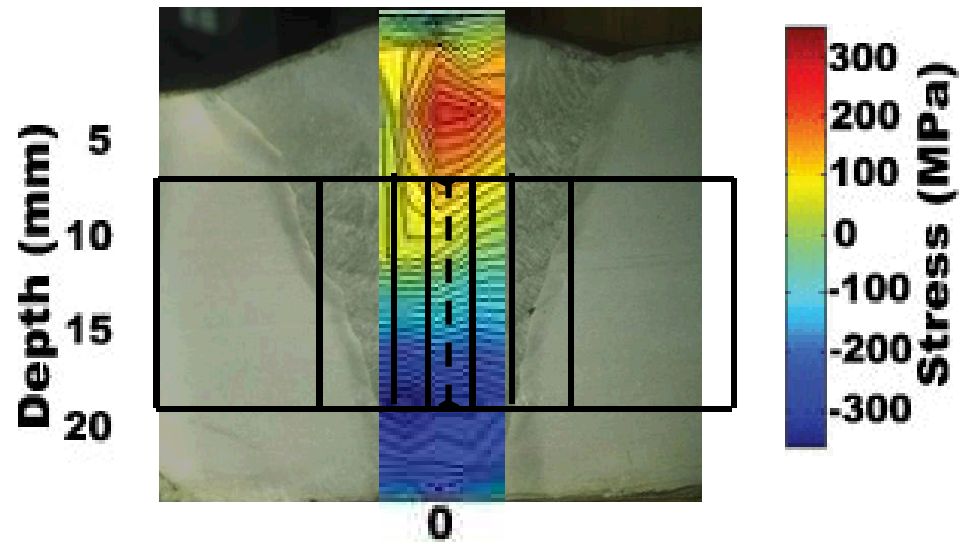


Specimen geometry for fusion zone measurements modified to improve reliability of results

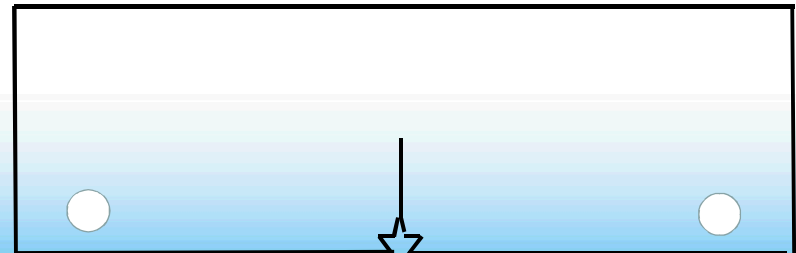
- Non-uniform pre-crack front in compact tension specimen attributed to residual stress gradient



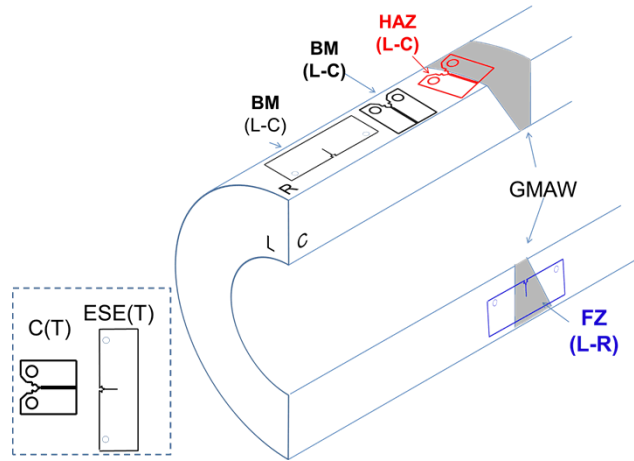
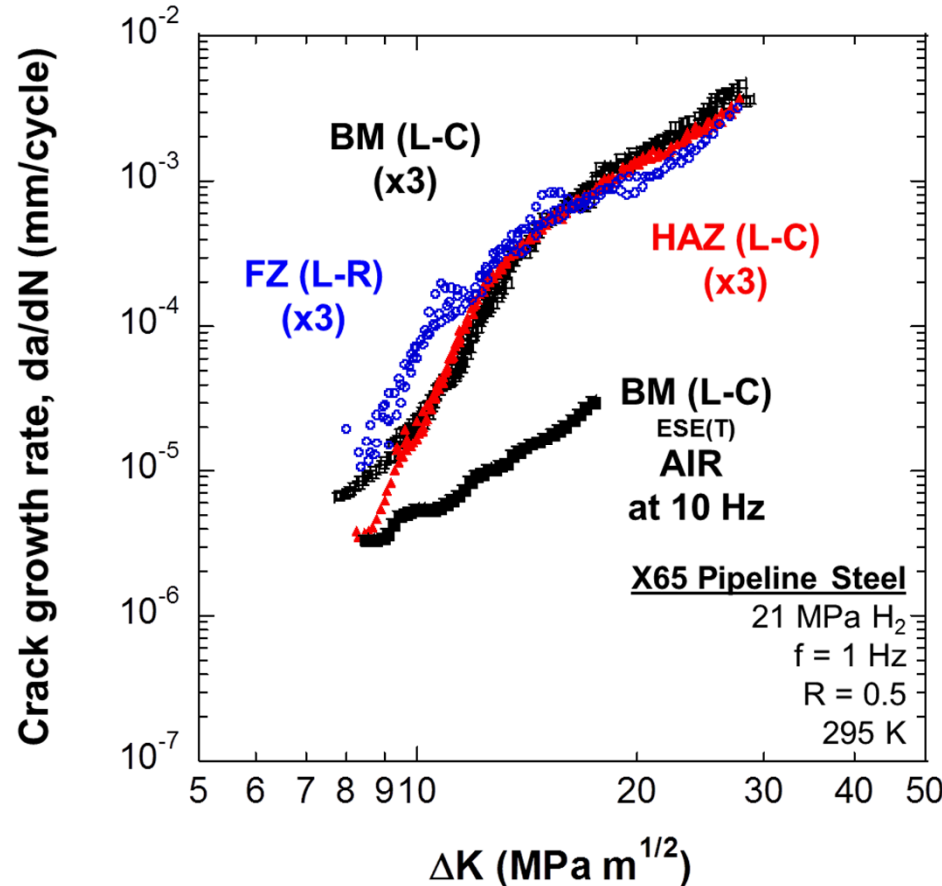
Measured residual stresses in X65 weld FZ
T. Neeraj, *Sci. Tech. Weld. Join.*, 2011



- Designed single-edge notched ESE(T) specimen to propagate crack parallel to wall thickness and across residual stress gradient in L-R orientation



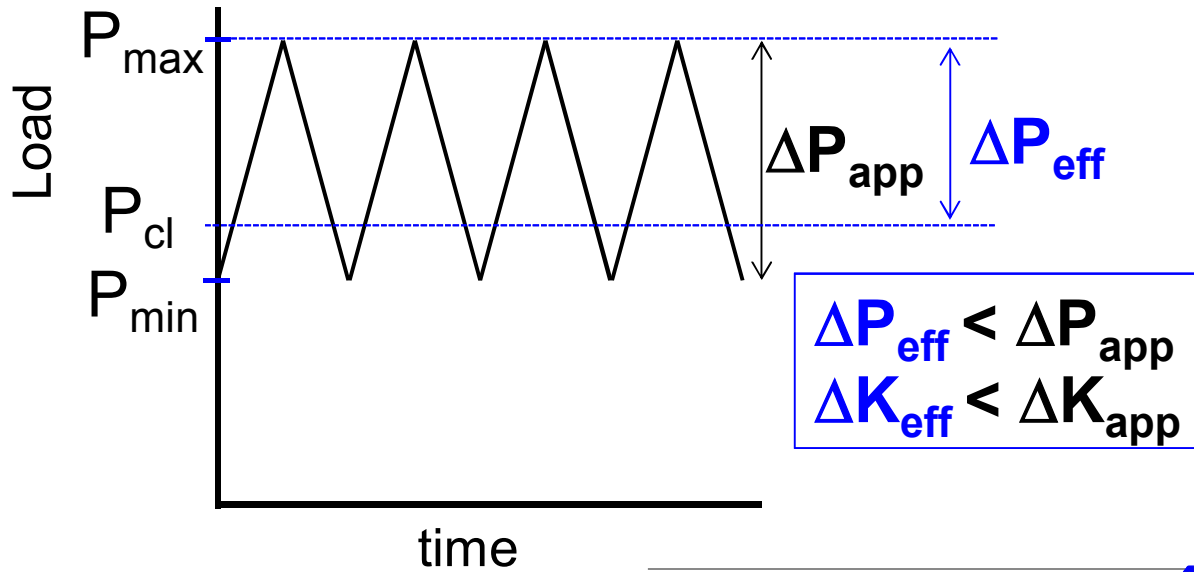
Modified specimen geometry allowed completion of triplicate measurements on fusion zone for X65



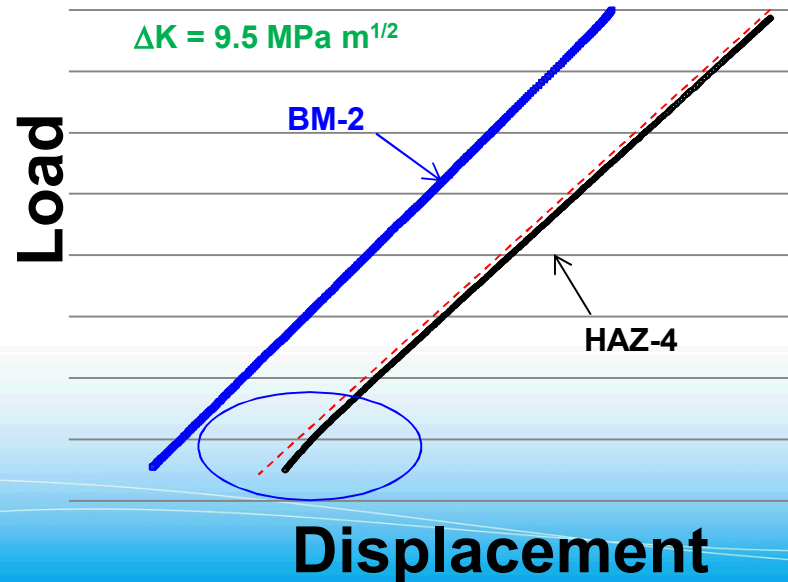
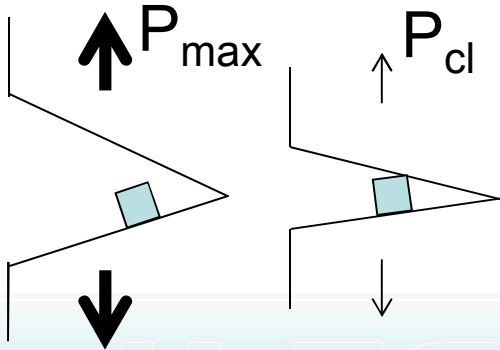
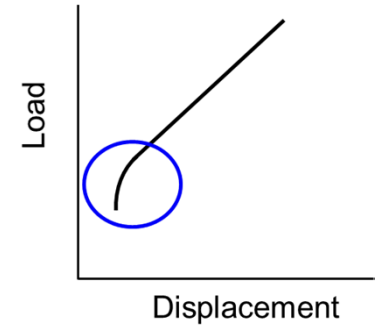
- Triplicate measurements completed for BM, FZ, HAZ, results reproducible **[Milestone]**

- Extrinsic factors such as compressive residual stress can result in:
 - 1) Induced crack closure
 - 2) Reduction in max stress (K_{max})
 → Necessitated more analysis to ensure accurate data for reliability assessment

Crack closure: crack remains in closed position even when tensile load is applied

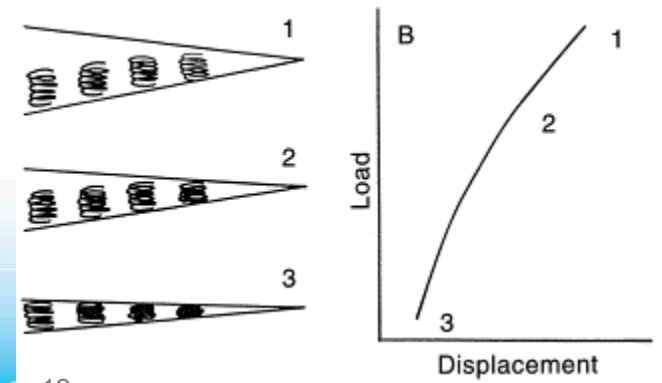
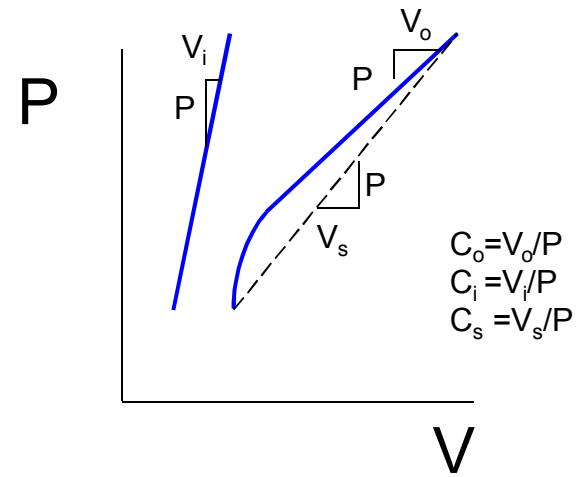
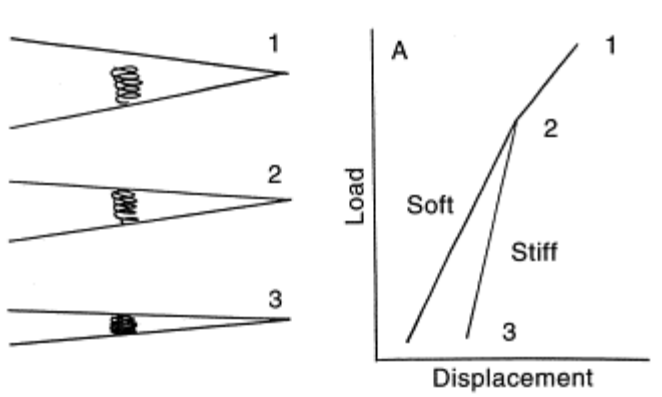


- Below P_{cl} , contribution to stress intensity is reduced
- Crack closure observed in load-displacement curves as change of slope at lower loads



Adjusted Compliance Ratio (ACR) was used to correct for crack closure

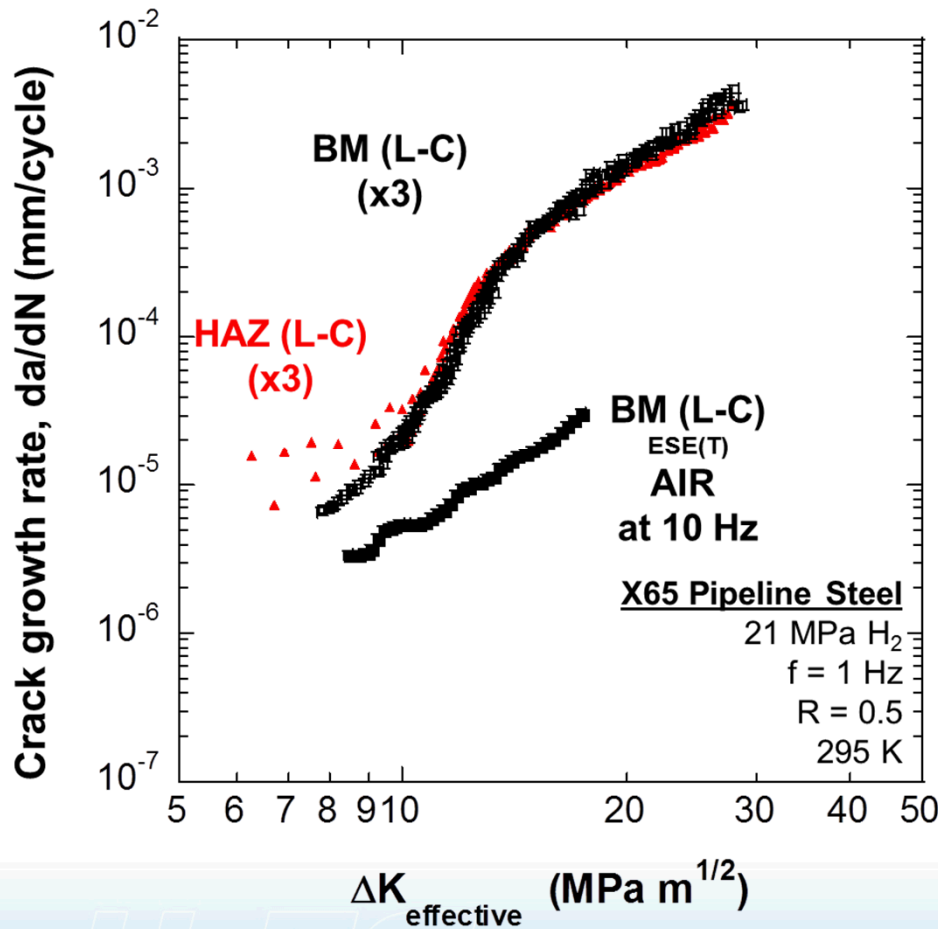
- Alternative method is ASTM 2% compliance offset method
- Both methods are used to determine $\Delta K_{\text{effective}}$
- $\Delta K_{\text{applied}} > \Delta K_{\text{effective}}^{ACR}$



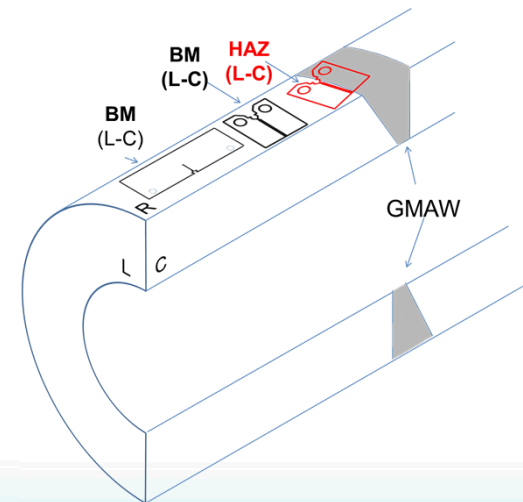
$$ACR = \frac{C_s - C_i}{C_o - C_i}$$

$$\Delta K_{\text{effective}} = \Delta K_{\text{app}} \times ACR$$

FCGR of HAZ appear to be greater than BM when plotted with $\Delta K_{\text{effective}}$

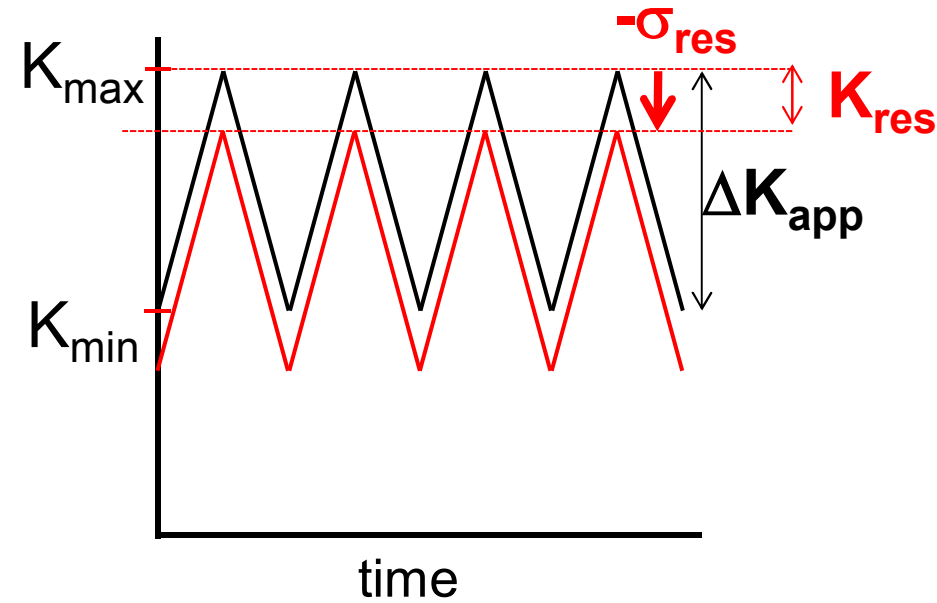


- Crack closure corrected data suggests that crack growth rates are greater for HAZ at low $\Delta K_{\text{effective}}$



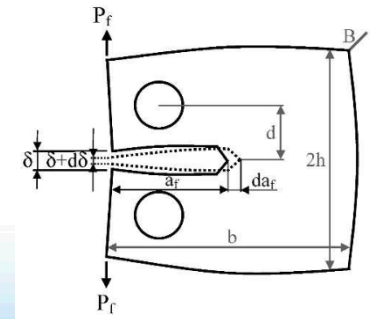
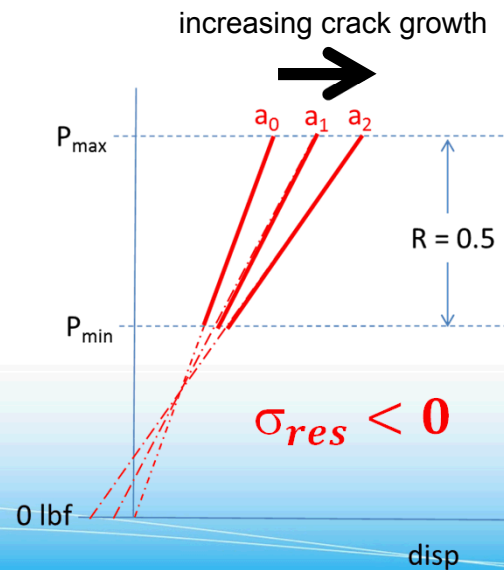
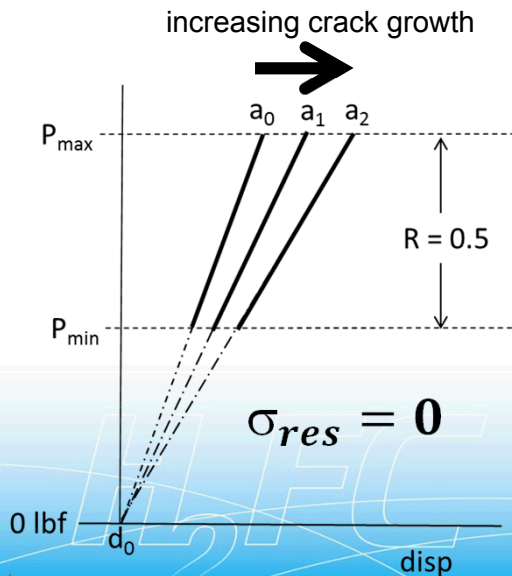
Possible source of crack closure → Compressive Residual Stress

Compressive residual stress can reduce K_{max}^{eff}



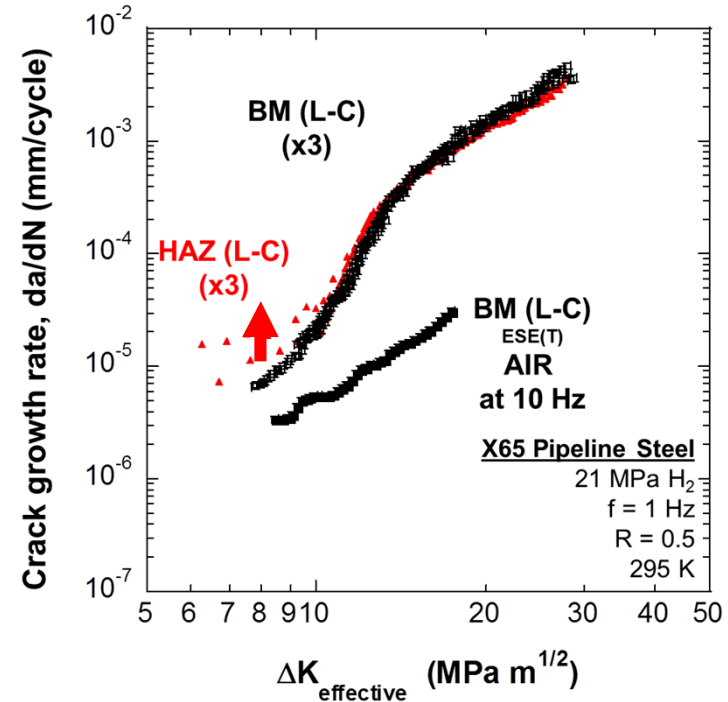
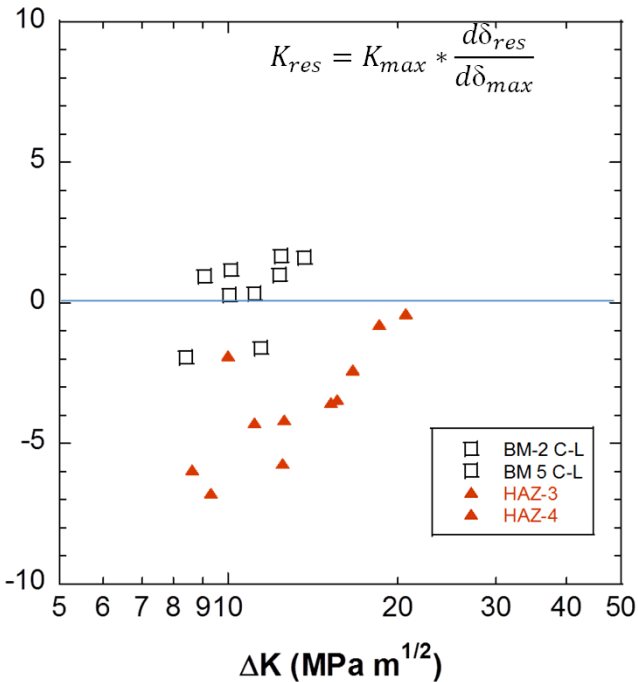
$$K_{max}^{eff} = K_{max} + K_{res}$$

- Calculate K_{res} from load-disp curves



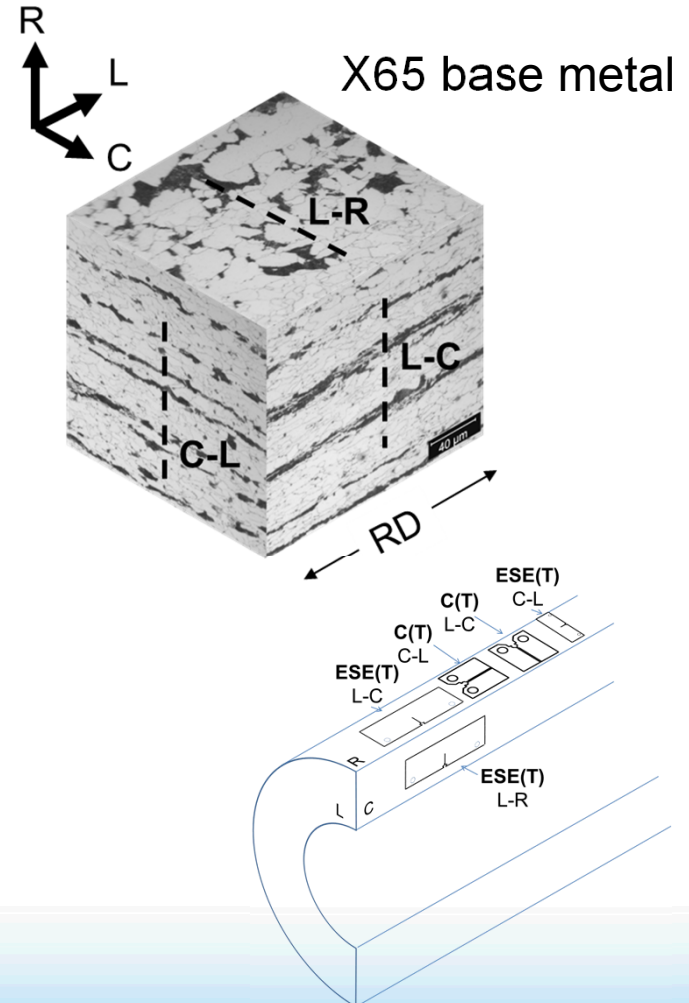
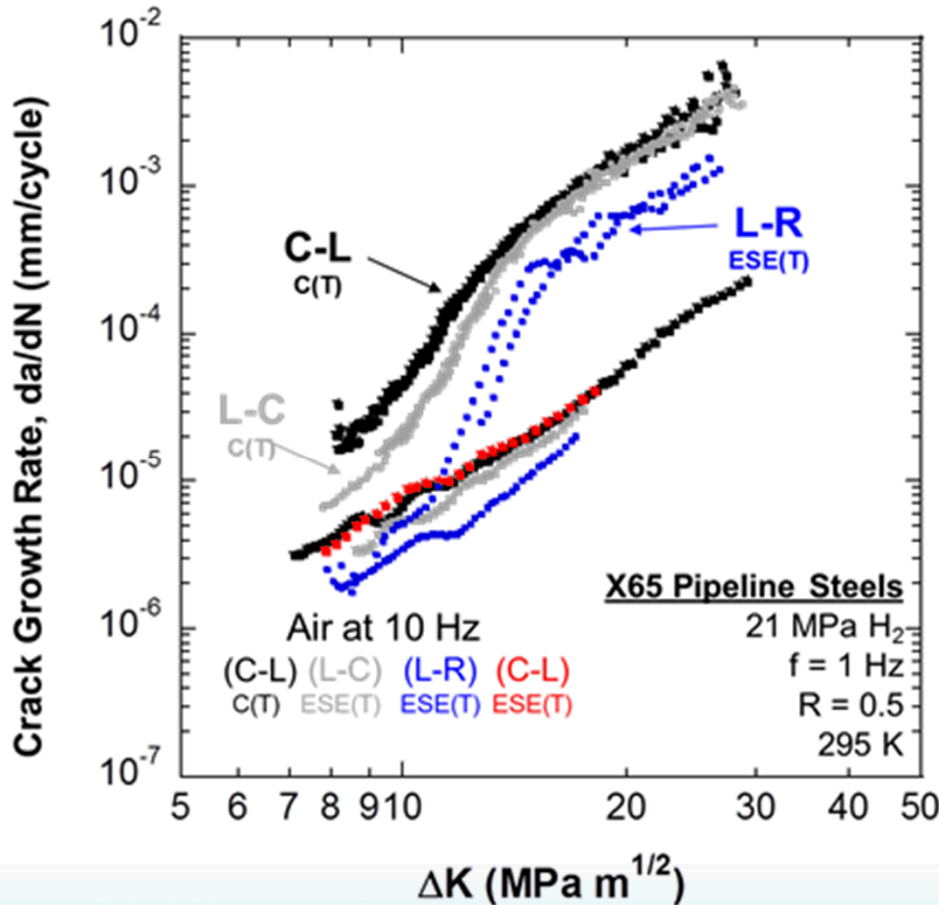
{Lados, 2006}

Reduction in K_{max} may shift HAZ curves to even higher crack growth rates



- Compressive residual stress observed in HAZ
- Diminishes at higher ΔK and longer crack lengths
- Absent in BM
- Reduction of K_{max} can influence onset of hydrogen accelerated FCG (K_{max}^T)

Results from alternate specimen orientations in base metal reveal potential dominant microstructure effect

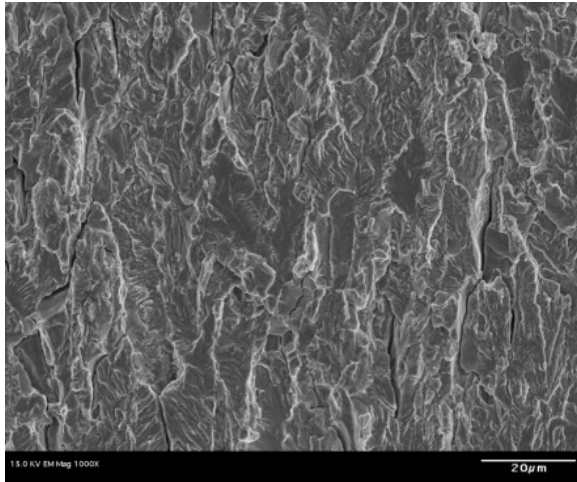


Does banded ferrite-pearlite microstructure reduce crack growth rates in L-R orientation?

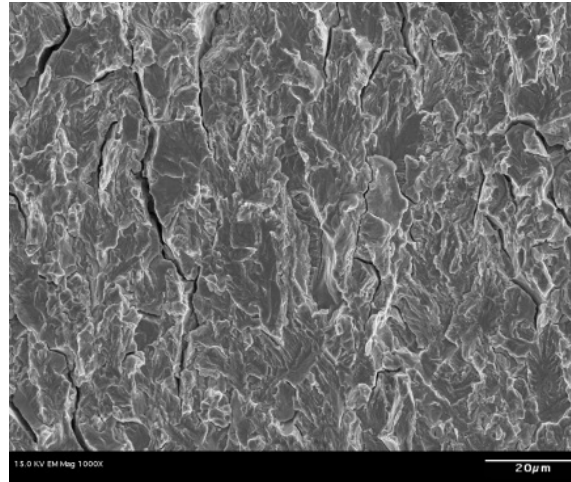
Reduced FCGRs when cracks propagated perpendicular to pearlite: crack branching

$$\Delta K = 12 \text{ MPa m}^{1/2}$$

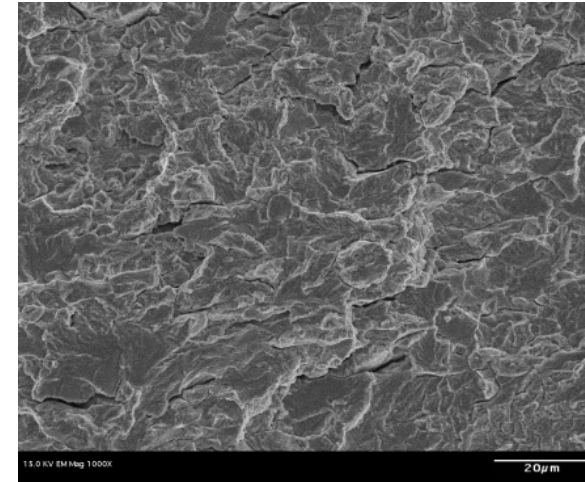
Crack growth direction ↑



C-L

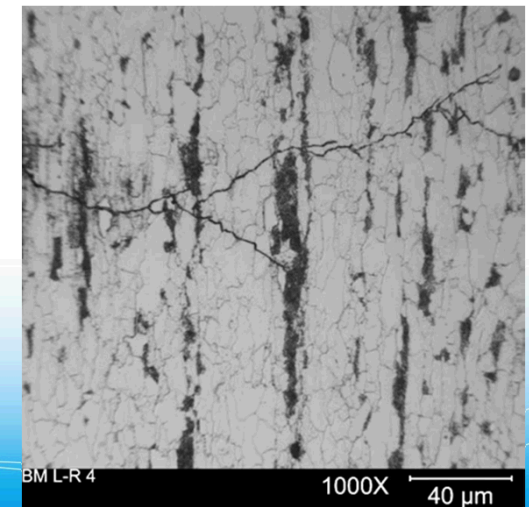


L-C

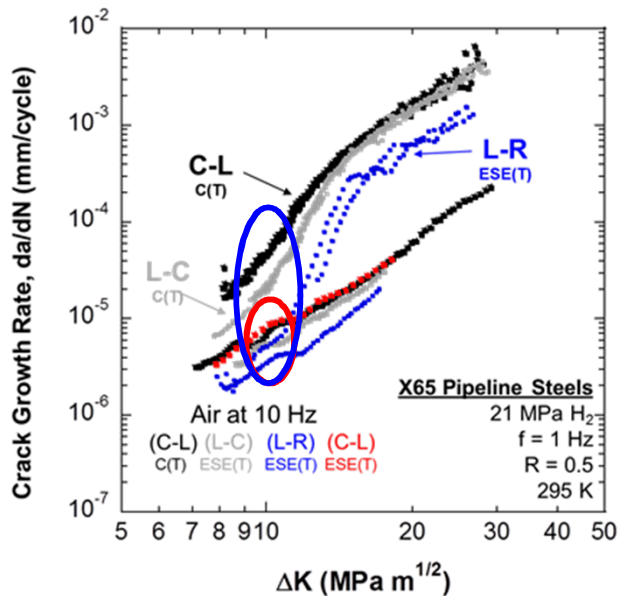


L-R

- Microcracks perpendicular to crack growth direction in L-R orientation
- Crack branching results in crack tip shielding and reduction in driving force for crack growth
→ lower crack growth rates



Pearlite impeded hydrogen diffusion and reduced fatigue crack growth rates



Orientation (Environment)	Crack growth rate, da/dN (mm/cycle) at select ΔK		
	10 MPa m ^{1/2}	12 MPa m ^{1/2}	15 MPa m ^{1/2}
C-L 3 (Air)	7.45E-06	1.13E-05	2.14E-05
L-R 1 (Air)	3.50E-06	4.47E-06	1.15E-05
L-C 3 (Air)	5.43E-06	9.27E-06	1.73E-05
Ratio in Air, $\frac{da/dN_{C-L}}{da/dN_{L-R}}$	2.1	2.5	1.9
Ratio in Air, $\frac{da/dN_{C-L}}{da/dN_{L-C}}$	1.4	1.2	1.2
C-L 1 (H ₂)	4.60E-05	1.76E-04	6.15E-04
L-R 4 (H ₂)	5.19E-06	2.16E-05	2.90E-04
L-C 12 (H ₂)	2.3E-05	1.16E-04	5.15E-04
Ratio in H ₂ , $\frac{da/dN_{C-L}}{da/dN_{L-R}}$	8.9	8.1	2.1
Ratio in H ₂ , $\frac{da/dN_{C-L}}{da/dN_{L-C}}$	2	1.5	1.2

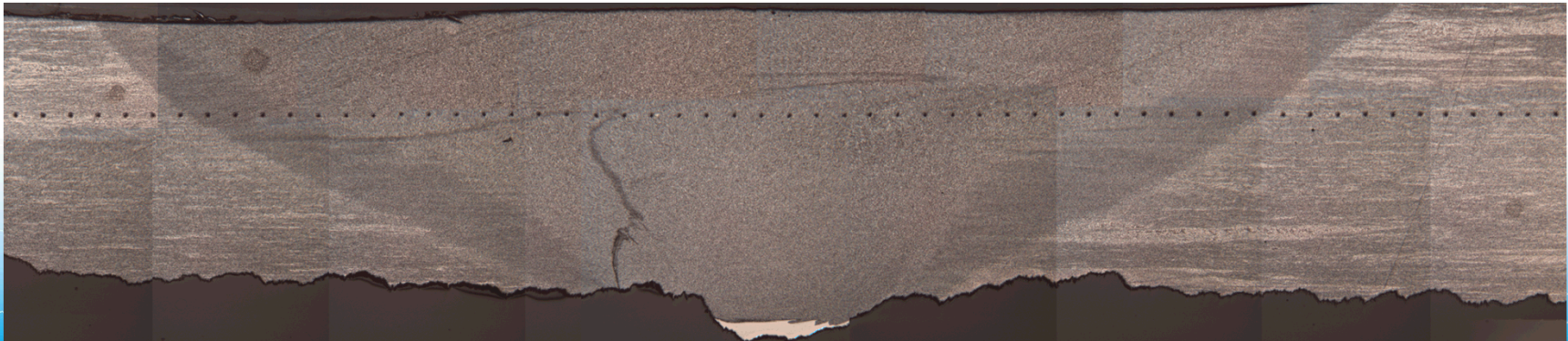
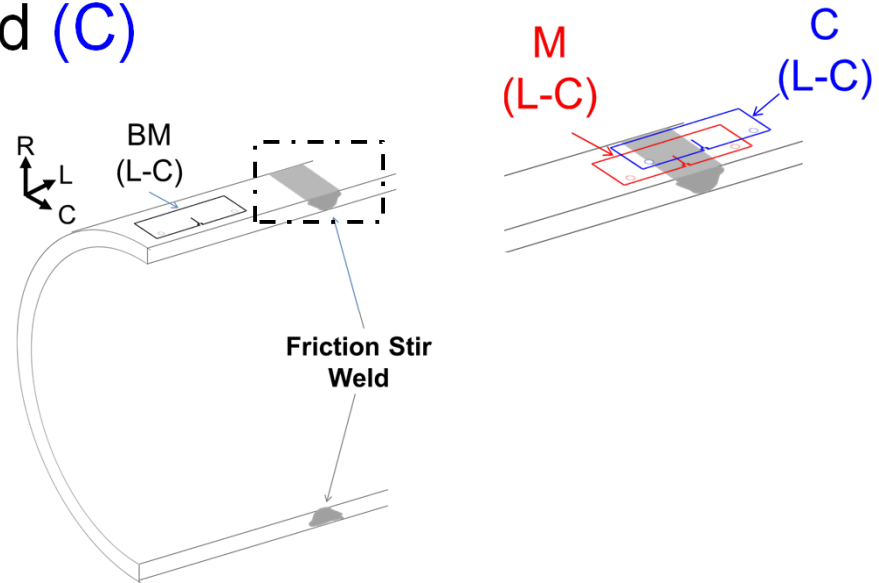
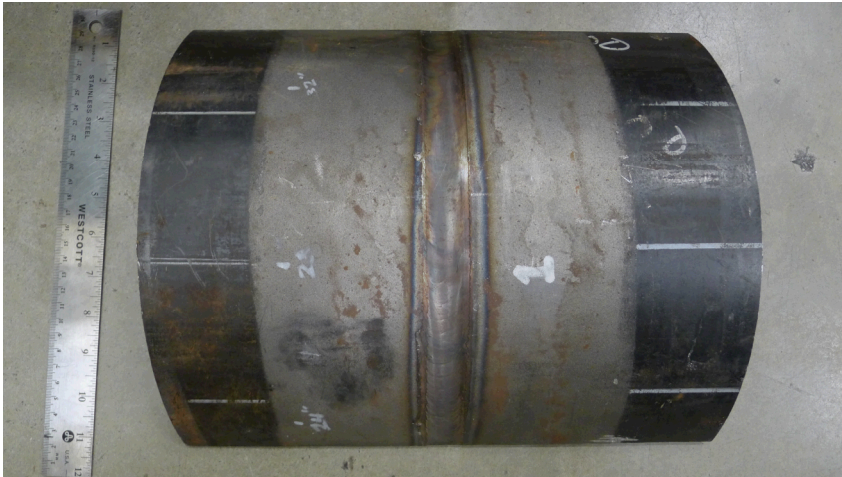
- Diffusivity of hydrogen in banded ferrite-pearlite microstructure is orientation dependent

$$D_H^L > D_H^C \gg D_H^R \text{ \{Tau, 96\}}$$

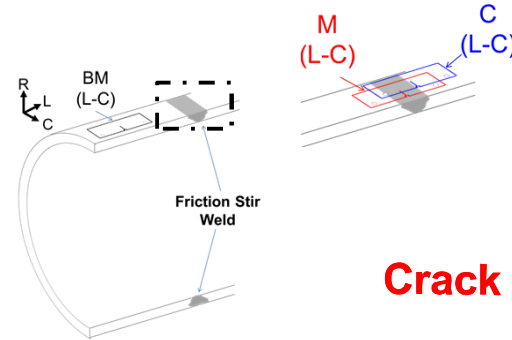
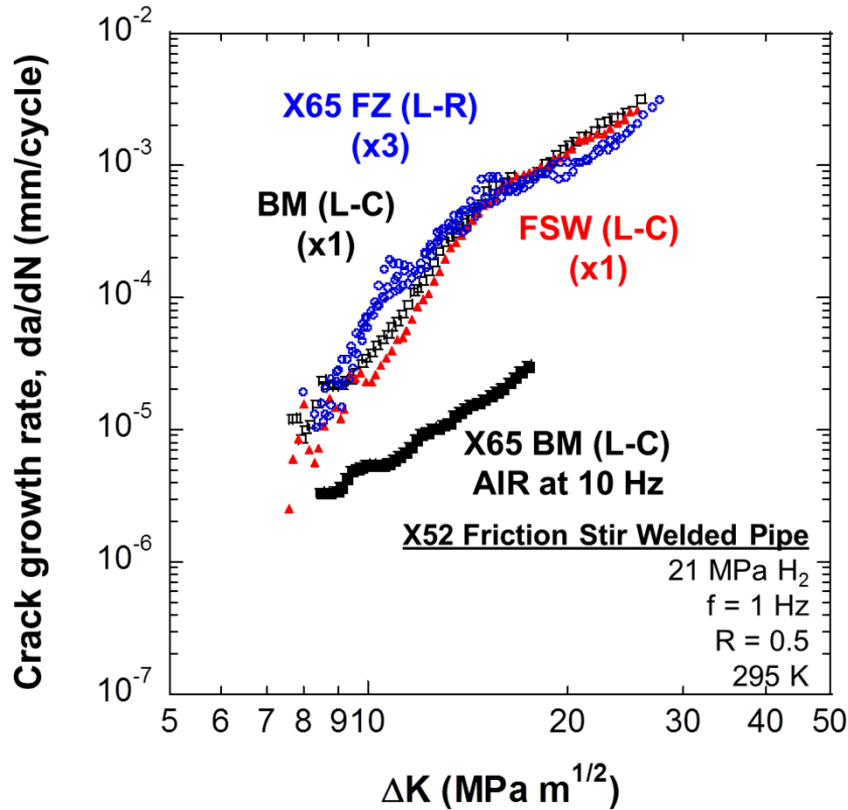
- Banded pearlite delays H-diffusion which reduces FCGR
- H-transport may *govern* hydrogen assisted fatigue [Go/No-Go Decision for FY15]

Friction stir welds

- Received from ORNL
- Nominal thickness 6.4 mm (0.25 in)
- Removed ESE(T) specimens base metal (BM), center of weld (M), and shoulder of weld (C)



Friction stir welds



BM



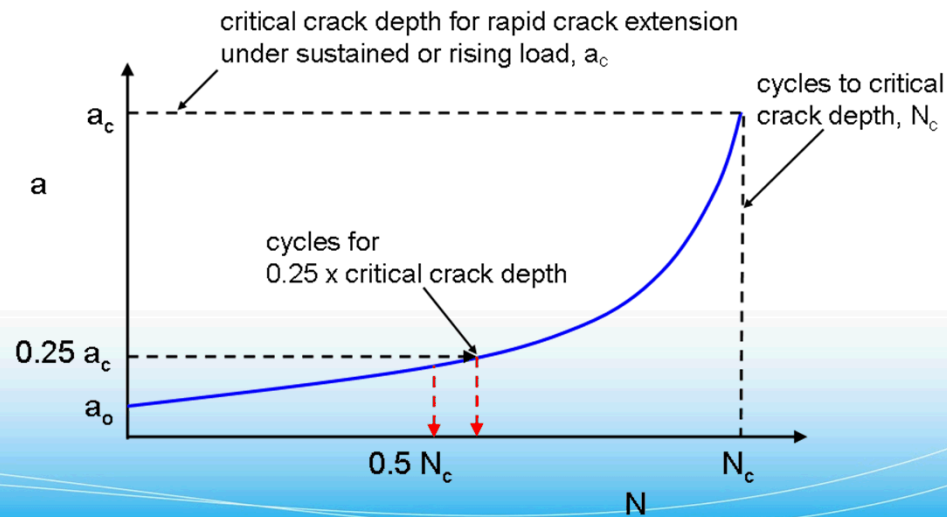
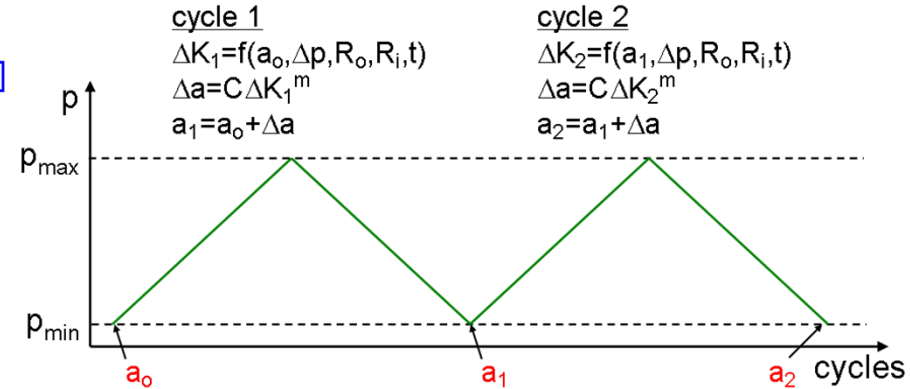
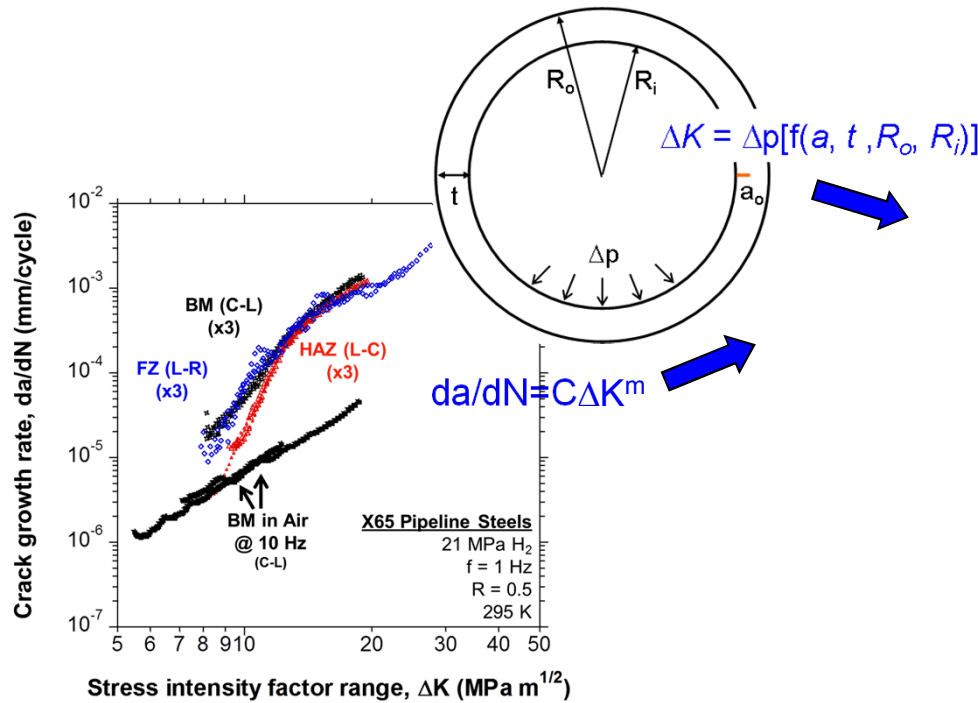
FSW



- Uniform crack fronts

- Preliminary results show crack growth rates are lower in FSW compared to BM
- Triplicate tests are planned for both base metal and friction stir weld

Measured fatigue crack growth relationships can be used to specify wall thickness for H₂ pipelines



• **Need:**

- Pipeline ID
- Pressure cycle range
- Initial flaw size (a_o)
- Inspection interval (cycles, N)

Summary

- **Measured fatigue crack growth relationships allow evaluation of reliability/integrity and cost of steel H₂ pipelines**
 - Hydrogen embrittlement accommodated by applying life assessment framework referenced in ASME B31.12 code
 - Framework allows calculation of steel pipeline wall thickness for specified inspection interval
- **Completed triplicate fatigue measurements of X65 pipe girth weld, HAZ, and BM in 21 MPa H₂ gas, results were reproducible [Milestone]**
 - Welds appear to be more susceptible to H₂-accelerated fatigue crack growth compared to base metal
 - HAZ results show slightly higher FCGR when extrinsic factors such as crack closure and residual stress effects were removed
 - Results for base metal show that microstructure can dominate H₂-accelerated fatigue crack growth, illustrating importance of specifying microstructure-performance relationships to qualify hydrogen pipeline steels
- **Completed initial fatigue of friction stir weld in 21 MPa H₂ gas [Milestone]**

Future Work

- Data from X65 girth welds will be disseminated in two papers:
 - 1) Effects of microstructure banding on hydrogen assisted fatigue crack growth in X65 pipeline steels
 - 2) Fatigue crack growth relationships in X65 pipeline girth welds in high pressure hydrogen gas
- In progress:
 - Fatigue tests on friction stir welded pipe at 1Hz, R=0.5, 21 MPa hydrogen.
 - Fatigue testing of fine and coarse grain ferrite-pearlite at 5.5 and 21 MPa to evaluate grain size effects on crack growth (at I²CNER)
- Friction Stir Weld:
 - Journal paper on friction stir welds in hydrogen

Collaborations

- NIST
 - Coordinate projects and exchange data on pipeline steel testing
- Oak Ridge National Laboratory
 - Coordinate projects and exchange data on pipeline steel testing
 - Supplied friction stir welded pipeline steel
- ExxonMobil
 - Supplying pipeline steel fusion welds
- ASME
 - Provides guidance on R&D needs for hydrogen pipeline codes
- International Institute for Carbon-Neutral Energy Research (I²CNER)
 - Collaborative basic research on H₂-accelerated fatigue crack growth in steels: define fundamental mechanisms and develop predictive models
- Workshop hosted by NIST in December 2013
 - Participants: NIST, ORNL, SNL, ASME, DOE, DOT
 - Outcome: NIST, ORNL, SNL, and ASME jointly authored white paper on R&D needs for hydrogen pipeline steels