

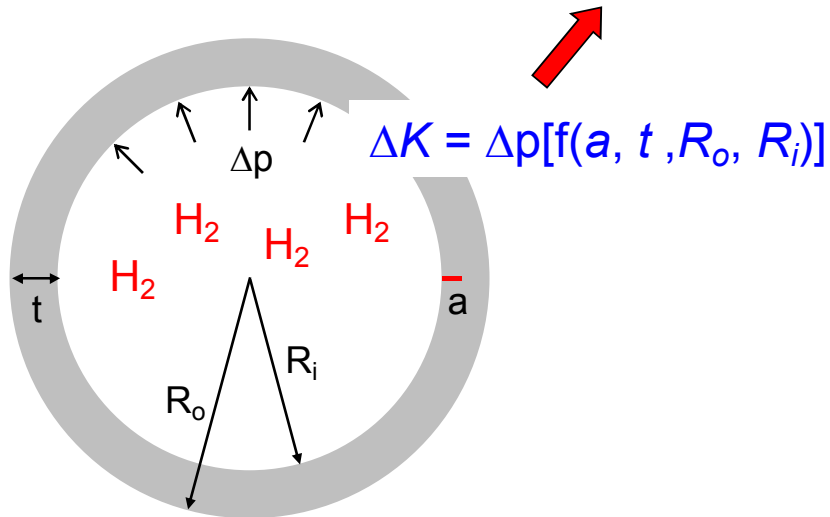
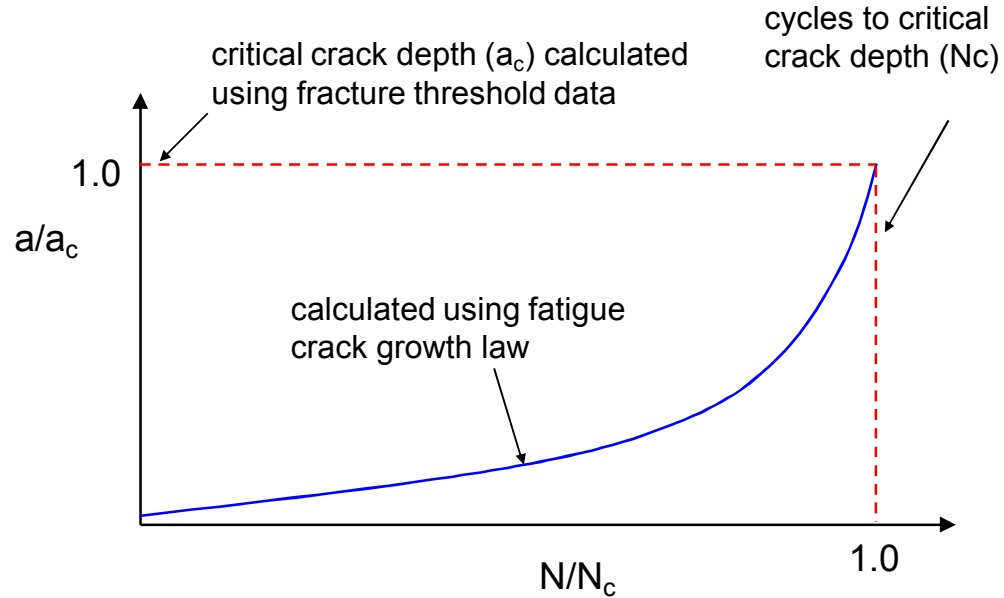
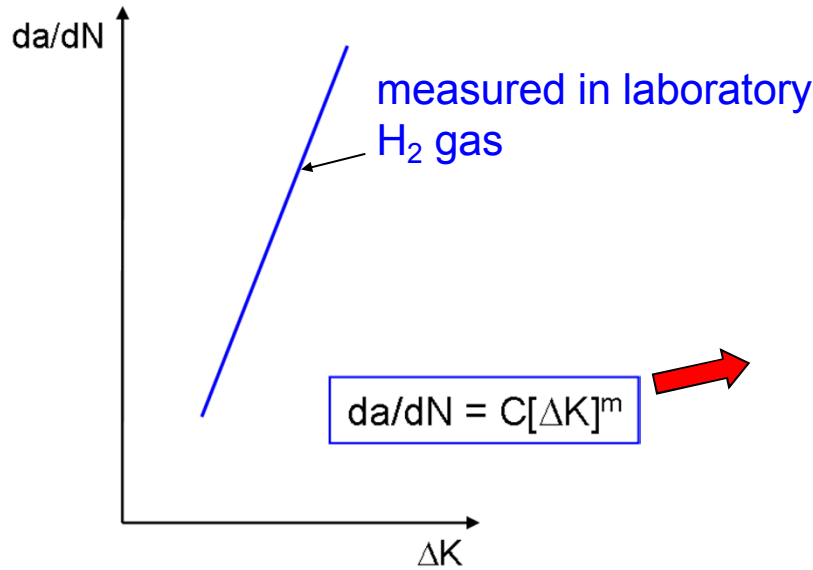
Hydrogen Embrittlement of Pipeline SAND2015-1643PE Steels and Welds



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



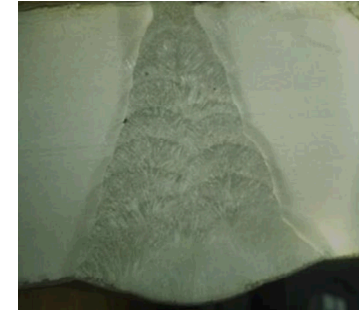
- Two fracture properties in H₂ needed
 - Fatigue crack growth law
 - Fracture threshold
- Reliability/assessment framework accommodates H₂ embrittlement

Material Tested: API 5L X65 steel with GMAW

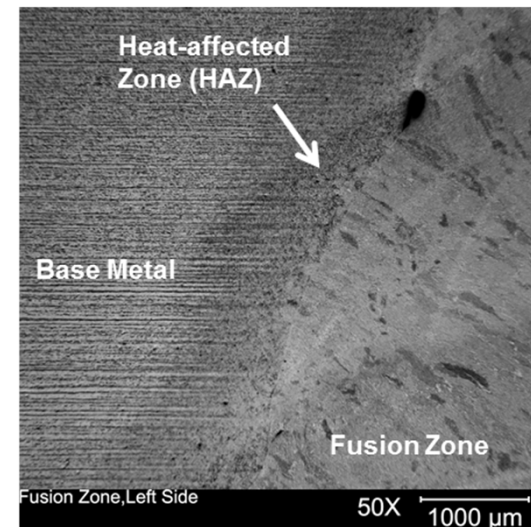
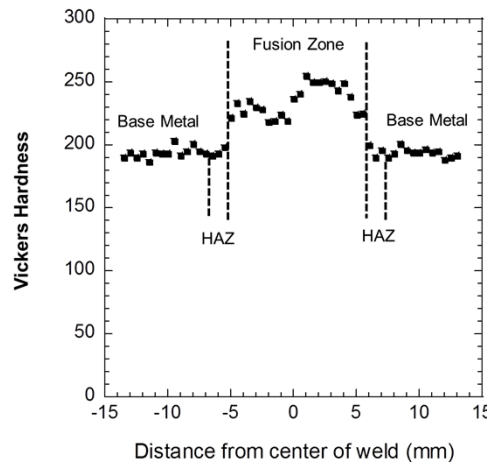
Gas Metal Arc Weld (GMAW)



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



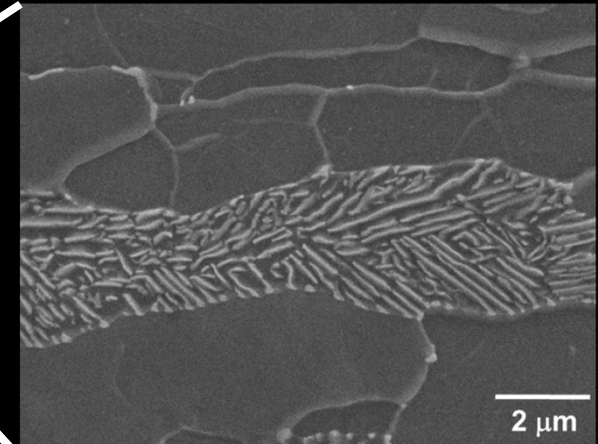
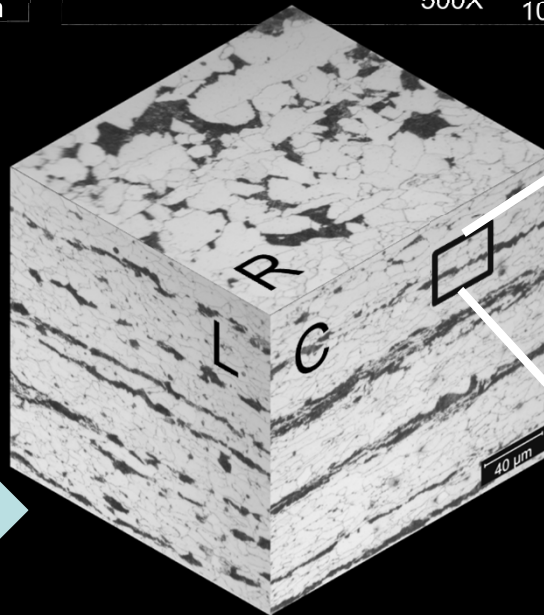
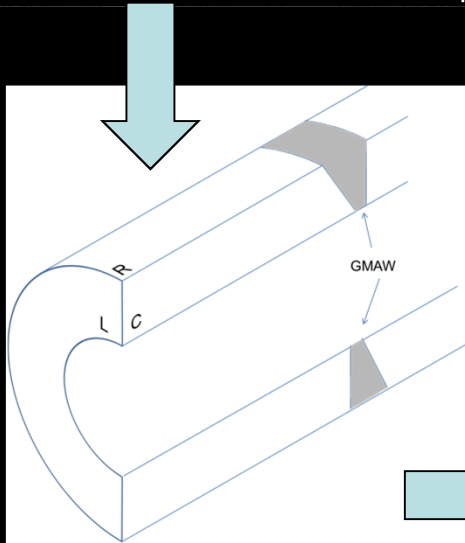
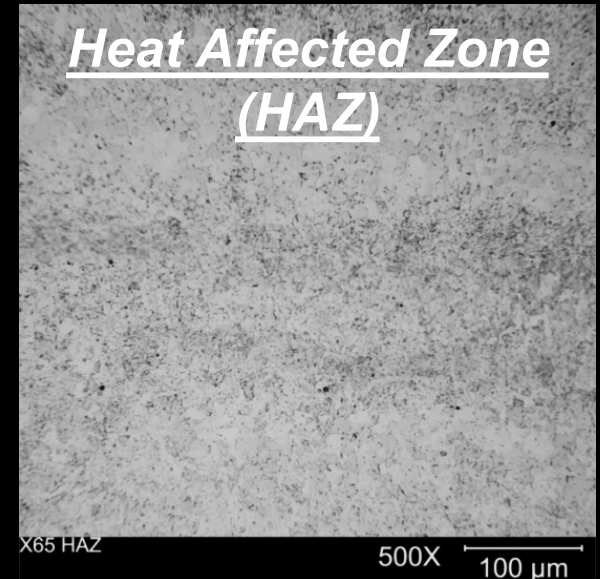
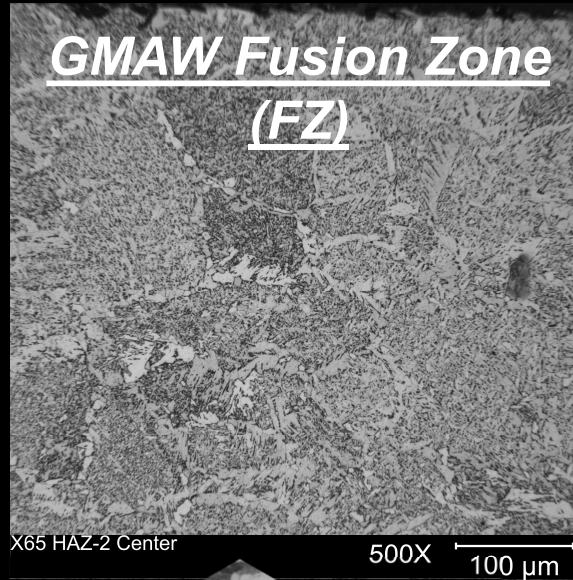
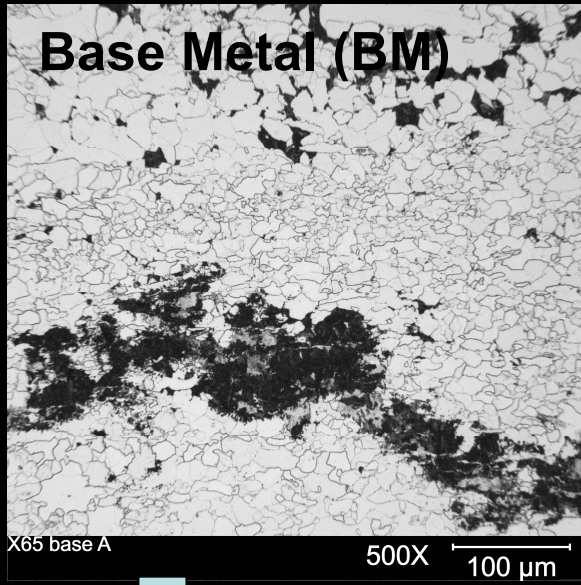
508 mm OD / 25.4 mm thickness
Filler metal: Thyssen TS-6 ER70S-G



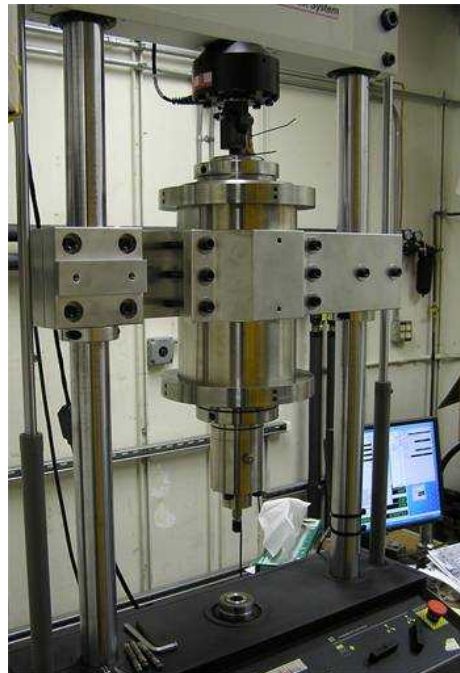
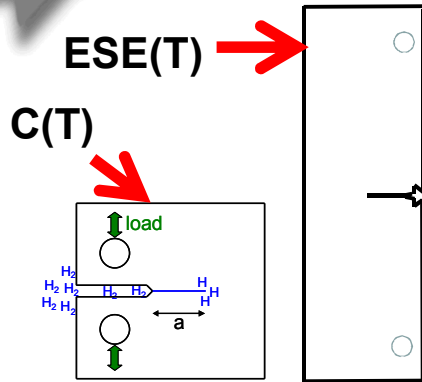
Base Metal Chemical Composition (wt %)

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



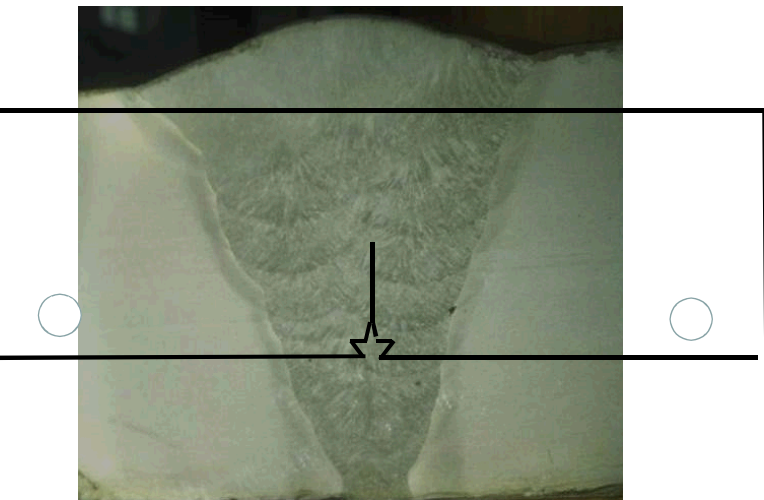
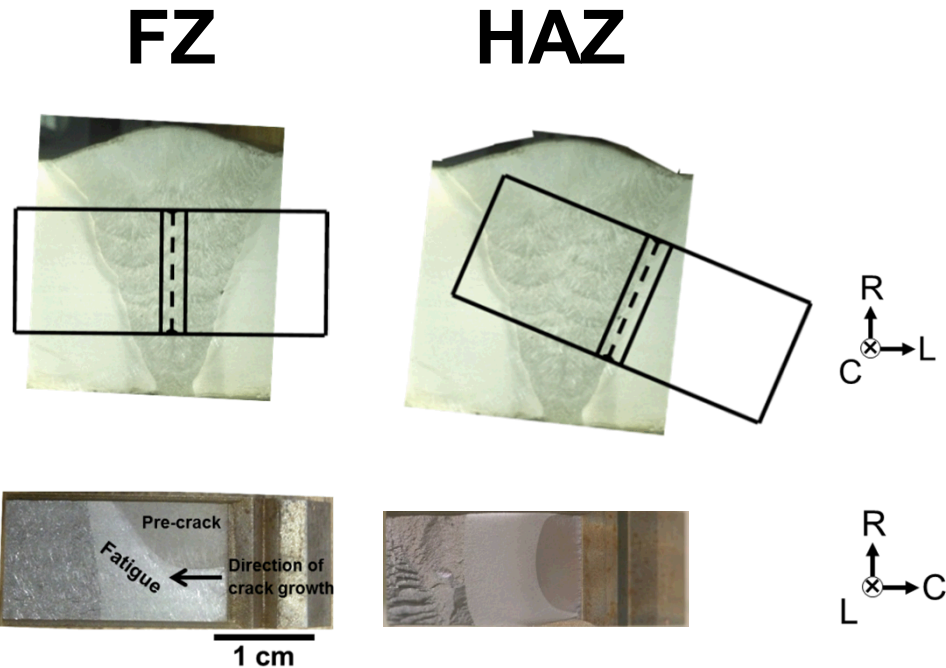
Measure fatigue crack growth in high-pressure H₂



- 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)
 - $R = \frac{P_{min}}{P_{max}} = 0.5$
- Environment
 - Primary supply gas: 99.9999% H₂
 - Pressure = 21 MPa (3,000 psi)
 - Room temperature (295 K)

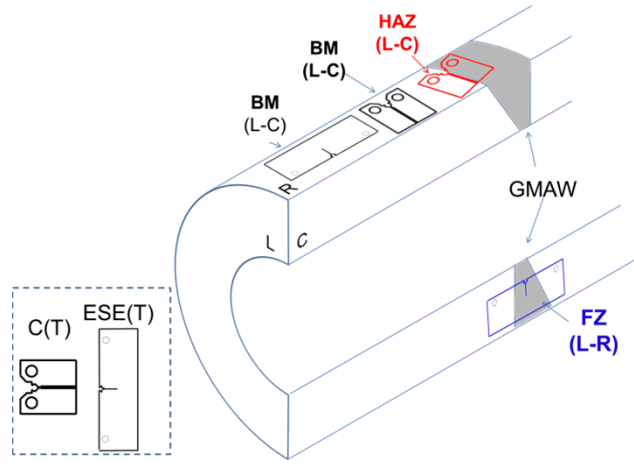
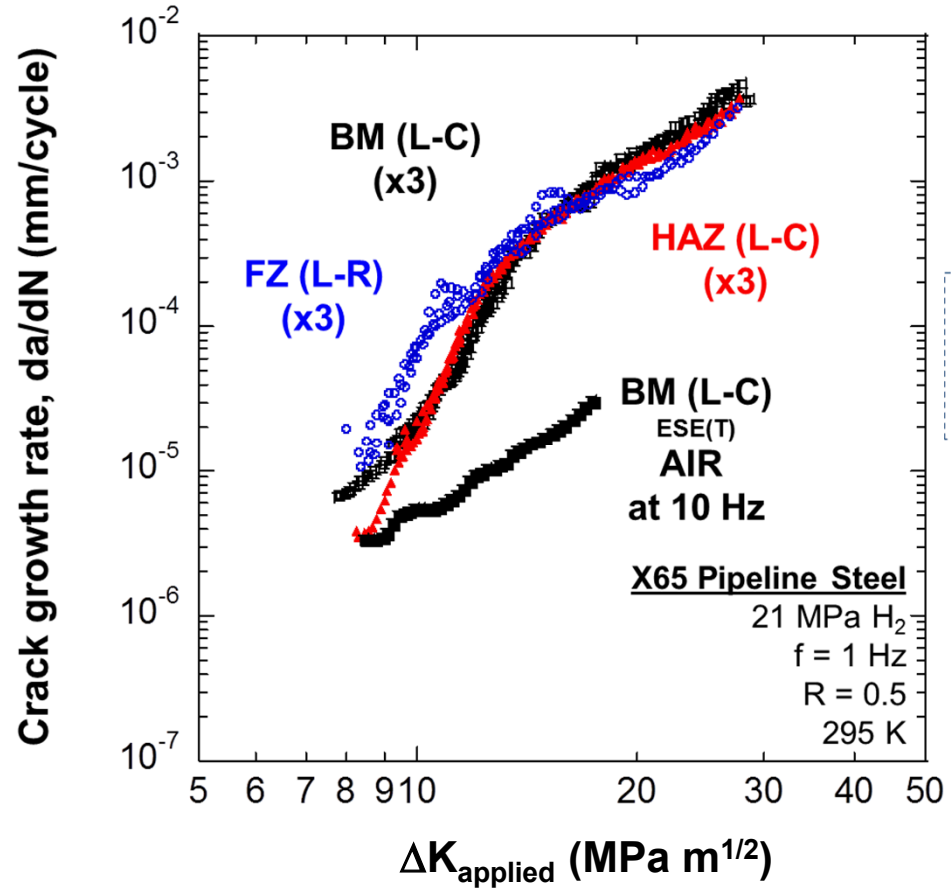
Non-uniform crack fronts in weld FZ and HAZ specimens

- Compact Tension C(T) specimens extracted from pipe
- Entire crack plane contained in FZ or HAZ
 - Non-uniform crack fronts observed
 - Attributed to residual stress



Alternate standardized test specimen geometry necessary for weld FZ testing: ESE(T)

Reproducible da/dN vs. ΔK curves for BM, FZ, and HAZ in 21 MPa H₂

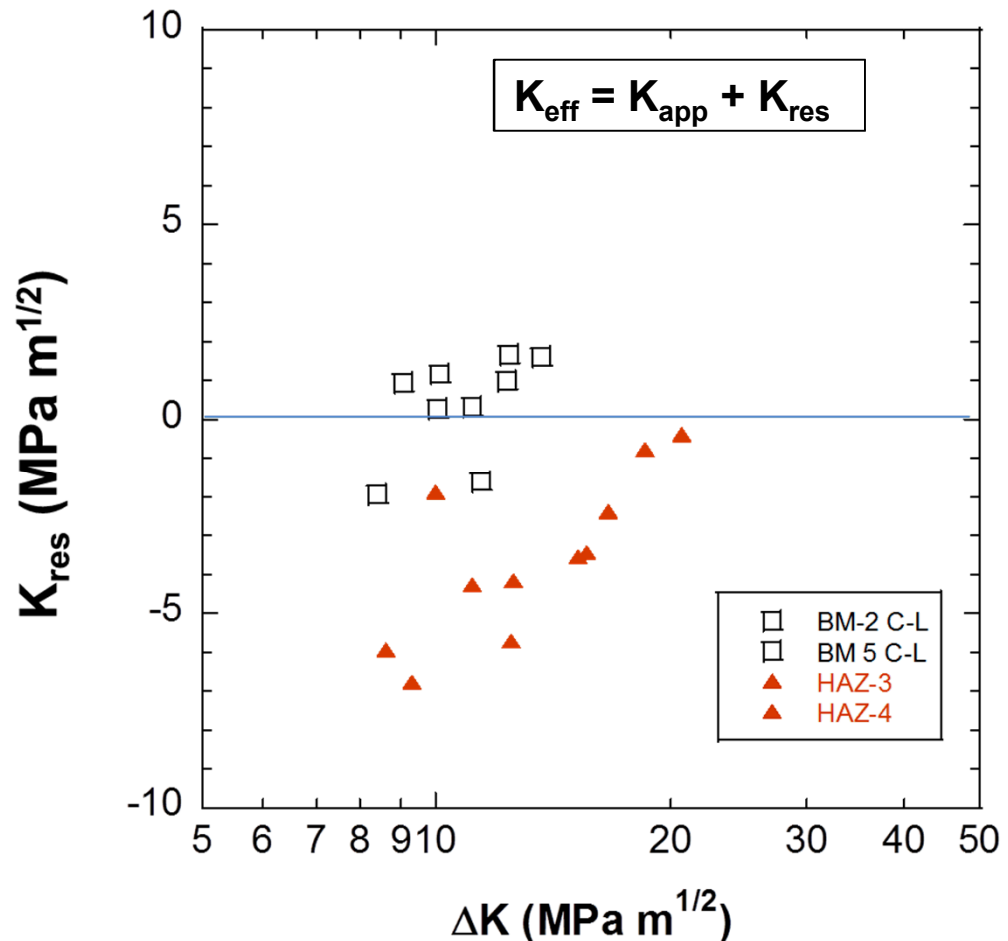


- Triplicate tests revealed reproducible results

$$\Delta K_{\text{effective}} = \Delta K_{\text{applied}} + \Delta K_{\text{residual}} + \dots$$

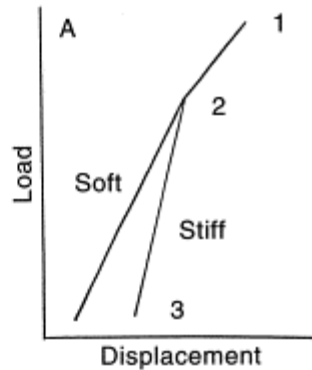
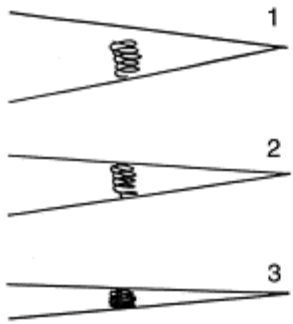
Compressive residual stress can reduce K_{\max}^{eff}

- Calculated residual stress effect on K_{\max}
 $\rightarrow K_{\text{res}}$
- BM exhibited negligible K_{res}
- **HAZ exhibited greater K_{res}**



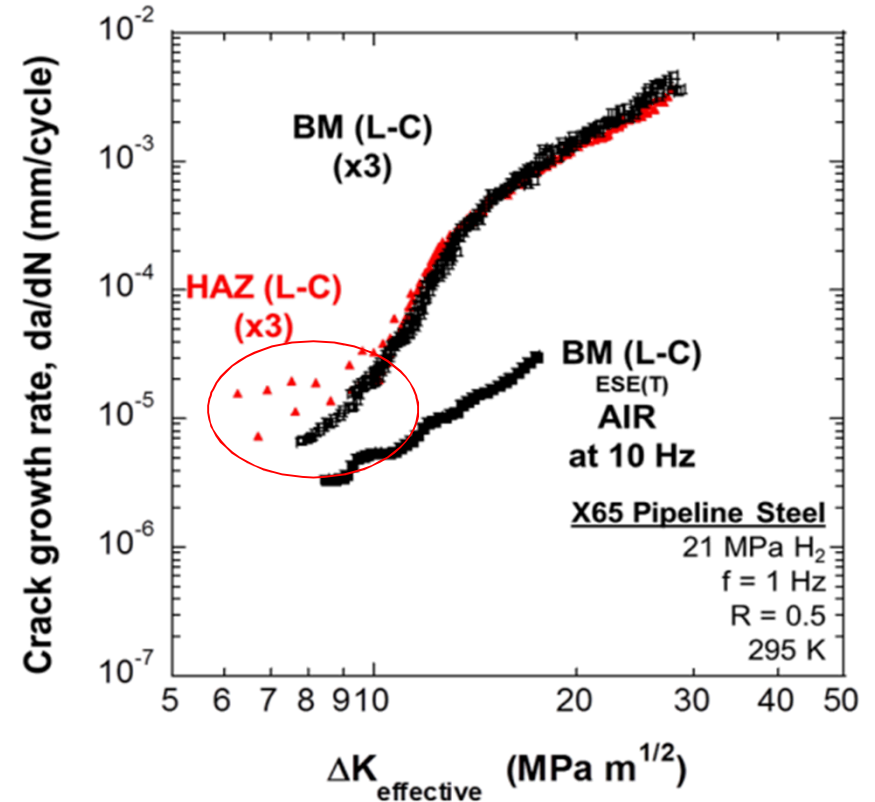
Reduction in K_{eff} could shift the onset of HA-FCG to lower ΔK values

Crack closure reduces $\Delta K_{\text{effective}}$



- Crack closure: crack remains closed for portion of loading cycle
- Adjusted Compliance Ratio (ACR) method implemented to remove effects of closure

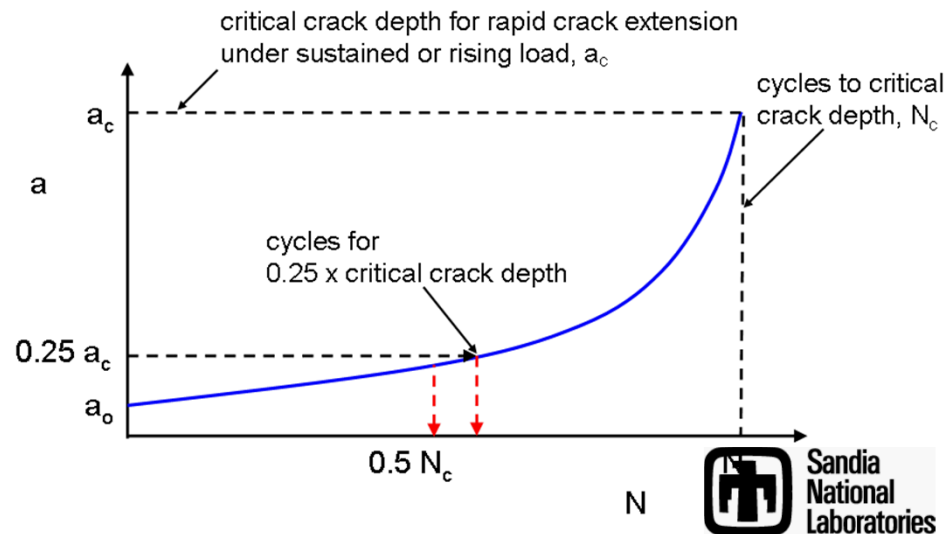
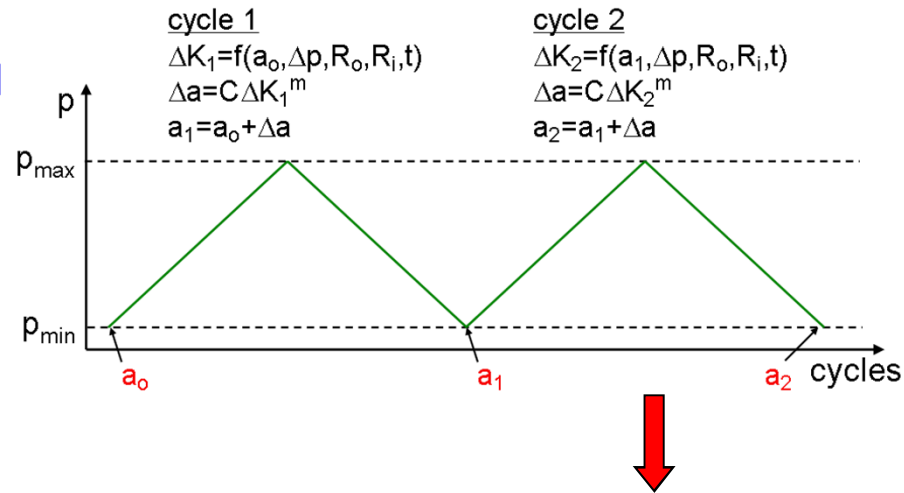
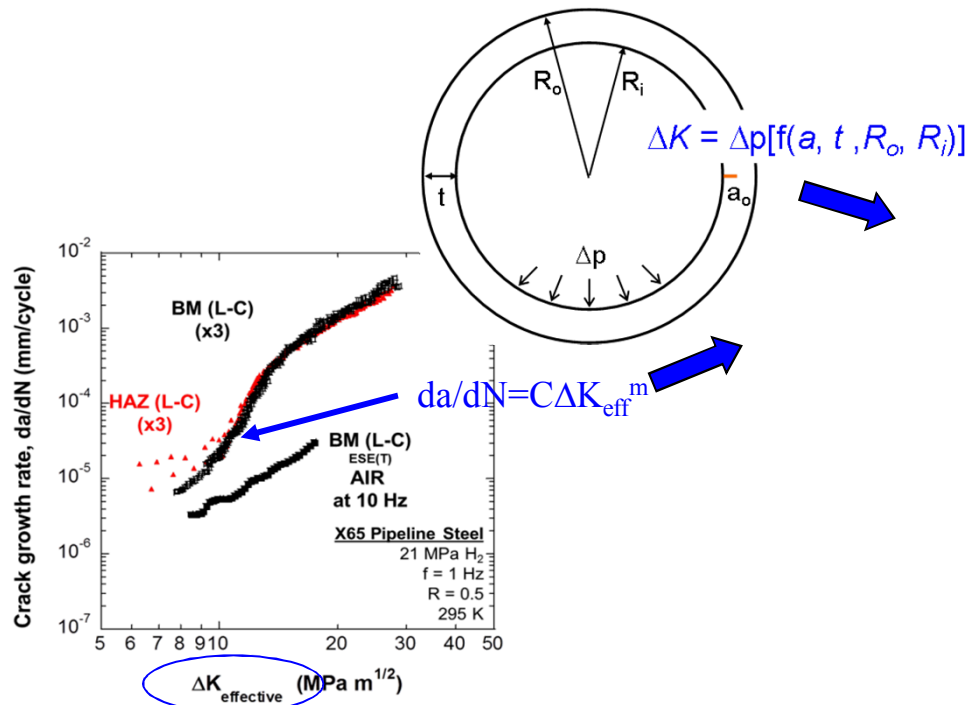
→ $\Delta K_{\text{effective}}$



- Reveals higher FCGR in HAZ compared to BM

Highlights importance in comparing intrinsic fatigue behavior

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

- Completed triplicate fatigue measurements of X65 pipe girth weld, HAZ, and BM in 21 MPa H₂ gas, results were reproducible
 - 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
- Comparison of intrinsic FCG behavior (e.g. ΔK_{eff}) is necessary for evaluating microstructure performance in hydrogen
 - Requires removal of extrinsic effects specific to pipe (crack closure, residual stress, etc...)
- Future Work
 - Testing on Friction Stir Welded X52 pipe is in progress



Acknowledgements / References

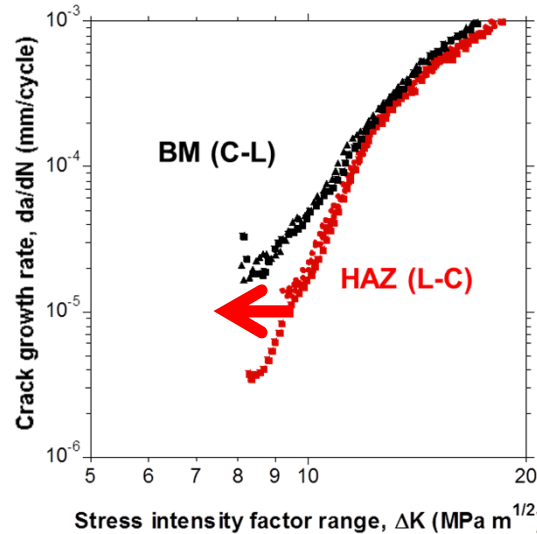
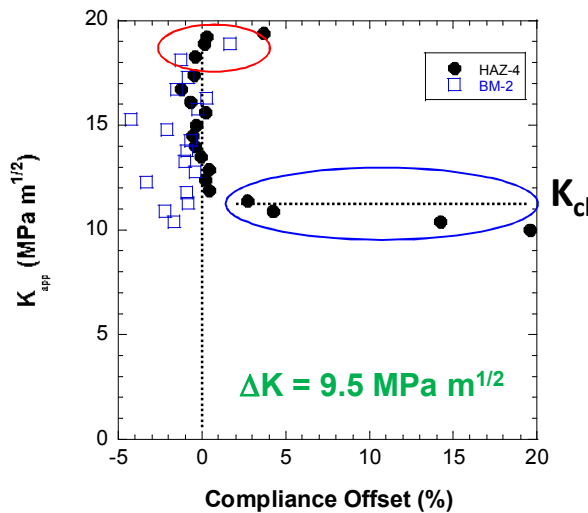
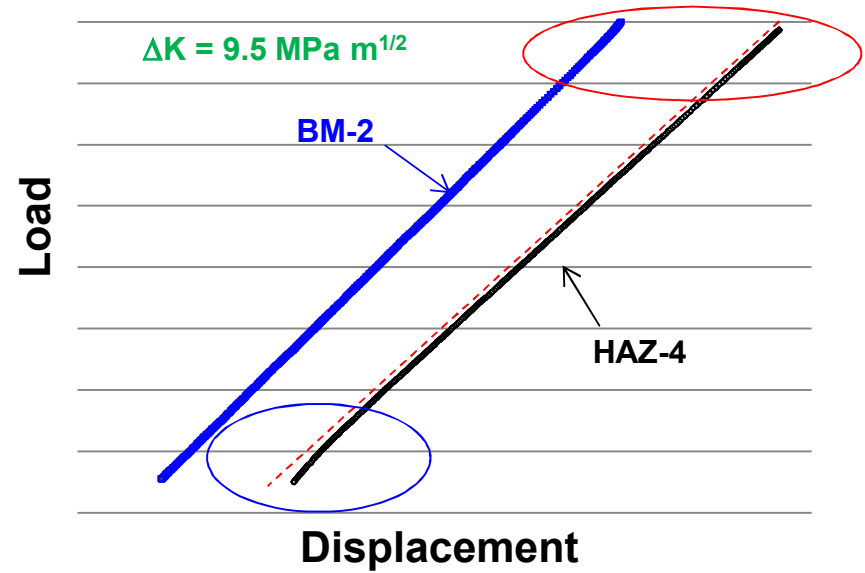
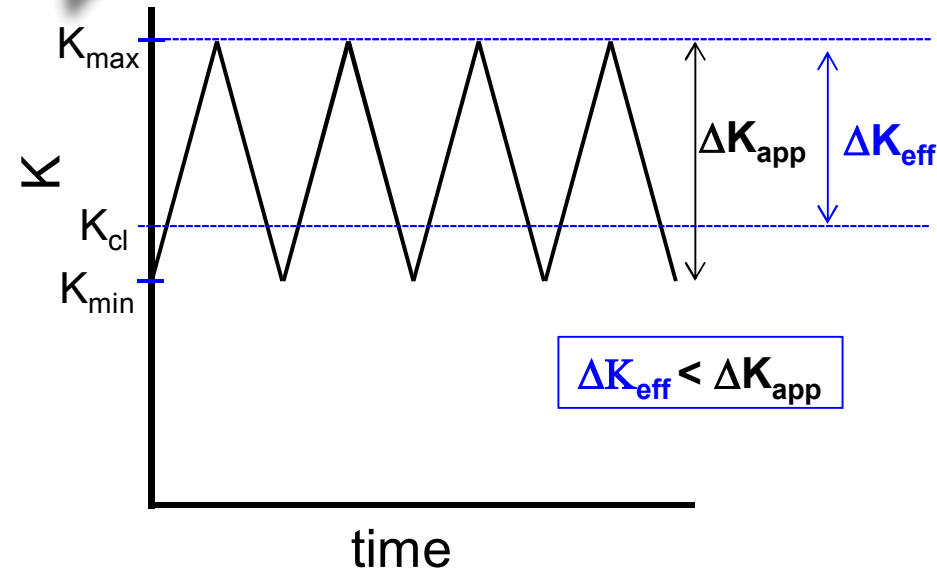
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- [3] Cialone, H.J. and Holbrook, J.H. “Effects of gaseous hydrogen on fatigue crack growth in pipeline steel.” *Metallurgical Transactions A*, vol. 16A, 1985, pp. 115-122.
- [4] Cialone, H.J. and Holbrook, J.H. “Microstructure and fractographic features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

Crack closure appears to occur in HAZ even at R = 0.5, resulting in $\Delta K_{\text{eff}} < \Delta K_{\text{applied}}$



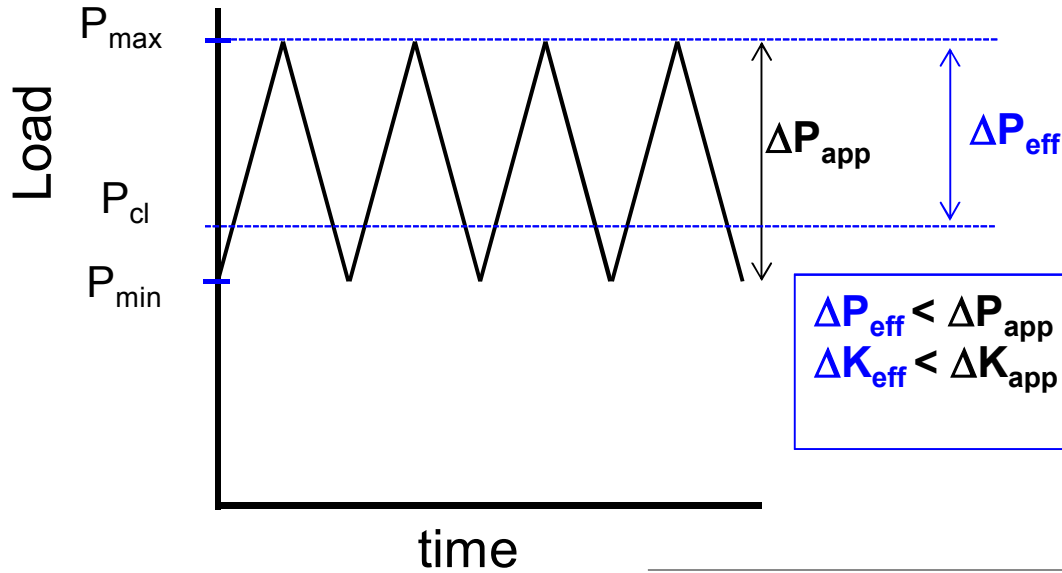
Possible sources of crack closure

- Residual stress
- More pronounced Mode II loading

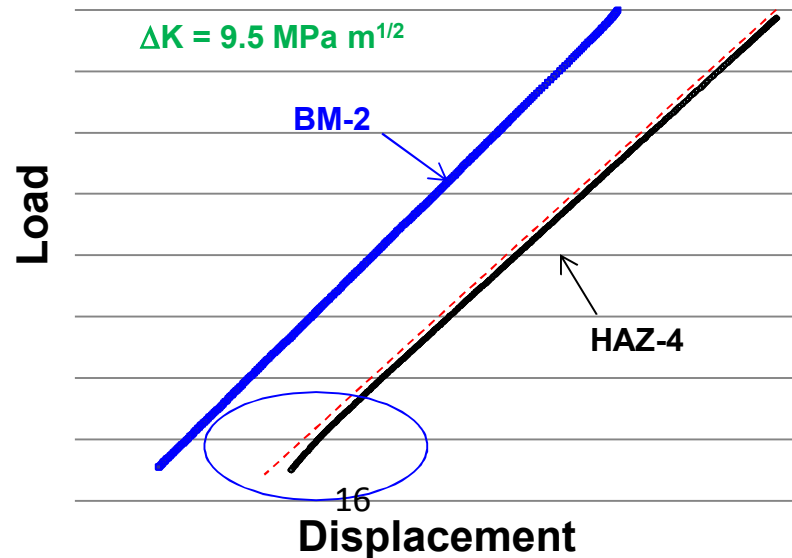
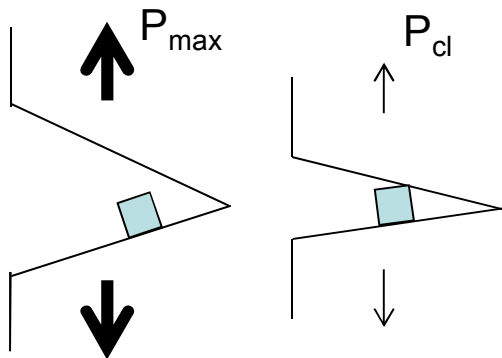
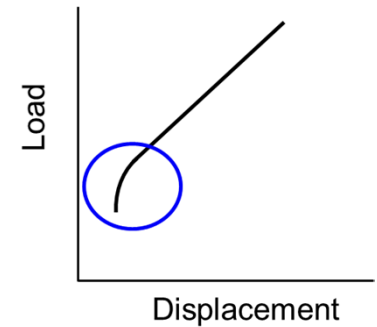
$$\text{Compliance offset} = \frac{[(\text{open} - \text{crack compliance}) - (\text{compliance}) * 100]}{(\text{open} - \text{crack compliance})}$$

Decreased ΔK_{eff} may account for reduced FCGR in HAZ

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

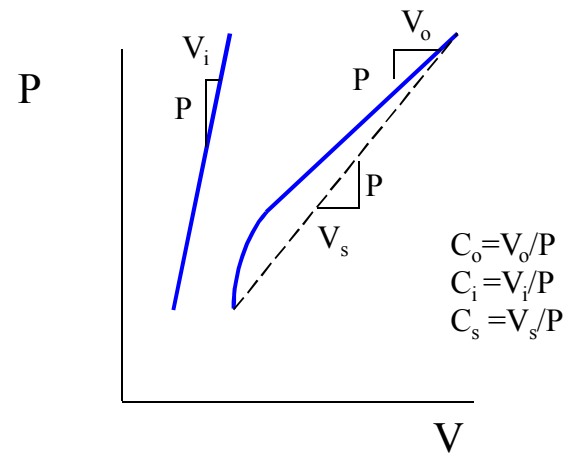
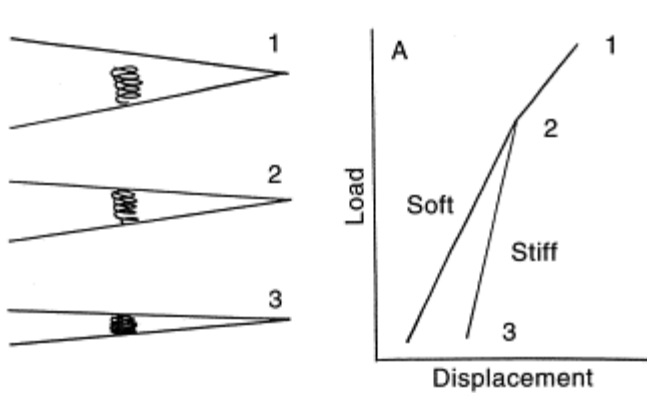


- Below P_{cl} , contribution to stress intensity is reduced
- Crack closure observed in load-displacement curves as change of slope at lower loads



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

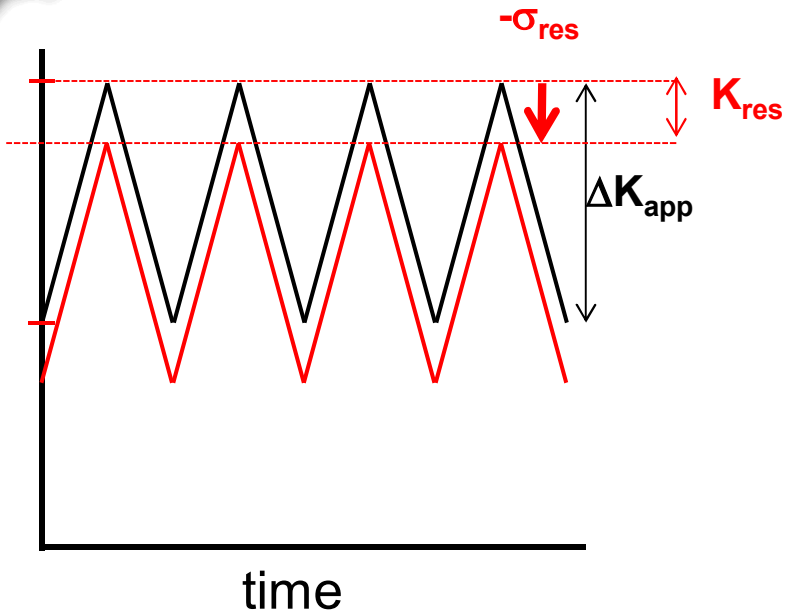
- Alternative method is ASTM 2% compliance offset method
- Both methods are used to determine $\Delta K_{\text{effective}}$
- $\Delta K_{\text{applied}} > \Delta K_{\text{effective}}^{ACR}$



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

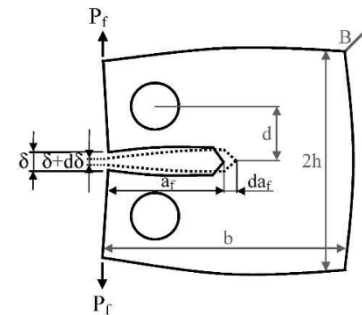
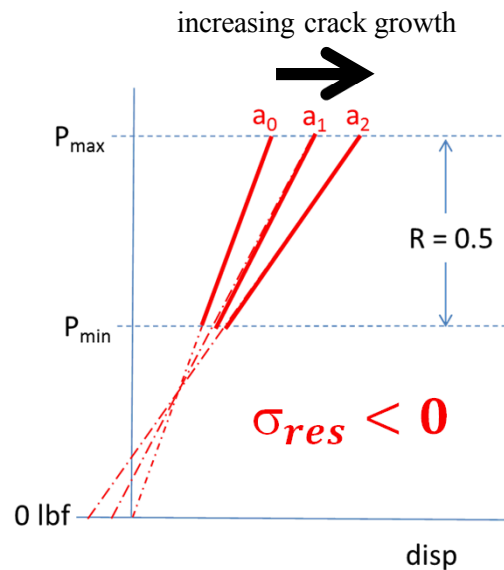
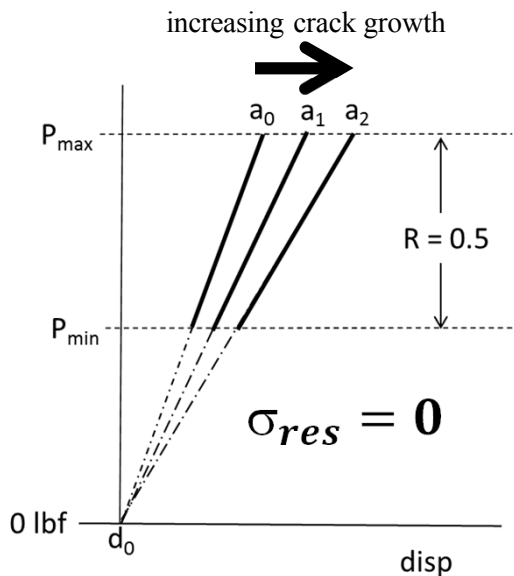
$$\Delta K_{\text{effective}} = \Delta K_{\text{app}} \times ACR$$

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



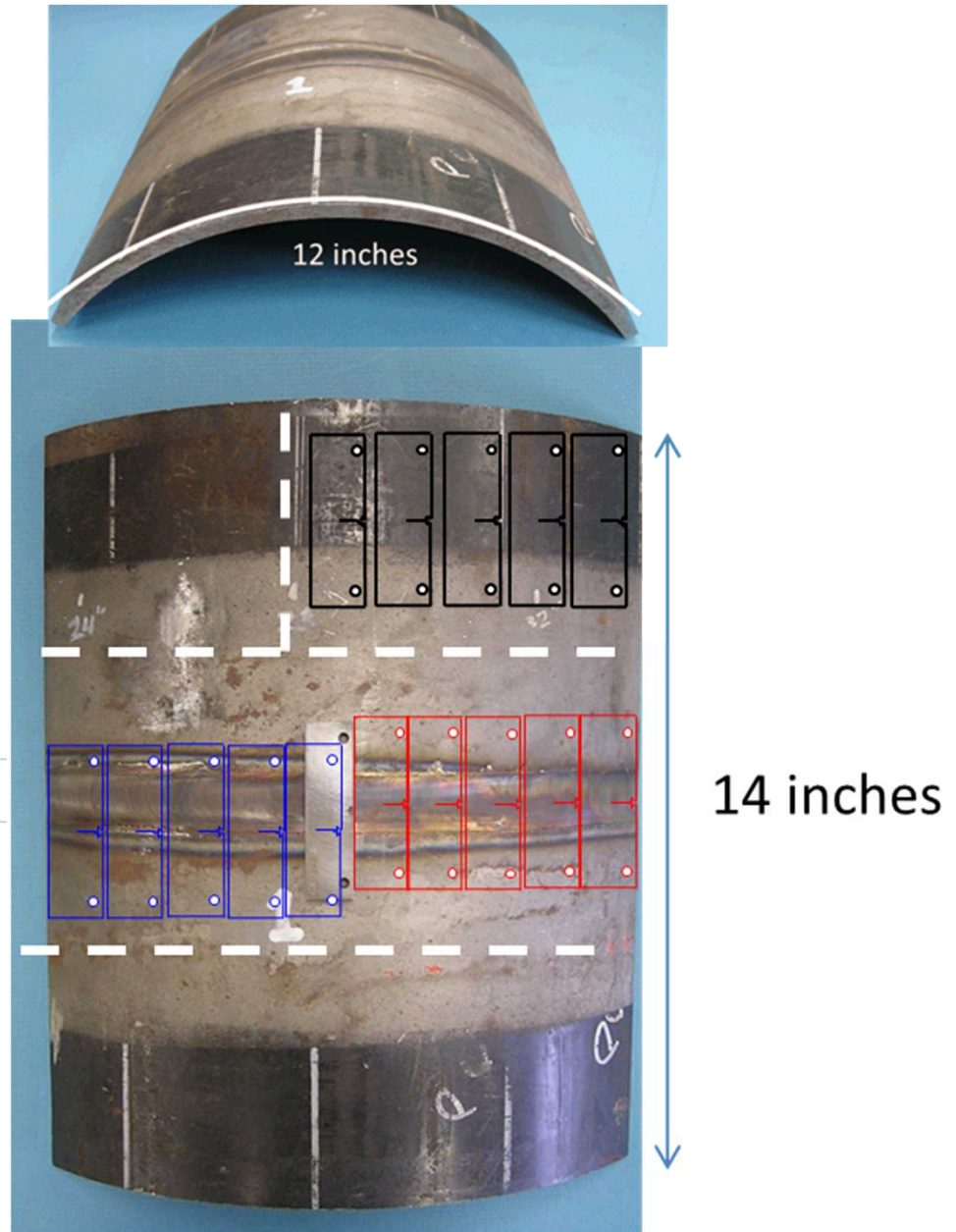
$$K_{max}^{eff} = K_{max} + K_{res}$$

- Calculate K_{res} from load-disp curves



{Lados, 2006}

- Pipe will be sectioned into 2 pieces for easier shipping and handling (see dashed lines)
- Nominal thickness of pipe is 0.25" although closer to 0.23" at weld
- Markings will be made on the pipe to identify reference point for center of ESE(T) specimen (i.e. notch location)



X52 Friction Stir Weld

