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Assessing Gaseous Hydrogen Assisted Fatigue Crack Growth Susceptibility of Pipeline Steel Weld Fusion Zones and Heat Affected Zones

Joe Ronevich & Brian Somerday

Sandia National Laboratories Livermore, CA

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***jaronev@sandia.gov**

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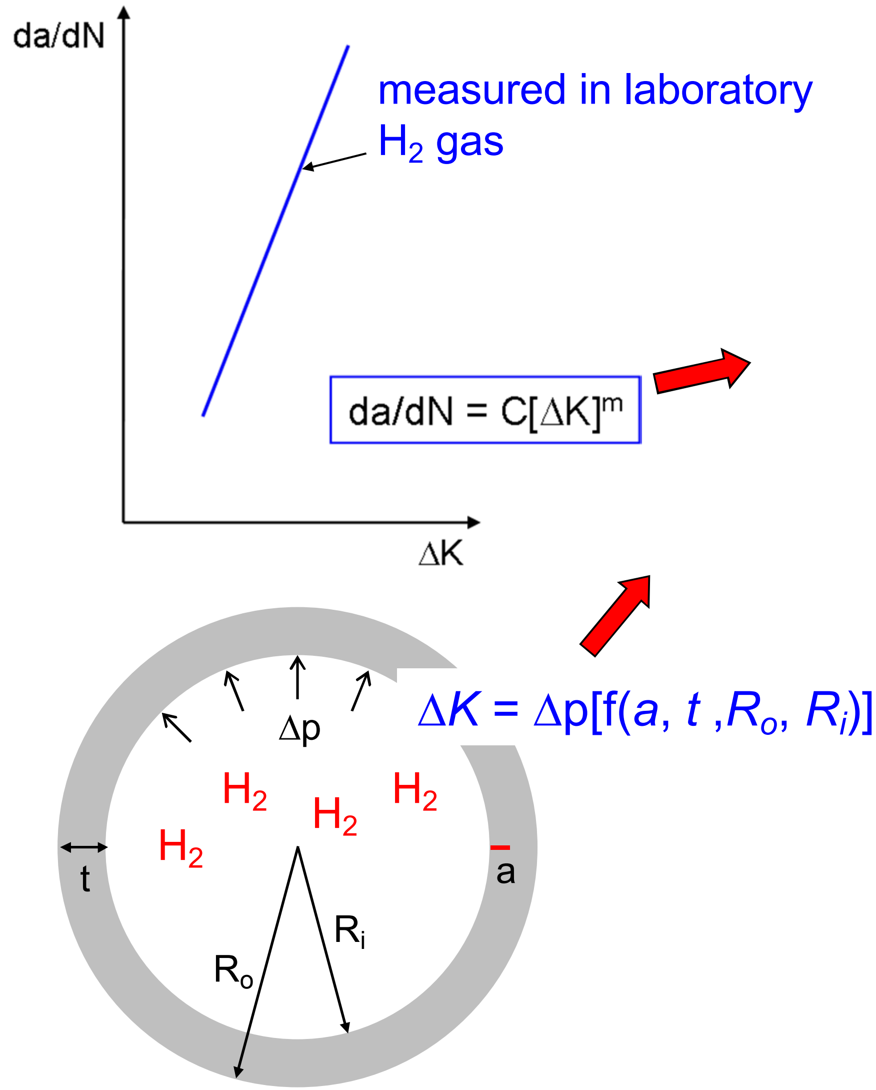
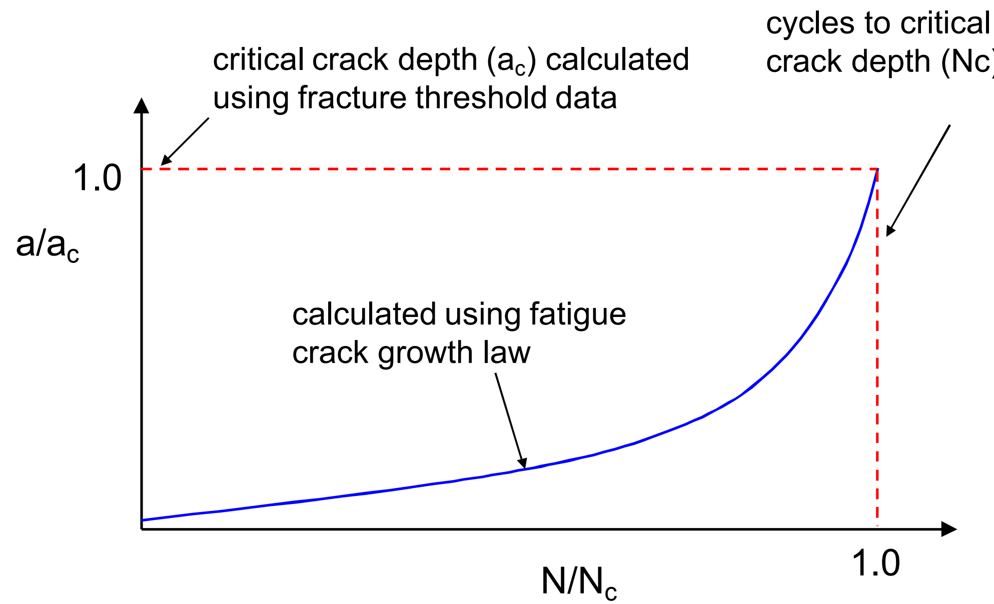
Reliability/integrity assessment framework in ASME B31.12 requires fracture data in H_2 gas





- Two fracture properties in H_2 needed
  - Fatigue crack growth law
  - Fracture threshold
- Reliability/assessment framework accommodates H_2 embrittlement

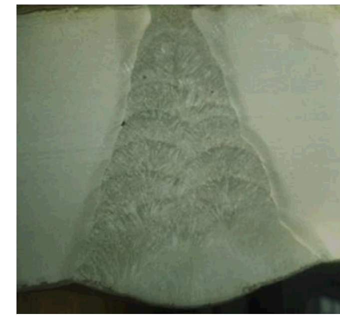
Material Tested: API 5L X65 steel with GMAW

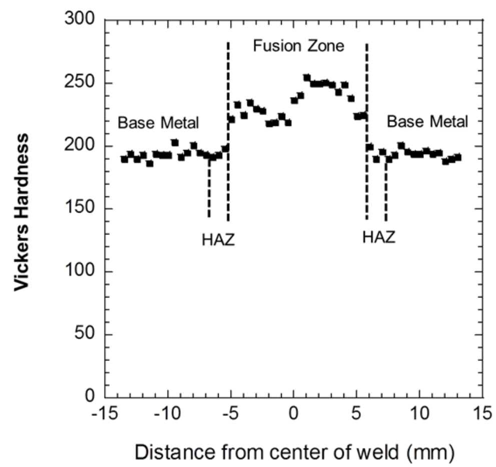
Gas Metal Arc Weld (GMAW)

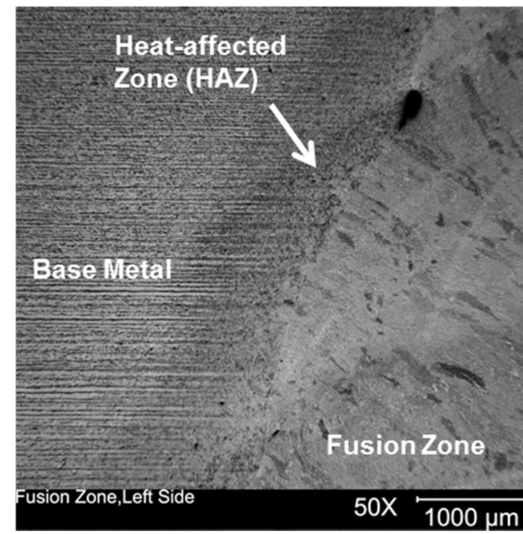
508 mm OD / 25.4 mm thickness

Filler metal: Thyssen TS-6 ER70S-G

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



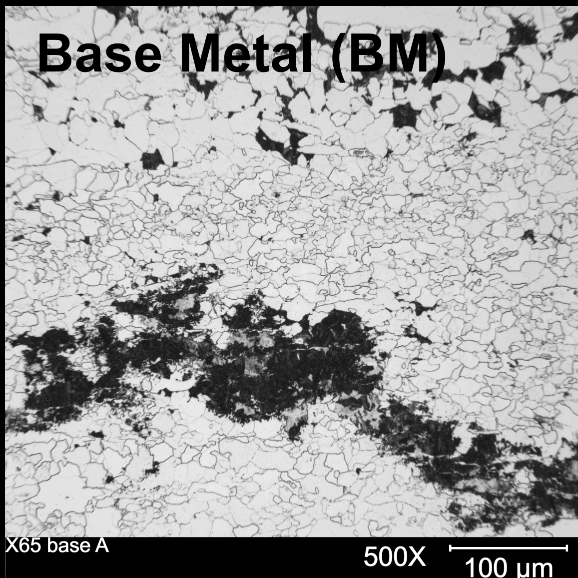


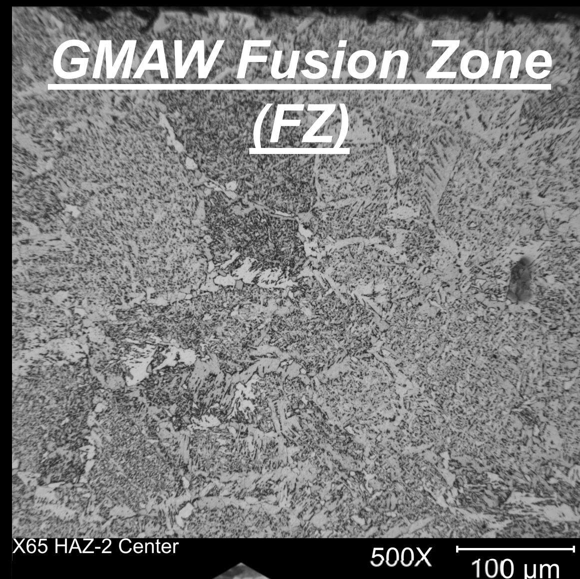


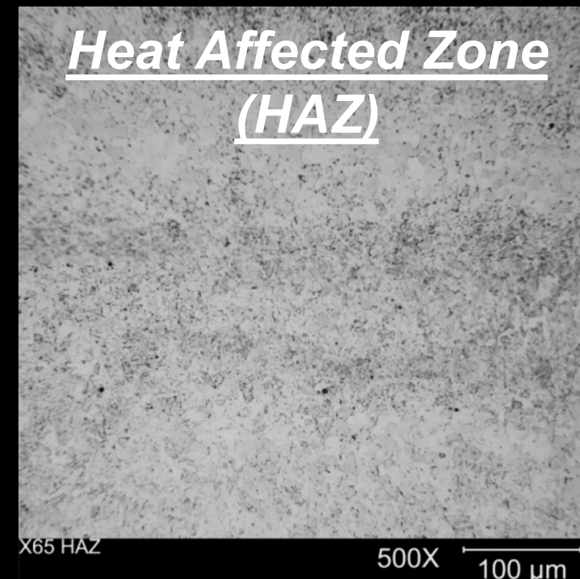
Base Metal Chemical Composition (wt %)

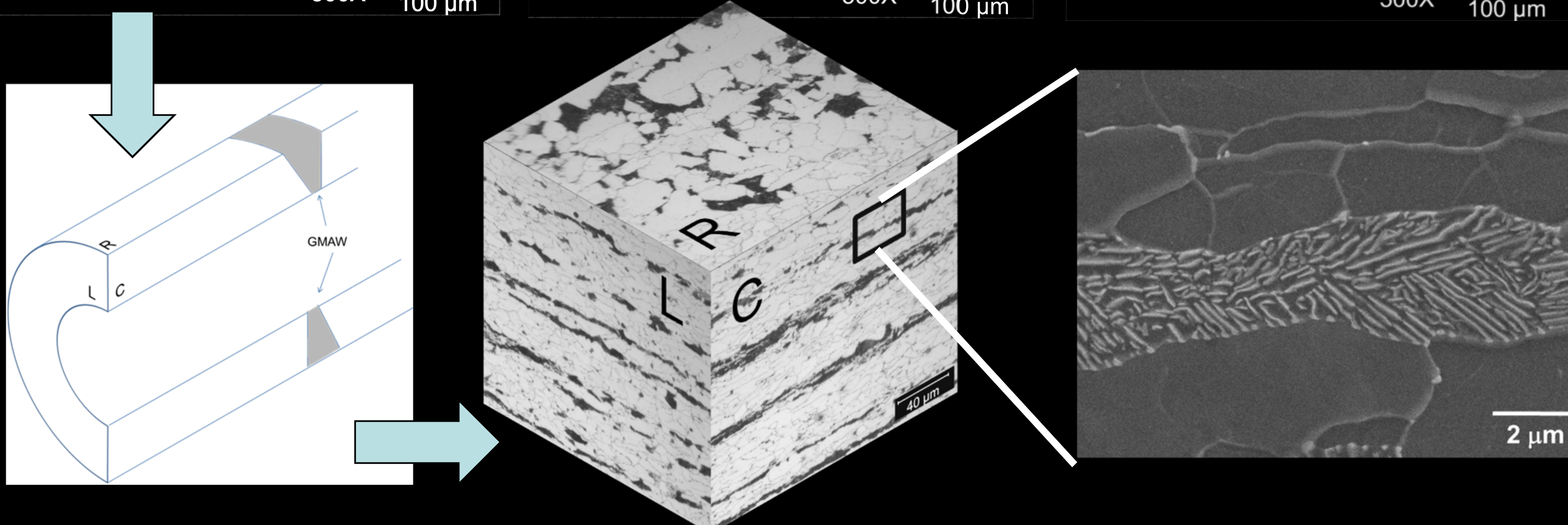
C	Mn	P	S	B	Si	Cu	Ni	Nb	Ti
0.08	1.53	0.01	0.001	0.002	0.32	0.024	0.038	0.039	0.002

Microstructure of X65

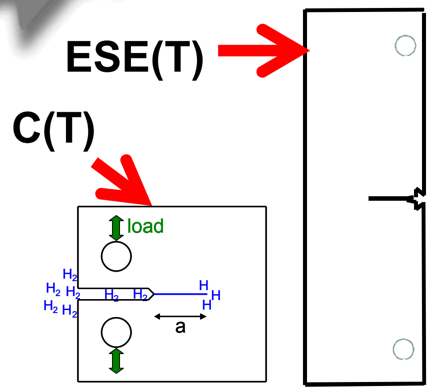


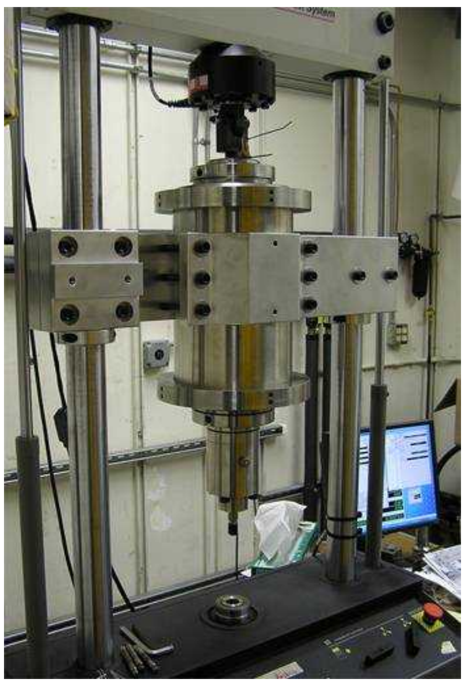






Measure fatigue crack growth in high-pressure H_2





- 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)
  - $R = \frac{P_{min}}{P_{max}} = 0.5$
- Environment
  - Primary supply gas: 99.9999% H_2
  - Pressure = 21 MPa (3,000 psi)
  - Room temperature (295 K)

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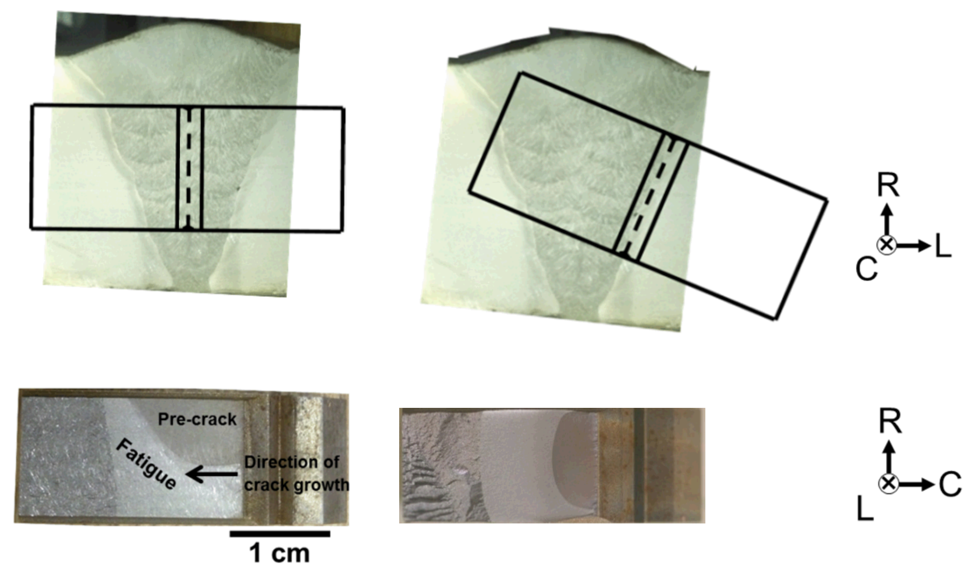
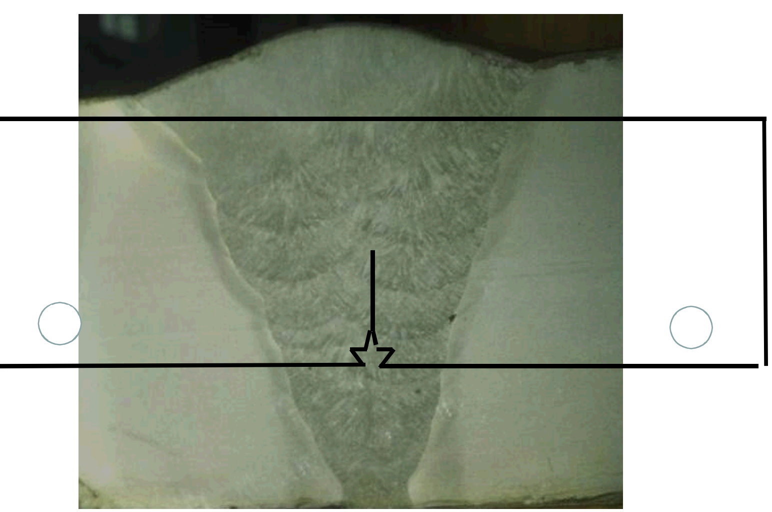
Non-uniform crack fronts in weld FZ and HAZ specimens

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**

FZ **HAZ**

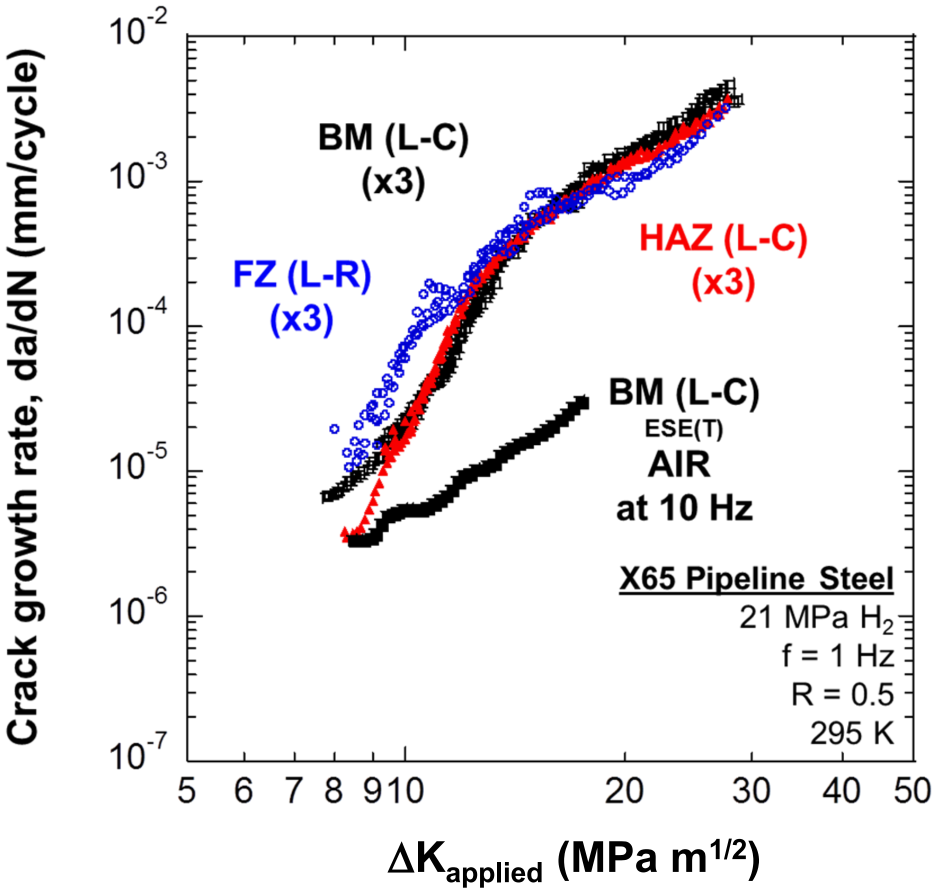


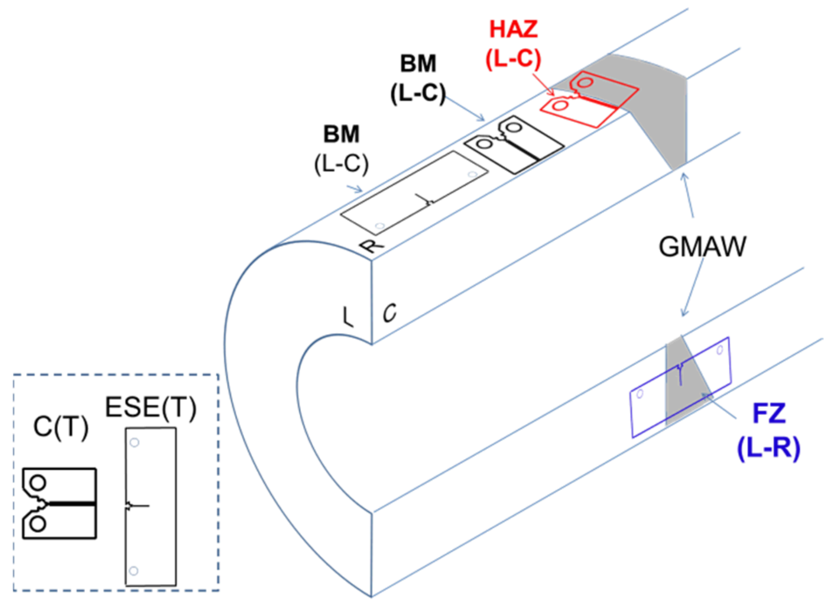


Alternate standardized test specimen geometry necessary for weld FZ testing: ESE(T)

T. Neeraj, *Sci. Tech. Weld. Join.*, 2011

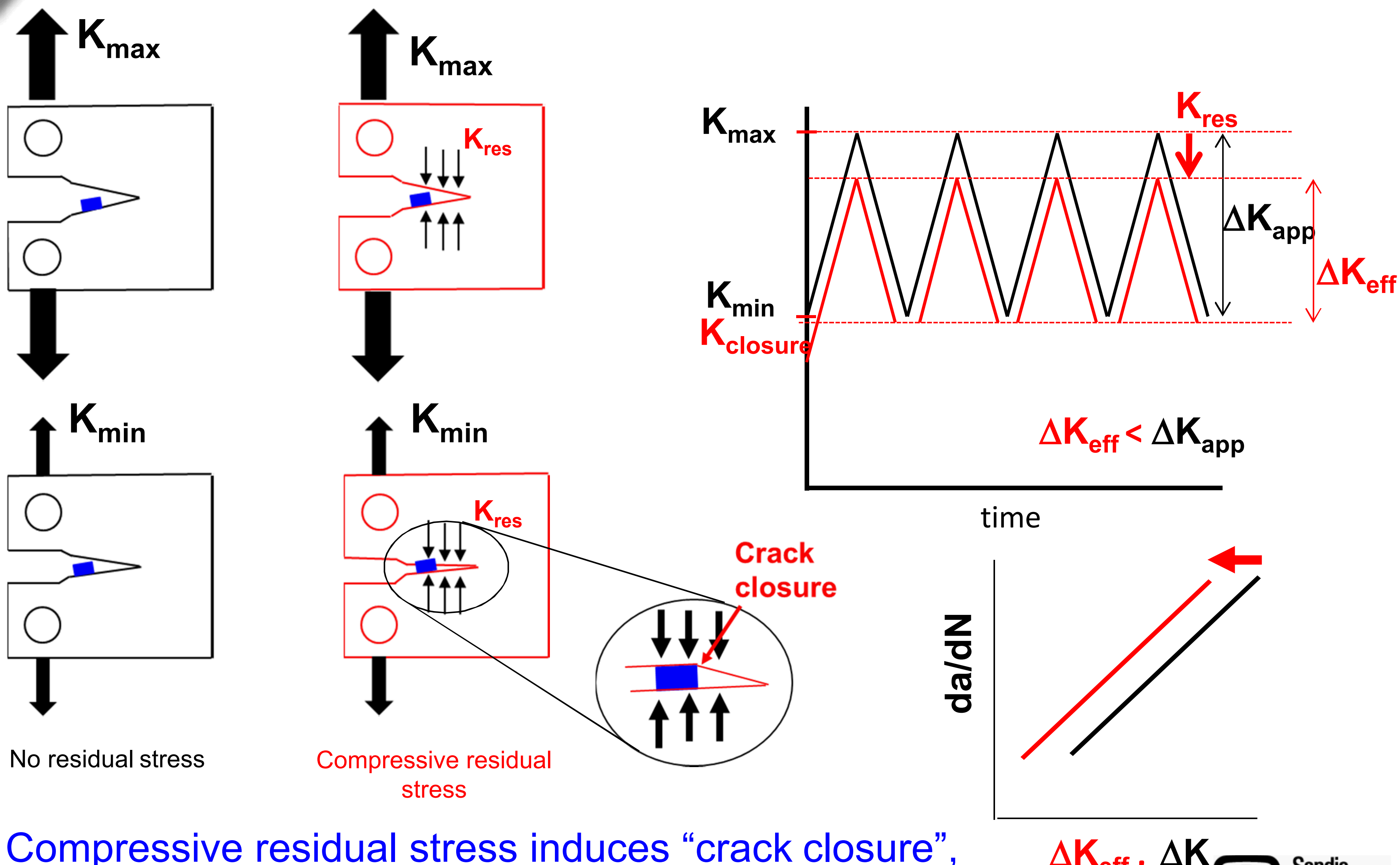
Repeatable da/dN vs. ΔK curves for BM, FZ, and HAZ in 21 MPa H_2





- Triplicate tests revealed repeatable results
- Results do not account for residual stress

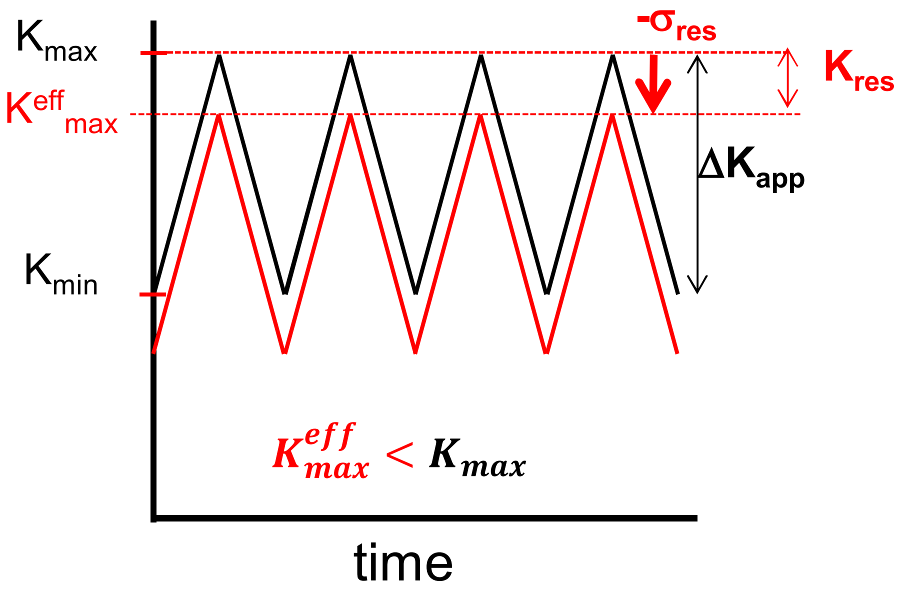
Analysis performed to account for effect of residual stress on crack-driving force

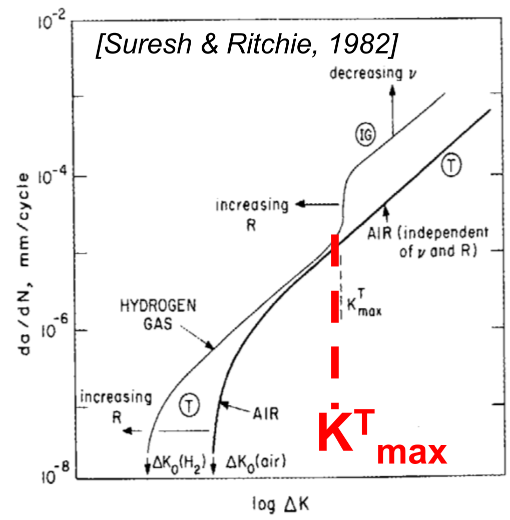


- Compressive residual stress induces "crack closure", reducing crack-driving force from ΔK to ΔK_{eff}

Residual stress can reduce K_{max} ~ affect onset of HA-FCG

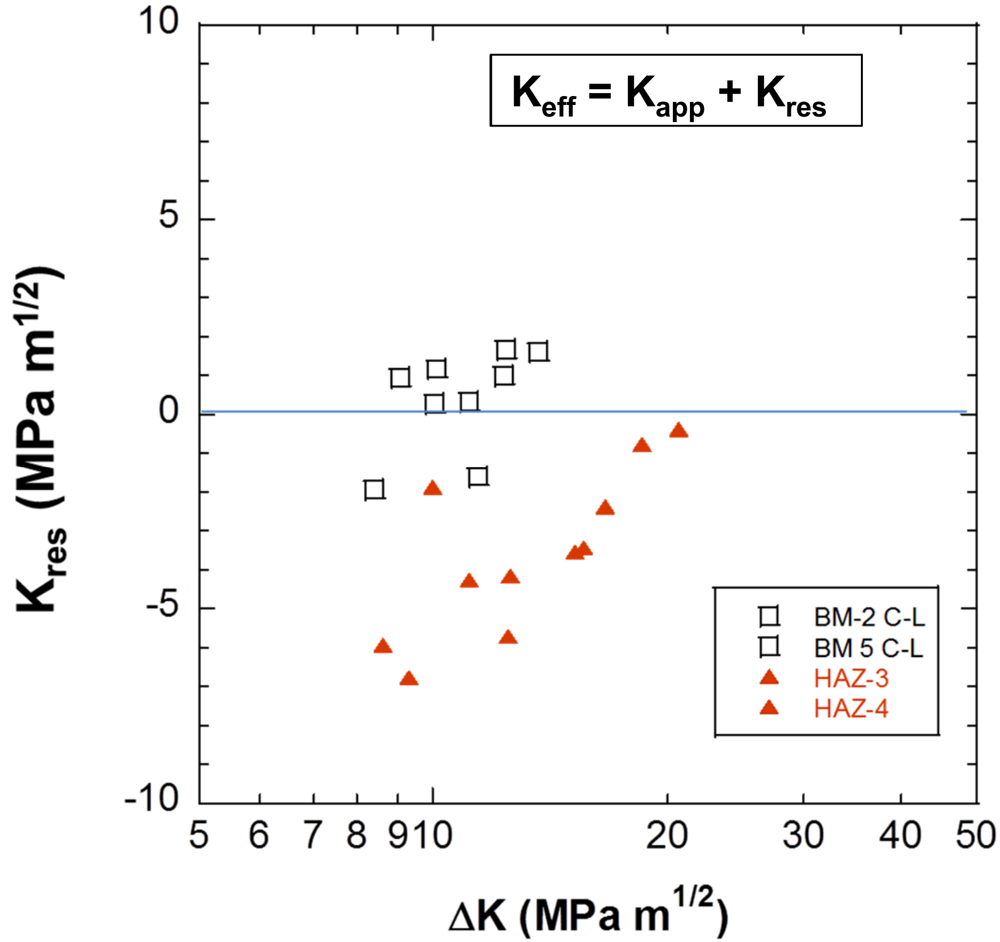
- **Compressive residual stress will reduce K_{max} to K^{eff}_{max}**





Compressive residual stress can reduce K^{eff}_{max}

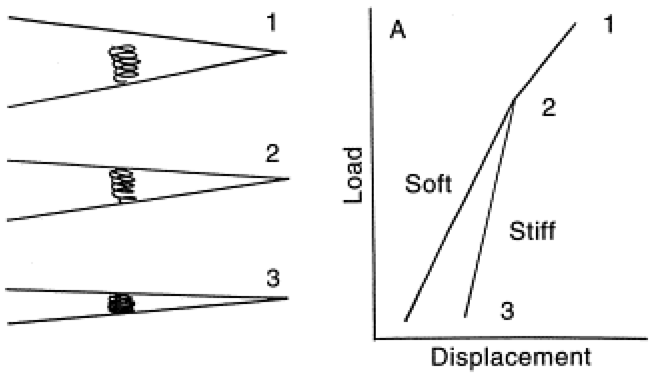
- **Calculated residual stress effect on K_{max} → K_{res}**
- **BM exhibited negligible K_{res}**
- **HAZ exhibited greater K_{res}**



(Lados, 2007)

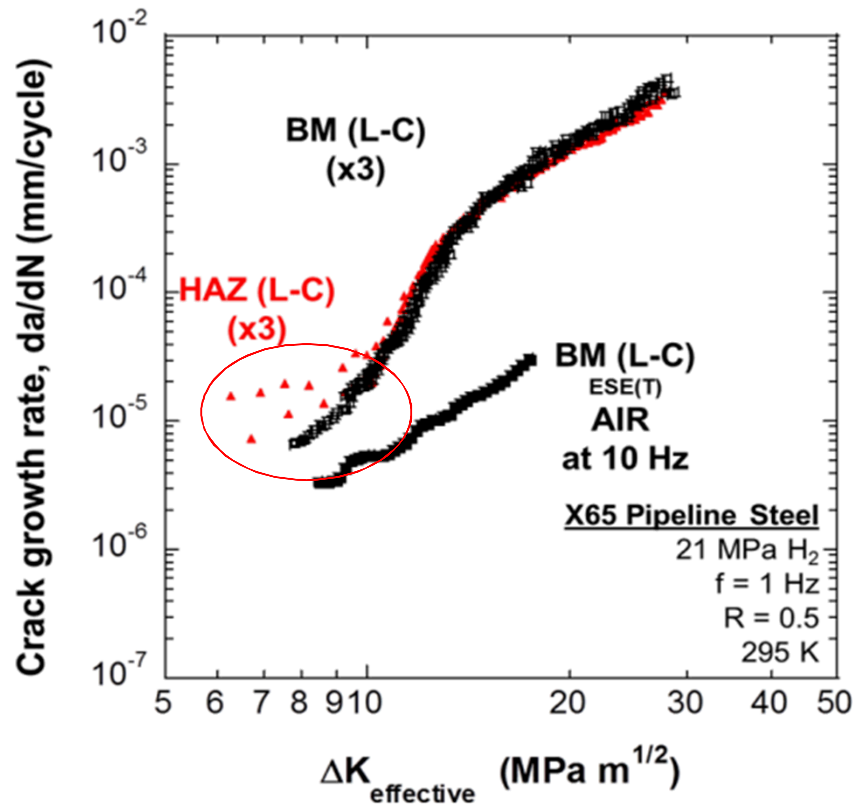
Reduction in K^{eff}_{max} could artificially shift the onset of HA-FCG to higher ΔK values

Crack closure reduces $\Delta K_{effective}$



(Donald, 1997)

- Crack closure: crack remains closed for portion of loading cycle
- Adjusted Compliance Ratio (ACR) method implemented to remove effects of closure
  → $\Delta K_{effective}$



- Reveals higher FCGR in HAZ compared to BM

Highlights importance in comparing intrinsic fatigue behavior

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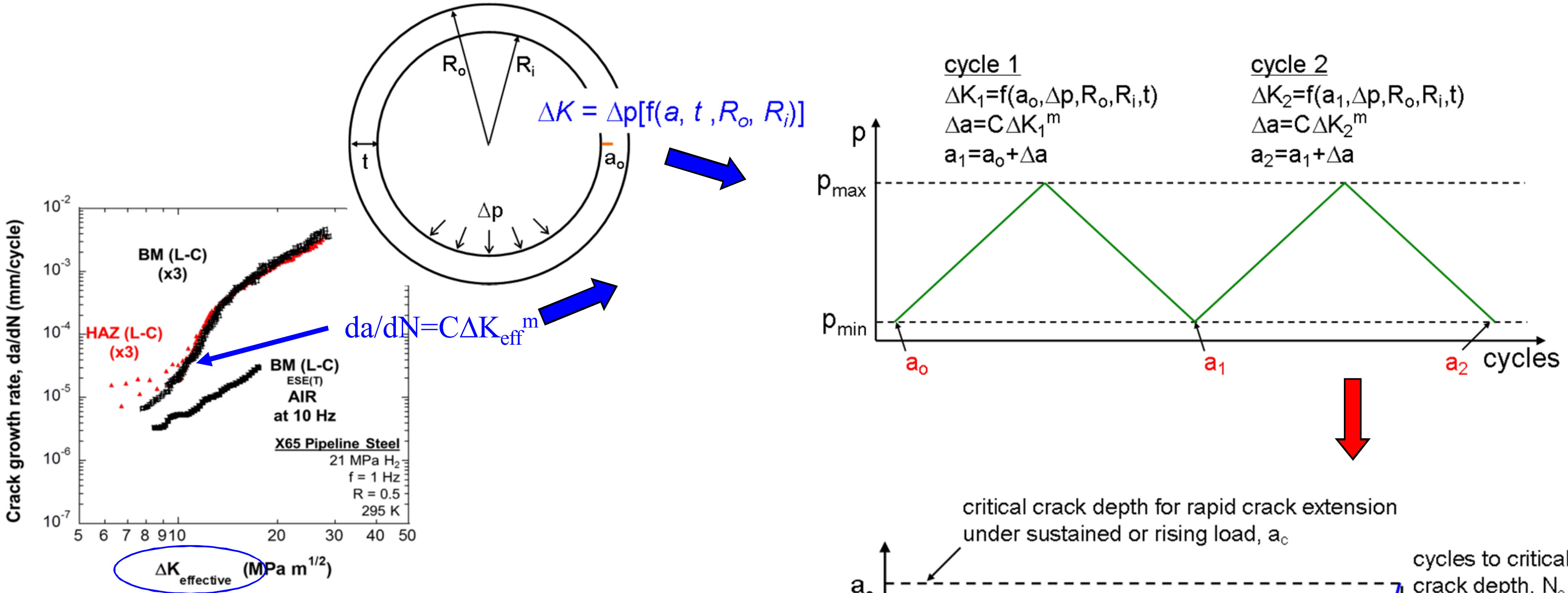
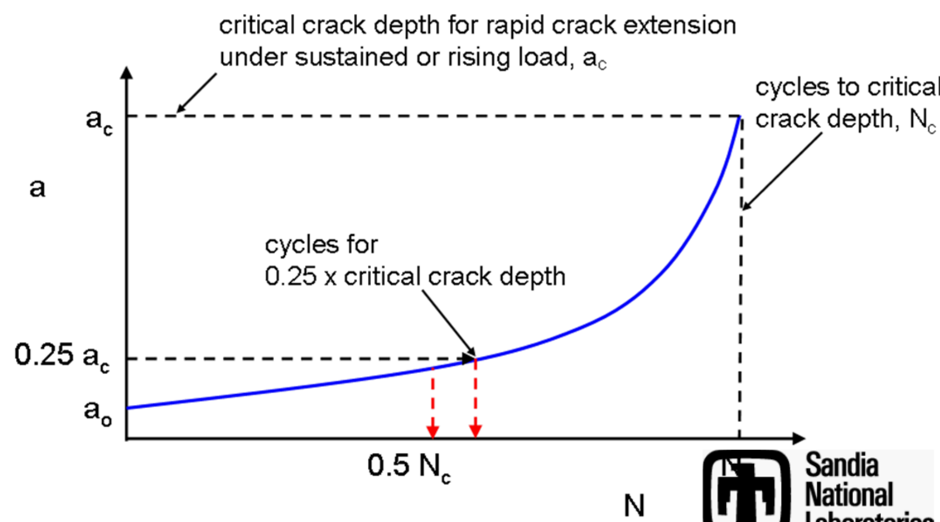
Measured fatigue crack growth relationships can be used to specify wall thickness for H_2 pipelines





- 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 H_2 gas, results were reproducible
  - Welds appear to be more susceptible to H_2-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…)

Acknowledgements / References

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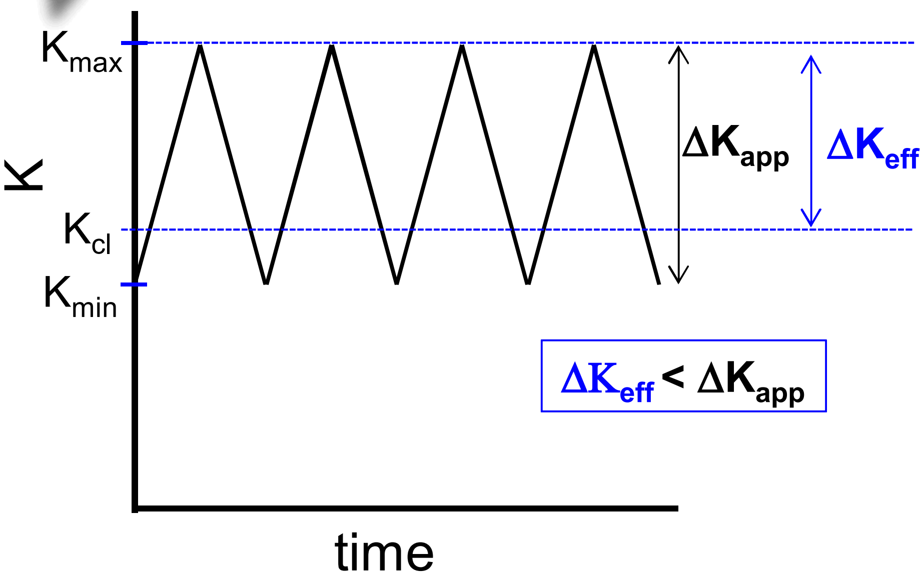
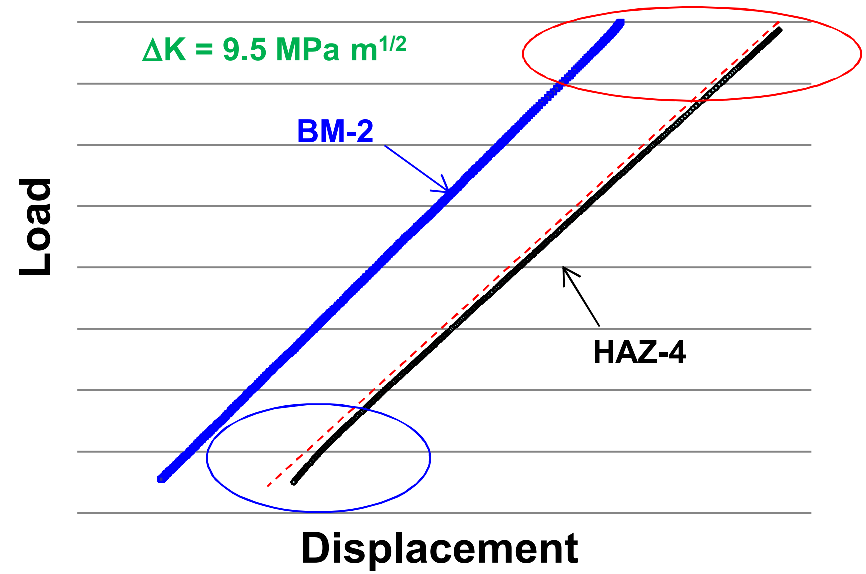
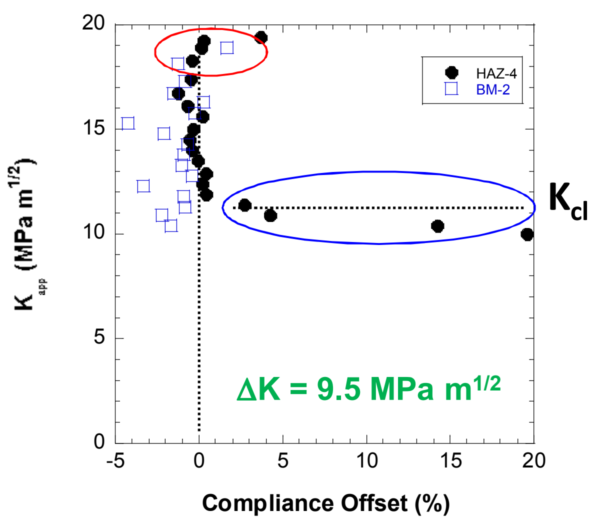
Back-up Slides

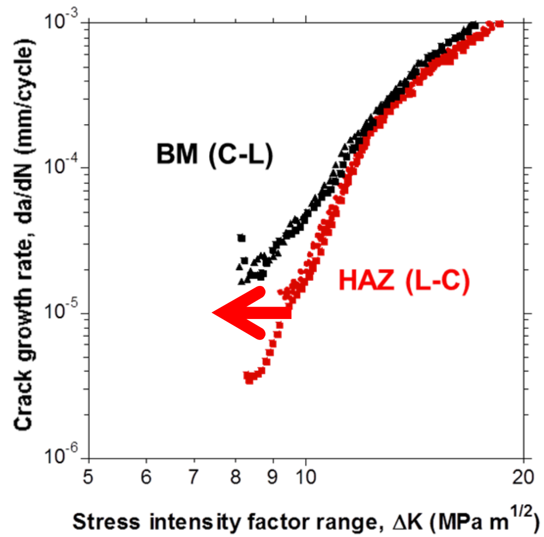
Crack closure appears to occur in HAZ even at R = 0.5, resulting in $\Delta K_{eff} < \Delta K_{applied}$







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



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

Possible sources of crack closure

- **Residual stress**
- **More pronounced Mode II loading**

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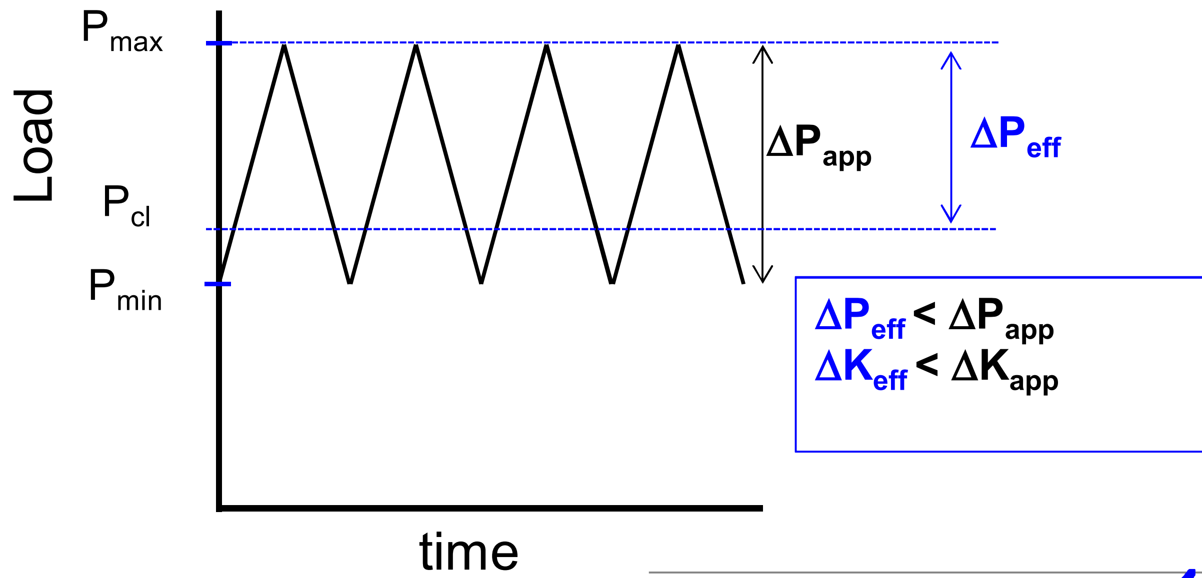
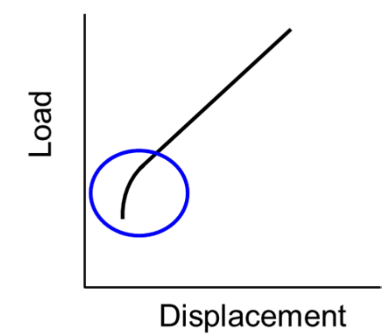
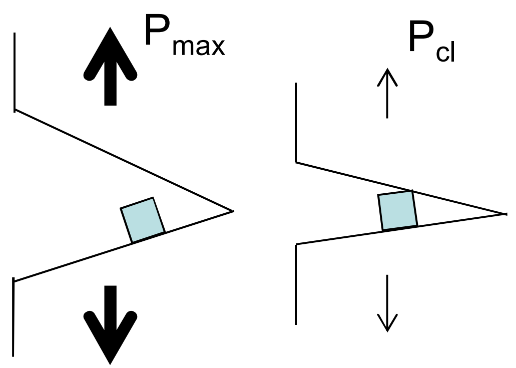
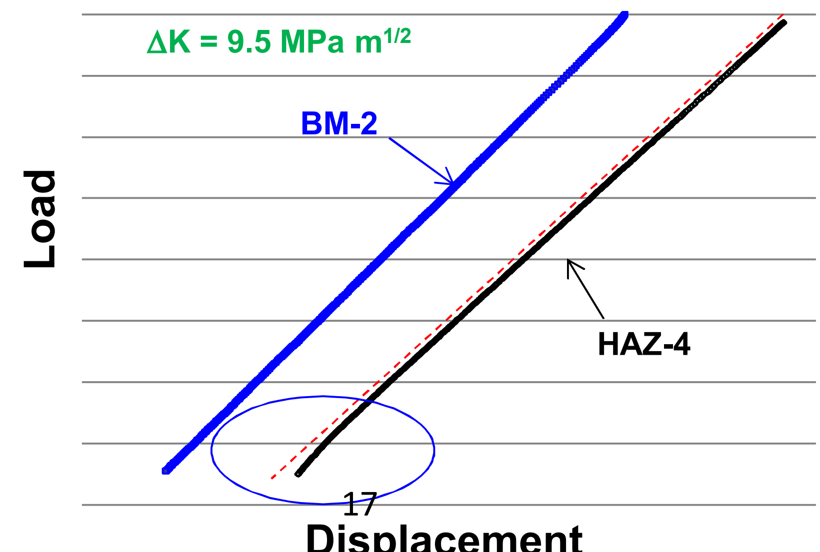
Crack closure: crack remains in closed position even when tensile load is applied

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



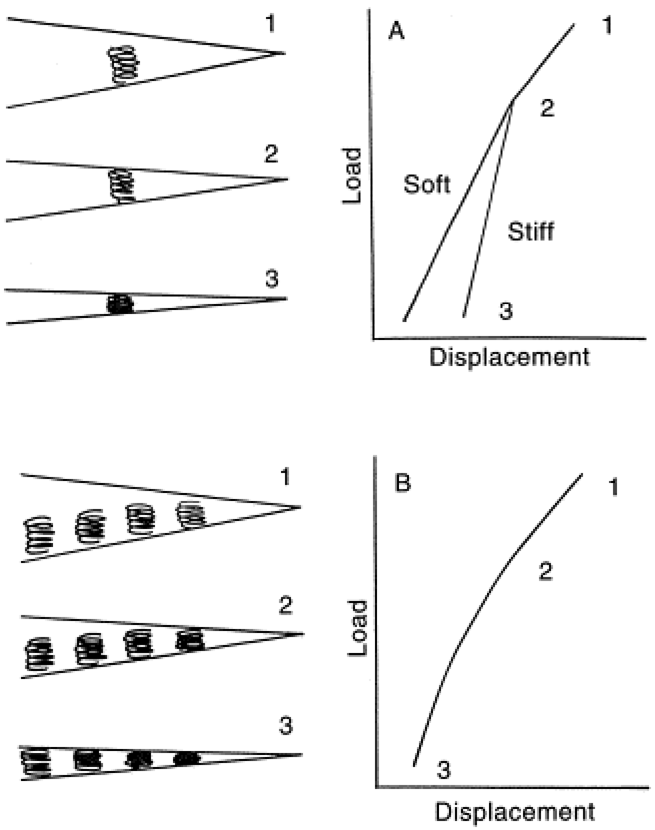


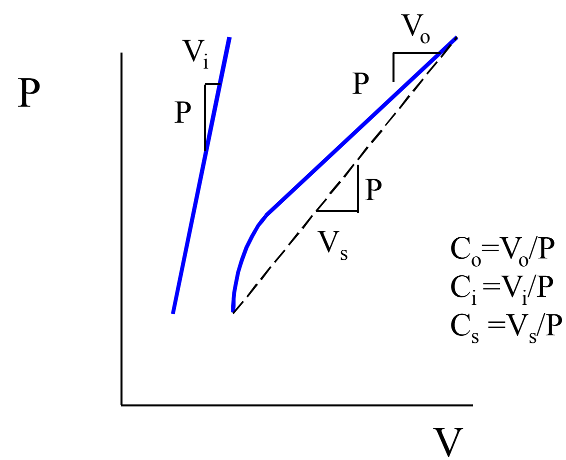




Adjusted Compliance Ratio (ACR) was used to correct for crack closure

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



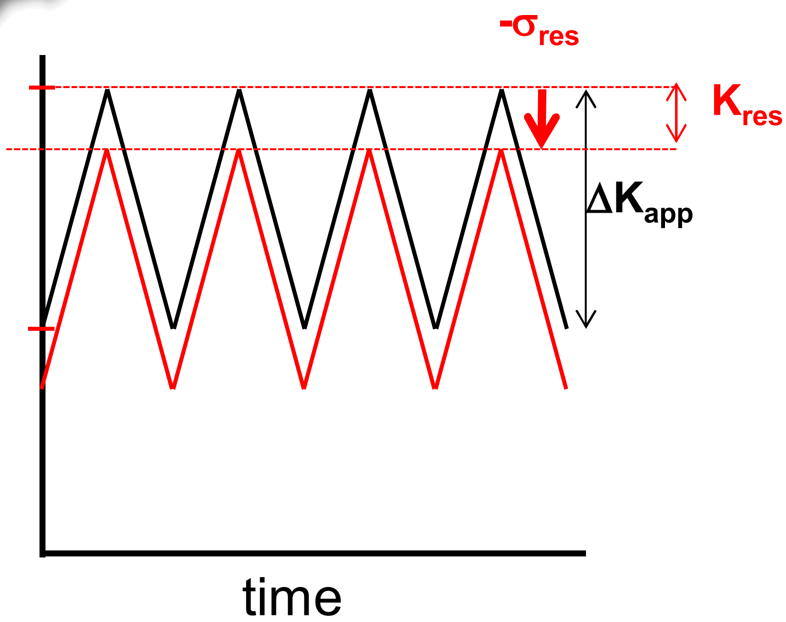


$$ACR = \frac{C_s - C_i}{C_o - C_i}$$

$$\Delta K_{effective} = \Delta K_{app} \; x \; ACR$$

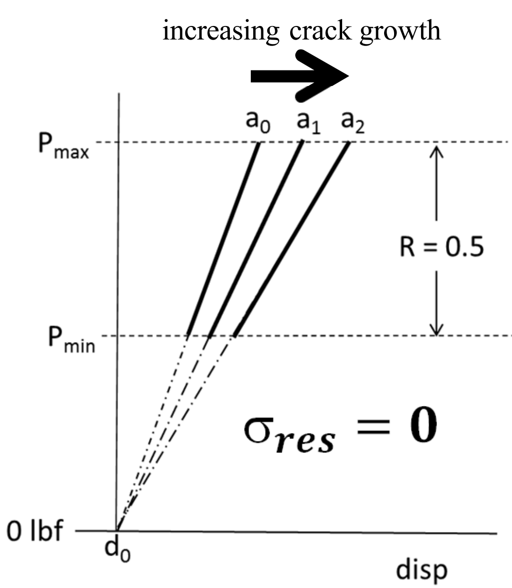
(Donald, J. K., 2007)

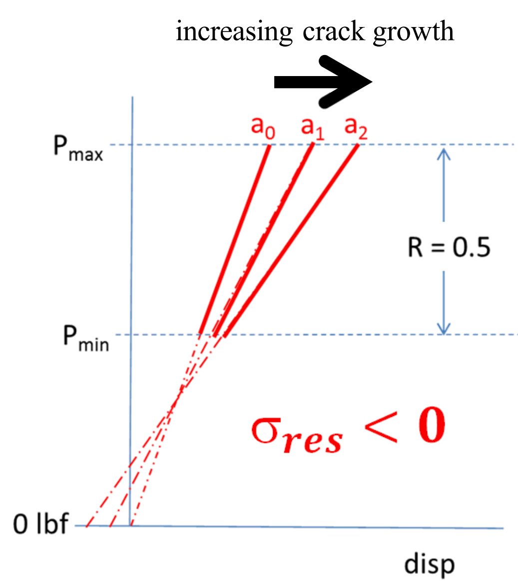
Compressive residual stress can reduce K^{eff}_{max}

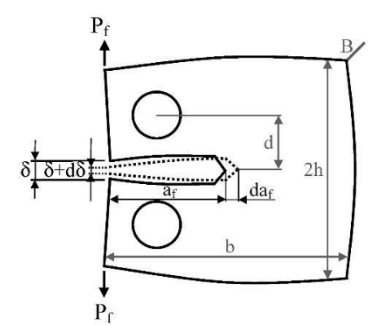


$$K^{eff}_{max} = K_{max} + K_{res}$$

- Calculate K_{res} from load-disp curves







{Lados, 2006}