SAND2015-3473C

H_2FC Hydrogen and Fuel Cells Program

Hydrogen Embrittlement of Structural Steels

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Sandia National Laboratories

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Project ID # PD025

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Overview

Timeline and Budget

- Project start date Jan. 2007
- FY14 DOE funding: $205K
- Planned FY15 DOE funding: $350K
- Total DOE project value: $1650K

Barriers & Targets

- K. Safety, Codes and Standards, Permitting
- D. High As-Installed Cost of Pipelines

Partners

- Federal Labs: ORNL, NIST
- Academia: International Institute for Carbon-Neutral Energy Research (I²CNER)
- Industry: ExxonMobil
- Standards Development Organizations: ASME

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*

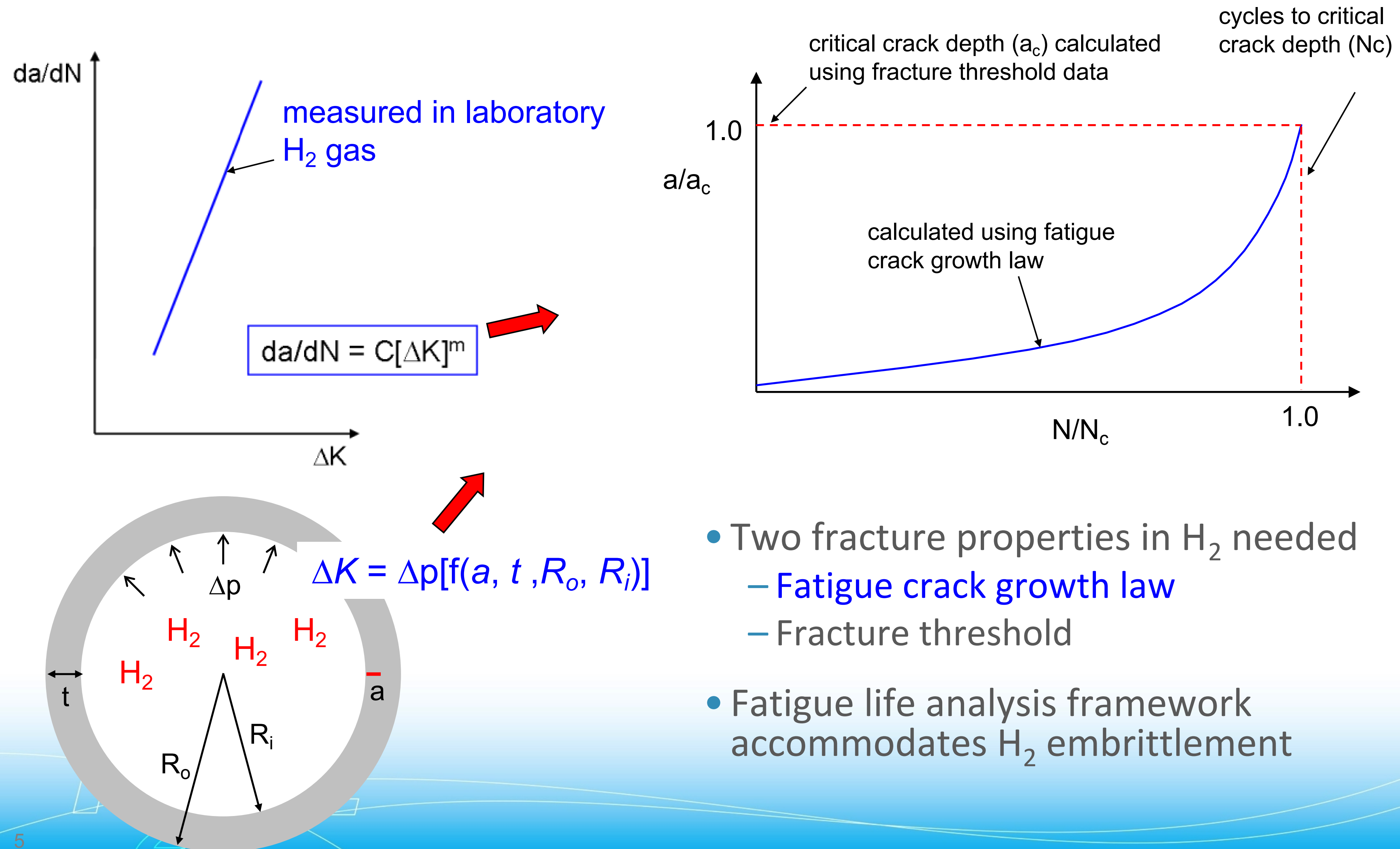
Project purpose is to:

- Enable data-informed design safety factors for hydrogen pipelines, which impacts both reliability/integrity and cost
  - Quantify fatigue crack growth aided by hydrogen embrittlement in pipeline steels, particularly for welds
- Answer specific questions about steel hydrogen pipelines
  - Are welds more susceptible to H_2-accelerated fatigue crack growth compared to base metal?
  - Do current techno-economic analyses need to assign a cost premium to steel hydrogen pipelines?
  - Can predictive microstructure-performance models be established to enable steel qualification for hydrogen pipelines?
- FY14-15 tasks
  - Measure fatigue crack growth laws in H_2 gas for pipeline friction stir welds

Approach

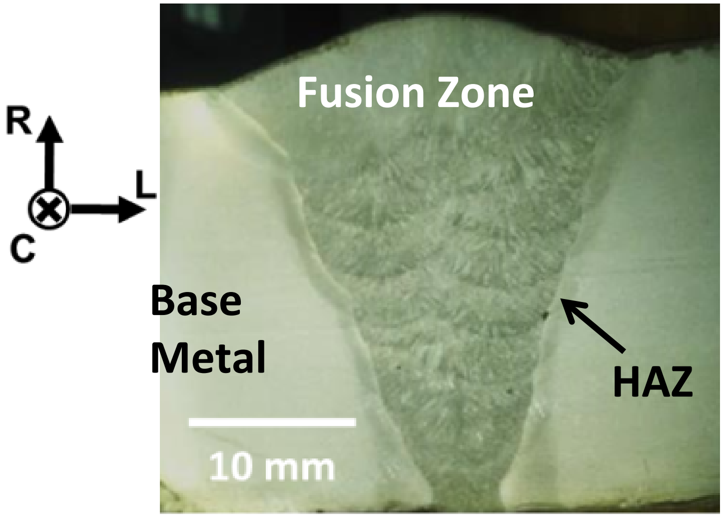
- Apply core capability to measure fatigue crack growth laws for steels in high-pressure H_2 gas
  - Fatigue crack growth laws serve as inputs into fatigue life analysis as referenced in ASME B31.12 code
  - Milestone: Complete fatigue tests on friction stir welds (at 1Hz, R=0.5, 3000 psi H_2 pressure) **(100% Complete)**
  - Milestone: Complete draft of peer-reviewed journal article on fatigue crack growth of X65 steel girth welds in H_2 **(75% Complete)**
  - Go/No-Go: Demonstrate that hydrogen diffusion governs H_2-assisted fatigue crack growth in pipeline steels **(50% Complete)**
- Pipeline steel welds were identified by stakeholders as a high priority
  - Provide feedback to stakeholders through ASME B31.12 committee

Fatigue life analysis framework in ASME B31.12 requires fracture mechanics measurements in H_2 gas

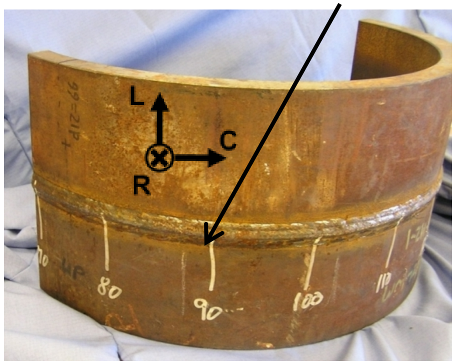


- Two fracture properties in H_2 needed
  - Fatigue crack growth law
  - Fracture threshold
- Fatigue life analysis framework accommodates H_2 embrittlement

H_2-assisted fatigue crack growth measured for steel girth welds: X65 gas metal arc weld and X52 friction stir weld

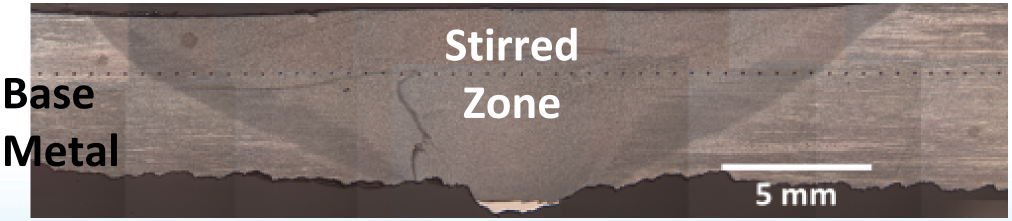


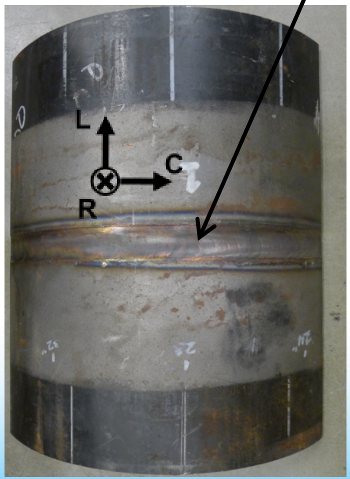
X65 gas metal arc weld (GMAW)



508 mm OD x 25.4 mm WT

X52 friction stir weld (FSW)

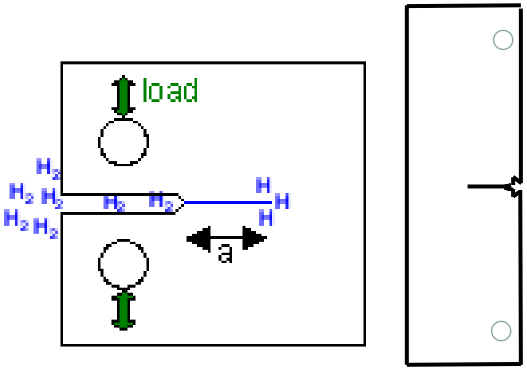


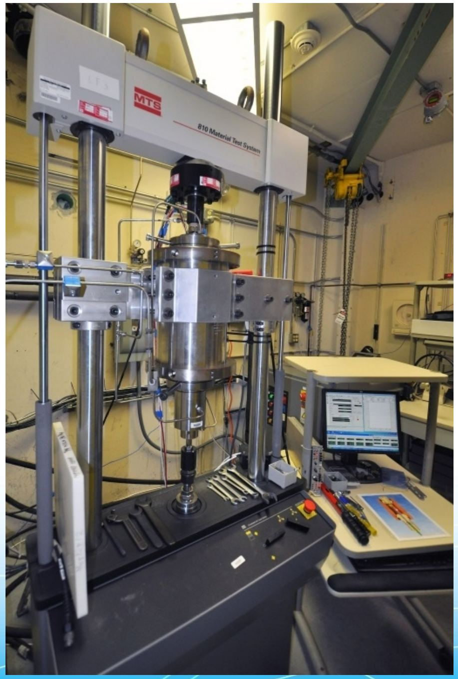


340 mm OD x 6.4 mm WT

- X52 friction stir welded pipe supplied by ORNL

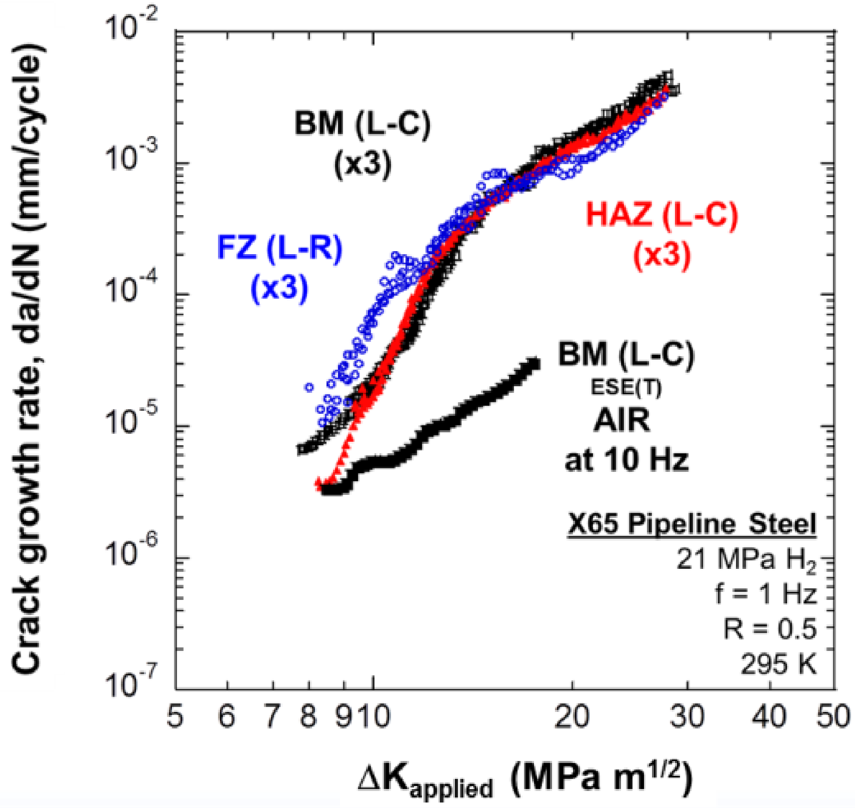
Fatigue crack growth laws measured in service environment, i.e. high-pressure H_2 gas

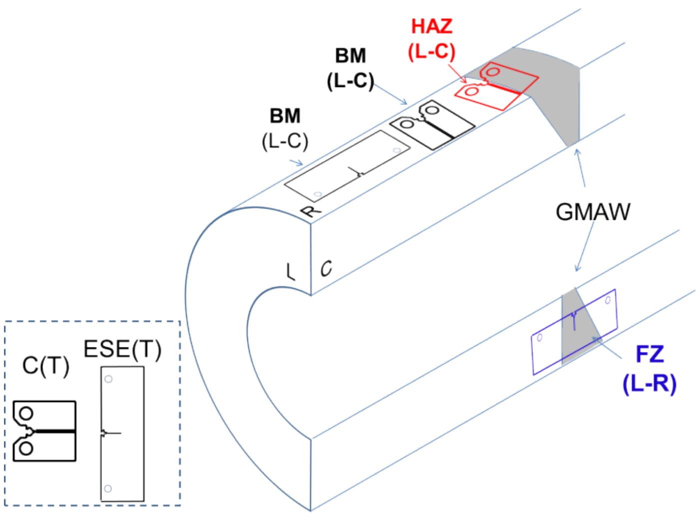




- Material
  - X65 gas metal arc weld (GMAW) and X52 friction stir weld (FSW)
- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude
- Environment
  - Supply gas: 99.9999% H_2
  - Pressure = 21 MPa (3,000 psi)
  - Room temperature

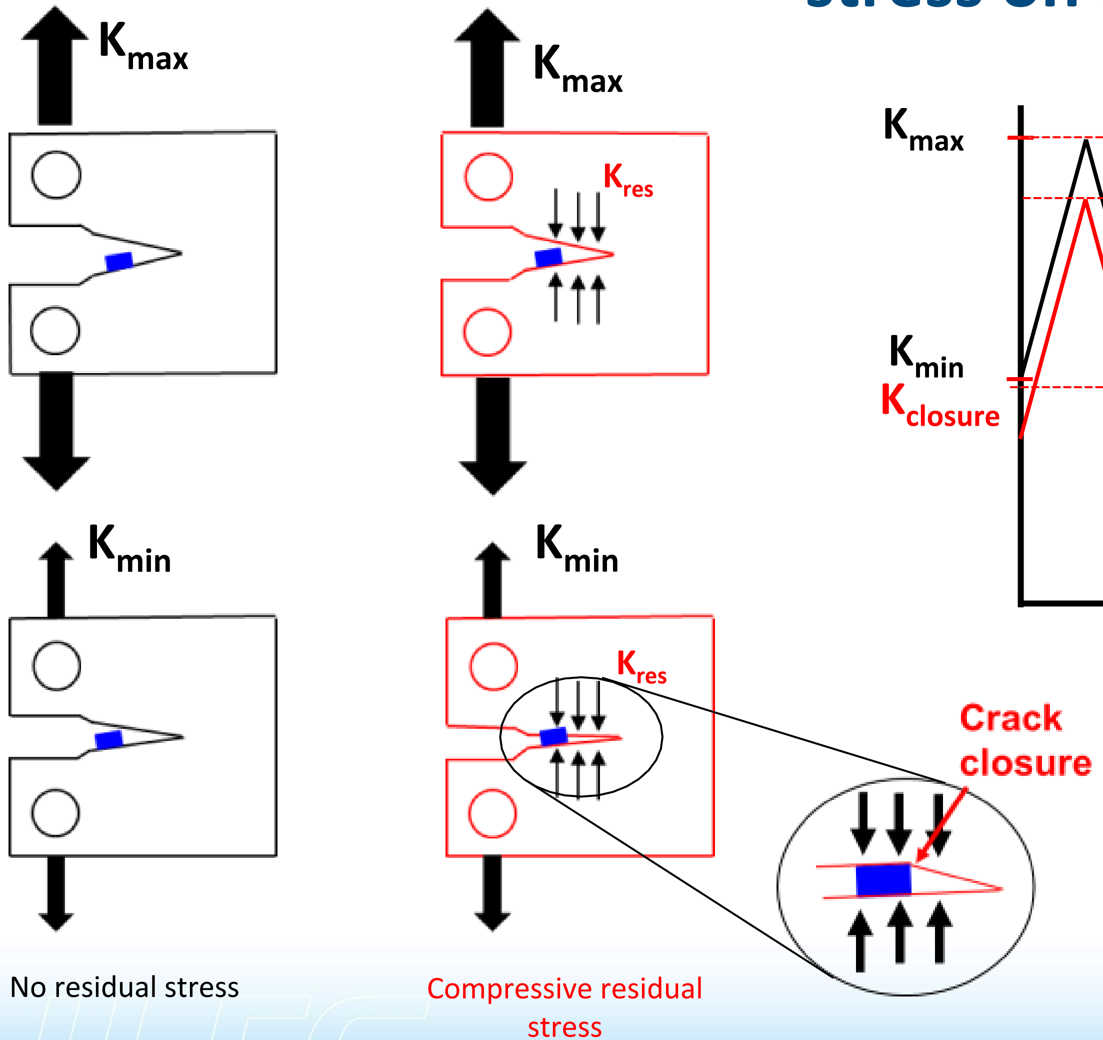
Completed triplicate measurements on base metal (BM), fusion zone (FZ) and heat affected zone (HAZ) for X65

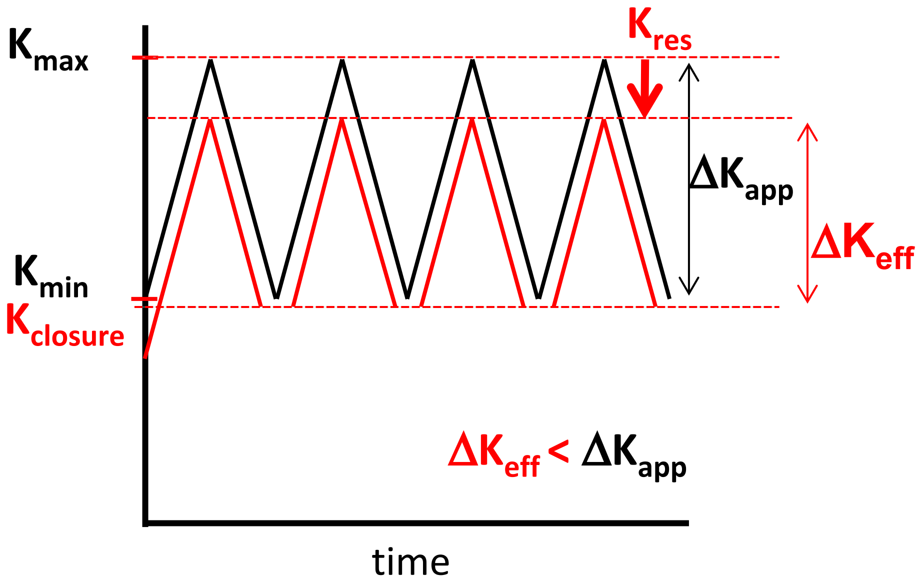


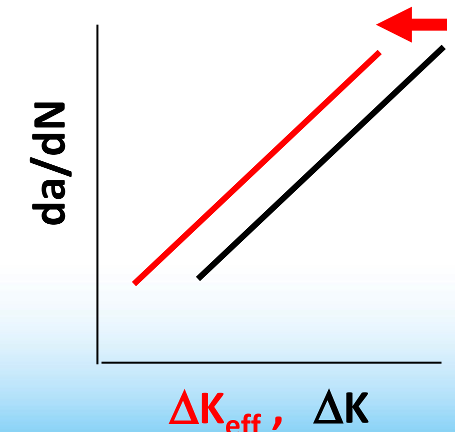


- Triplicate measurements for BM, FZ, and HAZ repeatable
- Results do not account for residual stress in weld

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

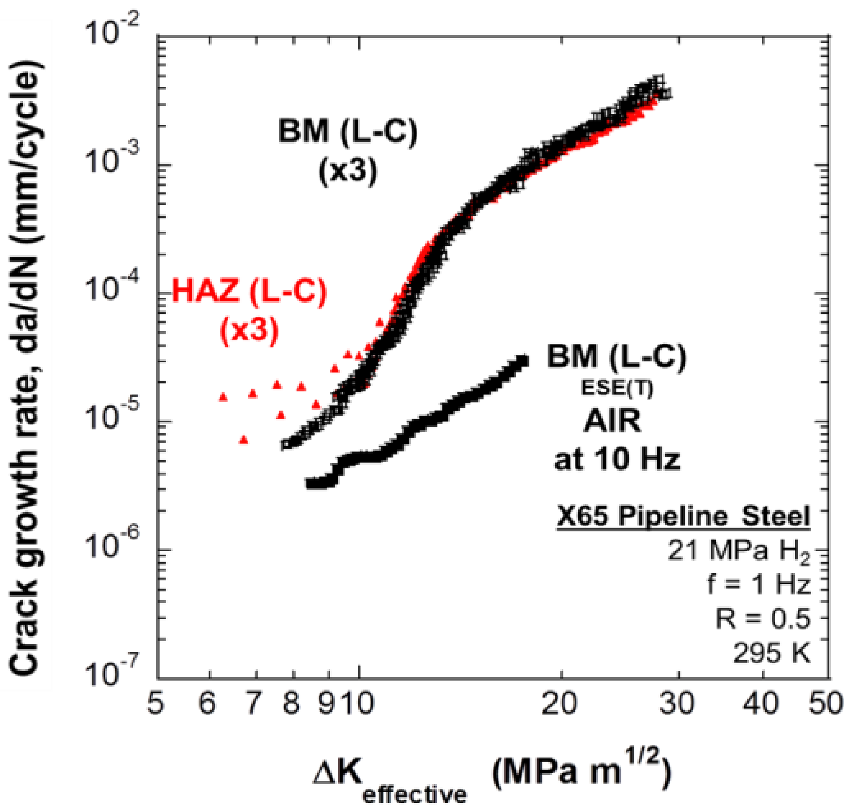


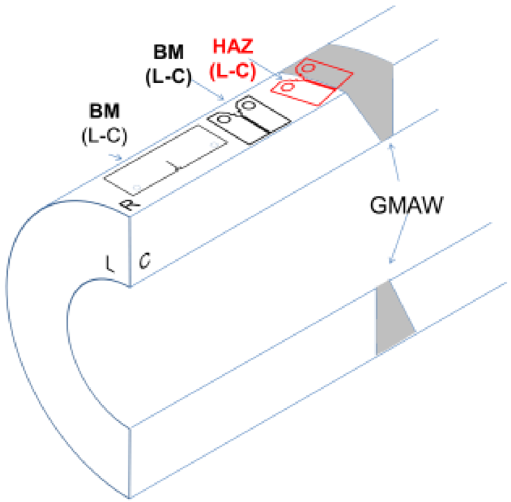




- Compressive residual stress induces "crack closure", reducing crack-driving force from ΔK to ΔK_{eff}

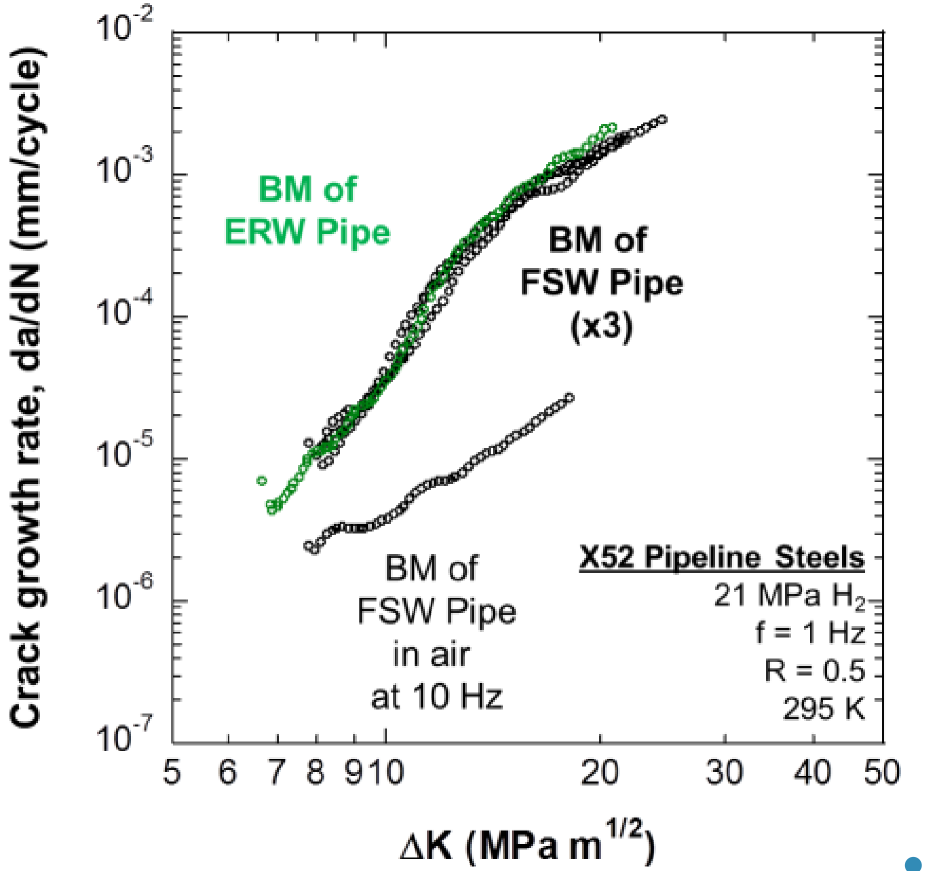
Correcting for crack closure reveals higher crack growth rates for heat-affected zone (HAZ) at lower $\Delta K_{effective}$

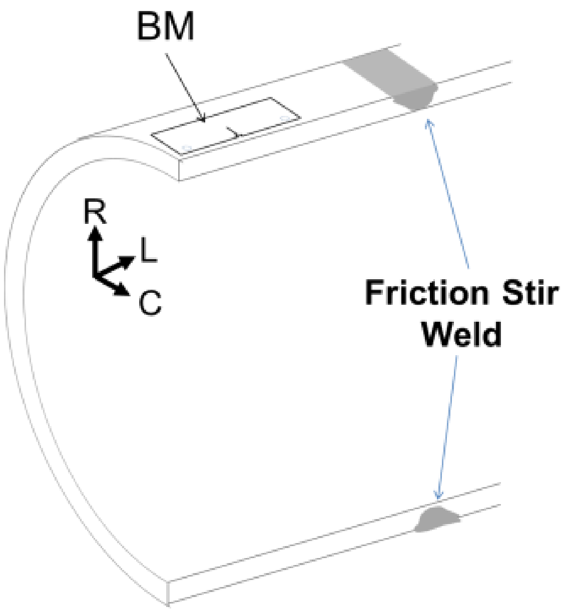




- Highlights importance of identifying extrinsic effects such as crack closure
- Crack closure corrections account for residual stress, providing more reliable relationships between crack growth rates and mechanical driving force

Completed triplicate fatigue crack growth rate measurements from base metal (BM) of friction stir weld

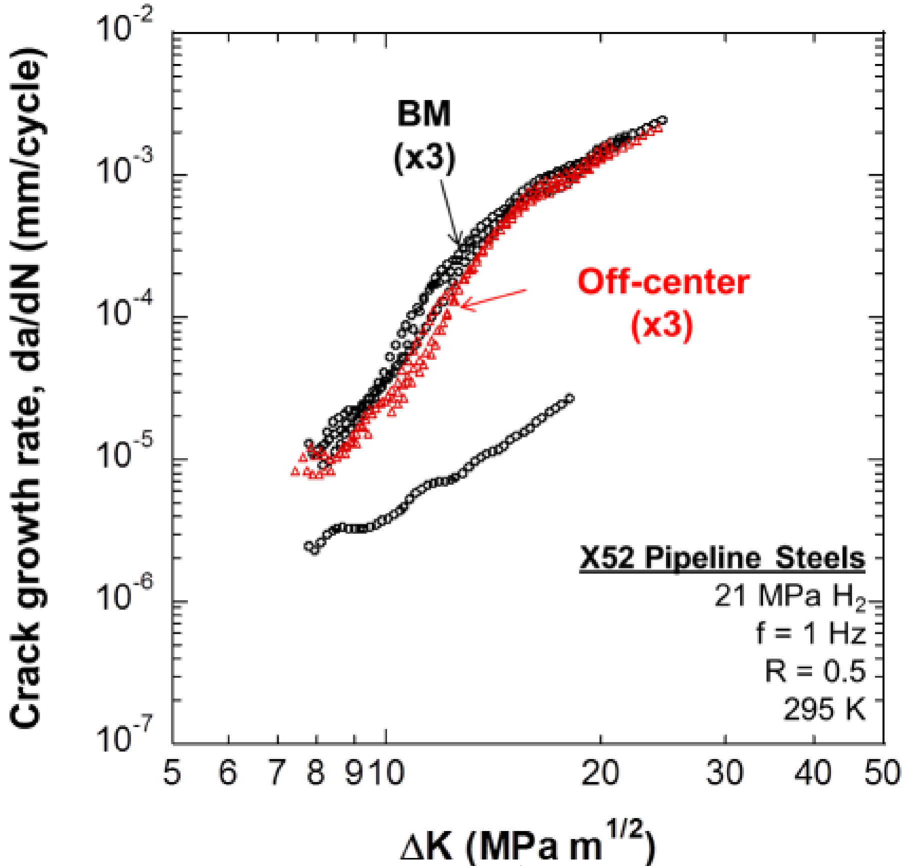


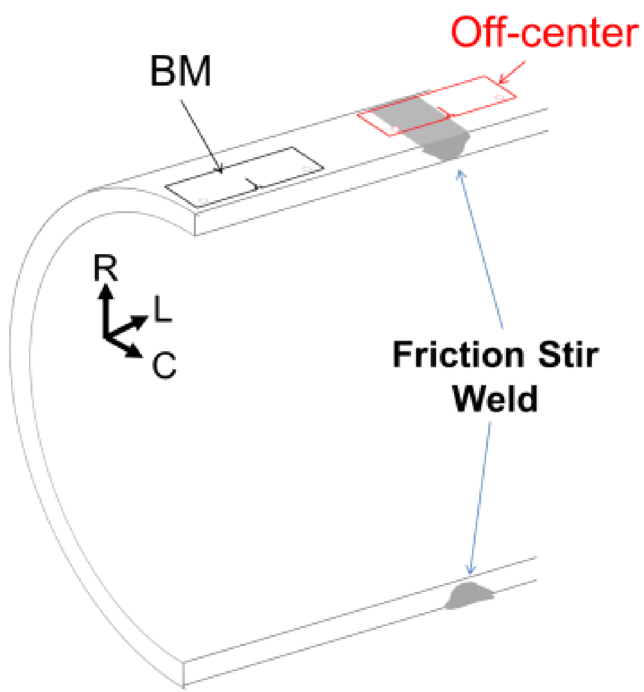


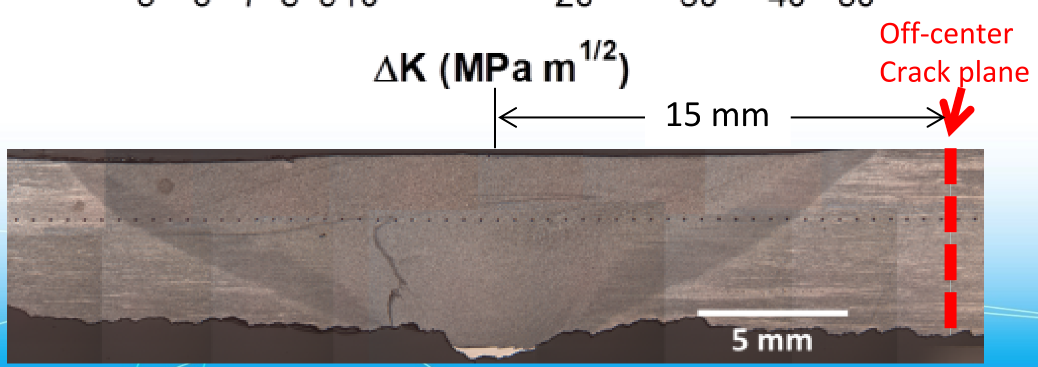
- X52 electric resistance welded (ERW) pipe: thickness = 12.7 mm, OD = 324 mm
- X52 friction stir welded (FSW) pipe: thickness = 6.4 mm, OD = 340 mm

- Crack growth rates are reproducible for two different X52 steels
- Crack growth rate measurements are repeatable for FSW pipe base metal (BM)

Completed triplicate fatigue crack growth rate measurements at off-center position in friction stir weld

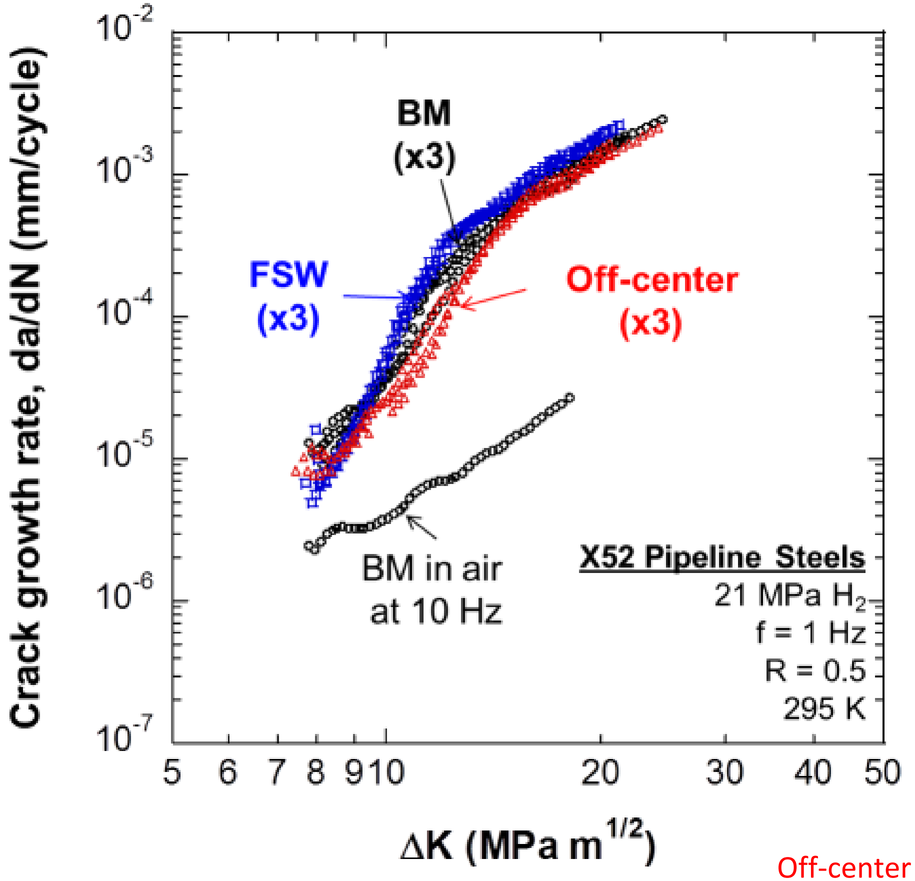


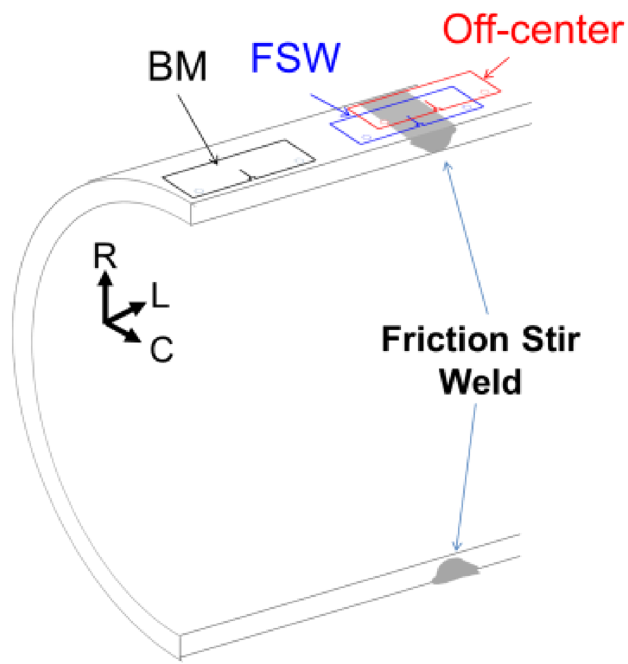


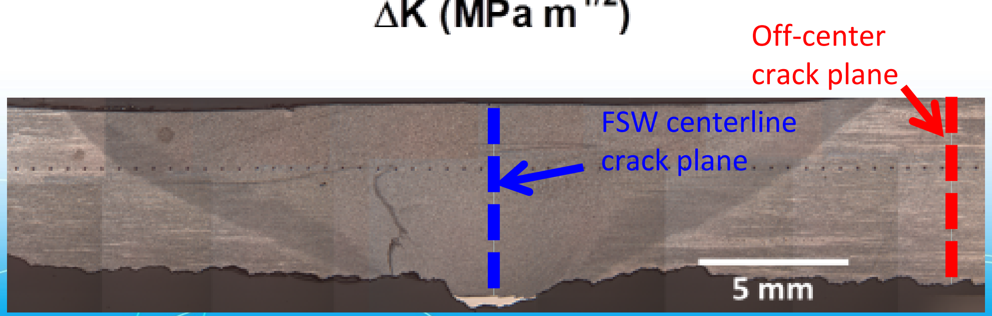


- Crack growth rate measurements at off-center position in friction stir weld are repeatable
- Crack growth rates at off-center position are modestly lower than rates for base metal (BM)

Completed triplicate fatigue crack growth rate measurements at friction stir weld (FSW) centerline



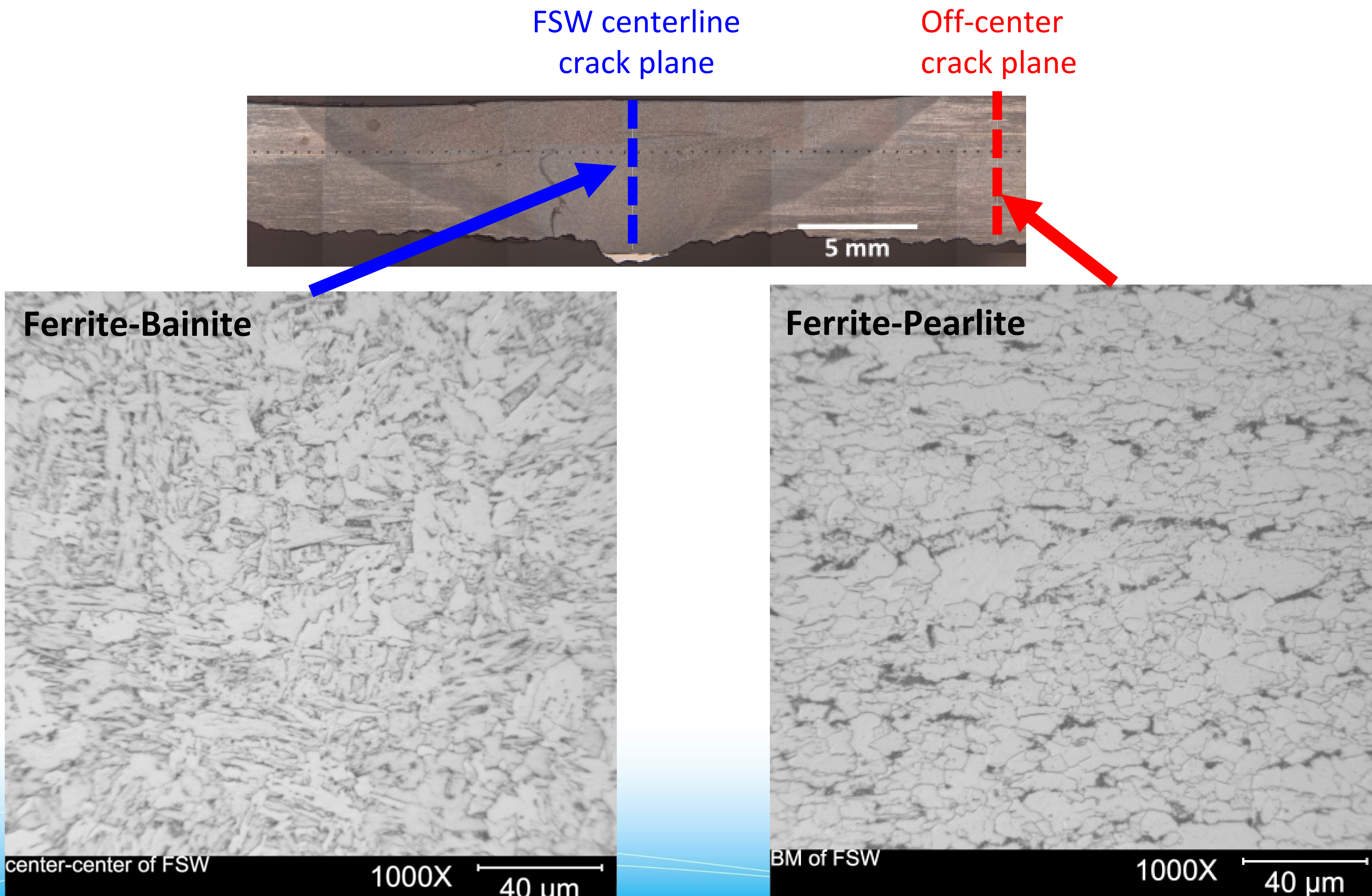




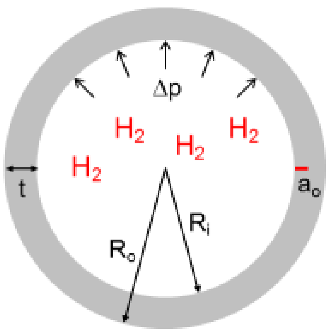
- Crack growth rate measurements at FSW centerline are repeatable
- Crack growth rates at center of FSW are higher than rates for base metal (BM)

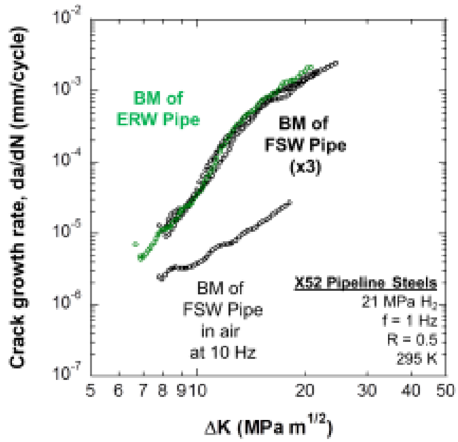
Accomplishment:

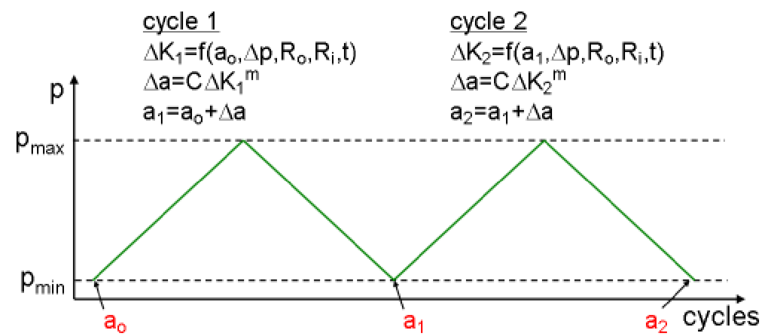
Differences in crack growth rates for FSW may be attributed to microstructure



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

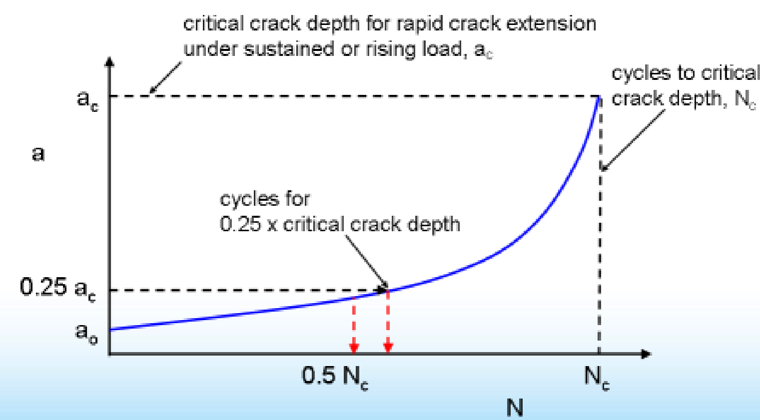






$\Delta K = \Delta p[f(a, t, R_o, R_i)]$

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



- 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 $0.5N_c$

Calculated wall thickness for steel H_2 pipeline depends on inputs such as pressure cycle and initial flaw depth

	Wall Thickness*	
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)

Wall thickness for H_2 pipeline may not exceed wall thickness for NG pipeline

- NG pipeline wall thickness calculated based on ASME B31.8
  - design pressure (P) = 3000 psi (21 MPa)
  - SMYS for X52 steel (S) = 52 ksi (359 MPa)
  - outside diameter = 24 in (610 mm)
  - Class 1 design factor (F) = 0.72
- Calculated wall thickness = 0.96 in (24.4 mm)

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

P = design pressure
S = SMYS
t = thickness
D = outside diameter
F= design factor
E = longitudinal joint factor = 1
T = temp derating factor = 1

Responses to Previous Year Reviewers' Comments

1. *"Future work needs to consider alternative welding approaches under consideration by the pipeline industry (e.g., friction stir welding); "…and look at girth weld with ORNL friction stir welded pipeline steel as planned."*

   As demonstrated on accomplishments slides 11-13, this project successfully completed the milestone of measuring fatigue crack growth laws in H_2 gas for friction stir welded pipe supplied by ORNL.

2. *"Future work is on track to meet DOE goals, except there are no efforts on cost analyses"; "The project should show how this information will be used to calculate steel pipe thickness for given conditions for hydrogen transport."; "There is a need to have models developed that will calculate wall thickness based on realistic operation and inspection parameters."*

   As presented on accomplishment slide 16, calculations were performed to determine minimum wall thickness to attain 50-year pipeline life, based on presumption that H_2-accelerated fatigue crack growth dictates life. These preliminary calculations provide insight into cost for steel H_2 pipelines by comparing calculated minimum wall thickness for H_2 pipelines to specified minimum wall thickness for NG pipelines.

3. *"More effort should go into collaborating with current pipeline companies"; "The project could benefit from a wider variety of stakeholder partnerships"; "A more complete sampling of steel pipe from multiple vendors would have improved this project"; "It is unclear whether the project team is doing enough to determine the usefulness of research for industries."*

   The project team is making a more concerted effort to participate in the ASME B31.12 committee. Since this committee is comprised of stakeholders from industrial gas companies, R&D laboratories, and regulatory agencies, it is expected that active participation in the committee will enhance project impact and partnership development.

Collaborations

- NIST
  - Coordinate projects and exchange data on pipeline steel testing → leveraging resources critical given limited number of H_2 test facilities
  - Collaboration to develop predictive, physics-based model of H_2-accelerated fatigue crack growth
- Oak Ridge National Laboratory (ORNL)
  - Supplied friction stir welded X52 pipeline steel → essential for completing milestone on measuring fatigue crack growth laws in H_2 gas
- ExxonMobil
  - Supplied X65 pipe with gas metal arc weld → enabled measurement of fatigue crack growth laws in H_2 gas for technologically relevant girth weld
- ASME B31.12 committee
  - Stakeholders from industrial gas companies, R&D laboratories, and regulatory agencies provide guidance on R&D needs for H_2 pipelines
- International Institute for Carbon-Neutral Energy Research (I^2CNER)
  - Collaboration to develop predictive, physics-based model of H_2-accelerated fatigue crack growth

Remaining Challenges and Barriers

- Establish data-informed safety factors for steel H_2 pipelines, particularly for high-strength steels
  - 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

Proposed Future Work

- Remainder of FY15
  - Complete draft of peer-reviewed journal article on measurement of fatigue crack growth laws for friction stir welds in H_2 gas (milestone)
  - Complete tests on fine grain and coarse grain ferrite-pearlite steel to evaluate effect of ferrite grain size on H_2-accelerated fatigue crack growth for the purpose of informing predictive modeling (milestone)
  - Complete draft of peer-reviewed journal article on measurement of H_2-accelerated fatigue crack growth for steels with varying grain size (milestone)

- FY16
  - Identify and evaluate next-generation steels and welding technologies for H_2 pipelines
    - Example: Measure fatigue crack growth laws in H_2 gas for high-strength X80 steels to impact safety and cost by informing design safety factors in ASME B31.12
  - Continue basic research collaboration with NIST and I^2CNER to define mechanisms of H_2-accelerated fatigue crack growth in steels and develop predictive, physics-based models of this phenomenon

Technology Transfer Activities

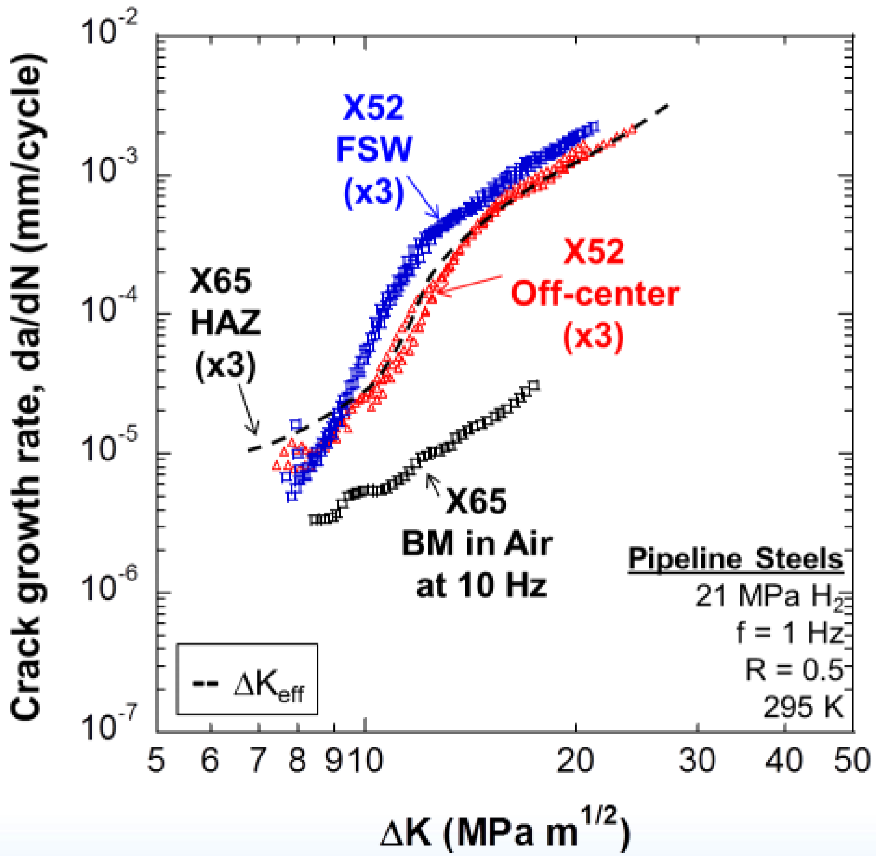
- Communicate data on fatigue crack growth of pipeline steels in H_2 gas to ASME B31.12 committee
  - Data-informed safety factors in ASME B31.12 essential for cost-effective deployment of steel H_2 pipelines
  - Presented results for X65 girth weld at ASME B31.12 committee meeting in March 2015

Summary

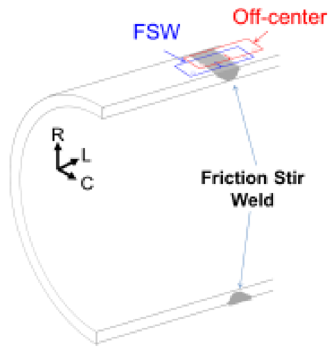
- Measured fatigue crack growth laws enable data-informed safety factors for steel H_2 pipelines
  - Fatigue crack growth laws are inputs to fatigue life analysis referenced in ASME B31.12 code
  - Analysis enables calculation of steel pipeline wall thickness for specified number of pressure cycles
- Fatigue crack growth laws measured in H_2 gas for X65 gas metal arc weld refined by accounting for residual stress-induced “crack closure”
- Fatigue crack growth laws measured in H_2 gas for X52 friction stir welded pipe at three locations: base metal, weld off-center position, weld centerline
  - Crack growth rates higher at weld centerline compared to base metal and off -center positions
- Employing X52 crack growth laws as inputs, fatigue life analysis indicates that H_2 pipeline wall thickness may not exceed NG pipeline wall thickness
  - H_2 pipelines may not require cost premium relative to NG pipelines

Technical Back-Up Slides

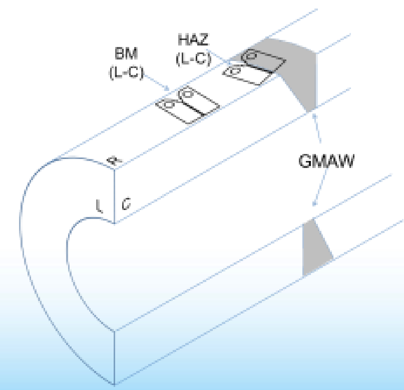
Fatigue crack growth rates for FSW centerline modestly higher than rates for GMAW heat affected zone (HAZ)



X52 friction stir weld (FSW)

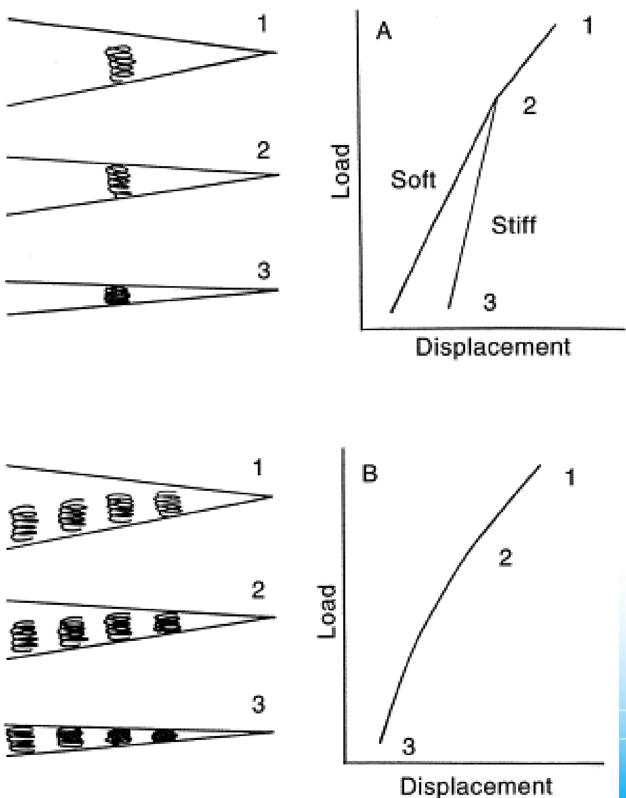


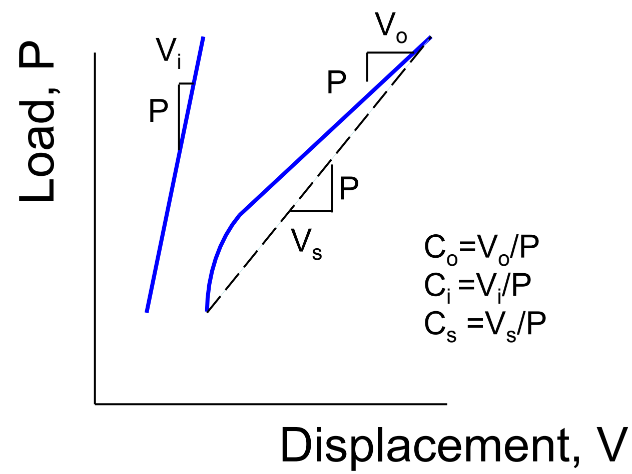
X65 gas metal arc weld (GMAW)



Crack closure analysis employed adjusted compliance ratio (ACR) method

- Adjusted compliance ratio (ACR): ASTM E647-13a approved method
- Alternative method is ASTM 2% Compliance Offset
- Both methods are used to calculate $\Delta K_{effective}$
- $\Delta K_{applied} > \Delta K_{effective}^{ACR}$





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

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

(Donald, J.K. 2007)

Reviewer-Only Slides

Critical Assumptions and Issues

1. Applying the results from this project to inform cost assessments for steel hydrogen pipelines depends on realistic specifications for the pipeline outside diameter, pressure cycle range, and detection limit for flaws in the pipeline wall. This information must be provided by the relevant stakeholders, e.g., hydrogen fuel pipeline operators.

2. Measurement of fatigue crack growth rate relationships for pipeline steels in hydrogen gas is focused on girth welds and seam welds. Fusion welds are intrinsically inhomogeneous, exhibiting gradients in microstructure as well as residual stress. Consequently, measurements of crack-growth properties can be challenging, since crack extension in standardized laboratory specimens can be non-uniform. Such non-uniform crack extension can compromise data analysis and cast uncertainty on the quality and reliability of the results. While the milestones for this project are focused on measurements of the fatigue crack growth relationships to enable reliability/integrity assessment of steel hydrogen pipelines, some effort is likely needed to develop more confidence in the test methods and procedures. This project is prepared to explore several potential pathways to improve test-method reliability, including different laboratory specimen designs.

3. We are dependent on stakeholders to supply technologically relevant materials for testing. It is imperative that we generate data for materials that represent those used in service. To date, we have been able to receive some materials through our interactions with stakeholders, e.g., ExxonMobil. We must maintain and expand relationships with stakeholders so that we continue to have access to materials.

Publications and Presentations

1. “Assessing Gaseous Hydrogen Assisted Fatigue Crack Growth Susceptibility of Pipeline Steel Weld Fusion Zones and Heat Affected Zones,” J. Ronevich and B. Somerday, 15th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics, Anaheim, CA, May 2015.

2. “Hydrogen Embrittlement of Pipeline Steels and Welds”, J. Ronevich and B. Somerday, ASME B31.12 Hydrogen Piping and Pipelines Section Committee Meeting, Atlanta, GA, March 2015

3. “Hydrogen Embrittlement of Pipeline Steels in Base Metal and Welds”, J. Ronevich and B. Somerday, Joint Delivery-Codes & Standards Tech Team Meeting, Sacramento, CA, Jan. 2015.

4. “Advancing Hydrogen Pipeline Integrity Management: Quantifying Susceptibility of Steel Welds to Hydrogen Gas-Accelerated Fatigue Crack Growth”, J. Ronevich and B. Somerday, International Conference on Fatigue Damage of Structural Materials X, Hyannis MA, Sept. 2014.

5. “Assessing Hydrogen Pipeline Reliability: Quantifying Susceptibility of Pipeline Steels to Hydrogen Gas -Accelerated Fatigue Crack Growth”, B. Somerday and J. Ronevich, ASME 12th Fuel Cell Science, Engineering and Technology Conference, Boston, MA, June 30 - July 2, 2014.