Hydrogen Embrittlement of Structural Steels

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Overview

Timeline

- Project start date Jan. 2007
- Project end date Oct. 2013*

*Project continuation and direction determined annually by DOE

Barriers & Targets

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

Budget

- FY13 DOE funding: $105K
- Planned FY14 DOE funding: $210K
- Total DOE project value: $1300K

Partners

- Federal Labs: ORNL, NIST
- Academia: International Institute for Carbon-Neutral Energy Research (I^2CNER)
- 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:

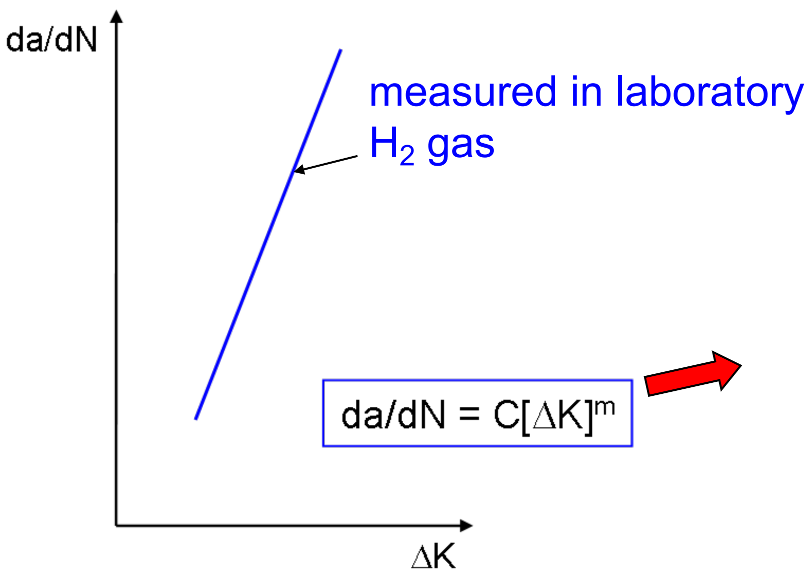
- Demonstrate reliability/integrity of steel hydrogen pipelines for *cyclic pressure* applications
  - Address potential fatigue crack growth aided by hydrogen embrittlement, particularly in welds
- Answer specific questions about steel hydrogen pipelines
  - Are welds more susceptible to H_2-accelerated fatigue crack growth compared to base metal?
  - Can microstructure-performance relationships be established to enable steel qualification for hydrogen pipelines?
  - Do current techno-economic analyses need to assign a cost premium to steel hydrogen pipelines?
- FY13-14 tasks
  - Measure fatigue crack growth laws in H_2 gas for pipeline steel girth welds

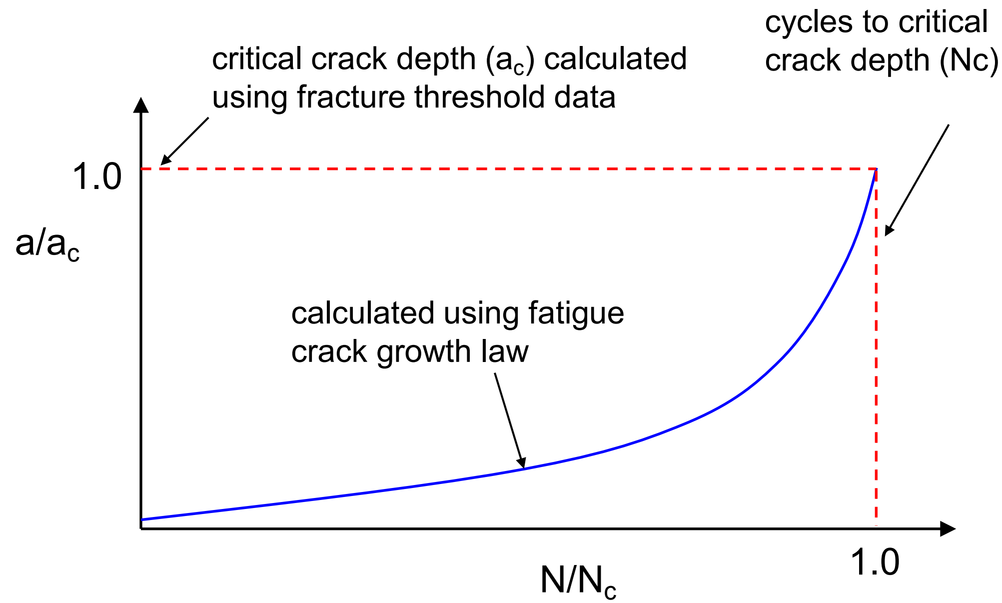
Approach

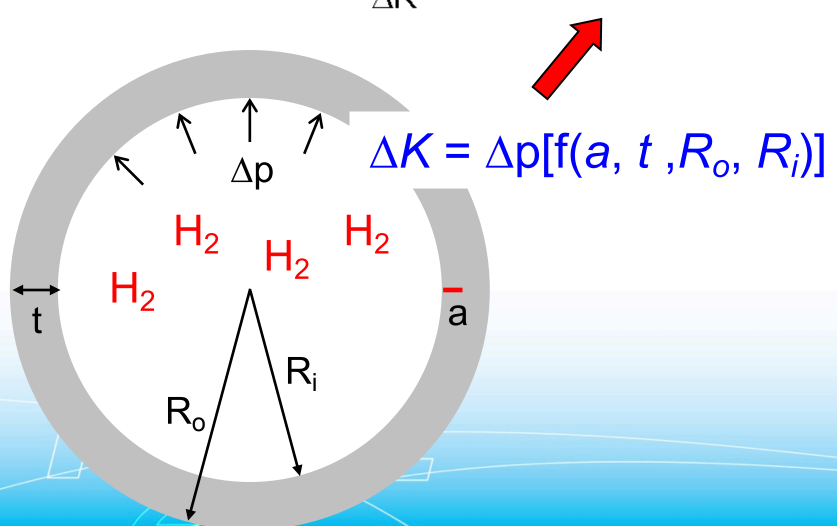
- Apply core capability to measure fatigue crack growth relationships for steels in high-pressure H_2 gas
  - Fatigue crack growth relationships serve as inputs into reliability/integrity assessment as specified in ASME B31.12 code
  - Milestone: Complete triplicate measurements (in each material region, 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)
- Pipeline steels and their welds were identified by stakeholders as a high priority
  - Provide feedback to stakeholders (e.g., ASME) through project meetings and workshops

Approach:

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





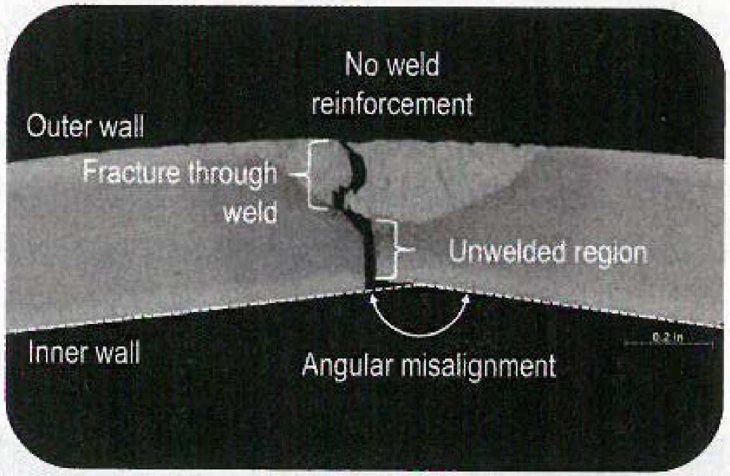


- Two fracture properties in H_2 needed
  - Fatigue crack growth law
  - Fracture threshold
- Reliability/assessment framework accommodates H_2 embrittlement

Approach:

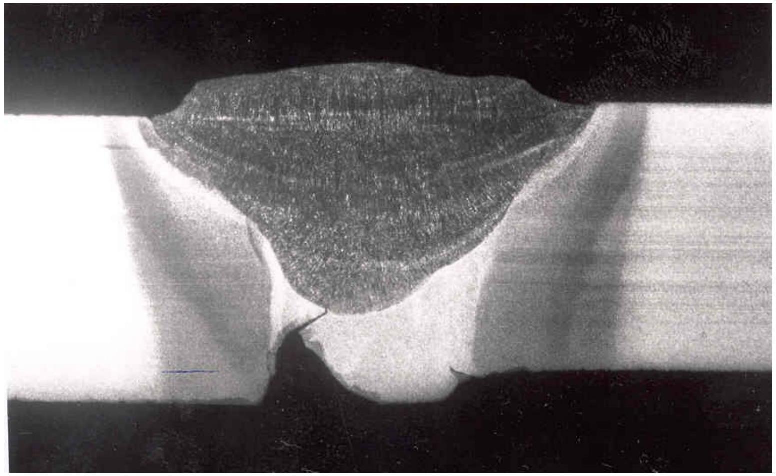
Reliability/integrity of steel hydrogen pipelines may be controlled by welds

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



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

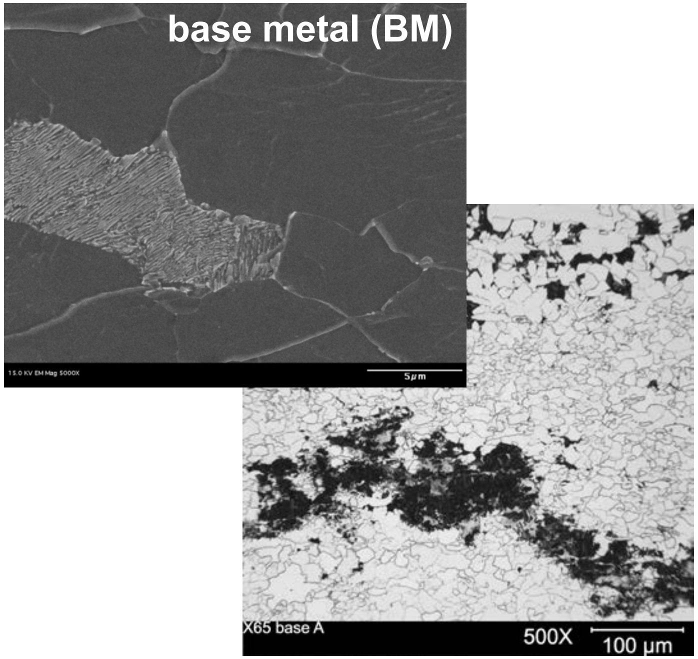
I. Alliat, NATURALHY EC project, 2007



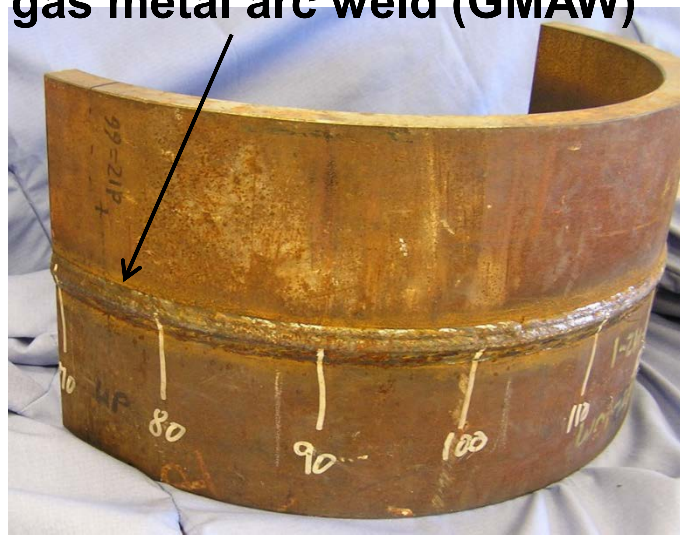
- Welding can create defects, increasing probability of crack growth in these regions
- Are weld microstructures (fusion zone, heat-affected zone) more susceptible to hydrogen embrittlement?

Approach:

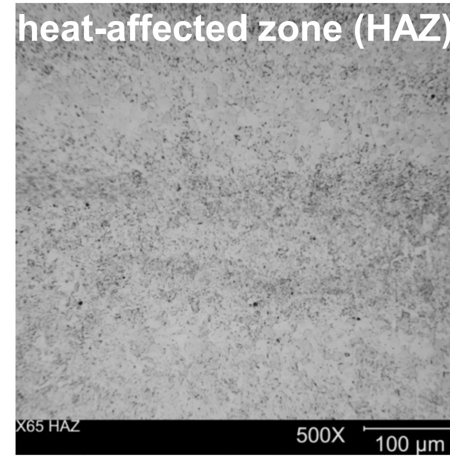
Fatigue crack growth measurements performed on API 5L X65 pipe with GMAW

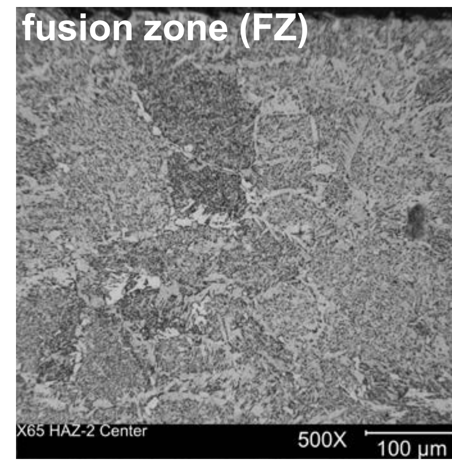


gas metal arc weld (GMAW)



508 mm OD x 25.4 mm WT





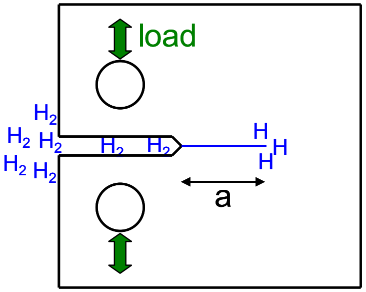
- Base metal tensile properties
  - Yield strength: 591 MPa (86 ksi)
  - Ultimate tensile strength: 662 MPa (96 ksi)

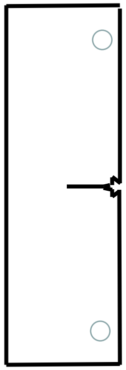
- Base metal composition

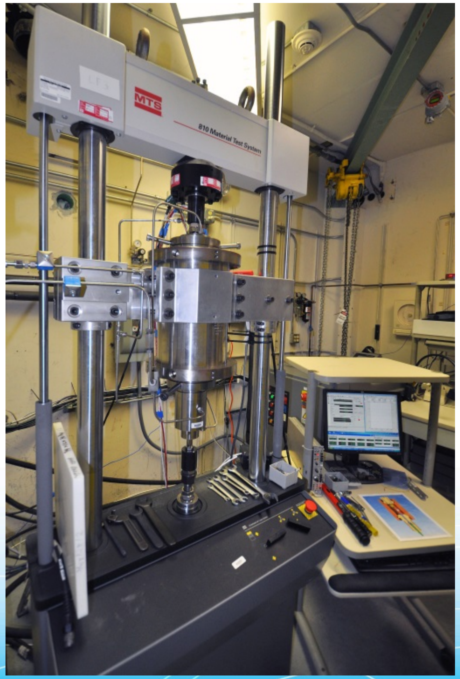
C	Mn	P	S	B	Si	Cu	Ni	Nb	Ti
0.08	1.53	0.01	0.001	0.002	0.32	0.024	0.038	0.039	0.002

Approach:

Fatigue crack growth relationships measured in high-pressure H_2 gas



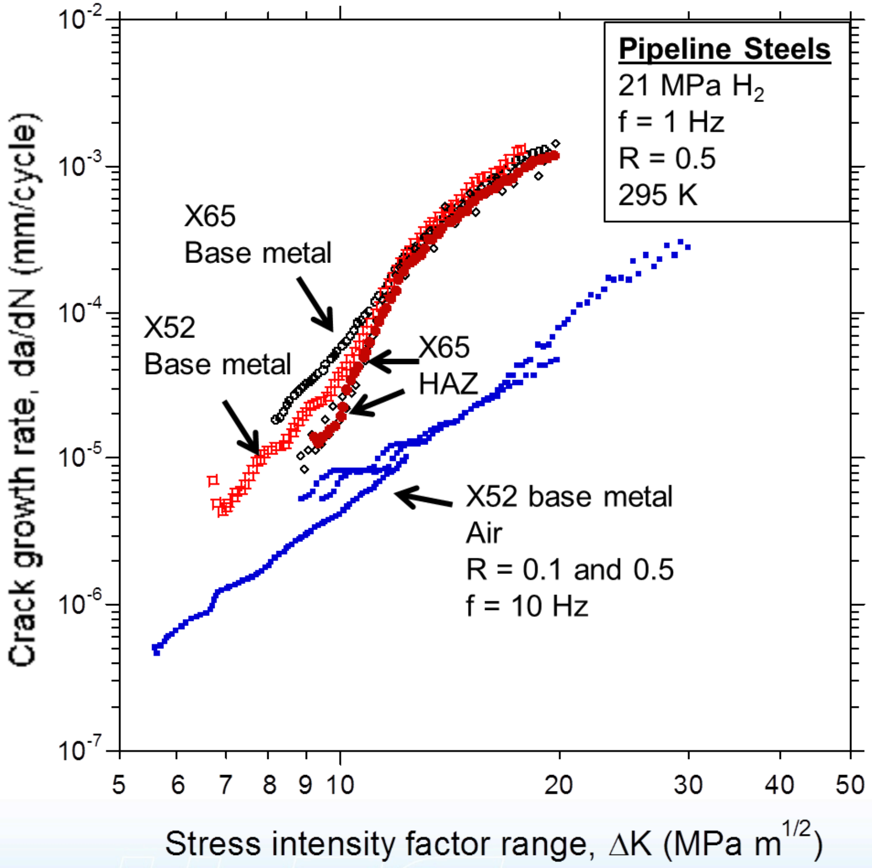




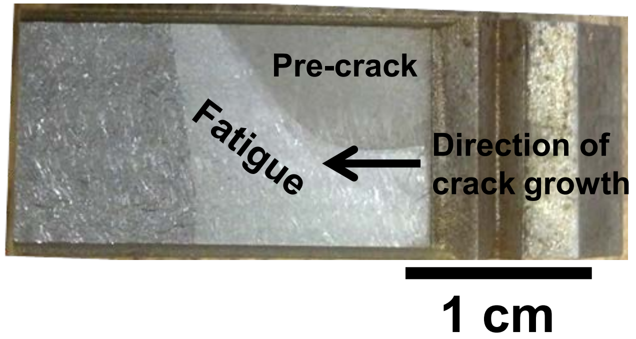
- Material
  - X65 base metal and GMAW
- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude
- Environment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

Previous Accomplishment:

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



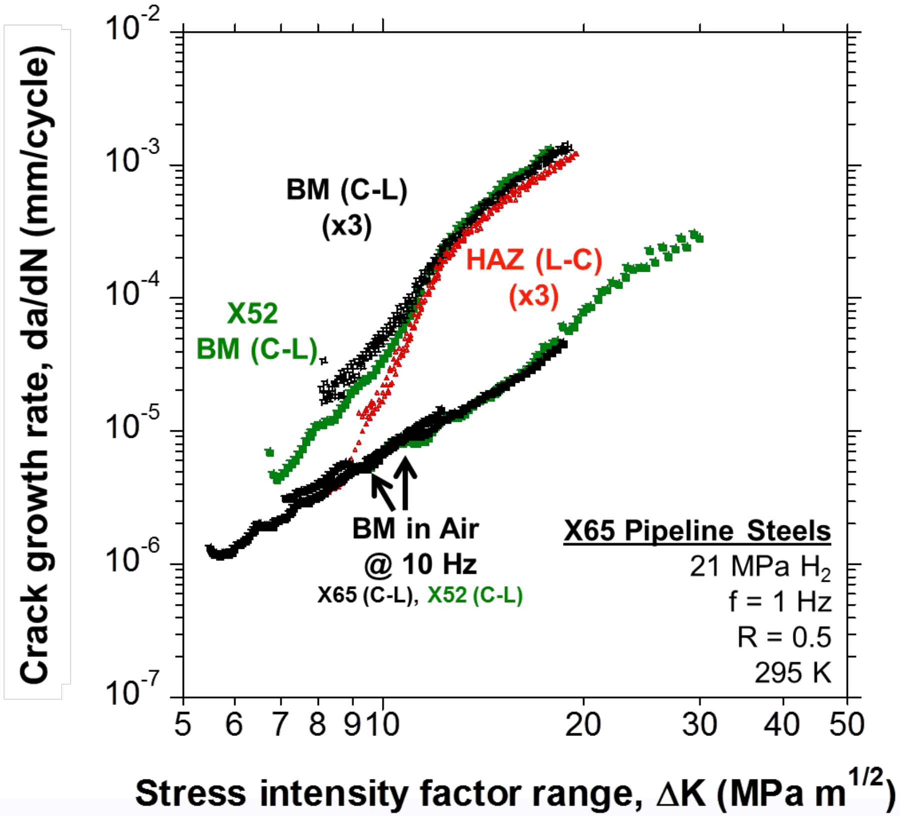
- Results from fusion zone specimen not valid due to non-uniform pre-crack front

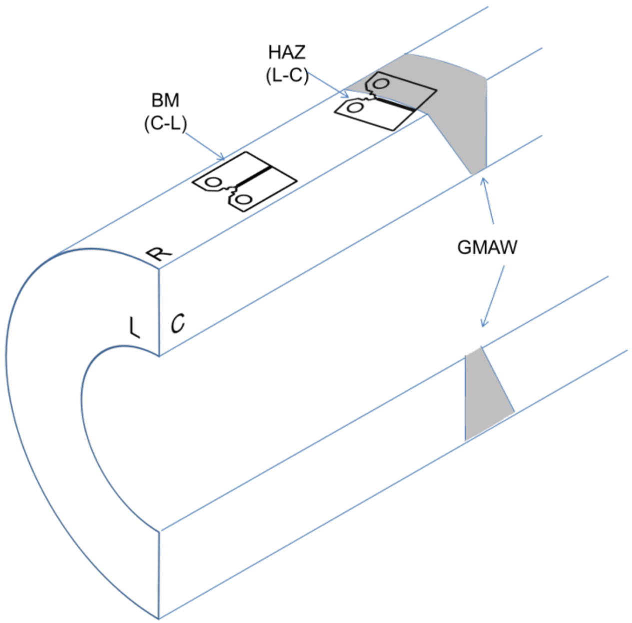


- Duplicate measurements for HAZ yield nearly identical results
- Initial results: crack growth rates lower for HAZ compared to base metal in lower ΔK range
- *Need modified procedures to establish reliable data for fusion zone*

Accomplishment:

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



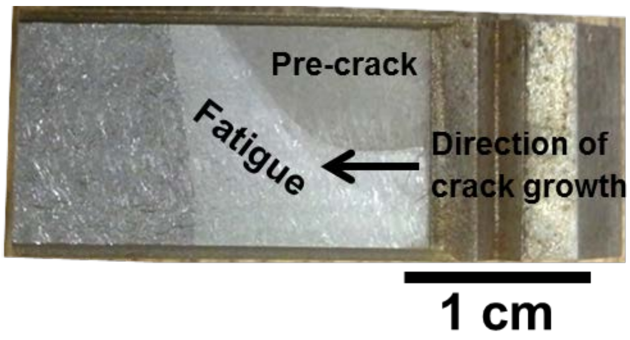


- Triplicate measurements for BM and HAZ reproducible
- Data for X65 BM consistent with previous results for X52 BM
- Results demonstrate reliability of measurements

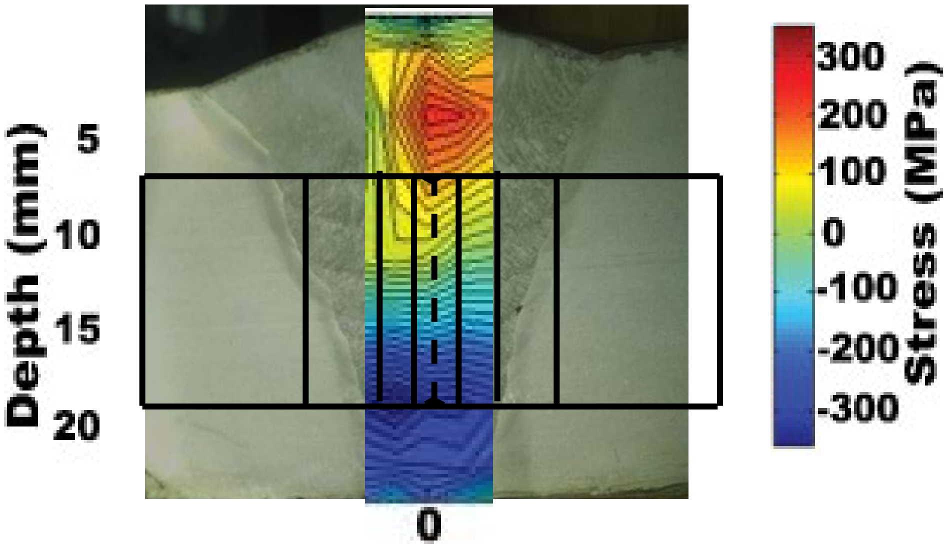
Accomplishment:

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

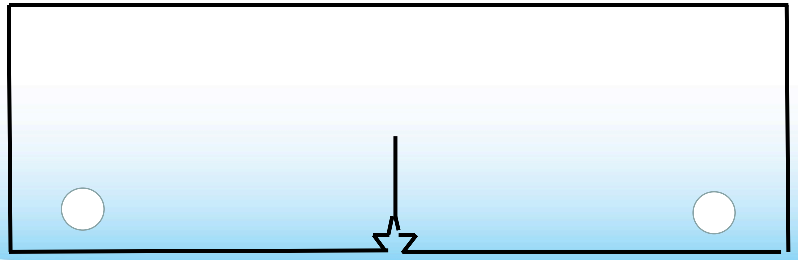
- Non-uniform pre-crack front in compact tension specimen attributed to residual stress gradient



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

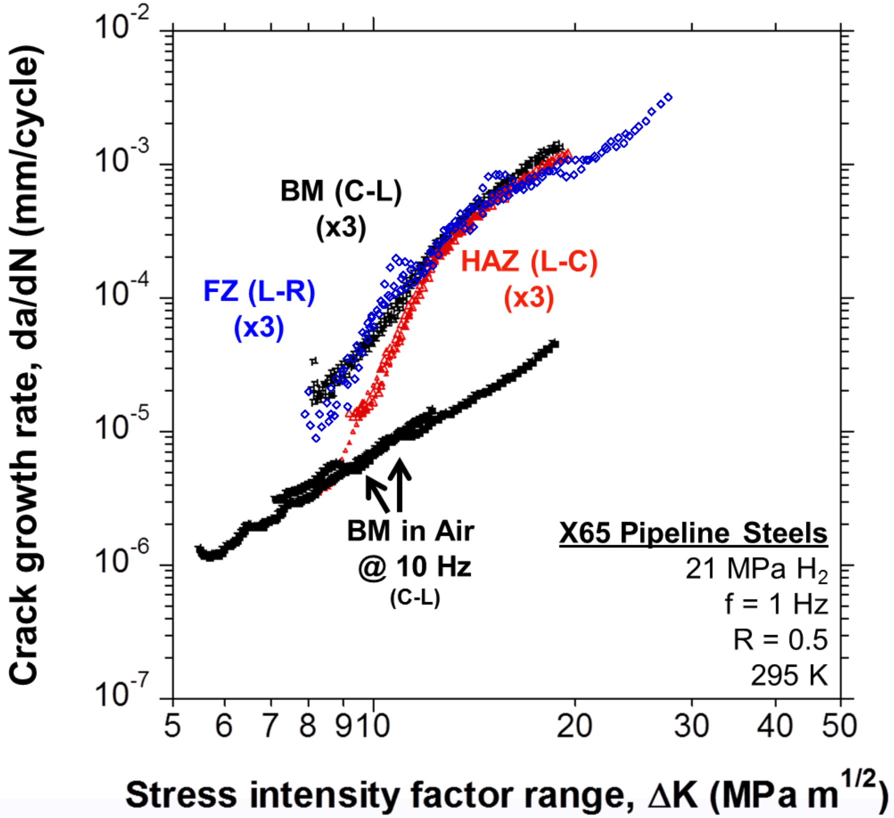


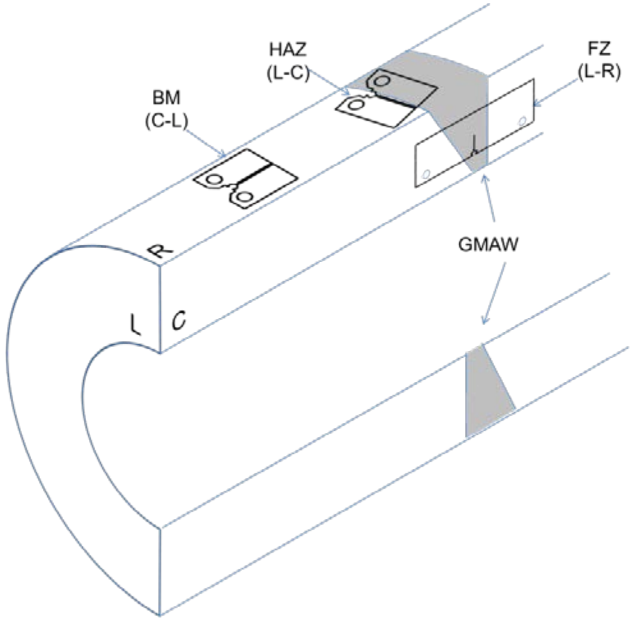
- Designed single-edge notched specimen to propagate crack parallel to wall thickness and across residual stress gradient



Accomplishment:

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



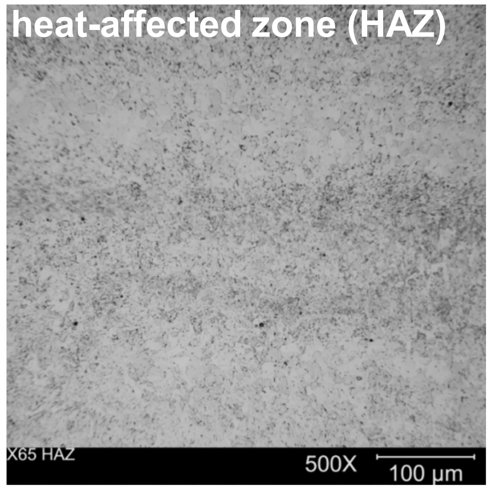


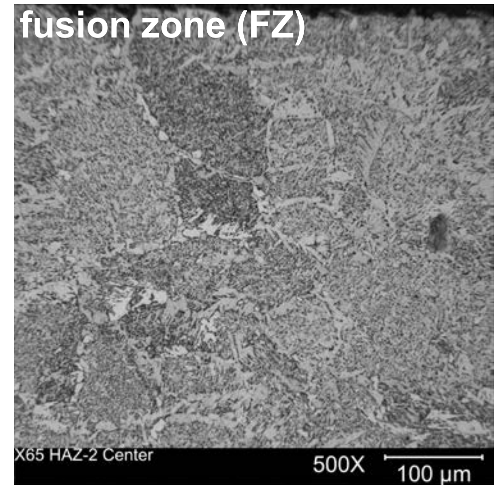
- Measurements for FZ reproducible
- Impact: welds may not be more susceptible to H_2-accelerated cracking than base metal
- Why are crack growth rates lower for HAZ in lower ΔK range?

Accomplishment:

Two features may account for difference in fatigue crack growth rates for HAZ vs. FZ

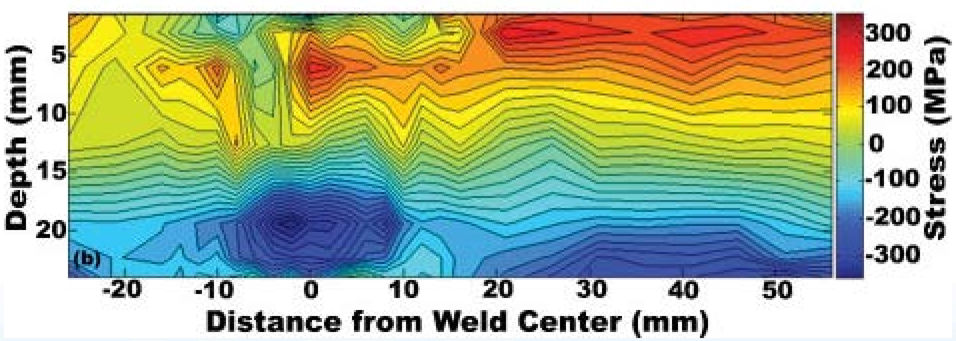
Microstructure





Residual Stress

longitudinal stress

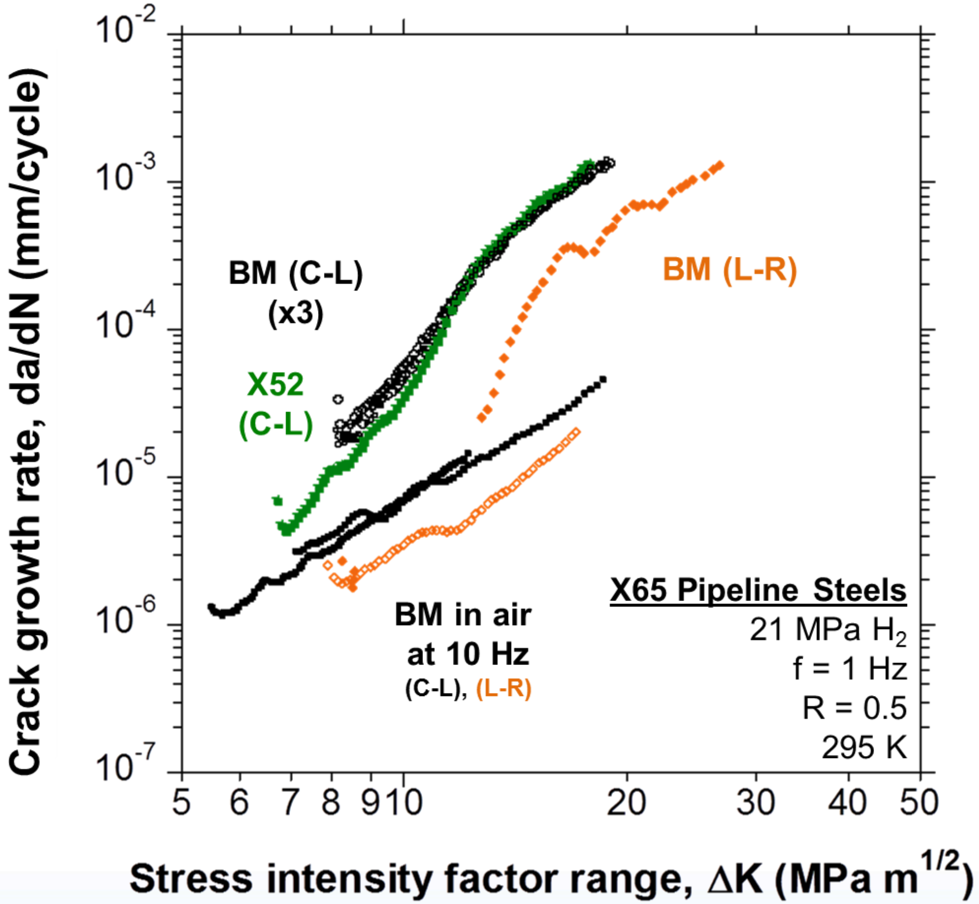


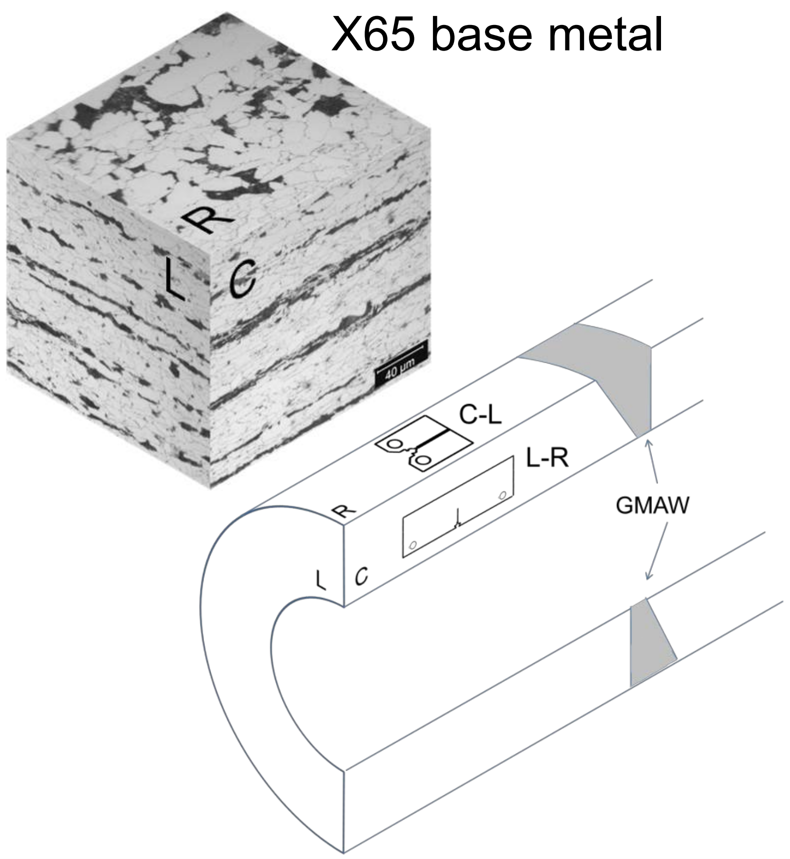
pipe longitudinal direction

T. Neeraj, *Science and Technology of Welding and Joining*, 2011

More testing planned to clarify feature controlling crack growth

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

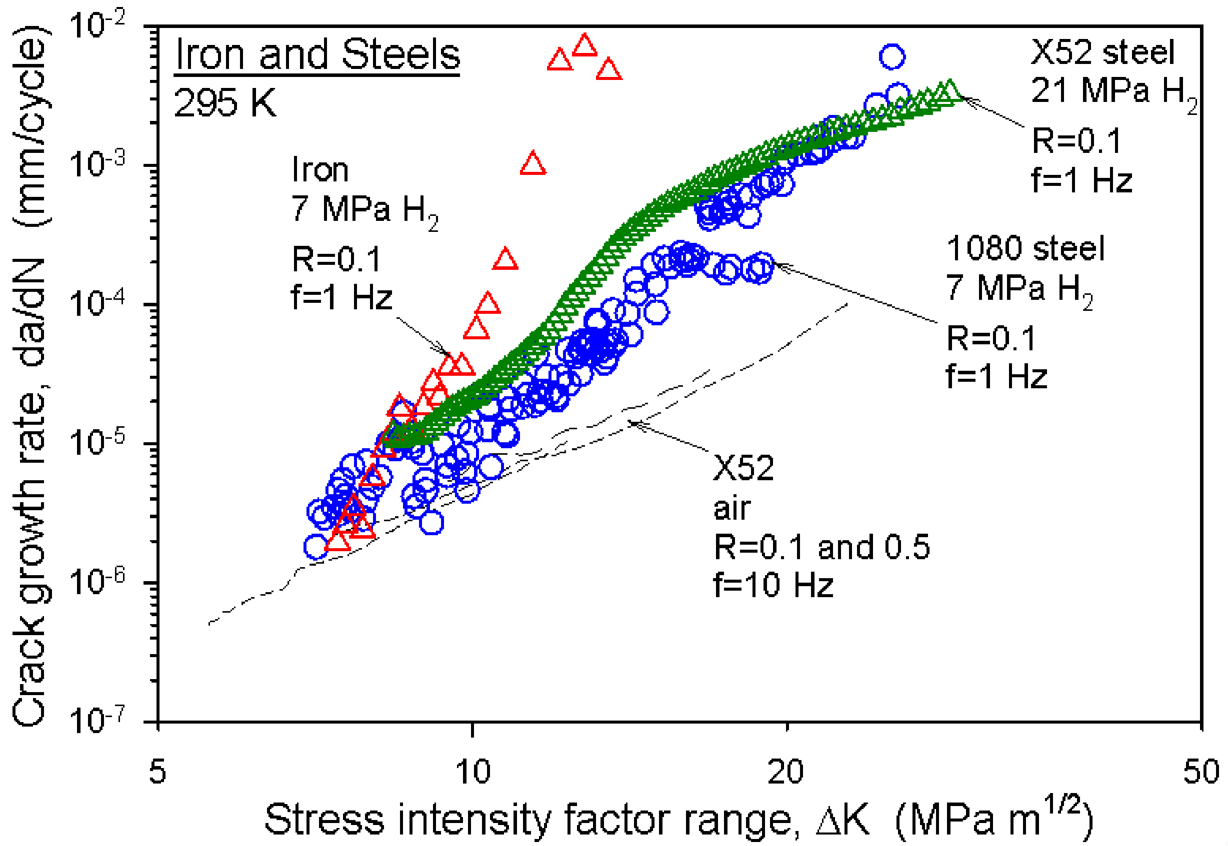


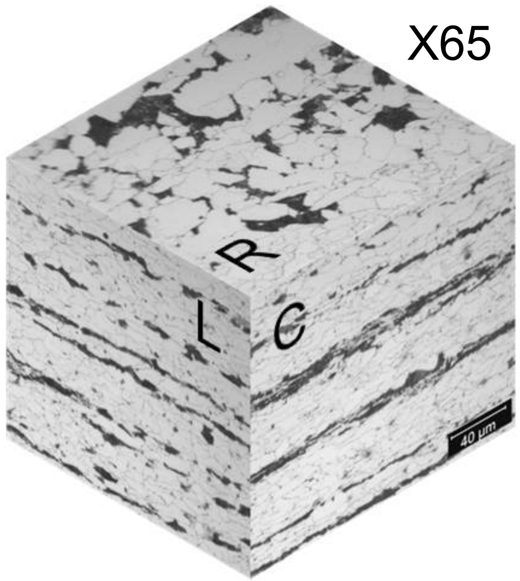


Does banded ferrite-pearlite microstructure reduce crack growth rates in L-R orientation?

Accomplishment:

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



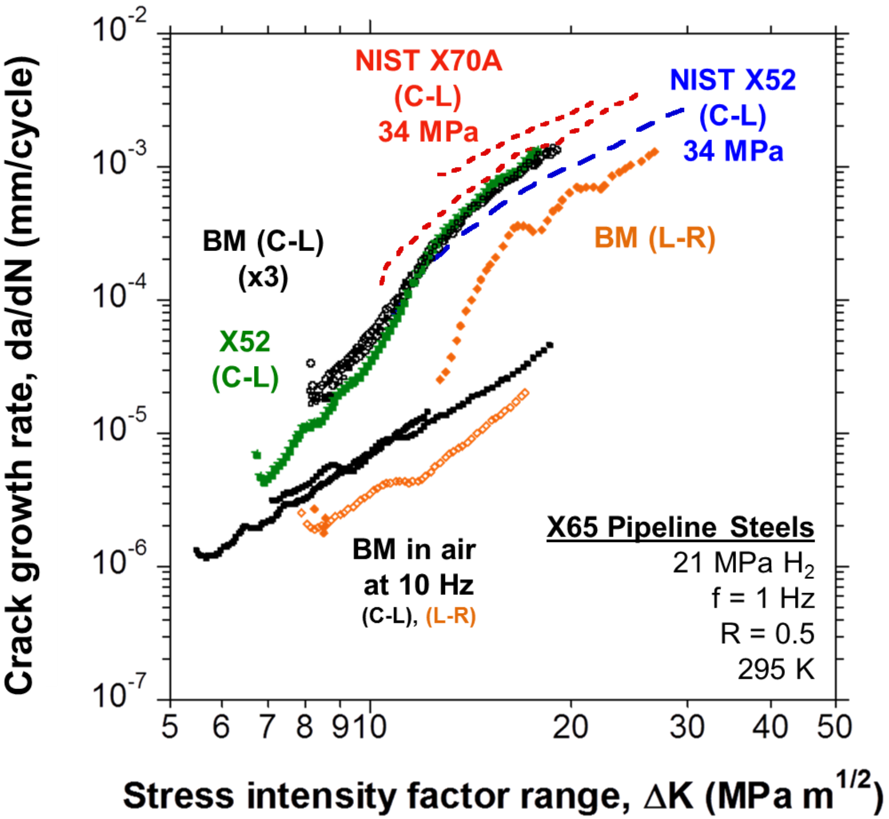


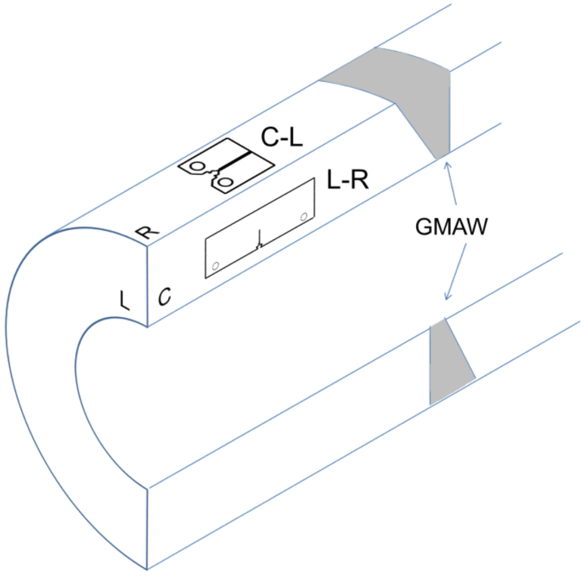
Iron and 1080 steel data:
H. Cialone and J. Holbrook,
Microstructural Science, 1987

Crack growth through ferrite and pearlite in series may contribute to reduced fatigue crack growth rates in banded X65 base metal

Accomplishment:

Pearlite-dominated fatigue crack growth rates less than typical range observed from NIST and Sandia data

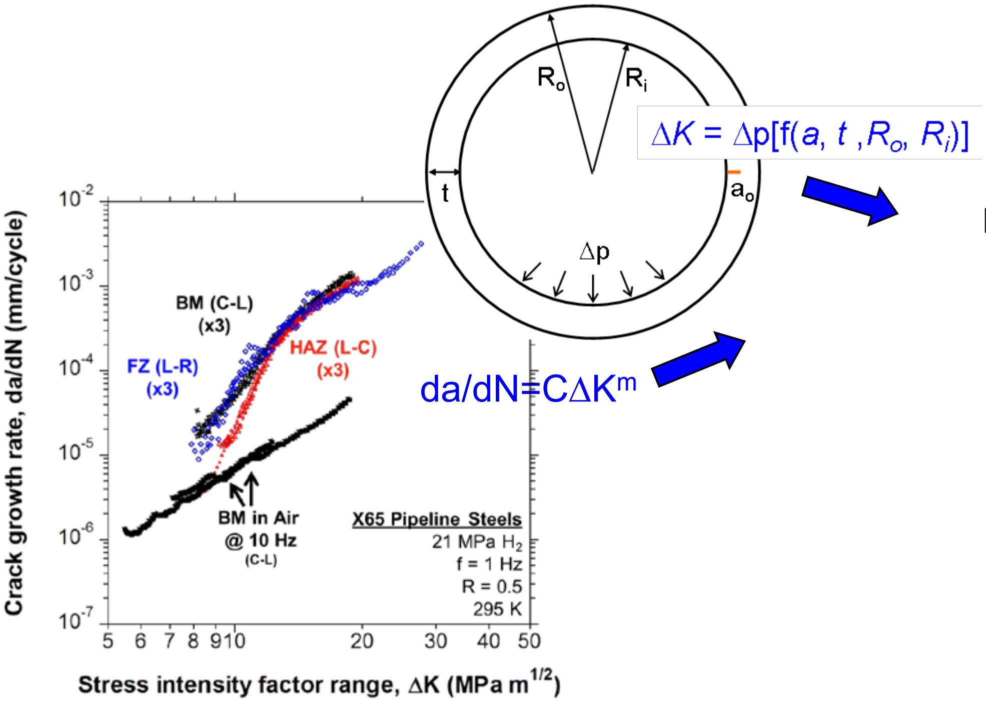


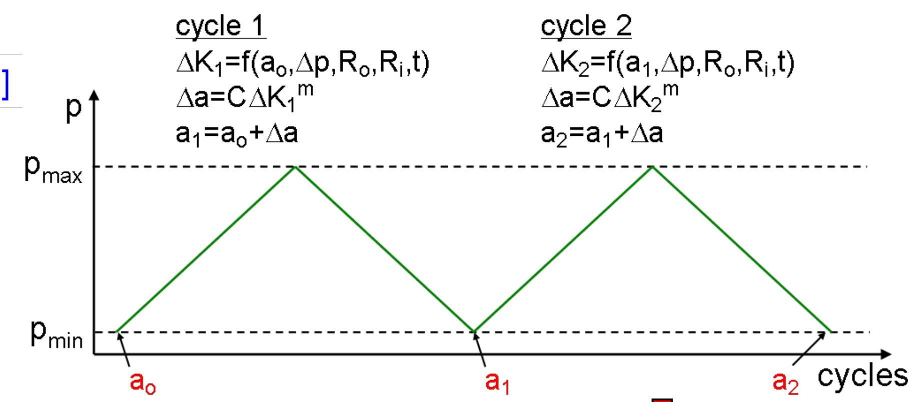


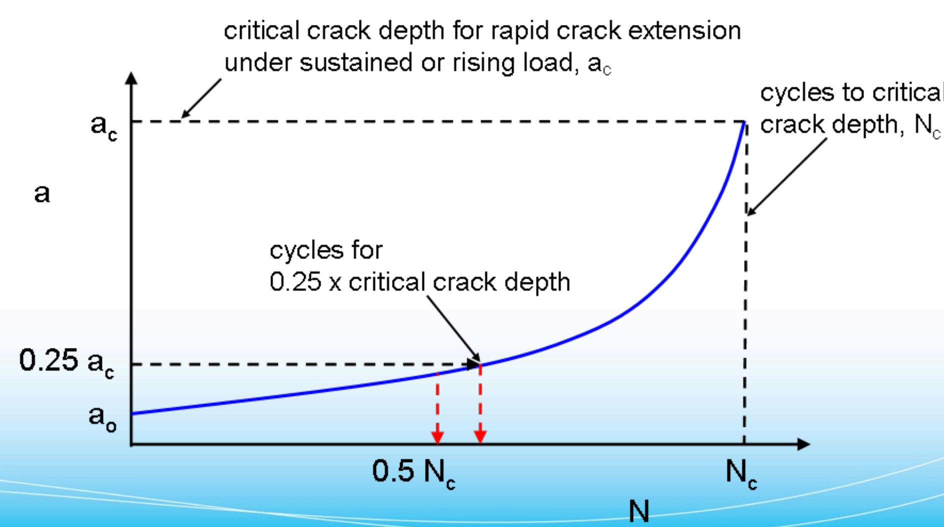
- Impact: results show that microstructure can dominate H_2-accelerated cracking in pipeline steels
- Illustrates need to establish relationships between microstructure and H_2-accelerated cracking for material qualification

Accomplishment:

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)

Responses to Previous Year Reviewers' Comments

1. *"The project should interface with Oak Ridge National Laboratory (ORNL) in regards to their friction stir welding research efforts; This project needs to focus on friction stir welding to determine and demonstrate the lower-cost approach for safely transporting hydrogen."*

   The Q4 milestone for this project is to measure the fatigue crack growth rates of friction stir welded pipeline steel in hydrogen gas. ORNL is planning to supply the friction stir welded steel pipe.

2. *"It is not clear how the results of this project could be applied to reduce the cost of hydrogen transport in steel pipelines; This project should attempt to determine how its results might be applied or extended to reduce the cost of transporting hydrogen in steel pipelines by better pipeline design, alternative steel compositions, or lower-cost welding"*

   As indicated in the presentation, there is a framework for calculating the steel pipeline wall thickness required to satisfy the inspection interval based on the measured fatigue crack growth rates in hydrogen gas. Solidifying the wall thickness calculation will allow more definitive assessments of steel pipeline costs.

3. *"This project should have a joint discussion with ASME B31.12 code committees, SAE J260, NIST-Boulder, the ORNL friction stir welding research team, and the DOT Pipeline and Hazardous Materials Safety Administration to jointly develop a research and development plan to address the remaining issues."*

   As highlighted in the presentation, there is more coordinated interaction with NIST-Boulder, ORNL, ASME, and DOT. For example, SNL, NIST, ORNL, ASME, DOT, and DOE participated in a workshop focused on pipeline steel project updates in December 2013. One outcome was for NIST, ORNL, SNL, and ASME to jointly author a white paper on R&D needs for hydrogen pipeline steels.

Collaborations

- NIST
  - Coordinate projects and exchange data on pipeline steel testing
- Oak Ridge National Laboratory
  - Coordinate projects and exchange data on pipeline steel testing
  - Supplying 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 (I^2CNER)
  - Collaborative basic research on H_2-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 authoring white paper on R&D needs for hydrogen pipeline steels

Remaining Challenges and Barriers

- Identify lower-cost welding technologies (e.g., friction stir welding) and provide reliable measurements of their fatigue crack growth relationships in H_2 gas
- Establish microstructure-performance (i.e., fatigue crack growth behavior in H_2 gas) relationships to enable qualification of steel base metal and welds for H_2 pipelines
  - Develop predictive, physics-based model for H_2-accelerated fatigue crack growth

Proposed Future Work

- Remainder of FY14
  - Complete multiple fatigue crack growth measurements for pipeline steel friction stir weld in H_2 gas

- FY15
  - Calculate wall thickness for steel hydrogen pipeline based on realistic operating parameters, initial flaw size, and inspection interval
  - Define relationship between limiting H_2-accelerated fatigue crack growth rates and microstructure constituents for pipeline steels
  - Continue basic research collaboration with I^2CNER to define mechanisms of H_2-accelerated fatigue crack growth in steels and develop predictive, physics-based models of this phenomenon

Summary

- Measured fatigue crack growth relationships allow evaluation of reliability/integrity and cost of steel H_2 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 measurements of fatigue crack growth relationships in H_2 gas for base metal, fusion zone, and heat affected zone in X65 pipe with girth weld
  - Welds may not be more susceptible to H_2-accelerated fatigue crack growth compared to base metal
  - Results for base metal show that microstructure can dominate H_2-accelerated fatigue crack growth, illustrating importance of specifying microstructure-performance relationships to qualify hydrogen pipeline steels