SAND2016-3003PE

Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service

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Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000

Relevance

Steel hydrogen pipelines have been safely operated for decades

- Operation of steel pipelines, and resistance to 3rd party damage is well-understood
  - Hydrogen pipelines function safely under *constant pressure* load
  - 1,500 miles of steel hydrogen pipelines already in use in the U.S.

Assess steel pipeline performance under conditions expected in mature hydrogen market

- Determine resistance of **base metal and welds to *fluctuating* loads**
- Experimental data and analysis can guide the **optimization of design codes and standards** to lower pipeline cost while maintaining reliability
- Establish **models that predict pipeline behavior as a function of microstructure** to guide future developments of novel steels

Research on hydrogen embrittlement will enable risk-informed design of lower cost hydrogen pipelines.

Objectives

Project purpose is to enable deployment of high-strength steel for H_2 pipelines by:

1) Demonstrating that girth welds in high-strength steel pipes exhibit fatigue performance similar to low strength pipes in H_2 gas

- Data exists that show similar performance in base metals over range of strengths
- Will high strength *welds* behave the same?

2) Identifying pathways for developing high-strength pipeline steels by establishing relationships between microstructure and hydrogen accelerated fatigue crack growth (HA-FCG)

- Basic understanding of relationship between microstructure and HA-FCG can inform future development pathways of high strength steels

- FY16 tasks
  - Measure fatigue crack growth rates of commercially available X100 welds
    - Establish relationships between microstructure and crack growth rate

Approach

- Evaluate fatigue performance of welds for X100 in high pressure H_2 gas
  - Complete HA-FCG tests at constant ΔK in 21 MPa hydrogen gas to identify most susceptible locations in the weld and HAZ of *current practice* arc welds of X100 girth weld. (Progress Measure)
  - Complete triplicate measurements of base metal, weld and HAZ in 21 MPa at 1Hz and R = 0.5. (Milestone)
  - Examine alternative high strength welds
    - Fusion weld with alternative consumable (FY17)
    - Friction stir weld (FY18)

- Identification of high-strength steel microstructures with acceptable HA-FCG performance
  - Develop controlled microstructures and quantify HA-FCG performance
  - Microstructure informed predictive model

Approach: Collaborative Effort

SNL – Project Lead

- Fatigue crack growth measurements of welds in high pressure H_2 gas
- Develop test procedures to evaluate microstructure vs. HA-FCG

ORNL

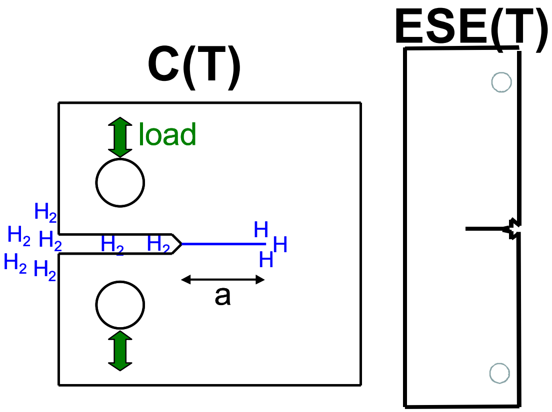
- High strength weld fabrication using: alternative consumables, friction stir weld
- Develop graded steel microstructures using Gleeble™
  - Gleeble™ -Thermo-mechanical simulator to control microstructures

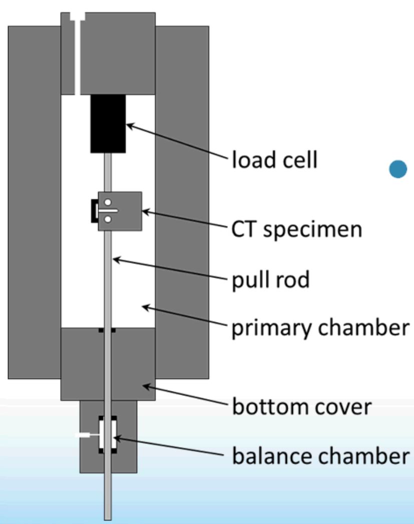
NIST

- Microstructure-informed predictive model for HA-FCG

	FY16				FY17				FY18			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Subtask 1.1. Measure HA-FCG performance for current-practice arc weld	SNL											
Subtask 1.2.1. Fabricate girth weld with alternate consumable		ORNL										
Subtask 1.2.2. Measure HA-FCG performance of arc weld with alternate consumable							SNL					
Subtask 1.3.1. Fabricate friction-stir girth weld					ORNL							
Subtask 1.3.2. Measure HA-FCG performance of friction stir weld									SNL			
Subtask 2.1.1 Develop graded microstructures with Gleeble™ device	ORNL											
Subtask 2.1.2. Measure HA-FCG in graded-microstructure specimens					SNL							
Subtask 2.2.1. Produce lab-scale high-strength steel							ORNL					
Subtask 2.2.2. Measure HA-FCG in lab-scale experimental steel											SNL	
Subtask 2.3. Microstructure-informed predictive model for HA-FCG in pipeline steels	NIST											
							Go/No-Go					

Approach: Fatigue crack growth relationships measured in high-pressure H_2 gas

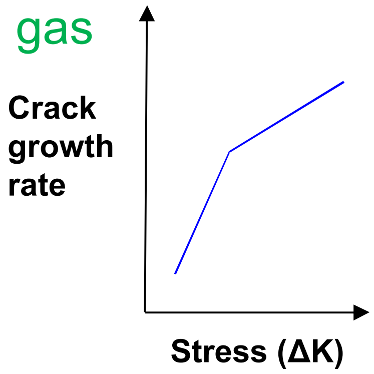




- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude
- Environment
  - Supply gas: 99.9999% H_2
  - Pressure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

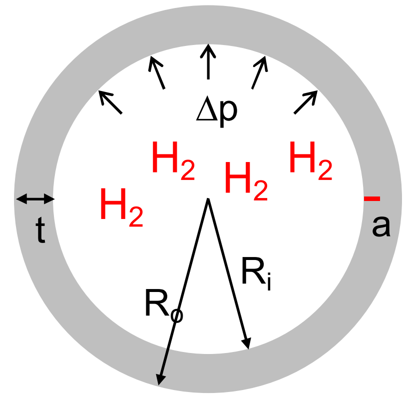
Approach: Optimization of Design

Experimentation: measurements in H_2 gas

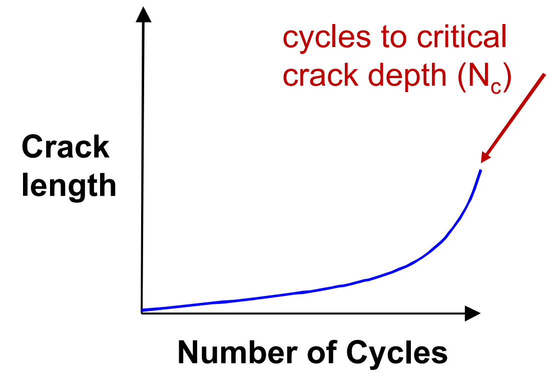


Fracture Mechanics Analysis

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



Assuming steel thickness, calculate:

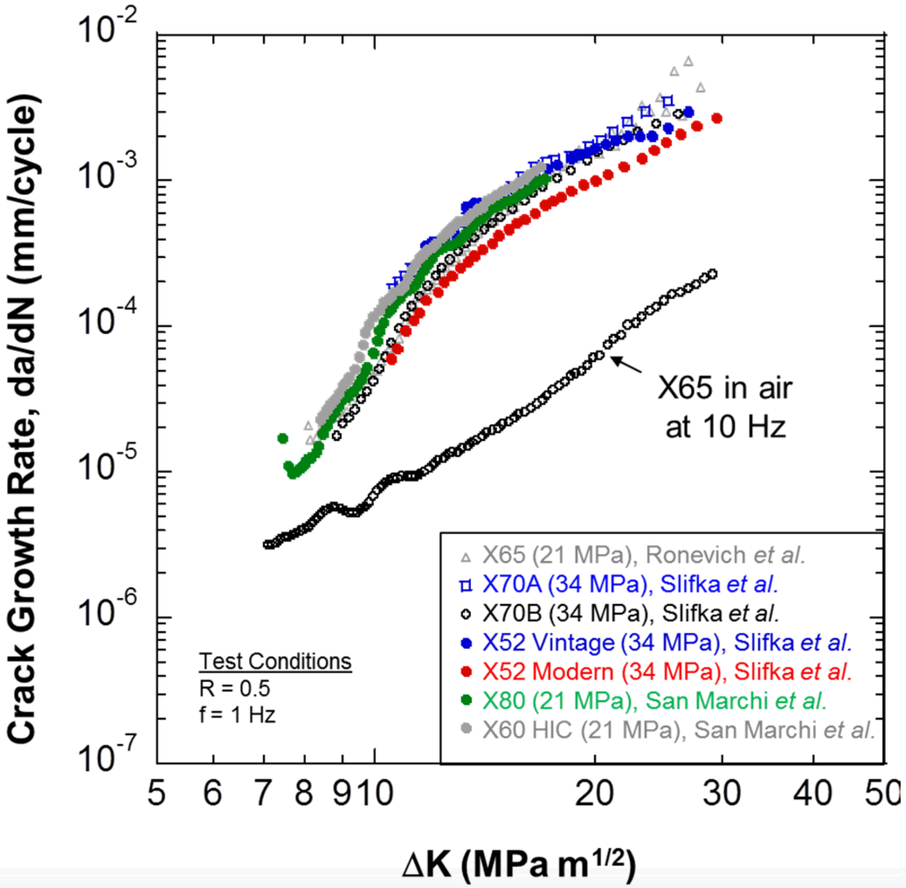


Design Analysis

Is steel pipeline life sufficient given expected service conditions, and ASME code requirements (life = 0.5 N_c)?

Fracture mechanics analysis to characterize steel reliability in H_2 gas.

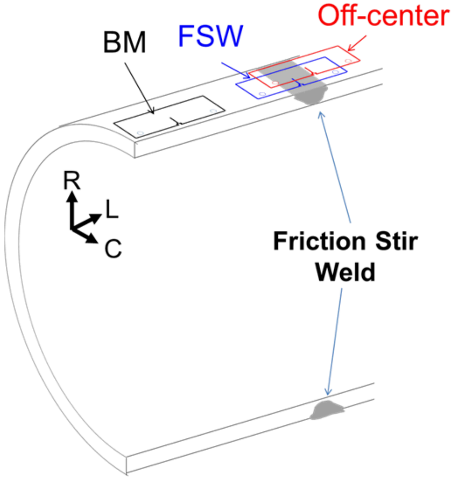
Previous Accomplishment – Fatigue tested moderate strength steels in high pressure hydrogen gas



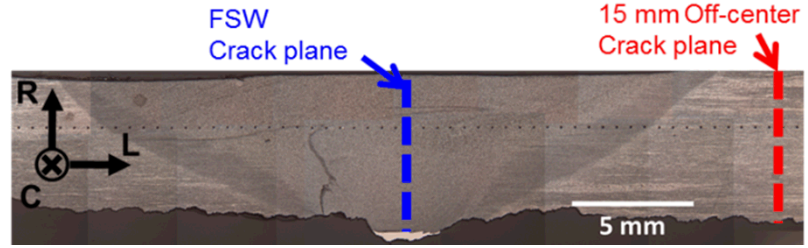
Data from SNL & NIST

Pipelines of different strength exhibited similar hydrogen accelerated fatigue crack growth

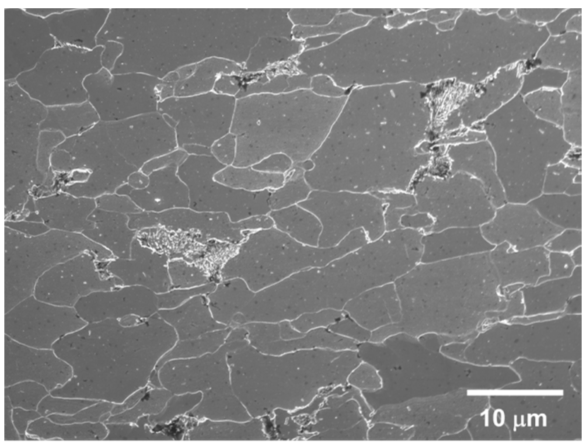
Previous Accomplishment:
X52 Friction Stir Welds (FSW) were tested in 21 MPa H_2



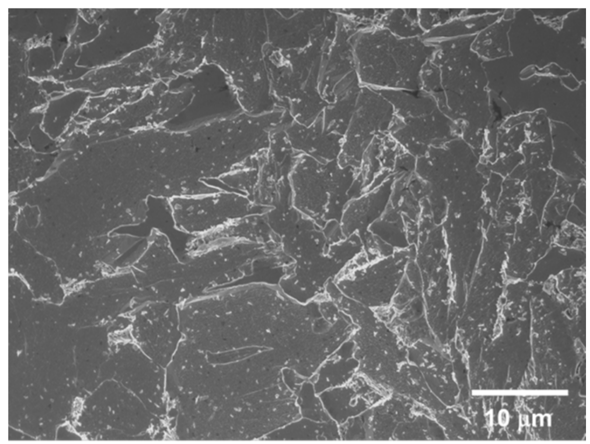
*Received weld from ORNL



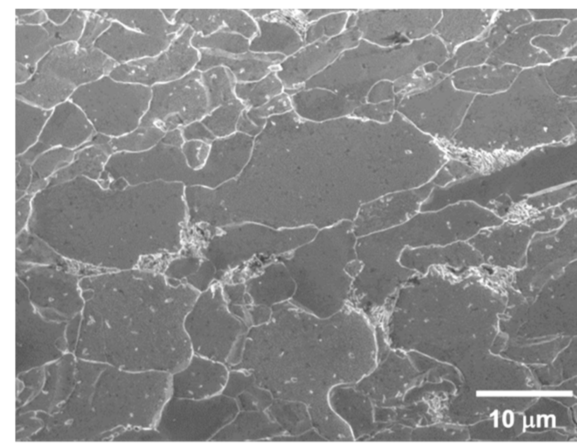
BM



FSW

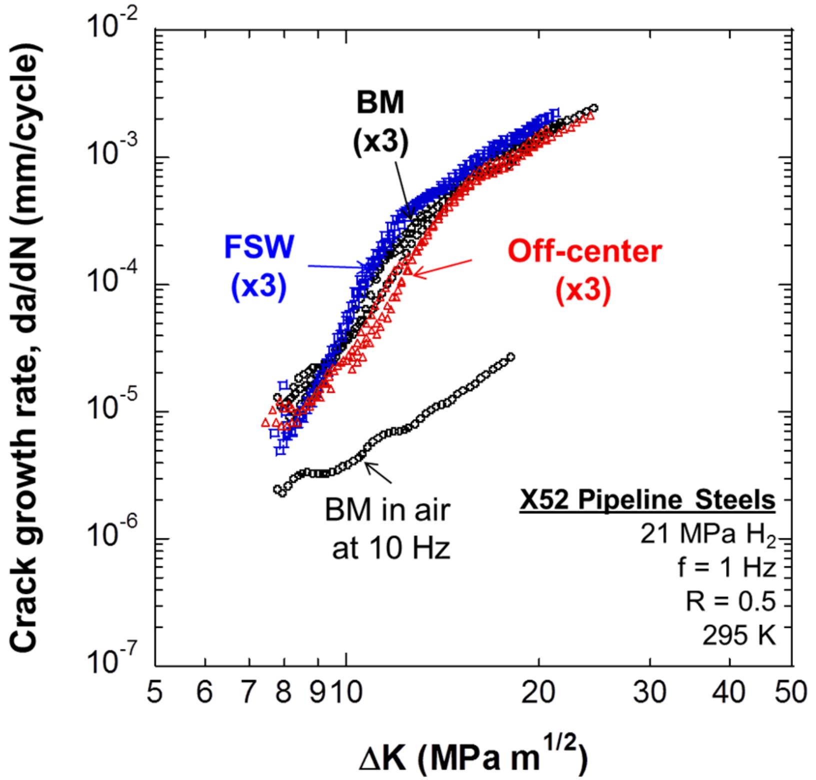


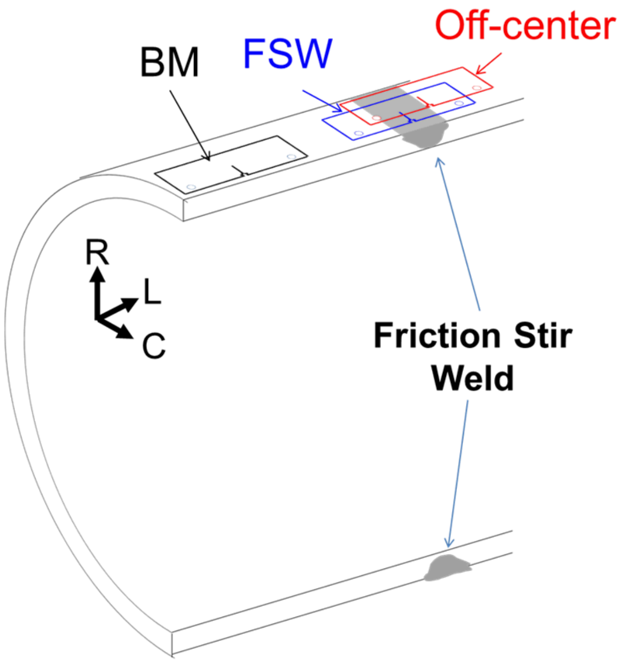
Off-Center

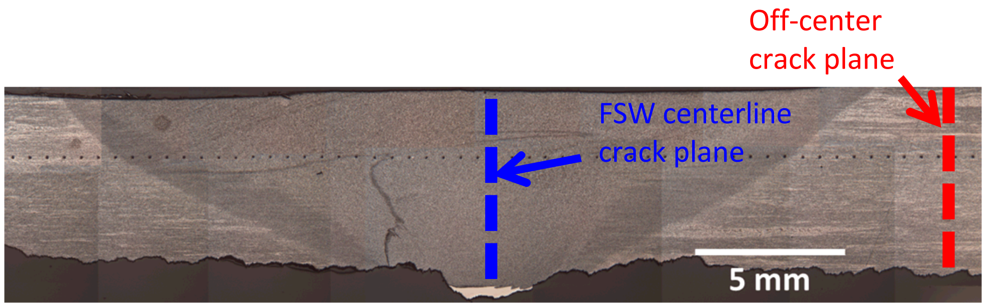


Microstructures consisted of ferrite with either pearlite or dispersed carbides

Previous Accomplishment: X52 Friction Stir Welds (FSW)



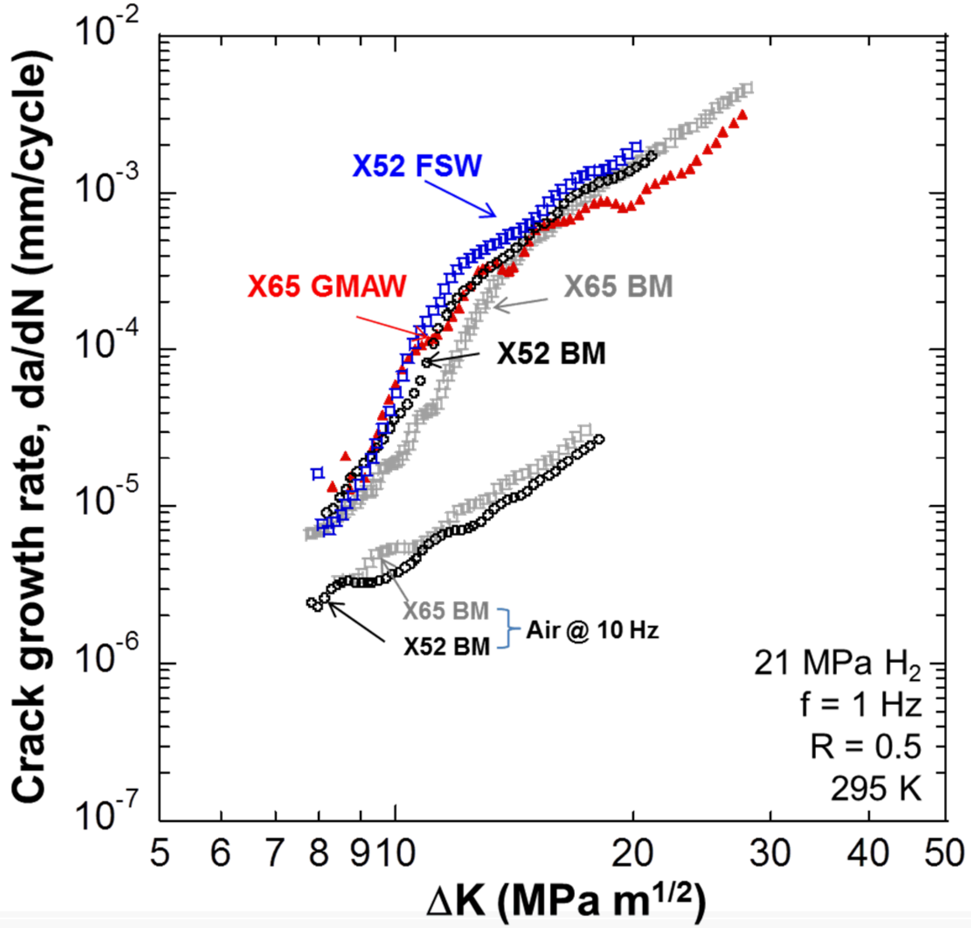




- Crack growth rate measurements in FSW are repeatable (triplicate results obtained)

X52: crack growth faster in center of FSW than in base metal, and faster in base metal than in off-center position.

Welds of X52 and X65 pipes exhibit modest increases in HA-FCG compared to base metal



X65 Gas Metal Arc Weld (GMAW)

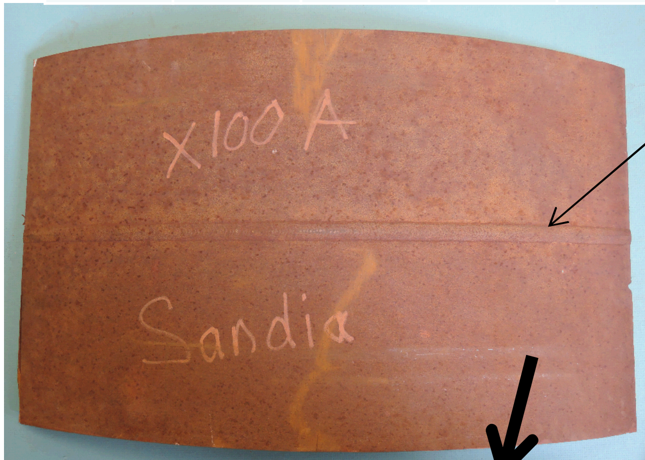
X52 Friction Stir Weld (FSW)

Two different welding processes yielded similar HA-FCG

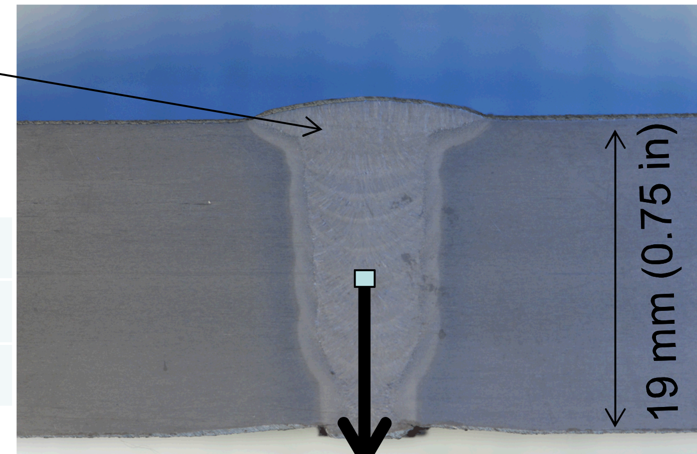
Current Work: X100A pipe Gas Metal Arc Weld

- Girth *welded using* ***current practices***

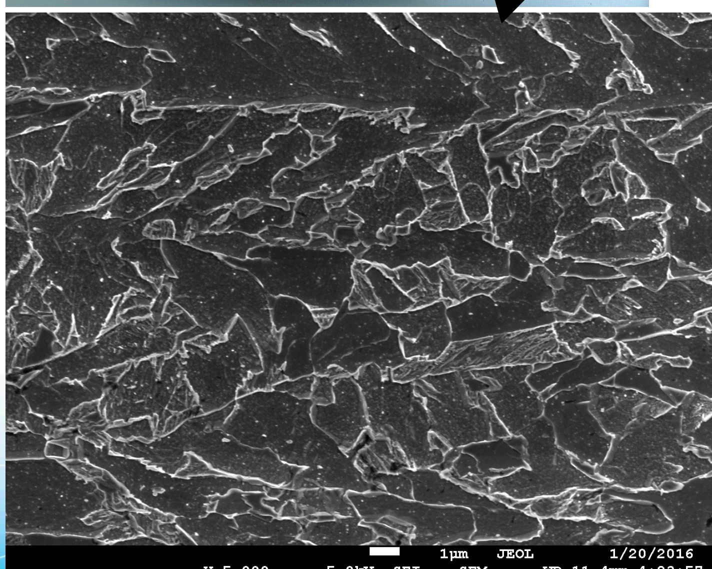
Fe	C	Mn	P	S	B	Si	Cu	Ni	Cr	Mo	Nb	Ti	Al
Bal	0.085	1.69	0.013	<0.001	0.0015	0.26	0.14	0.24	0.19	0.17	0.047	0.017	0.029

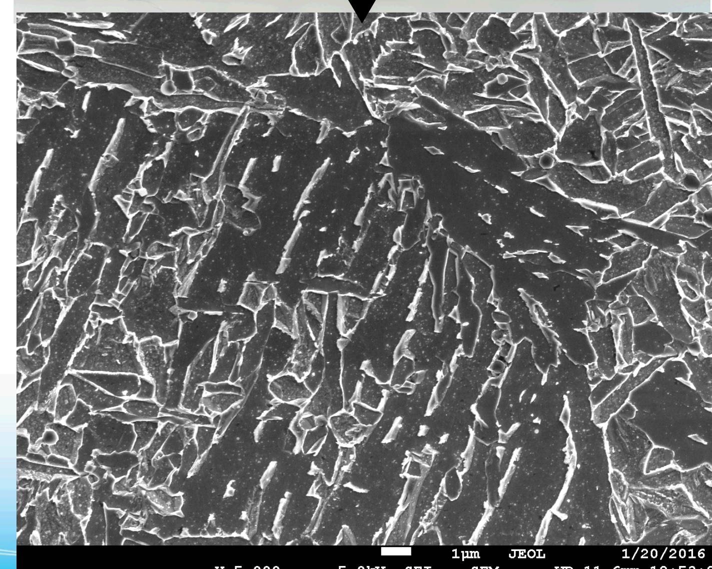


Girth weld



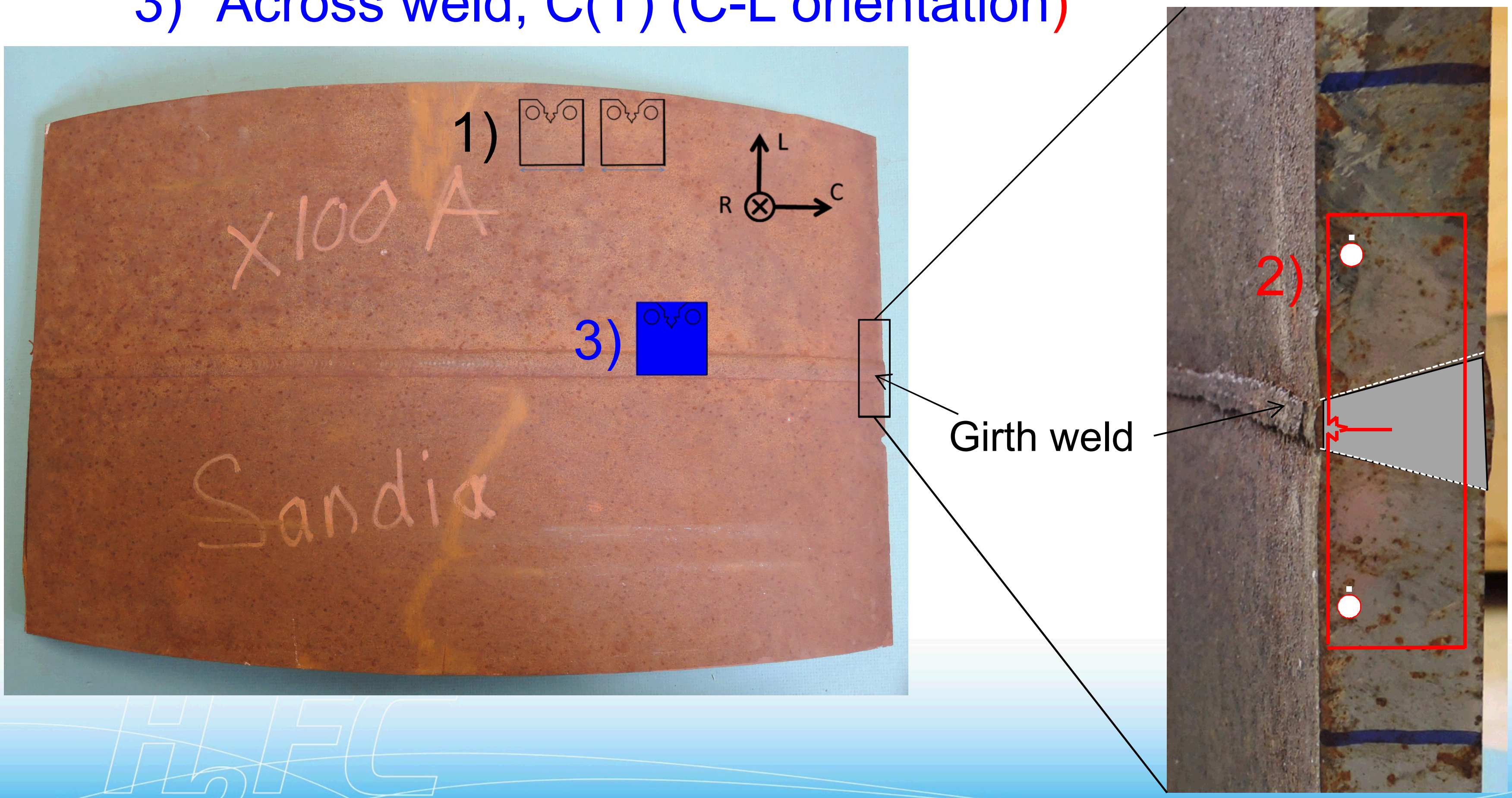
	MPa	ksi
YS	732	106
UTS	868	126



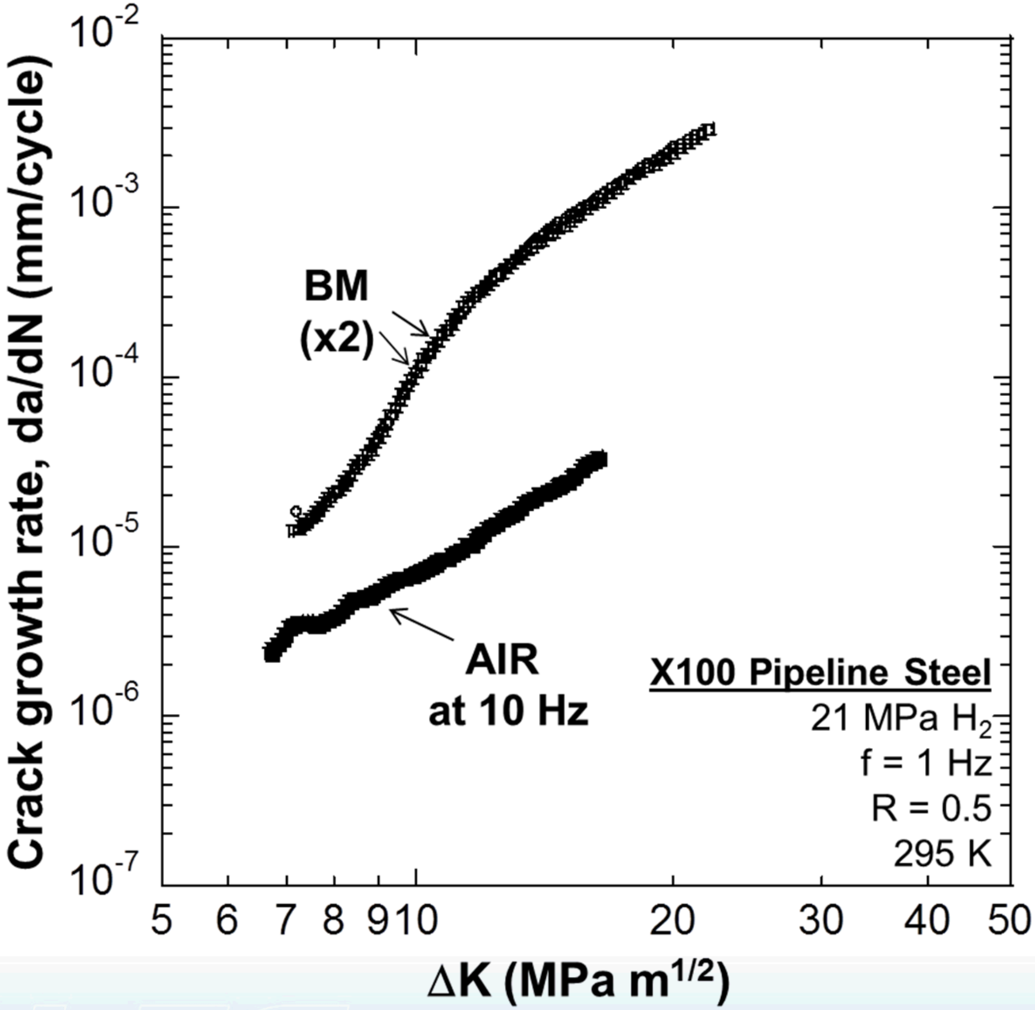


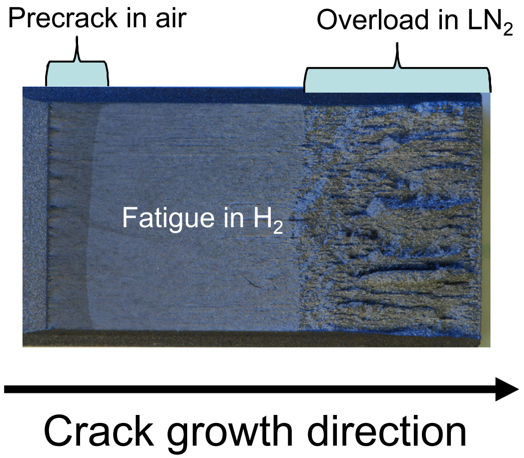
Specimens were extracted from base metal, fusion zone, and across the weld

1) Base metal, C(T) (C-L orientation)
2) Fusion zone, ESE(T) (L-R orientation)
3) Across weld, C(T) (C-L orientation)



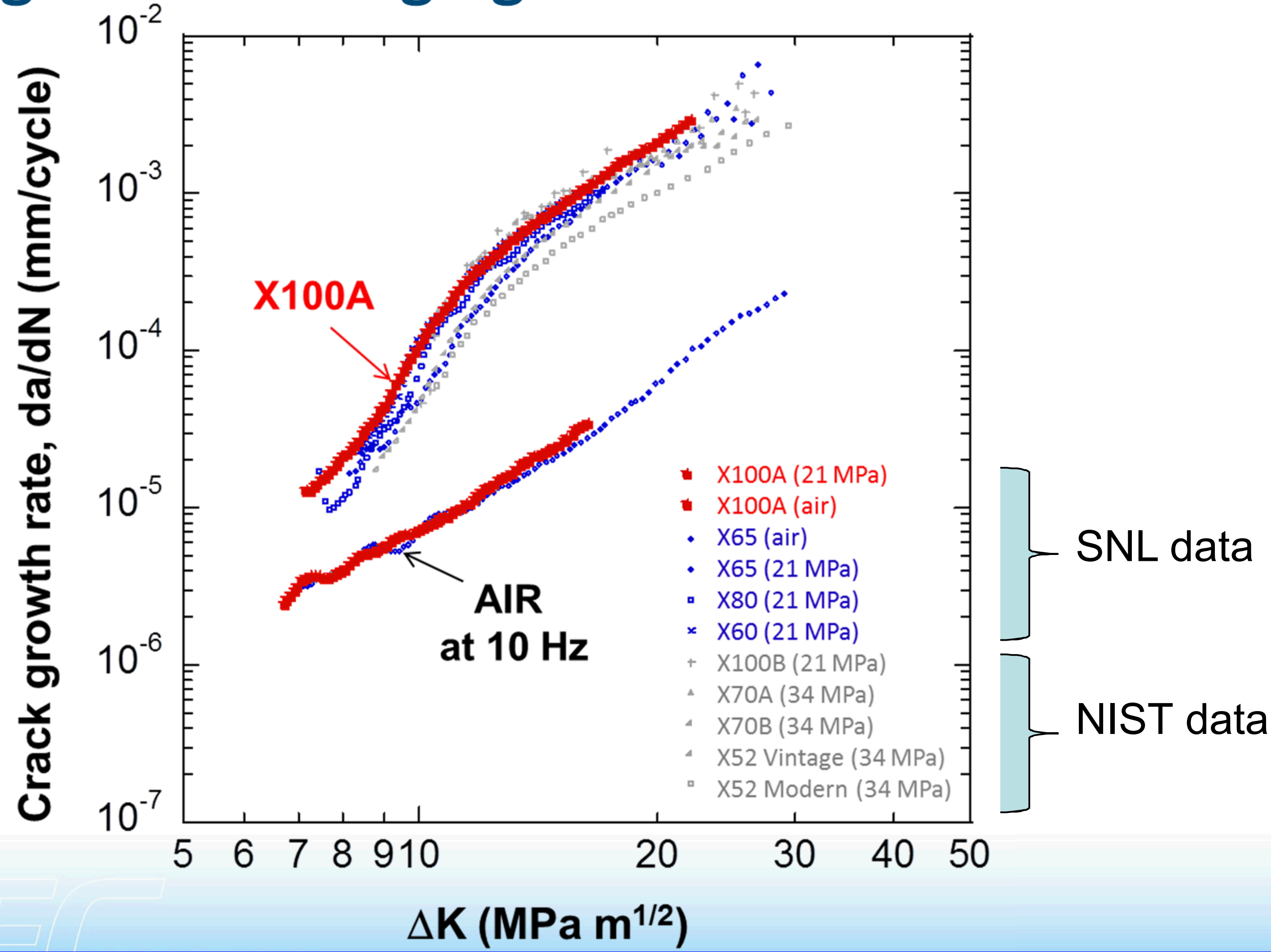
X100A base metal tested in 21 MPa H_2 gas at R = 0.5 and frequency of 1 Hz





Preliminary results show good repeatability for X100 base metal

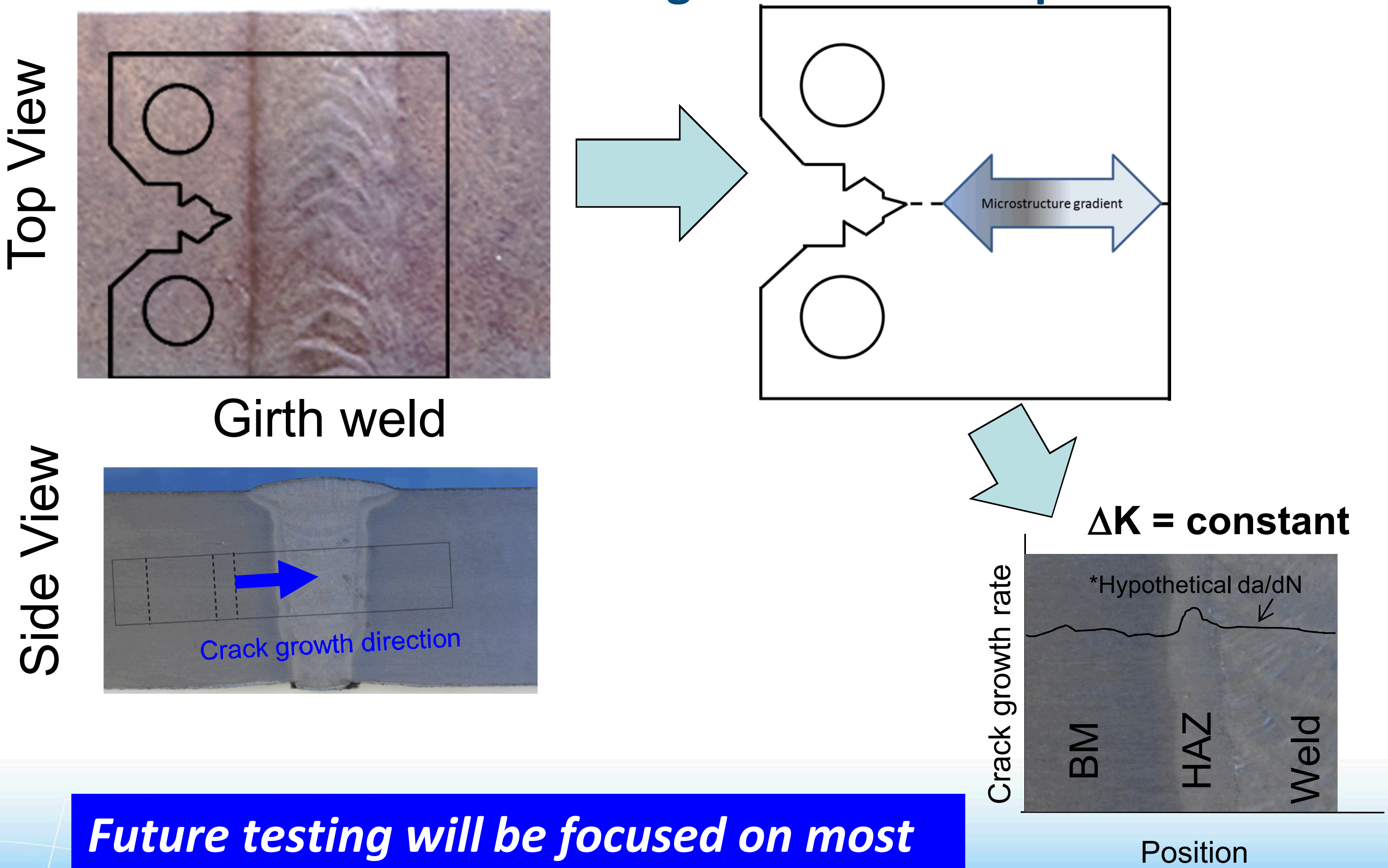
High strength steel pipeline base metals were compared with strength levels ranging from SMYS 52 to 100 ksi



X100A exhibited comparable HA-FCG to lower strength pipelines

Constant ΔK test → Optimize testing of weld and HAZ

Assess microstructural regions most susceptible to HA-FCG



Future testing will be focused on most susceptible regions of FZ and HAZ

Identify high strength microstructures with acceptable HA-FCG performance

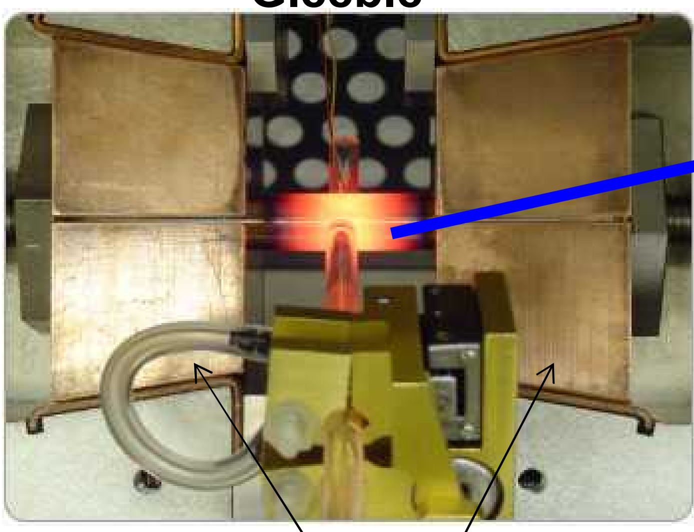
ORNL

- Use thermal-mechanical testing system (Gleeble™) to develop graded microstructures
  - Represent various constituents present during processing of high strength steels

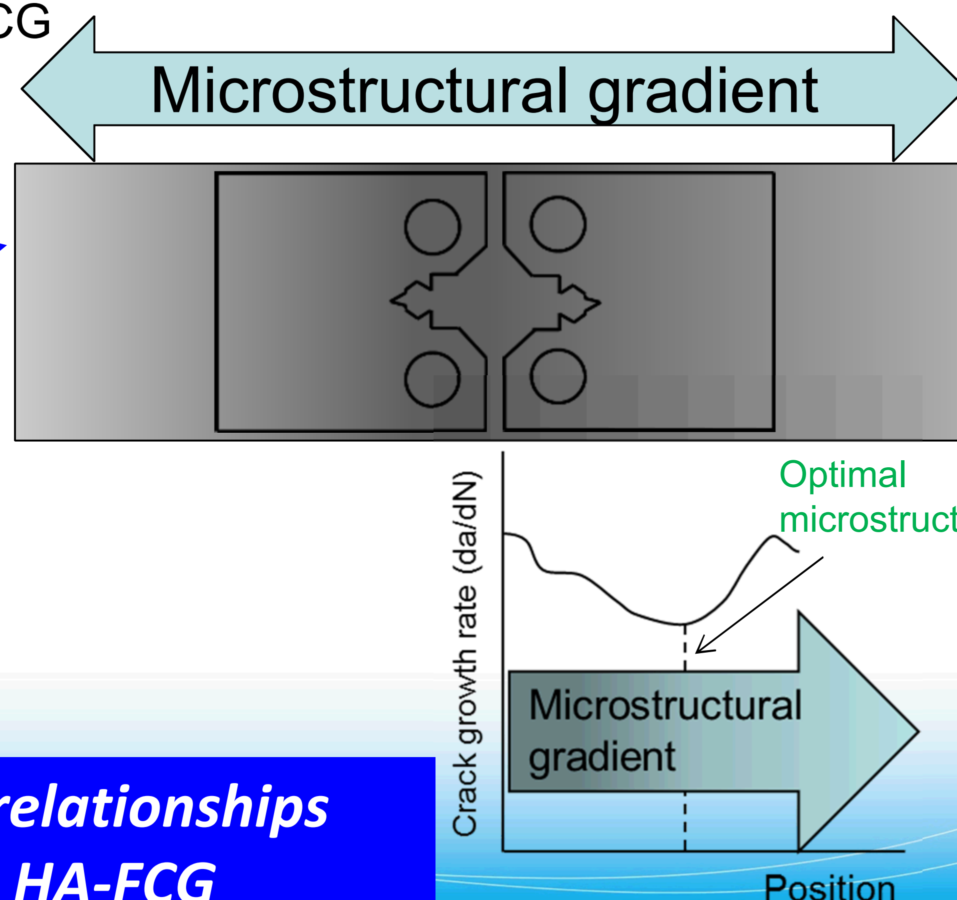
SNL

- Measure HA-FCG in graded microstructure
- Correlate microstructure with HA-FCG

Gleeble™

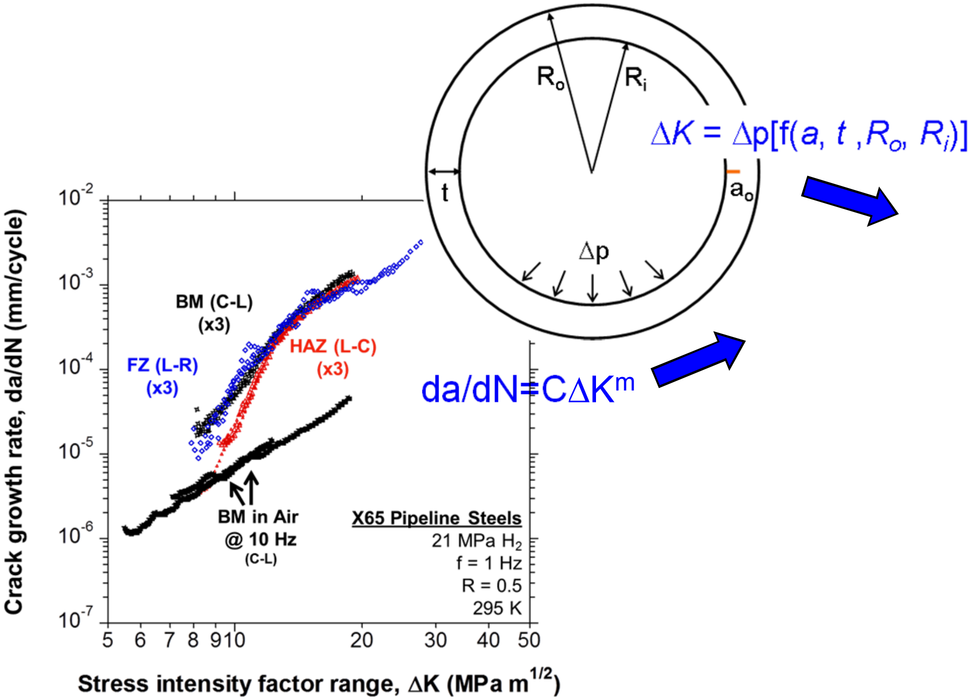


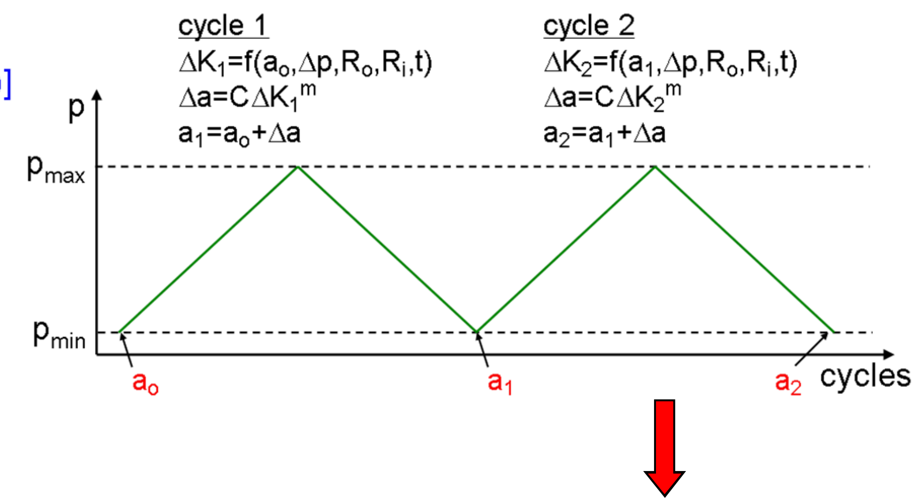
Copper Chill blocks

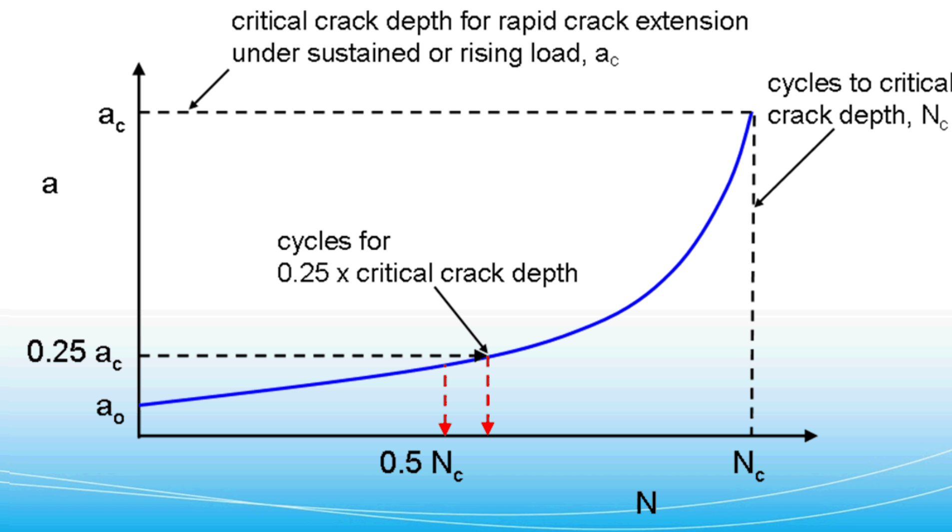


Provide basic knowledge of relationships between microstructure and HA-FCG

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)

H_2 Pipeline Design

	H_2 Pipeline Wall Thickness Necessary*	
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)

- NG pipeline thickness necessary calculated based on ASME B31.8

Thickness: 0.96 in (24.4 mm)

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

P = design pressure = 21 MPa
S = SMYS = 52 ksi (X52)
t = thickness
D = outside diameter = 24 in.
F= design factor = 0.72 (Class 1)
E = longitudinal joint factor = 1
T = temp derating factor = 1

H_2 pipelines may not require a thickness premium relative to current natural gas codes.

Publications

- J. A. Ronevich, B. P. Somerday, and C. W. San Marchi, "Effects of microstructure banding on hydrogen assisted fatigue crack growth in X65 pipeline steels," *International Journal of Fatigue,* vol. 82, Part 3, pp. 497-504, 2016.
- J. A. Ronevich, B. P. Somerday, "Assessing Gaseous Hydrogen Assisted Fatigue Crack Growth Susceptibility of Pipeline Steel Weld Fusion Zones and Heat Affected Zones," *Materials Performance and Characterization,* accepted, in press.

Presentations

Joe Ronevich and Brian Somerday, "Hydrogen Embrittlement of Pipeline Steels and Welds." presented at ASME B.31.12 Committee Meeting, Atlanta, GA, USA, March 4th, 2015.

J. Ronevich and B. Somerday, "Assessing Gaseous Hydogen Assisted Fatigue Crack Growth Susceptibility of Pipeline Steel Weld Fusion Zones and Heat Affected Zones." 15th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics in Anaheim, CA, May 20-22, 2015.

Invited talk at U.C. Davis - *J. Ronevich*, "Assessing the Effects of Crack Closure and Residual Stress on Fatigue Crack Growth Rates of Pipeline Steel Welds in H_2." September 23rd, 2015.

B. Somerday and J. Ronevich, "Hydrogen-Accelerated Fatigue Crack Growth in Pipeline Steels and Their Welds," presented at EUROMAT 2015, Warsaw, Poland, September 24, 2015.

J. Ronevich, B. Somerday, "Assessing Steel Pipeline and Weld Susceptibility to Hydrogen Embrittlement," FCTO webinar, January 12th, 2016.

J. Ronevich, B. Somerday, "Accelerated Fatigue Crack Growth in Pipeline Steels and Their Welds in High Pressure Hydrogen Gas," NACE Corrosion conference, Vancouver, Canada, March 9th, 2016.

Summary

- Higher strength steel base metals exhibit comparable hydrogen accelerated fatigue crack growth rates to lower strength base metals
  - Compared results of pipeline specified minimum yield strengths (SMYS) ranging from 52 ksi to 100 ksi
- Commenced testing of X100A welded using *current* weld practices to compare to base metal [in progress]
- Constant ΔK testing across weld and HAZ
  - Identify susceptible regions of weld and heat affected zone microstructures
  - Provides means of correlating crack growth rate to variety of microstructures

Future Work

- Identify microstructural regions of weld that exhibit accelerated crack growth rates in H_2 gas
  - Correlate da/dN from constant ΔK tests with microscopy
- Investigate alternative high strength welds
  - ORNL will fabricate weld with alternative consumable
  - ORNL will fabricate high strength friction stir weld
- Planned:
  - Complete testing of X100 base metal at low pressures (800 psi) to complement high pressure (3,000 psi).
    - Data is needed for physics based model - NIST.
- Communicate results:
  - Present results of welded X100 at International Hydrogen Conference in Sept. 2016
  - Journal paper on friction stir welds in hydrogen
  - ASME B31.12 committee