Sandia National Laboratories

H2FC Hydrogen and Fuel Cells Program

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

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PD025

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Overview

Timeline and Budget

- Project Start Date: Oct. 2015
  - Year 2 of 3
- FY17 Planned DOE Funding: $1000K Total
  - $400K – SNL
  - $500K – ORNL
  - $100K – NIST/CSM
- Total DOE Funds Received to Date: $900K
- 3 year budget total: $2.65M

Barriers & Targets

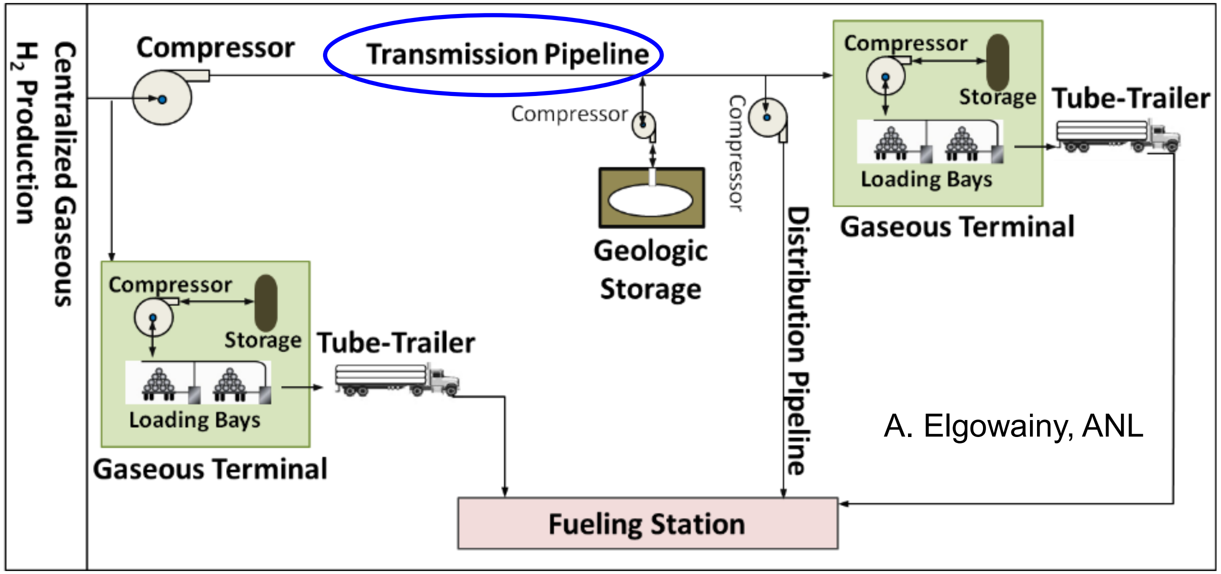
- K. Safety, Codes and Standards, Permitting
- D. High As-Installed Cost of Pipelines

Partners

- Federal Labs: ORNL, NIST
- Industry: ExxonMobil
- Standards Development Organizations: ASME B31.12
- Academia: Colorado School of Mines, U.C. Davis

Relevance: Pipelines are lowest cost pathway to transport 100,000s kg of hydrogen per day

Gaseous Delivery Pathways



> 1,500 miles of steel hydrogen pipeline in the U.S. today!

Insufficient understanding of the risk of H_2 embrittlement restricts choice of steels for H_2 pipelines

Relevance: U.S. DOE Fuel Cell Technologies Office Targets

Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a]

Category	FY 2011 Status[bb]	FY 2015 Status	FY 2020 Target	Ultimate Target[cc]
Gaseous Hydrogen Delivery				
Pipelines: Transmission				
Total Capital Investment ($/mile for an 8-in. diameter equivalent pipeline) [excluding right-of-way][b]	765,000	765,000	695,000	520,000
Transmission Pressure[c] (bar)	70	70	100	120
H_2 Leakage (% of hydrogen transported)[d]	–	<0.5%	<0.5%	<0.5%
Lifetime[e] (years)	–	–	50	50

https://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf

Cost of Steel Pipelines

2015 status based on 30 years of data on the costs of natural gas pipelines, excl. right-of-way.[a]

Higher strength **pipes enables both** **<u>higher pressures</u>** **and** **<u>lower costs</u>**
→ Design codes (ASME B31.12) place penalties (increased thickness) on higher strength pipes, restricting cost savings

Using X100 (instead of X52) can result in 42% cost reduction for 24" pipe operated at 110 bar[b]

a. http://www.ogj.com/articles/print/volume-109/issue-1/transportation/national-lab-uses-ogj-data-to-develop-cost-equations.html
b. Preliminary analysis by Amaro based on Fekete *et al. 2015 (Int. J of Hydrogen Energy)*

Objective(s)

Enable deployment of high-strength steel for H_2 pipelines to facilitate ***cost reductions:***

Task 1) Determine whether girth welds in high-strength steel pipes exhibit fatigue performance similar to low strength pipes in H_2 gas

- Base metal has similar performance over range of strengths
- **Will high strength *welds* behave the same across range of strengths?**

Task 2) Identify pathways to develop high-strength pipeline steels that can be used in H_2 service

- **Develop predictive models that correlate microstructure to hydrogen accelerated fatigue crack growth (HA-FCG)**

Use of higher strength steels = Less material = Lower cost

Approach: Collaborative Efforts

Oak Ridge National Laboratory

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

Sandia National Laboratories

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

NIST / Colorado School of Mines

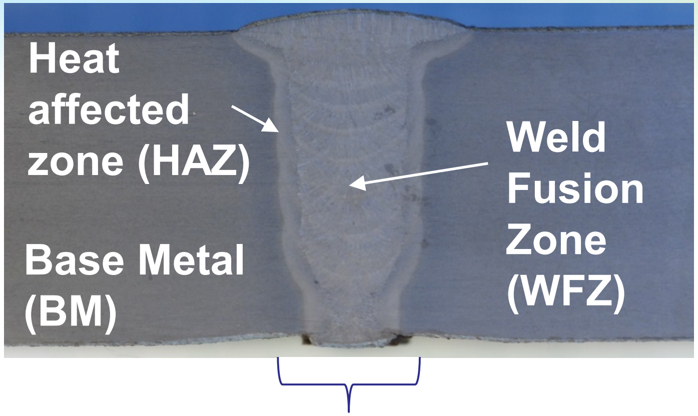
- Build database of pipeline behavior in H_2 based on microstructure
- Develop microstructure-informed predictive model for HA-FCG

	FY 16				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 (100%)											
Subtask 1.2.1 Fabricate girth weld with alternative consumable		ORNL (100%)										
Subtask 1.2.2 Measure HA-FCG performance of arc weld with alternative consumable							SNL (20%)					
Subtask 1.3.1 fabricate friction stirw girth weld					ORNL (50%)							
Subtask 1.3.2 Measure HA-FCG performance of friction stir weld									SNL (0%)			
Subtask 2.1.1 Develop graded microstructures with Gleeble device	ORNL (100%)											
Subtask 2.1.2 Measure HA-FCG in graded-microstructure specimens							SNL (50%)					
Subtask 2.2.1 Produce lab-scale high strenth steel							ORNL (0%)					
Subtask 2.2.2 Measure HA-FCG in lab-scale experimental steel											SNL (0%)	
Subtask 2.3 Microstructure-informed predictive model for HA-FCG in pipeline steels	NIST/CSM (50%)											
							Go/No-Go					

Approach for Task 1: Evaluate fatigue performance of welds for X100 in high pressure H_2 gas

1. Complete **fatigue tests on commercially available X100 welded pipe** (Milestone FY16Q3 - Complete)

2. Fabricate and evaluate **fatigue performance of high strength welds** with alternative consumables



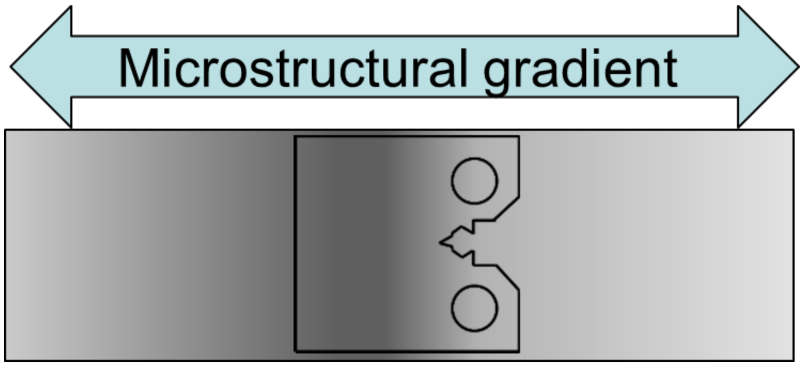
Alternative Weld	Filler Metal	Fabrication Progress (FY16-17)	Testing Progress (FY17-18)
W1	100 ksi filler ER100S-G (commericial)	(100%)	(20%)
W3	120 ksi filler ER120S-1 (commercial)	(100%)	(20%)
W4	LTTW Designed for H_2 resistance (ORNL)	(100%)	(20%)
Friction Stir weld (FSW)	No filler	(50%)	(0%)

Impact: Comprehensive study of suitability of high strength steel welds for high-pressure H_2 service

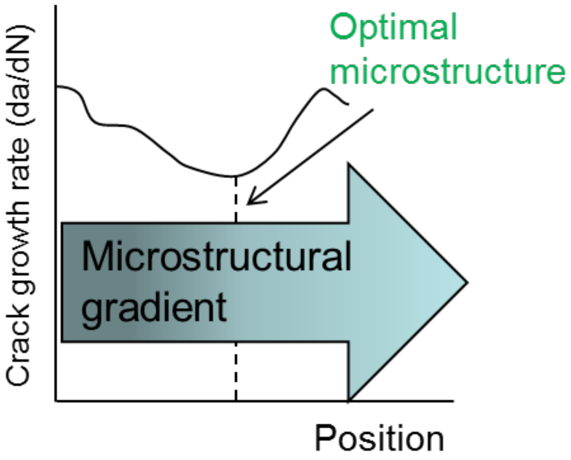
Approach for Task 2: Develop controlled microstructures and quantify HA-FCG

- Use Gleeble™ to generate microstructural gradients (ORNL)
  - Measure HA-FCG as function of microstructure (SNL – FY17 Q2/Q3)
- **Go/No-Go**: If microstructures are identified that demonstrate HA-FCG performance equivalent or superior to X100 base metal,

  → **Fabricate optimized laboratory scale experimental steel**



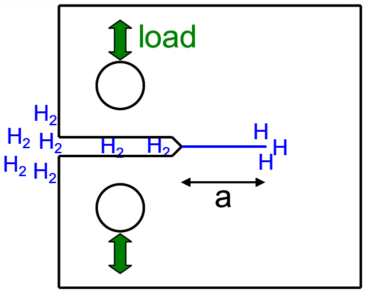
Gleeble Specimen



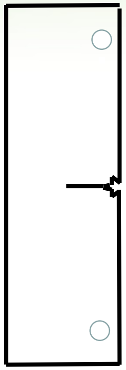
Impact: Identify microstructure constituents that moderate or exacerbate HA-FCG for purposes of developing novel steel

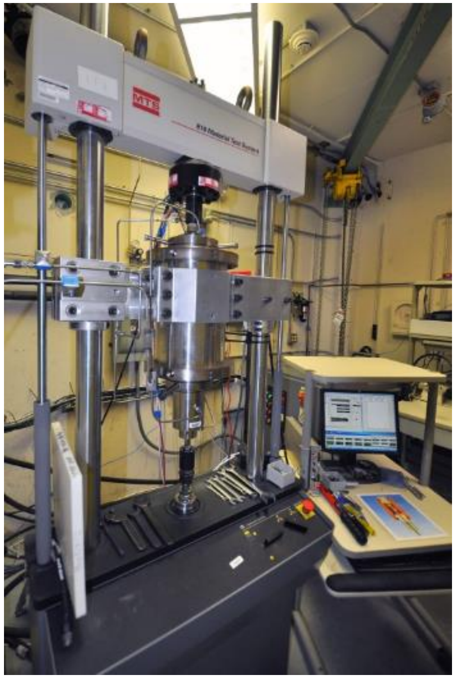
Approach: Fatigue crack growth laws measured in service environment, i.e. high-pressure H_2 gas

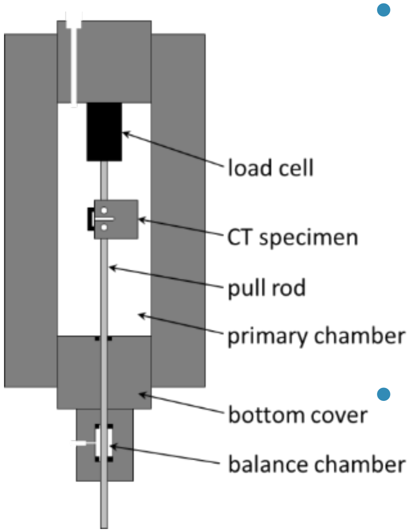
Compact Tension (C(T))



ESE(T)





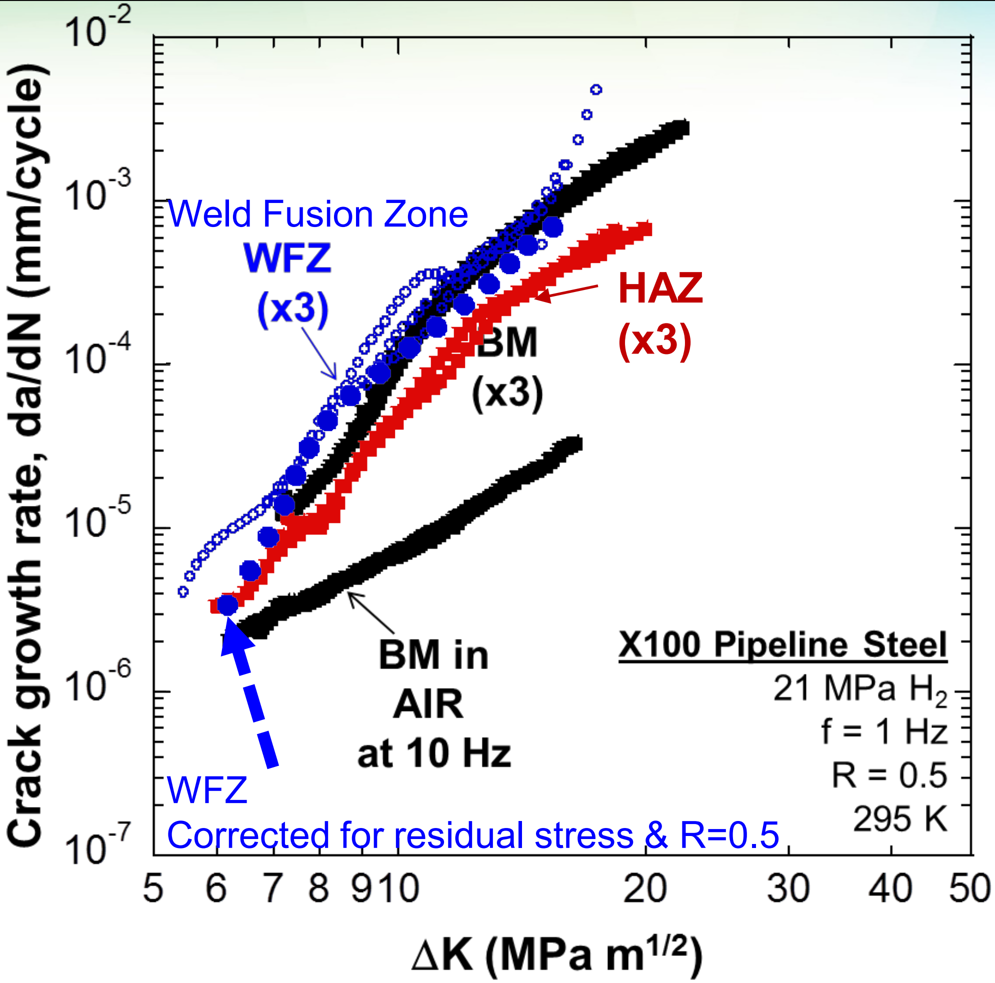


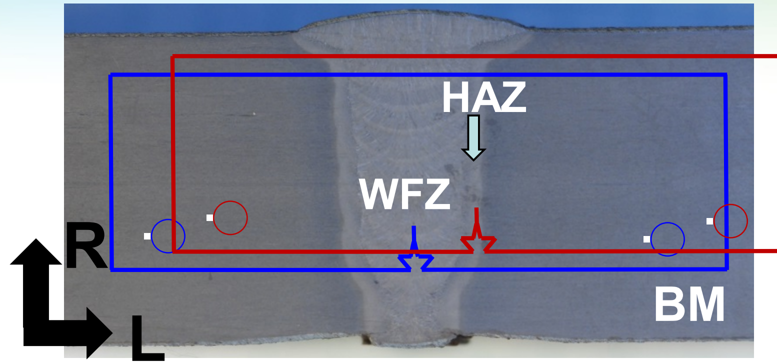
- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT or clip gauge
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude

$$R = \frac{P_{min}}{P_{max}} = 0.5 \qquad frequency = 1Hz$$

  -
    - *Represents pressure fluctuations to ½ P_{max}*
- Environment
  - Supply gas: 99.9999% H_2
  - Pressure = 21 MPa (3 ksi)
  - Room temperature

Accomplishment: Completed Triplicate tests on X100 pipe, weld and HAZ in 21 MPa H_2 gas

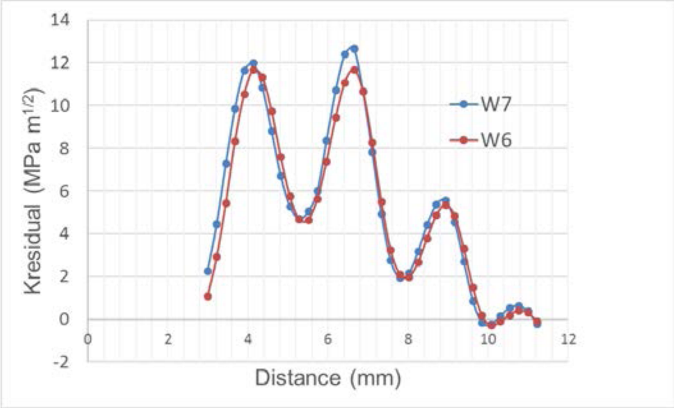




Residual stresses of weld were measured using slitting method at U.C. Davis

→ Calculate $K_{residual}$

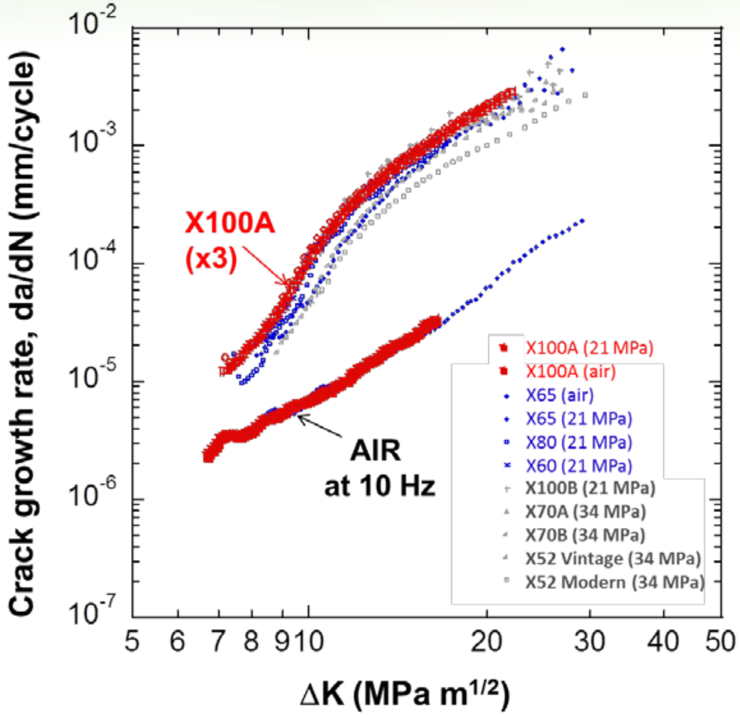
→ Corrected for residual stress effects



Base metal and weld have similar HA-FCG when residual stress is discounted

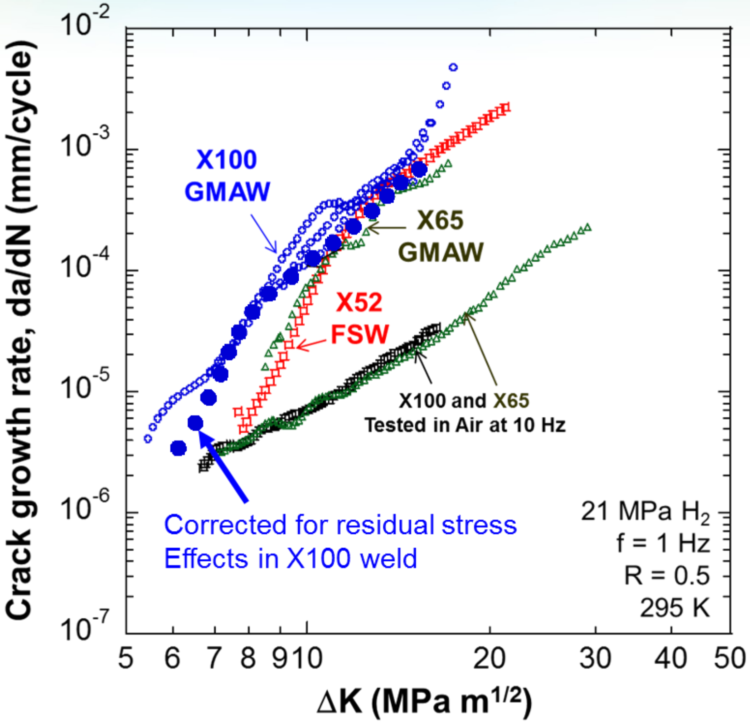
Accomplishment: Assess impact of strength on fatigue performance of Base Metals and Welds

Base Metals



High strength base metals perform similar to low strength

Welds



Weld Types

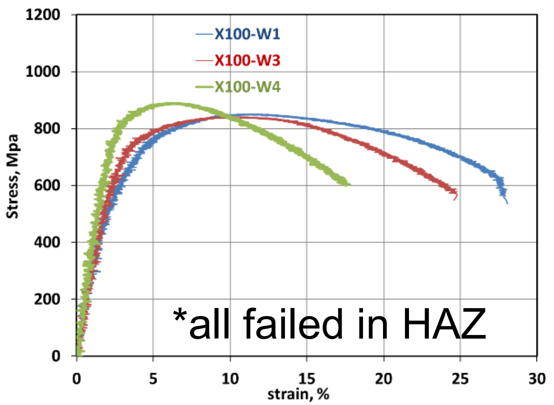
GMAW: Gas metal arc weld

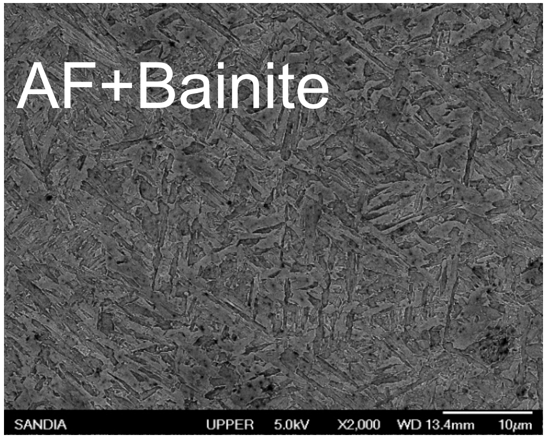
FSW: friction stir weld

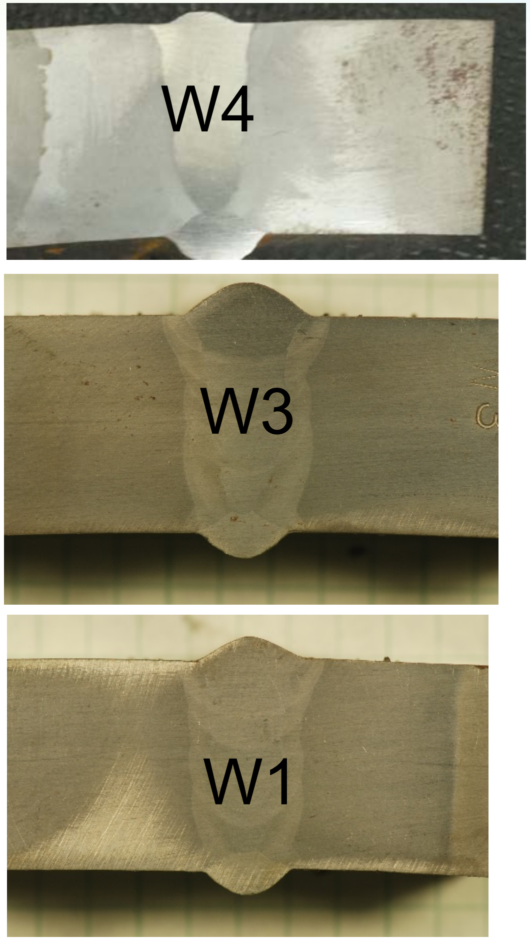
X100 welds exhibit higher crack growth rates than lower strength welds

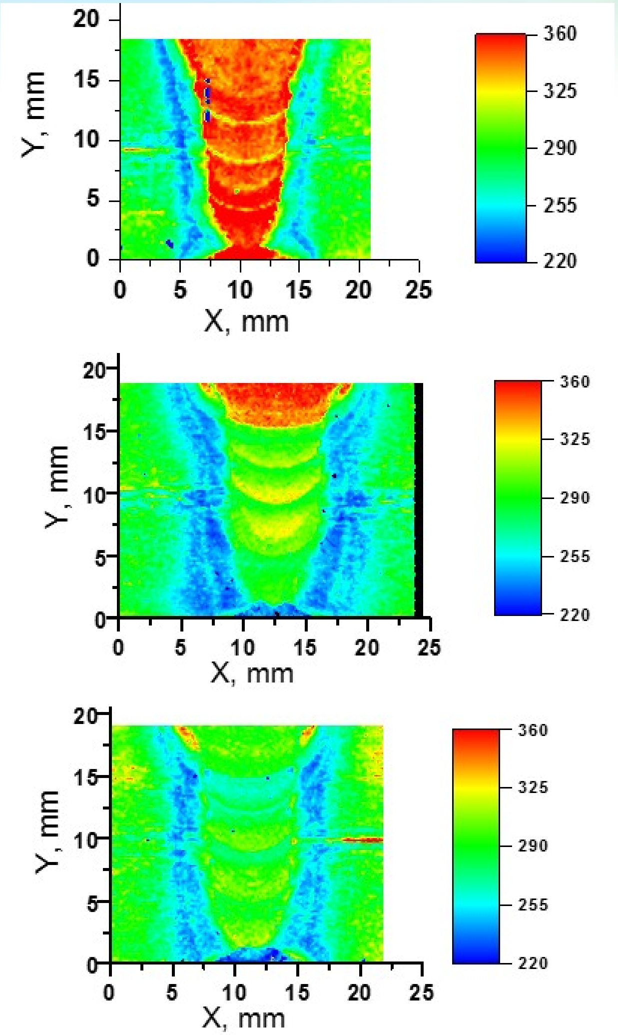
Base metal performance in H_2 appears less sensitive to strength than welds

Accomplishment: Fabricated High Strength Welds from Alternative Consumables using same X100 base metal









W1 - ER100S-G (Commercial), 100C preheat
W3 – ER120S-1 (Commercial), 125C preheat
W4 – LTTW – low temp transformation weld (ORNL developmental), no preheat

Impact → Comprehensive fatigue study of high strength steel welds

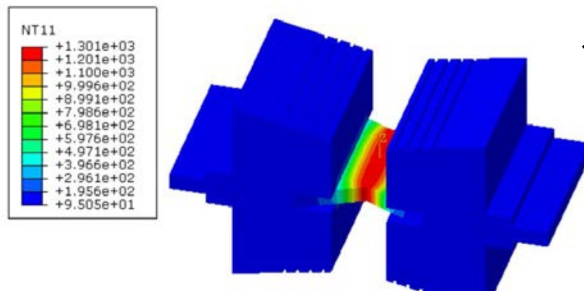
Accomplishment: Developed a novel technique to produce gradient microstructures for Constant ΔK testing

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

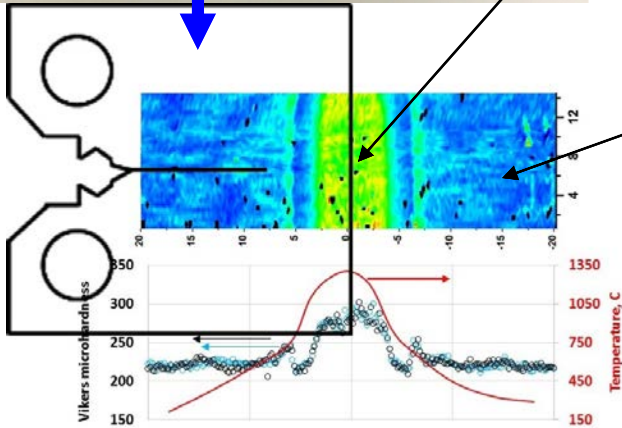
OAK RIDGE National Laboratory

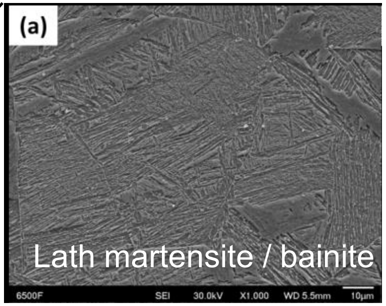
Gleeble™

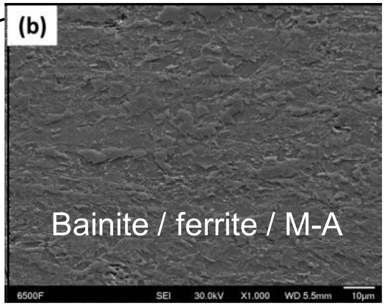
Copper Chill blocks



- **FE modeling to assist development of sample geometry and testing procedure to produce desired microstructure gradient**





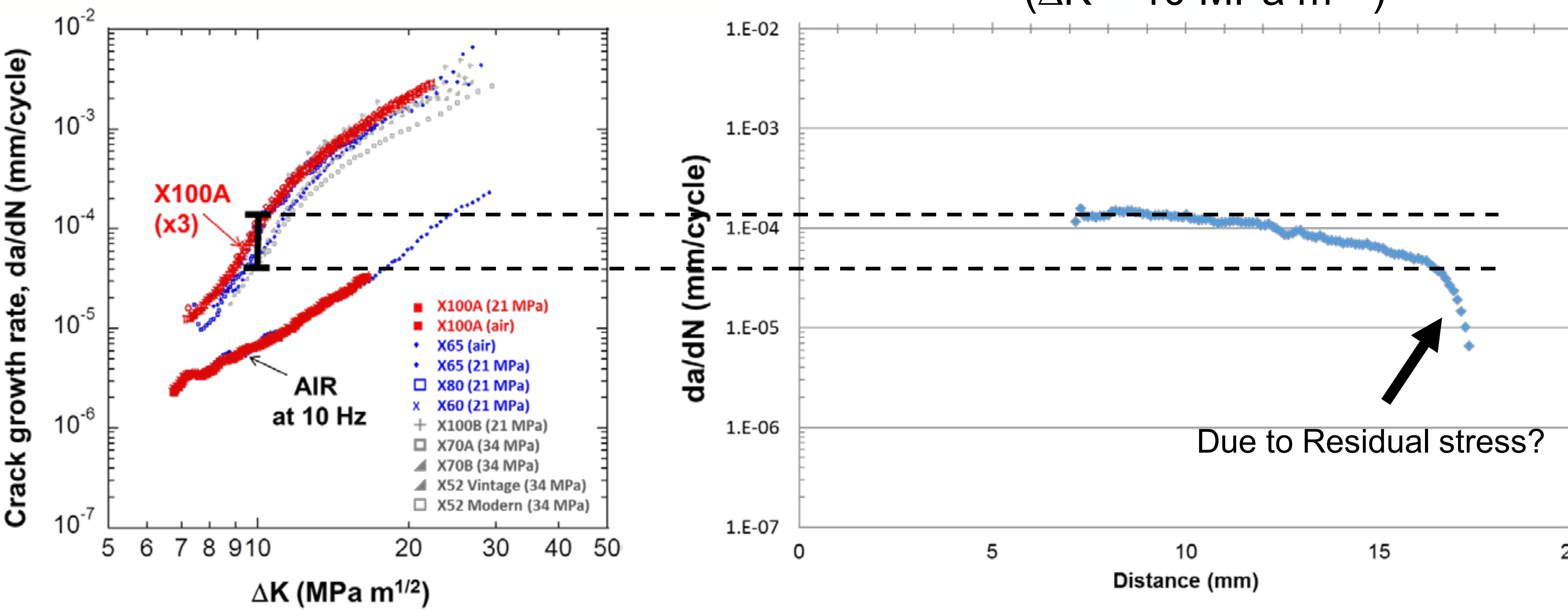


- **Suitable graded microstructures have been achieved**
- **Temperature profile, microstructure and micro hardness gradients of Gleeble™ samples were fully characterized to assist HA-FCG test**

Progress: Performed initial Constant ΔK test in Gleeble samples to assess impact of residual stress on fatigue testing results

Anticipated da/dN range

Actual da/dN Range for Gleeble™ sample
(ΔK = 10 MPa m$^{1/2}$)



- da/dN exhibited steady decrease as crack penetrated further into sample thickness
  - Large decrease likely due to residual stress

In subsequent specimens: Slower cooling rate in Gleeble™ samples will reduce residual stresses

From Phenomenological to Predictive Model

Current Status

- ASME B31.12 design based on phenomenological model
  - Implementation provides a conservative prediction of HA-FCG
  - 2017 revision (based on experimentation) allows for the use of higher strength pipeline steels without penalty
    - **~30% cost savings in pipeline installation (if X70 used in place of X52)**

Advantages

- Can predict HA-FCG as function of pressure and mechanical loading parameters
- Revision demonstrates ASME committee is open to including predictive models in future

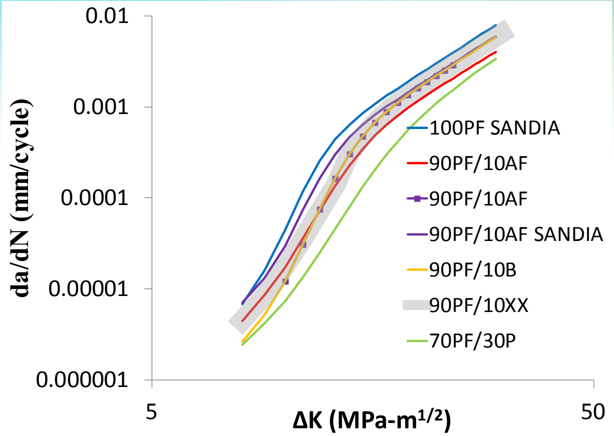
Short-comings

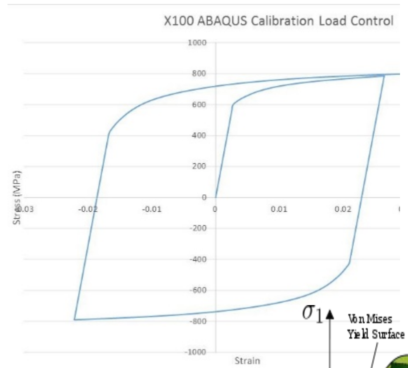
- Needs to be calibrated for each lot of material **(inefficient)**
- Provides upper bound, without accounting for microstructure
  - May be **over-conservative** for microstructures commonly found in high strength steels and welds

Predictive model will incorporate each individual microstructural constituent's hydrogen/deformation response to macroscopic HA-FCG

Progress: Develop microstructure relationships

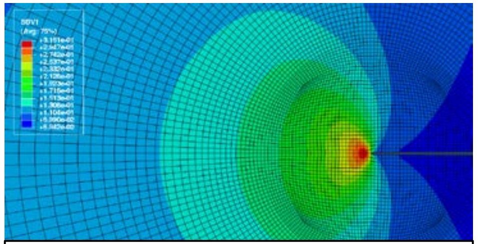
- Discretize results as a function of pipeline steel microstructural constituents
  - Polygonal ferrite (PF)
  - Acicular ferrite (AF)
- Create model module that is sensitive to volume fraction of PF



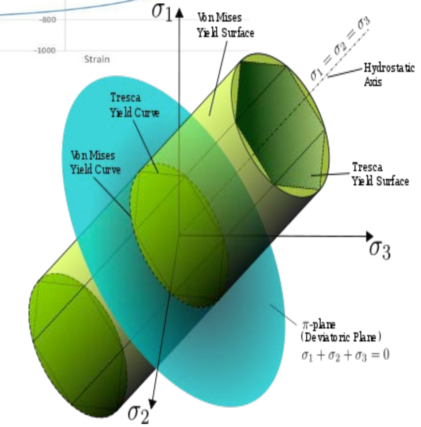


Approach for Physics Based Model

- Begin with a continuum representation
- Constitutive model (J2 isotropic plasticity)
- Incorporate hydrogen diffusion response to microstructure
  - Implemented user defined Material (UMAT) in ABAQUS

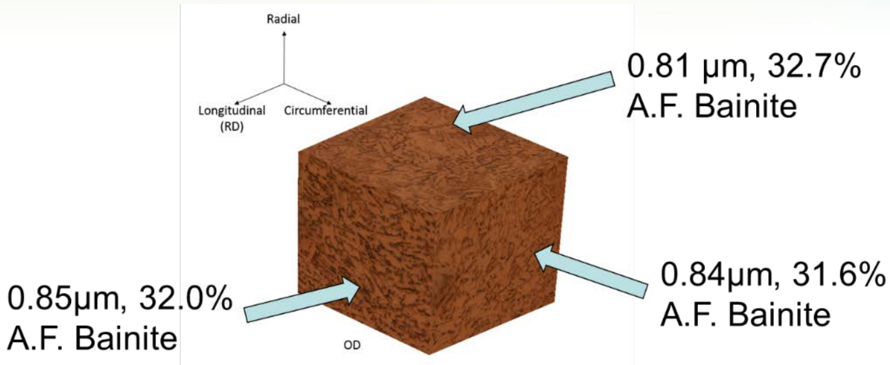


Hydrogen concentration at crack tip

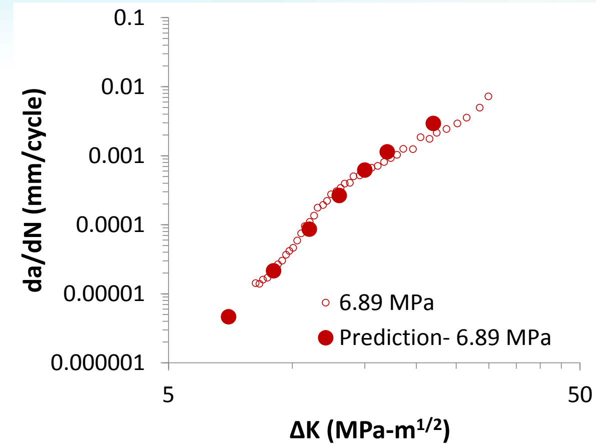


Progress: HA-FCG data used to calibrate model

- Characterize microstructures of interest: X100B BM



- Calibrate model to existing HA-FCG X100B data



	FY 16				FY 17				FY 18			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1	100% complete											
Task 2					20% complete							
Task 3					0% complete							
Task 4					20% complete							
Task 5								0% complete				
Task 6										0% complete		

Task 1: Incorporate calibrated phenomenological model of X100 base metal into framework of physics-based model for validation of physics-based model.

Task 2: Modify physics-based model to account for FCGR in current-practice girth welds and heat affected zones using data obtained from SNL.

Task 3: Modify physics-based model to account for FCGR of microstructures studied by SNL using Gleeble specimens.

Task 4: Define meshes for each microstructure of interest in X100 steel and welds

Task 5: Modify physics-based model to include effects of each microstructure of interest.

Task 6: Use model to predict HA-FCG of experimental steel

Goal: Predict HA-FCG response as function of ANY microstructure built into library

Remaining Challenges and Barriers

Current industry status

ASME B31.12 code currently limits specified minimum yield strength (SMYS) with significant **design penalties** on higher strength pipes

- Generating data on higher strength steels and their welds will enable establishment of **data-informed safety factors** for steel H_2 pipelines and improve likelihood of adoption of higher strength pipes into code.

Materials R&D Challenges

- Pipeline steel microstructures and strength can vary drastically and qualifying pipe for hydrogen use can involve a **significant test burden**
  - Focused testing on gradient microstructures can capture HA-FCG and aid in deriving **microstructure-performance relationships** (foundation for predictive, physics based model).
- **Residual stresses** can significantly affect HA-FCG measurements
  - Residual stresses will be measured in order to de-couple effects from $K_{residual}$ and $K_{applied}$ thus allowing more direct comparisons of microstructure and performance.

Proposed Future Work

- Remainder of FY17
  - **Complete** HA-FCG testing on alternative high strength welds (SNL)
  - **Fabricate** friction stir weld (FSW) on X100 pipe (ORNL)
  - **Develop** lab-scale high-strength steel if microstructures are identified that exhibit equivalent/superior performance to X100 base metal (ORNL)
  - **Incorporate** inelastic stress-strain response of microstructural constituents and characterize microstructures for use in model (NIST/CSM)
  - **Publish** results from HA-FCG testing of current-practice X100 arc weld in peer-reviewed journal (SNL)
- FY18
  - **Fabricate** lab-scale high strength steel and evaluate mechanical properties (ORNL)
  - **Measure** HA-FCG performance in FSW & lab-scale experimental steel (SNL)
  - **Characterize** microstructures of gradient steels to develop and populate database for predictive model (SNL / ORNL / NIST / CSM)
  - **Define** mechanisms of H_2-accelerated fatigue crack growth in steels and develop predictive, physics-based models of this phenomenon (NIST/CSM)

(Any proposed future work is subject to change based on funding levels)

Technology Transfer Activities

- Communicate data on fatigue crack growth of pipeline steels in H_2 gas to ASME B31.12 committee
  - Physics-based model for fatigue crack growth design set to be included in next B31.12 Revision (April 2017)
    - Model based on data generated in high pressure H_2 gas
  - Data-informed safety factors in ASME B31.12 essential for cost-effective deployment of steel H_2 pipelines
- Publications
  - Int. J. of Hydrogen Energy
  - Conference proceedings:
    - International Hydrogen Conference 2016
    - ASME Pressure Vessels and Piping 2016
- Contribute fatigue data to Hydrogen Effects Database
  - Part of Safety Codes and Standards Program at SNL

Responses to Project Reviewers' Comments

1. *"It is not clear how the team will utilize the data from the experiments, or how the data will help in developing the models to predict pipeline behavior as a function of microstructures."*

   The experimental data is used to calibrate the model. Microstructure, mechanical properties, and fatigue crack growth response of experimental steels are being used to build a library that the model can pull from to predict crack growth behavior.

2. *"It is yet to be seen how effective collaboration with CSM will be. The Gantt chart references NIST, but the work scope appears to be from CSM."*

   The modelling work is predominantly being performed by Amaro at CSM (formerly of NIST). However, Slifka and Drexler of NIST are working closely with Amaro and provide guidance and experience on hydrogen pipeline steels.

3. *"The project should test the threshold stress intensity factor range for hydrogen-induced accelerated fatigue."*

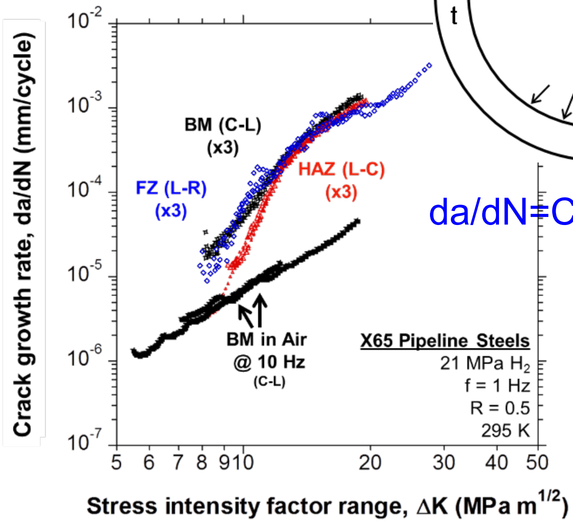
   One of the challenges with fatigue crack growth measurements at lower frequencies is striking a balance between testing efficiency and acquiring relevant data. Tests at 1 Hz, particularly at lower ΔK values can require many days to weeks to complete a single test. The team is trying to generate data at lower ΔK values, near the threshold stress intensity factor range for hydrogen-induced accelerate fatigue, however a balance must be obtained to permit efficient use of the equipment.

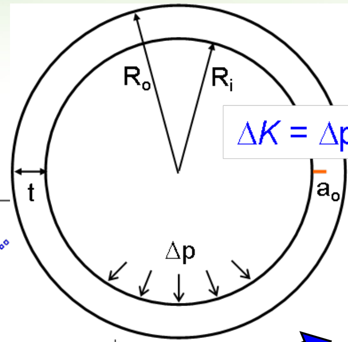
Project Summary

Objective	▪ Enable deployment of high-strength steel for H_2 pipelines to facilitate *cost reductions*
Approach	▪ Determine whether girth welds in high-strength steel pipes exhibit fatigue performance similar to low strength pipes in H_2 gas ▪ Fabricate and test graded-microstructures to identify optimum microstructures for future pathways of reducing pipeline costs ▪ Develop microstructure-based predictive fatigue crack growth model
Accomplishments	▪ Fatigue testing of X100 revealed weld exhibited only slightly higher HA-FCG compared to base metal and HAZ, after residual stress effects were removed. ▪ Developed methods to fabricate specialized test samples: high strength welds and gradient microstructure Gleeble™ samples ▪ Improved fidelity of model by including microstructure-dependency
Collaborations	▪ Multi-lab project with team experts: SNL, ORNL, NIST, CSM ▪ H_2 pipeline and pressure vessel committee ASME B31.12 input ▪ Industry partners to supply materials ▪ UC Davis – residual stress measurements
Future Plan	▪ Develop and evaluate alternative welding processes (e.g. conventional and friction stir welding) ▪ Design and fabricate laboratory heat of steel with optimized microstructure ▪ Characterize microstructures tested to build library for predictive model ▪ Incorporate inelastic stress-strain response of microstructural elements to macroscopic loading for predictive model

Technical Back-Up Slides

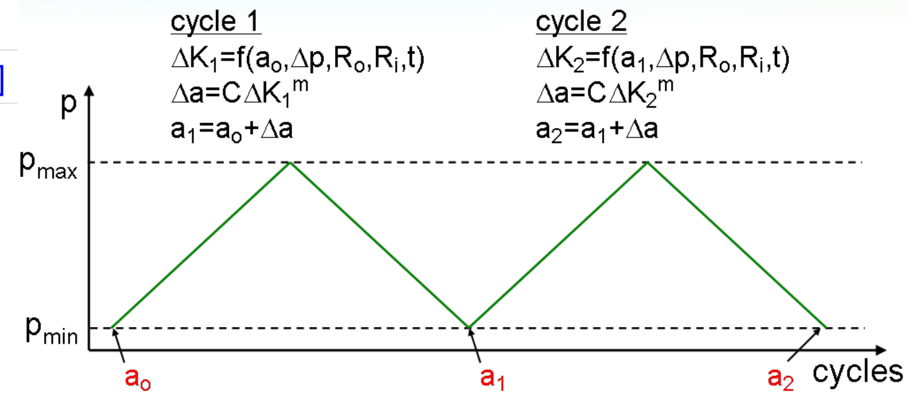
Measured fatigue crack growth relationships can be used to specify wall thickness for H_2 pipelines

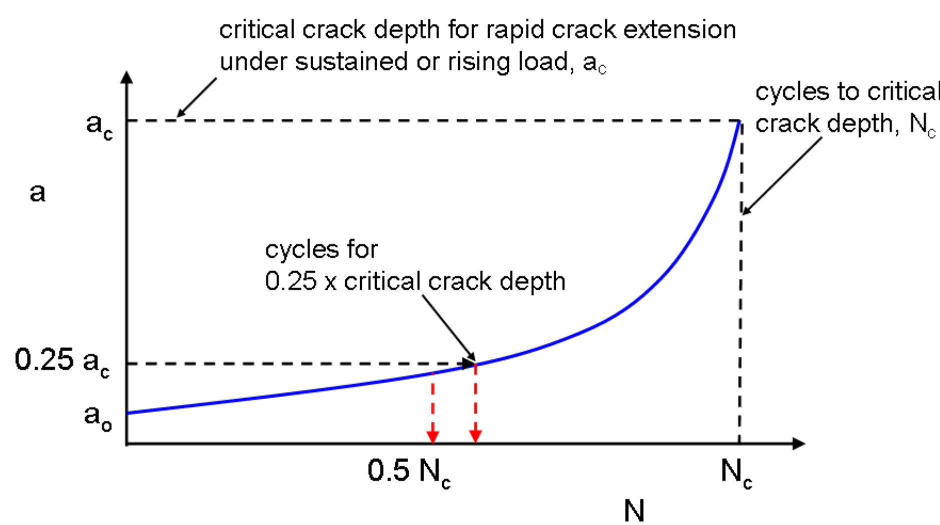




$\Delta K = \Delta p[f(a, t, R_o, R_i)]$

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





- Need:
  - Pipeline ID
  - Pressure cycle range
  - Initial flaw size (a_o)
  - Inspection interval (cycles, N)

Relevance: Current Design codes (ASME B31.12) apply thickness premiums to higher strength hydrogen pipelines

- ASME B31.8 ***Natural Gas*** pipeline thickness

$$t = \frac{PD}{2SFET}$$

F= design factor = 0.72 (Class 1)

- ASME B31.12 ***Hydrogen*** pipeline thickness
  - Prescriptive Design Method

$$t = \frac{PD}{2SFETH_F}$$

P = design pressure = 3ksi (21 MPa)
S = specified min yield stress
t = thickness
D = outside diameter = 24 in (610mm)
E = longitudinal joint factor = 1
T = temp derating factor = 1
F= design factor = 0.5 (Class 1)
H_F=Materials Performance Factor

Table IX-5A Carbon Steel Pipeline Materials Performance Factor, H_f

Specified Min. Strength, ksi		System Design Pressure, psig						
Tensile	Yield	≤1,000	2,000	2,200	2,400	2,600	2,800	3,000
66 and under	≤52	1.0	1.0	0.954	0.910	0.880	0.840	0.780
Over 66 through 75	≤60	0.874	0.874	0.834	0.796	0.770	0.734	0.682
Over 75 through 82	≤70	0.776	0.776	0.742	0.706	0.684	0.652	0.606
Over 82 through 90	≤80	0.694	0.694	0.662	0.632	0.610	0.584	0.542

Do H_2 pipelines need a thickness premium compared to current natural gas codes?