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 3 of 3
- FY18 Planned DOE Funding: $1000K Total
  - $650K – SNL
  - $150K – ORNL
  - $100K – NIST/UA/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: Univ. of Alabama, Colorado School of Mines, U.C. Davis

Relevance: Cost reductions can be achieved via higher strength steels

FCTO targets include lowering costs and increasing operating pressures

Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a]

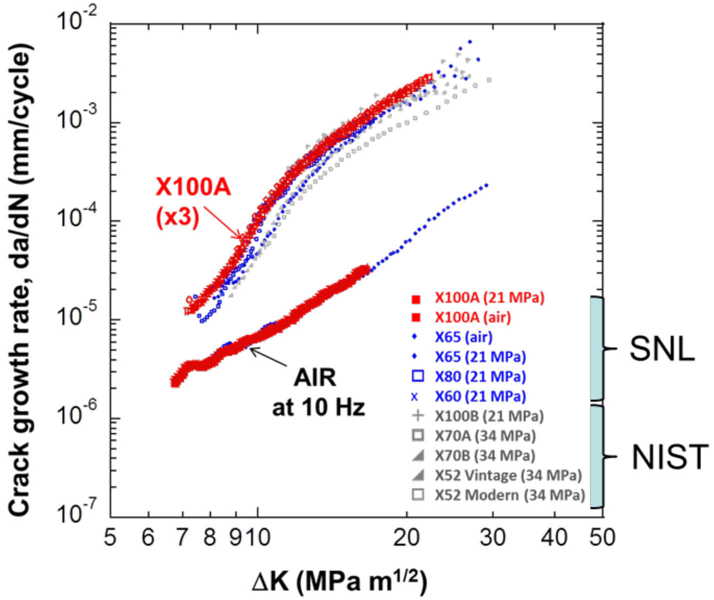
Category	FY 2011 Status[bb]	FY 2015 Status	FY 2020 Target	Ultimate Target[cc]
Gaseous Hydrogen Delivery				
Pipelines: Transmission				
Total Capital Investment ($/mile for an 8-in. diameter equivalent pipeline) [excluding right-of-way][b]	765,000	765,000	695,000	520,000
Transmission Pressure[c] (bar)	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]

Recent research indicates that hydrogen assisted fatigue is not driven by *strength*



Using X100 (instead of X52) can result in 42% cost reduction for 24" pipe operated at 110 bar (1600 psi)[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

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

Understanding material compatibility can lead to improved materials selection resulting in lower costs

Approach: Collaborative Efforts

Oak Ridge National Laboratory

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

Sandia National Laboratories

- Fatigue crack growth measurements of steels in high pressure H_2 gas
- Develop test procedures to evaluate microstructure vs. HA-FCG
- Residual stress evaluation in collaboration with U.C. Davis

NIST

School of Mines Colorado 1874

Alabama Crimson Tide

- Build database of behavior in H_2 based on microstructure
- Synchrotron measurements of strain
- Develop microstructure-informed predictive model for HA-FCG
- Leveraging DOT project on developing models for pressure vessels

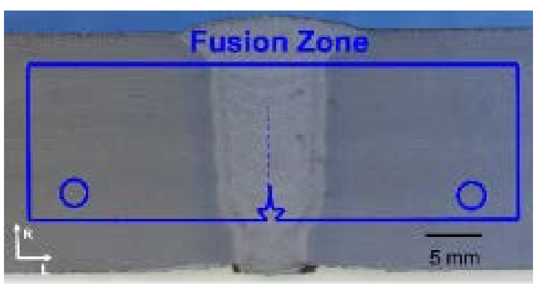
	FY 16				FY17				FY18			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Subtask 1.1 Measure HA-FCG performance for current practice arc weld	SNL (100%)											
Subtask 1.2.1 Fabricate girth weld with alternative consumable		ORNL (100%)										
Subtask 1.2.2 Measure HA-FCG performance of arc weld with alternative consumable							SNL (100%)					
Subtask 1.3.1 fabricate friction stir girth weld					ORNL (100%)							
Subtask 1.3.2 Measure HA-FCG performance of friction stir weld									SNL (100%)			
Subtask 2.1.1 Develop graded microstructures with Gleeble device (Re-develop)	ORNL (100%)				Re-develop graded microstructure							
Subtask 2.1.2 Measure HA-FCG in graded-microstructure specimens (Delayed)							SNL (100%)					
Subtask 2.2.1 Produce lab-scale high strength steel							ORNL (30%)					
Subtask 2.2.2 Measure HA-FCG in lab-scale exp. steel (Added 100% PF model steel)											SNL (50%)	
Subtask 2.3 Microstructure-informed predictive model for HA-FCG in pipeline steels	NIST/UA/CSM (75%)											

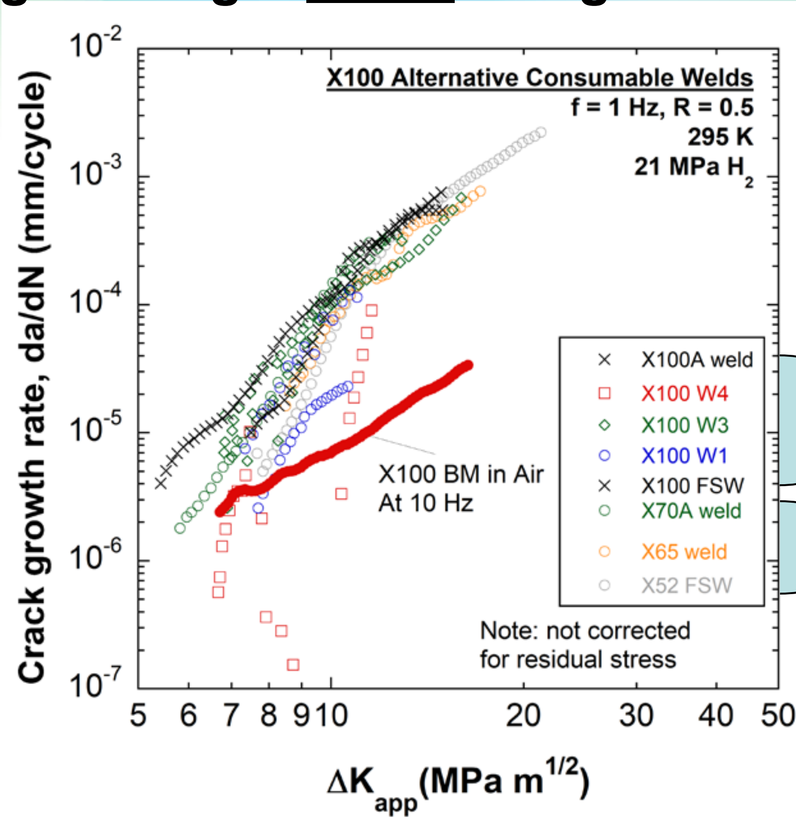
Go/No-Go

Approach/Accomplishment for Task 1: Evaluate fatigue performance of high strength *welds* in high pressure H_2 gas

Fabricated and evaluated 5 different welds with strength greater than 100 ksi (all fabricated from same X100 steel)

Weld Name	Filler Metal (Fabricator)	Testing Progress
X100 A	Initial weld commercial fabrication (Industry)	(100%)
X100 W1	100 ksi filler ER100S-G (ORNL)	(100%)
X100 W3	120 ksi filler ER120S-1 (ORNL)	(100%)
X100 W4[1]	LTTW Designed for H_2 resistance (ORNL)	(100%)
X100 Friction Stir Weld (FSW)	No filler (ORNL)	(100%)





Weld Types

FSW: friction stir weld

Other welds are gas metal arc **GMAW**

High σ_{YS}

Low σ_{YS}

- **Higher strength welds appear to exhibit slightly higher FCGR compared to lower strength welds but large variability**

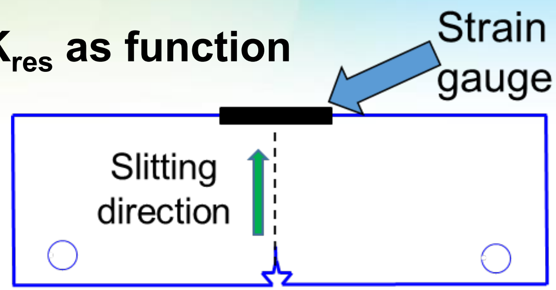
Weld FCGR variability associated with *residual stress*

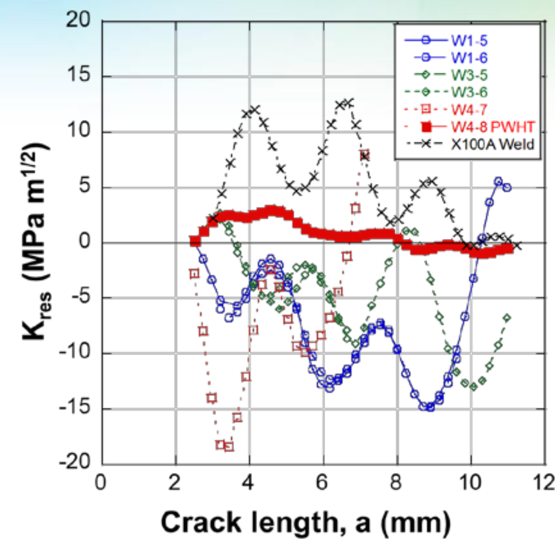
1. Innovative weld material developed by ORNL: https://www.rd100conference.com/awards/winners-finalists/6780/filler-materials-welding-and-3d-printing/

Results: Residual stress measurements performed on high strength welds to decouple from FCGR

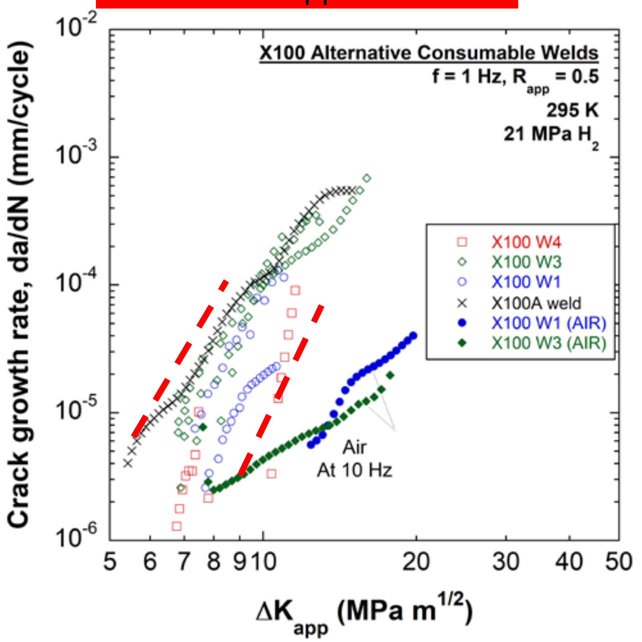
Slitting method used to measure K_{res} as function of crack length

(*Collaboration with Prof. Mike Hill at U.C. Davis)

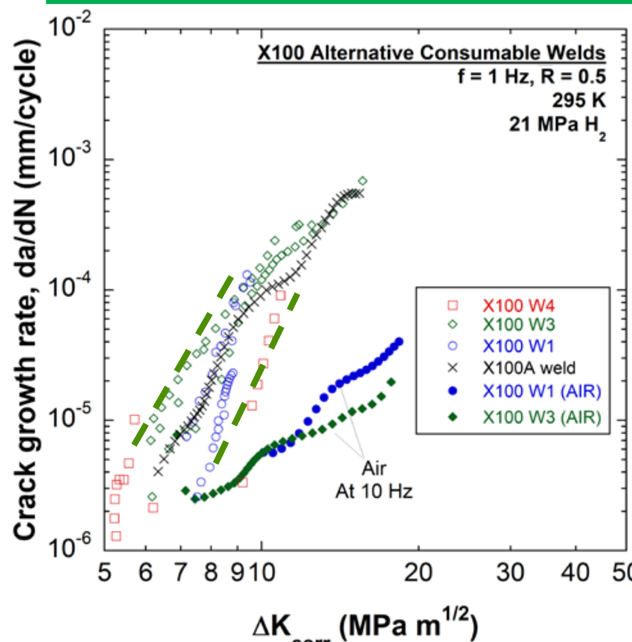




Raw $\Delta K_{applied}$ data



$\Delta K_{corr:}$: K_{res} effects removed

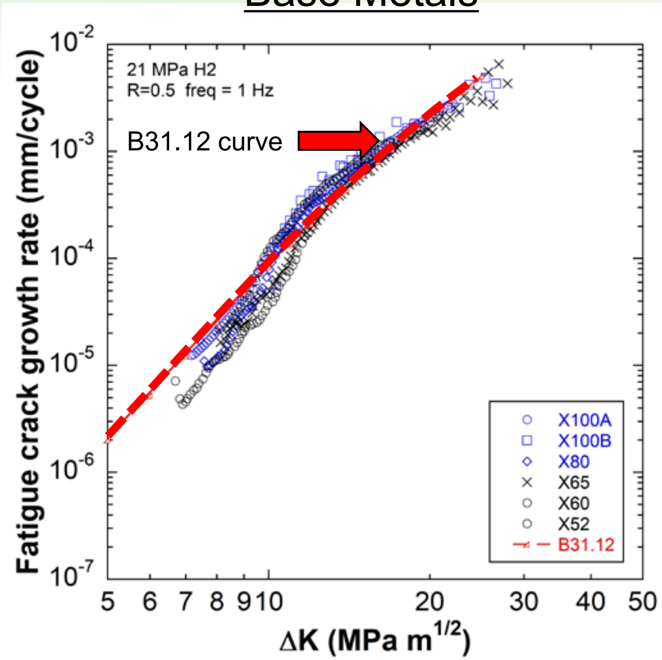


- **Correcting for residual stress allows assessment of microstructures role in fatigue**
- **Shifts curves & reduces scatter**

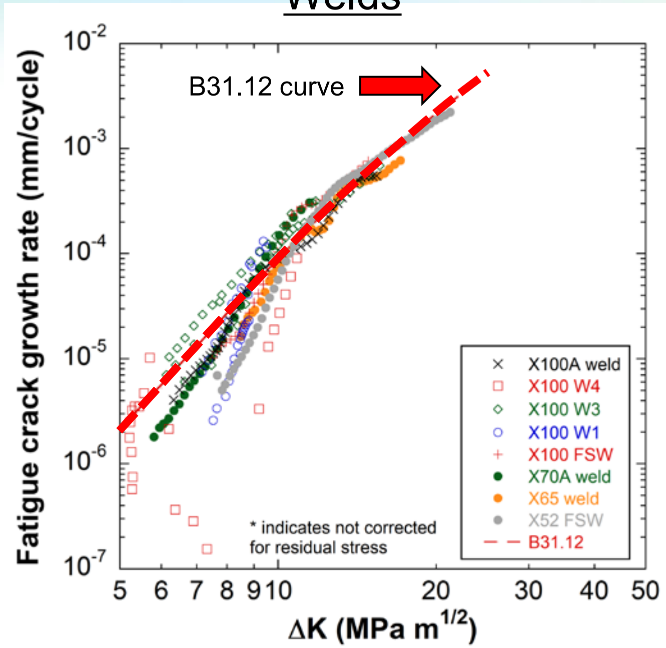
Removal of residual stress effects provides high fidelity FCGR curves

Accomplishment: Compare high strength pipeline results to Hydrogen Pipeline and Piping B31.12 Newly Approved Design Curve

Base Metals



Welds

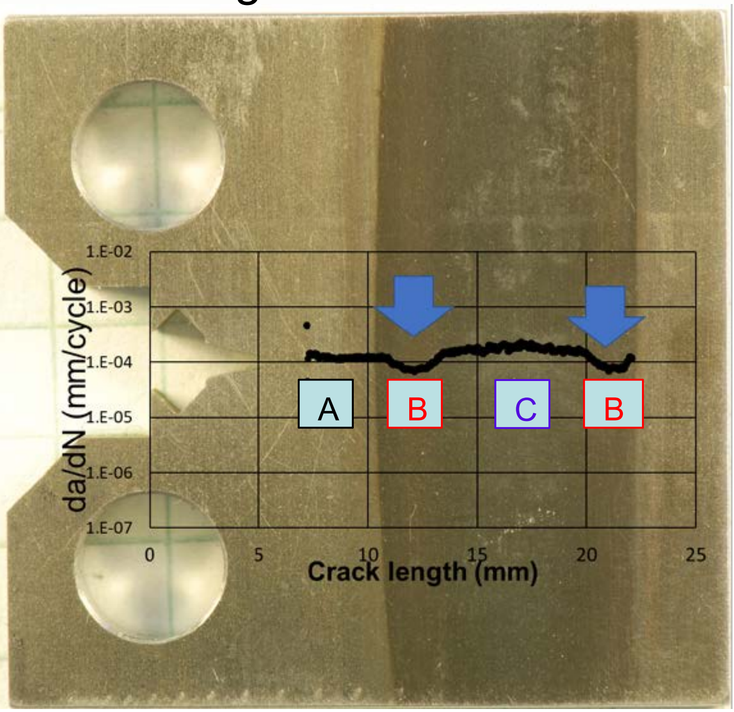


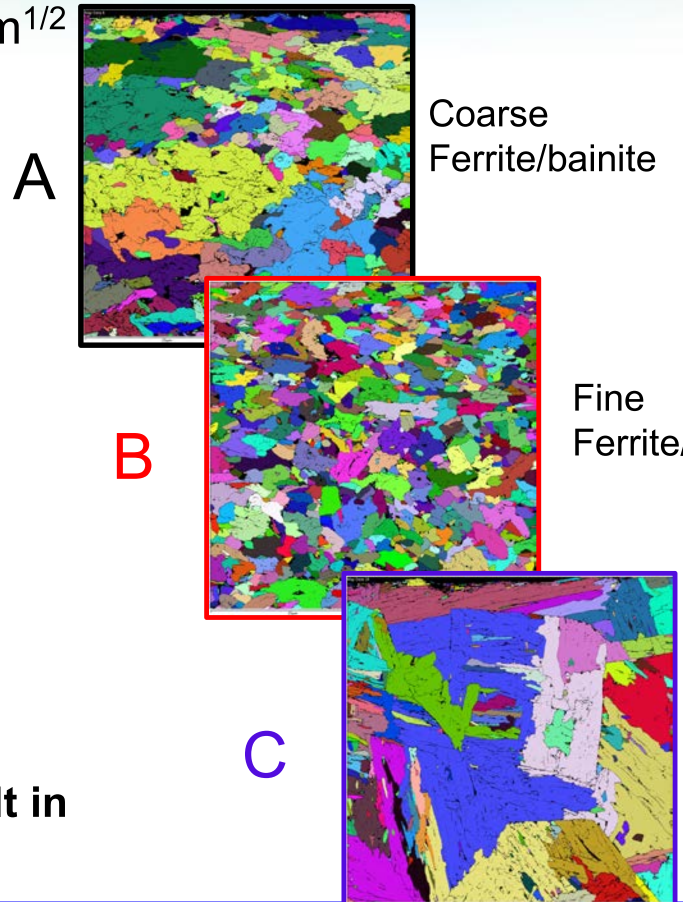
- **Red dashed line (- - -) represents newly approved B31.12 design curve**
  - **Can be used in lieu of testing for pipes up to X70 and to 21 MPa without incurring thickness penalty**
- **Higher strength base metals & welds fall only slightly above B31.12 design curve**

High strength weld data can *now* provide basis for acceptance of higher strength steel pipelines with slight adjustment of B31.12 design curve

Accomplishment: Fabricated gradient microstructure using Gleeble™ and measured changes in FCGR as function of position (Task 2)

Approach: Determine relationships between microstructure and HA-FCG by measuring da/dN at constant $\Delta K = 10$ MPa $m^{1/2}$

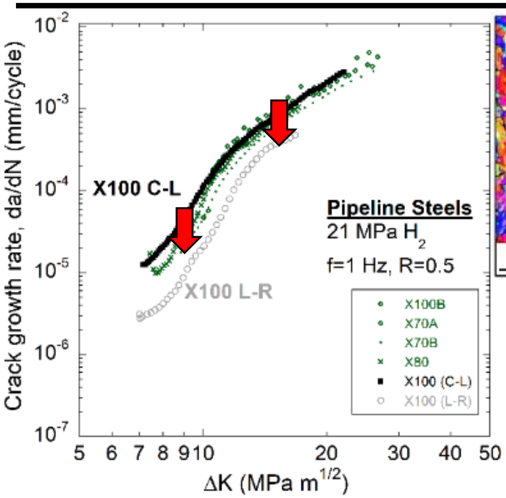


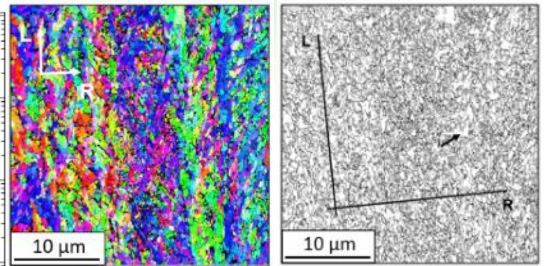


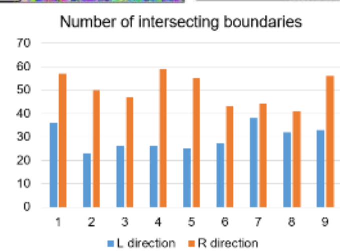
- **Changes in microstructural constituent result in only factor of 2 difference in da/dN**

Microstructural constituents **may not provide means to reduce da/dN significantly**
→ Other features may provide greater reduction in FCGR

Accomplishment: High Angle Grain Boundary (HAGB) intersections appear to have significant effect on HA-FCG when tests conducted in 2 different orientations



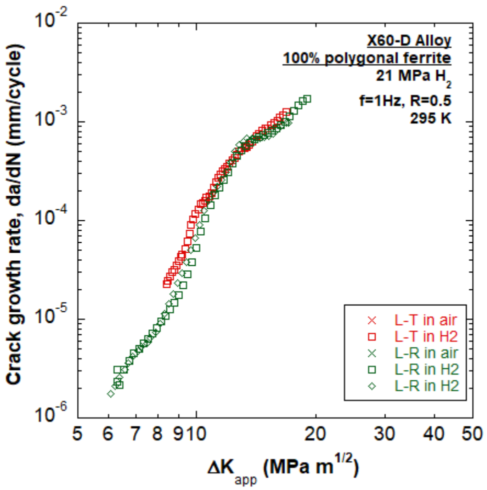


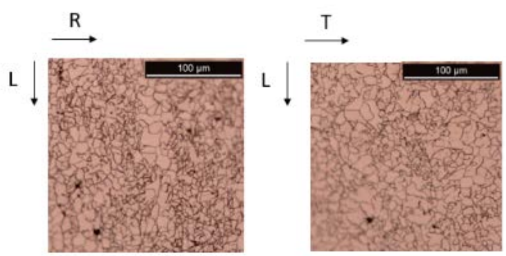


(HAGB: >15°)

X100 Base metal exhibited **4-5 times lower** HA-FCG when crack propagated in R direction compared to L-direction

- ***71% more*** HAGB encountered in R





X60 Base metal exhibited similar HA-FCG in both orientations (< 2 difference in da/dN)

- ***10% more*** HAGB encountered in R

- **Go/No-Go: If microstructures are identified that demonstrate HA-FCG performance equivalent or superior to X100 base metal, fabricate steel**

Grain boundary interaction appears to have more pronounced effect than microstructural constituents

Approach: Advancing Beyond Phenomenological Model

Simplified Model

- Recently included in B31.12 to output generic da/dN curve
- A_i's and b_i's required for every case
- Not predictive: need to adjust for every pressure, every R, every frequency

Full Model

$$\frac{da}{dN}_{total} = \frac{da}{dN}_{fatigue} + \delta\left(P_H - P_{H_{th}}\right)\frac{da}{dN}_H$$

$$\frac{da}{dN}_{fatigue} = A\Delta K^b$$

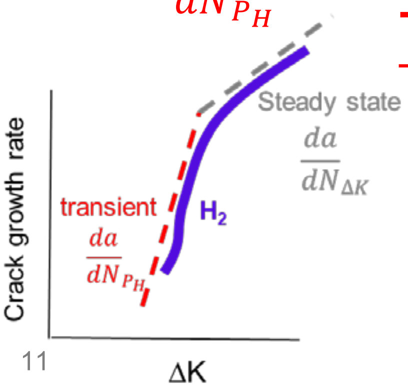
$$\frac{da}{dN}_H = \left[\left(\frac{da}{dN}_{P_H}\right)^{-1} + \left(\frac{da}{dN}_{\Delta K}\right)^{-1}\right]^{-1}$$

$$\frac{da}{dN}_{P_H} = a1\Delta K^{B1}\left(P_H^{m1} exp^{\left(\frac{-Q+V\sigma_h}{RT}\right)}\right)^{d1}$$

Transient

$$\frac{da}{dN}_{\Delta K} = a2\Delta K^{B2}\left(P_H^{m2} exp^{\left(\frac{-Q+V\sigma_h}{RT}\right)}\right)^{d2}$$

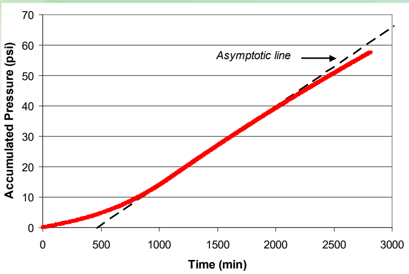
Steady state



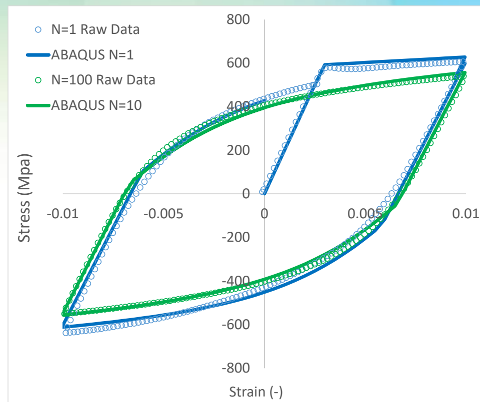
Moving to Predictive Model will include:

- **Cyclic hardening behavior, microstructures, diffusivities, trap densities, Local H_2 concentration**

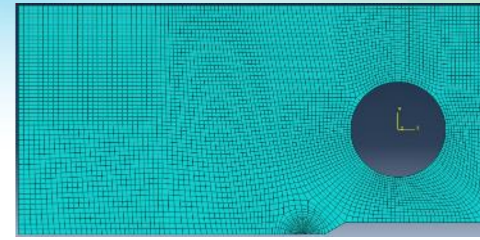
Approach: Methodology for Continuum Model



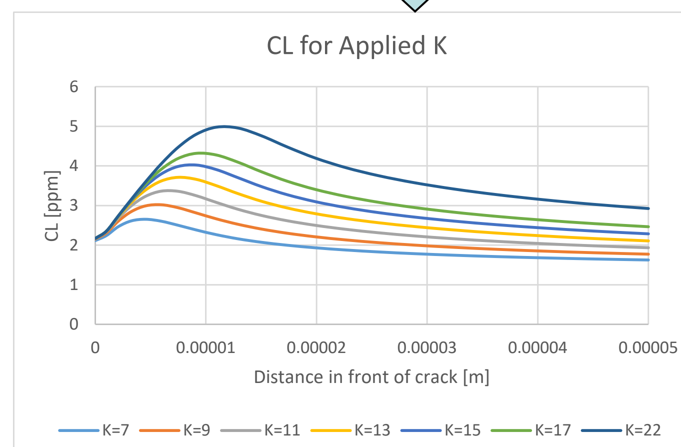
Material/microstructure-specific hydrogen diffusion (ORNL)



Macro material response as a function of accumulated cycling



Model of CT Specimen

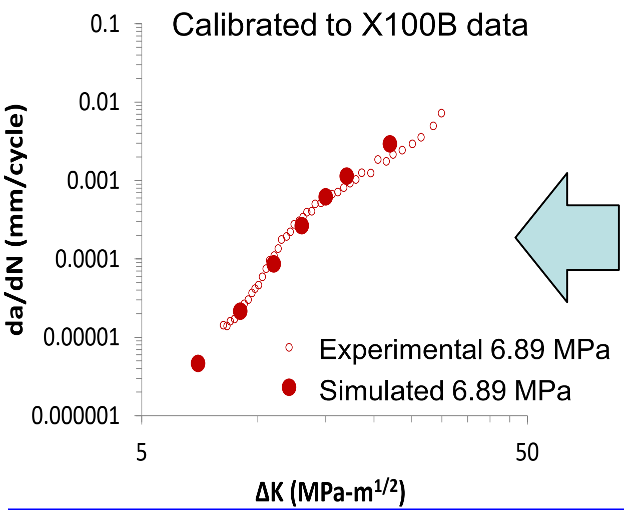


Hydrogen concentration along crack plane for given ΔK

$$\frac{da}{dN_{\mathrm{H}}} = \left[\left(\frac{da}{dN_{\mathrm{P_H}}}\right)^{-1} + \left(\frac{da}{dN_{\Delta K}}\right)^{-1}\right]^{-1}$$

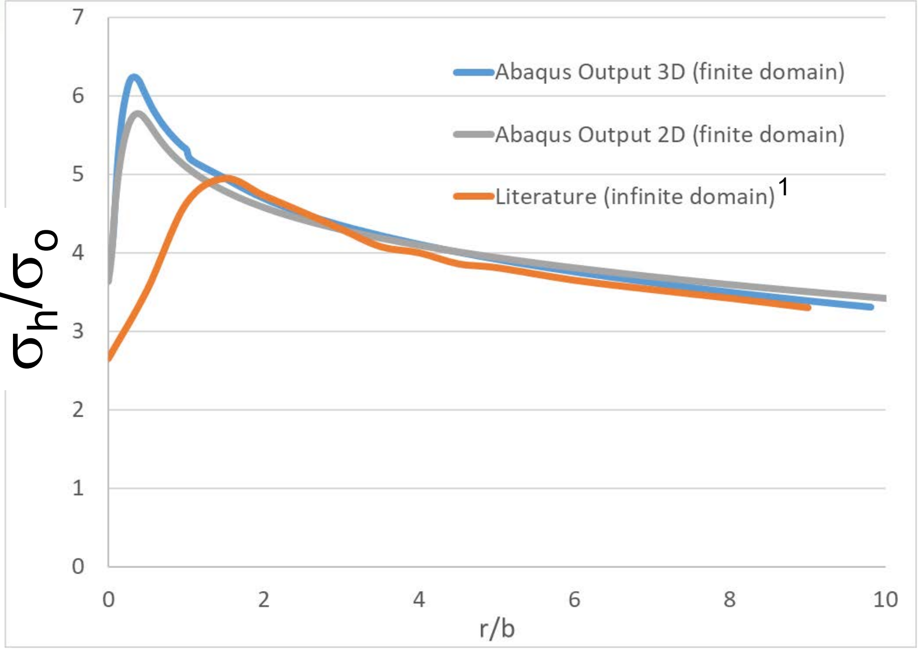
$$\frac{da}{dN_{\mathrm{P_H}}} = a1\Delta K^{B1}\left(C_{\mathrm{L\_max}}\right)^{d1}$$

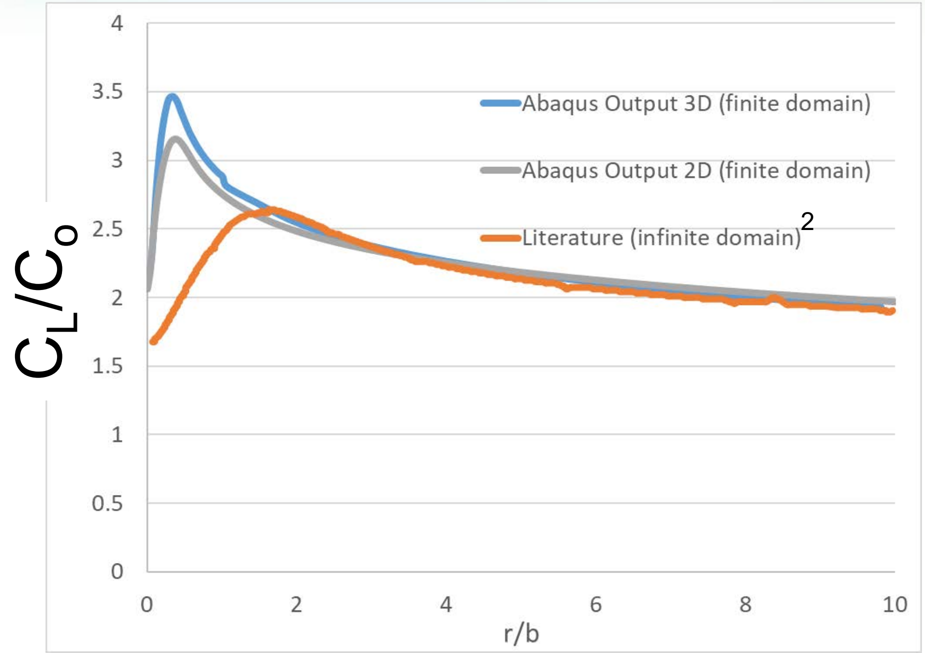
$$\frac{da}{dN_{\Delta K}} = a2\Delta K^{B2}\left(C_{\mathrm{L\_max}}\right)^{d2}$$



Phenomenological model updated to simulate HAFCG as a function of ABAQUS coupled hydrogen diffusion-deformation predictions

Results: 1st Order Calibration of deformation and hydrogen diffusion model to literature values





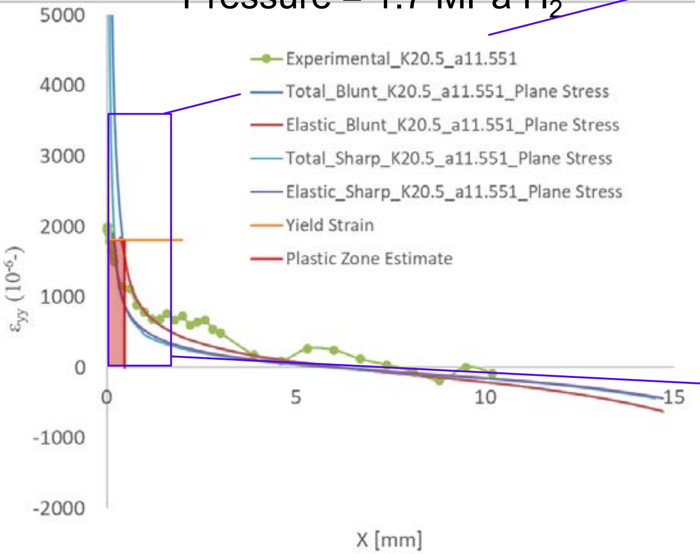
- **Normalized stress at crack tip**
- **Normalized hydrogen concentration at crack tip**

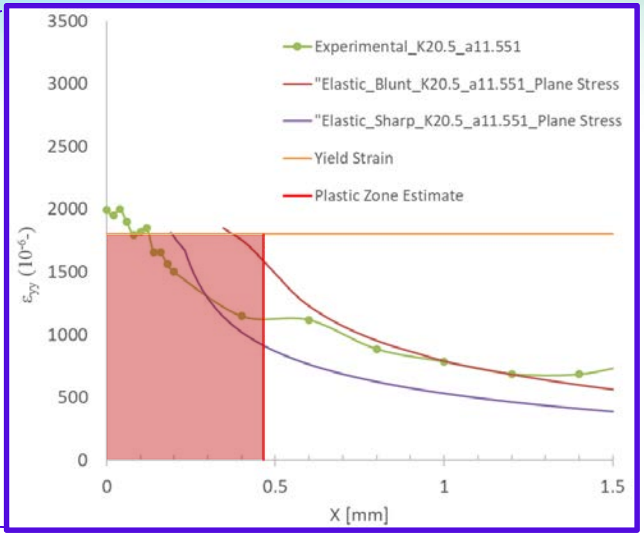
1. Model source: Sofronis, Krom, DiLeo
2. Model Source: DiLeo

ABAQUS model matches far-field literature well while also incorporating large plasticity finite domain results

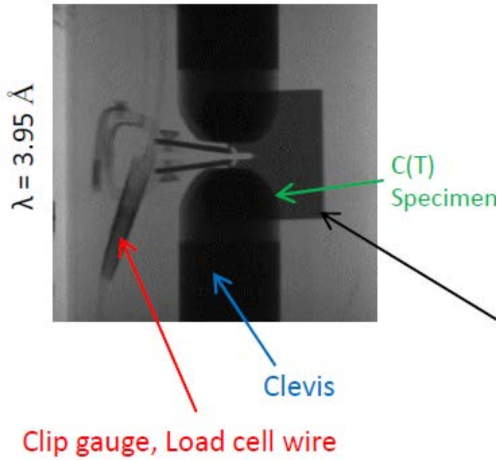
Results: Validation of strain predictions by use of Synchrotron (elastic strain) data

K_{app} = 20.5 MPa $m^{1/2}$
Pressure = 1.7 MPa H_2





- Synchrotron experiments performed by NIST on precracked sample

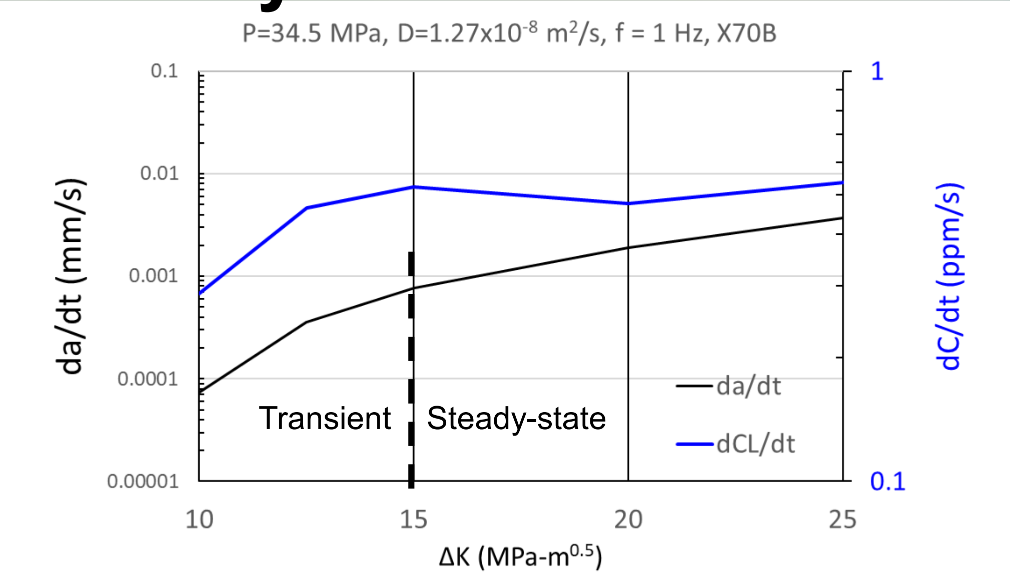


Synchrotron: Measured strain fields from transmission Bragg edge via high energy X-rays diffraction

- **Crack type**
  - → **Blunt tip : 5 μm**
  - → **Sharp tip: perfectly sharp**

Predicted elastic strains match Synchrotron experimental data well

Transition in FCGR behavior from Transient to Steady-state



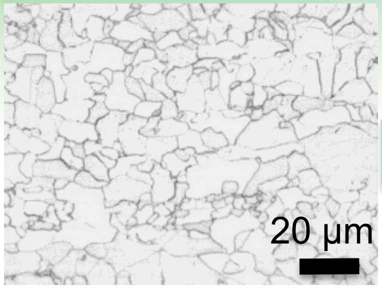
- da/dt: X70B experimental data
- dC/dt: calculated H_2 at crack tip

Additional parametric studies on:
1) Pressure dependence
2) Diffusivity
3) Cycle time

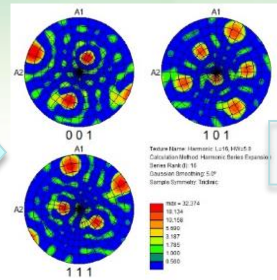
- **Transient: crack growth rate (da/dt) and H_2 concentration rate (dC/dt) both increase as function of ΔK**
- **Steady-state: da/dt and dC/dt start to plateau**

Predictions support theory that, at higher crack growth rates, crack tip extensions "outrun" the region of high hydrogen concentration

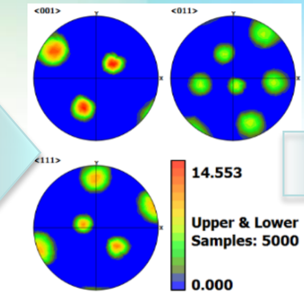
Future Work: Methodology for microstructure-specific model



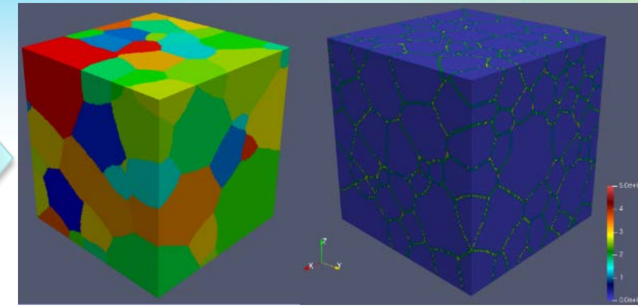
Model steel alloy
(100% polygonal ferrite)



Measured pole figures
(EBSD)

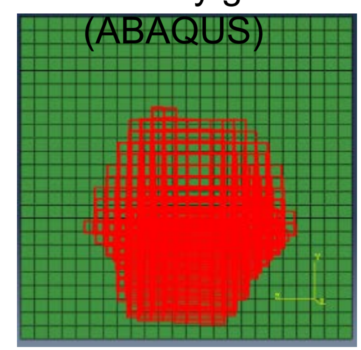


Synthetic pole figures
(Dream3D)

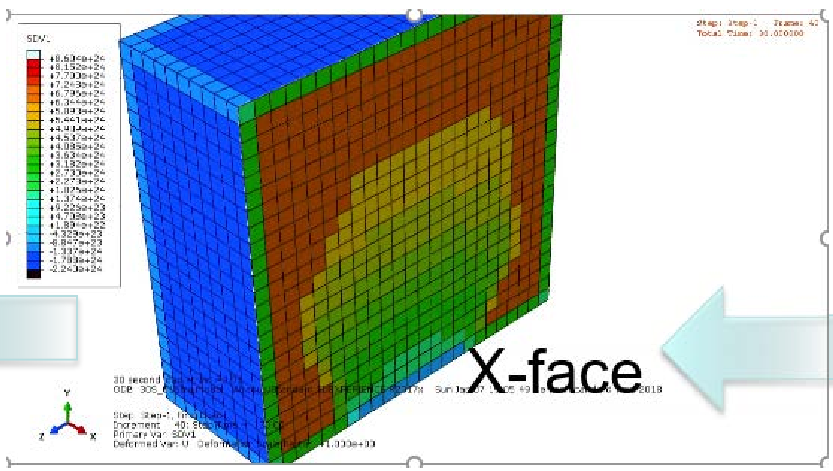


Grain tessellation (Dream 3D)

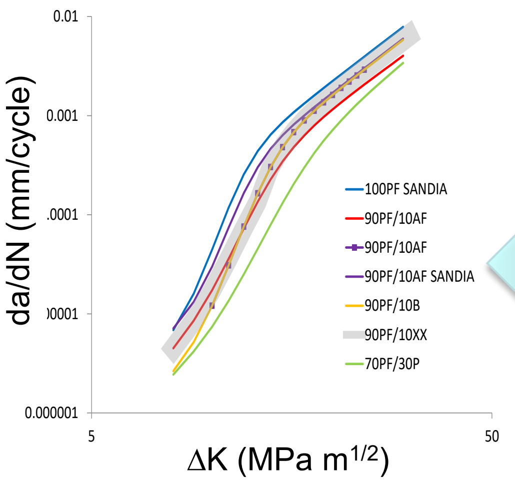
Cube consisting of
model alloy grains
(ABAQUS)



X-face



Single grains response to coupled
environmental-mechanical
loading



PF = polygonal ferrite, AF = acicular ferrite, B = bainite, P = pearlite.

Remaining Challenges and Barriers

Materials R&D Challenges

- High strength steel weld microstructures are complex and deriving **microstructure-performance relationships** have been challenging which is further complicated by **residual stresses**
  - Mitigation strategy: Detailed control of microstructure has been used to try and identify microstructure dependence of HA-FCG
    - Residual stresses were measured in order to de-couple effects from $K_{residual}$ and $K_{applied}$ thus allowing more direct comparisons of microstructure and fatigue performance.
    - Grain boundaries, microstructural constituents, & residual stress all appear to have influence in fatigue behavior → Separating their respective influences = challenge
- Fracture toughness may be limiting high strength usage not fatigue.
  - **(Current B31.12 requires K_{IH} > 50 ksi in$^{1/2}$. For X100 base metal, measured K_{IH} ~ 40 ksi in$^{1/2}$)**

Acceptance by industry

- ASME B31.12 code currently limits specified minimum yield strength (SMYS) with significant **design penalties** on higher strength pipes
  - Recent acceptance of curve fit based on **data-informed** results of X52 and X70 improves likelihood of adoption of higher strength pipes into code in future.

Responses to Project Reviewers' Comments

1. "There is no explanation as to why the X100 base metal behaves similarly to low-strength steel and why the X100 weld does not."

Higher X100 weld FCGR was due to residual stresses which when measured and accounted for in the analysis, resulted in FCGR comparable with base metal. (See *Ronevich et al.* in *Eng. Fract. Mech. 2018.)*

2. "The project is behind schedule and is projecting a go/no-go decision six months late." AND "Development of new steel seems unnecessary, considering the large variety of steels commercially available."

The Go/No-Go milestone was: "if microstructures are identified that demonstrate HA-FCG performance equivalent or superior to X100 base metal, fabricate novel steel."

This milestone was hinged on the Gleeble^{TM} tests, which exhibited significant residual stresses & therefore required redesign & use of compression to relieve residual stresses. This delayed the Go/No-Go. While redesign & fabrication of new Gleeble specimens were under development, the team examined the effects of grain orientation on X60 and X100 steels which showed significant reductions is FCGR by increasing interaction of HAGB along the crack path. These findings satisfied the Go/No-Go milestone; however, development of a novel microstructure has been reconsidered as alloy design and development is not practical given the remaining time in the project. Instead the team is focusing on already fabricated steels that possess more model type microstructures with distinct differences such as grain size or anisotropy in order to better understand microstructure-property relationships.

3. "Regarding model validation, many models fall apart when an attempt is made to use them to interpret data not used in their development. Validation of any predictive model is just as important as generating the model."

Validation is forth-coming on-going. We are collecting necessary input data such as diffusivity specific to alloys to be used in calibration & validation studies. The group has a considerable amount of experimental data set aside to be used for validation purposes (e.g. this data will not be used for calibration).

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 (2018)
    - 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
  - Engineering Fracture Mechanics, 2018
  - Conference proceedings:
    - 3rd International Steely Hydrogen Conference (2018)
    - ASME Pressure Vessels and Piping 2018
- Contribute fatigue data to Hydrogen Effects Database (Granta Mi)
  - Part of Safety Codes and Standards Program at SNL

Proposed Future Work

- Remainder of FY18
  - **Examine** role of grain size and grain boundaries in HA-FCG using previously fabricated steels (SNL)
  - **Perform** measurements on additional Gleeble™ specimens (SNL)
  - **Calibrate** model to diffusivity measurements performed at ORNL (NIST/ORNL/UA)
  - **Publish** results from HA-FCG testing on alternative X100 welds in peer-reviewed journal (SNL)
- Proposed Follow on Work
  - **Investigate** test protocols to measure *fracture toughness* of welds and heat affected zones (no current data and often have material constraints at these regions). Fracture toughness may be limiting factor in design. Higher strength often correlates with lower toughness.
  - **Broaden** approach used in this project to influence other steels used in H_2 infrastructure
    - Examination of residual stress and influence of microstructure/grain boundary on fatigue & fracture properties.
    - Expand modeling efforts into fracture by combined efforts from SNL, ORNL, and NIST.
    - Expand models microstructure library for future steel development.

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

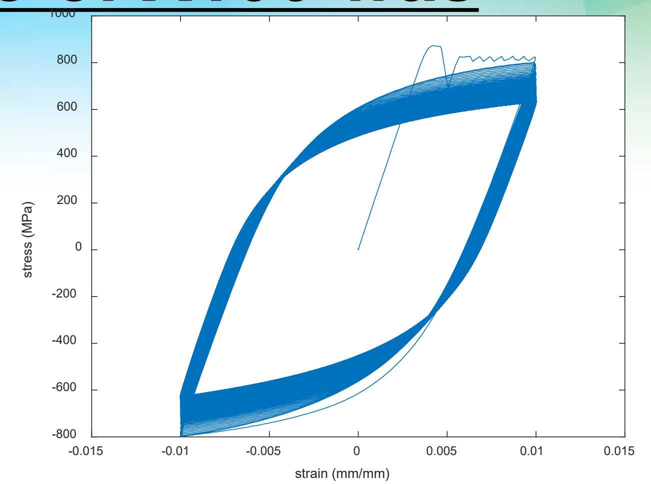
Summary

- **Task 1: Performance of High strength welds**
  - 5 welds were fabricated and examined in high pressure hydrogen gas
  - Higher strength welds possessed ***significant residual stresses*** which were measured and corrected for to provide high fidelity da/dN curves
  - Higher strength welds appear to have ***higher HA-FCG*** compared to lower strength welds
  - Comparison of high strength materials to current accepted B31.12 code design curves provides ***basis for potential future acceptance*** in H_2 pipeline code
- **Task 2: Pathways to develop high-strength pipes for use in H_2 service**
  - Fabricated gradient microstructures and performed constant ΔK tests
  - Evaluated orientation effects in X100 and X60 and discovered large influence of high angle grain boundaries
    - Grain boundaries have **greater influence** on moderating HA-FCG than microstructural constituents & can **reduce FCGR 4-5 times**
  - Welds of high compressive residual stresses (X100-W4) are highly resistant to crack growth. It may lead to an alternative pathway for mitigating HIC of hydrogen pipelines
  - Coupled hydrogen diffusion-deformation model calibrated to experimental and literature data- parametric studies underway to determine material characteristics producing 1st order effects on HA-FCG
  - Phenomenological HA-FCG model updated to incorporate ABAQUS results

Technical Back-Up Slides

Results: Inelastic strain response of X100 was measured and modeled

- Strain controlled test under +/- 0.01 strain
- Identify cyclic softening
- Stabilized in <100 cycles



- Modeled stress-strain response in ABAQUS

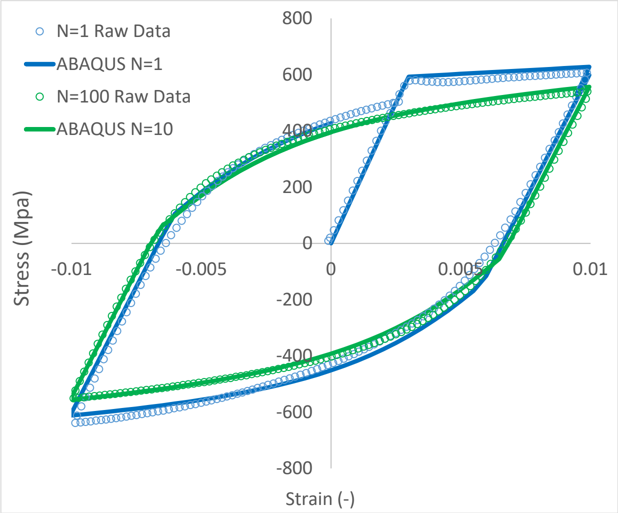
Flow rule:

$$F = f(\sigma - \alpha) - \sigma^0 = 0$$

Nonlinear isotropic /kinematic hardening:

$$\dot{\alpha} = C\frac{1}{\sigma^0}(\sigma - \alpha)\overline{\dot{\varepsilon}^{Pl}} - \gamma\alpha\overline{\dot{\varepsilon}^{Pl}}$$

$$\sigma^0 = \sigma|_0 + Q_\infty\left(1 - e^{-b\bar{\varepsilon}^{Pl}}\right)$$



Capturing the evolution of stress-strain behavior of the material is necessary for modeling damage at crack tip

Stress-, strain-, and ambient pressure-driven hydrogen diffusion modeled

Lattice concentration as a function of time — *Gradient driven diffusion* — *Hydrostatic stress driven diffusion* — *Hydrogen accumulation at trap sites as a function of plastic strain (sinks)*

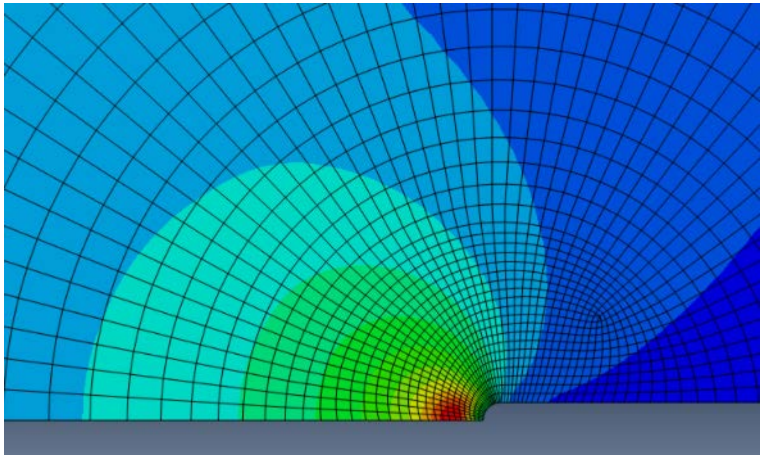
$$\frac{D}{D_{eff}}\frac{\partial C_L}{\partial t} = DC_{L,ii} - \left(\frac{DV_H}{3RT}C_L\sigma_{kk,i}\right)_{,i} - \left(\sum_j \alpha^j\theta_T^j\frac{\partial N_T^j}{\partial \varepsilon^p}\right)\frac{\partial \varepsilon^p}{\partial t}$$

Effective Diffusion

$$\frac{D}{D_{eff}} = 1 + \sum_j \frac{\partial C_T^j}{\partial C_L}$$

Equilibrium between lattice and trap sites

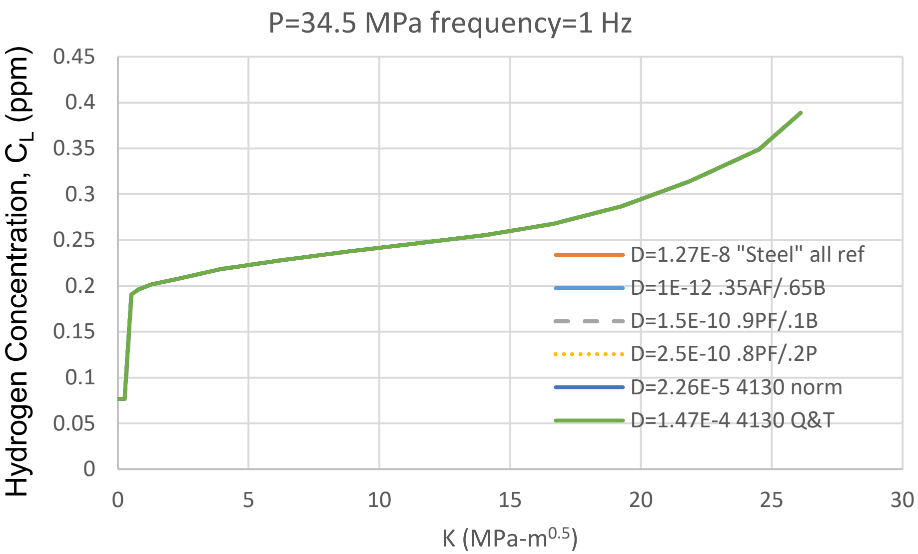
$$\frac{\theta_T^j}{1-\theta_T^j} = \frac{\theta_L}{1-\theta_L}\exp\left(\frac{W_B^j}{RT}\right)$$

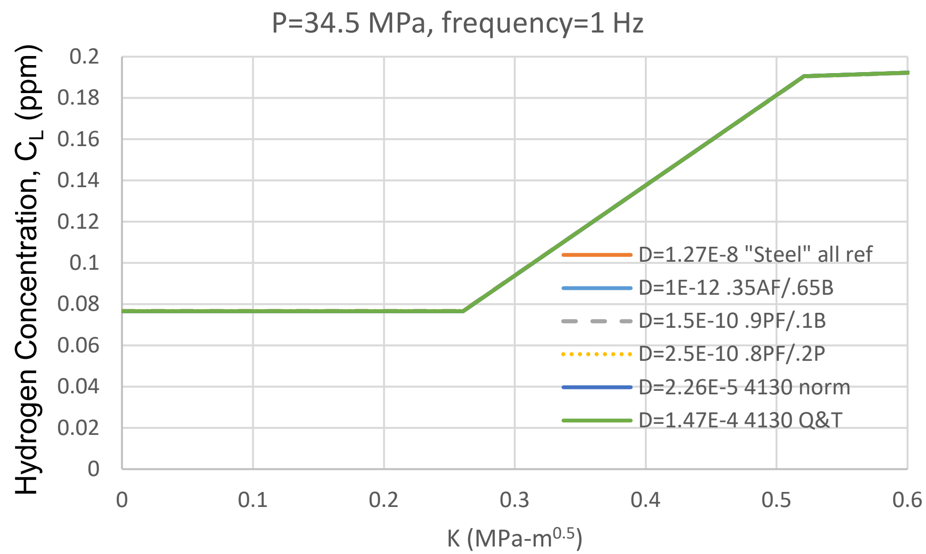


- **Hydrogen concentration in the lattice at the crack tip**

Predicting hydrogen concentration at crack tip critical for modelling of accumulated damage

Parametric Studies

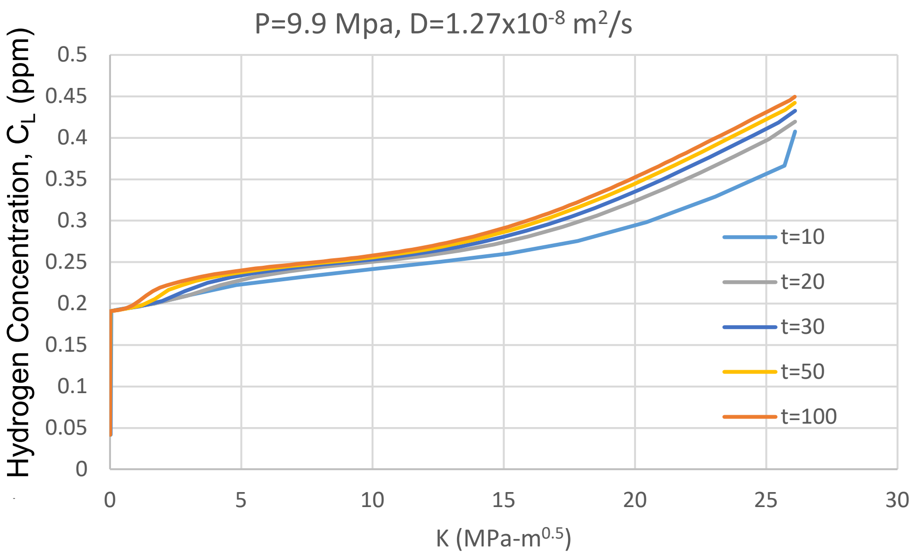


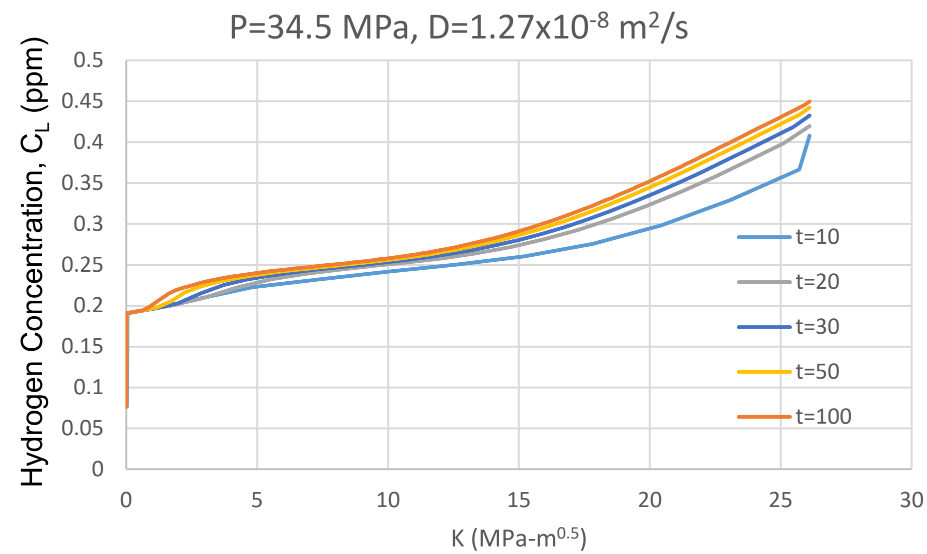


- **Prediction of change in lattice hydrogen concentration as a function of changing diffusivity.**
- **Zoom in to initial application of load**

Hydrogen concentration at crack tip reaches similar levels regardless of diffusivity at 1 Hz

Parametric Studies

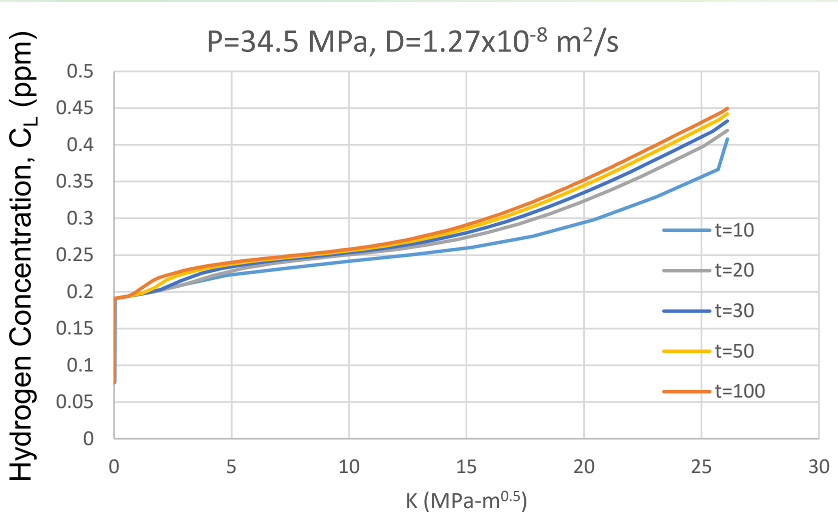


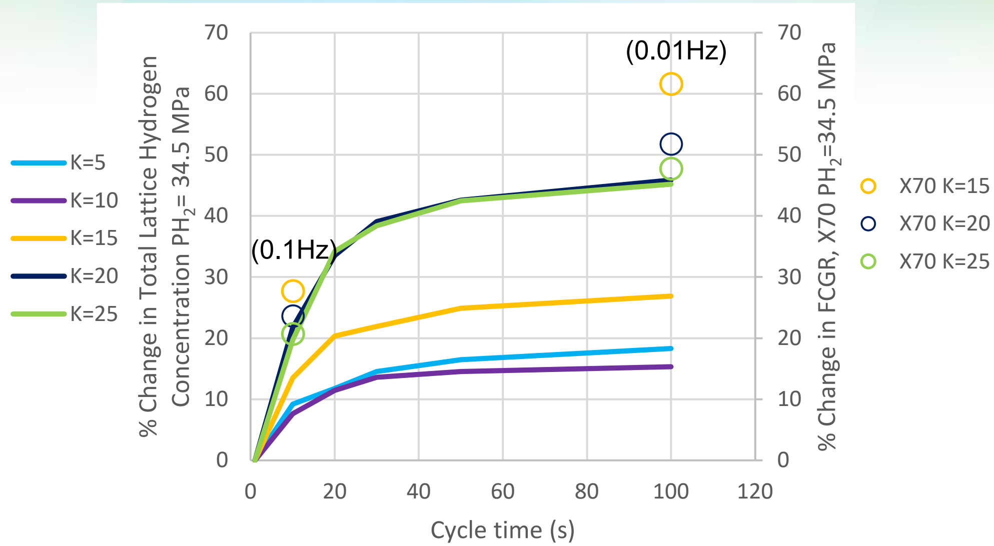


- **Prediction of change in lattice hydrogen concentration as a function of load rate**
- **Results indicate that hydrogen concentration is hydrogen pressure independent- indicating that the stress-driven diffusion dominates at large stresses**

Load rate affects hydrogen concentration
For a given load rate, hydrogen concentration is pressure independent

Parametric Studies





- **Predictions indicate that rate dependence saturates as you approach 100s cycle (0.01Hz)**
- **Predictions indicate that dC_L/dt saturates near 0.03Hz for all K**

Predictions of rate dependence perform well when compared to experimental data → Can be used for in-service predictions