

Study Group on Materials Testing and Qualification for Hydrogen Service

Friday, July 24, 2026

Location: **Pacific A**
Hilton Anaheim, Anaheim CA
8:00am – 5:00pm (local time)

8:00	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.3, B31.8, CSA/ANSI CHCM1 and other codes, open discussion</i>
	<i>Standardizing fracture measurements in high-pressure GH2 (BPVC VIII.3), Paolo Bortot (Tenaris)</i>
	<i>Recent activity of API 1104, Ken Lee (DNV)</i>
9:30	Break
Component testing and design methods	
	<i>Full-scale pipeline testing, Bostjan Bezensek (Shell) & Mark Cuglietta (CFER)</i>
	<i>Stress-based (S-N) fatigue design for hydrogen service, Mihaela Cristea & Paolo Bortot (Tenaris)</i>
	<i>Hollow specimen method for measuring low cycle fatigue design data in high pressure gaseous hydrogen, Ken Wackermann (Fraunhofer IWM)</i>
12:00	Lunch (no host)
Challenges with test methods for hydrogen	
	<i>Influence of specimen geometry (CT vs SENT) on fracture resistance, Michelle Kent (SNL)</i>
	<i>Testing for sustained-load cracking, Ramgo Thodla (DNV)</i>
	<i>Determining fracture initiation: electrical potential difference (EPD) method, Kevin Nibur (HyPerformance Materials Testing)</i>
	<i>Identification of Threshold in DCPD Data – da/dK vs K Method, Mario Macia (ExxonMobil)</i>
	<i>EPRG fracture round robin, Bostjan Bezensek (Shell)</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Challenges testing welds for hydrogen service, Michelle Kent & Quinten Yurek (SNL)</i>
	<i>Effects of ultra-low hydrogen partial pressure on fatigue and fracture, Chris San Marchi (SNL)</i>
	<i>Effect of temperature on fatigue and fracture, Joe Ronevich (SNL)</i>
	<i>Role of impurities in CO₂ streams on gaseous H₂ embrittlement of pipeline steels, Rob Wheeler (DNV)</i>
Free Discussion/Wrap-up	
17:00	Adjourn



Exceptional service in the national interest

Study Group on Materials Testing and Qualification for Hydrogen Service

Anaheim CA, 24 July 2026



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SAND2026-#####



Agenda

- Standards for materials testing and hydrogen infrastructure
 - *Update on ASME B31.3, B31.8, CSA/ANSI CHCM1 and other codes*
 - *Standardizing fracture measurements in high-pressure GH2 (BPVC VIII.3)*
 - *Recent activity of API 1104*
 - *Summary of March 2026 Study Group*
- Component testing and design methods
 - *Full-scale pipeline testing*
 - *Stress-based (S-N) fatigue design for hydrogen service*
 - *Influence of specimen geometry (CT vs SENT) on fracture resistance*
 - *Hollow specimen method for measuring low cycle fatigue design data in high pressure gaseous hydrogen*
- Challenges with test methods for hydrogen
 - *Testing for sustained-load cracking*
 - *EPRG fracture round robin*
 - *Determining fracture initiation: electrical potential difference (EPD) method*
 - *Identification of Threshold in DCPD Data – da/dK vs K Method*
 - *Challenges testing welds for hydrogen service*
- Trends of hydrogen-assisted fatigue and fracture
 - *Effects of ultra-low hydrogen partial pressure on fatigue and fracture*
 - *Effect of temperature on fatigue and fracture*



Codes and Standards

- ANSI CSA CHMC1 (2026 update)
 - Revised as materials testing standard
 - Clarified requirements for fracture testing
- ASME B31.3
- ASME B31.8
- ASME B31.12
- ASME BPVC VIII.3
 - Moisture content (code case)
 - Fracture toughness measurement (code case)
 - Frequency (future item?)



Study Group on Fracture Testing in Gaseous Hydrogen

- Motivation for Meeting and Industry Needs: From Science to Engineering Practice
- Tenaris Experience on Tubulars for Gaseous Hydrogen Service
- Hydrogen-assisted fracture testing at Shell: sustained load cracking challenges and ways forward
- Hydrogen-assisted fracture testing at ExxonMobil
- Hydrogen-assisted fracture testing in HyBlend™
- Fracture threshold testing for integrity assessment in hydrogen service
- Review of Sustained-Load Cracking for Ferritic Steels in H₂ Gas
- Mechanics of Sustained-load Cracking in Gaseous Hydrogen and Issues with Embrittlement Mitigation by Impurities
- Case Studies: Influence of Crack Tip Hydrogen on Fracture Behavior of Ferritic Materials



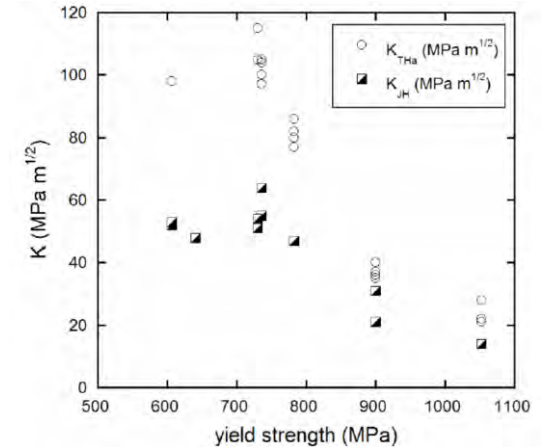
Standardizing fracture measurements in high-pressure GH2 (BPVC VIII.3)

Study Group on Materials Testing
and Qualification for Hydrogen
Service – PVP 2026

Paolo Bortot,
Tenaris, Dalmine, Italy

Background

- Current ASME VIII-3 art. KD-10 requires fracture testing as per ASTM E1681.
- This method uses a bolt-load compact tension specimen under constant load or constant displacement conditions in gaseous hydrogen environment.
- In 2013 ASME published STP-PT-064 report "Evaluation of fracture properties test methods for hydrogen service".
- Recently item 25-702 was discussed in Section VIII Div.3 to review the recommendations from this report, which suggested the introduction of rising load test method as per ASTM E1820.
- CSA/ANSI CHMC 1 was approved in 2026 with testing guidelines for gaseous hydrogen, including measurement of hydrogen-assisted fracture as per ASTM E1820.



Comparison of testing procedures

	Current Art. KD-10 (Ed. 2025)	Recommendations from STP-PT-064
Testing Procedure	Follow ASTM E1681: constant load or constant displacement testing type.	Conduct tests with concurrent straining and hydrogen exposure, i.e. Rising Load Test Method as per ASTM E1820.

- ASTM E1681 is based upon linear elastic fracture mechanics.
- The application of this method to materials exhibiting large scale plasticity, may result in invalid test data based on specimens' size requirements in art. KD-1043.

Ligament check: to maintain the linear-elastic assumption



KD-1043 SPECIMEN CONFIGURATIONS AND NUMBERS OF TESTS

(a) A specimen geometry described in ASTM E1681 shall be used. All specimens shall meet

(1) the validity requirements of ASTM E1681, para. 9.3.1, or

(2) the validity requirements of ASTM E1681, para. 9.3.2 provided the specimen thickness is greater than or equal to 85% of the design thickness of the vessel

9.3 Validity Check:

9.3.1 Calculate the value of the parameter $2.5 (K_{IEAC}/\sigma_{YS})^2$, where σ_{YS} is the 0.2 % offset tensile yield strength at the same temperature as the threshold K test (see Methods E8/E8M). This quantity must be less than each of B , a_o , and $W-a_o$ to meet the primary plane strain validity criteria for K_{IEAC} .

9.3.2 Calculate the value of the parameter $(4/\pi)(K_{EAC}/\sigma_Y)^2$; (in this calculation, σ_{YS} may be replaced by σ_Y for high work-hardening materials with an ultimate to yield strength ratio greater than 1.3. This quantity must be less than $(W-a_o)$ to meet the validity criteria for K_{EAC} .

On going activity

- A new item is open (26-1138) to update KD-10 to introduce rising load test method based on ASTM E1820 in addition to existing E1681.
- B31.8 has a similar item open 24-2576 for inclusion of fracture toughness as per CSA/ANSI CHMC 1:26 standard.



API 1104 Hydrogen Pipeline Welding Requirements

Study Group on Materials Testing and Qualification for Hydrogen Service

Ken Lee July 24, 2026

API 1104

- ASME B31.12 & B31.8 require welding to meet API 1104
- API 1104
 - Most widely used standard for welds on petroleum and natural gas pipelines
 - However, it was not intended and has no explicit requirements for hydrogen pipelines

Welding of Pipelines and Related Facilities

API STANDARD 1104
TWENTY-SECOND EDITION, JULY 2021



SINGLE USER GRATIS COPY PROVIDED TO COMMITTEE VOLUNTEER FOR THEIR WORK IN THE DEVELOPMENT OF API STD 1104

API 1104: History

- 1st edition (tentative standard) 1956; 4th edition (standard) 1956 *Standard for Field Welding of Pipe Lines* published to support surge in construction of petroleum & gas pipelines
- Focused on SMAW Exx10 butt welds, fixed & rolled pipe (API 5L & 5LX), radiographic inspection
- Simple one-size-fits-all requirements for:
 - Qualification of welding procedures & welders:
 - Bend tests, nick-break tests, crossweld tensile tests
 - Weld acceptance: Fast go/no-go defect assessment:
 - Based on good workmanship “high quality welds obtainable by skilled welders”

API 1104 Hydrogen Task Group

- Welding of Hydrogen Fuel Gas Pipeline Task Group was formed January 2025
 - Co-Chair: Nathan Nissley (nathan.e.nissley@exxonmobil.com)
 - Co-Chair: Ken Lee (ken.lee@dnv.com)
 - Deputy Co-Chair: Ben Pierce (bpierce@entrustsol.com)
 - Editor: Simon Slater (sslater@rosen-group.com)
- March 2026 Draft
- Status: Awaiting Main Committee Ballot

H2 Full Scale testing Roadmap

Completed

National Gas

- Vintage material (Girth weld)
- Fatigue cycling



EPRG

- Modern and vintage material (seam and girth welds)
- Internal notches
- Fatigue cycling



SGN

- Vintage material
- Dents, gouges & internal crack
- Burst without preconditioning



SANDIA Lab (Subscale)

- Modern material (seam weld)
- External and internal notches
- Fatigue cycling & mill scale effect



Ongoing

HyScore JIP:

- Modern material (seam weld)
- Internal notch
- Burst



- Modern and Vintage material (SMLS & seam welds)
- Fatigue pre - conditioning & Burst
- External Damages

PRCI - EFI:

- Vintage USA Material
- 7 damage types (SCC, hard spots, wrinkle bends planar defects, dents, corrosion, laminations)
- Fatigue preconditioning & Burst



SGN

- Additional burst on crack like flaws



Future proposals

Industry & JIPs works:

- Sustained load crack growth from sharp cracks

SafeH2Pipe Phase 2

Active damages and time delayed failures



SAFEH2PIPE: GUIDELINES FOR MATERIAL SELECTION FOR H₂-NG PIPELINE TRANSPORT



— SafeH2pipe Project

- **Objective:** develop guidelines for material selection, qualification and integrity assessment of both new H₂ pipelines and repurposed existing pipelines.
- **Approach:** combine advanced engineering analyses, experimental testing (lab scale and full scale), and collaboration with certification bodies and international research organizations.
- **EU RFCS-funded project (GA 101112650)**, running from July 2023 to December 2026.

Project Partners & organisation

RINA Consulting CSM

CPW

Tenaris Dalmine

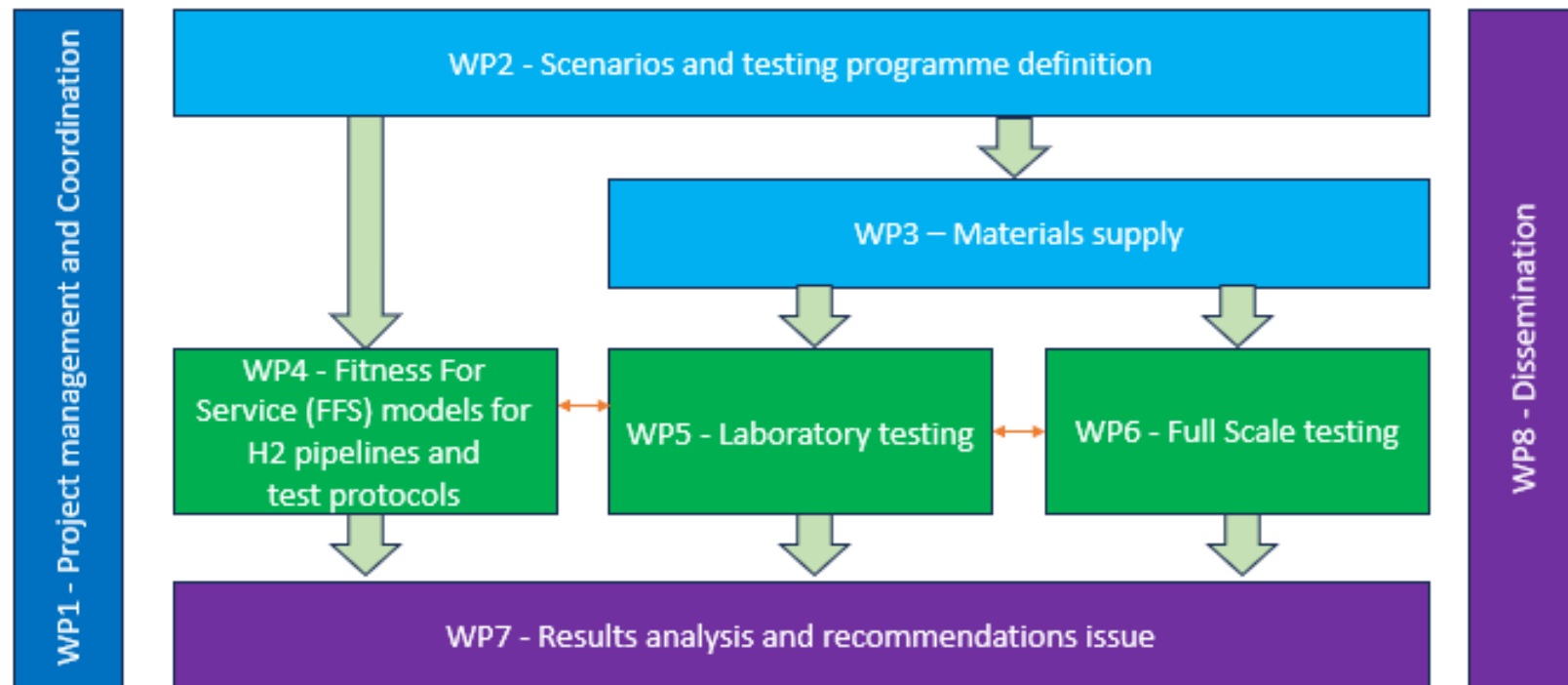
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ROSEN

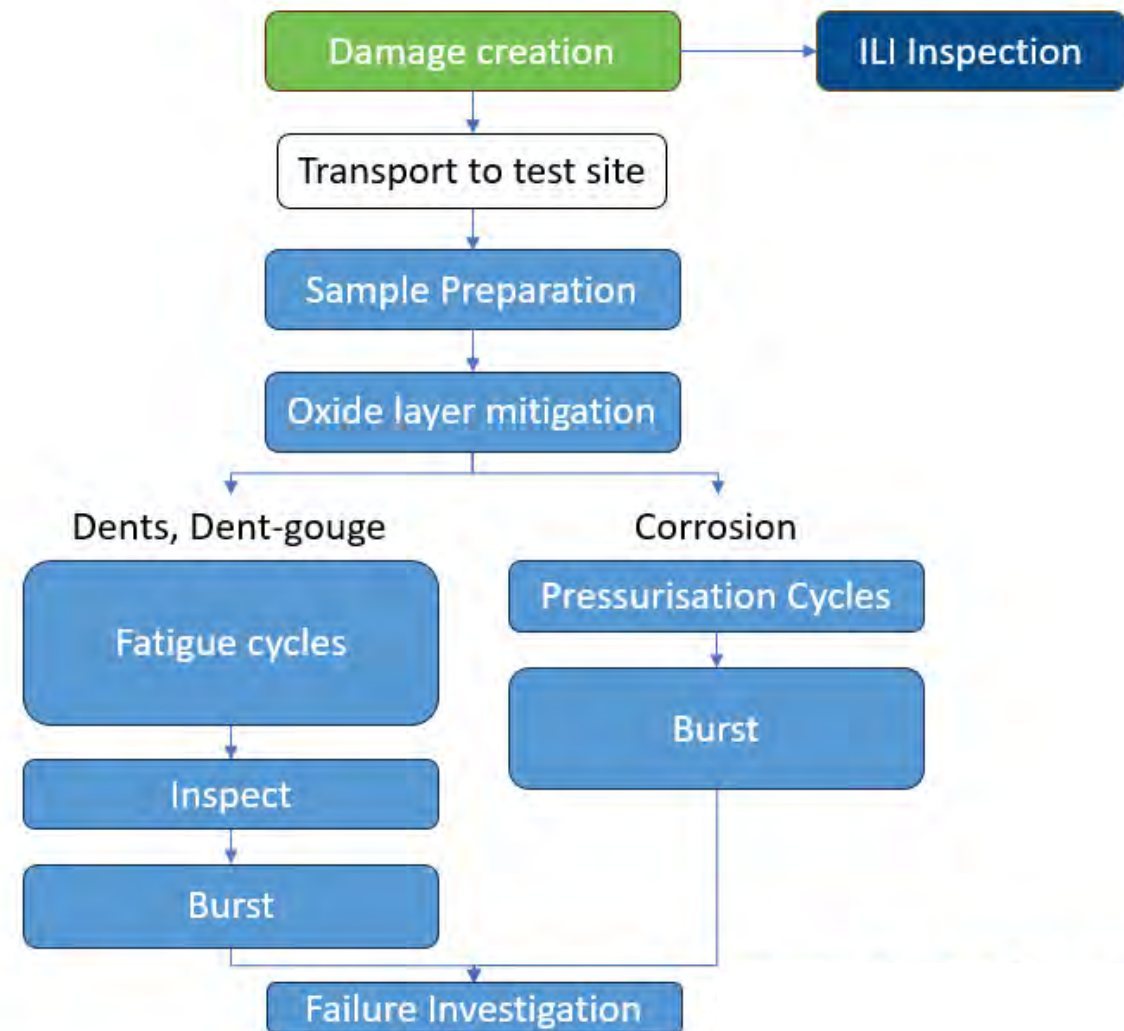
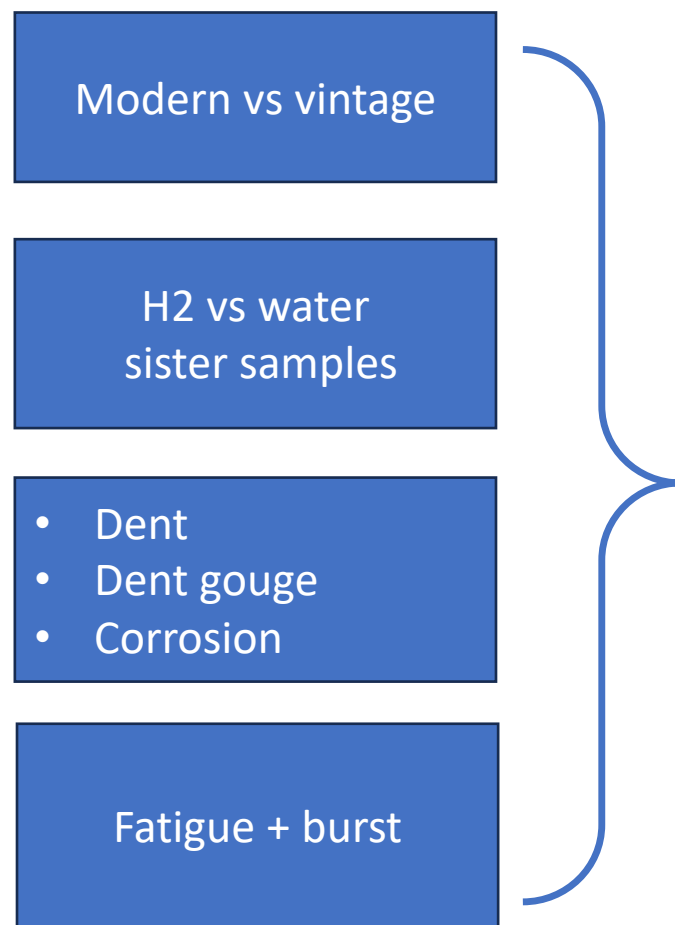
Shell Global Solutions

NaTran

EPRG (Ext. Advisor)



Philosophy for full scale testing & execution



Damage selection overview

- Target 6% OD on parent pipe as a common limit for natural gas in several codes
 - 2% OD dent on the long seam weld to validate the current B31.12 limits on dent depth for hydrogen pipelines and include a dent on the weld into the study
- Target 15% WT gouge on a modern SMLS pipe
- Target 60% WT external corrosion wall loss to ensure failure from the corrosion (and due to test facility capacity limits)

Geometry	Damage size	Fluid	3.3b Vintage LSAW onshore	3.2b Modern LSAW	3.1b Modern SMLS	3.3a Vintage LSAW offshore
			26'' 11.1mm API 5L X60	30'' 14.3 mm API 5L X65	24'' 12.7mm API 5L X70	36'' 22mm API 5L X60
Dent on Weld	Dent height 2% OD	H ₂		●		
Plain dent	Dent height 6% OD	H ₂	●	●		
Dent- Gouge	Dent height 6% OD Gouge: 1.5mm x 300mm	H ₂			●	
Corrosion	60% WT; 300 mm long	H ₂				●

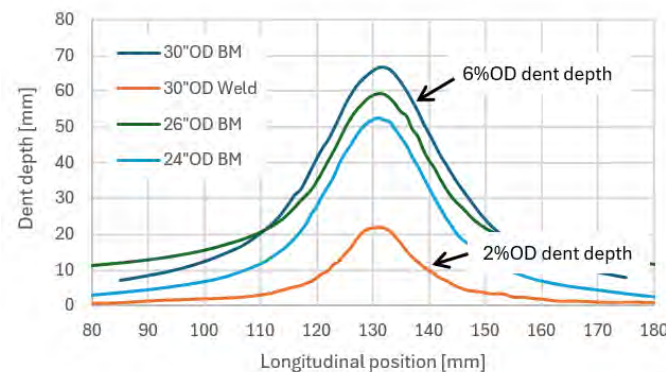
Identical samples are tested in water

Creation of Dents

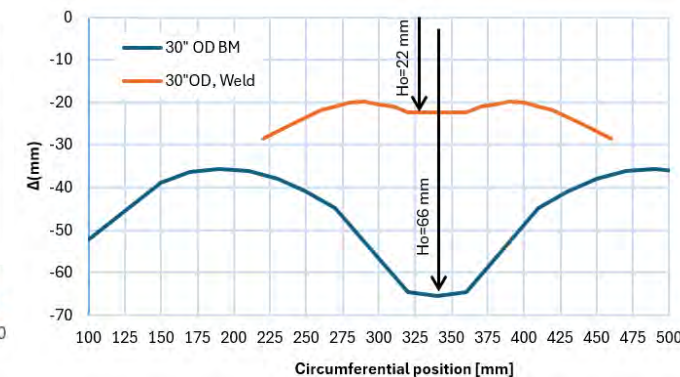
- Mechanical defects (dents and dent-gouge) were introduced using controlled and repeatable procedures to achieve target geometry and strain
- **Dents made on an unpressurised pipe with a hydraulic press**
- **Governing dent height set under pressure and adjusted for unpressurised pipe using the EPRG / PDAM's factor 1.43x**
- The preparation methods ensure realistic, comparable defects for Fitness-For-Service evaluation



TEST SETUP FOR MAKING DENTS IN 26" VINTAGE LSAW



FINAL DENT PROFILES IN THE LONGITUDINAL DIRECTION



FINAL DENT PROFILE ON THE 30"OD PIPE IN THE TRANSVERSE DIRECTION

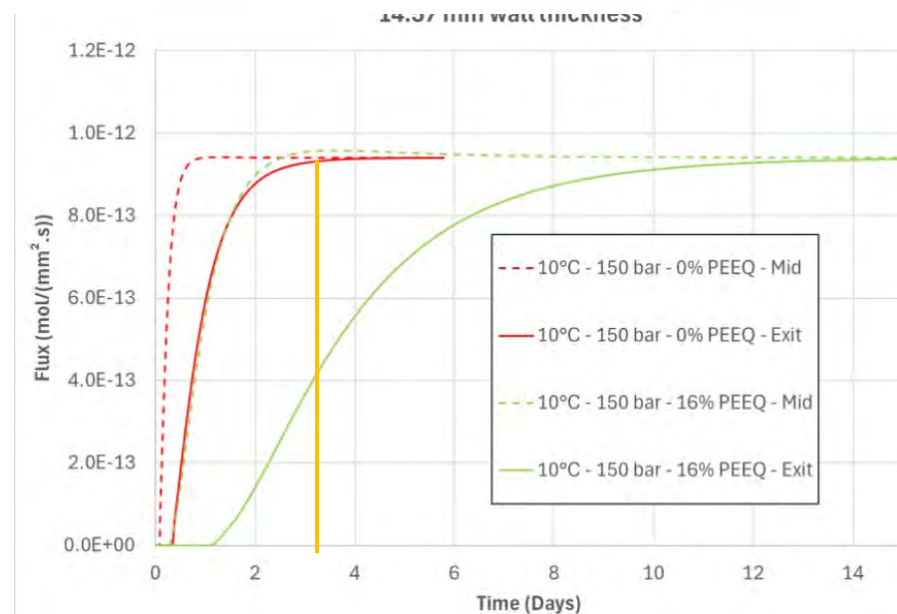
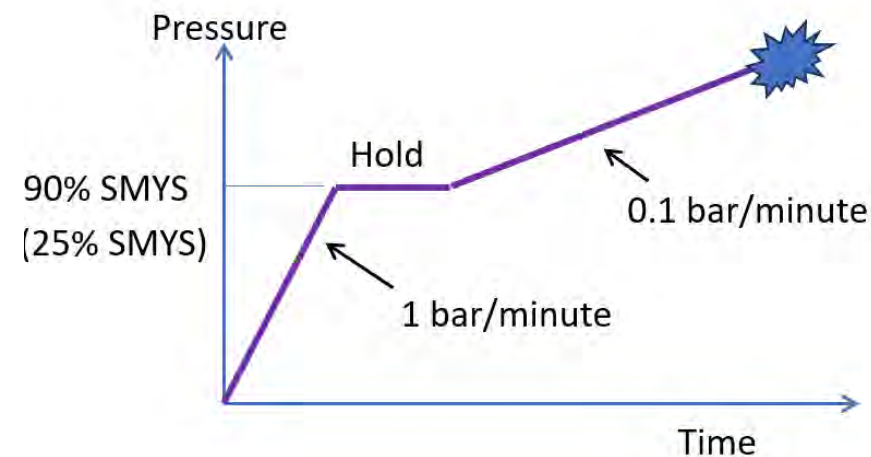
Definition of Corrosion damage

- **LPC-1 (i.e. DNV RP F101) model based on the NG-18 equation with Folias factor :**
- **Defect size of 60% wall thickness x 220mm long** chosen to promote failure from the corrosion and to fail below 250 barg test capacity
- Checked by Elastic-plastic solid FE model with von Mises yield theory to predict burst pressure (calibrated on the historic in-air data, within 20% of the test data)
- Care taken to avoid sharp corners for the H₂ test geometry
- Selected relatively large corrosion to be sure that the pipe fails due to this corrosion



Full scale test approach → Monotonic burst strategy

- The fundamental philosophy is to give time for hydrogen diffusion and interaction with the damage before final burst
- Two steps taken to achieve this:
 - Slow rates of pressurisation
 - Introduction of a pressure hold at high utilization
 - 90% SMYS for plane dent and corrosion
- Duration of hold informed by diffusion calculations (calibrated on a modern material)
 - 3 days hold inferred to saturate the pipe wall at mid-thickness for a strained dent material



Specimen preparation

- Specimens capped with suitable endcap, designed for smooth transitions to avoid stress concentration
- Proper WPS adopted in order to ensure proper resistance during testing. NdT carried out to check the welds once realized
- Specimens instrumented with strain gauges in the damaged area and, as reference, on the pipe wall
- At test site, 2 pressure transducers installed on the endcaps, 1 or 2 thermocouples on the specimen



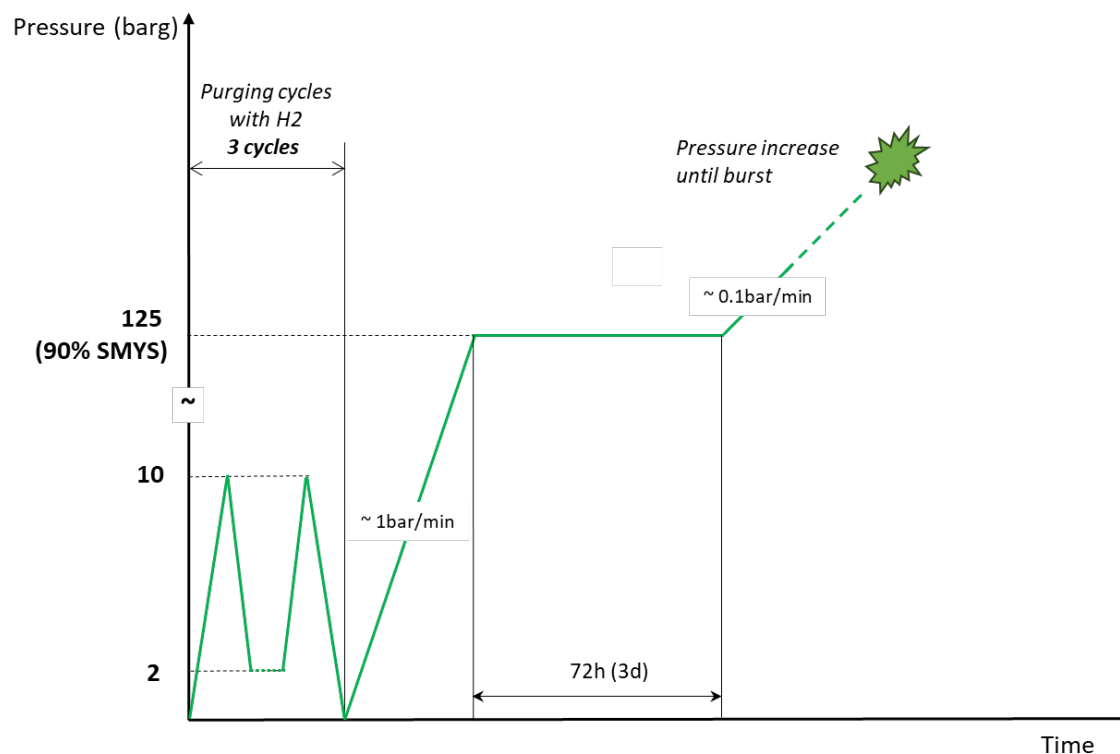
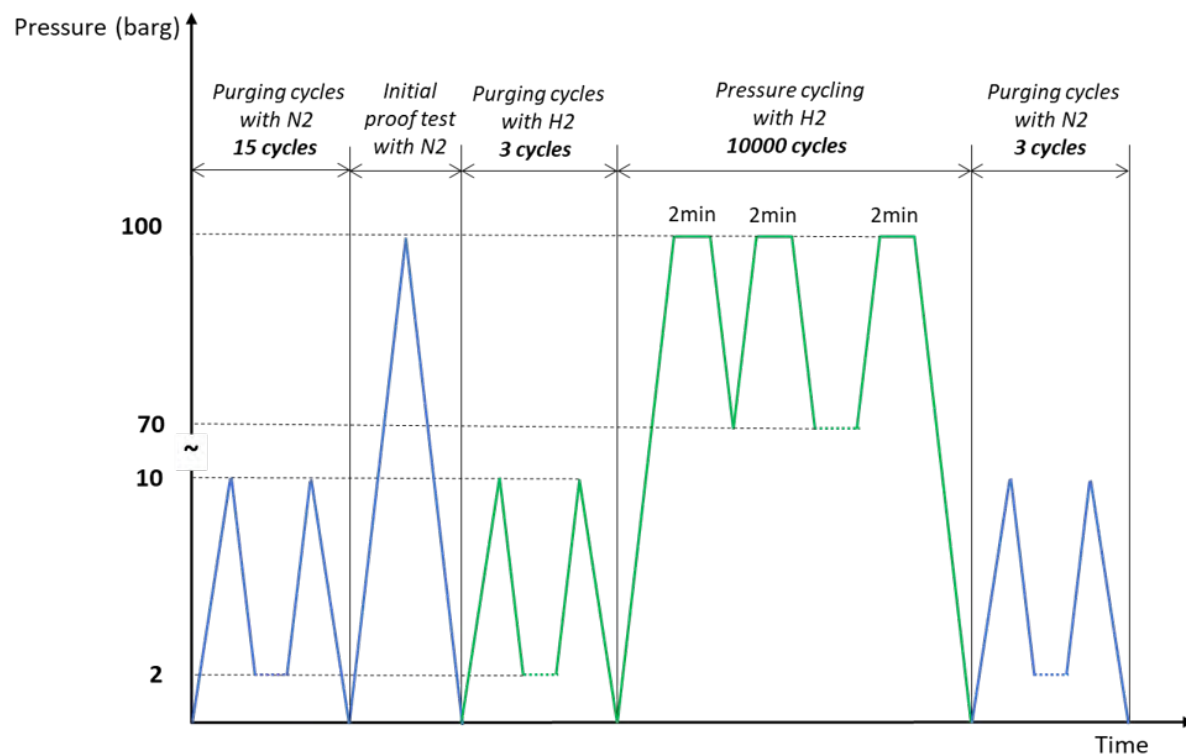
26" specimen with welded endcaps



SG instrumentation on the damage area of one 24" specimen

Test program plan

- Specific number of pressure cycles have been defined for each specimen, including a minimum number of purging cycles
- Purging achieved O₂ to ~1.3 ppmv . Several times repeated purging during fatigue cycling (helps to remove moisture)

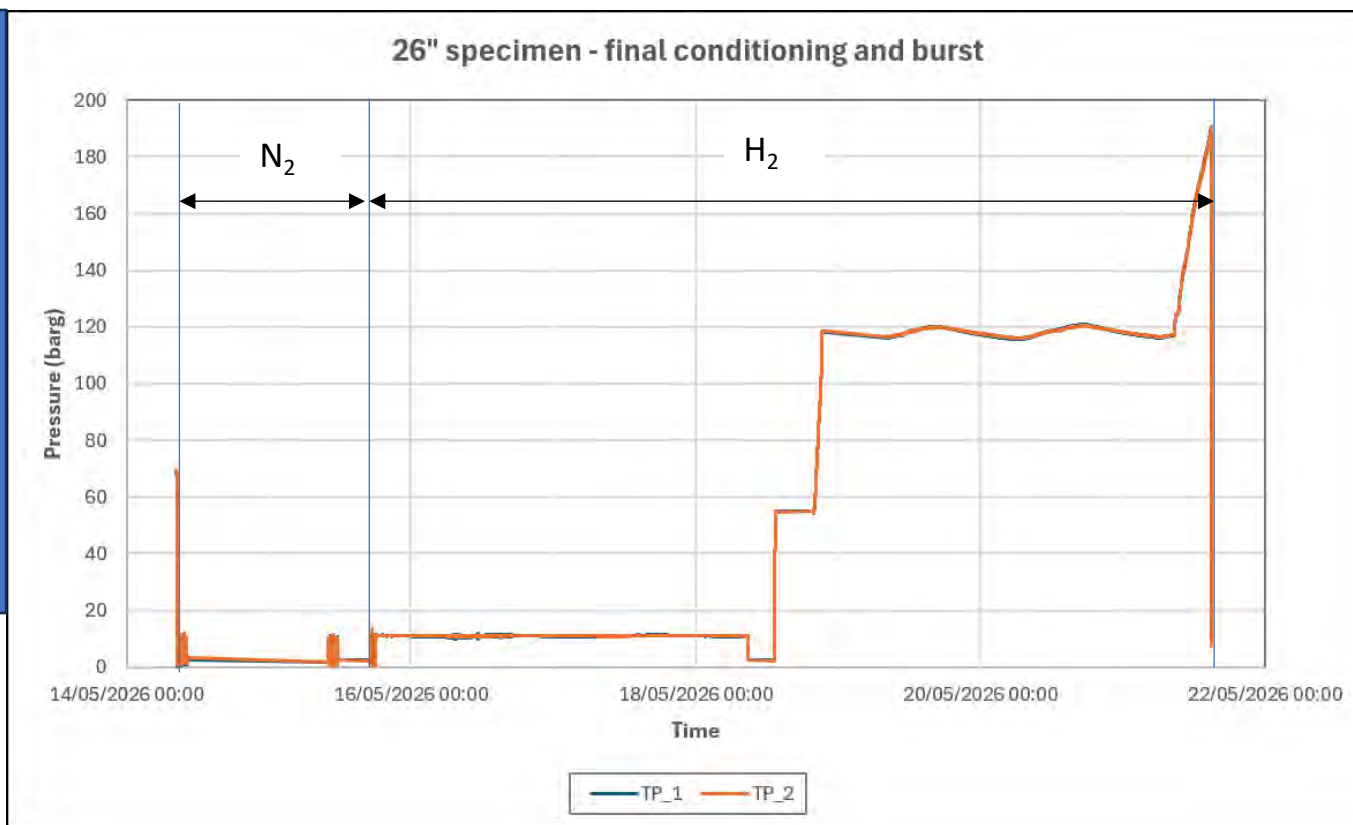


Planned test program for the 26" specimen

Test results – 26" OD plain dent sample

- After pressure cycling and N₂ purging, UT and MPI were carried out on the damage. No significant issues were observed
- Specimen was then moved to the burst site (with a small N₂ overpressure) and prepared for the burst.
- H₂ purging and O₂ measurement carried out again prior to final burst sequence
- Specimen failed away from damage

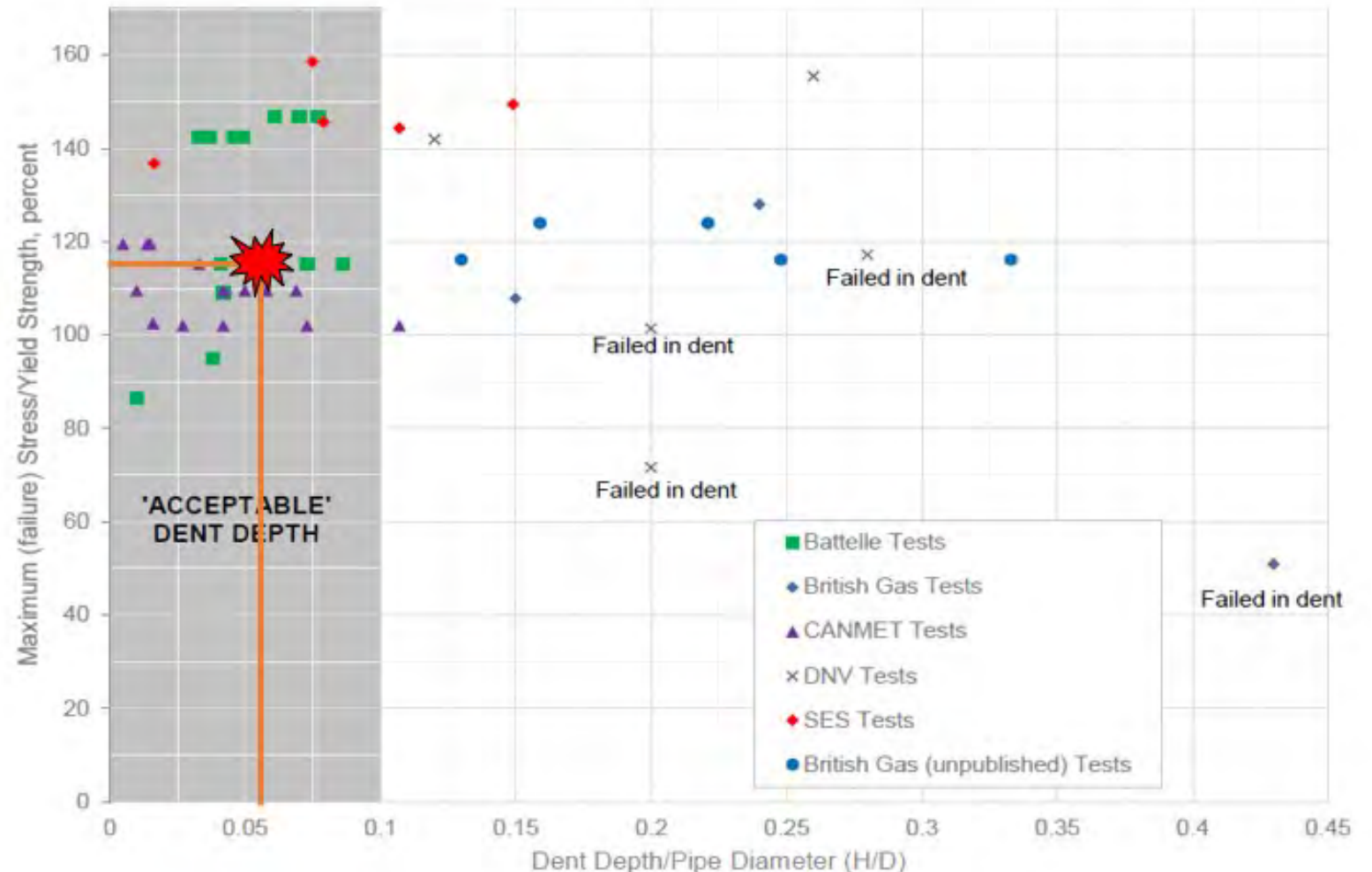
Fatigue
cycles
10,000



Plain dent burst test outcomes

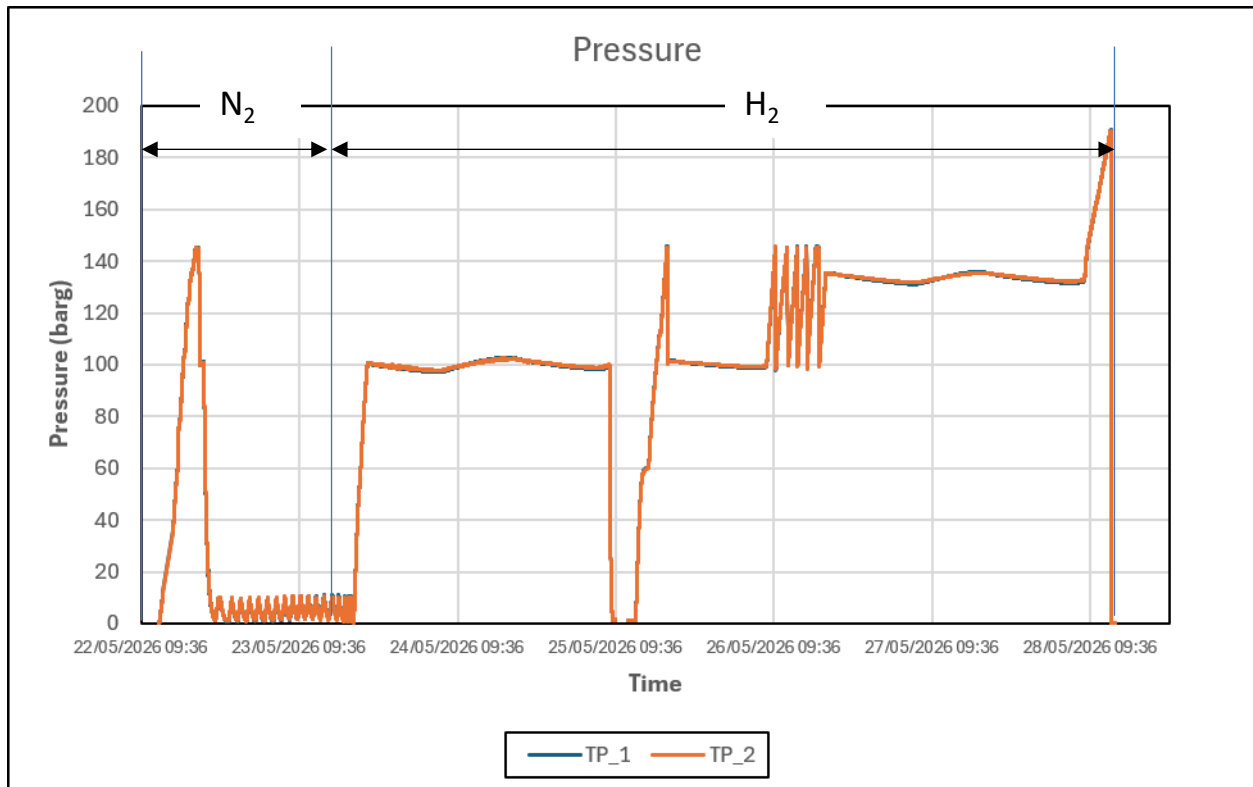


- 26" OD vintage pipe with a 6% OD plain dent (PDAM) or ~4% OD plain dent (FEA)
- Burst at 190 barg (115% AYS)
- No significant difference compared to the historic hydraulic burst tests on vintage pipe materials per PDAM
- Failure out of Dent



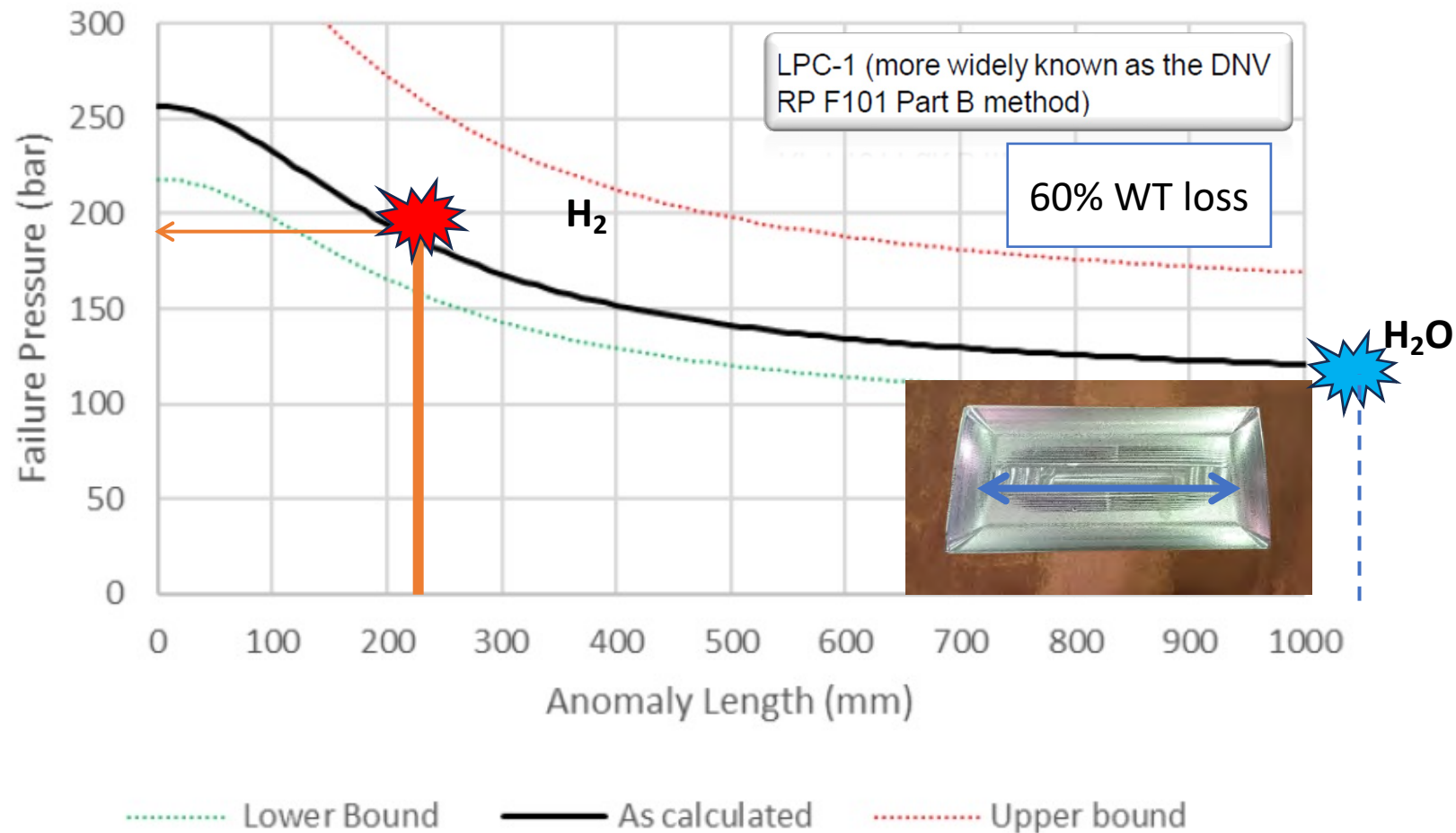
Test results – 36” OD machined corrosion wall loss

- No fatigue
- Pressure hold and a number of pressure cycles (7 achieved) for mitigating the oxide layer barrier applied within practical constraints
- Final pressure increase performed at rate about 0.21 bar/minute
- Burst occurred at about 190.6 bar (average of the two pressure transducers).
- Specimen fail on the damage.



Corrosion test outcome

- 36" OD vintage pipe with a 60% WT local wall loss
- Burst at 190 barg in H₂ near the model median line
- Historic burst test in water on the model median line
- No significant difference compared to the LPC-1 (DNV RP F101) model and historic hydraulic burst test on the vintage pipe material



→ Draft recommendations

- Based on the tests performed so far in this study (including 2 full scale tests), no evidence has been found to change the existing burst capacity assessment procedure of vintage pipes for service in hydrogen gas:
 - ☐ in the presence of **smooth** mechanical damages on base metal
 - ☐ with external corrosion wall loss on base metal
- A factor of safety on the fatigue life of dents may be required for H2 service due to accelerated fatigue crack growth rates post crack initiation
- Work in progress for the modern pipe materials (dent on weld and dent+gouge)

— The SafeH2Pipe team

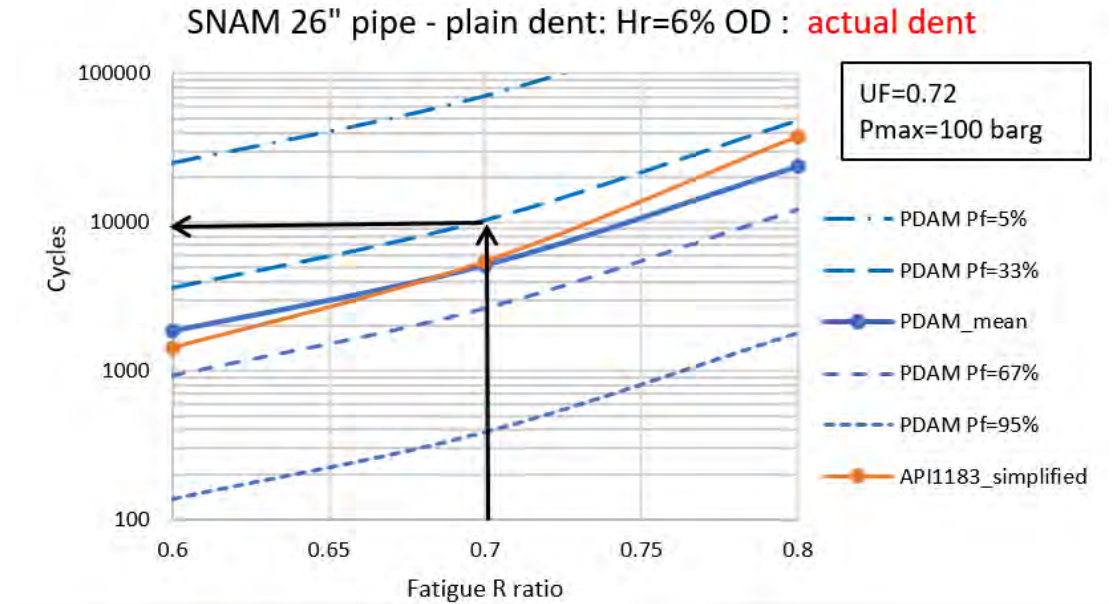


Thank you for your attention



Full scale test approach → fatigue cycling strategy: Dents

- Mean+1stdv assessed number of cycles to burst according to the methodology developed by EPRG for PDAM.



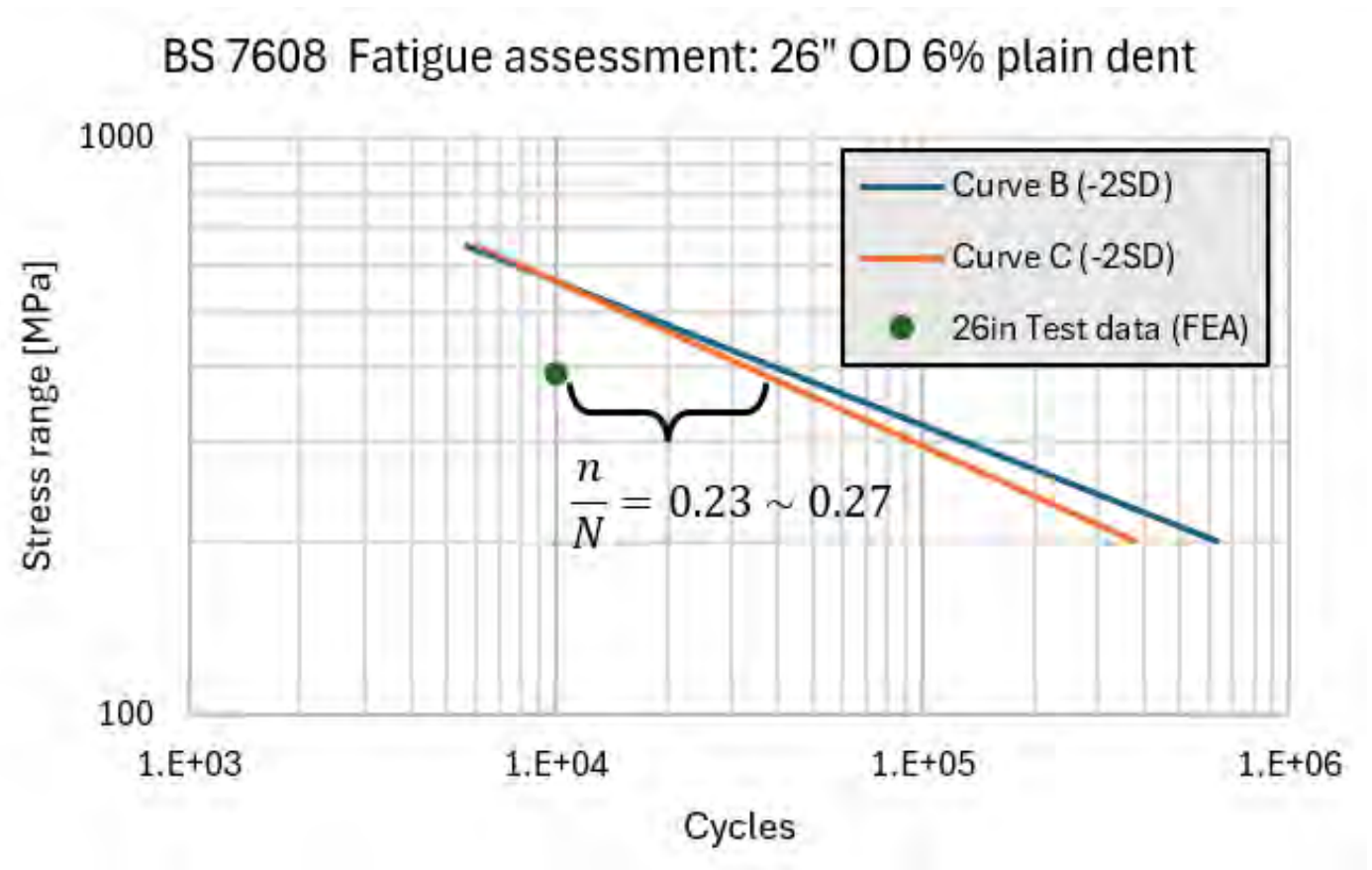
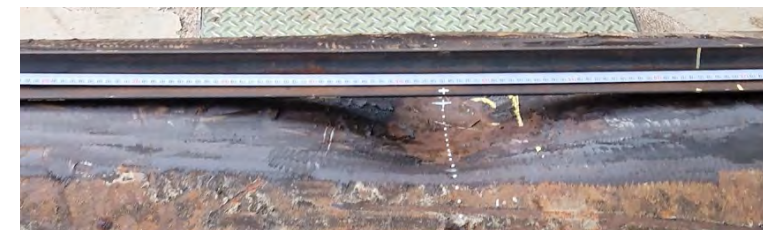
26" OD pipe:

Plane dent: 10,000 cycles

Max pressure: 72% SMYS

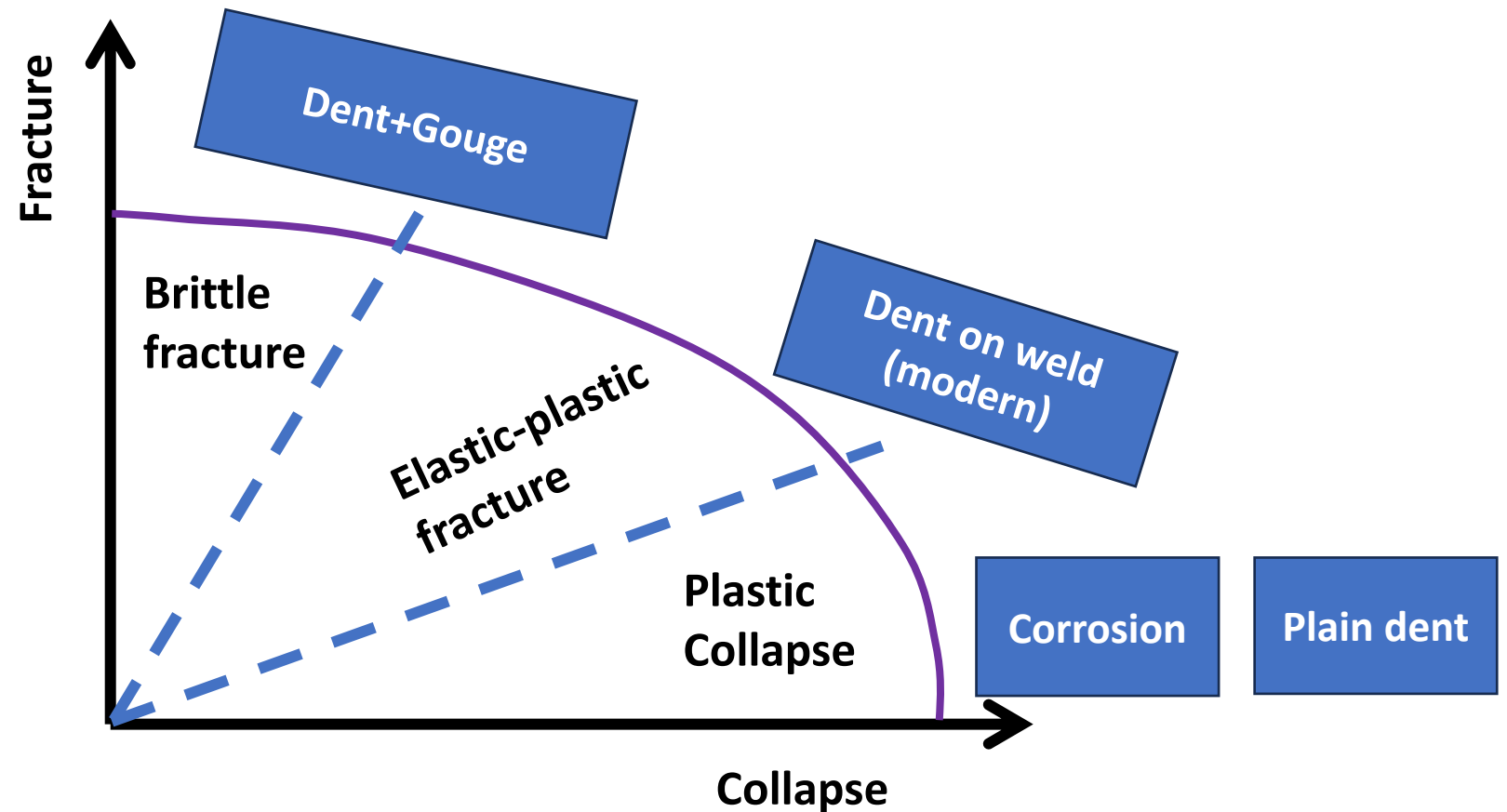
Plain dent fatigue test outcomes

- 26" OD vintage pipe with a 6% OD plain dent (PDAM) or ~4% OD plain dent (FEA)
- 10,000 fatigue cycles → high utilisation of 0.23~0.27 per BS7608 SN design curves
- Stress range in the dent calculated by 3D FEA
- No cracks observed in the dent and no significant effect on the subsequent burst capacity (failed away from the dent)



→ Damages, failure modes and material input data

J-R fracture
toughness tests



SSRT data

Full-Scale Testing of Legacy Pipeline Specimens in Hydrogen Environments

PRCI Project JEFI 04-08

July 24, 2026

ASME PVP 2026 Hydrogen Study Group

High Volume Hydrogen Gas Cycling System (GPS)

- Pressure cycling rates ≤ 0.5 cycle/min for two (2) specimens simultaneously
- Temperature control to $\pm 3^{\circ}\text{C}$
- Max pressure 4,000 psig (275 bar)
- Specimen test bay:
 - All ex-proof equipment
 - Active ventilation
 - Fire prevention construction
 - Fire-eye monitoring
 - Pressure-relieving bay doors
 - Blast shield protection



C-FER's High-Volume Hydrogen Gas Pressurization System Site

High Volume Hydrogen Gas Cycling System (GPS)

GPS Specimen Test Bay



Rear Side Specimen Test Bay



GPS High-Volume Hydrogen Gas Boosting System

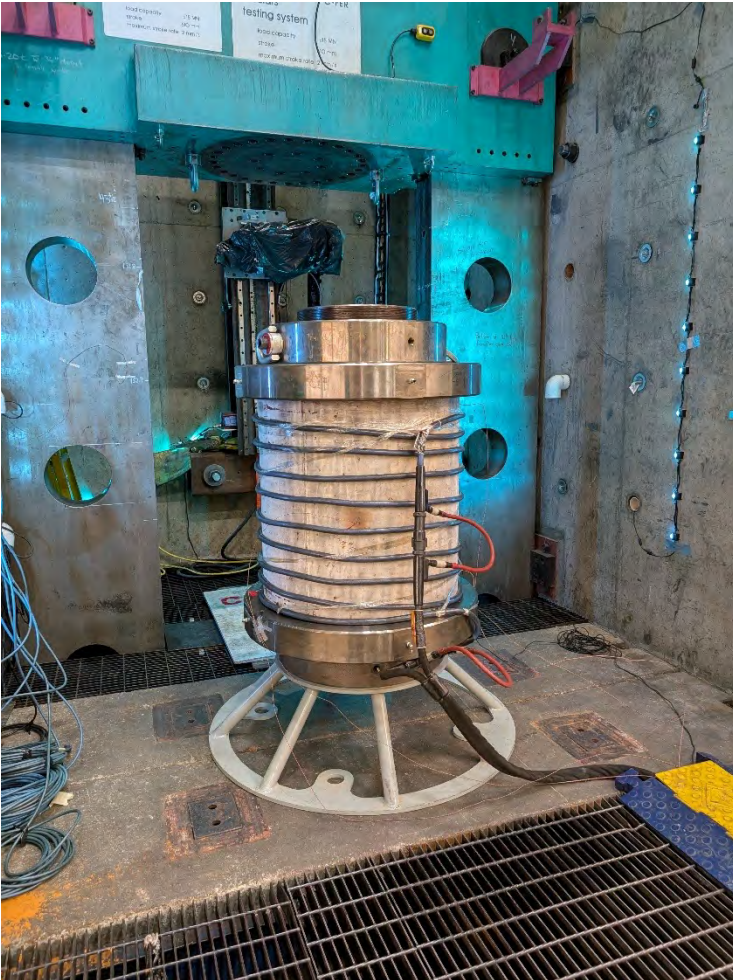


Full-scale Testing Impurity Control



- Specimen assembly includes large filler plates (aluminum) to:
 - Reduce gas test gas volume
 - Provide for higher gas cycling rates, if necessary
 - Increase test safety
- Initial measurements
 - < 1 ppm O₂
 - > 400 ppm H₂O

Specimen Moisture Removal



- Plan:
 - Induction heating of specimen and entire assembly to 150°C
 - Steady purging of specimen volume with dry nitrogen
- Moisture reduced to < 10 ppm after an extended heating and purging period

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Stress-based (S-N) fatigue design for hydrogen service

Study Group on Materials Testing
and Qualification for Hydrogen
Service – PVP 2026

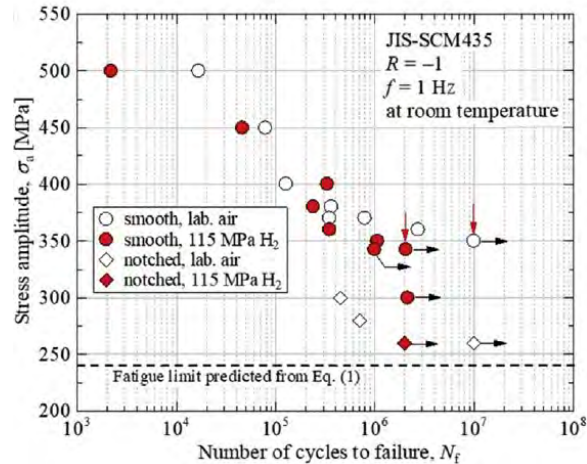
Mihaela E. Cristea, Paolo Bortot
Tenaris, Dalmine, Italy

Background

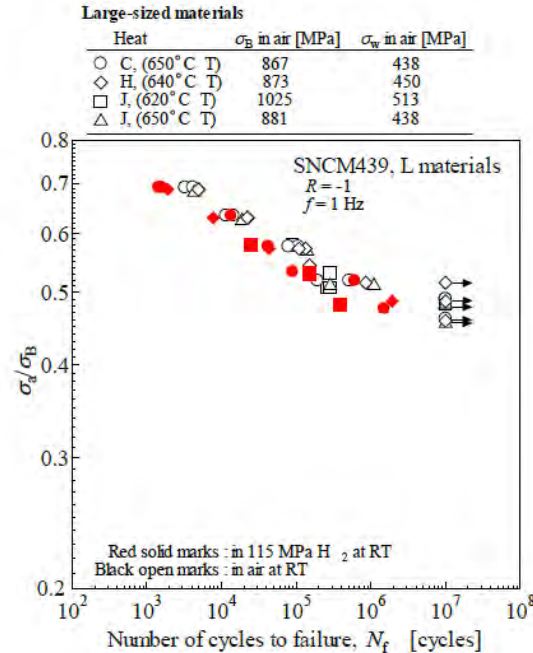
- Traditional fatigue analysis in air relies on S-N curves which are typically provided in codes & standards.
- For hydrogen service no specific guidance exists as well as limited experimental data.
- Existing data are not conclusive or not consistent.

Effect of hydrogen on PV steels

S-N Testing



Ref.: Ogawa et al., J. of Hydrogen Energy, 43, 2018



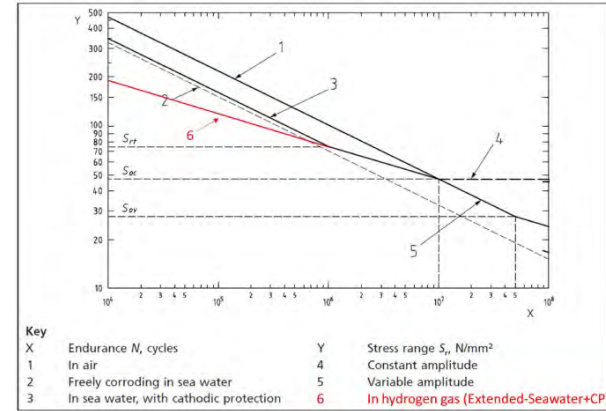
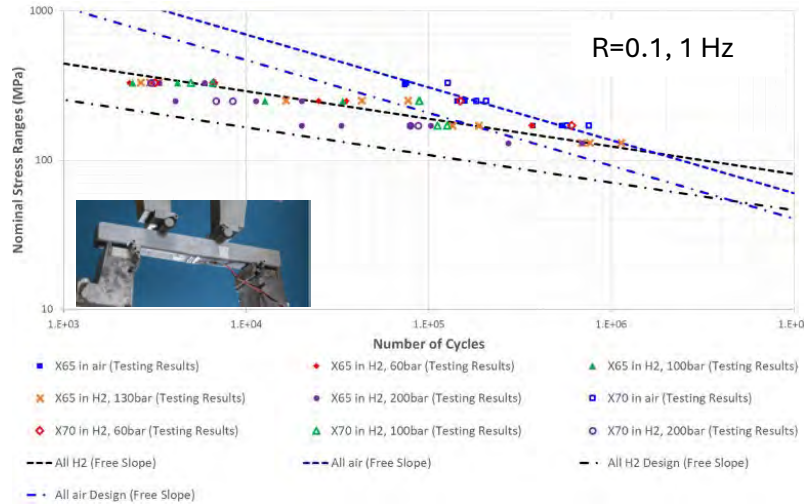
Ref.: Bulletin of the JSME, Vol.83, No.854, 2017

No significant effect on fatigue life at low stress ($N > 1,000,000$).

Larger effect in the finite life regime.

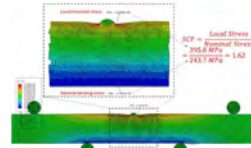
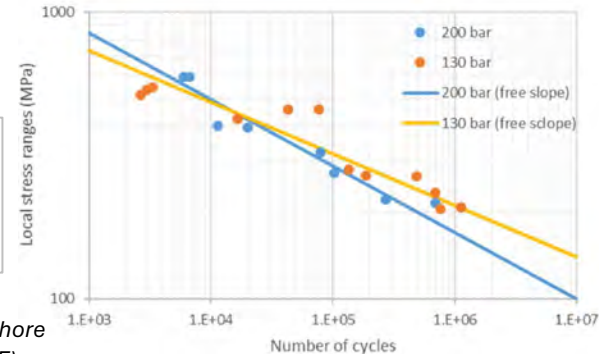
Effect of hydrogen on LP steels

S-N Testing



Proposed S-N curve for hydrogen transportation pipelines in seawater (Modified BS 7608:2015, F-curve in seawater and cathodic protection)

KDF of approx. 20 times at large stress ranges (200 MPa); Lower KDF at lower stress ranges and meets the sea water with CP curve at a stress range of approx. 75 MPa.

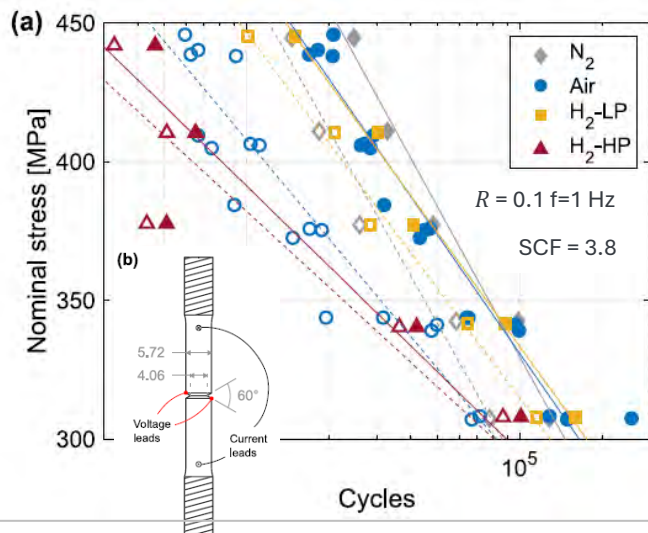


Ref.: LM. Haldorsen et al. "Perspectives and Investigations on Re-purposing of Large Diameter Offshore Pipelines for H2 transport" 2024 by the International Society of Offshore and Polar Engineers (ISOPE)

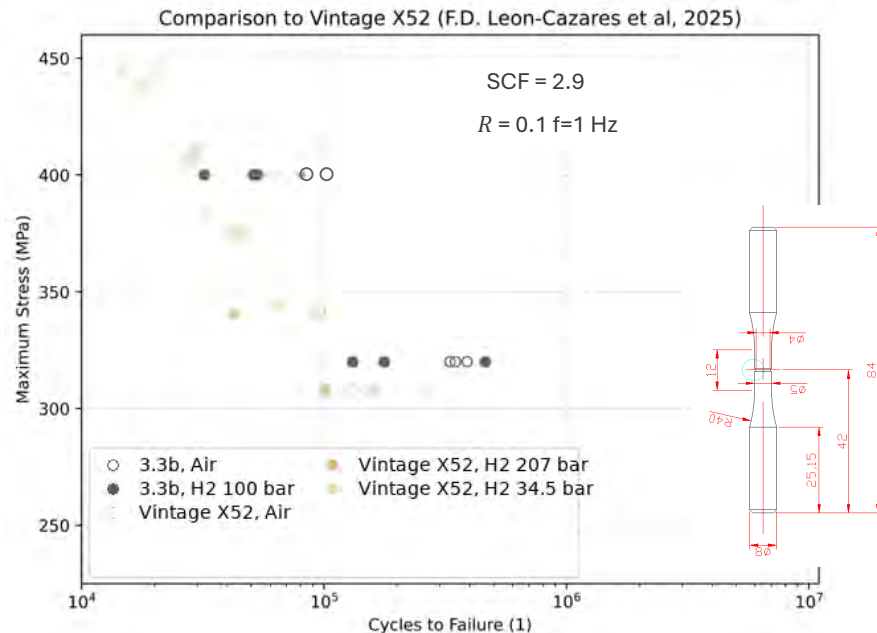
Effect of hydrogen on LP steels

S-N Testing

Open symbols and dashed lines: cycles to crack initiation
Solid symbols and solid lines: cycles to failure.



At low pressure (~ 34.5 bar) H_2 has little to no effect on crack initiation



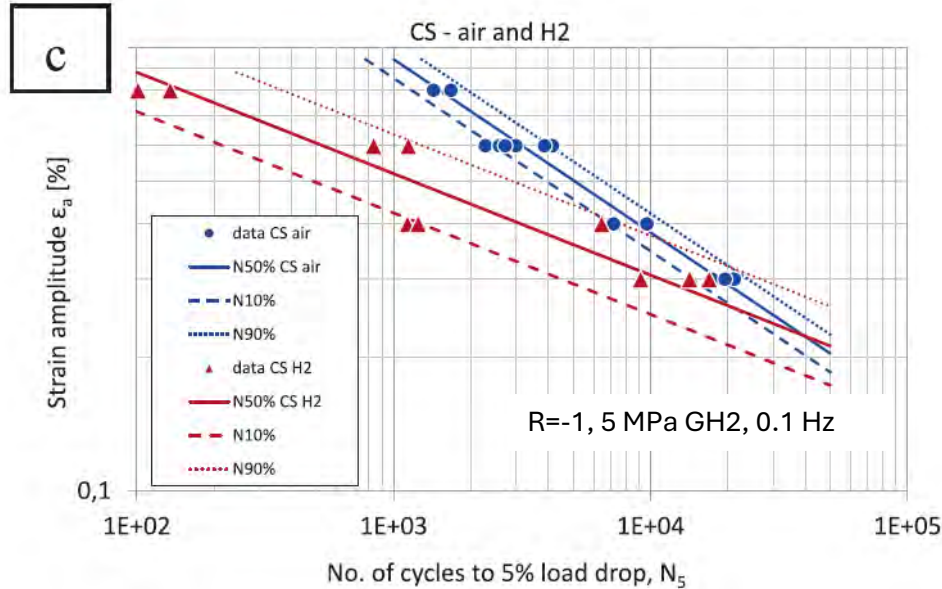
Similar results on 3.3b material (X60) as León-Cázares et al. work for vintage material

Ref.: León-Cázares et al., "Effects of hydrogen partial pressure on crack initiation and growth rate in vintage X52 steel, <https://doi.org/10.1016/j.ijhydene.2024.02.292>"

Ref.: WM. Williams, SafeH2Pipe Workshop, 4th CONFERENCE & EXPO 2026. Genoa, Italy, 9-12 June 2026

Effect of hydrogen on LP steels

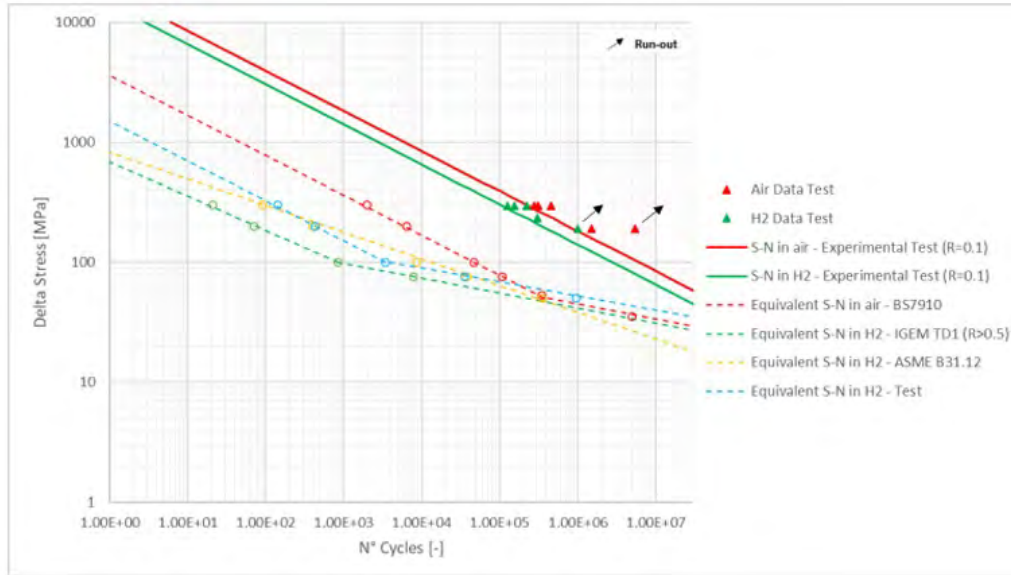
LCF Testing



H2 effect depends on strain amplitude: lifetimes reduced by a factor of 10 at high ε_a and by a factor of about 2 at low ε_a

Ref.: M. Thorsten et al. "Crack initiation due to low cycle fatigue in X60 pipeline steel tested in high pressure gaseous hydrogen using hollow and conventional specimens" - International Journal of Fatigue 204 (2026) 109354

Effect of hydrogen on LP steels



S-N vs. fracture mechanics approach?

FCGR assessments long cracks/surface flaws are typically assumed -> fatigue lives are significantly shorter.

Ref.: D. Scarsciafratte et al., "Fracture mechanics at the core of hydrogen pipelines design: a fracture mechanics approach in design life prediction based on material performance measured in H2 environment", PVP2025-154573

Key Questions - 1

Do we need S-N curves specifically for hydrogen?

- S-N can complement fracture mechanics approach to provide the total lifetime of the component, including nucleation time.

What data in hydrogen is needed to establish a rationale for hydrogen? Are existing curves in codes & standards sufficient? Or do we need new curves?

- Existing data appear to be quite limited and not always consistent.
- C&S today do not have provisions for hydrogen service.
- Low and high cycle fatigue as well as fatigue limit should be investigated.

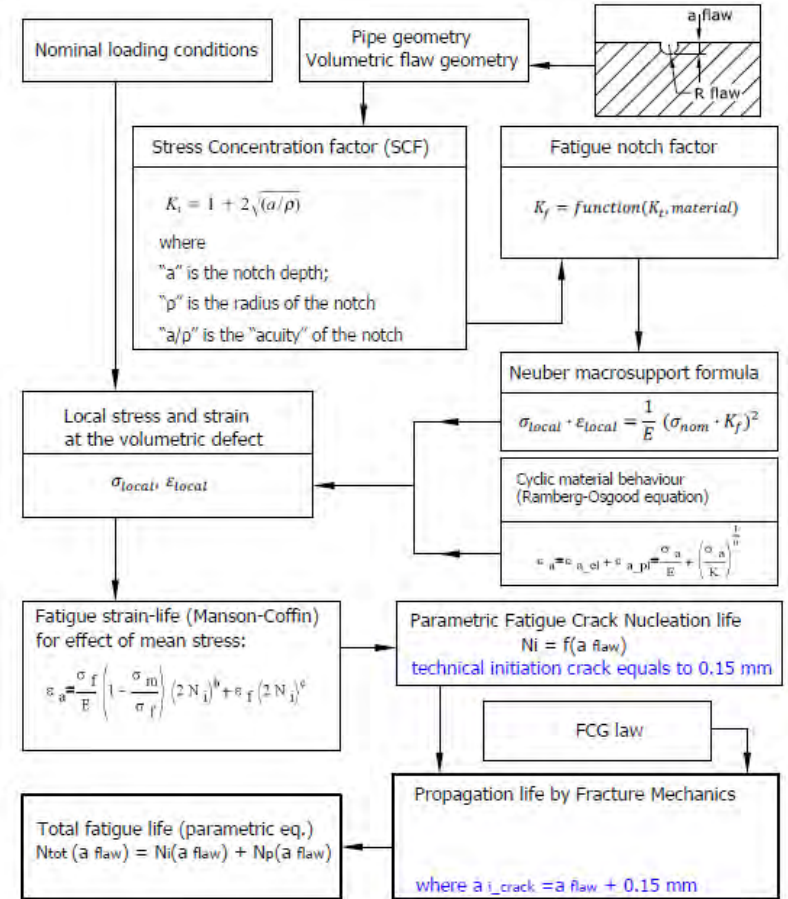
Key Questions - 2

Can notched fatigue data be a surrogate for strain-based data?

- Notched fatigue data seem promising and should be compared with strain based data.
- A more comprehensive understanding would be needed to assess notched fatigue data compared with traditional curves.

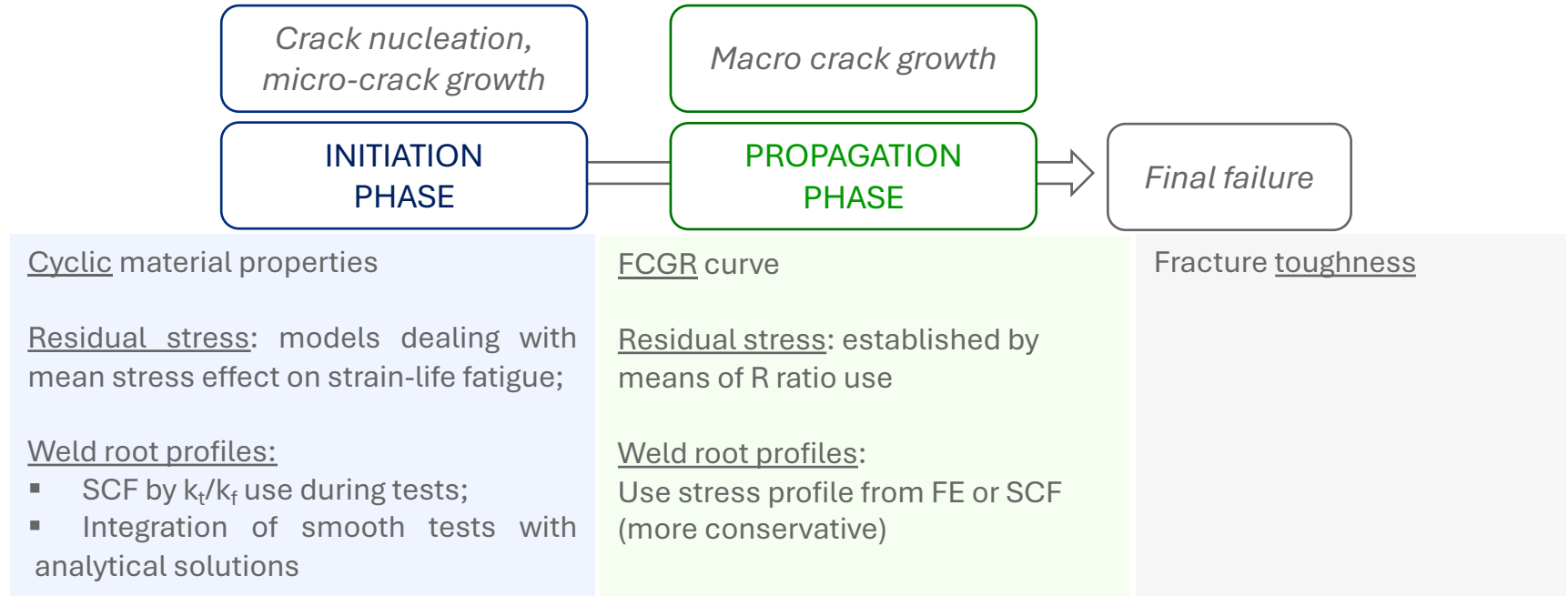
Alternative framework - 1

Can a framework be established for using initiation from stress/strain-based data be used to complement classic fracture mechanics approaches?



Alternative framework - 2

Can a framework be established for using initiation from stress/strain-based data be used to complement classic fracture mechanics approaches?



HOLLOW SPECIMEN METHOD FOR LOW CYCLE FATIGUE TESTING IN HIGH PRESSURE GASEOUS HYDROGEN

IWM: Ken Wackermann, Heiner Augenstein, Thorsten Michler

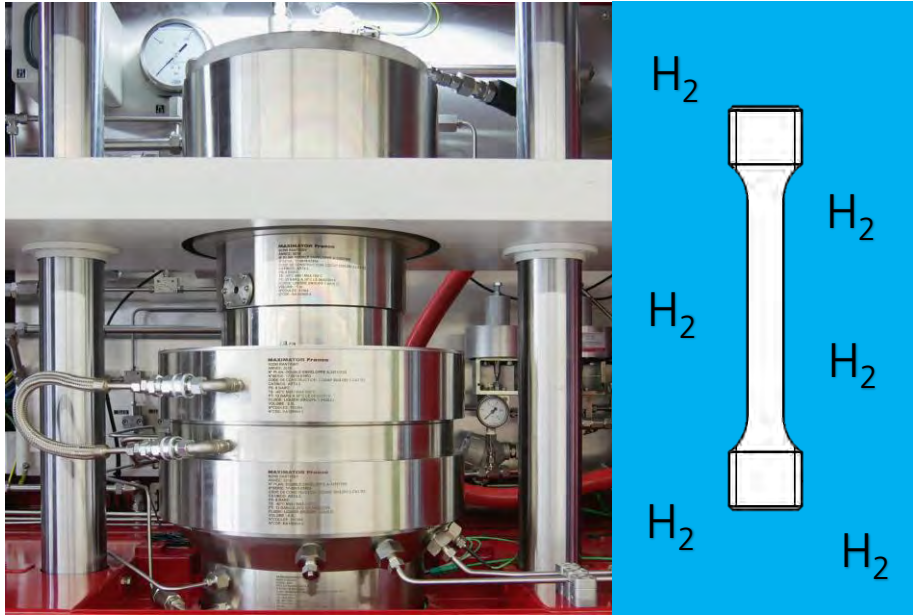
MPA: Brian Kagay

PVP 2016, July 19-24, Anaheim, California, USA – PVP2026-182639

Motivation

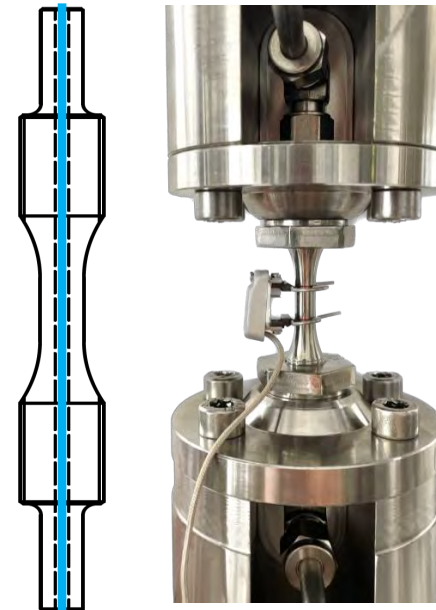
What are hollow specimen?

Autoclave testing



- Test are standardized in ANSI/CSA CHMC 1
- Accepted technology

Hollow Specimen



- So far only tensile test is standardized: ISO 7039
- Hydrogen in central borehole of the specimen
- Cost effective especially in fatigue tests lasting days or weeks

Motivation

Advantages of hollow specimen

Liquid nitrogen bath (-196 °C)



Temperature chamber (-100 to +200 °C)



© Fraunhofer IWM, Foto: Kai-Uwe Wudtke

Induction heating (+100 to +1000 °C)

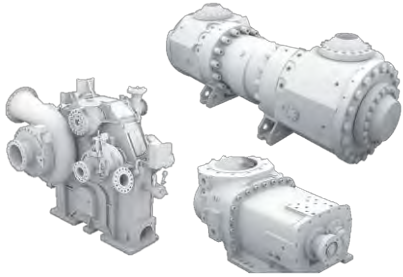


© Fraunhofer IWM, Foto: Kai-Uwe Wudtke

+ TMF testing

Use Case and Motivation – Turbo Compressor for Hydrogen Applications

Wheel: Steel 1.4313 (AISI CA6-NM, UNS S41500)



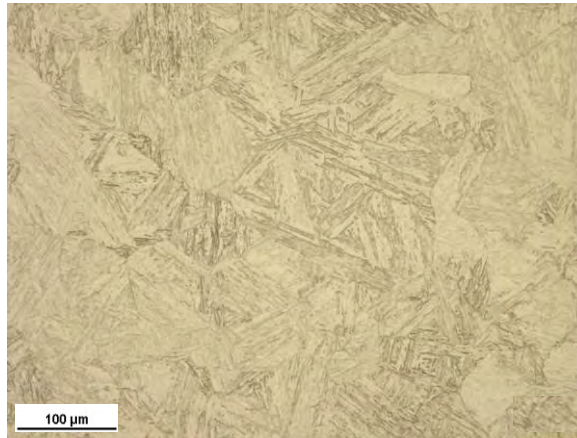
© Everllence



- Can hollow specimens be an alternative for fatigue tests for materials qualification with hydrogen?
- Establish basis for standardization of hollow specimen for fatigue testing.

Material and Testing

- Soft martensitic steel 1.4313 (AISI CA6-NM, UNS S41500)
- Heat treated to (QT900)
 - $R_m = 900$ MPa
 - $R_{p0.2} = 783$ MPa
 - $A = 19$ %



Chemical composition

El.	C	Si	Mn	P	S	Cr	Ni	Mo
Wt%	0.025	0.39	0.56	0.015	0.001	12.62	4.24	0.38

- Low Cycle Fatigue
- Strain-controlled
- $R = -1$
- $f = 1$ Hz
- Pressure 100 bar
- Hydrogen
 - Hollow specimen H2 5.0 (99.999%)
 - Conventional specimen H2 6.0 (99.9999%)
- Reference test
 - Hollow specimen: ambient air
 - Conventional specimen: Helium

Steps of Production



100



Geometry

Hollow specimen

- Inner gauge diameter: 2 mm
- Outer gauge diameter: 6 mm
- Gauge length: 12 mm

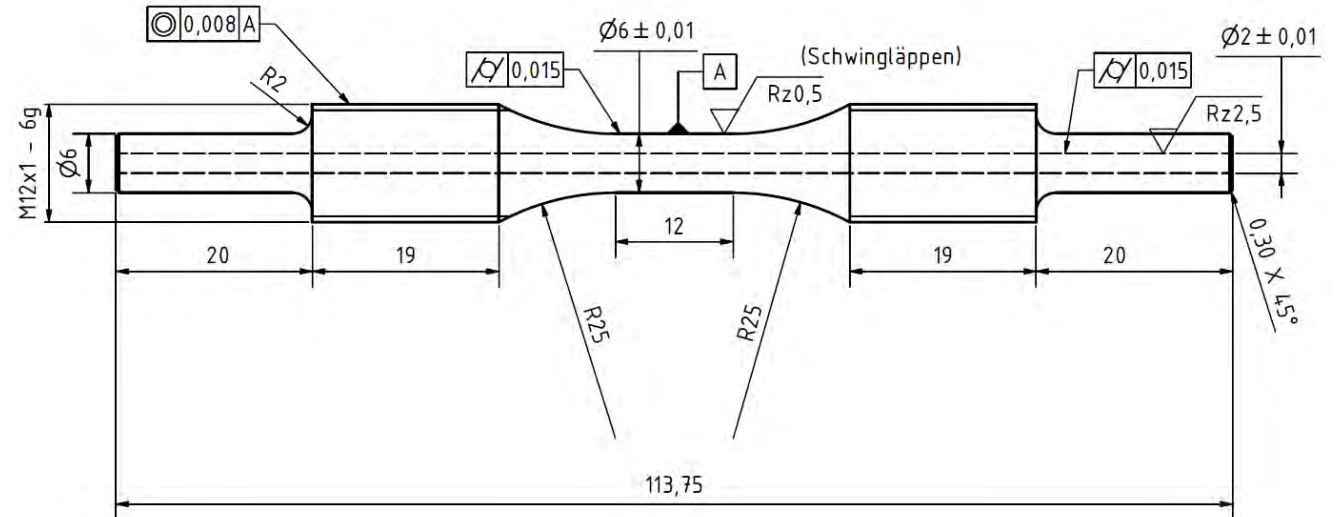


Conventional specimen

- Same size of gauge length
- No inner hole



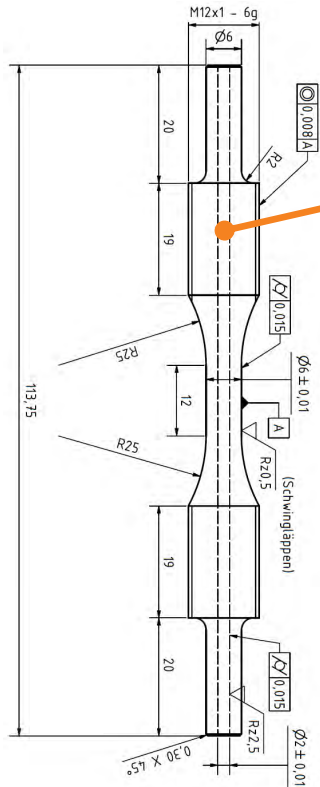
4. Outer Contour by turning + lapping leading to final specimen geometry



Results

Inner gauge surface quality of hollow specimen

Microscope image of the inner gauge surface



Shallow axial grooves caused by abrasive AFM particles

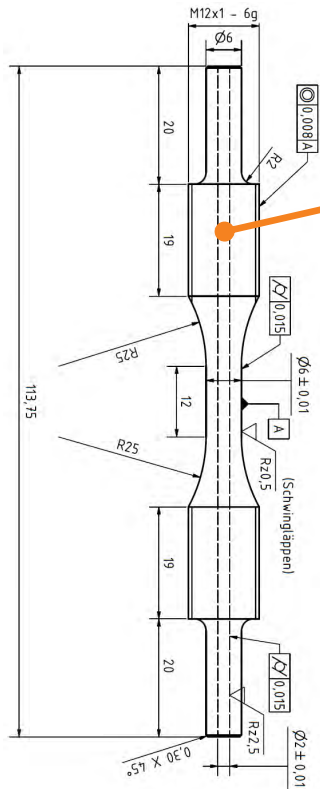
Tiny pits (black dots), $\varnothing < 1\mu m$, reason unclear at the moment

- Roughness $Rz \sim 0.4 \mu m$ (*)

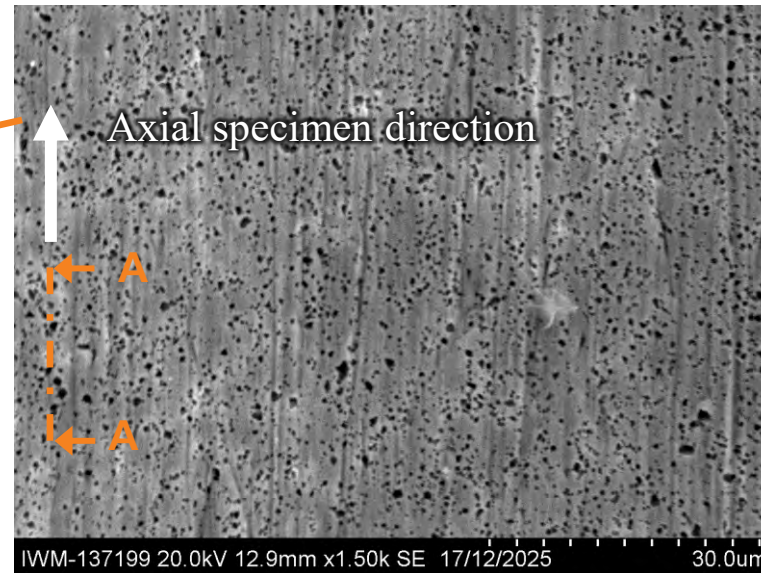
(*) ISO 12106 or ASTM E606 specify $Rz < 0.2 \mu m$

Results

Inner gauge surface of hollow specimen

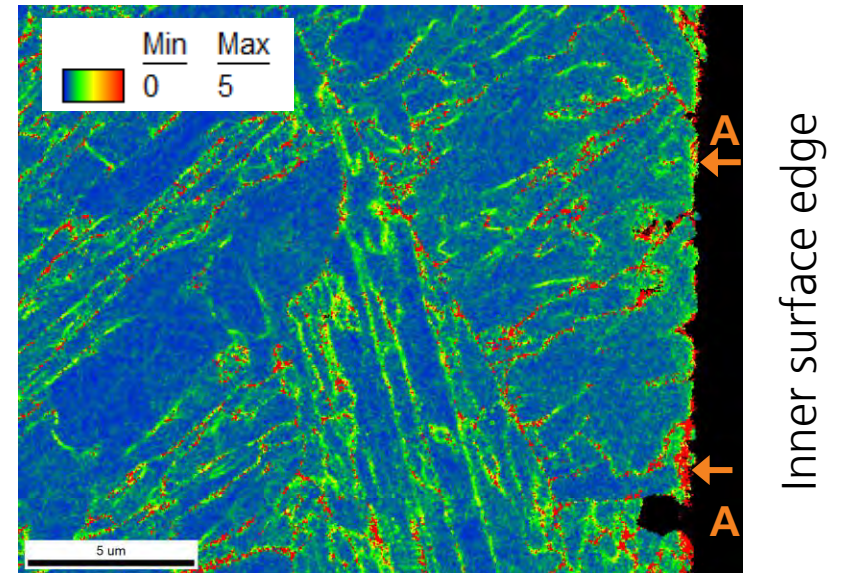


Microscope image of the inner gauge surface



- Shallow axial grooves caused by particles of AFM
- Tiny pits ($\varnothing < 1\mu\text{m}$)

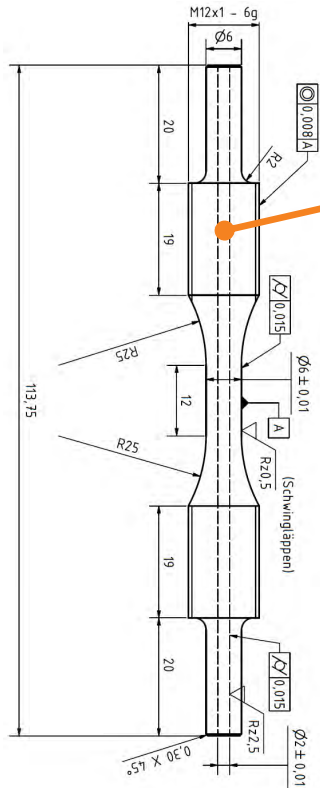
KAM-EBSD of the inner gauge section



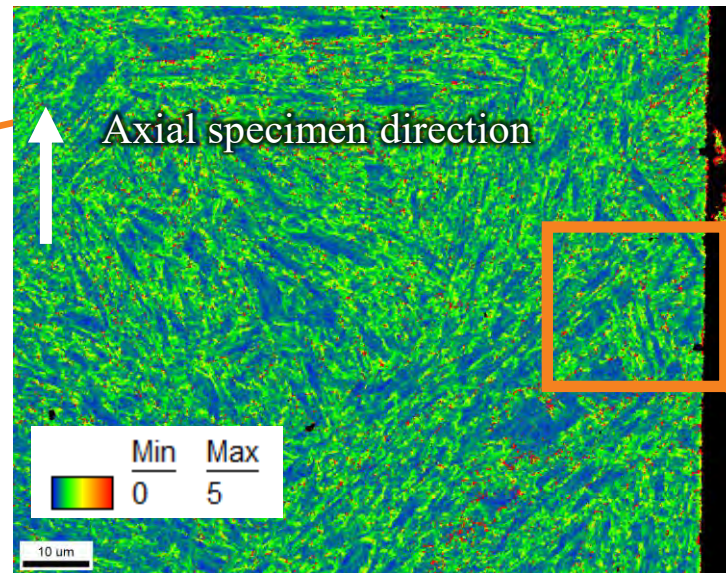
- EDM layer removed
- $R_z = 0.4\mu\text{m}$
- R_z about factor 2 higher compared to lapped CS
- ASTM normally defines surface roughness $< 0.2\mu\text{m}$

Results

Inner gauge surface of hollow specimen

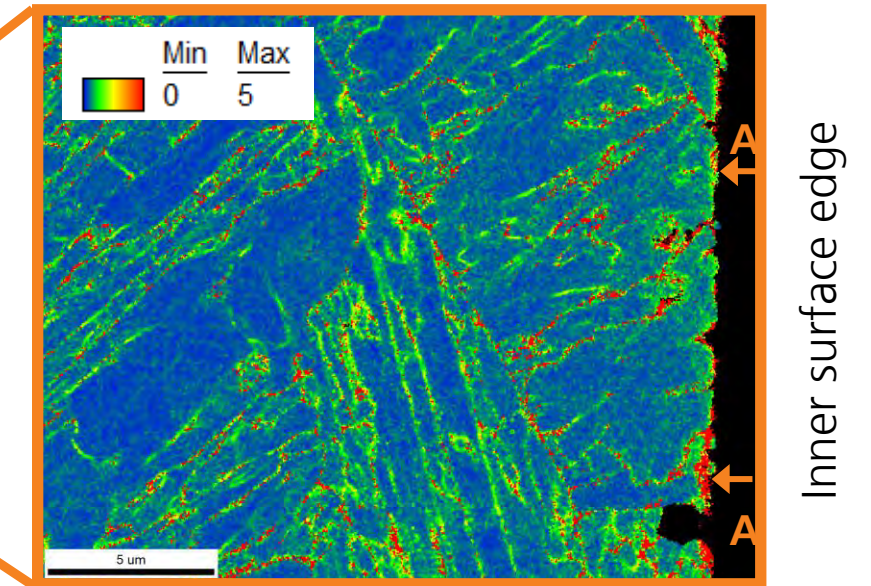


EBSD of the inner gauge section



- Lower magnification

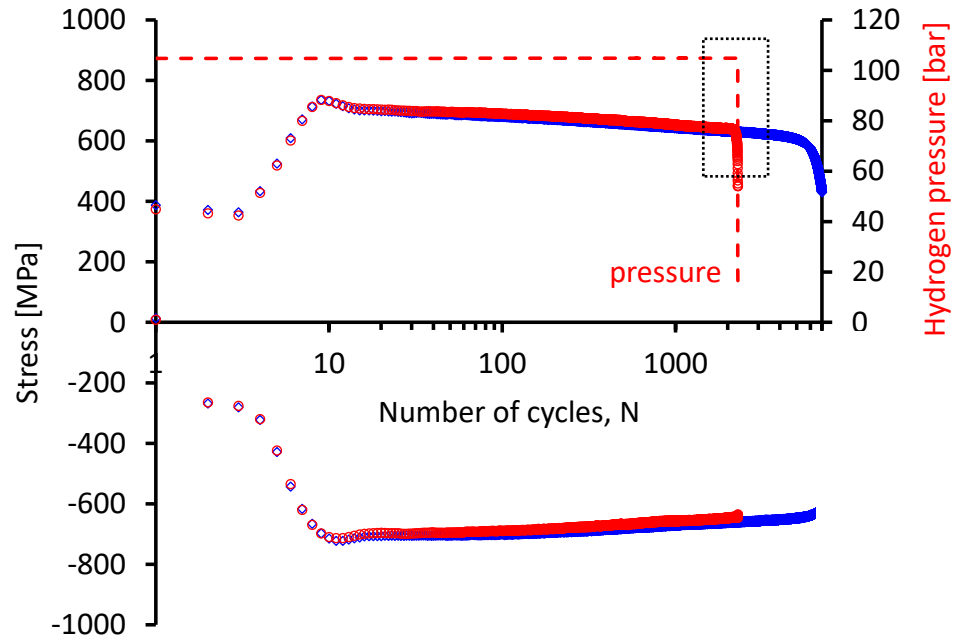
KAM-EBSD of the inner gauge section



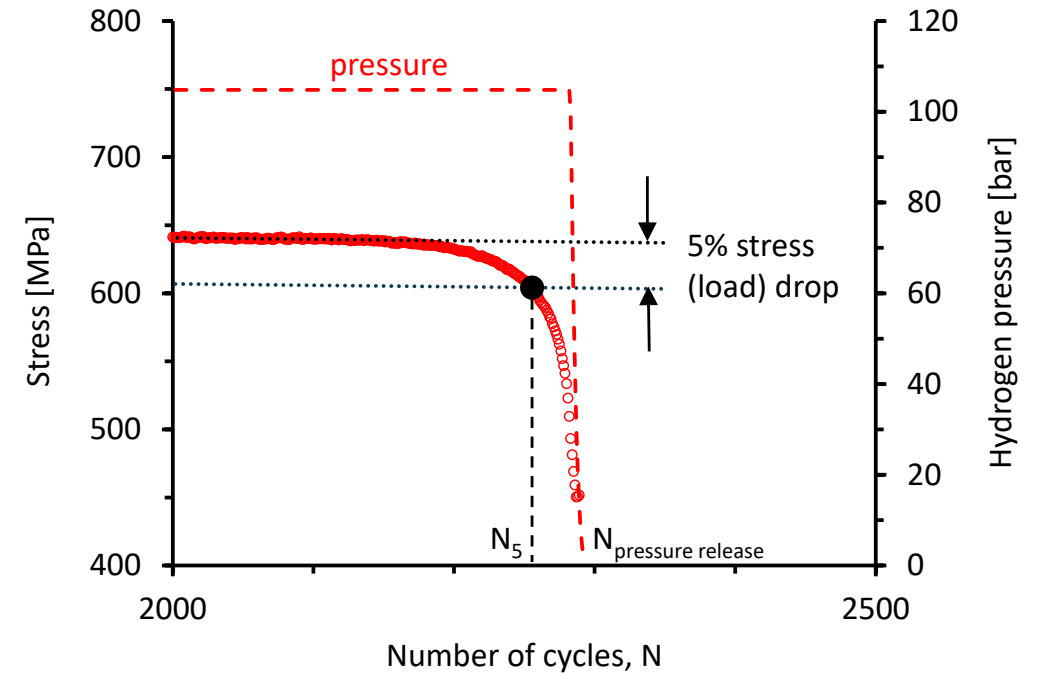
- EDM layer removed
- $Rz = 0.4 \mu m$
- Rz about factor 2 higher compared to lapped CS

Results

Hydrogen gas pressure and minimum and maximum stresses of HS



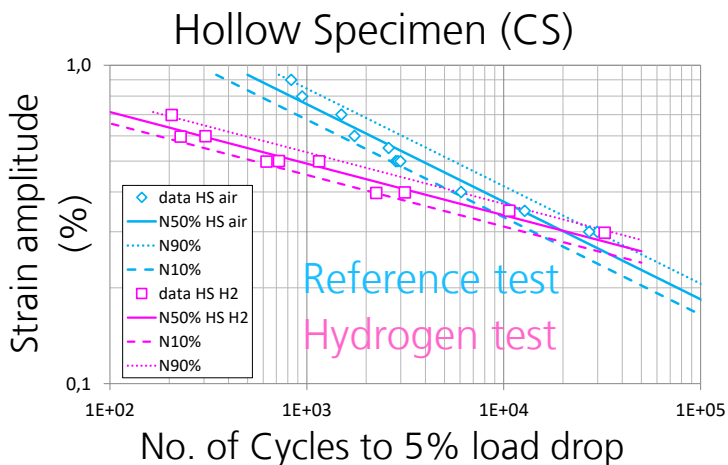
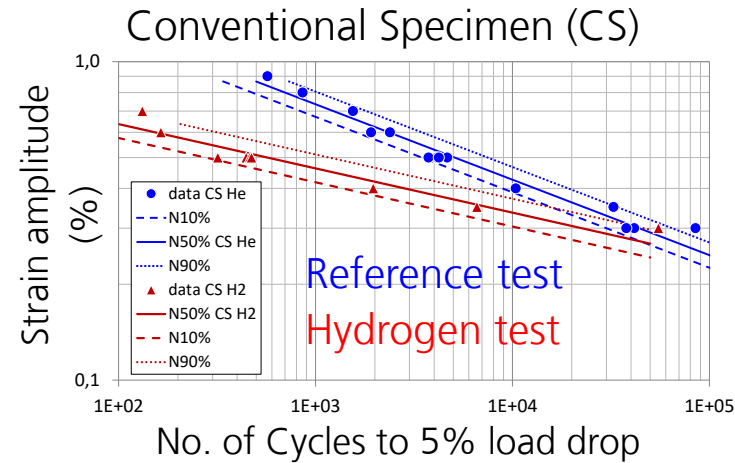
Hydrogen test
Reference test



- Comparable evolution of stress in both atmospheres
- Pressure is effective until the 5% load drop criterion
- Hydrogen affects life-time

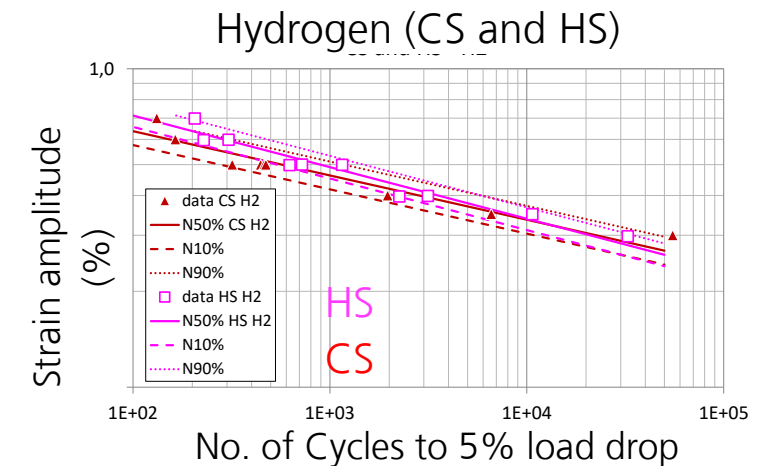
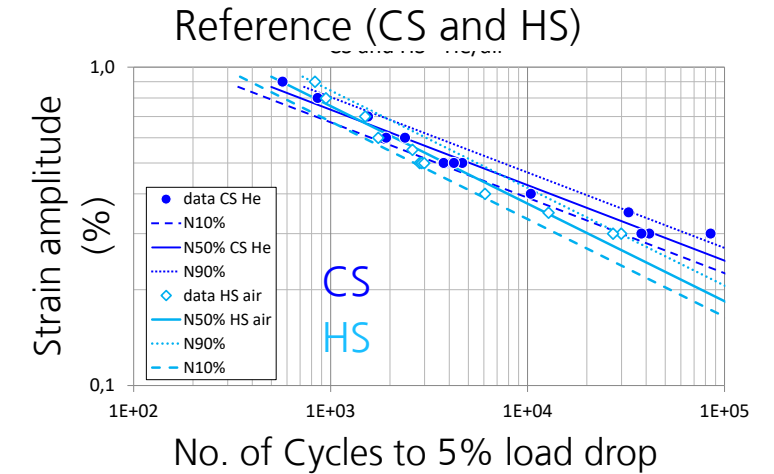
Results

Strain life diagrams



Conclusion

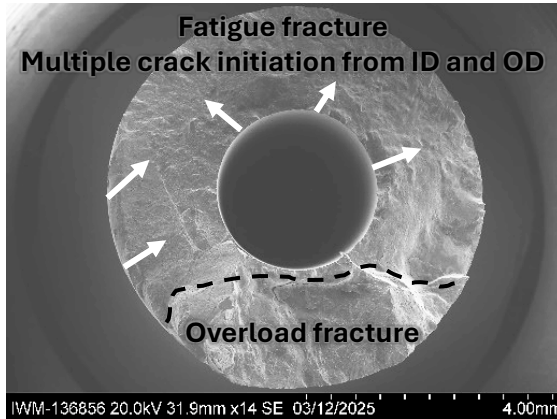
CS and HS show comparable lifetime for H2 and reference



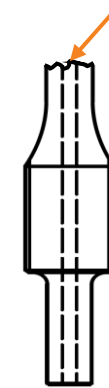
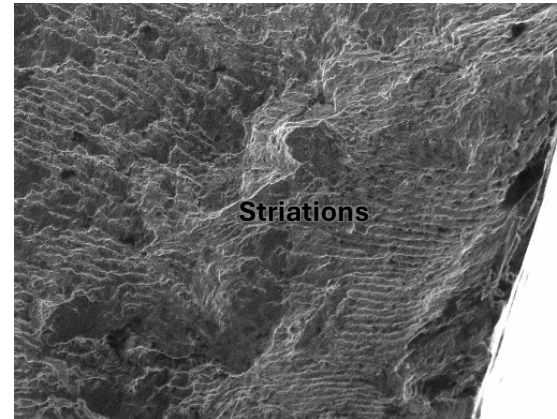
Results

Fracture morphology of hollow specimen

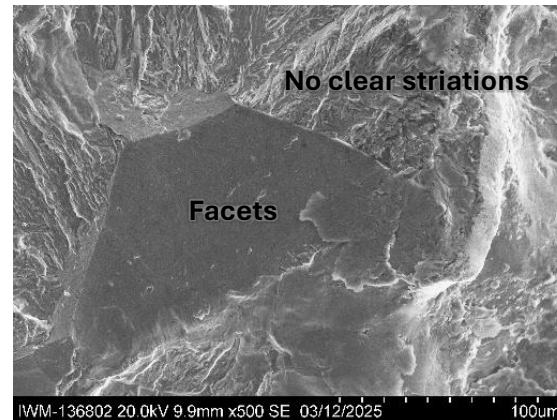
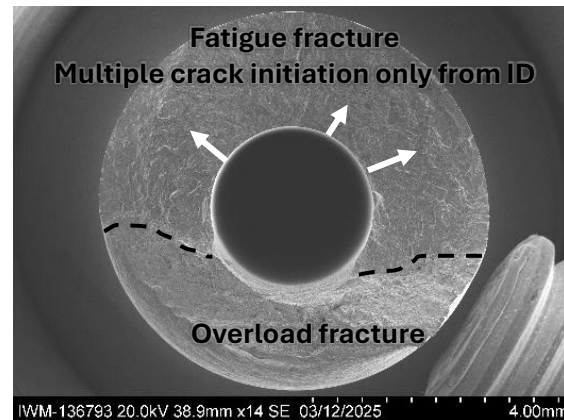
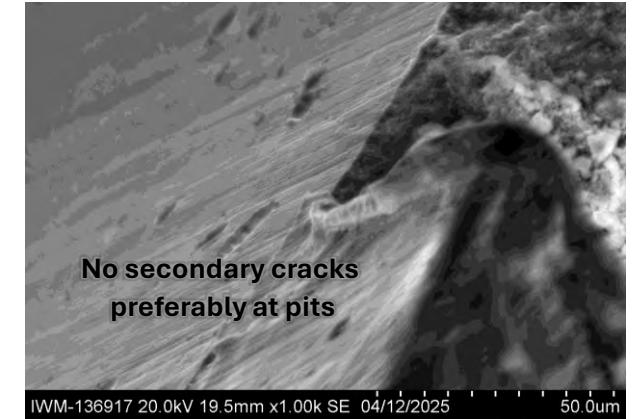
Overview of fracture surface



Some characteristic details



Tilted view of the inner borehole surface



Summary and conclusion

Test condition

- Undistorted gauge surface of HS is reached by EDM and subsequent AFM, which results in a surface comparable to lapped CS.
- Scatter bands of strain life diagrams overlap for HS and CS for both, H2 and reference tests.
- CS and HS provided almost identical test results for the steel and conditions tested.

Acknowledgment

We would like to express our gratitude for the financial support by the German Federal Ministry of Education and Research (BMBF) under grant number 03HY202F (TransHyDE).



Thanks for Your Attention

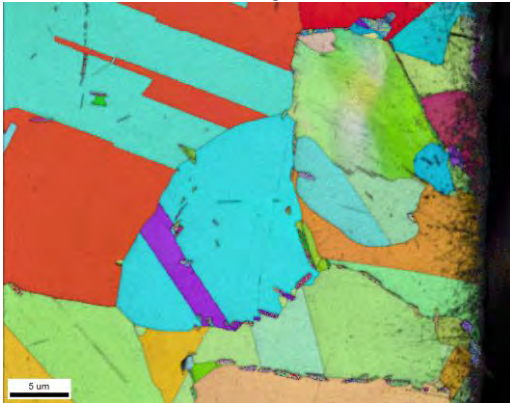
Ken Wackerman



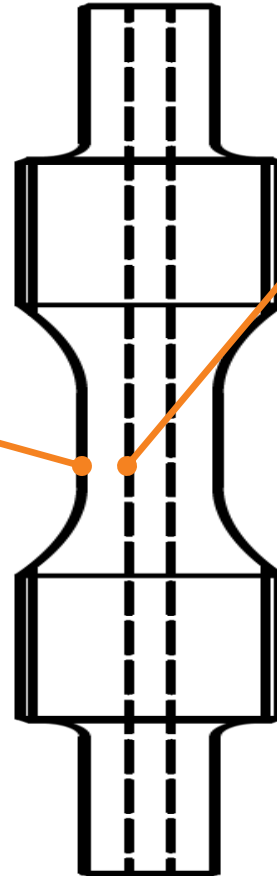
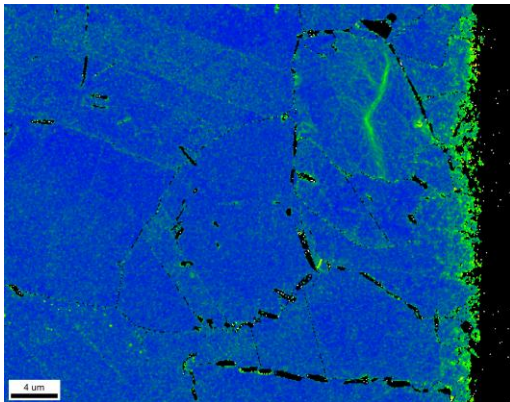
Results

Surface of gauge length of hollow specimen of IN718 on inside and outside

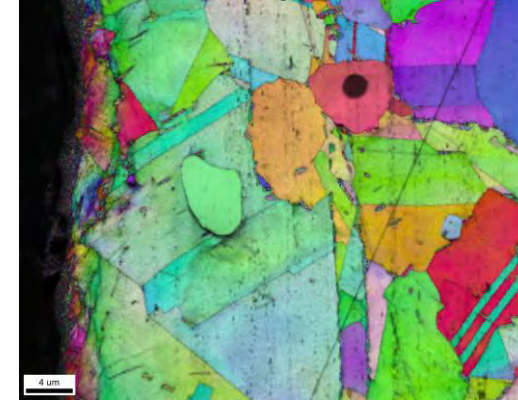
EBSD quality – inside



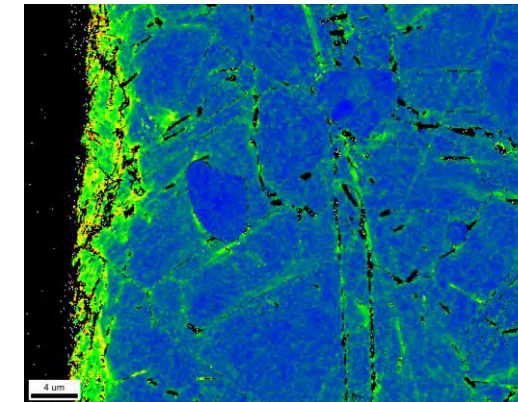
EBSD KAM – inside



EBSD quality – outside



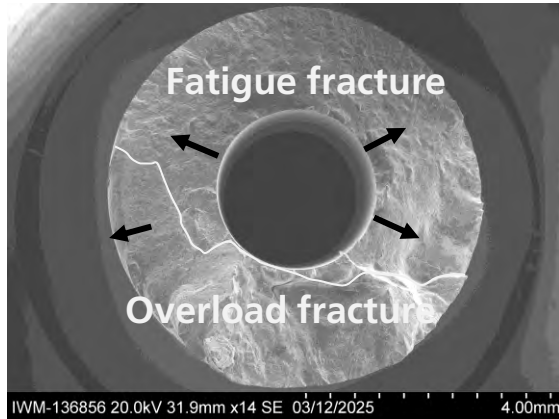
EBSD KAM – outside



Results

Fracture morphology of hollow specimen

Overview of fracture surface

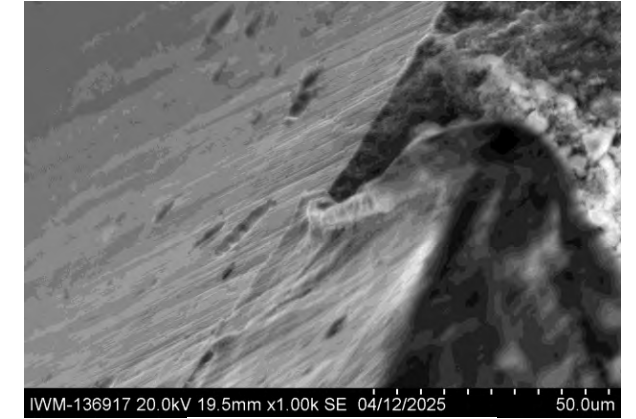


Specimen tested in air

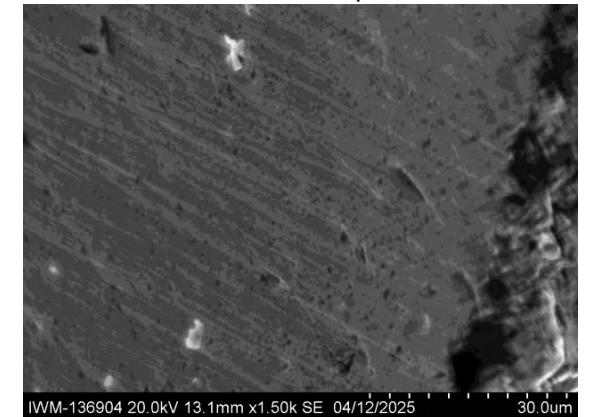


Tilted view of the inner borehole surface

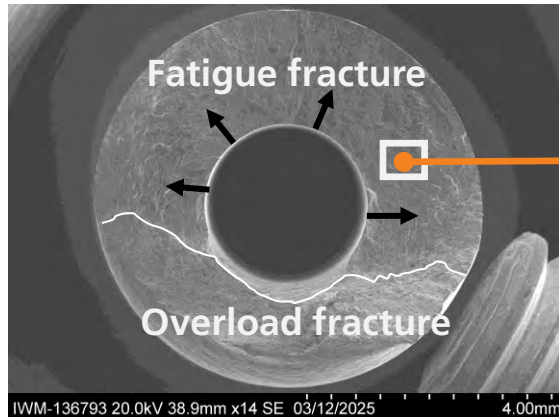
View direction



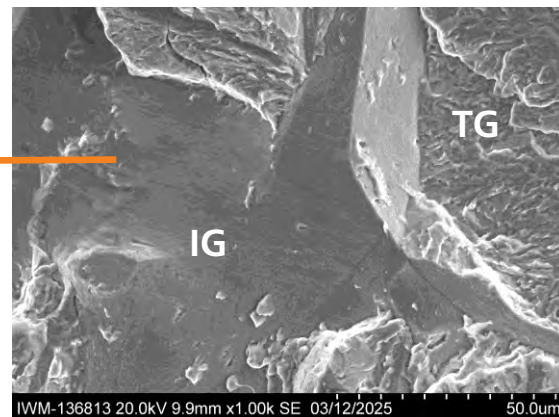
No secondary crack
at inner pits



Overview of fracture surface



Detail of fracture surface





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Hydrogen-assisted Fracture Response of Pipeline Steel: Comparison of Compact Tension (CT) and Single Edge Notch Tension (SENT) Specimens

Michelle Kent,

Joe Ronevich, Chris San Marchi

Sandia National Laboratories
Livermore, CA

ASME PVP Conference, Anaheim, CA

July 19-24, 2026

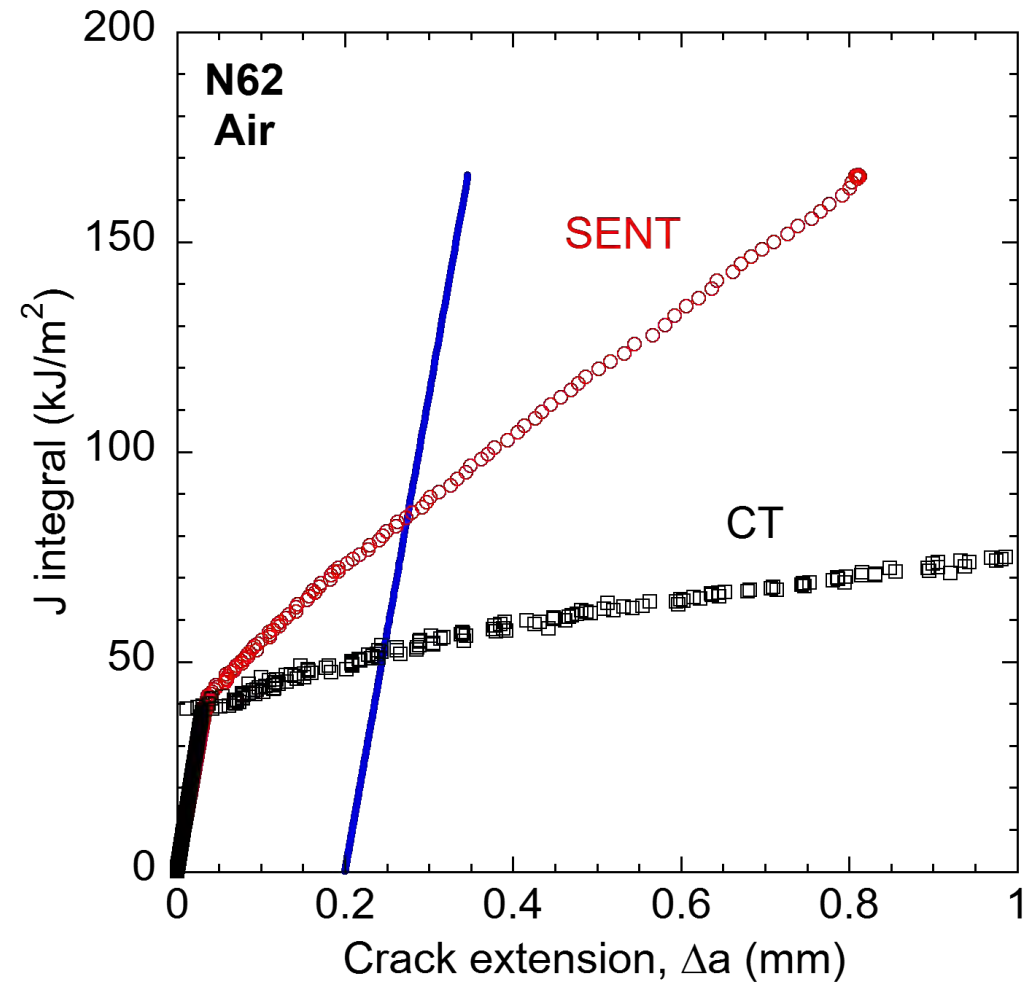
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.





Vintage Steels Also Show Higher J_Q in SENT Compared to CT in Air

The margin between SENT and CT is lower in vintage compared to modern steel (E21)

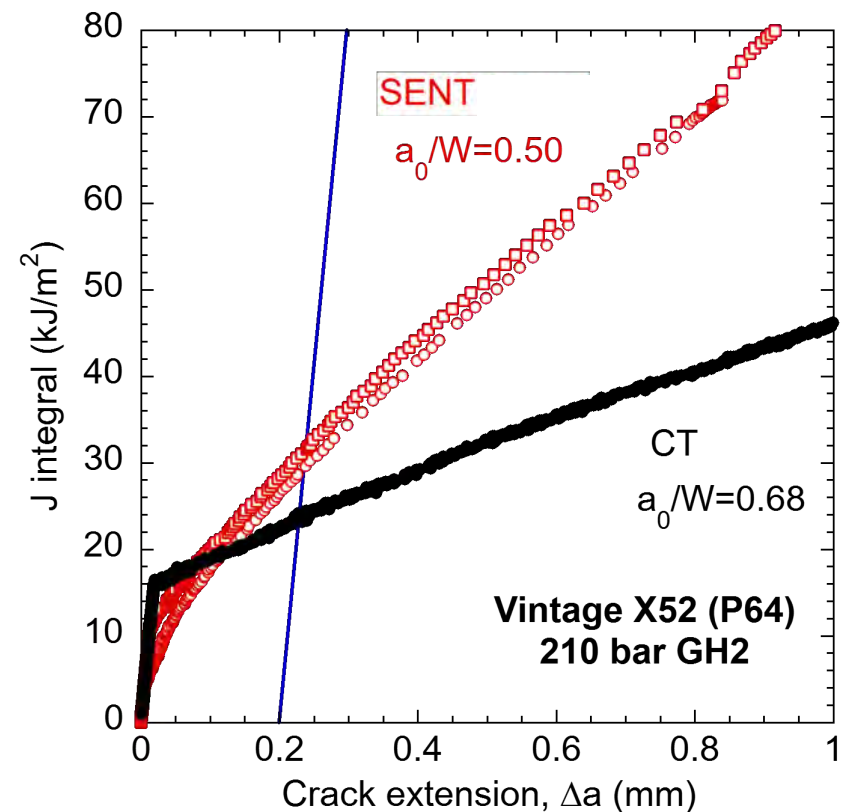
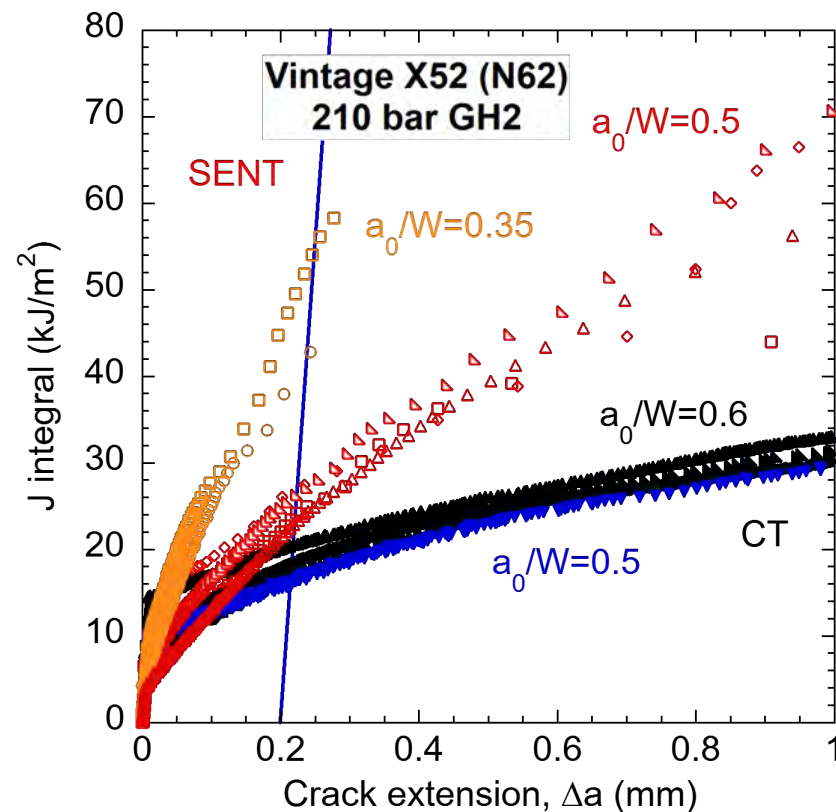




X52 Vintage Steels (N62, P64) Show Similar Fracture Resistance to One Another in CT and SENT Geometries

Vintage X52 SENT specimens show lower J_{0-H} and higher J_{Q-H} than CT specimens

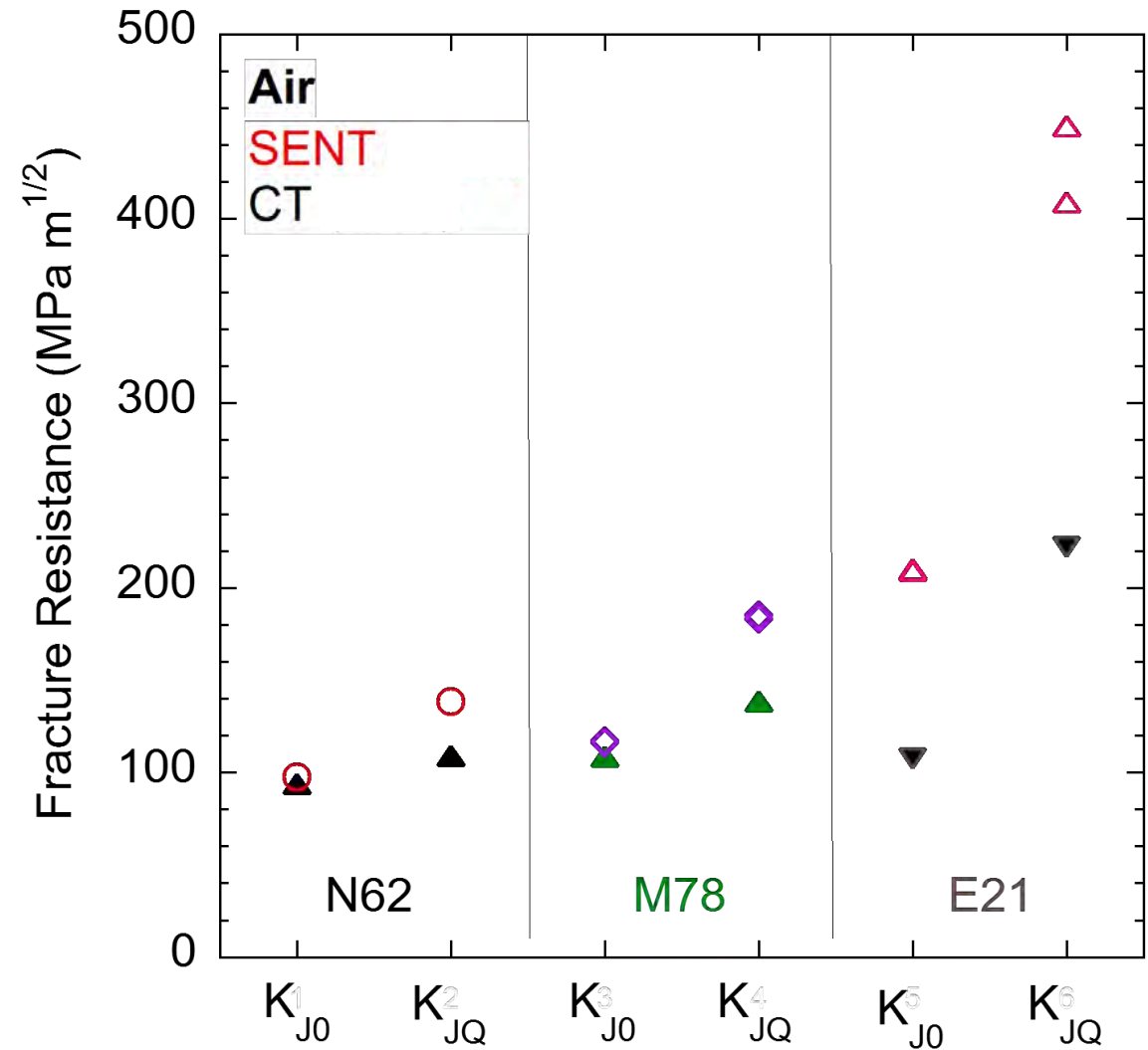
N62: Shorter crack length $\rightarrow$ Higher Fracture resistance in SENT; no crack length effect in CT





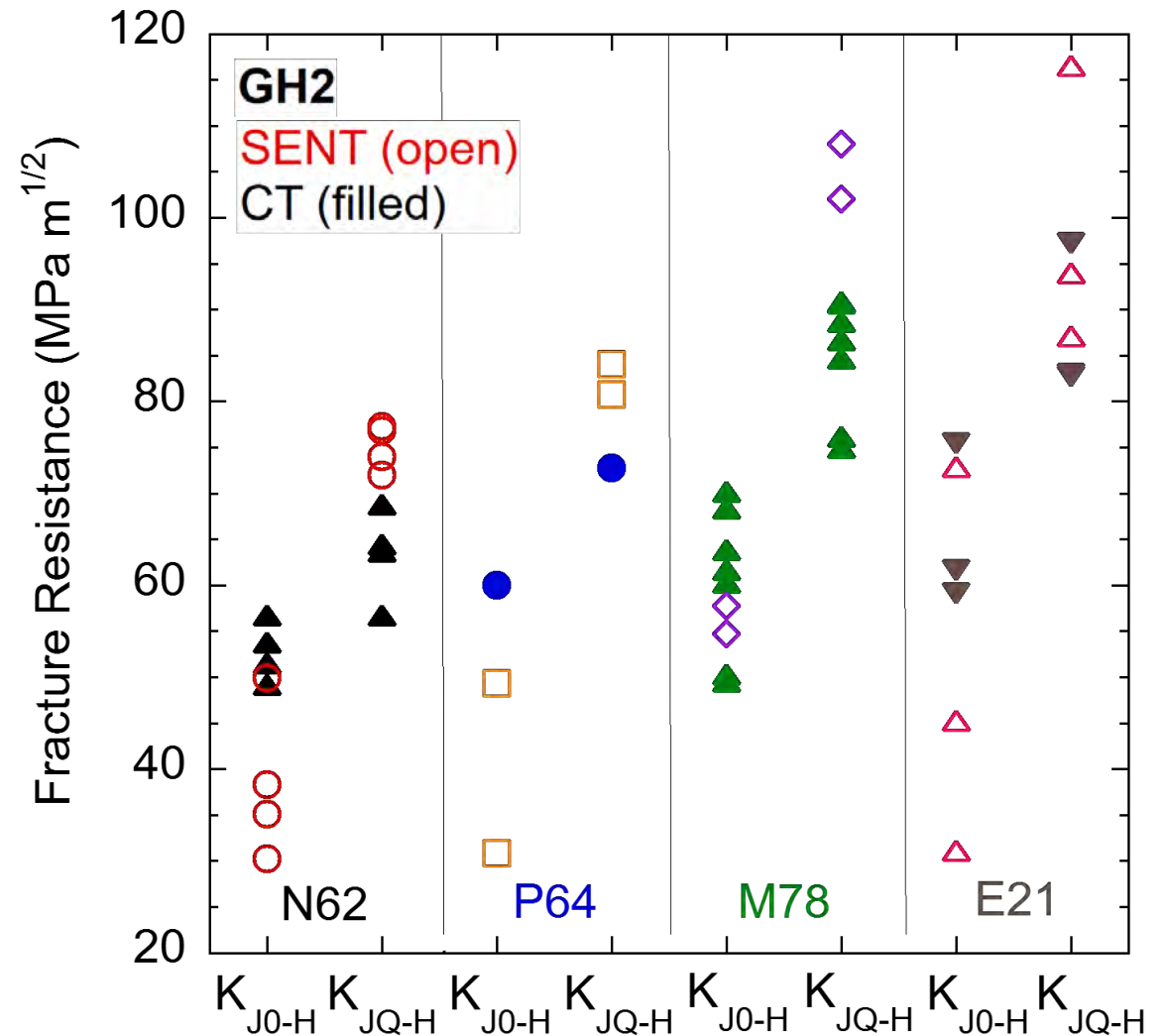
Fracture Resistance K_{J0} and K_{JQ} are both Higher in SENT than in CT Tested in Air

Difference between SENT and CT is greatest for modern X70 (E21) compared to vintage grades (N62, M78) with lower nominal K_{JQ}



Pipeline Steels

- Some constraint dependence remains in the SENT geometry in GH2 despite a large reduction in plasticity compared to air
- Hydrogen reduces the constraint effect between SENT and CT geometries, especially for long cracks
- For long crack length ($a_0/W \sim 0.5$) specimens tested in GH2, SENT specimens have lower K_{J0-H} while CT specimens have lower K_{JQ-H}

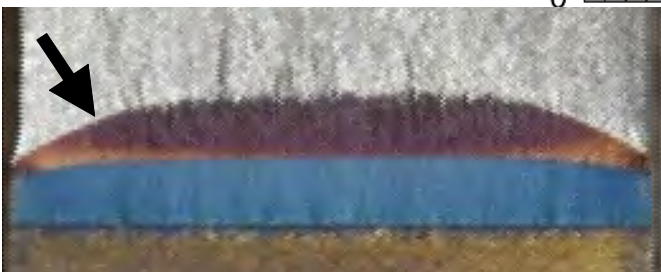
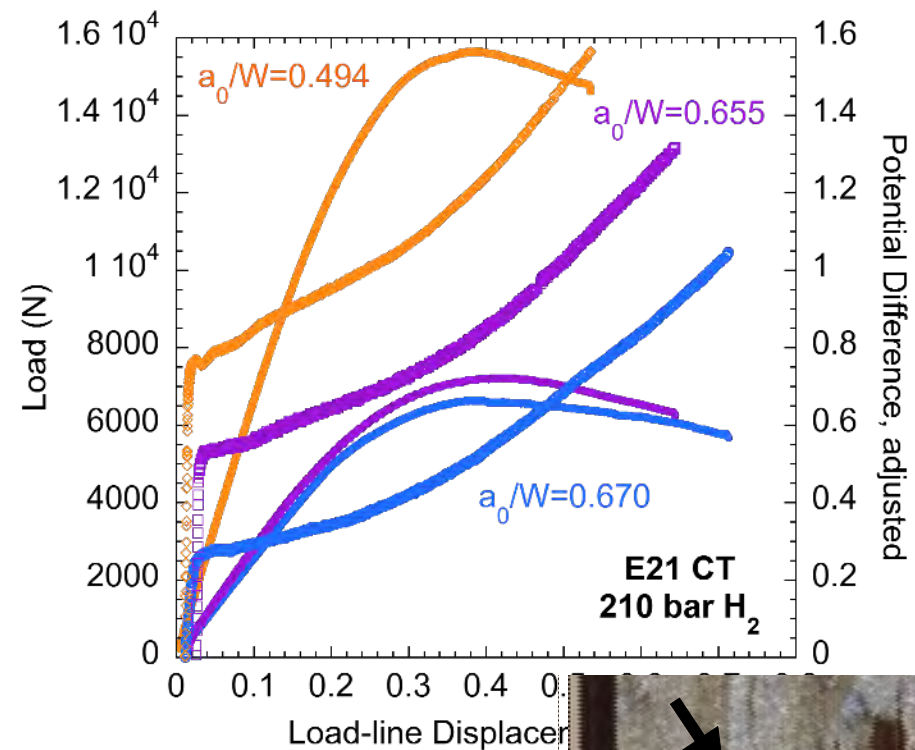
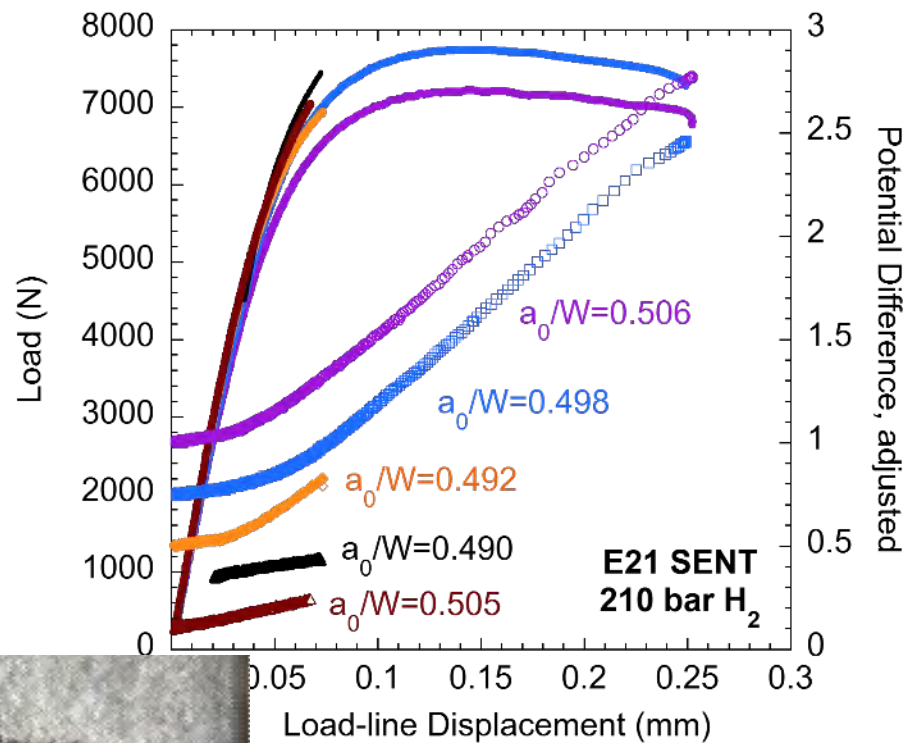




Monday Discussion

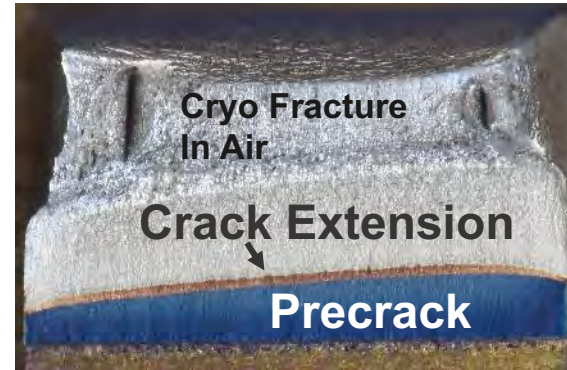
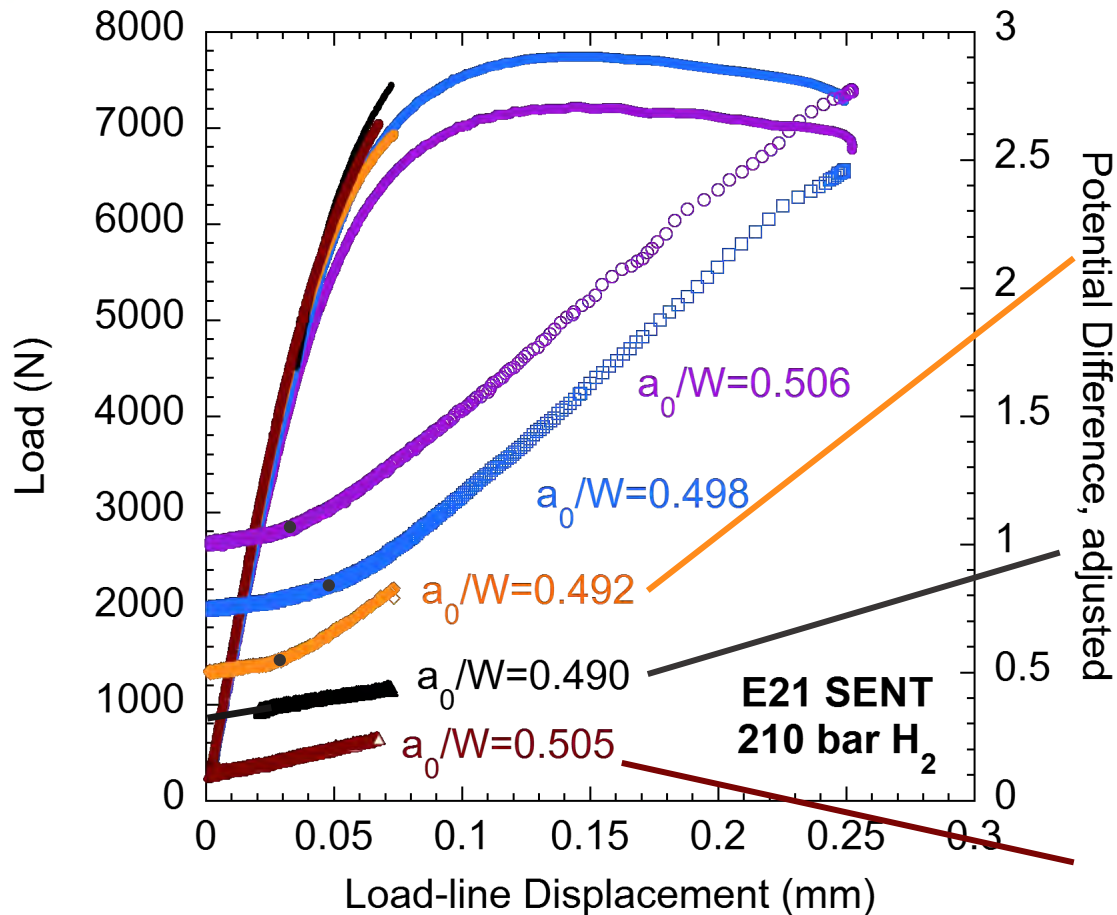
Why does SENT exhibit lower fracture initiation than CT?

-More splitting in CT vs. SENT would reduce triaxiality, leading to higher initiation and more gradual DCPD curves in CT compared to the abrupt DCPD transition at initiation in SENT



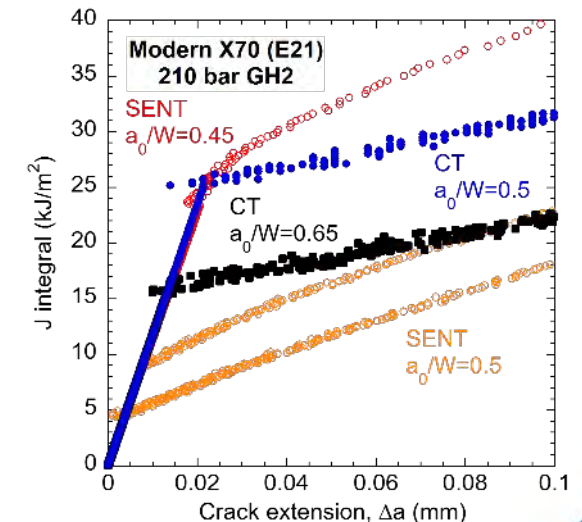


Crack Extension Behavior in Interrupted Tests was used to Verify Point of Initiation in SENT Specimens



Initiation was determined as the abrupt slope increase in potential difference for SENT specimens

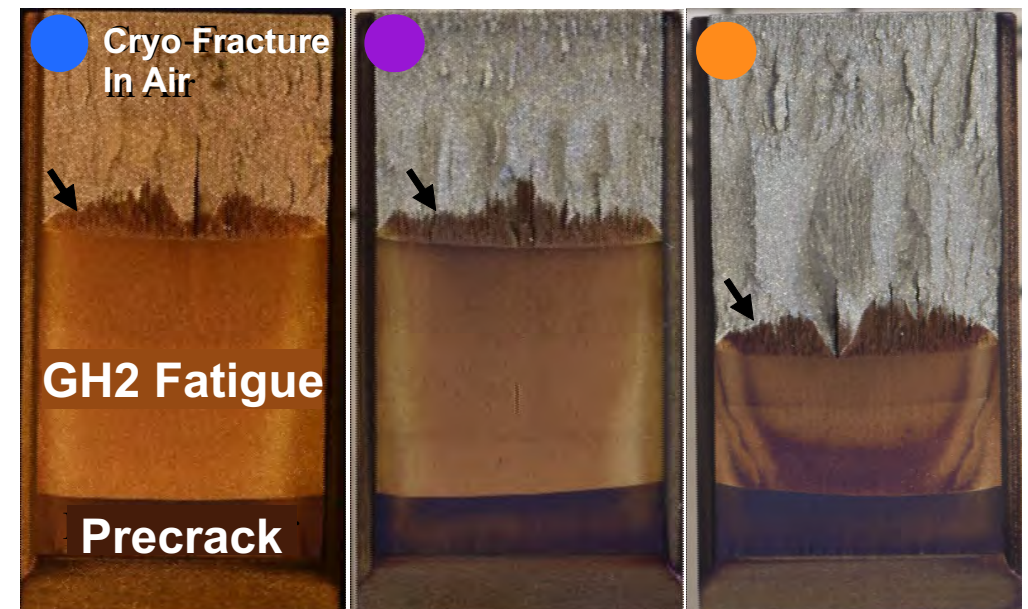
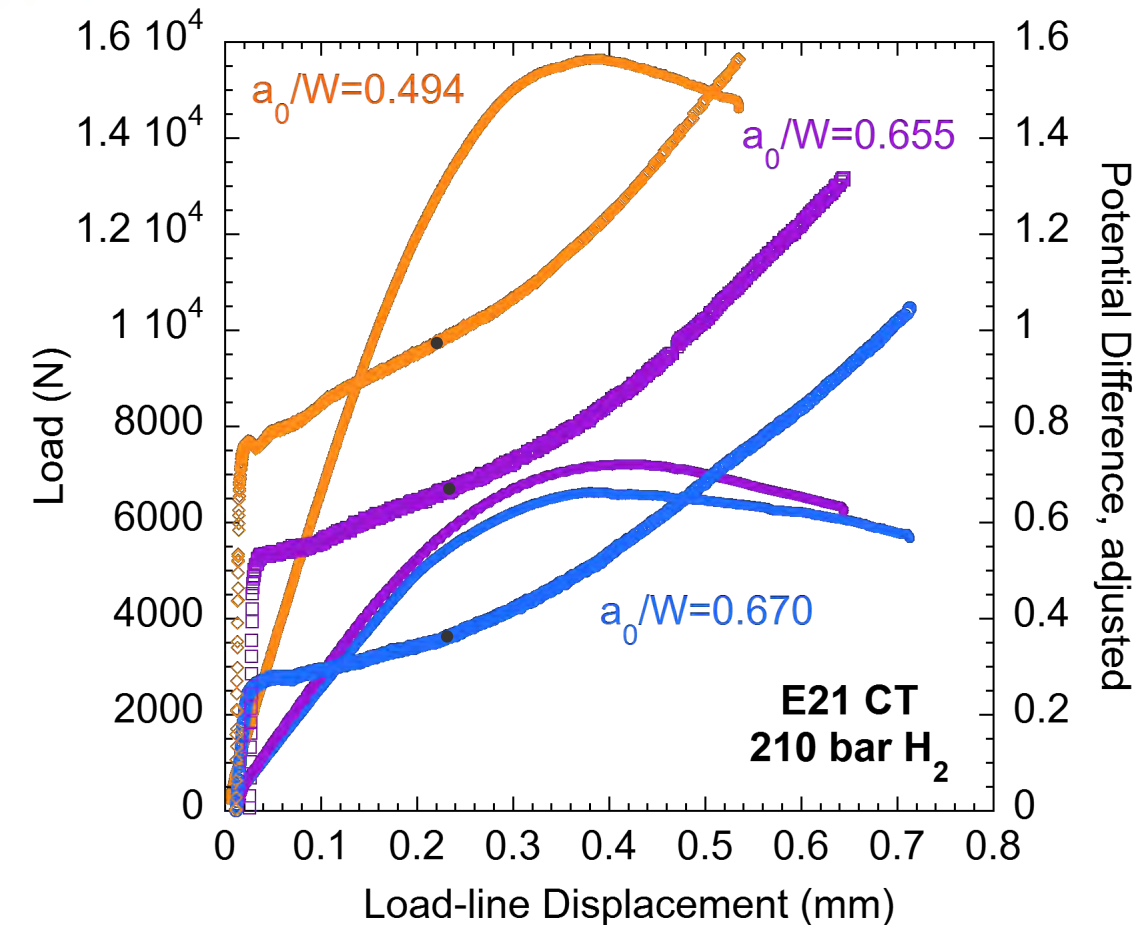
Load-line displacement at initiation does not scale clearly with initial crack length across the minor initial crack length differences



Initiation Identified in CT Specimens led to Higher J_{0-H} than in SENT

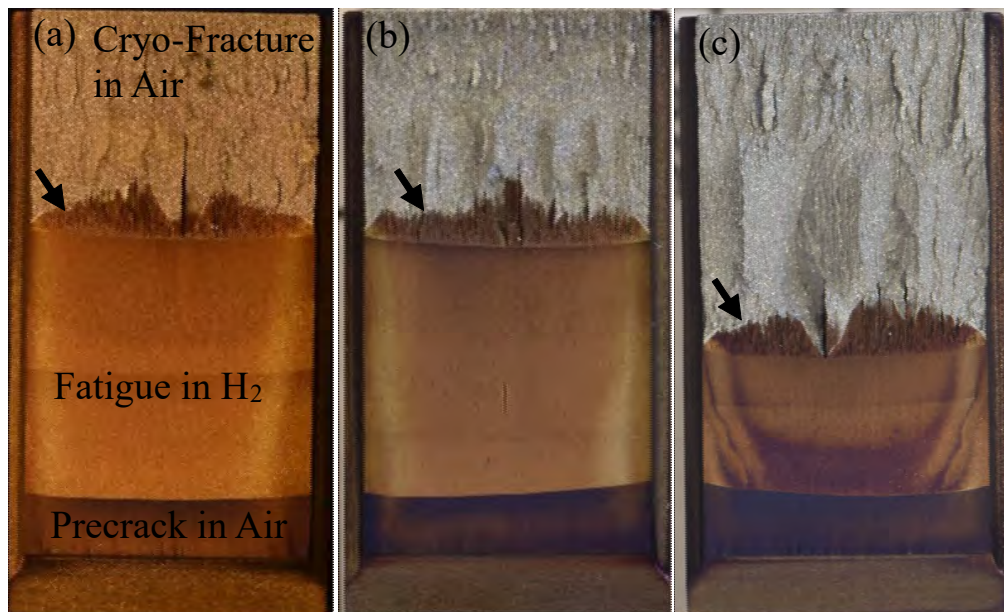
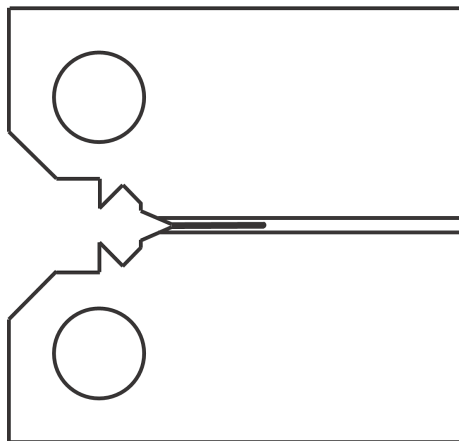
Initiation is defined with more gradual slope change in potential difference in CT specimens

As in SENT, initial crack length did not have a strong effect on load-line displacement at initiation

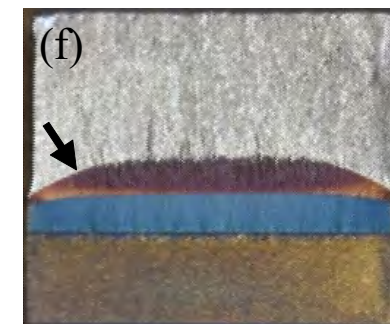
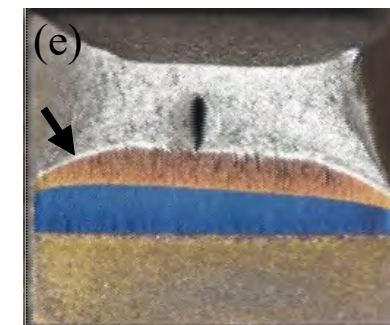
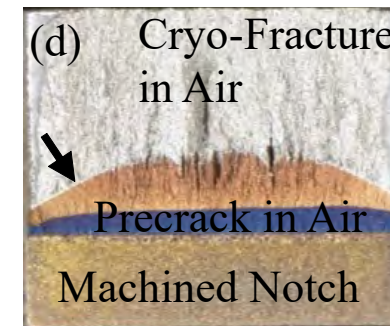
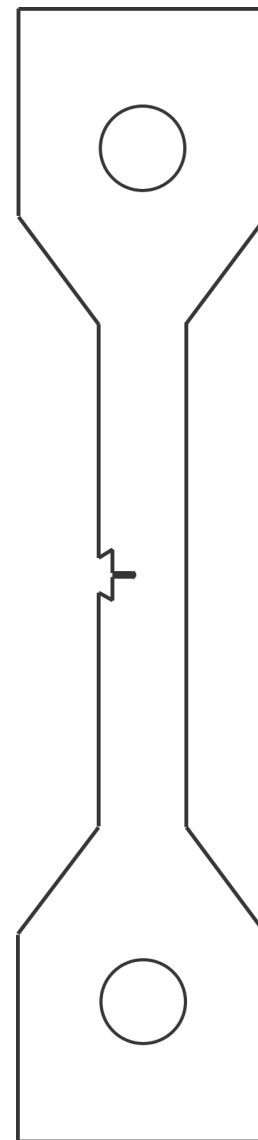




CT

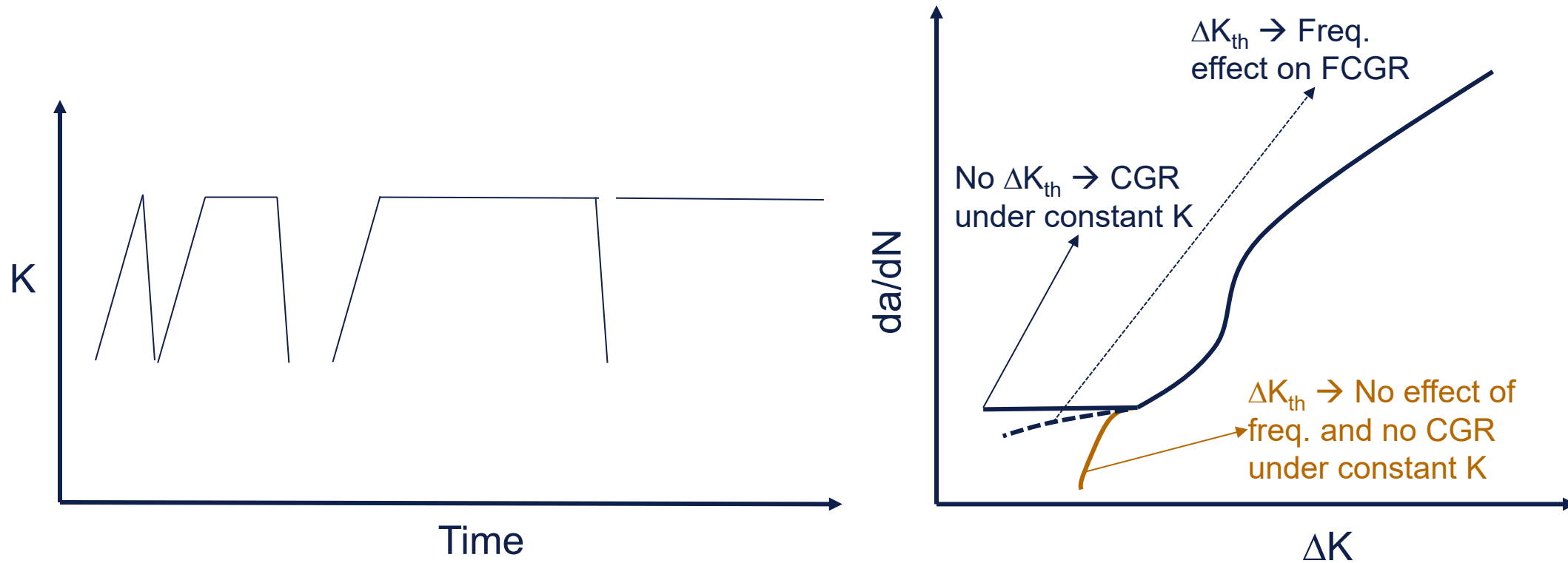


SENT



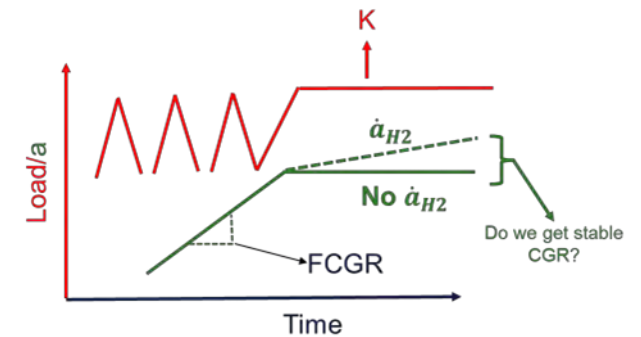
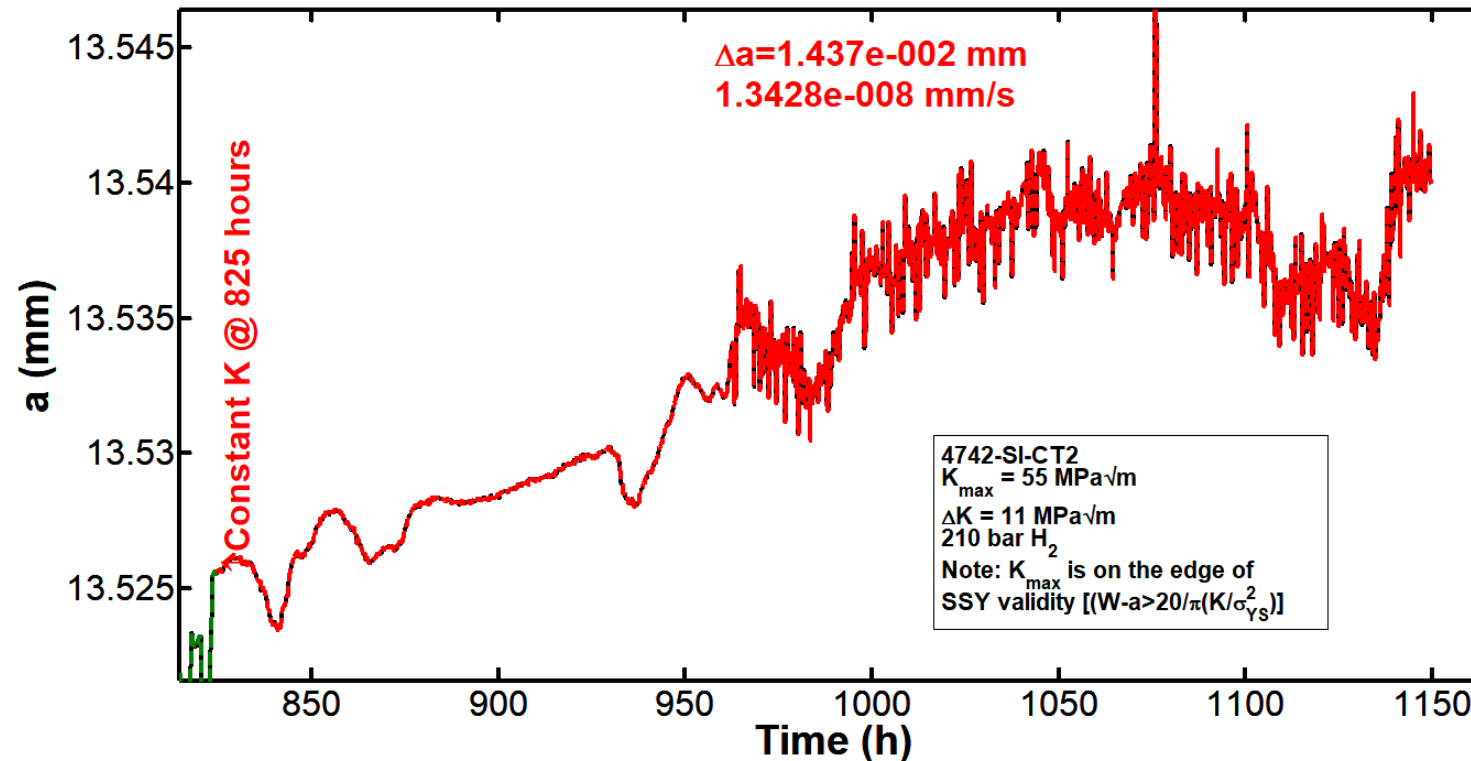
Summary Constant Load/Constant K Behavior in H₂

Constant K Tests



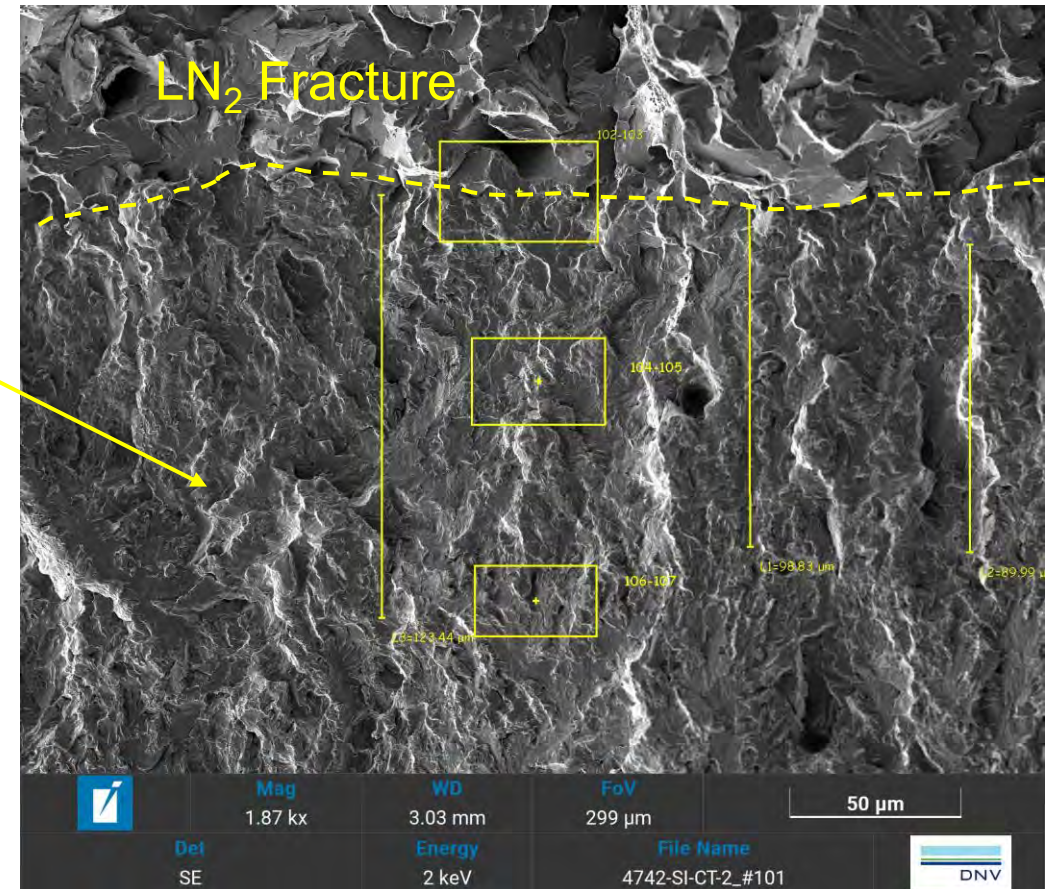
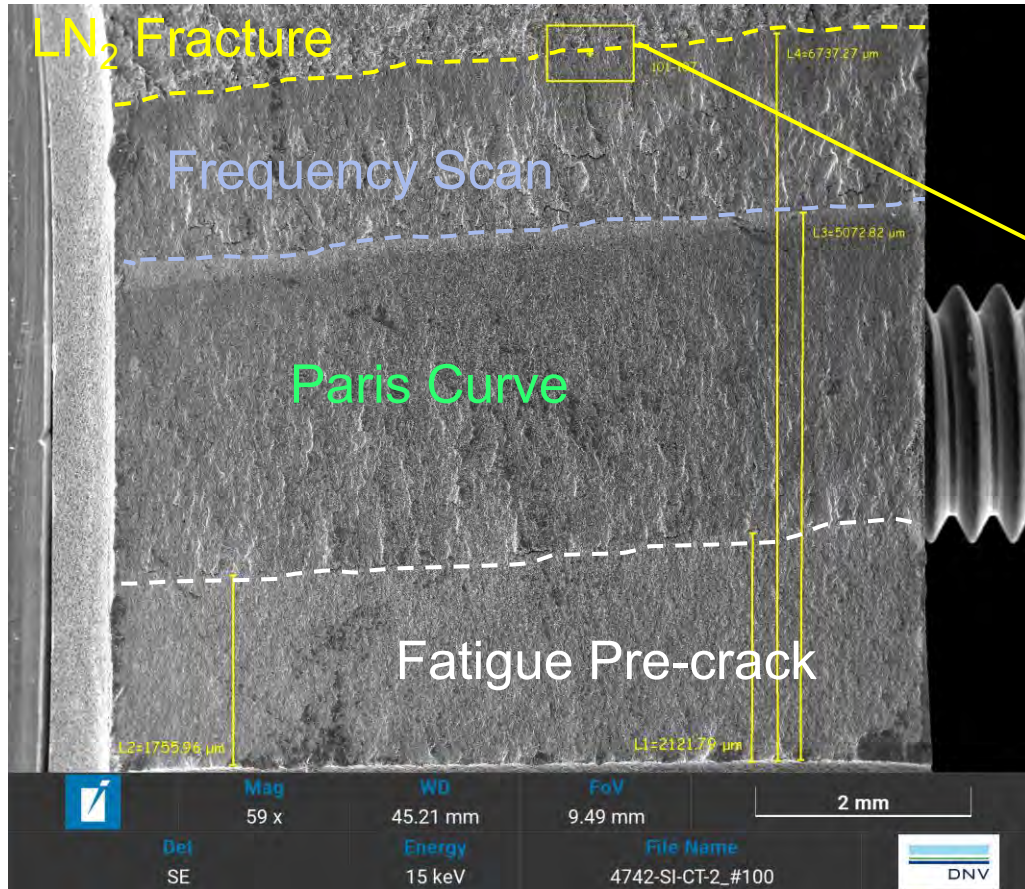
- Influence of various variables on CGR under constant K conditions
 - Impact of cycling
 - Influence of K value

Constant K Behavior - 4742 (Modern Seamless Pipe - X65)



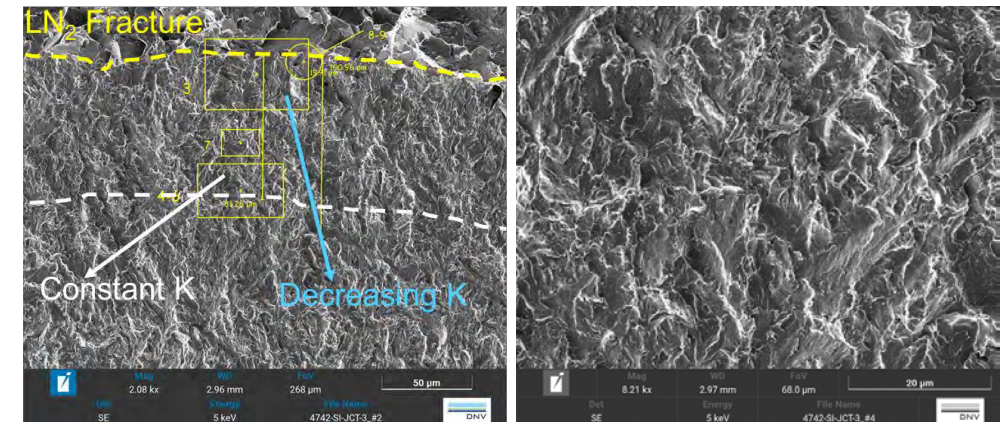
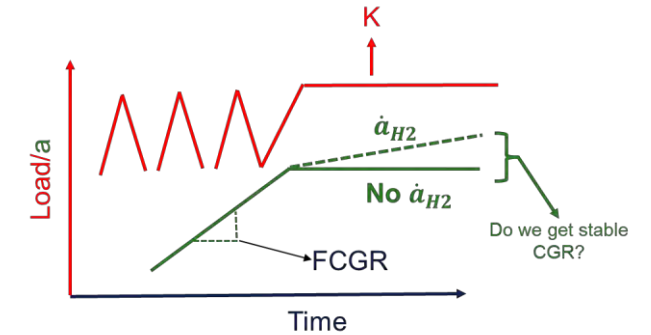
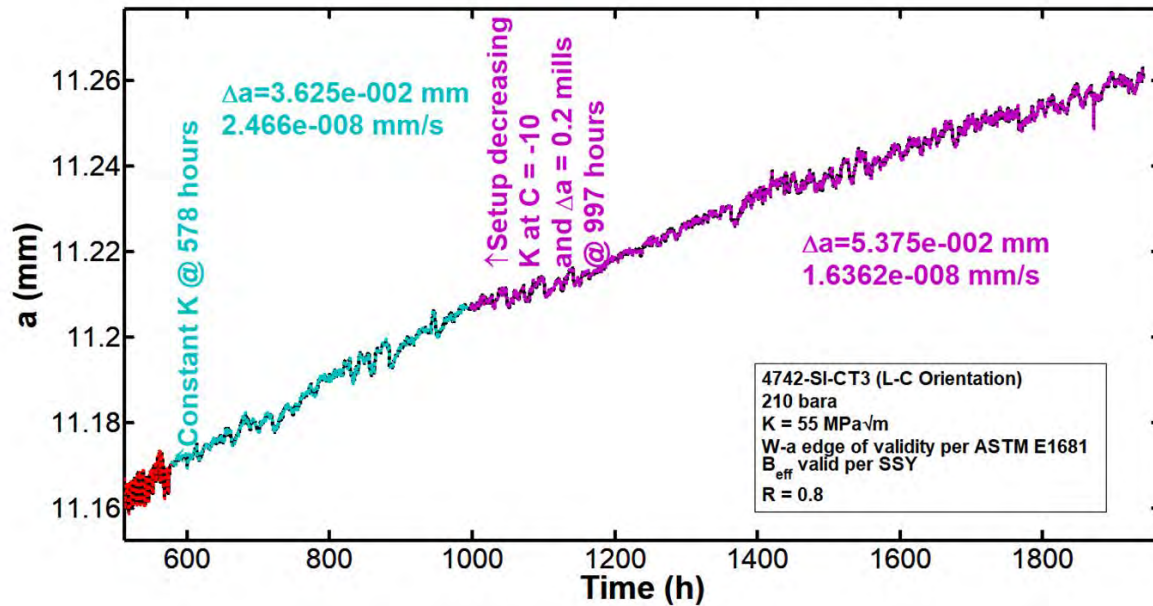
- Steady SCGR observed at a constant K of $55 \text{ MPa}\sqrt{\text{m}}$ → SCGR confirmed in SEM observations

SEM on 4742-CT2



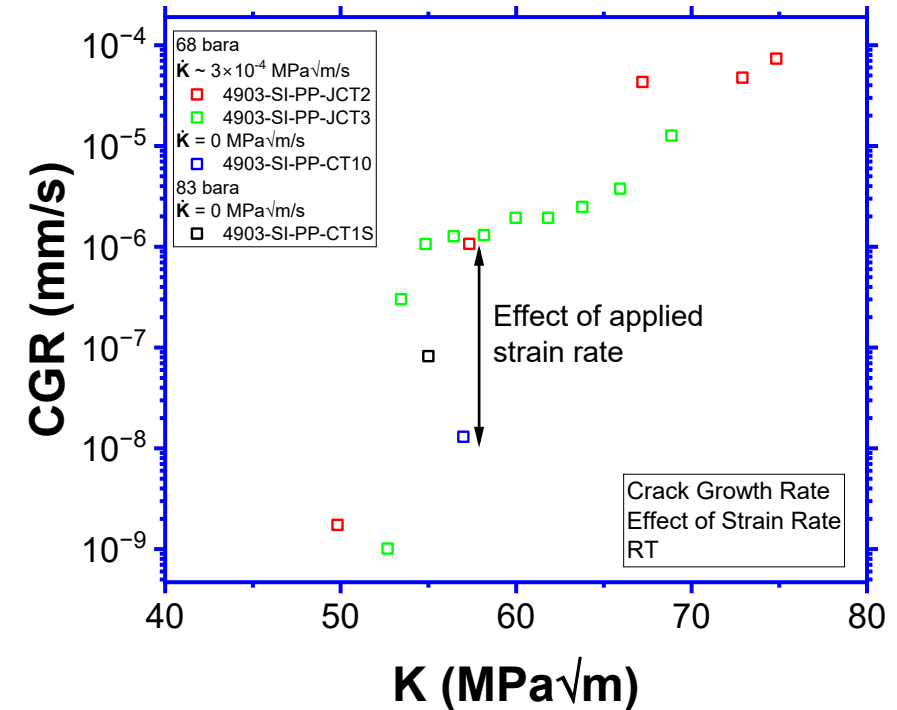
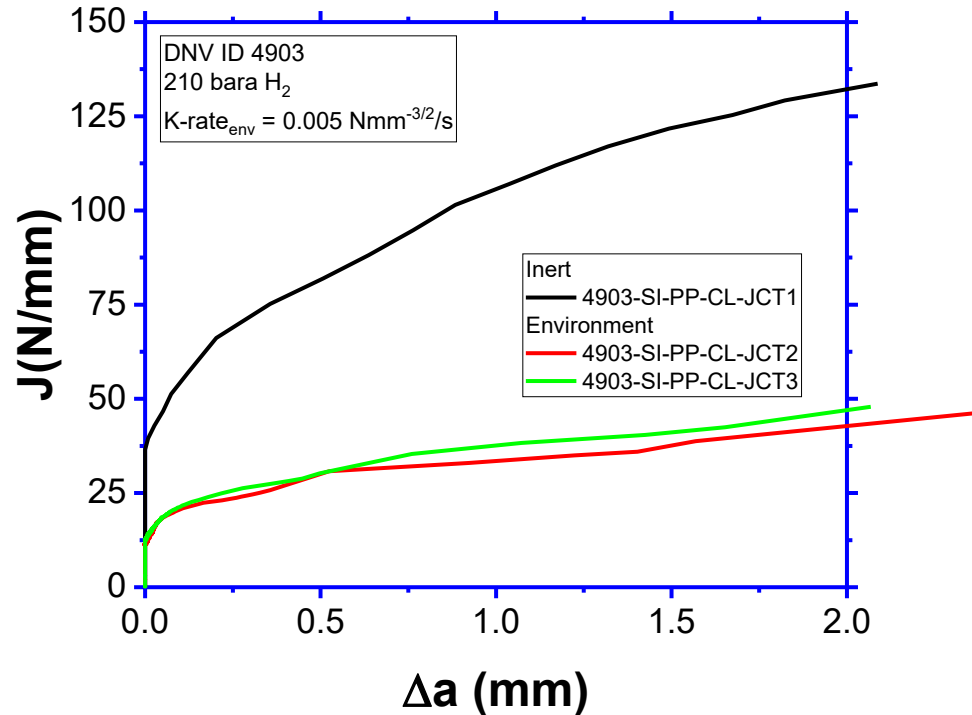
- SEM observations exhibits evidence of quasi cleavage as well as some IGC

Cycle + Hold $\rightarrow$ 4742 (Modern Seamless Pipe - X65)



- In modern seamless pipe $\rightarrow$ clear evidence of crack growth under constant K conditions after cycling.
- Crack growth appears to be stable even under decreasing K conditions

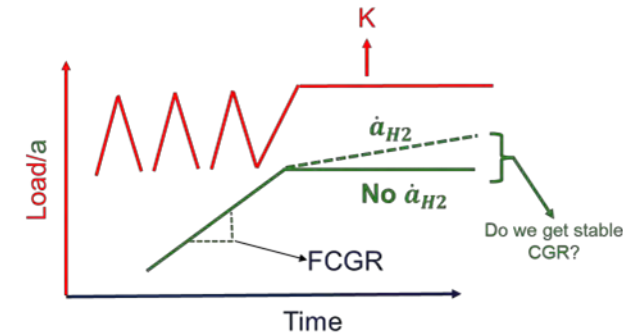
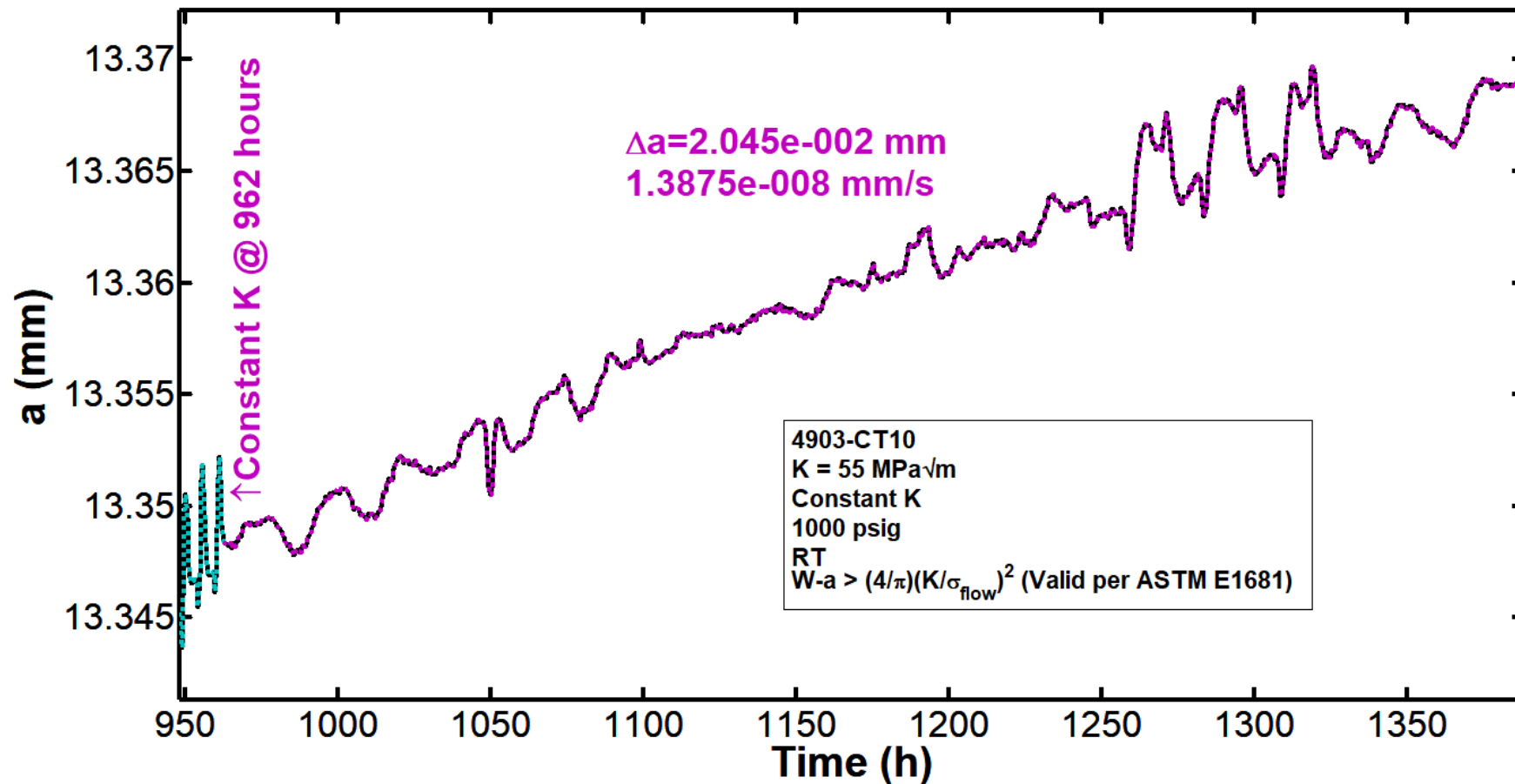
Fracture Toughness → 4903 (Vint. TMCP – X52)



Sample ID	Relationship	Notch Location	Orientation	p _{H2} (bara)	K-rate (MPa√m/h)	J _{th} (N/mm)	J _{0.05mm} (N/mm)	J _{0.2mm} (N/mm)	J _{1mm} (N/mm)	J _{maxload} (N/mm)	K _{th} (MPa√m)	K _{th0.05mm} (MPa√m)	K _{th0.2mm} (MPa√m)	K _{th1mm} (MPa√m)	K _{thmaxload} (MPa√m)
4903-SI-JCT-1		Parent Pipe	C-L	NA	3.64	36.53	46.68	66.16	105.61	46.68	91.63	103.58	123.31	155.80	103.58
4903-SI-JCT-2		Parent Pipe	C-L	68.49	0.46	11.11	18.49	23.05	33.52	19.36	50.52	65.19	72.78	87.77	66.70
4903-SI-JCT-3		Parent Pipe	C-L	68.49	0.57	12.44	18.67	24.91	37.05	21.37	53.47	65.51	75.66	92.28	70.08
4903- Average		Parent Pipe	C-L	68.49		11.77	18.58	23.98	35.29	20.37	52.02	65.35	74.24	90.05	68.41

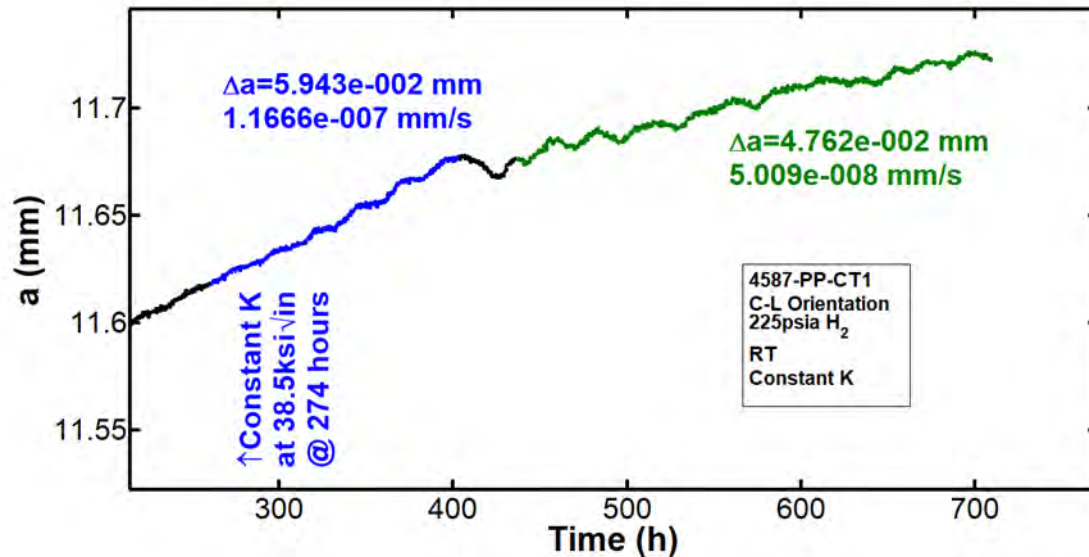
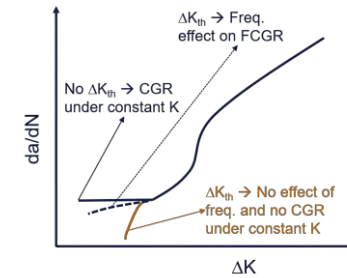
- Fracture toughness in 68 bara H₂ is about 50 MPa√m. The slope of the R-curve is shallow.
- Currently a ramp and hold test is in progress → Ramping at decreasing rates → At constant load

Constant K Behavior → 4903 (Vint. TMCP – X60)

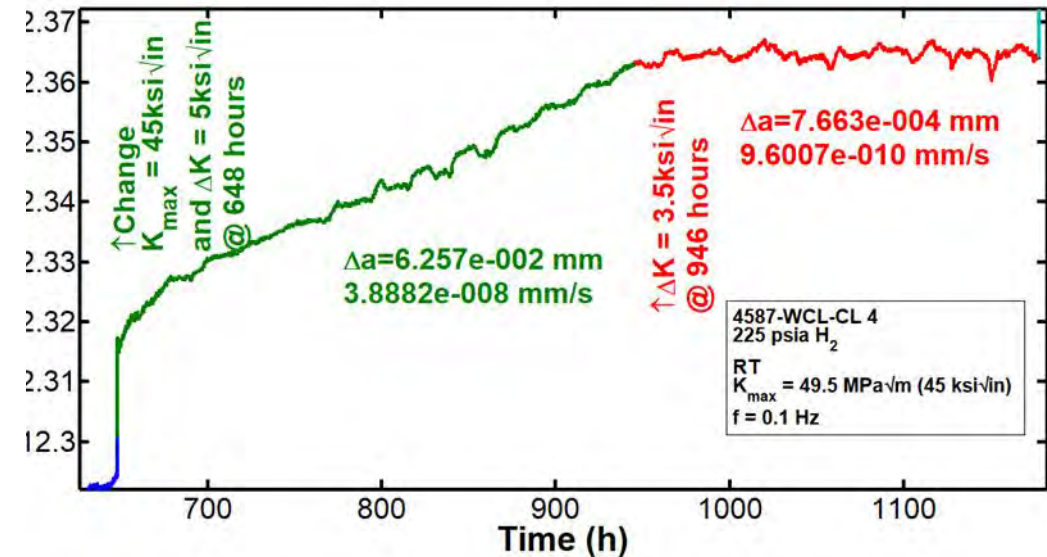


- Stable SCGR of $1.4 \times 10^{-8} \text{ mm/s}$ at 55 MPa√m.

Vintage X60



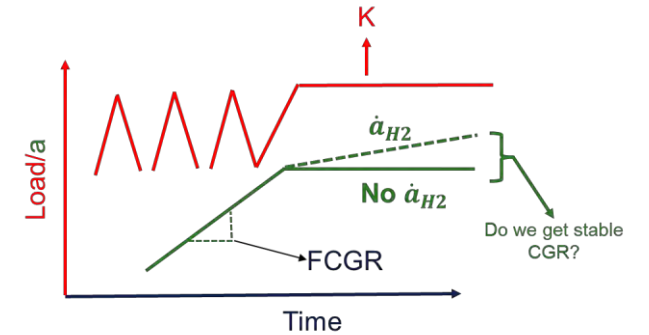
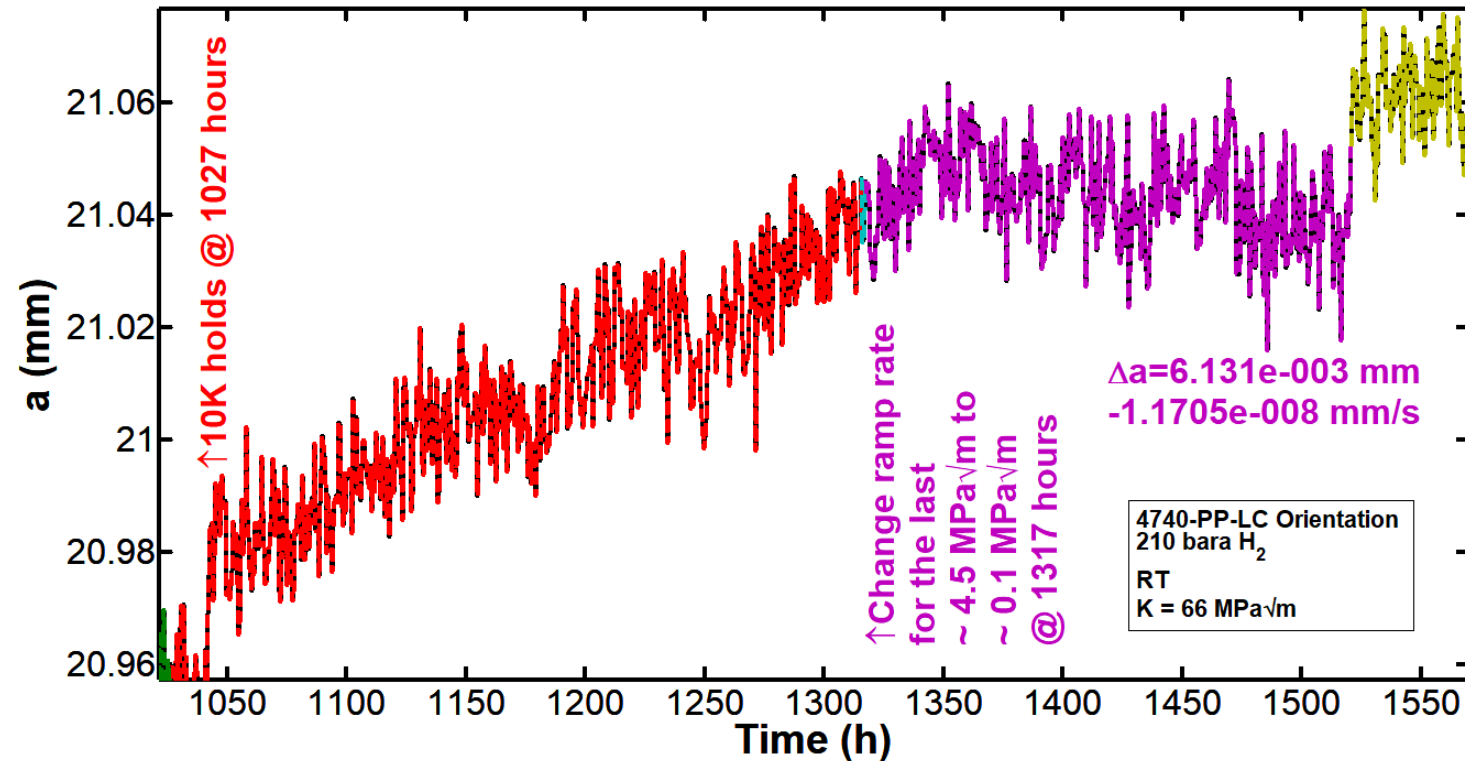
PP



WCL

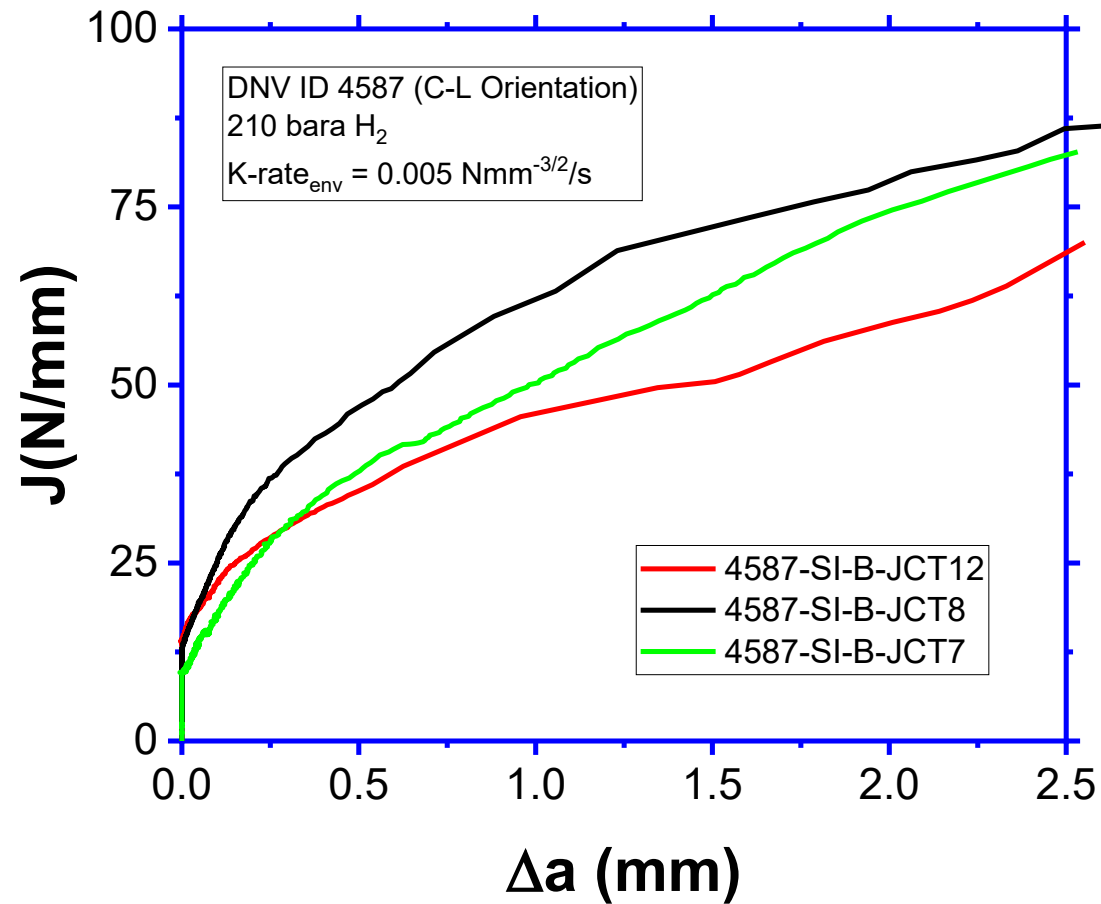
- Transitioning from low ΔK to constant K stabilized SCGR in the PP.
- However when transitioning in the WCL no stable CGR was possible under low ΔK conditions even at high values of K_{max} .

Cycle + Hold $\rightarrow$ 4740 (Modern Sour Service Pipe – X65)



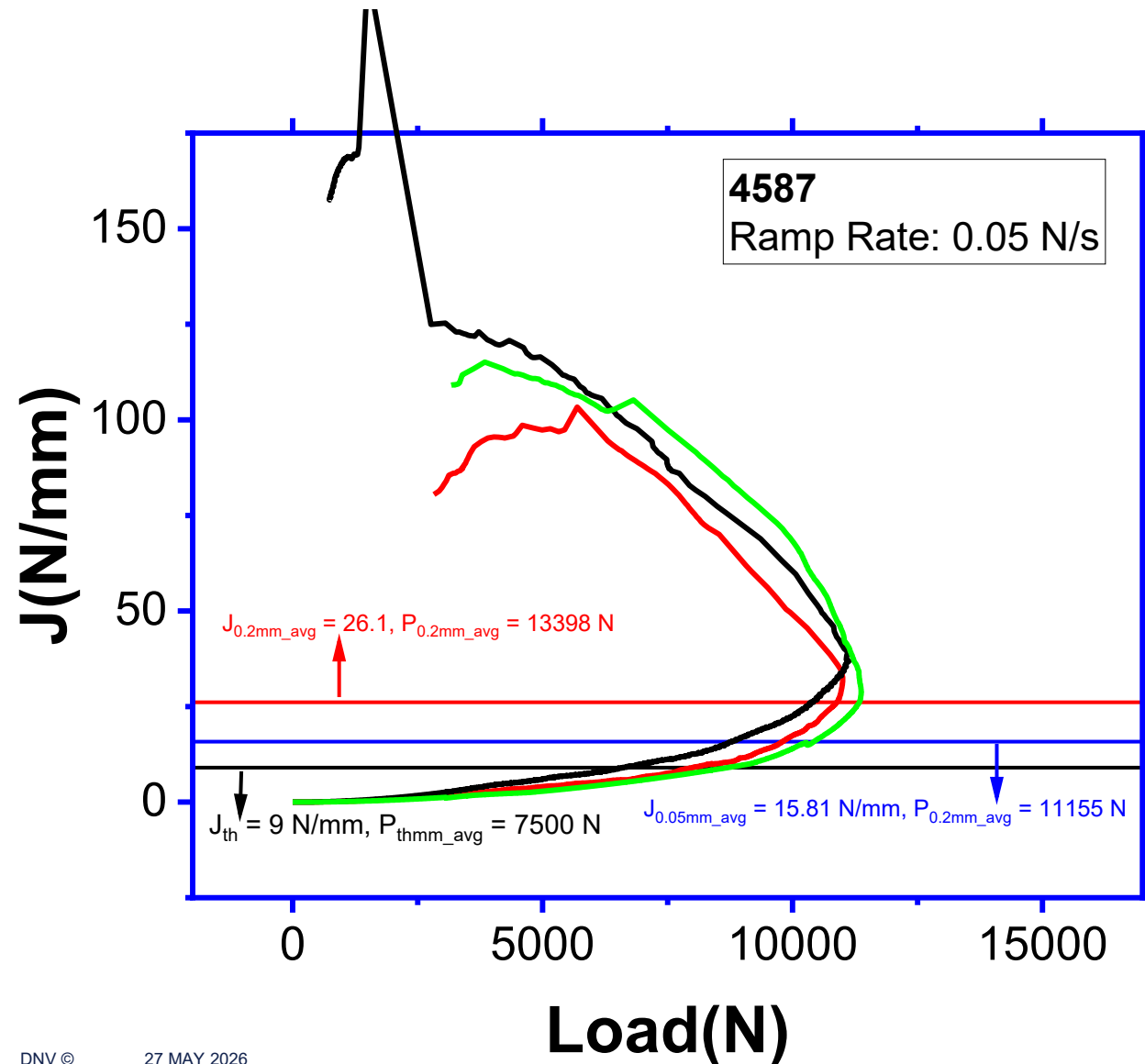
- No evidence of subcritical crack growth following cycling.

Background



- J-R curves in environment exhibit significantly lower than in-air and also exhibit shallower slope.
- **Critical question → At value of J/conditions do cracks propagate?**

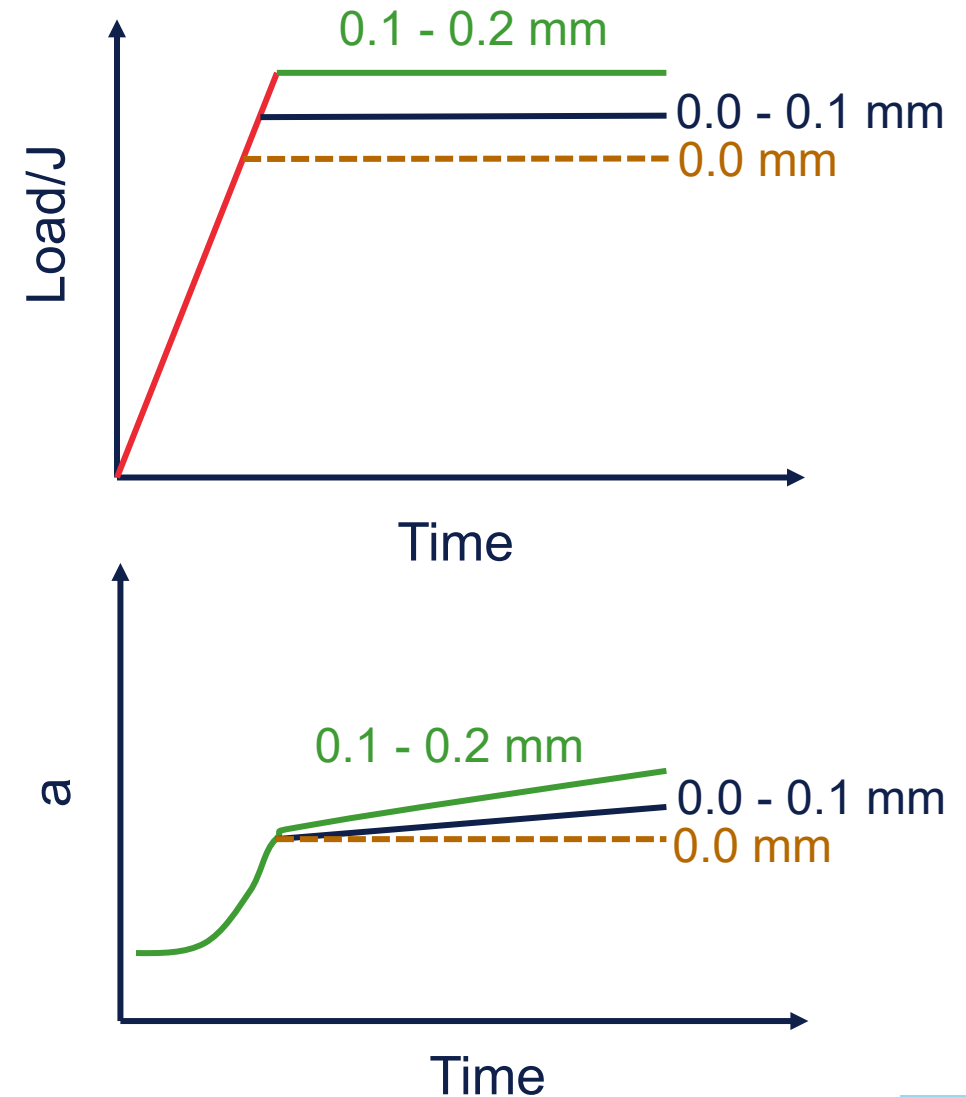
Constant Load Tests



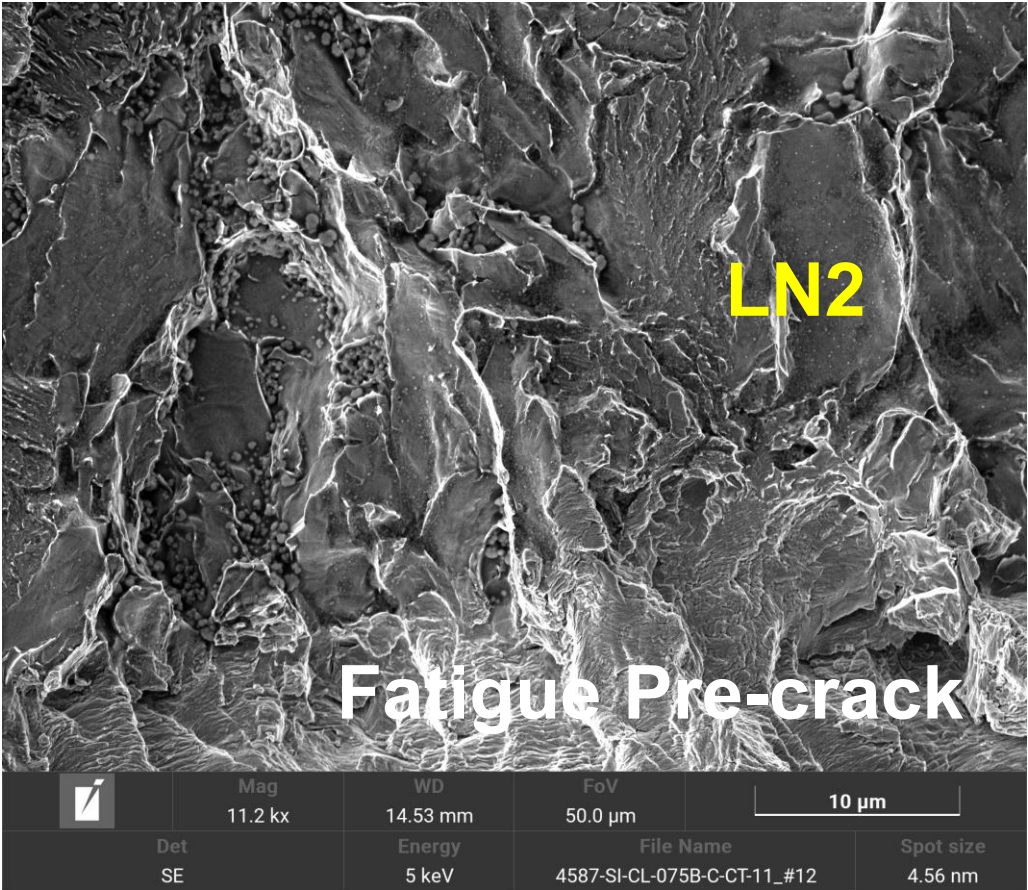
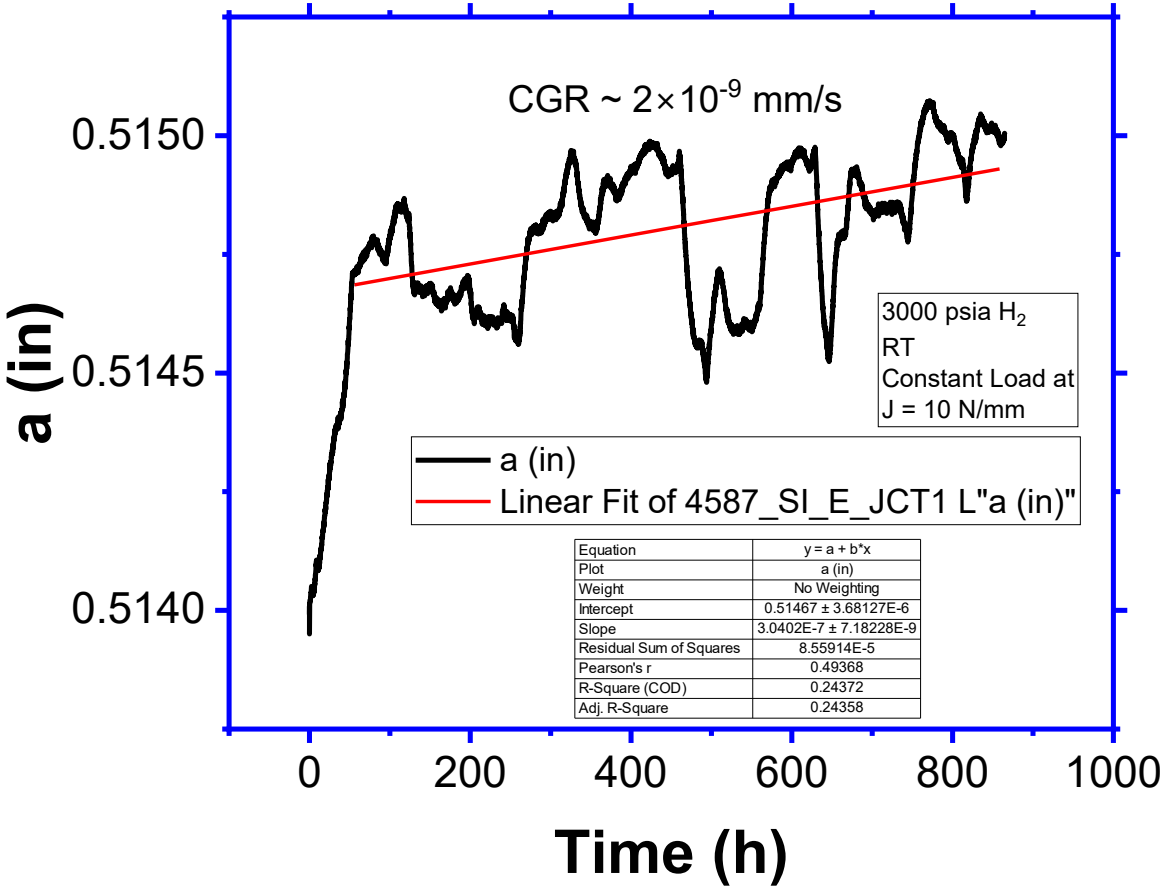
- Constant Load tests performed at values near J_{th} and $J_{0.05\text{mm}}$.
- Tests performed under rising load conditions to target certain crack extension, following which load was held constant.

Constant Load Tests

- Influence of various variables on constant load tests were explored
 - Material Type → Modern vs Vintage
 - Applied value of J
 - Influence of crack extension
 - Remaining ligament
 - Sample geometry
- Crack extension measured for ~ 30 days.

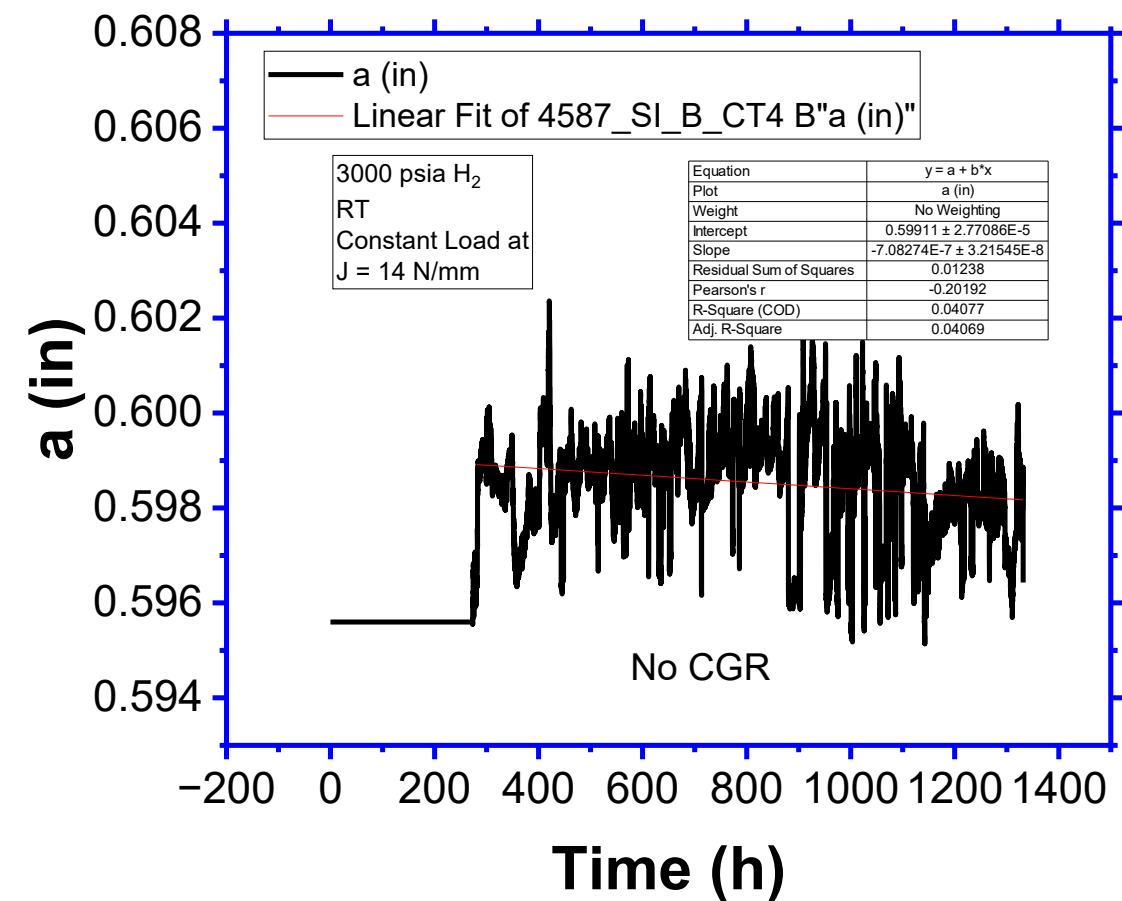


Constant Load – 4587 → N₂



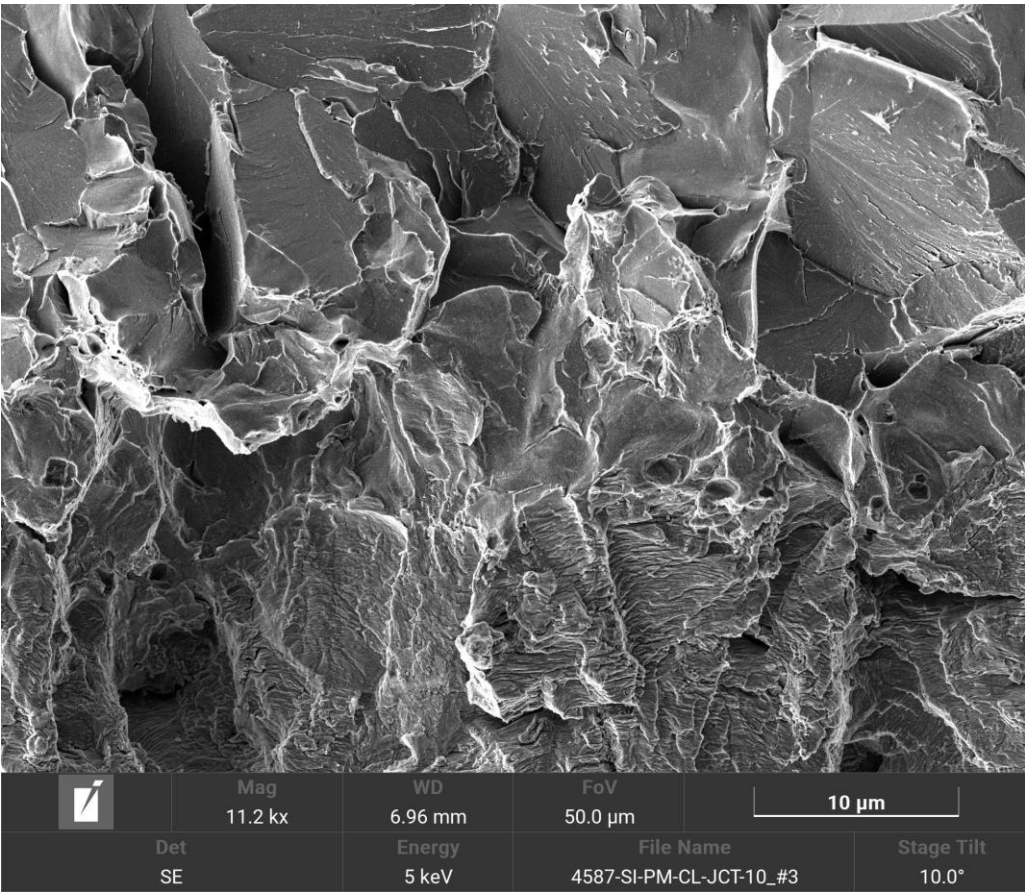
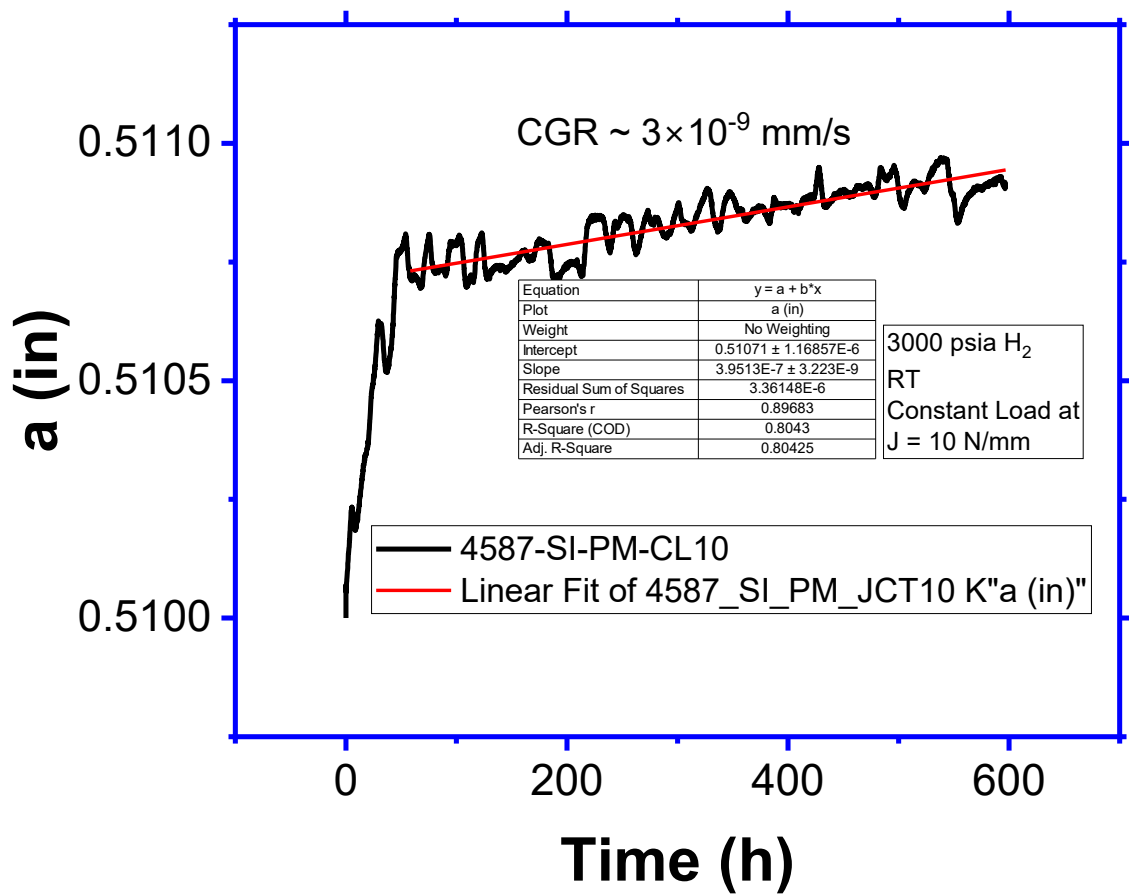
• Effect of creep rate in N₂ → 2×10^{-9} mm/s

Constant Load $\rightarrow$ 4587 in H_2



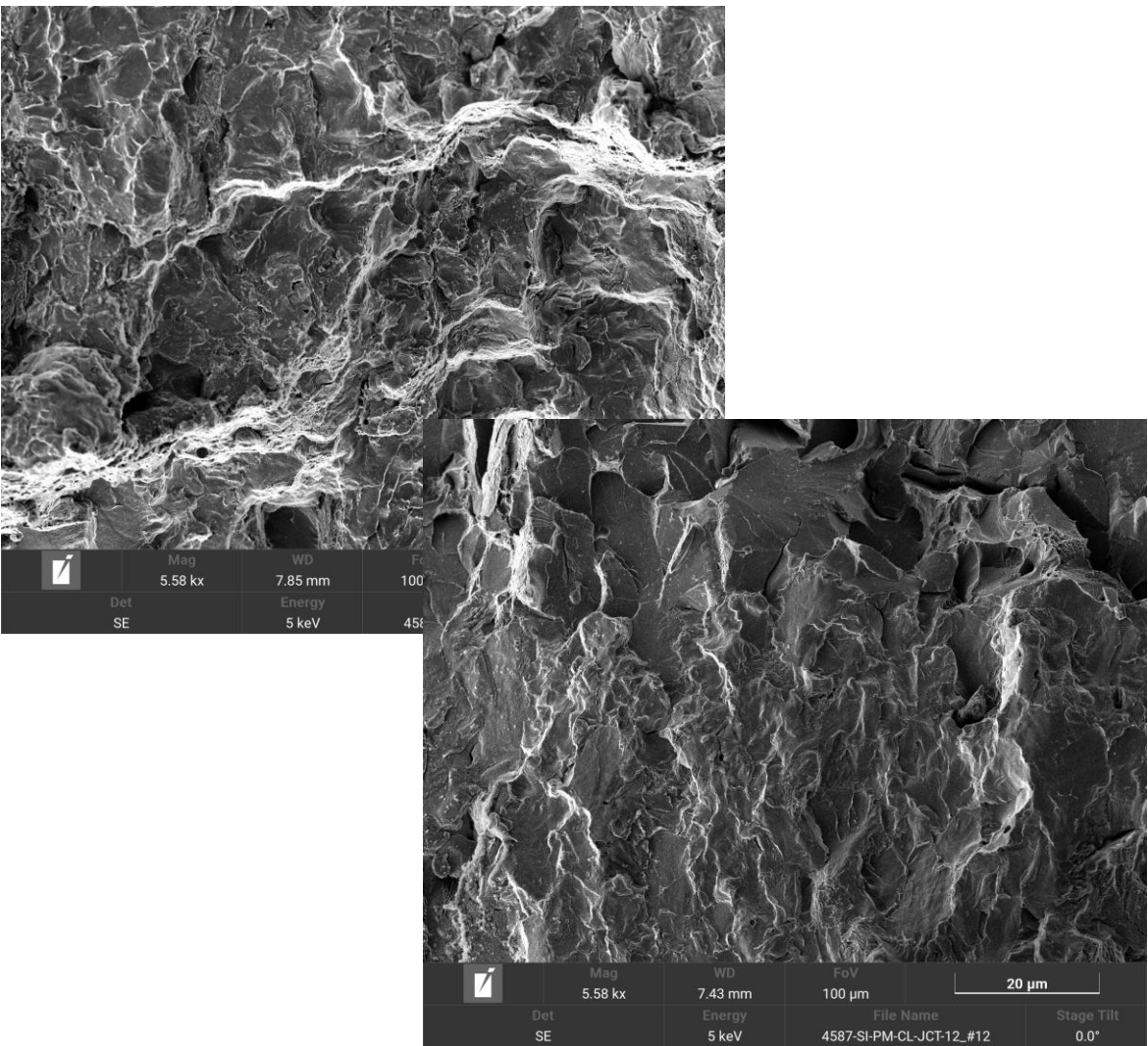
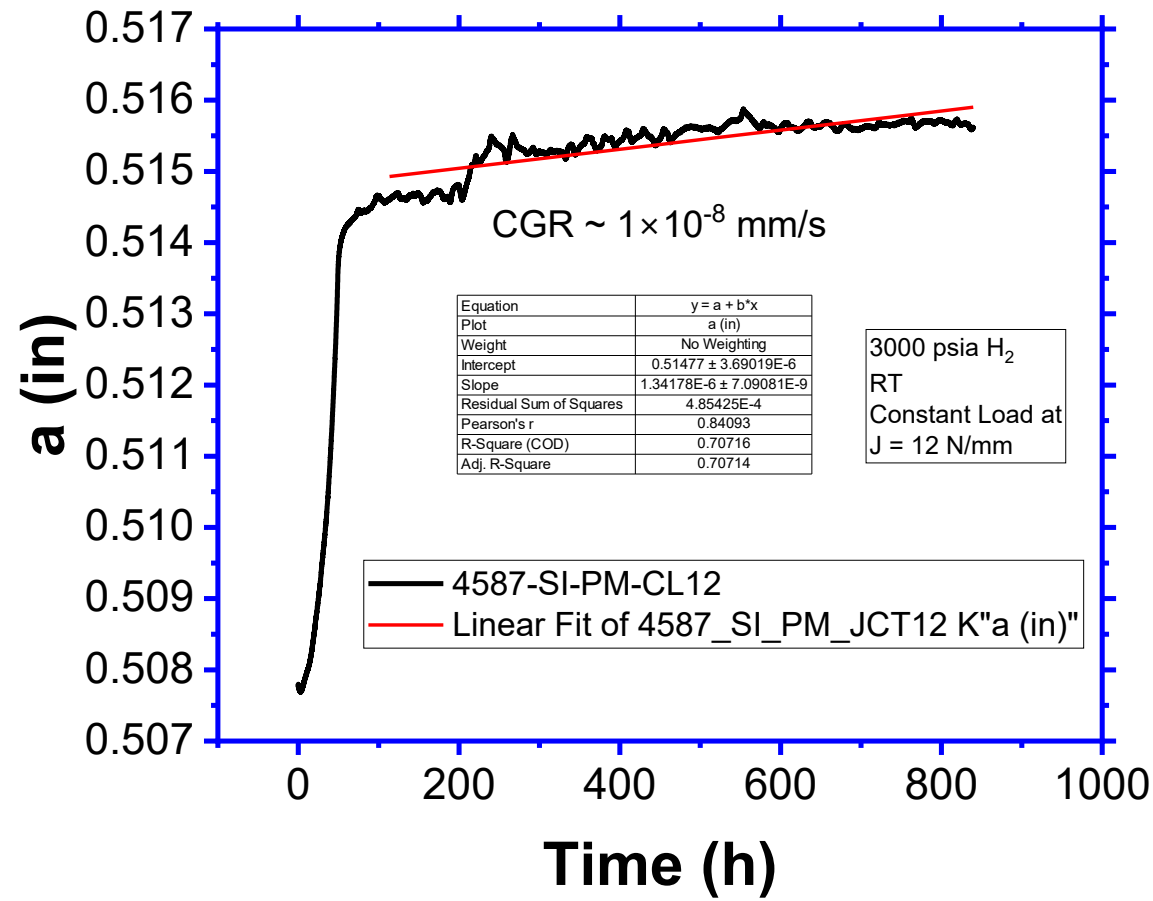
- No evidence of CGR when no crack extension was observed i.e. values of J below J_{th}

Constant Load → 4587 in H₂

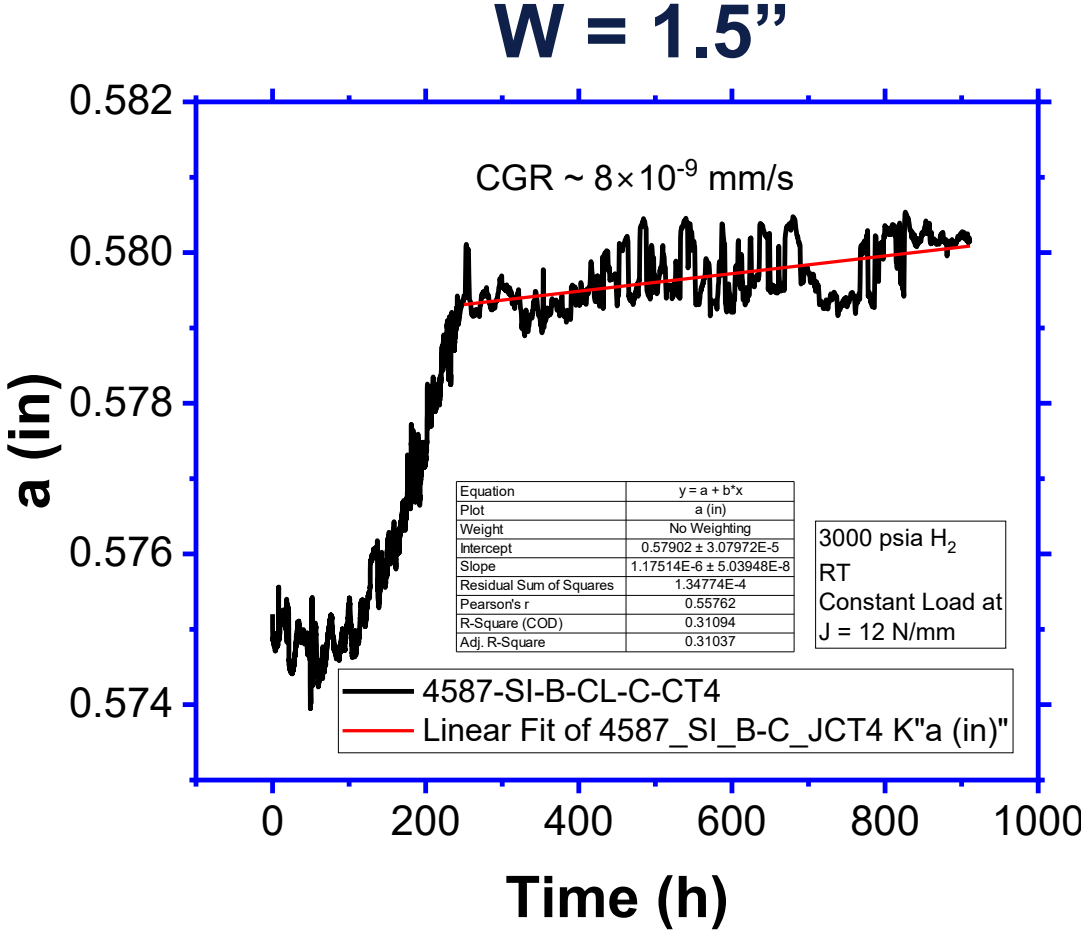
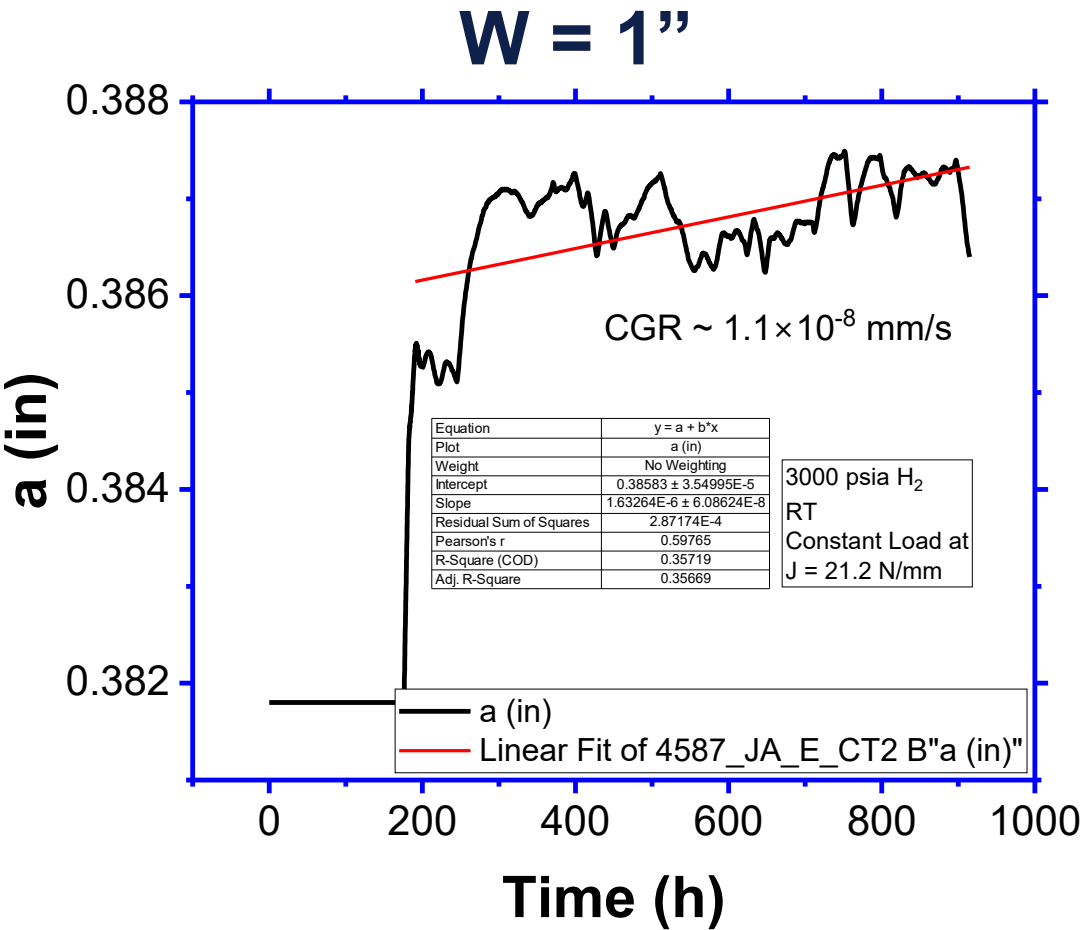


- Pockets of crack extension observed.

Constant Load – 4587 in H₂

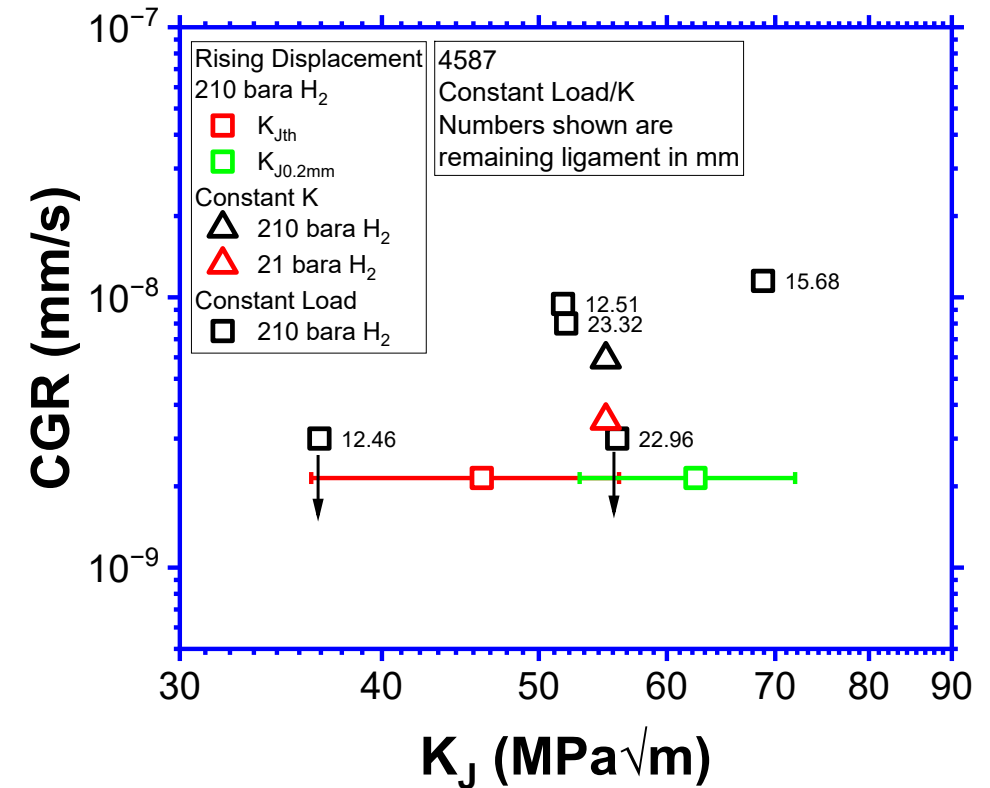
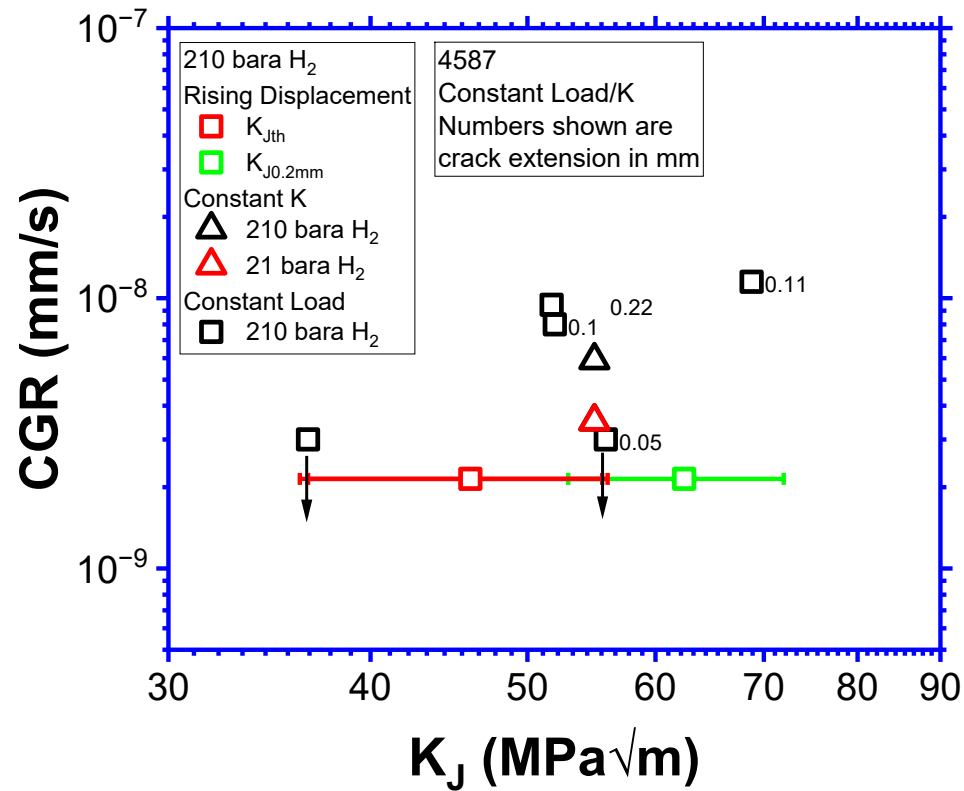


Constant Load – 4587 in H₂ → Shallower a/W



- Shallower a/W of 0.35 to 0.4 also appears to exhibit evidence of slow CGR

Summary → Constant Load Tests



- Steady CGR observed at K_I values after 0.1 to 0.2 mm of crack extension.
- Does not appear to be dependent on remaining ligament length in the range of 12 to 23 mm

Summary → Constant Load

- Slow CGR observed in constant load tests → Values of CGR are above that of the pure N₂ case.
- Slow CGR on the vintage ferrite/pearlite observed at K/J values in the range of 50-60 MPa√m associated with crack extension values of ~ 0.1 mm.
- Slow CGR appears to be independent of the remaining ligament length.

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Environmental Effects

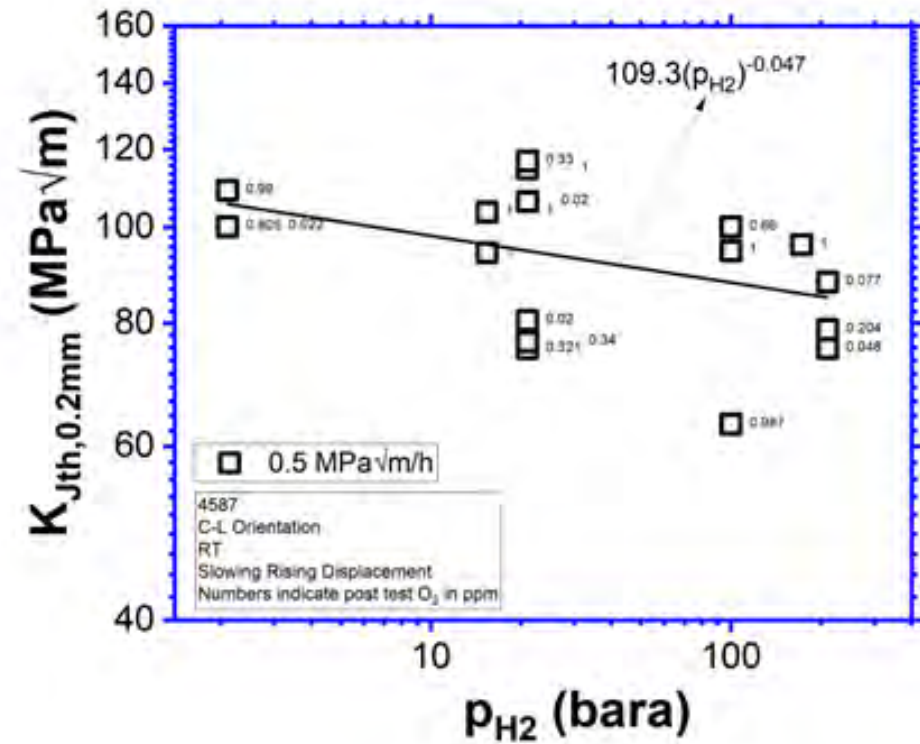
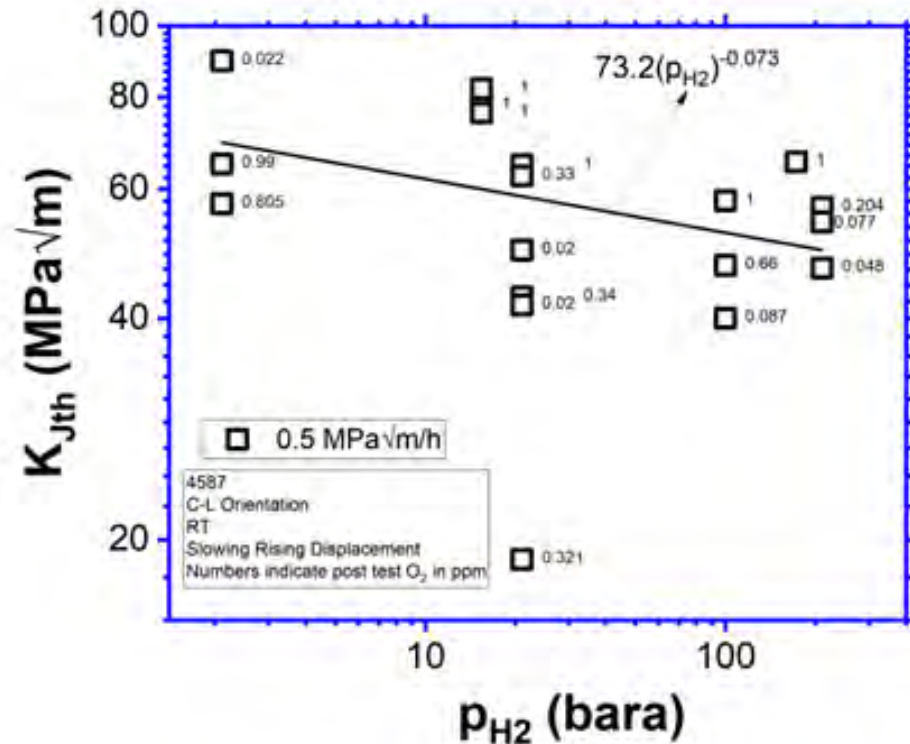
27 May 2026

Background

- Influence of p_{H_2}
 - Relevant for blending/low p_{H_2} in CO_2 lines.
- Influence of O_2 content
 - Impact of 1 ppm vs 0.1 ppm O_2 content on the fracture toughness behavior → Relevant to ANSI CSA/CHMC-1 requirements
- Influence of T
 - Relevant for subsea pipelines that may experience temperatures in the range of 4°C to 60°C
- Influence of K-rate

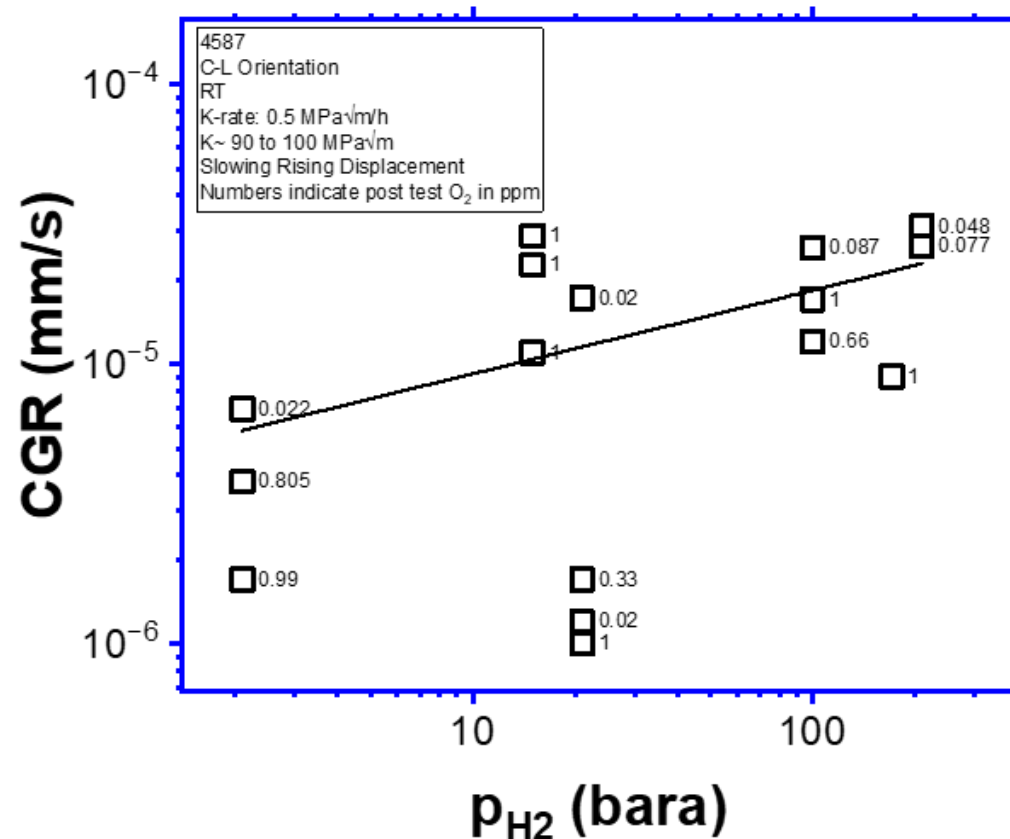
• What is the impact of these variables on various microstructures?

Influence of $p_{H_2} \rightarrow$ Vintage Pipeline Material



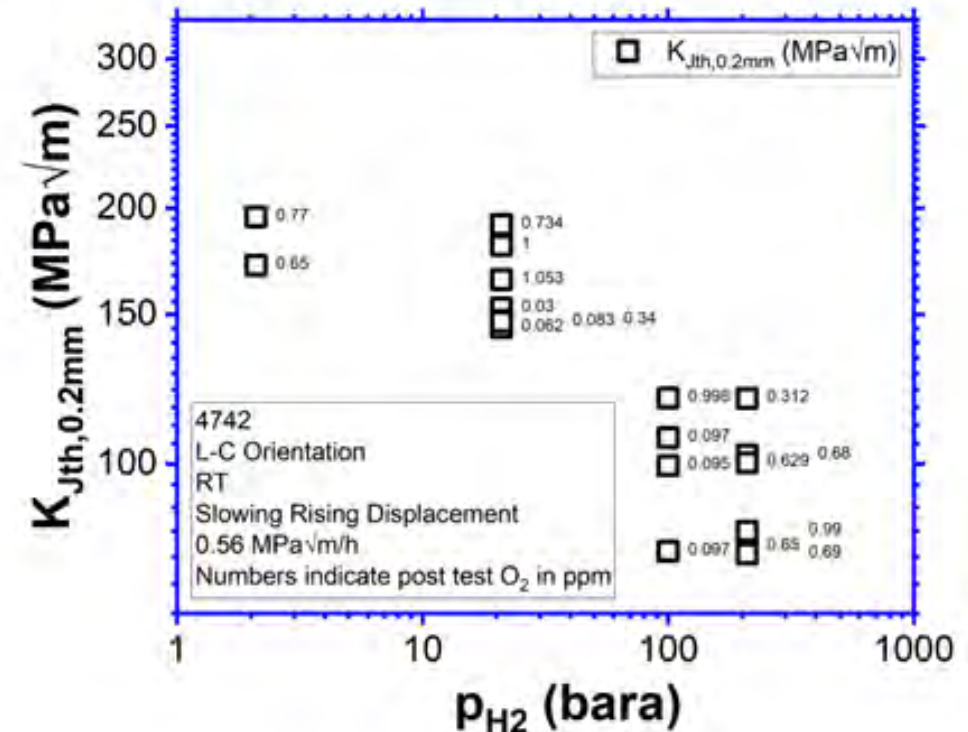
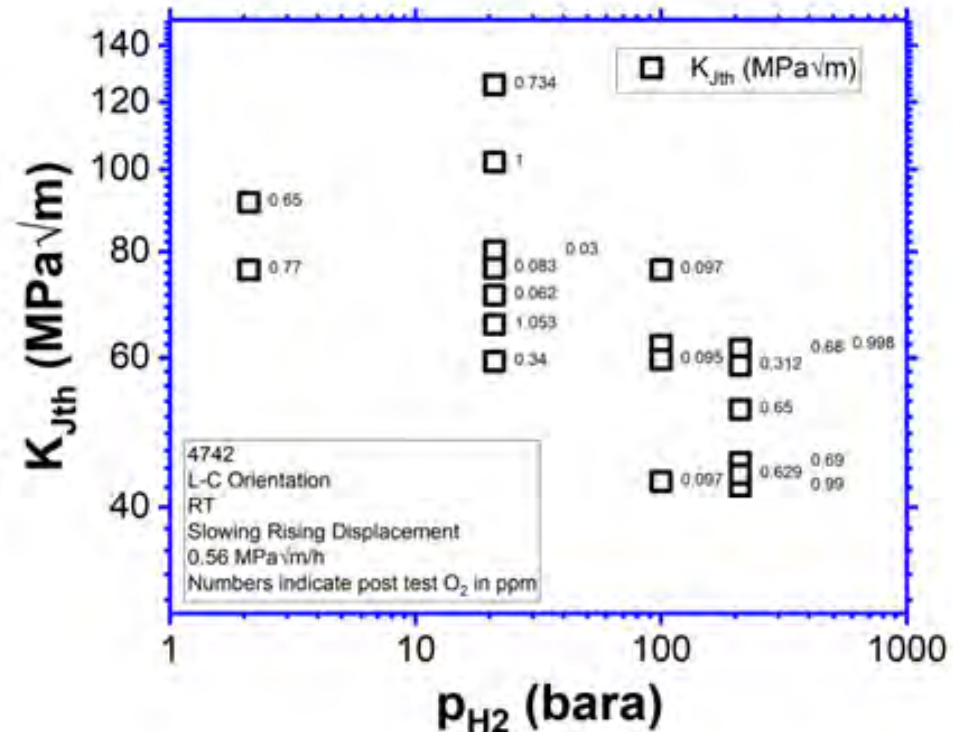
- Weak dependence of K_{Jth} and $K_{J0.2mm}$ on p_{H_2} for vintage ferrite/pearlite steel

Influence of p_{H_2} → Vintage Pipeline Material



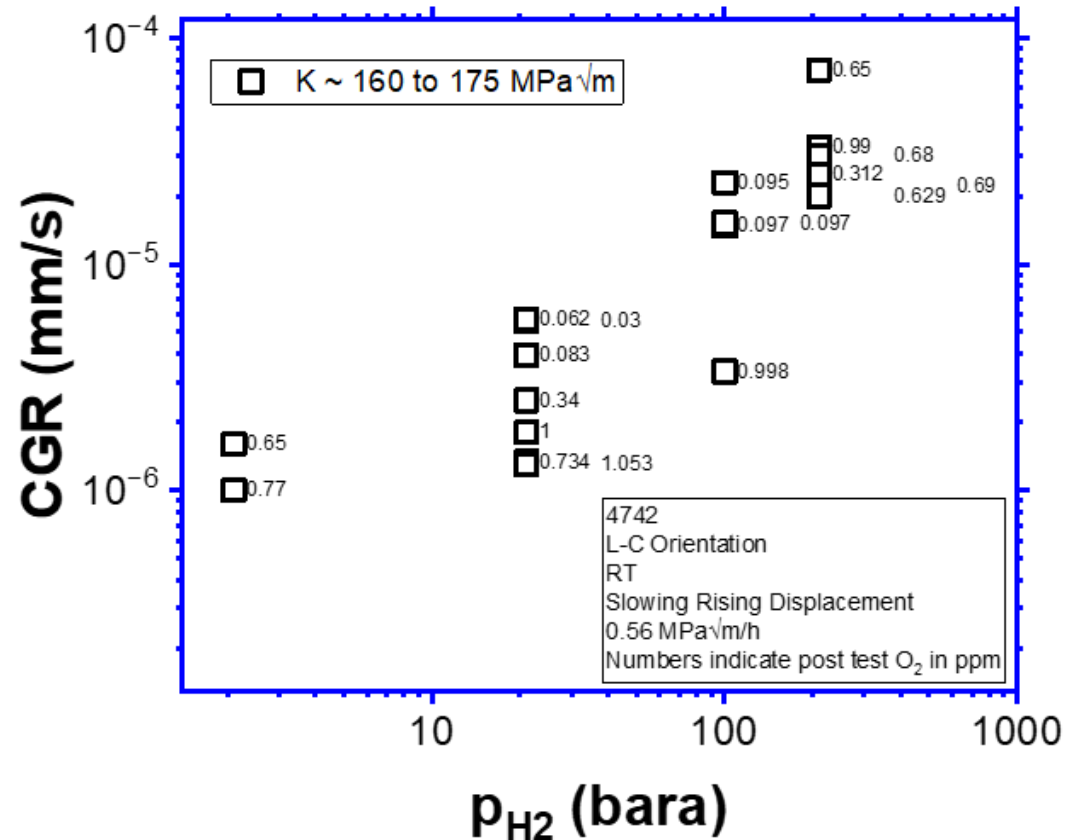
- CGR in the range of 90-100 MPa√m decreases with p_{H_2}

Influence of p_{H_2} → Seamless X65



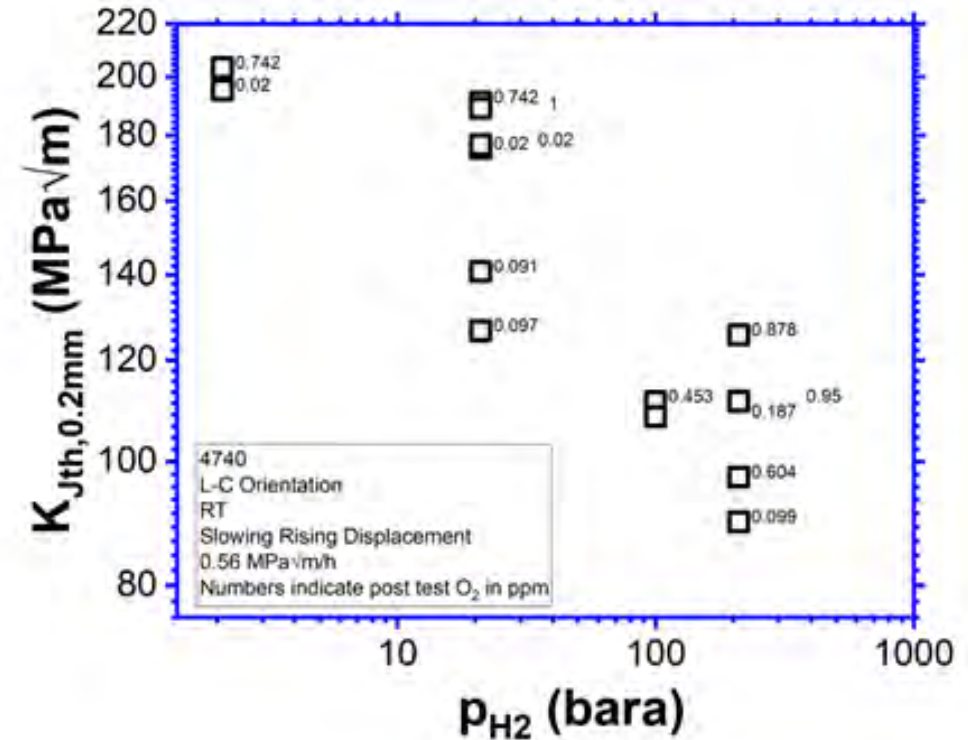
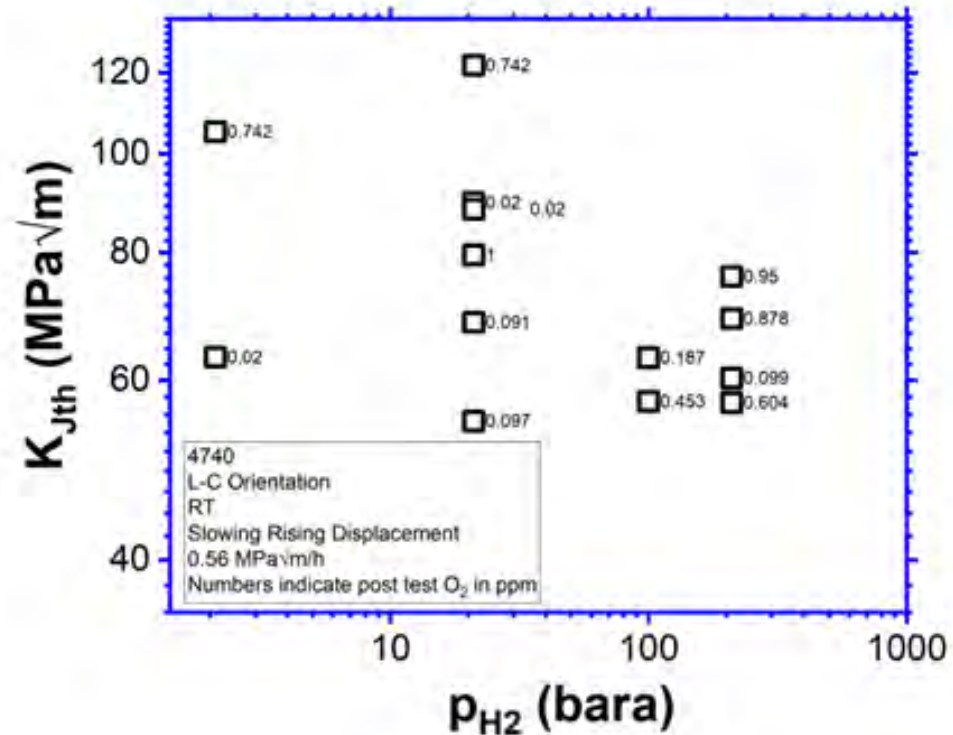
- K_{Jth} at low p_{H_2} is high though it decreases sharply at higher pressures
- $K_{J0.2mm}$ is similar at 2.1 and 21 bara but decreases sharply at higher p_{H_2}

Influence of $p_{H_2} \rightarrow$ Seamless X65



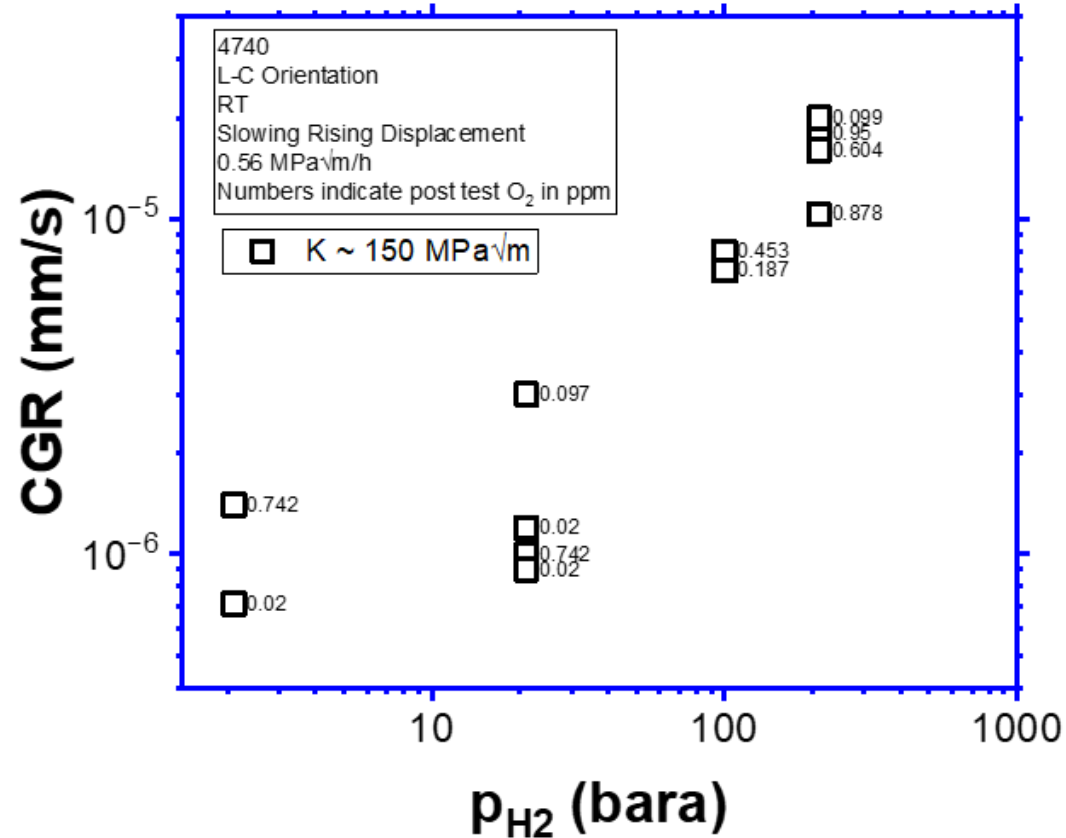
- CGR increases sharply with p_{H_2} at values above 21 bara H_2

Influence of p_{H_2} → Modern Sour Service X65



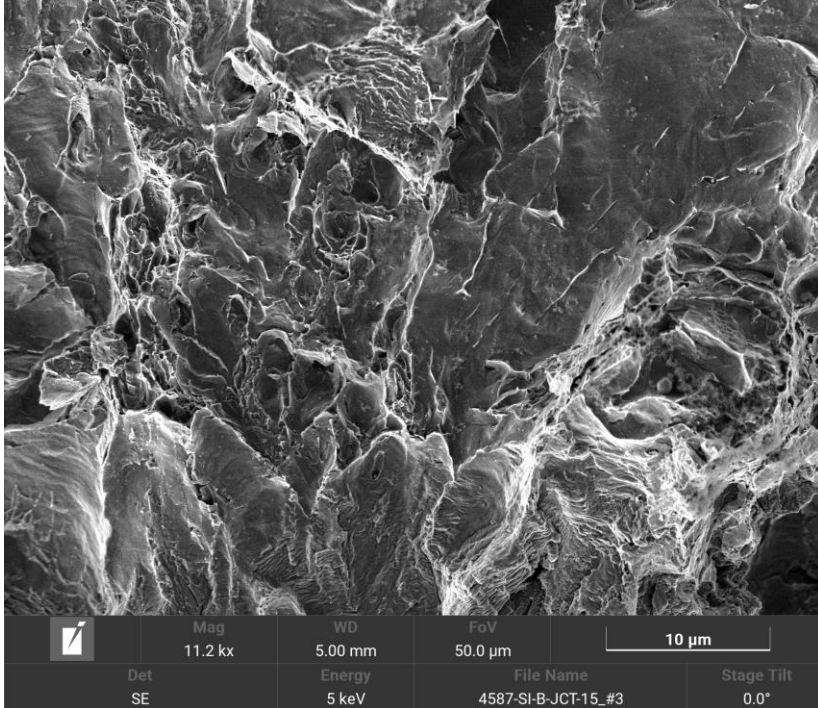
- $K_{J0.2mm}$ is similar at 2.1 and 21 bara but decreases sharply at higher p_{H_2}

Influence of p_{H_2} → Modern Sour Service X65



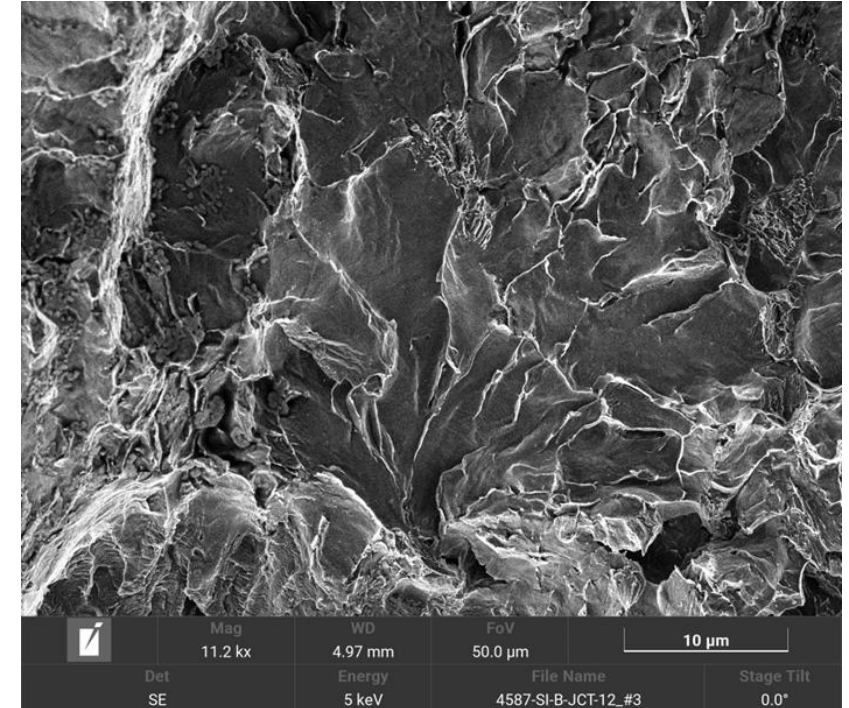
- CGR increases sharply with p_{H_2} at values above 21 bara H₂

Influence of p_{H_2} → Vintage Ferrite/Pearlite X60



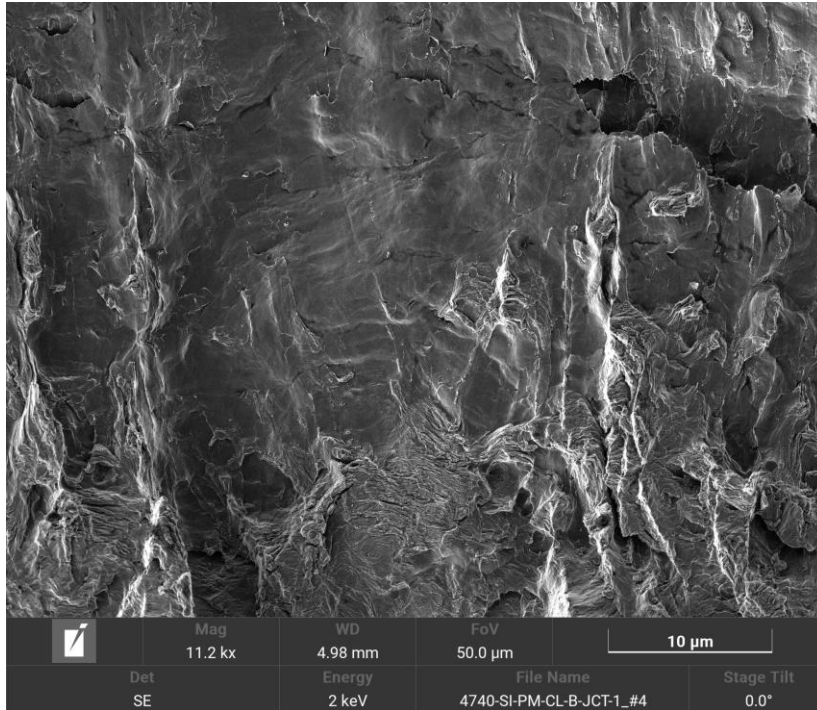
- 4587 – 2.1 bara/0.02 ppm

• **Fracture morphology appears to show different morphology at low pressure of 2.1 bara H_2**

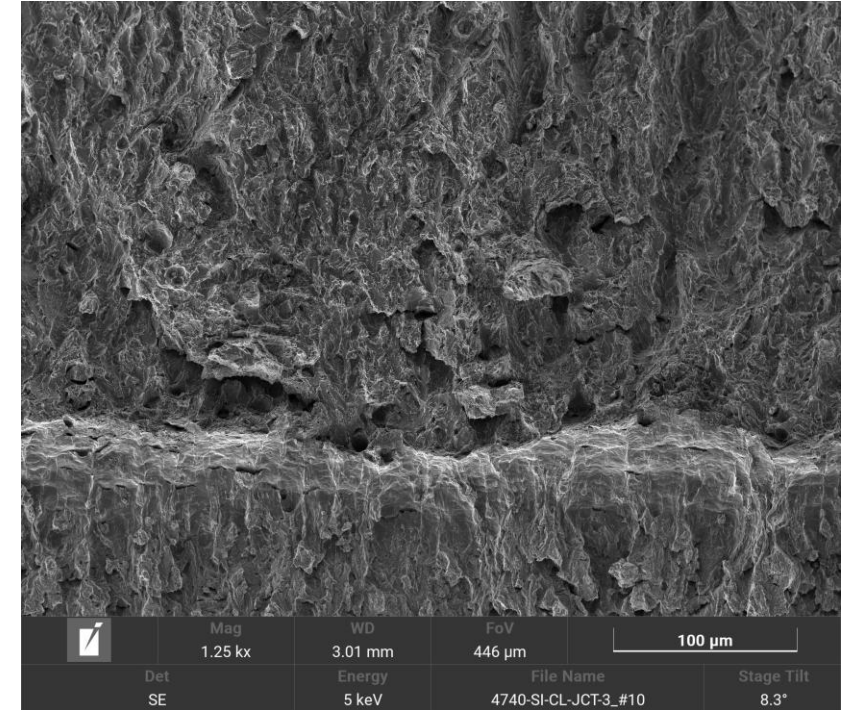


- 4587 – 210 bara/0.2 ppm

Influence of p_{H_2} → Modern Sour Service X65



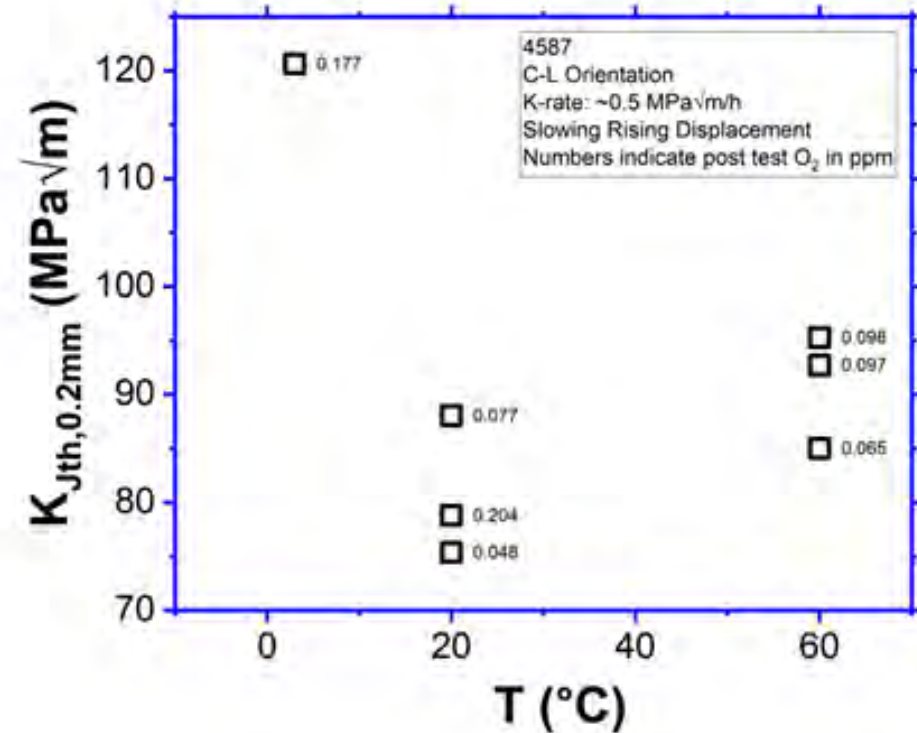
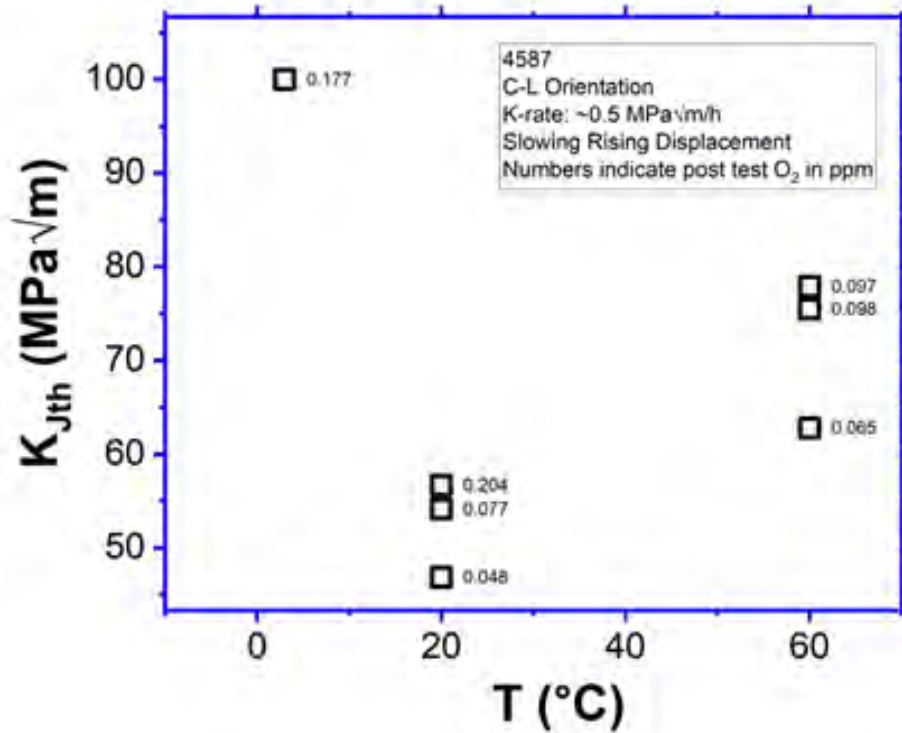
- 4740 – 2.1 bara/0.7 ppm



- 4740 – 21 bara/0.02 ppm

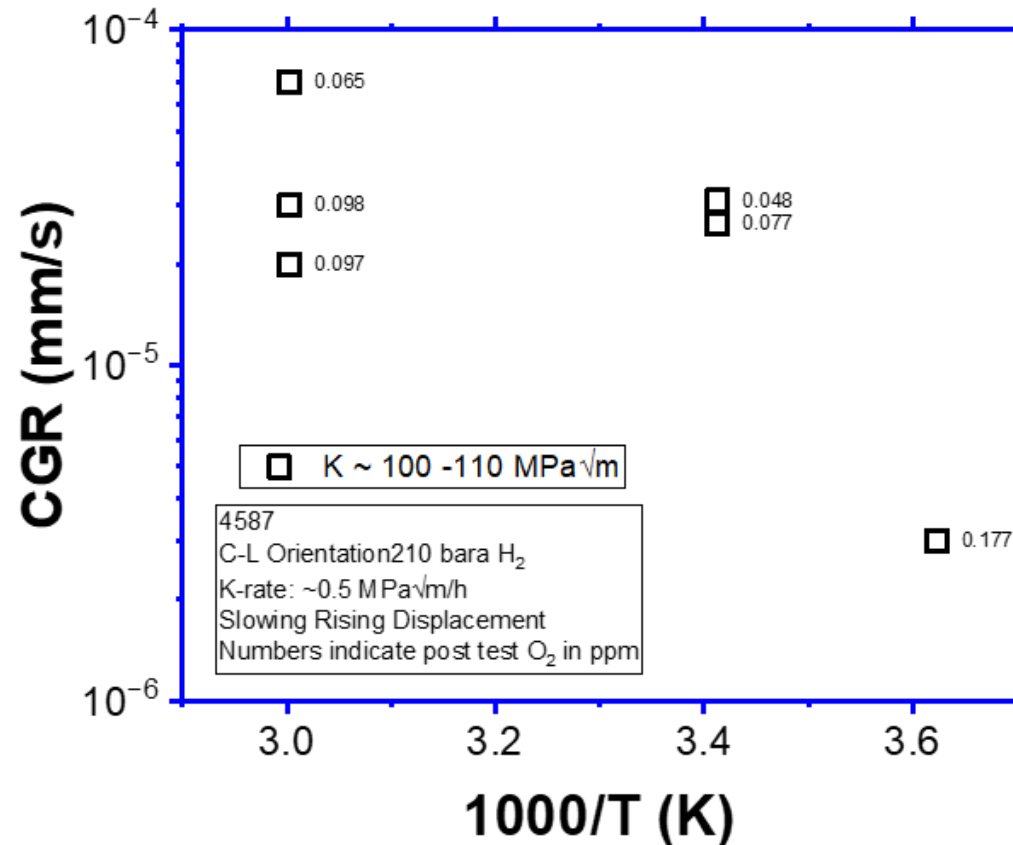
- **At low p_{H_2} and in the presence of O_2 → Large stretch zones are apparent**

Influence of T → Vintage Ferrite/Pearlite



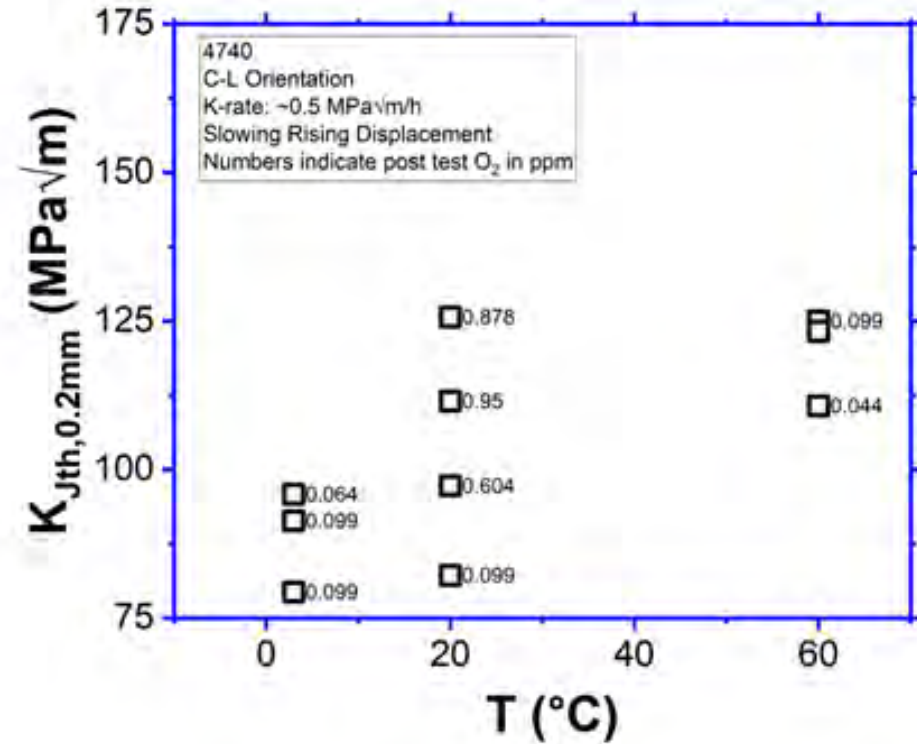
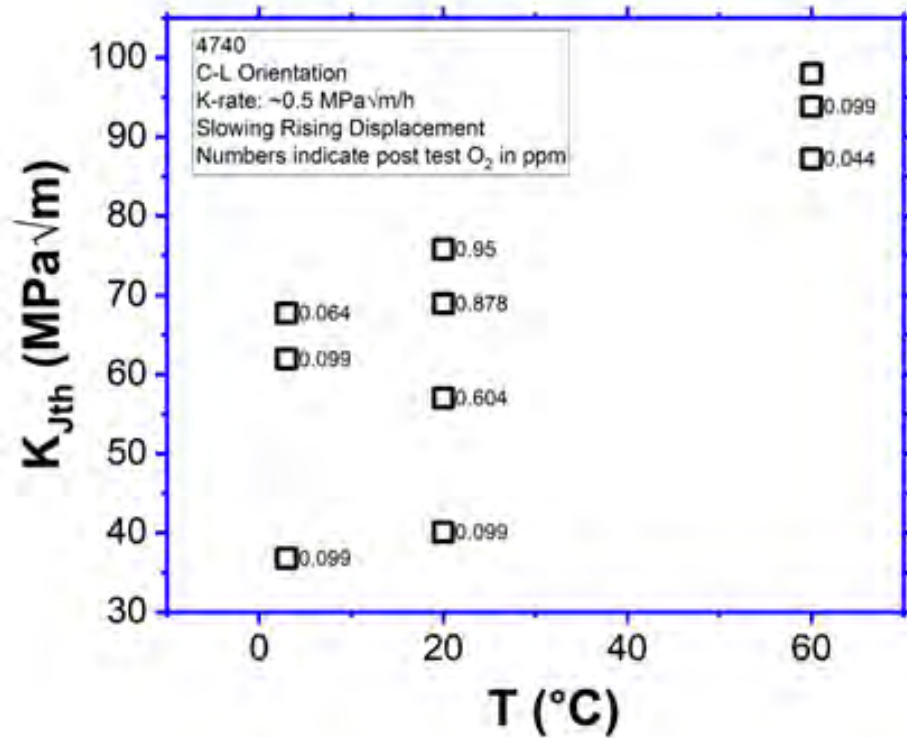
- **K_{Jth} and K_{J0.2mm} appears to be lowest at RT.**

Influence of T → Vintage Ferrite/Pearlite



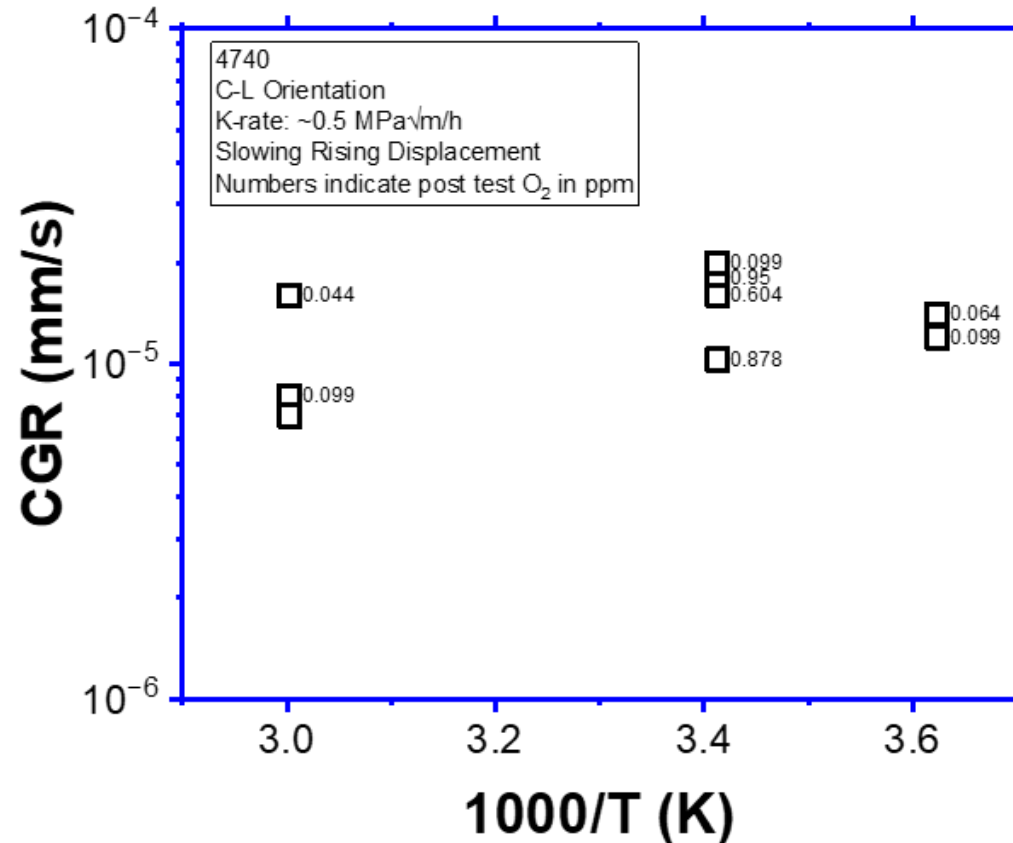
- CGR at 3°C is significantly lower than at RT

Influence of T → Modern Sour Service X65



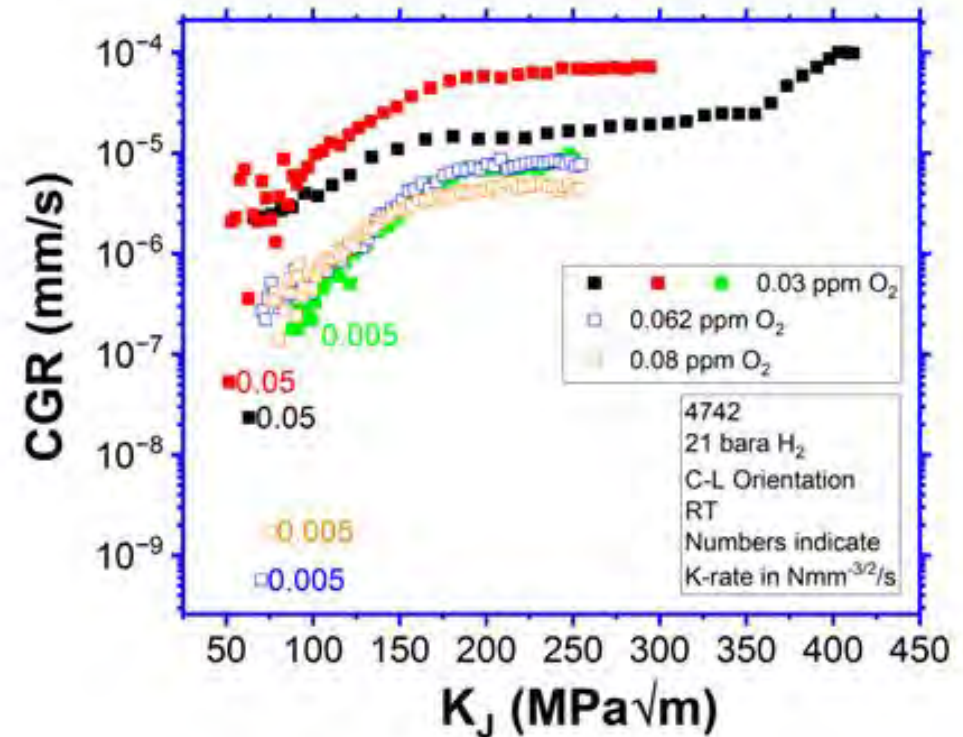
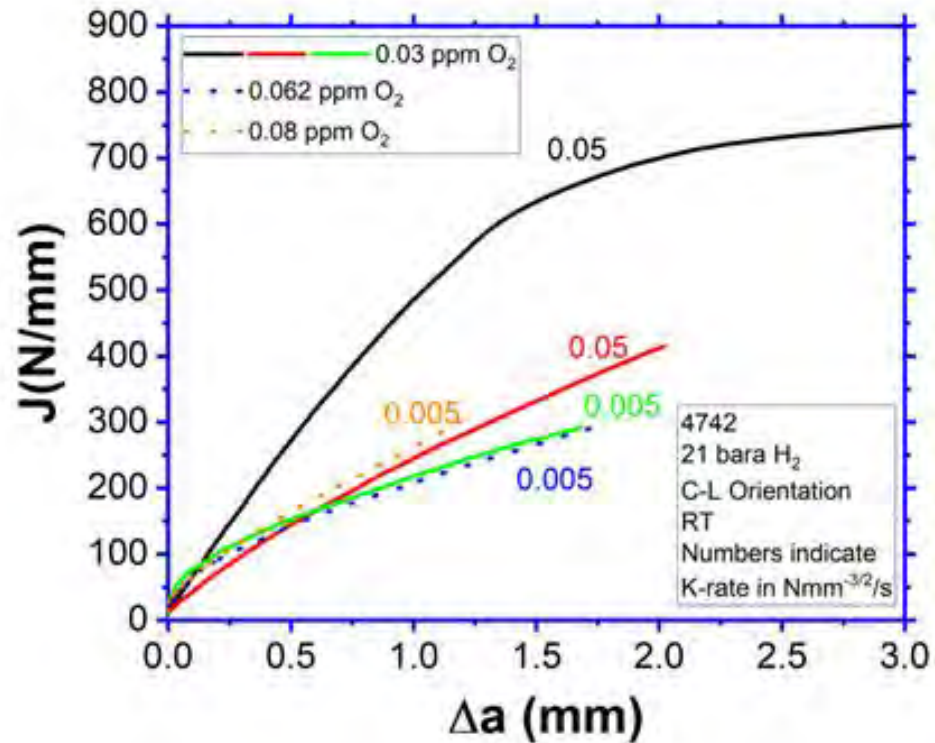
- **K_{Jth} and K_{J0.2mm} appears to be higher at 60°C compared to 3°C and RT.**

Influence of T → Modern Sour Service X65



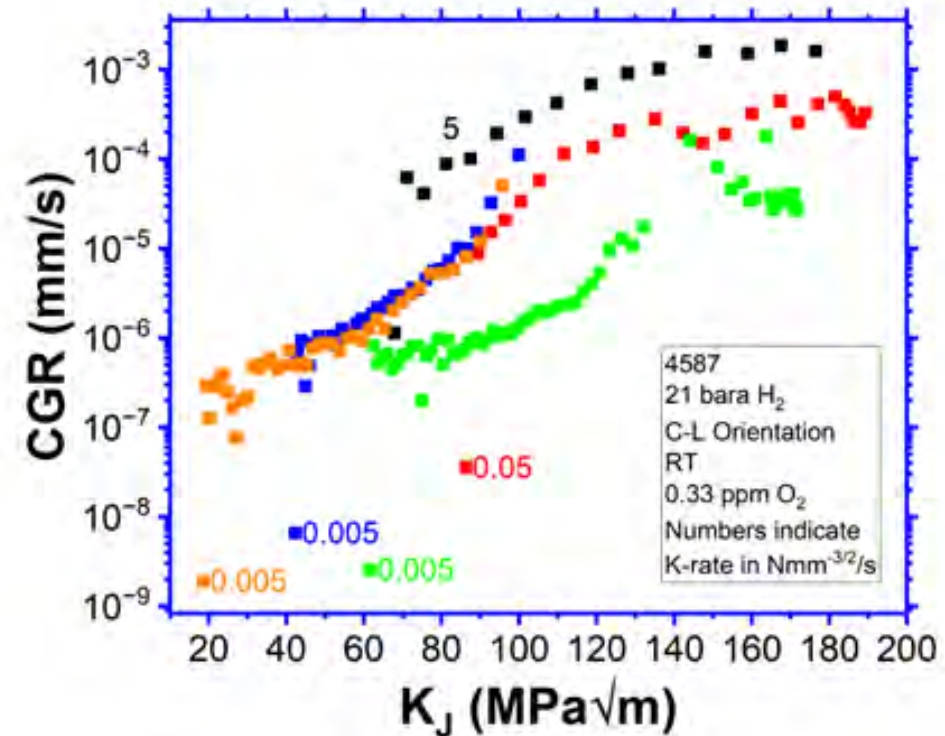
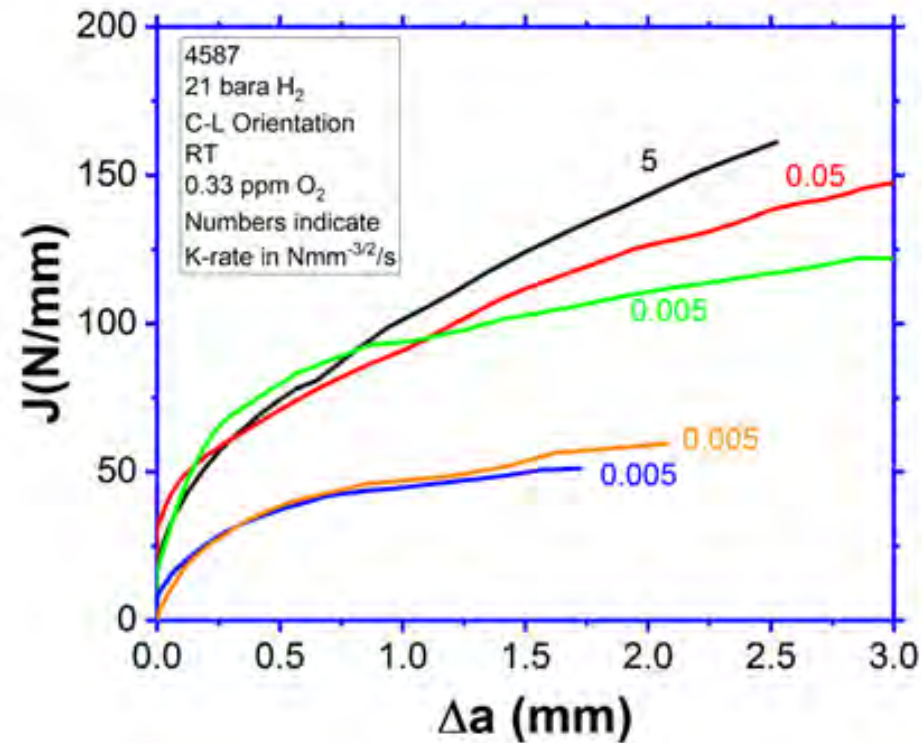
- No significant influence of T on CGR

Influence of p_{O_2} /K-rate $\rightarrow$ Modern Seamless X65



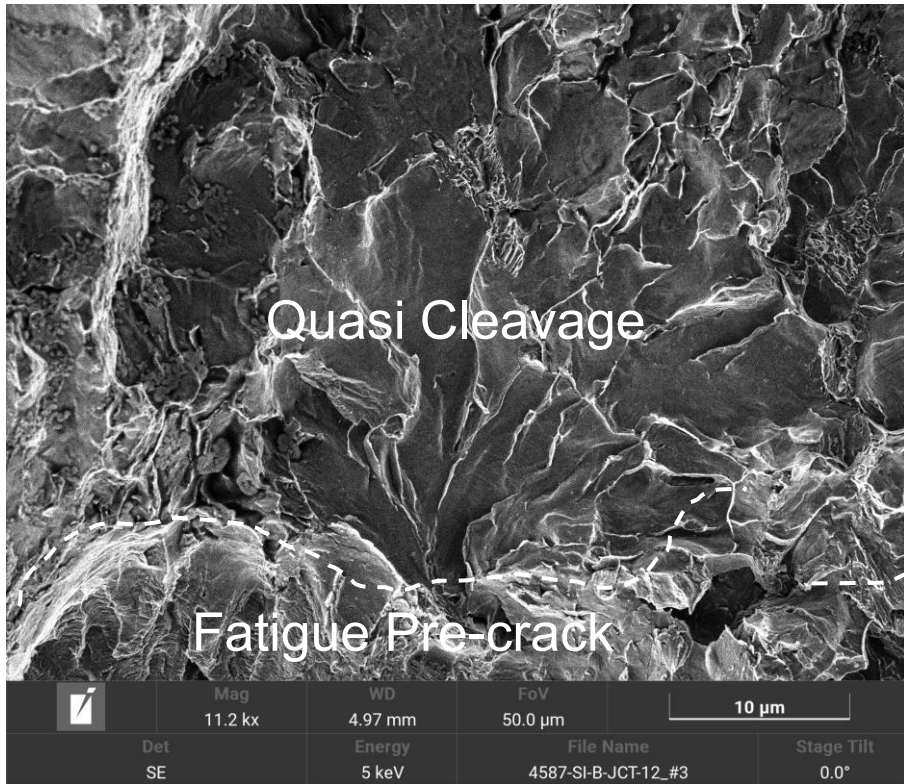
- At low p_{O_2} levels, effect of K-rate is not as significant

Influence of p_{O_2} /K-rate $\rightarrow$ Vintage Ferrite/Pearlite X65

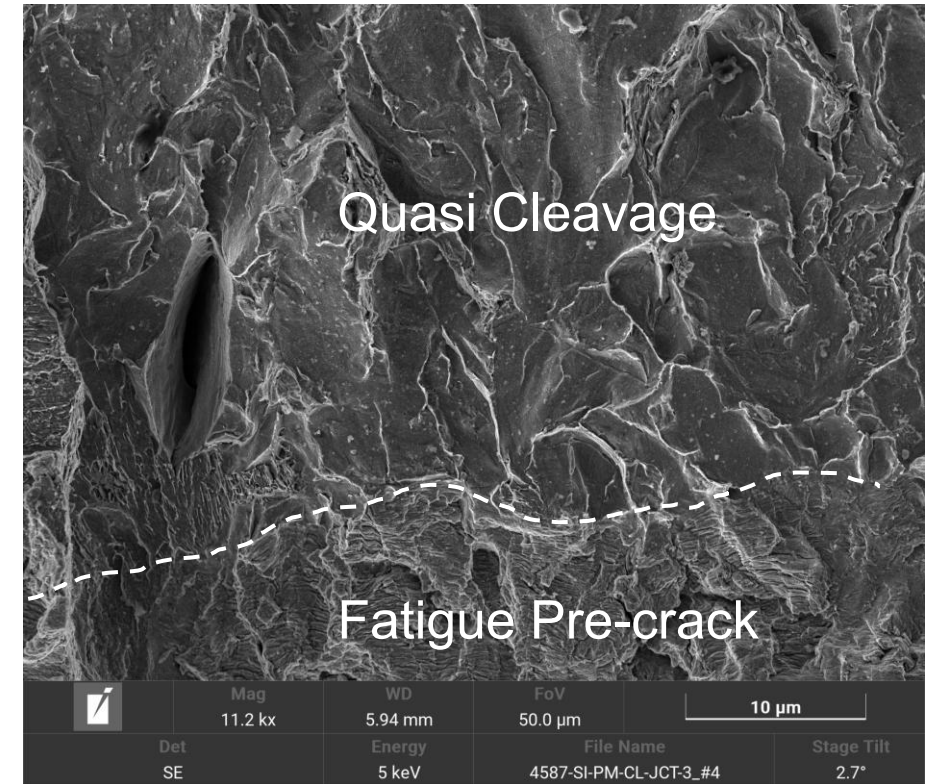


- At high p_{O_2} $\rightarrow$ Effect of K-rate is significant

SEM Ferrite Pearlite → T Effect



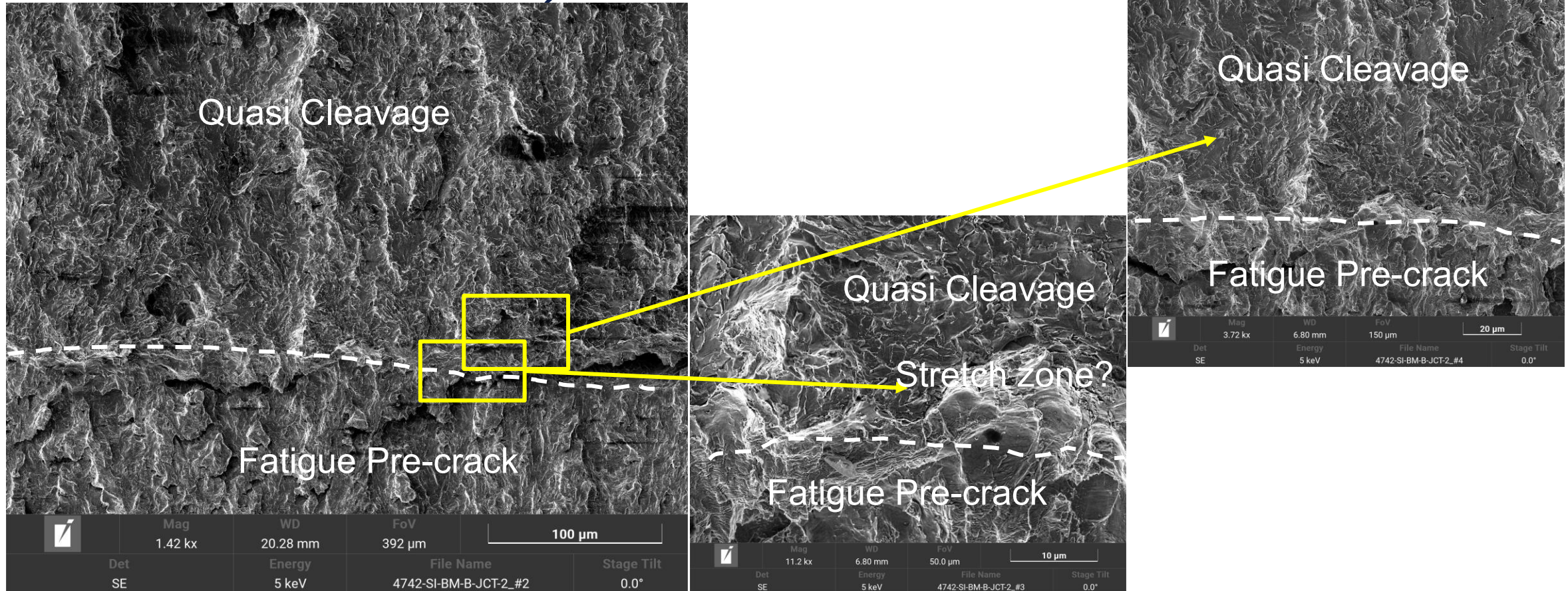
4587-SI-B-CL-JCT12 - RT



4587-SI-PM-CL-JCT3 – 60°C

- Fracture morphology exhibits quassi cleavage → No obvious evidence of a stretch zone
- Quassi cleavage features appear to be less pronounced at elevated temperature

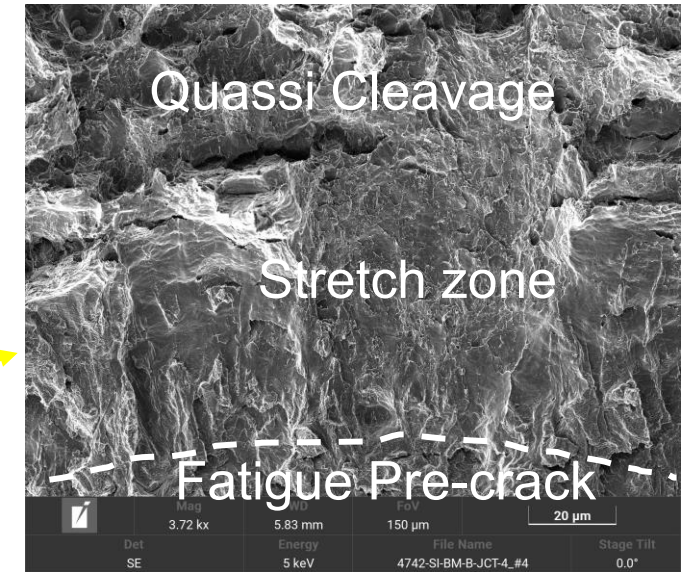
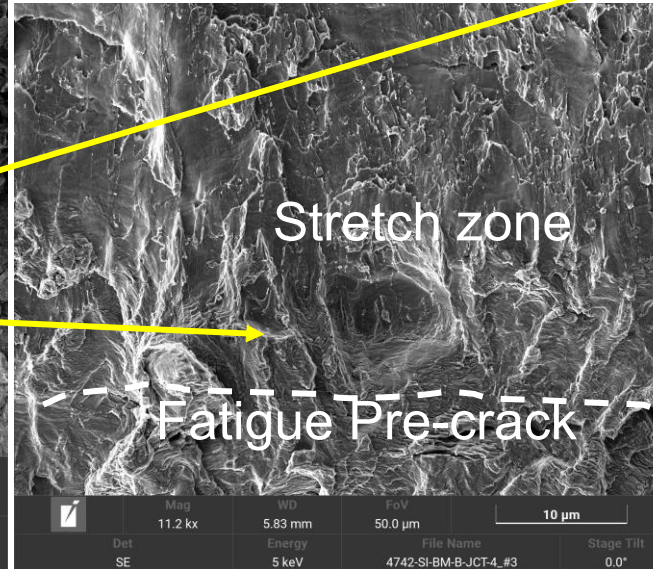
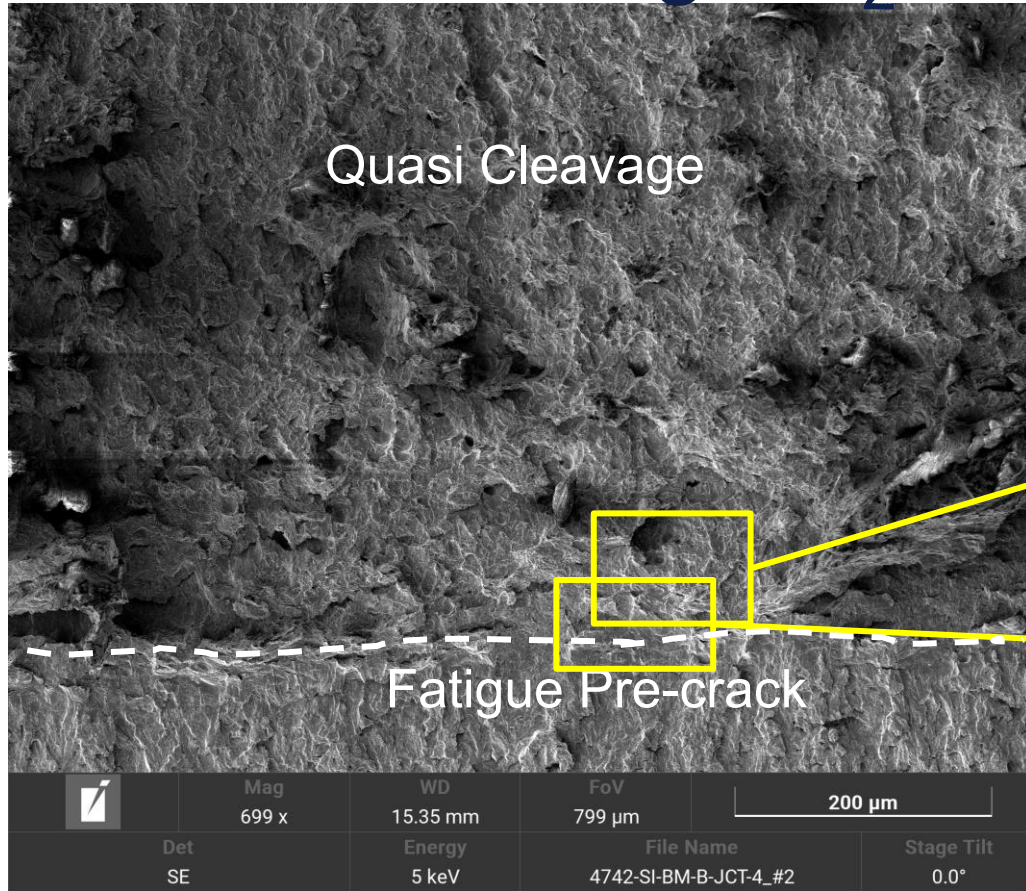
Influence of O₂ on Fracture Morphology at 21 bara → Slow K-rate/Low O₂



4742-SI-BM-JCT2 → 0.03 ppm/0.5 MPa√m/h

- Limited evidence of stretch zone in low oxygen environment at a slow K-rate.

Influence of O₂ on Fracture Morphology at 21 bara → Slow K-rate/High O₂



4742-SI-BM-JCT4 → 1 ppm/0.5 MPa√m/h

- Evidence of a large stretch zone in high oxygen environment at a slow K-rate.

Summary → Environmental Effects

- Varying O_2 concentration from 0.1 to 1 ppm appears to influence the fracture morphology and the optimum K-rate for testing → Critical when interpreting the requirements in ANSI CSA/CHMC-1
- At low pressures of H_2 (21 bara)
 - Significant effect of O_2 was observed on the J-R curves for the seamless pipe
 - Even at low O_2 concentration significant effect of K-rate was observed on seamless pipe
 - Fracture morphologies showed evidence of larger stretch zone in the presence of higher O_2 and higher K-rates
- Modern sour service TMCP and seamless appear to exhibit a pressure dependence
- Vintage TMCP is more susceptible than the modern materials and appears to exhibit a shallow dependence on p_{H_2} and K-rate.
- Fracture toughness parameters appear to be minimum at RT

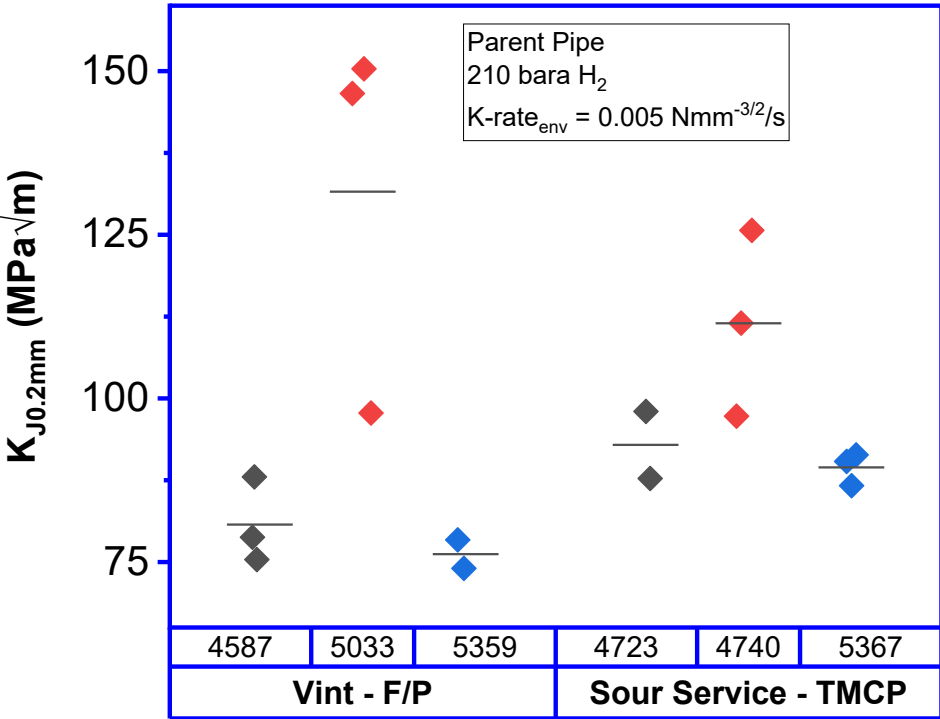
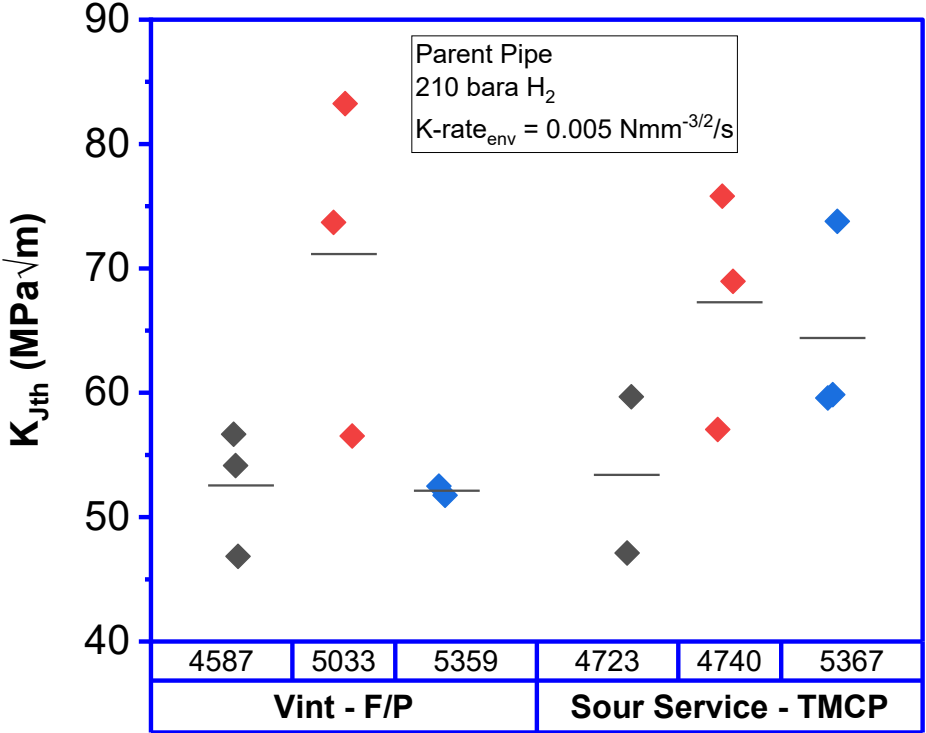
Microstructural Effects

27 May 2026

Background

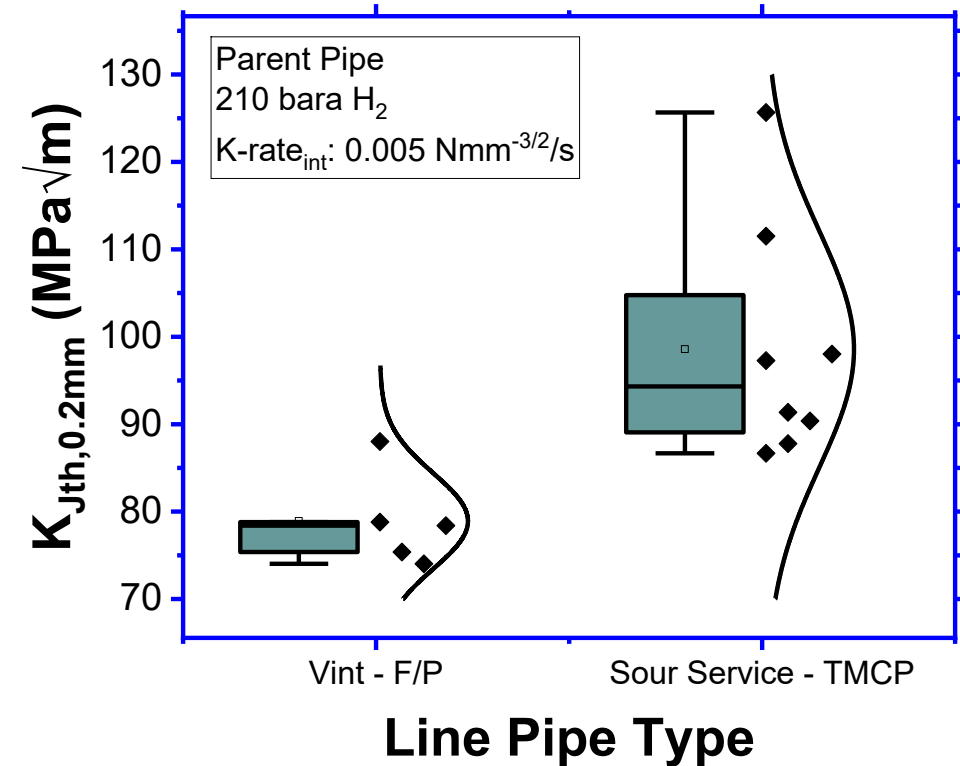
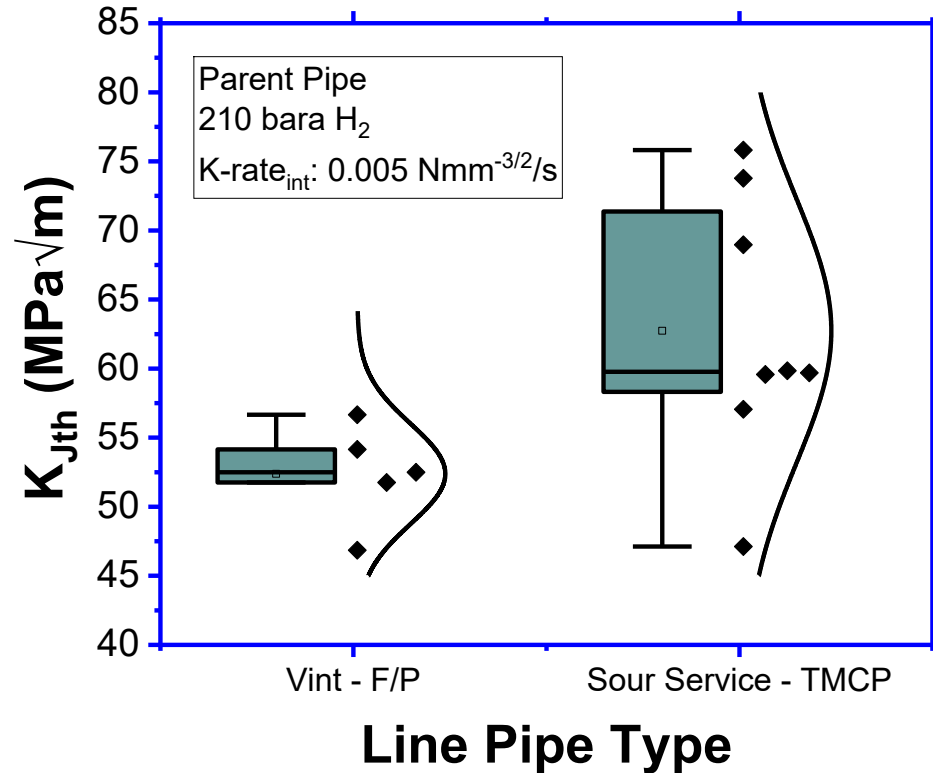
- Characterizing the influence of various microstructures on high pressure H₂ performance.
- Materials Evaluated
 - Vintage Ferrite Pearlite Microstructures
 - Modern Sour Service TMCP steels
 - Modern Sour Service Seamless
 - Influence of welds
 - Influence of strain aging

Comparison of Vintage & Modern Steels



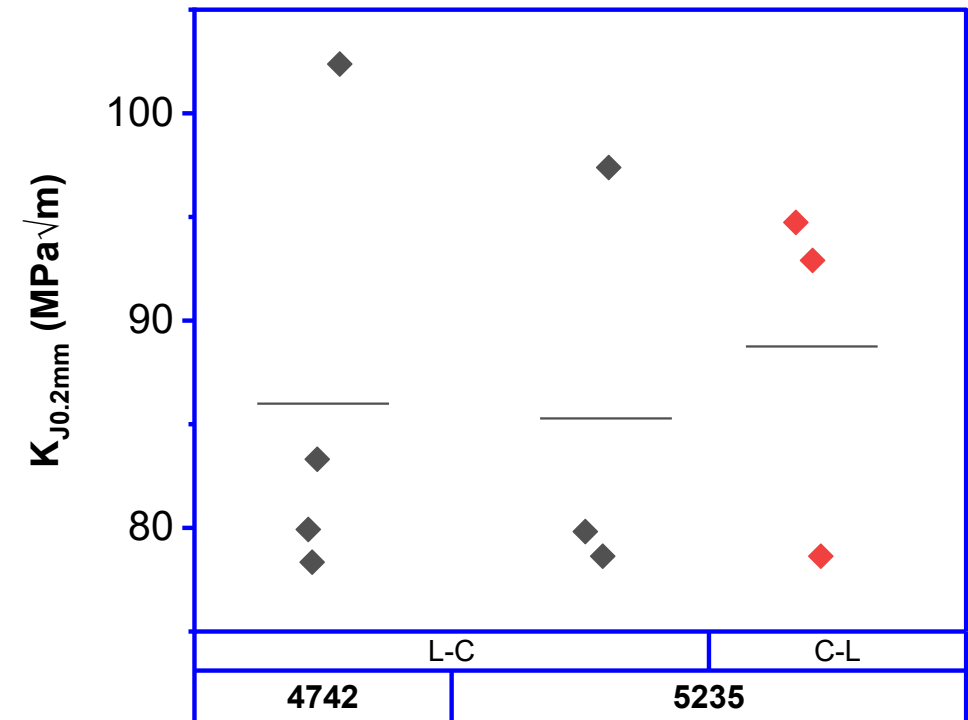
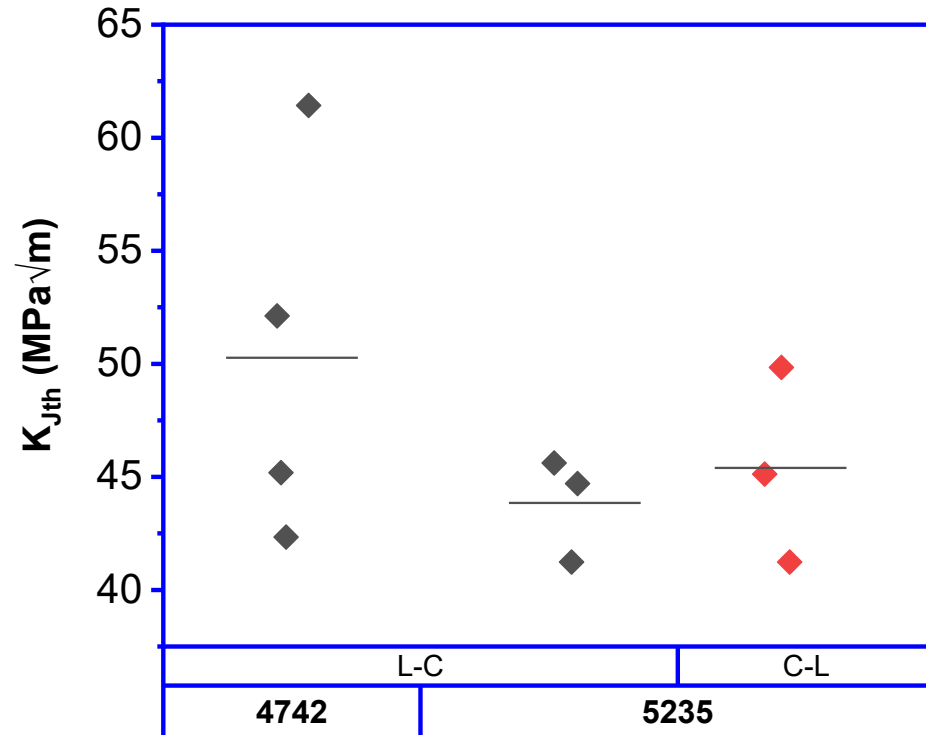
- Modern steels in general appear to have higher K_{Jth} and $K_{J0.2mm}$ in the range of 65 MPa√m and 90 MPa√m

Comparison of Vintage & Modern Steels



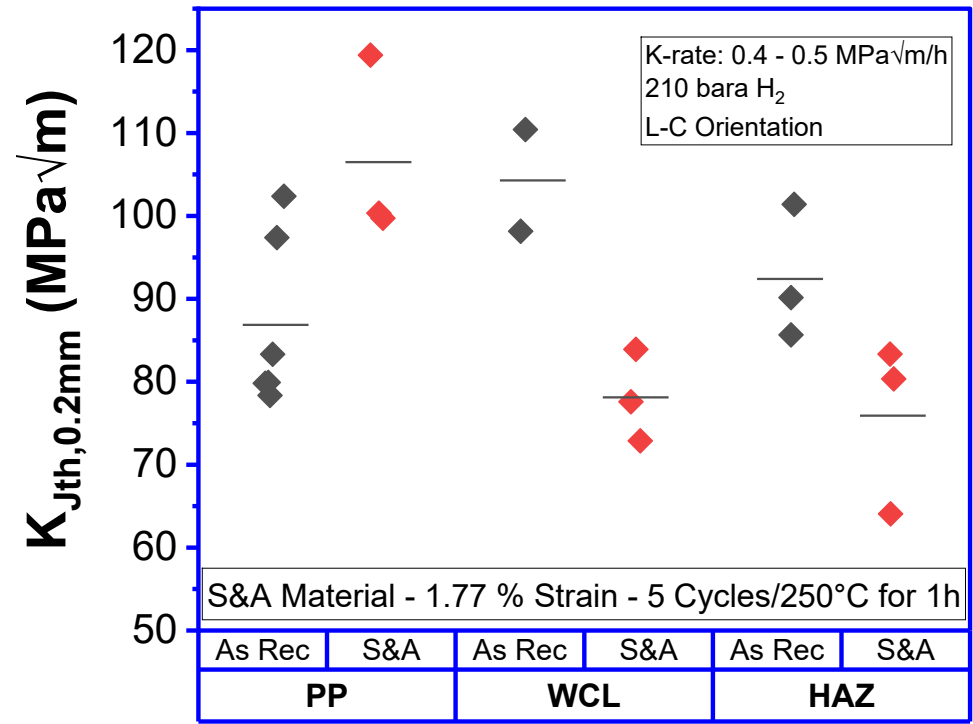
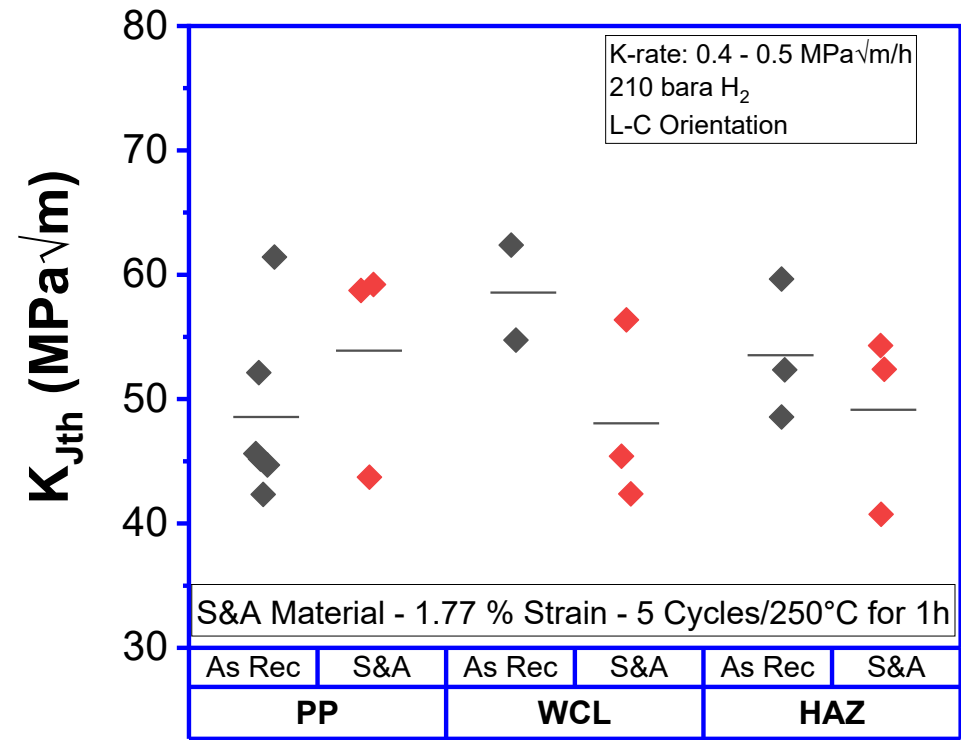
- Differences are readily apparent when the data sets of the vintage and modern steels are combined.

Influence of Orientation → Modern Seamless X65



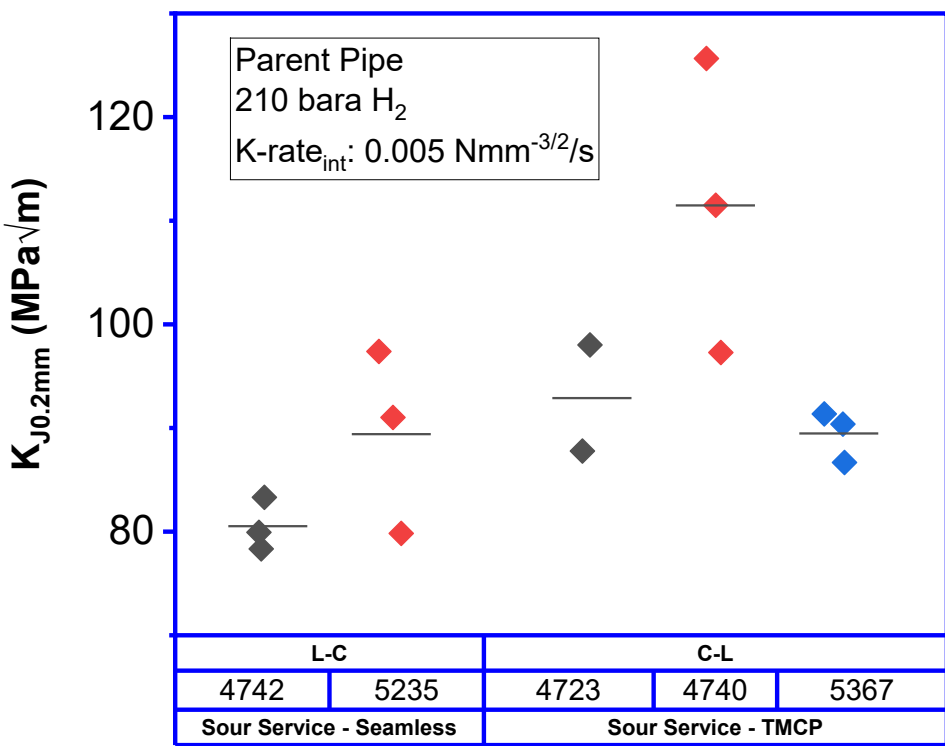
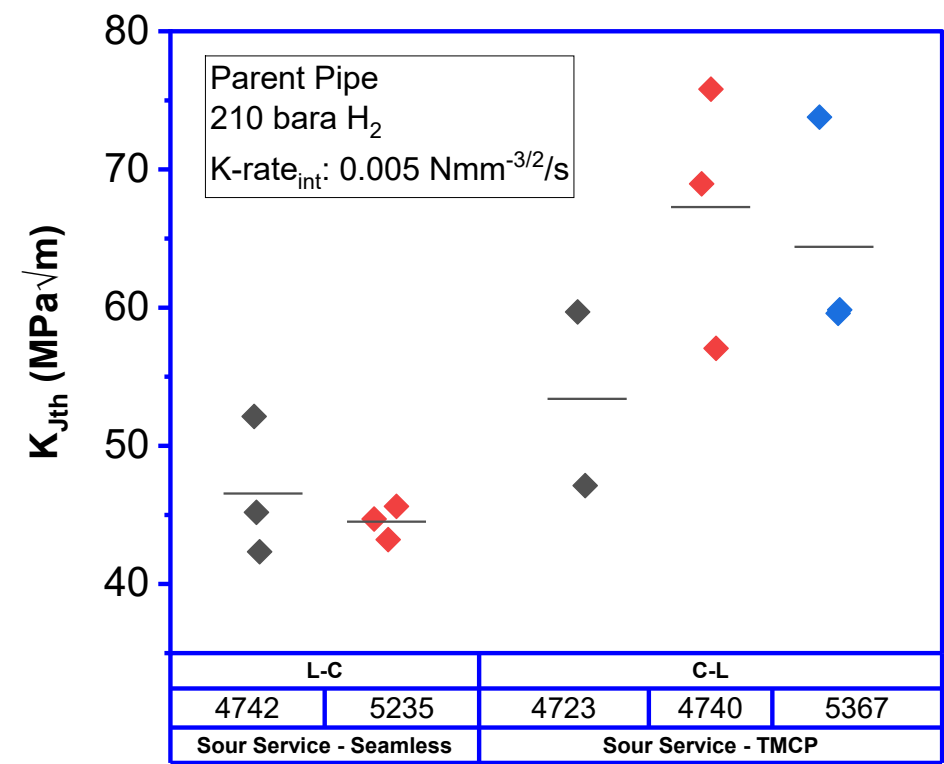
- There does not appear to be a significant influence of orientation on the K_{Jth} and $K_{J0.2mm}$ for the modern seamless parent pipe

Comparison of Microstructure and Strain Aging



- There is no significant difference between the behavior of the PP/WCL and HAZ microstructures.
- Strain Aging appears to result in a slight decrease in performance of WCL and HAZ

Comparison of Seamless and TMCP



- Modern sour service TMCP steels have higher K_{Jth} than seamless
- Difference in $K_{J0.2mm}$ is not as significant as K_{Jth}

Summary

- The K_{Jth} and $K_{J0.2mm}$ of the vintage ferrite pearlite steels is lower than that of the TMCP sour service steels.
- The K_{Jth} of the seamless line pipe is lower than that of the TMCP line (45 MPa $\sqrt{m}$ vs 65 MPa $\sqrt{m}$), and the $K_{J0.2mm}$ of the seamless line pipe are slightly lower than that of the TMCP (85 MPa $\sqrt{m}$ vs 95 MPa $\sqrt{m}$).
- The K_{Jth} and $K_{J0.2mm}$ of the seamless PP, GWCL, and GHAZ are similar to each other. There is also no significant influence of strain aging on the K_{Jth} . However, the GWCL, and GHAZ exhibit lower values of $K_{J0.2mm}$ in the strain aged condition.
- There does not appear to be a strong influence of orientation (C-L vs L-C) on the K_{Jth} and $K_{J0.2mm}$ of the seamless parent pipe.

July 2026

Identification of Threshold in DCPD Data – da/dK vs K Method

Mario Macia, Ashwini Chandra, Greg Pioszak

Challenges in Identification of Threshold Toughness using DCPD

- ASTM E1820 has two methods for identifying start of crack growth and threshold toughness

Deviation from linearity of normalized voltage vs load line displacement

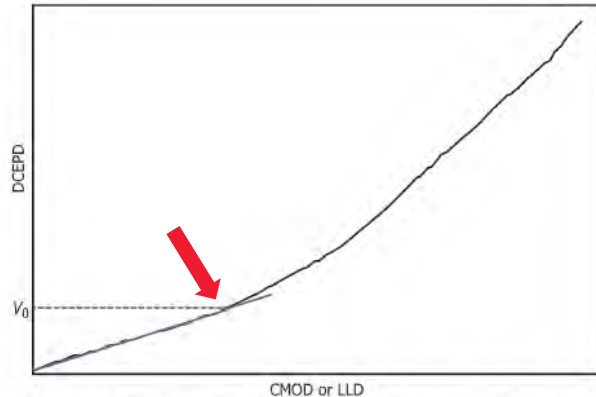


FIG. A18.3 Example of V versus $CMOD$ or LLD Record for a Structural Steel

Deviation from linearity of Force vs normalized voltage

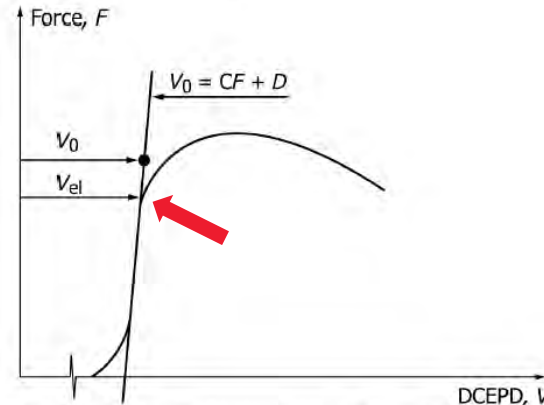
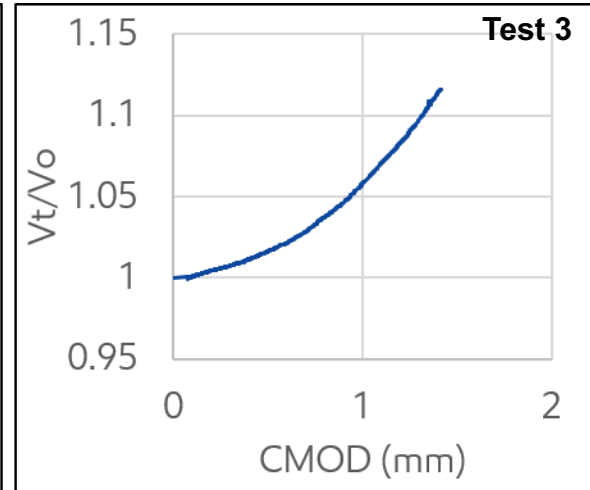
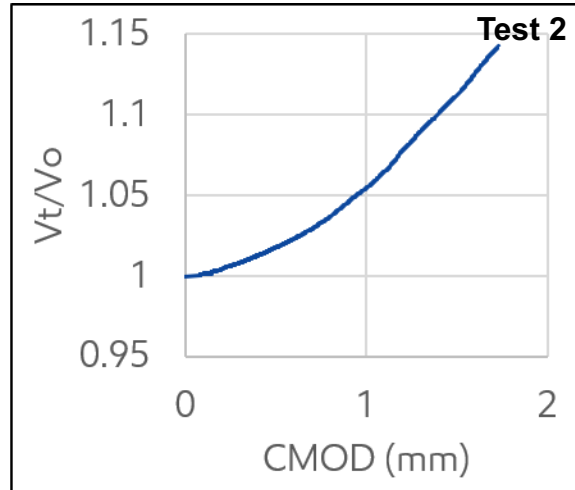
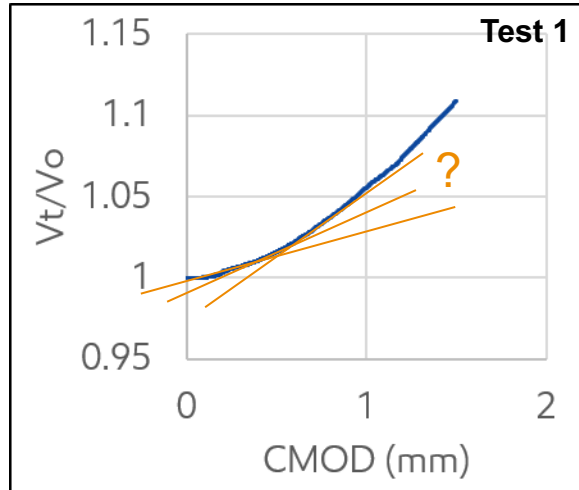


FIG. A18.4 Example of Force versus $DCEPD$ Test Record for a Structural Steel

- Test data often does not produce clear trends with easily identifiable initiation points based on the above methods

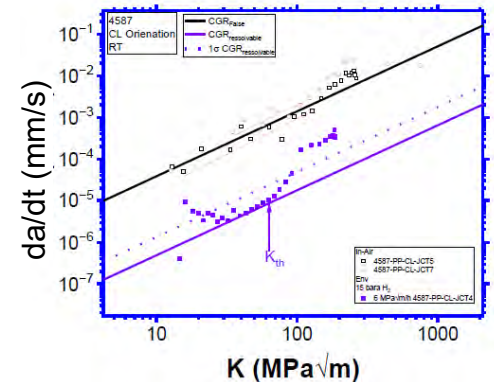
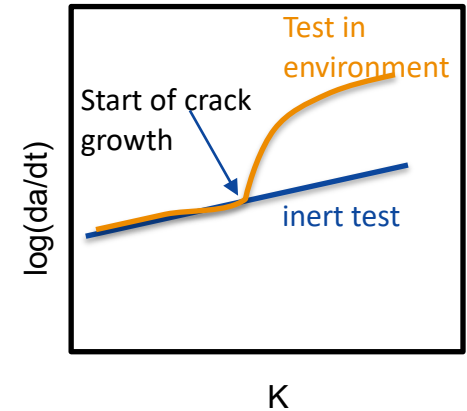
Examples of Normalized Voltage vs LLD/CMOD plots

- No clear linear region or deviation point on normalized voltage vs CMOD plot even when DCPD data quality is good
- Interpretation of start of crack growth and threshold toughness is very subjective
- Range of reasonable choices made by competent individuals can result in large impact on identified threshold toughness



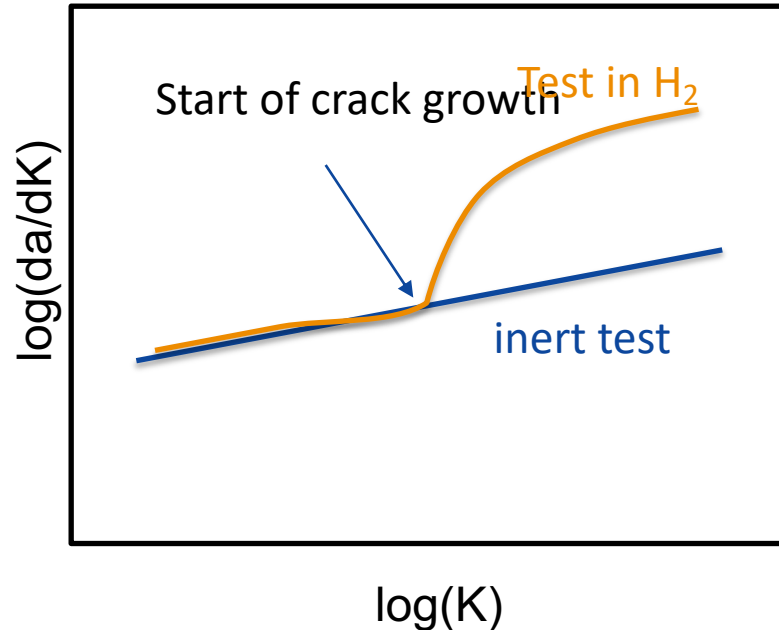
da/dt vs K method of threshold toughness determination

- Crack growth rate (da/dt) vs K has been proposed as an alternate approach to identify start of crack growth in Monel K-500 [Gangloff, et al, Met Trans A, Vol 45A, 2014, pp. 3814-3834]
 - Inert and in-environment tests performed with constant K rate (dK/dt)
 - $\log(da/dt)$ plotted vs K. Linear trend of false crack growth due to plasticity observed in inert test
 - Deviation of da/dt vs K in test in environment from trend for inert environment used to identify initiation
- da/dt is a linear function of K rate in Monel K-500 [Harris, et al, Theoretical and Applied Fracture Mechanics 111 (2021) 102846]
 - Illustrates that constant K rate testing is required to use of da/dt method
- Thodla, et al plotted $\log(da/dt)$ vs $\log(K)$ and showed it is linear for a pipeline steel prior to the initiation of crack growth [Thodla, et al, PVP2025-154581]



da/dK Methodology for Determining K_0 – Concept

Like da/dt method, da/dK method identifies deviation from trend in plasticity driven “false crack growth” determined an inert environment to identify initiation in H_2 environment.



Key Advantages:

- E1820 tests are often conducted with a constant displacement rate. Once plasticity starts, K rate varies
- As plasticity begins, K rate changes and affects da/dt vs. K
- da/dK approach is not sensitive to variations in K rate

da/dK Method Equations

a_f – false crack growth due to plasticity. Fit with a power law.

$$\Delta a_f = AK^b \quad \xrightarrow{\text{Taking the log of each side of the equation}} \quad \log_{10} \Delta a_f = \log_{10} A + b \log_{10} K \quad \Delta a_f \text{ vs } K \text{ is linear on a log-log plot}$$

$$\frac{da_f}{dK} = AbK^{b-1} \quad \xrightarrow{\text{Taking the log of each side of the equation}} \quad \log_{10} \frac{da_f}{dK} = \log_{10} Ab + (b-1) \log_{10} K \quad \frac{da_f}{dK} \text{ vs } K \text{ is also linear on a log-log plot, even if } dK/dt \text{ is not constant}$$

How does this relate to da/dt method?

$$\frac{da_f}{dt} = \frac{da_f}{dK} \frac{dK}{dt} \quad \text{chain rule can be applied because } a \text{ is a function of } K \text{ and } K \text{ is a function of } t$$

$$\frac{da_f}{dt} = AbK^{b-1} \frac{dK}{dt} \quad \xrightarrow{\text{Taking the log of each side of the equation}} \quad \log_{10} \frac{da_f}{dt} = \log_{10} Ab + (b-1) \log_{10} K + \log_{10} \frac{dK}{dt}$$

When dK/dt is constant, da_f/dt is linear on a log-log plot.

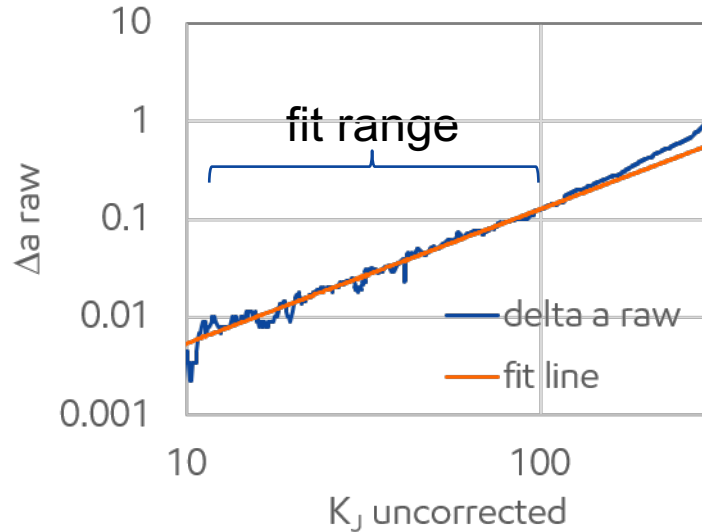
However, when dK/dt varies, da_f/dt becomes nonlinear on a log-log plot if the power law equation describes false crack growth as a function of K

Example of Application – Inert Reference Line

Parameters for inert reference line fit to plot of Δa vs K_J uncorrected for crack growth.

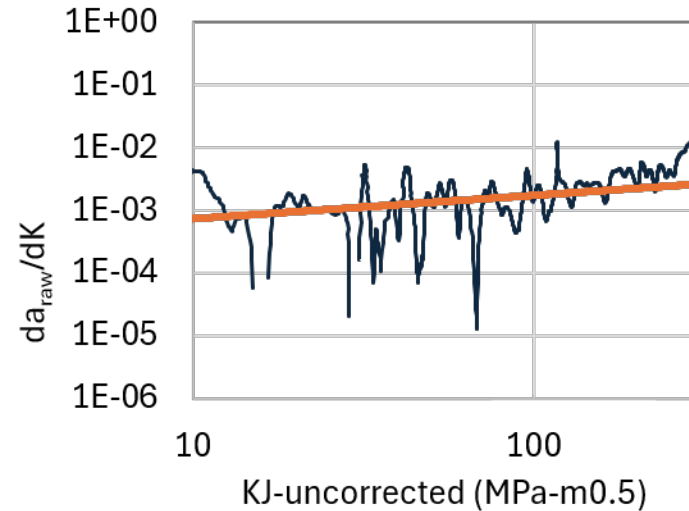
$$\log_{10} \Delta a_f = \log A + b \log_{10} K$$

A	0.000227
b	1.37



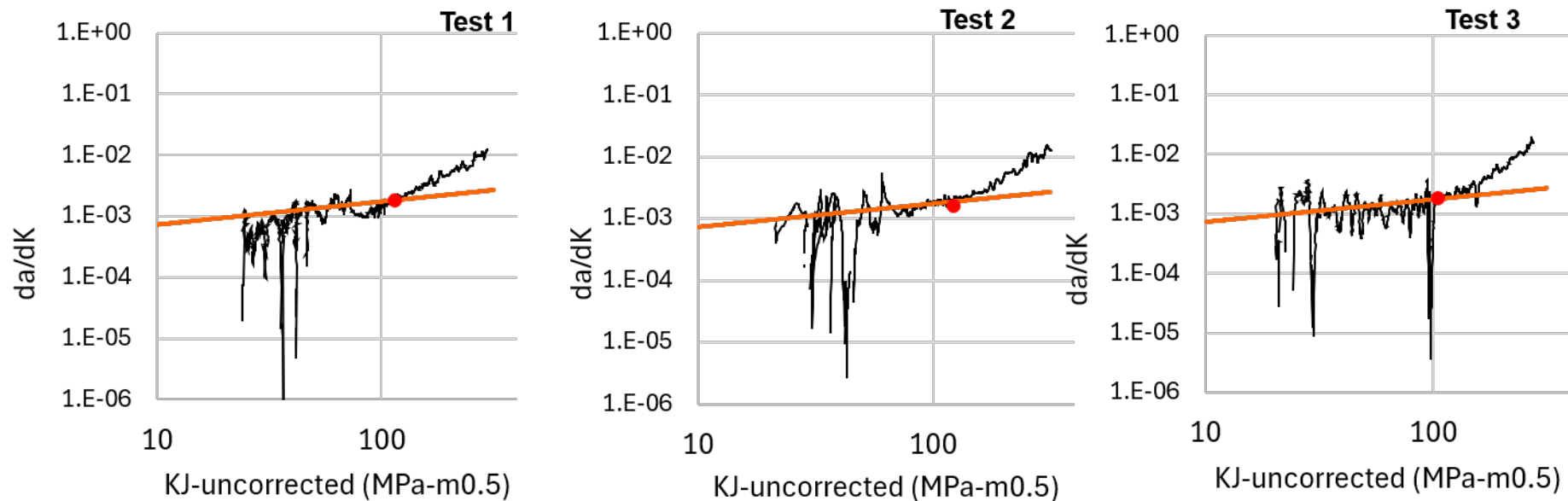
Inert reference line vs da/dK for inert test data

$$\log_{10} \frac{da_f}{dK} = \log_{10} Ab + (b - 1) \log_{10} K$$



Reference line parameters may also be fit directly to da_{raw}/dK vs K .

Application to Tests in 23 psi H₂ partial pressure

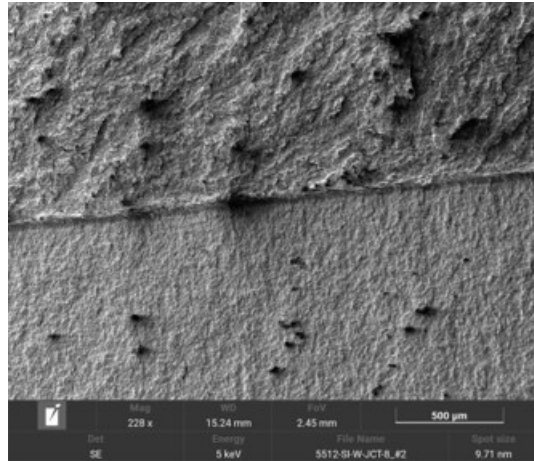


- Test data in 23 psi H₂
- Inert reference line
- Crack growth initiation point

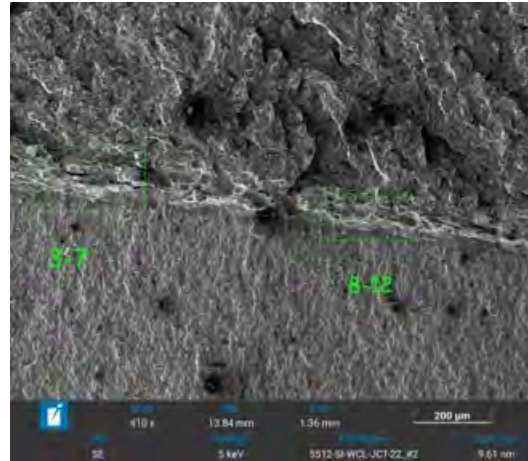
Validation with Interrupted Tests

- Targeted interrupting tests at 0.05 mm crack growth based on prior test results analyzed using da/dK method.
- Reasonable agreement reached with observed crack growth

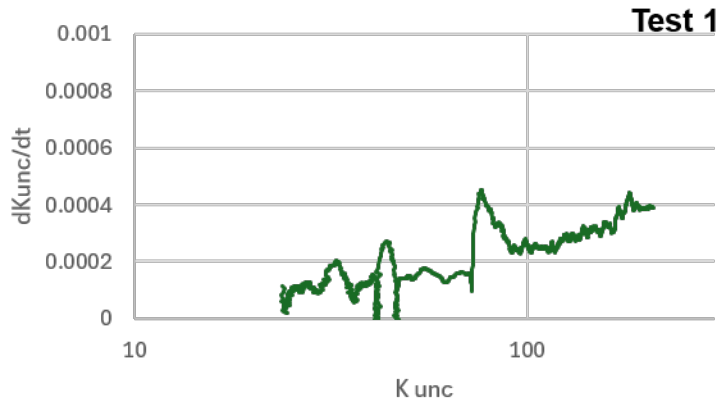
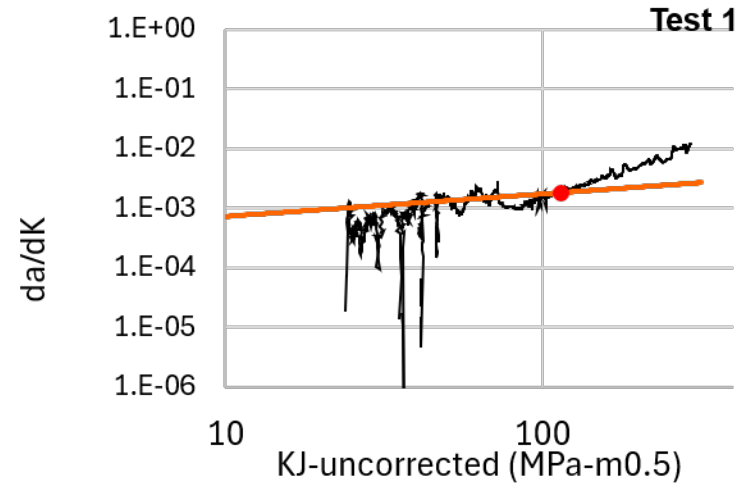
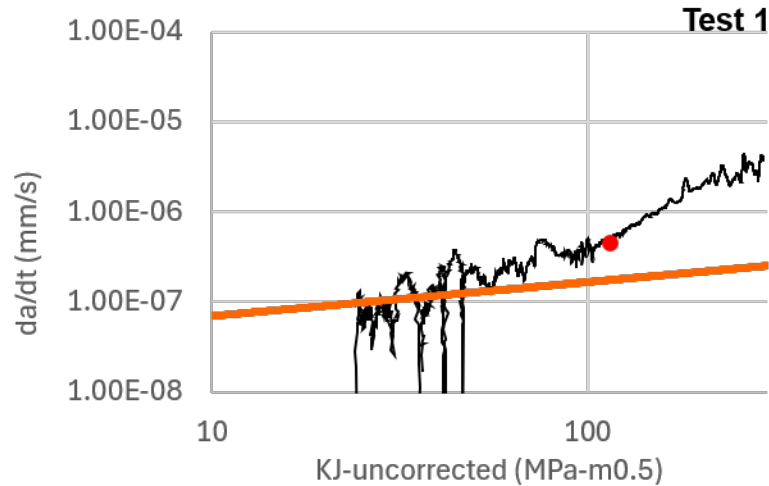
Δa actual at end of test = 0.033



Δa actual at end of test = 0.063



Comparison of da/dK and da/dt methods for varying K rate



Earlier departure from reference line is an artifact of increasing K rate when da/dt method is used with varying dK/dt



EPRG Round robin benchmark study on the fracture toughness testing in hydrogen – Update for the Sandia Study group @ Anaheim

Bostjan Bezensek, Shell ; Neil Gallon, ROSEN, Holger Brauer, Mannesmann Line Pipe

July 2026

- ❑ Multi laboratory study following the EPRG Guidelines based test procedure
- ❑ Generate consistent set of baseline data for closing the knowledge gaps
- ❑ Identify industry baseline performance (ISO 13528 /ASTM E691)
- ❑ Provide improvement & learning opportunity for each participating lab

List of participating labs for the RR



EPRG	Europe non EPRG	Americas	Asia	Australia
Corinth Pipe Works	CETIM France	C-FER Edmonton	DNV Singapore	Uni Wollongong / Rosen Australia
CSM RINA	CEA LITEN	DNV Columbus	KRISS (SKorea)	
Element	Fraunhofer IWM	EWI Columbus	HydroGENIUS/ IC2NER (Japan)	
Natran	French Institute of corrosion	EMC ²	PipeChina	
OCAS	H2 IIS SIDERLab Italy	HyPerformance		
Rosen	MPA Stuttgart	INT Brasil		
	Tecnalia Spain	NIST Boulder		
	TWI	Sandia Livermore (lead lab)		
	University of Burgos (UBU)	SWRI		

28 participants
+ Sandia lead lab
+ 5 parallel participants

- Samples with most labs (couple re-machined)
- Testing has been ongoing since winter (slowly)
- Initial results in from the lead lab and from 4 participants
- Outlook -- results requested by October,
feedbacks to participants by year end and
wider sharing in 2027





Exceptional service in the national interest

SAND2026-

Fracture Toughness Trends with Other Attributes in Base Metal and Welds of Pipeline Steels

Michelle Kent

Quinten Yurek

Joe Ronevich

Chris San Marchi

Sandia National Laboratories
Livermore, CA

ASME PVP Conference, Anaheim, CA

July 19–24, 2026

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.





How do mechanical properties, microstructure, impurities, etc. affect fracture toughness in hydrogen environments?

- Do welds follow different trends than their base metals?
- Do modern and vintage steels follow different trends?
- Incorporate composition, nominal mechanical properties, and microstructure to compare fracture toughness in gaseous hydrogen
- A work in progress

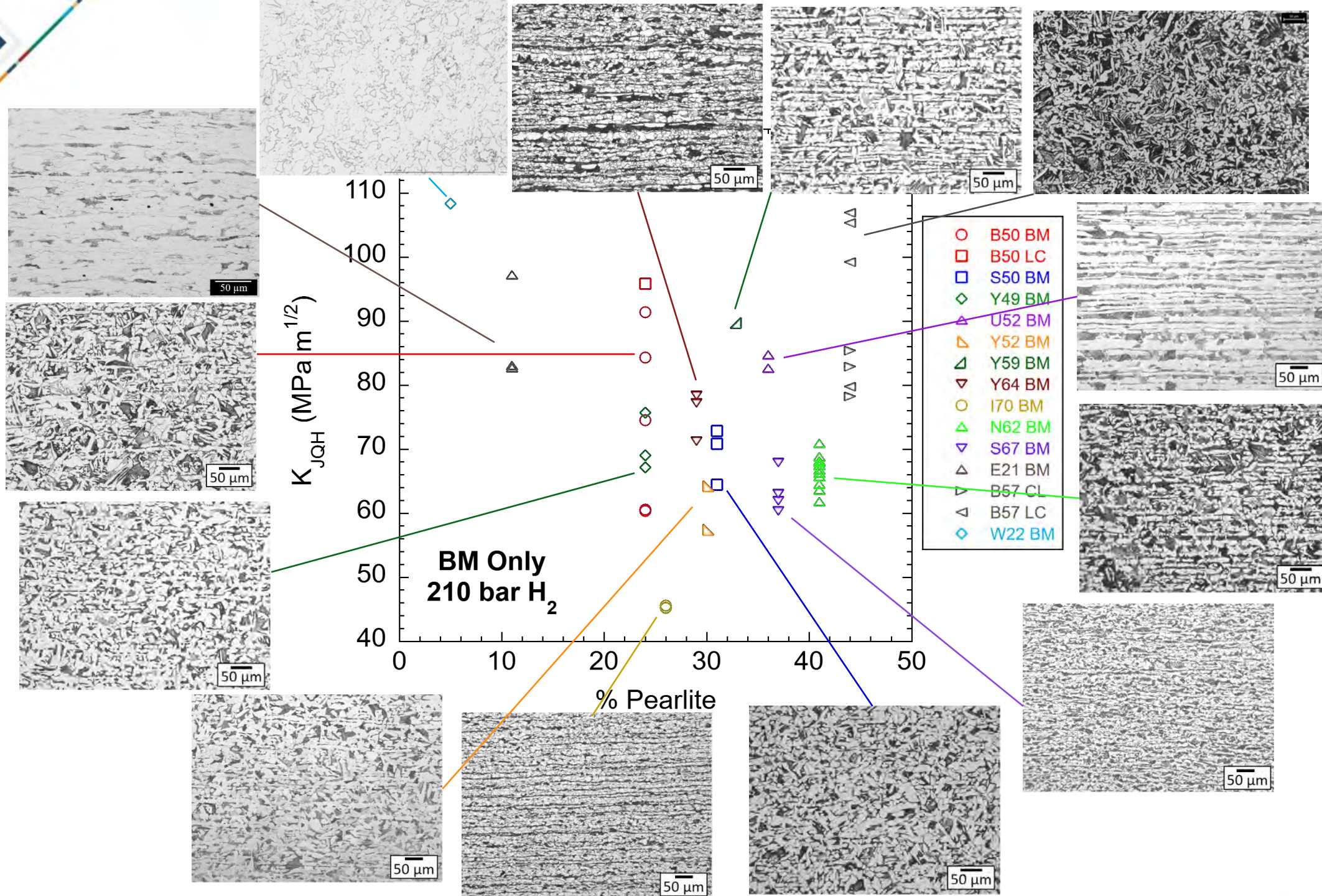


Several Pipeline Steels have been Fracture Tested in 210 bar GH2

- Vintage X42 (Y49), with LF-ERW SW
- Vintage X46 (S50), with EFW SW
- Vintage X52 (B50), with DSAW SW and GW
- Vintage X52 (U52), with LF-ERW SW
- Vintage X52 (Y52), with LF-ERW SW
- Vintage X52 (Y59), with LF-ERW SW
- Vintage X52 (Y64), with LF-ERW SW
- Vintage X52 (N62), with EFW SW
- Vintage X52 (B57), with DSAW SW and GMAW GW
- Vintage X60 (I70), with GW
- Vintage X60 (S67), with EFW SW
- Modern X52 (W22), with GW
- Modern X70 (E21)

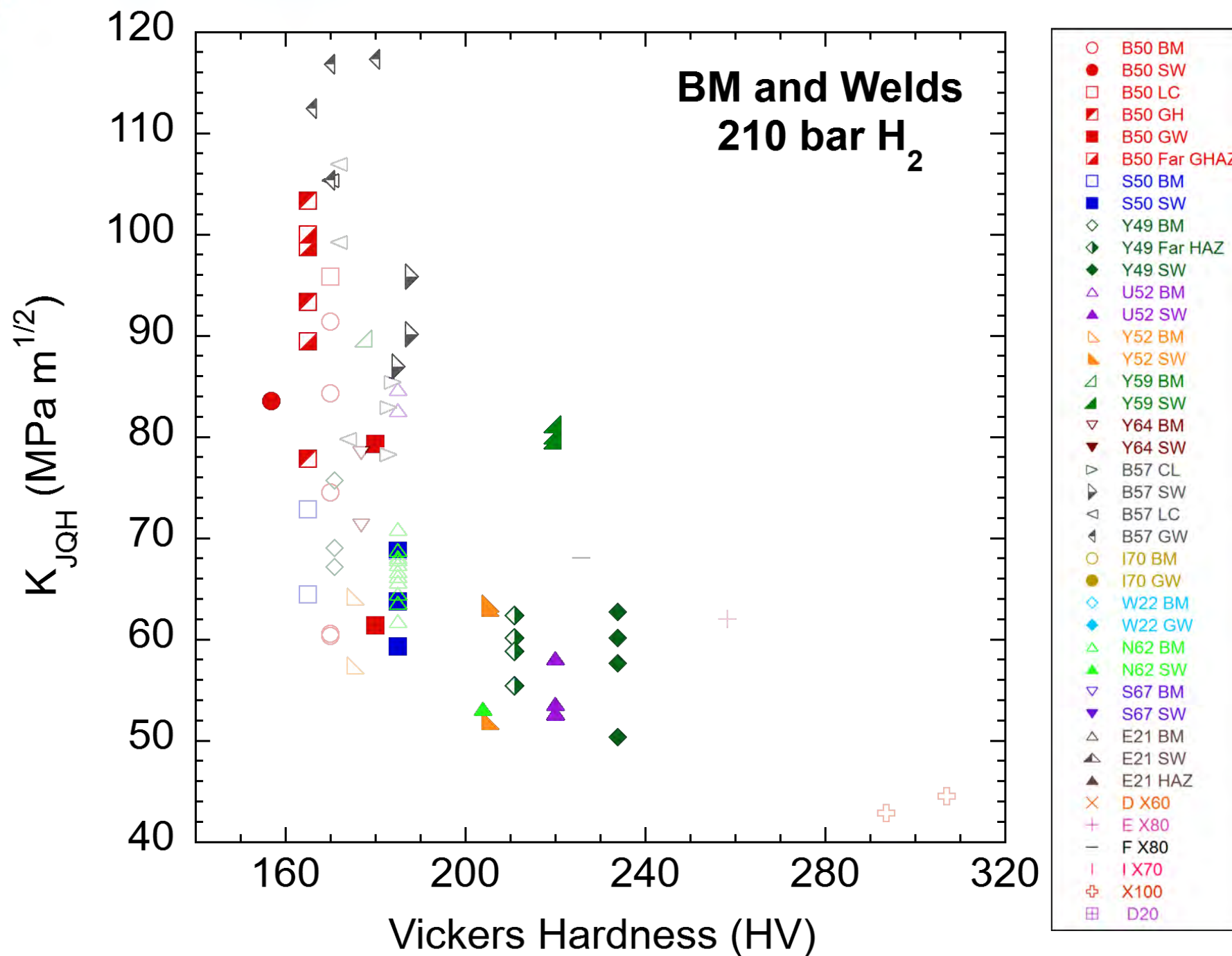


% Pearlite – Base Metal





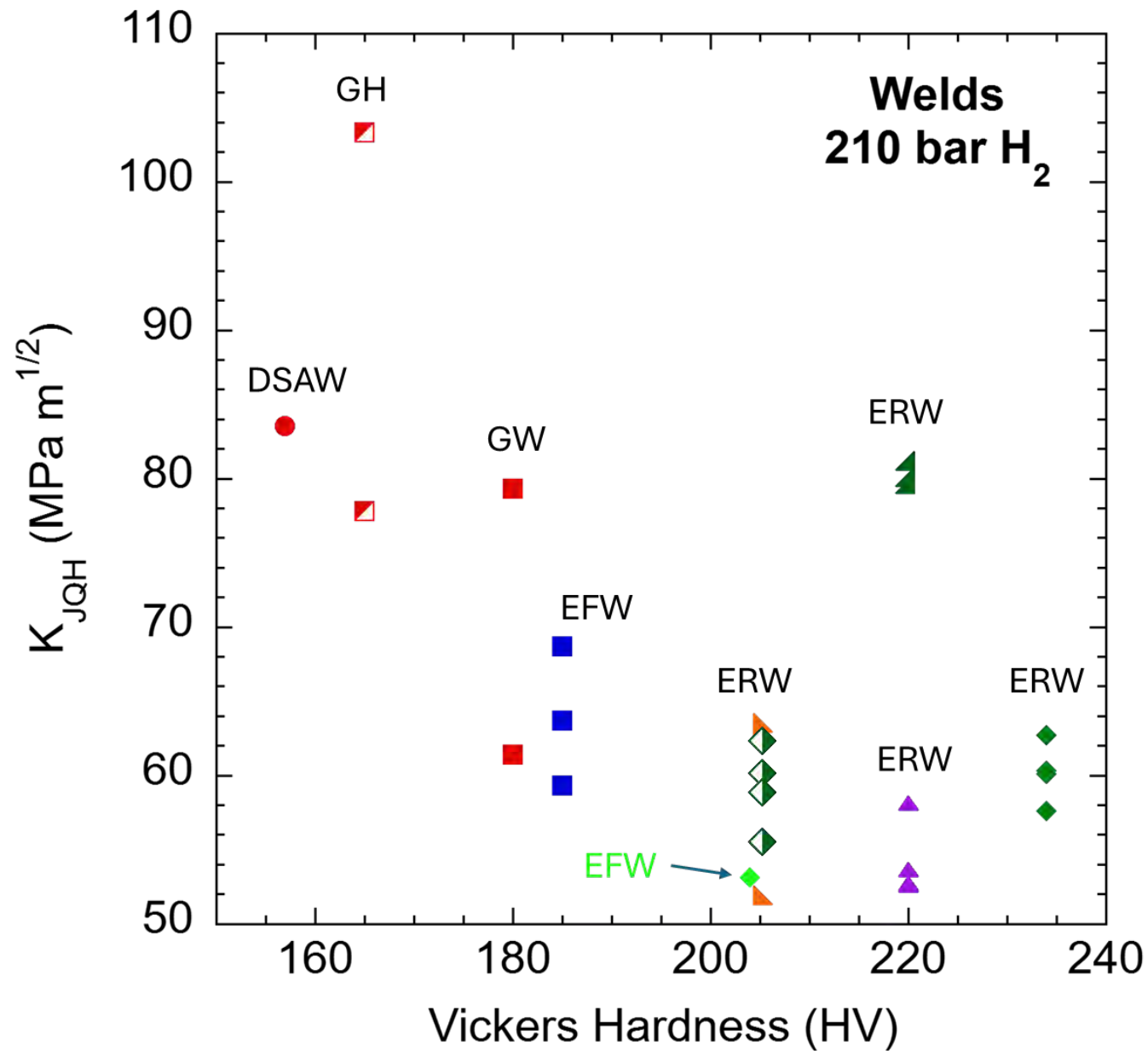
HARDNESS



26 conditions



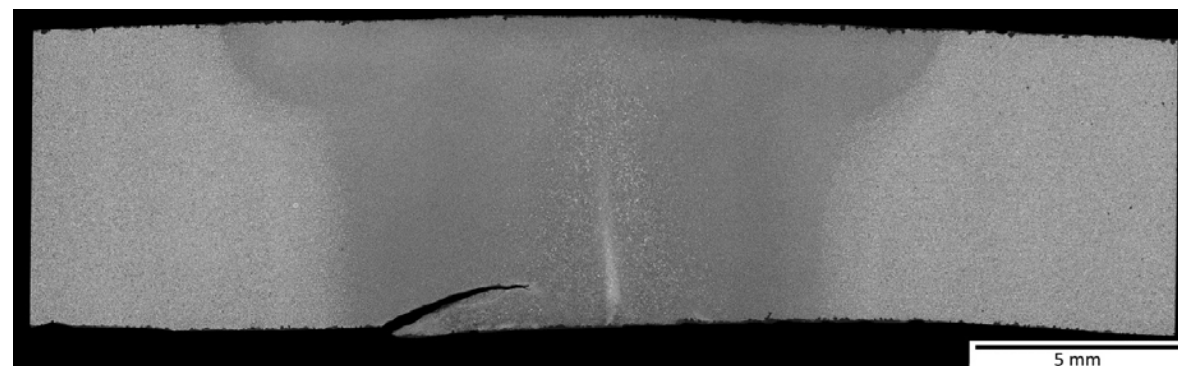
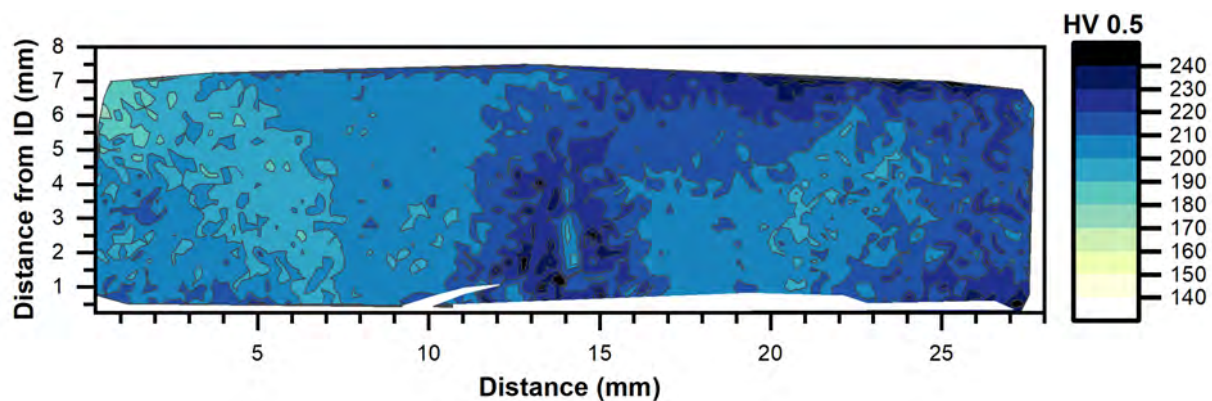
HARDNESS – Welds



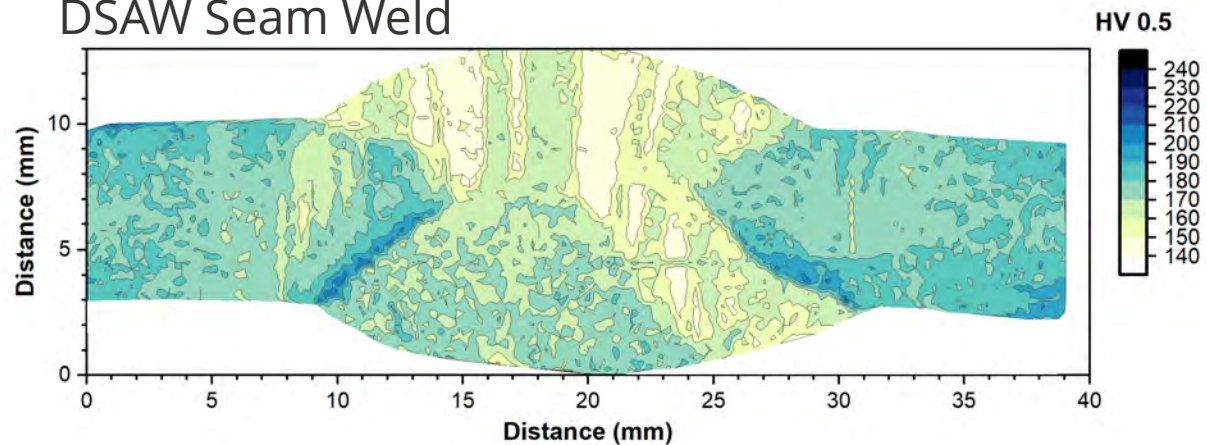


Weld Characterization by EPRI (in progress)

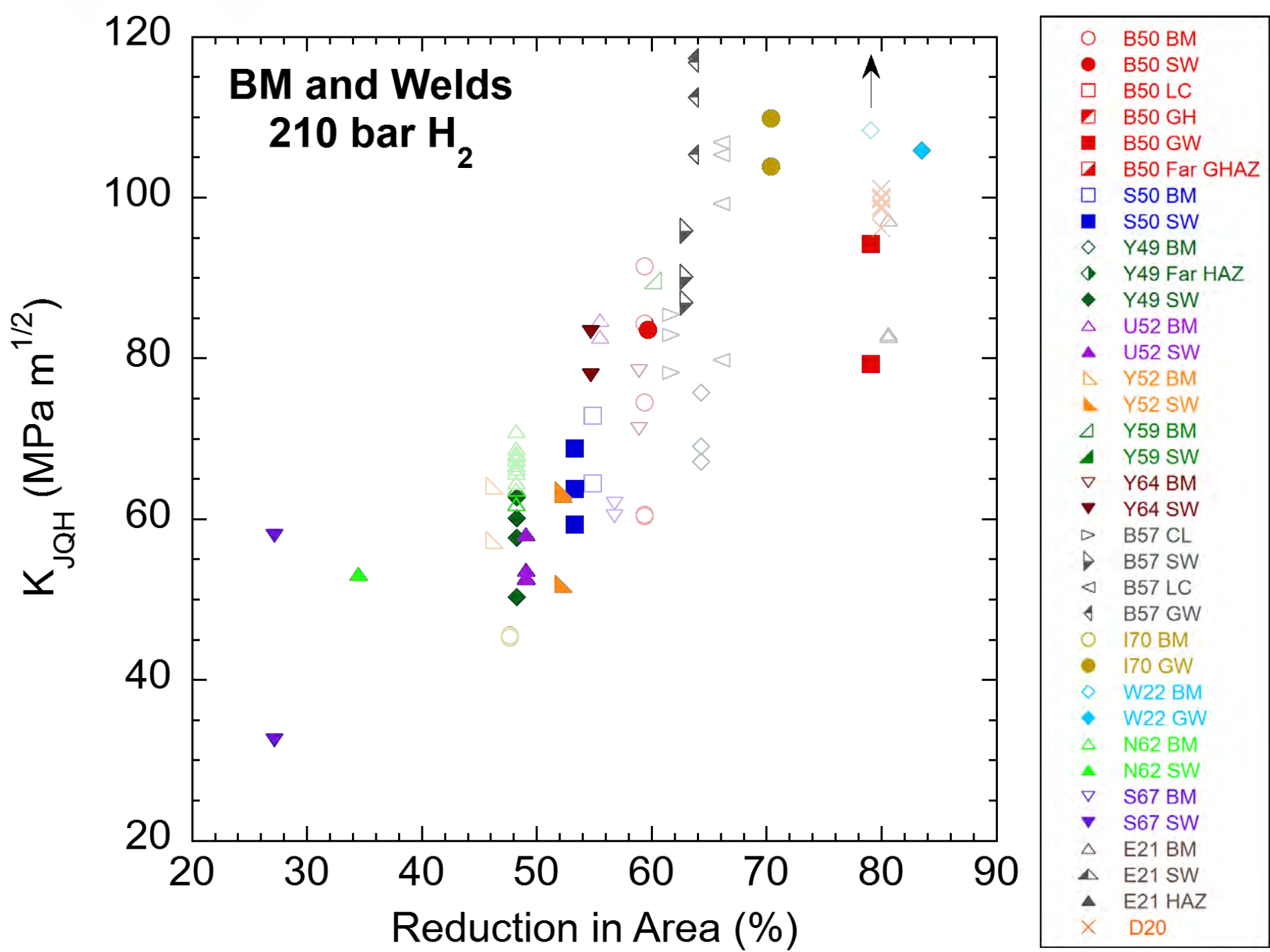
X52 (Y59)
LF-ERW Seam Weld



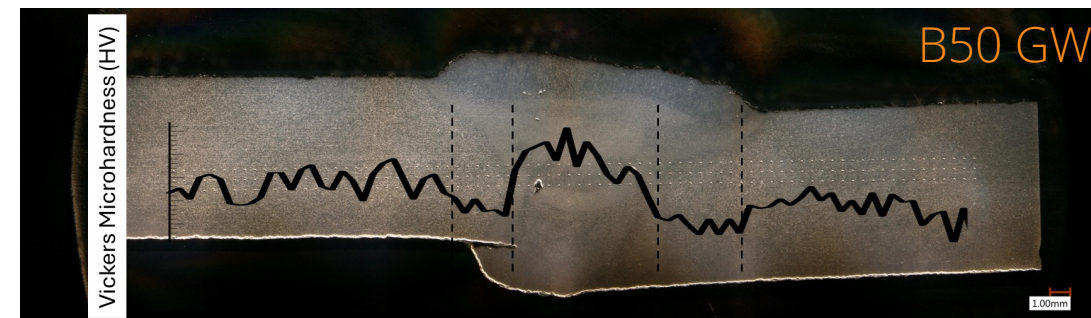
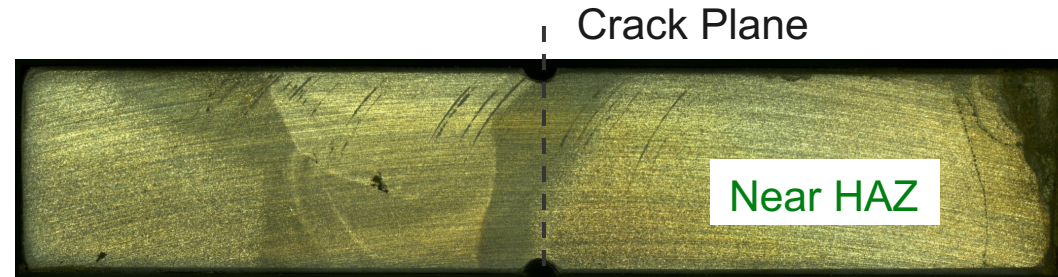
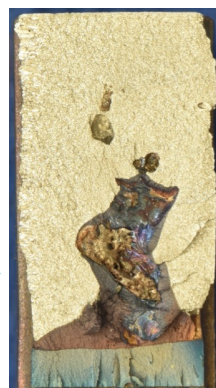
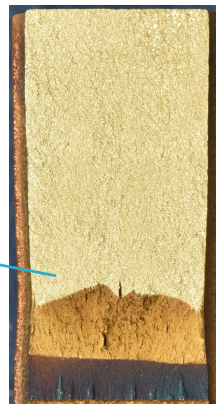
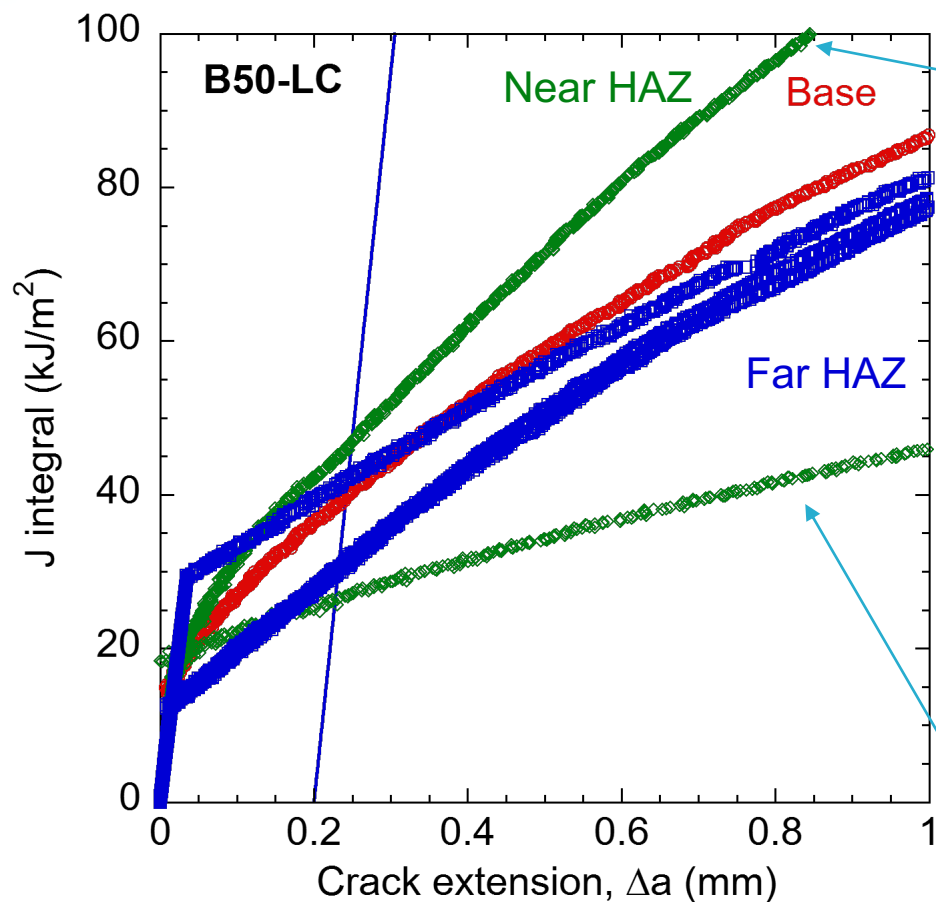
X52 (B50)
DSAW Seam Weld



Reduction in Area



28 conditions



B50 GW contains many defects, but HAZ has lower hardness and higher toughness compared to the BM in the absence of defects. Emphasizes materials property vs. defect-driven performance.



Questions / Feedback

Is this exercise / information useful?

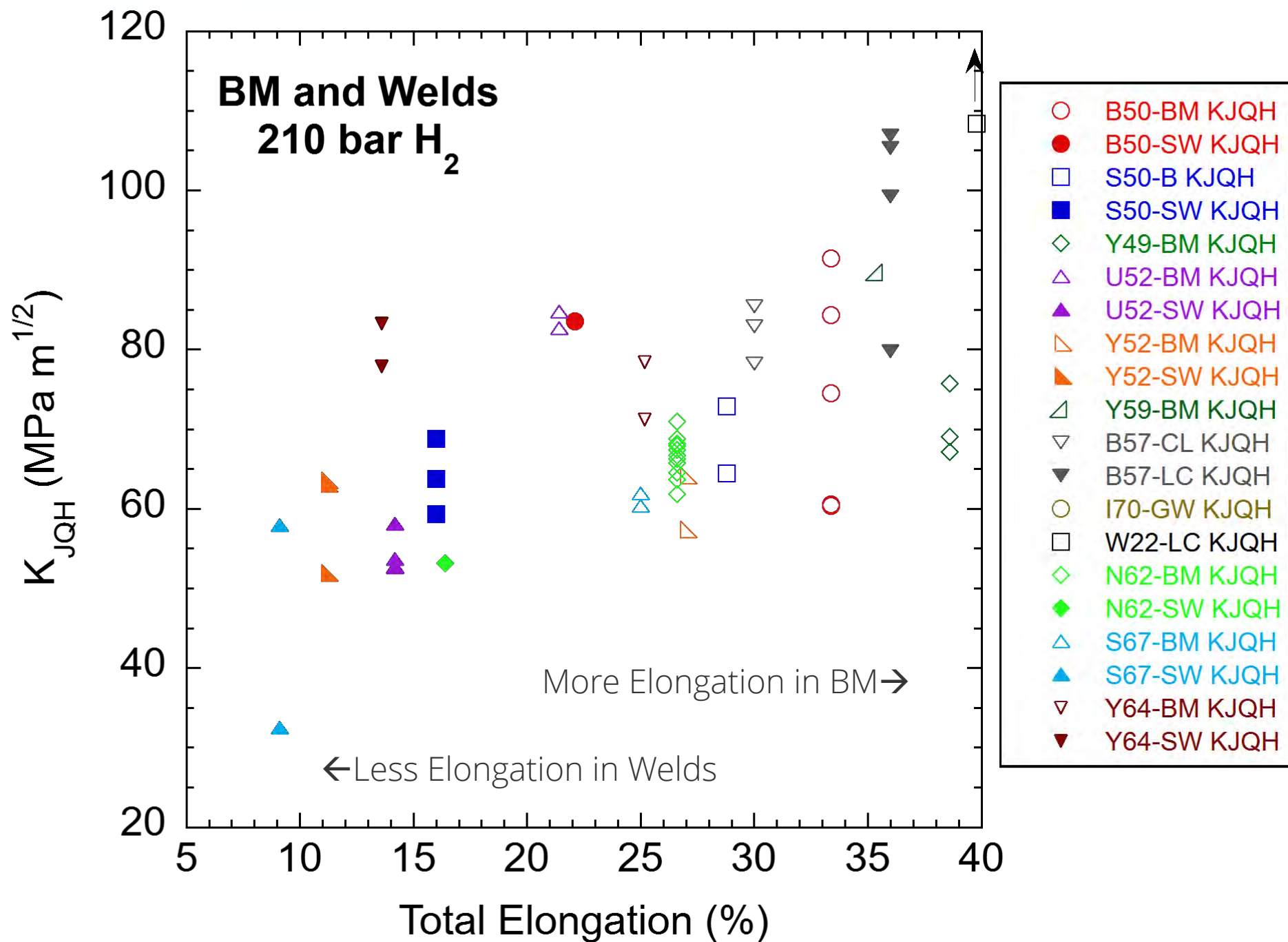
Are there other welds that should be tested? What's missing?

What other feedback would you like to share?





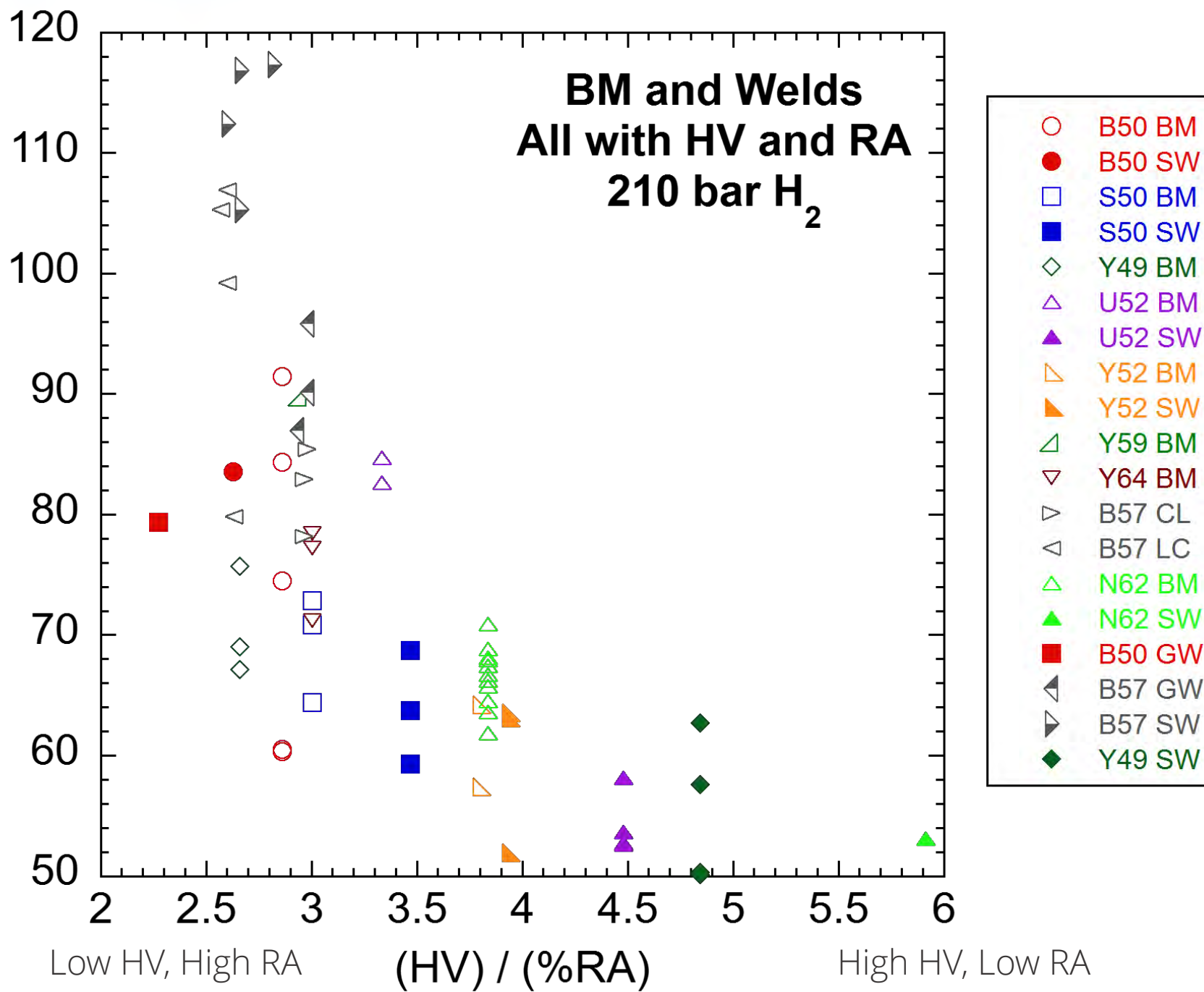
TOTAL ELONGATION





HV / RA

K_{JQH} (MPa m^{1/2})





Exceptional service in the national interest

Challenges With Testing Welds for Hydrogen Service – XM-19 Gas Tungsten Arc Weld Case Study

H₂ Study Group, PVP 2026, Anaheim, CA

Quinten Yurek, Michelle Kent

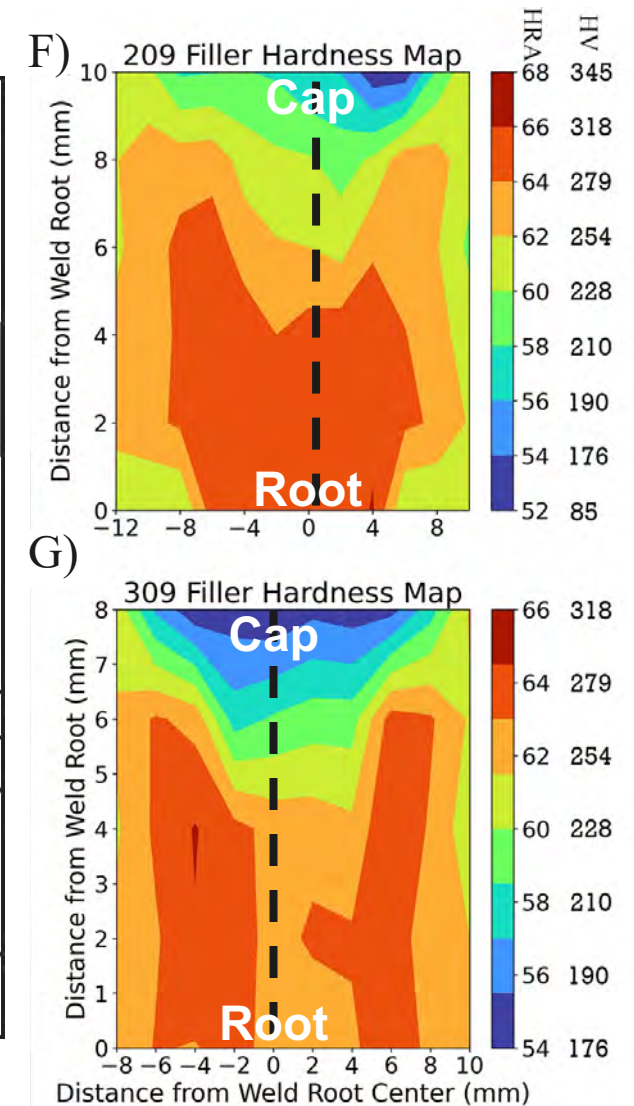
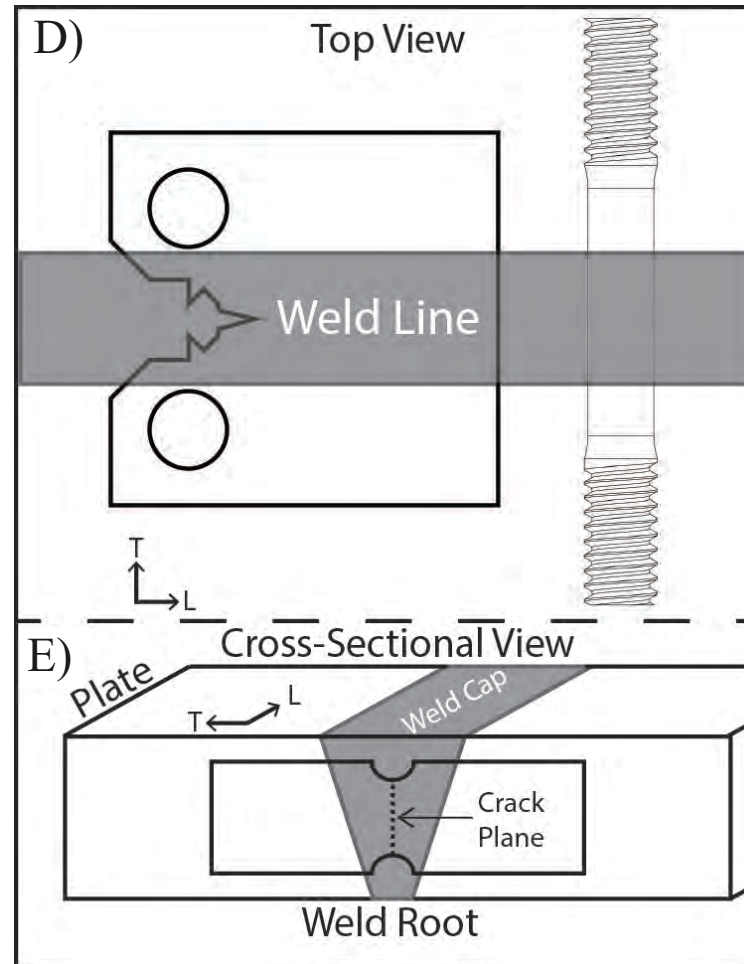
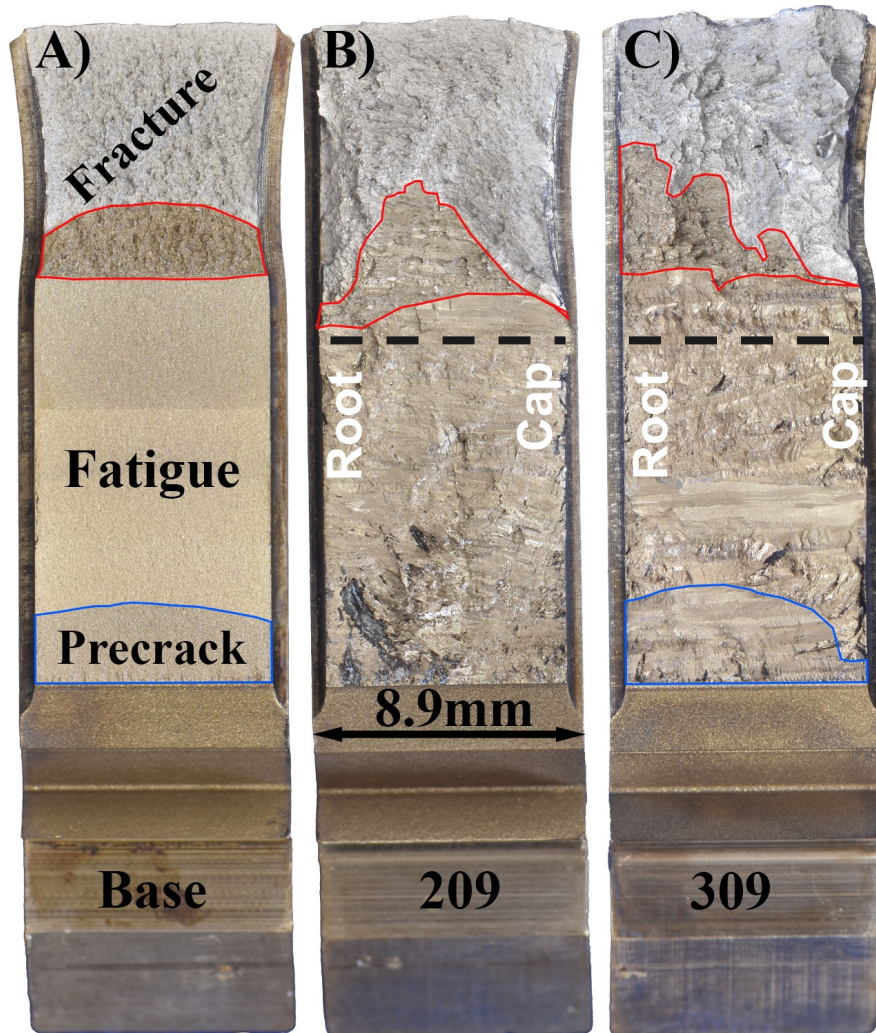
Sandia National Laboratories, Hydrogen Effects on Materials Lab

July 24 2026

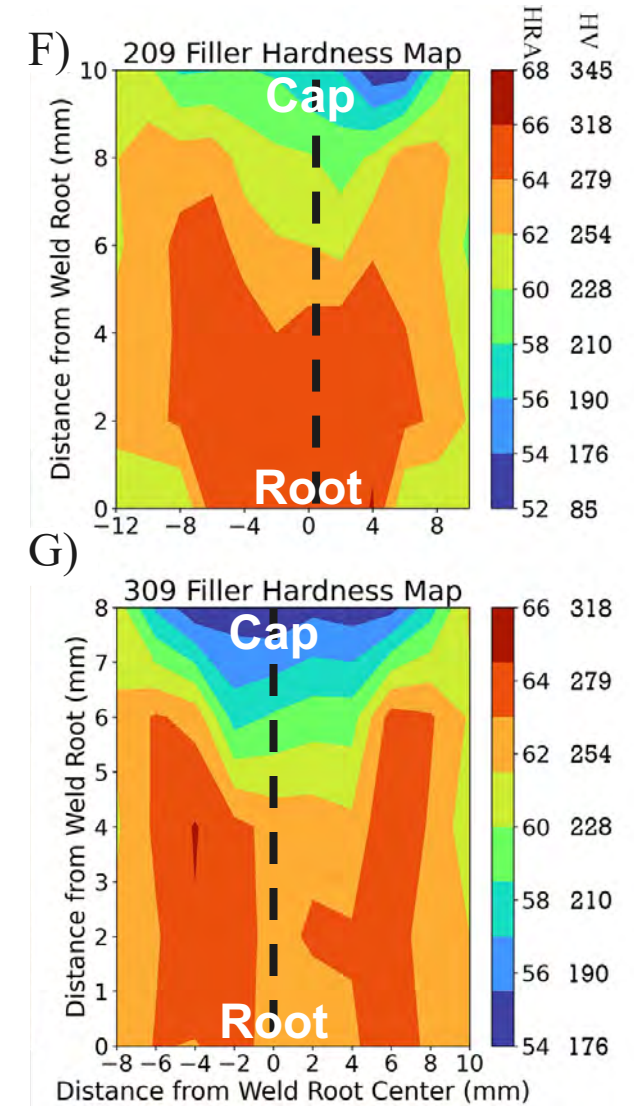
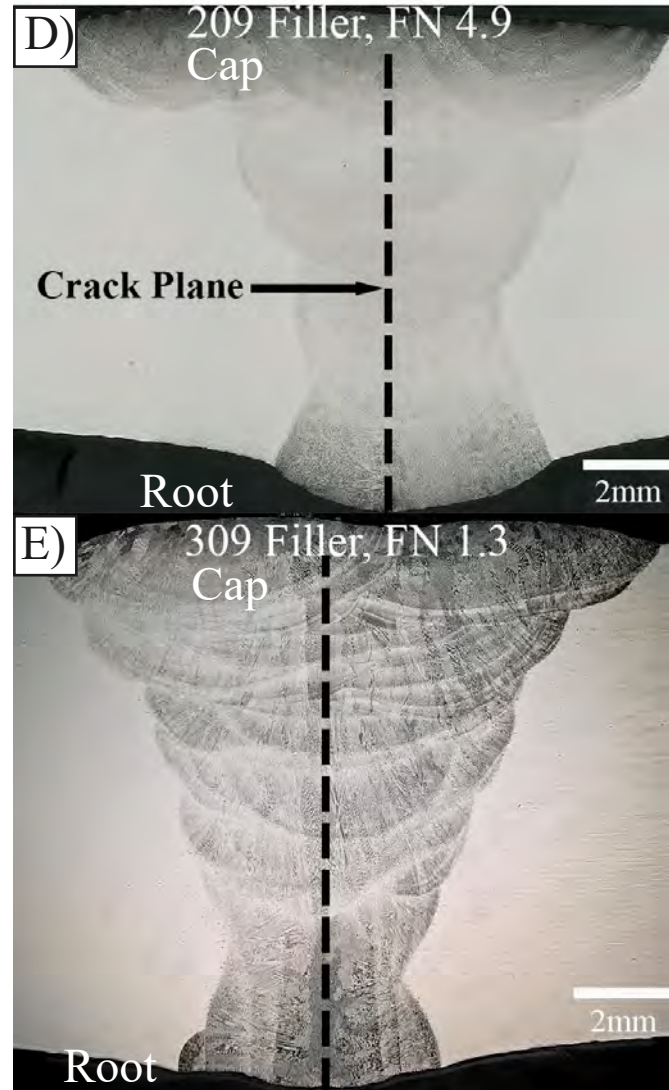
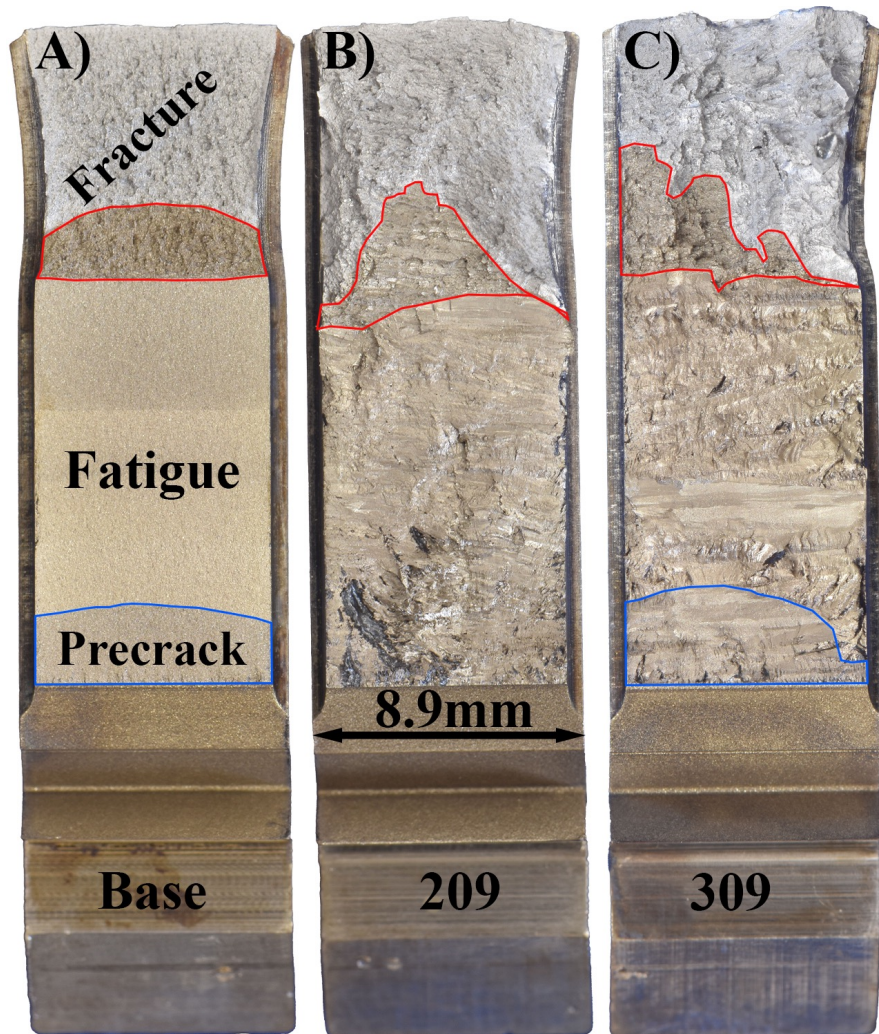


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Hardness gradient influences fracture path



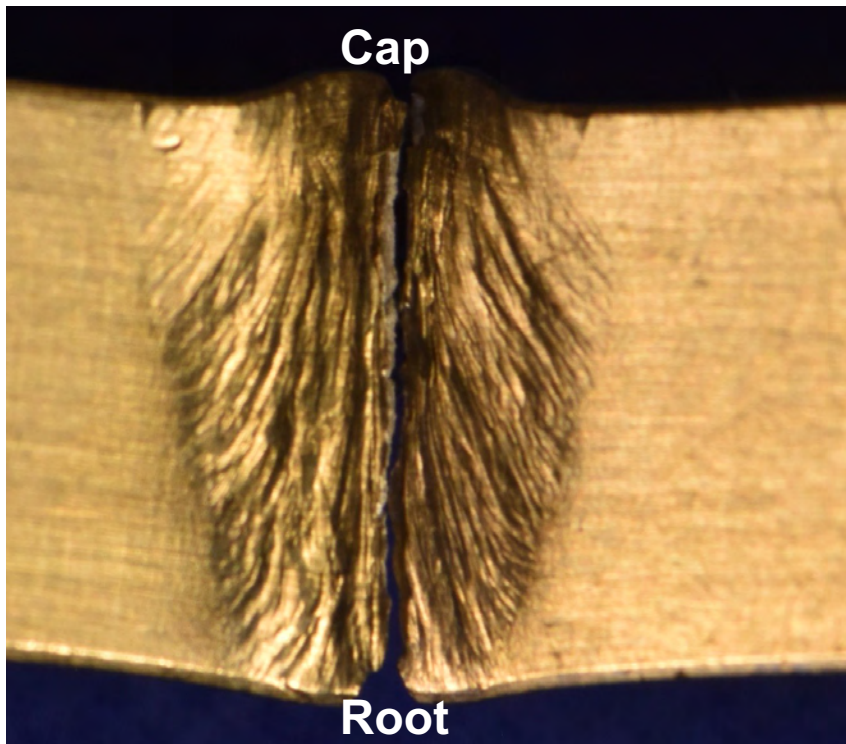
Hardness gradient influences fracture path



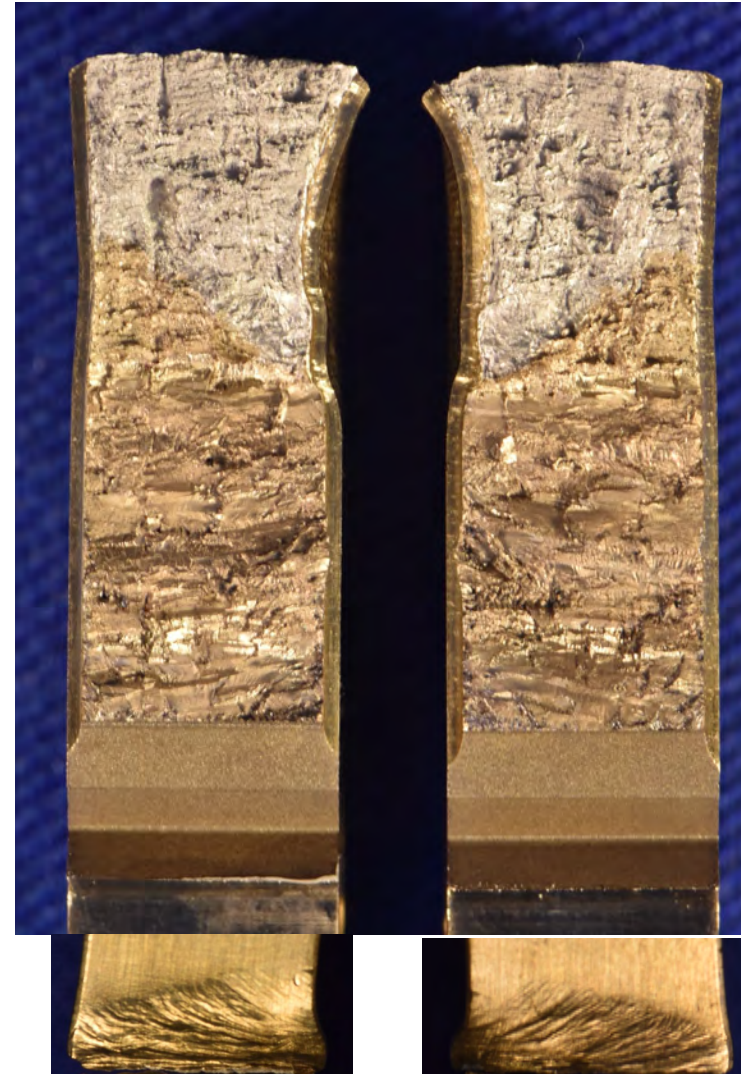
Fracture path always moves away from low hardness side



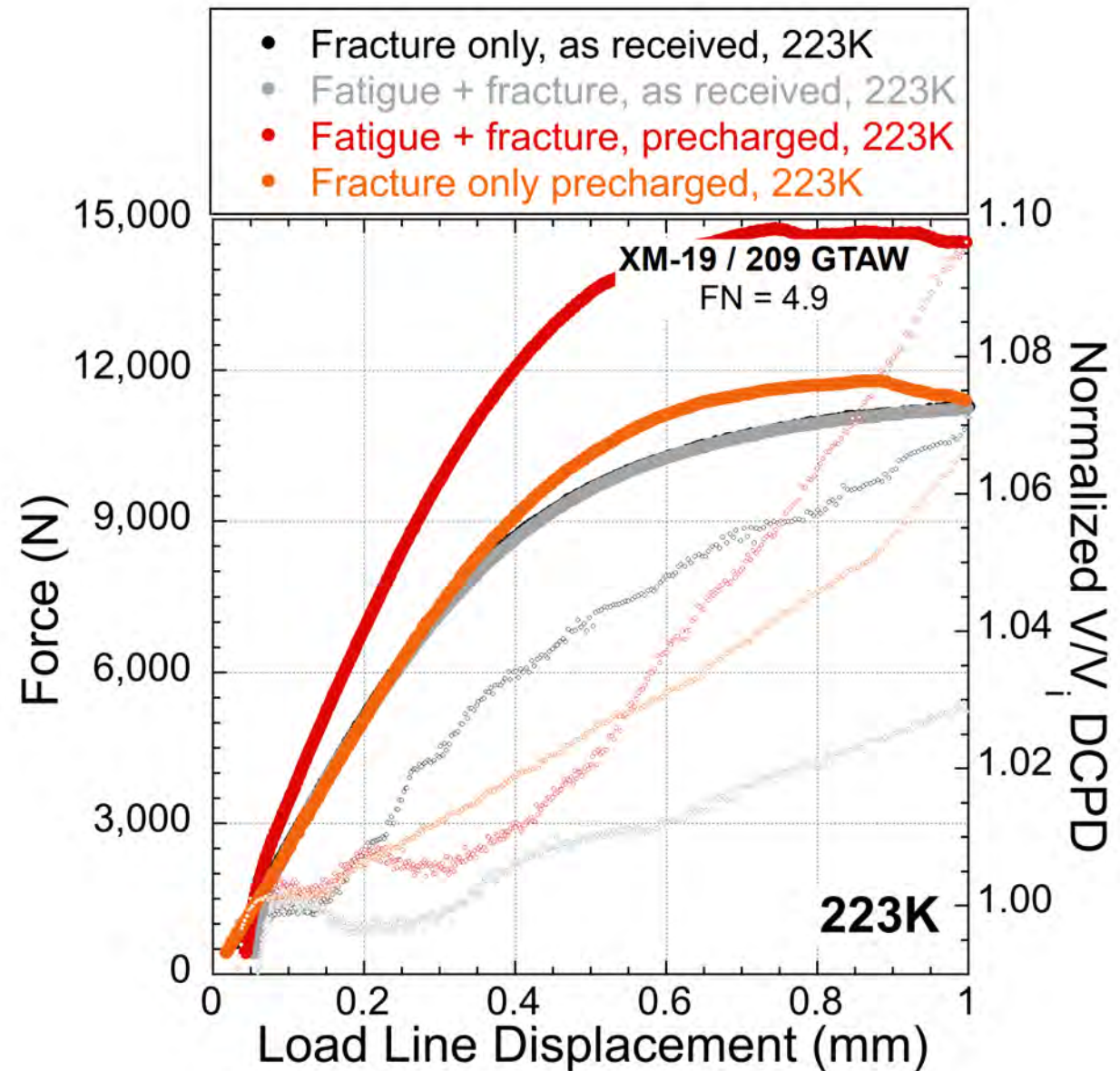
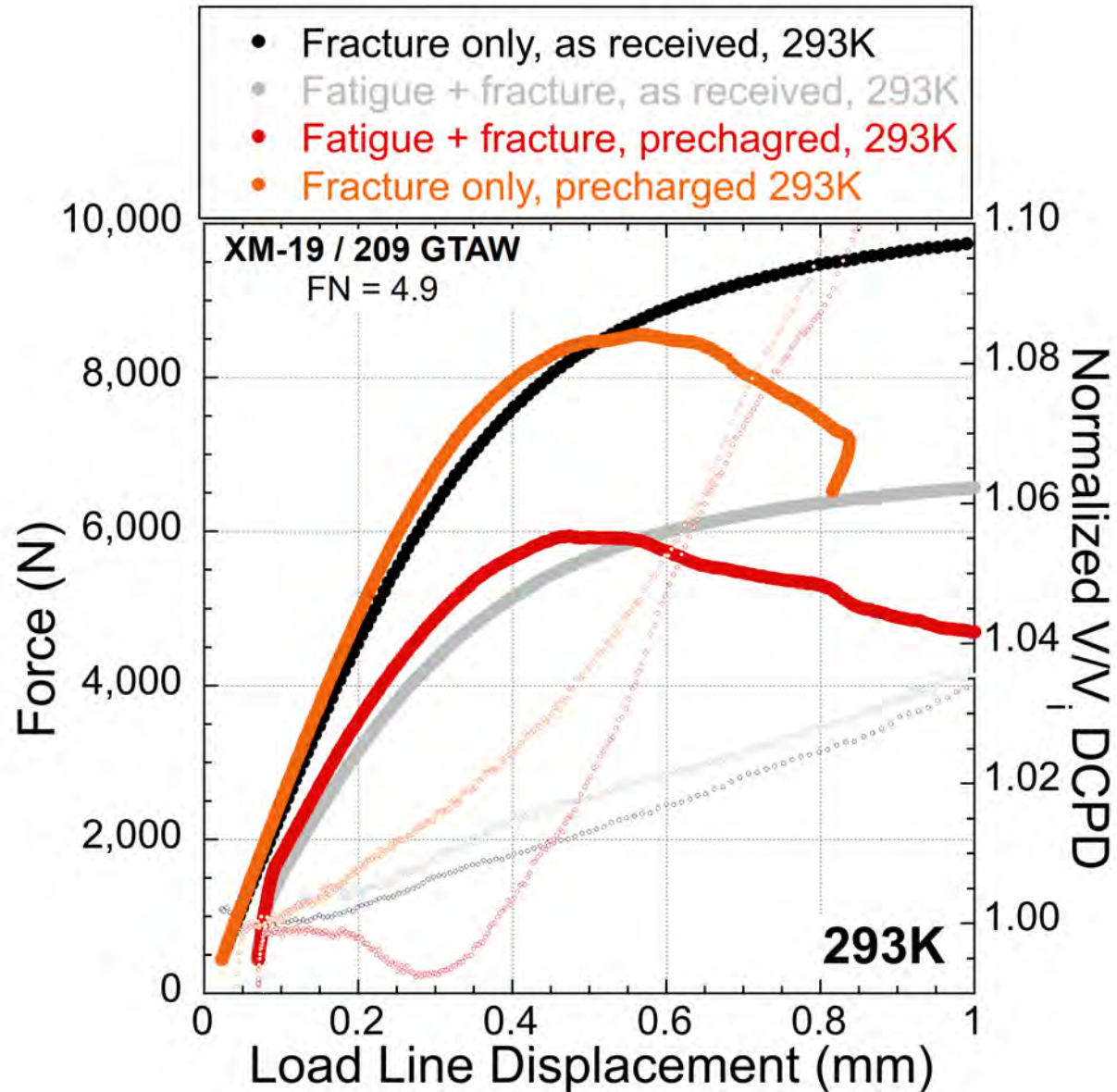
Back face of CT specimen: weld imprint is seen via plastic deformation



309 Filler Weld no-H, Air

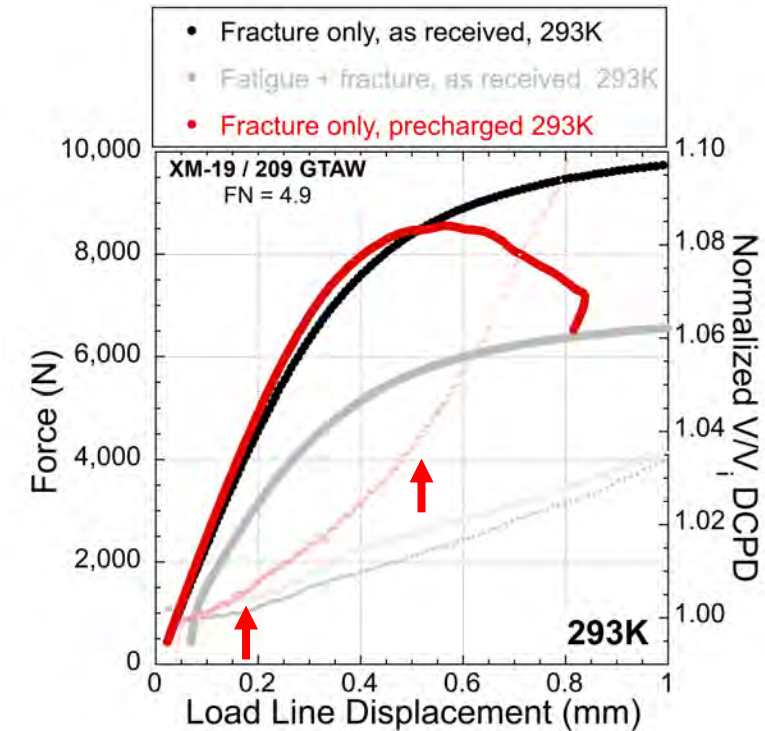
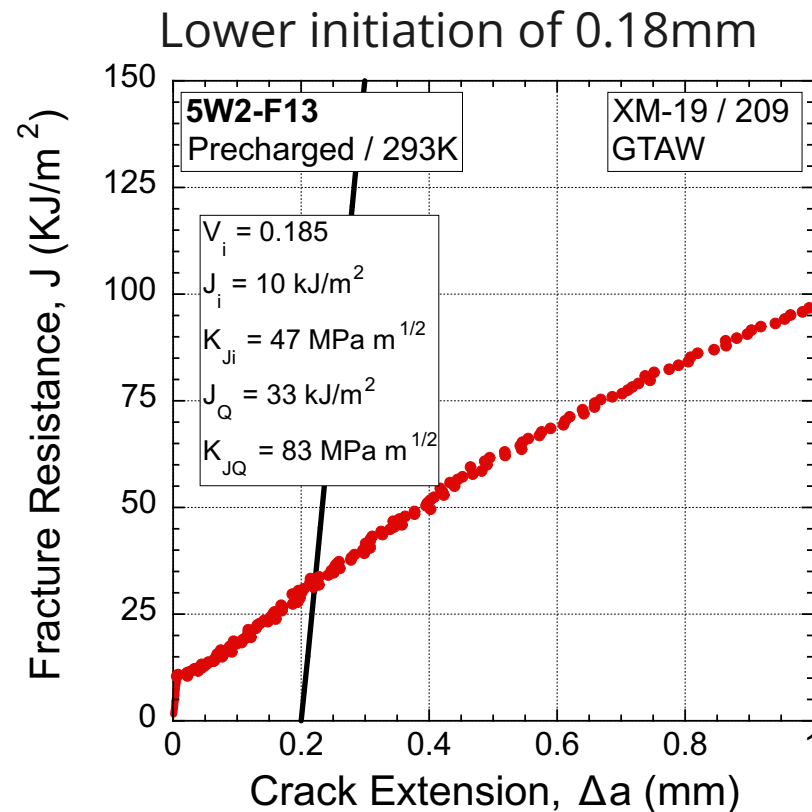
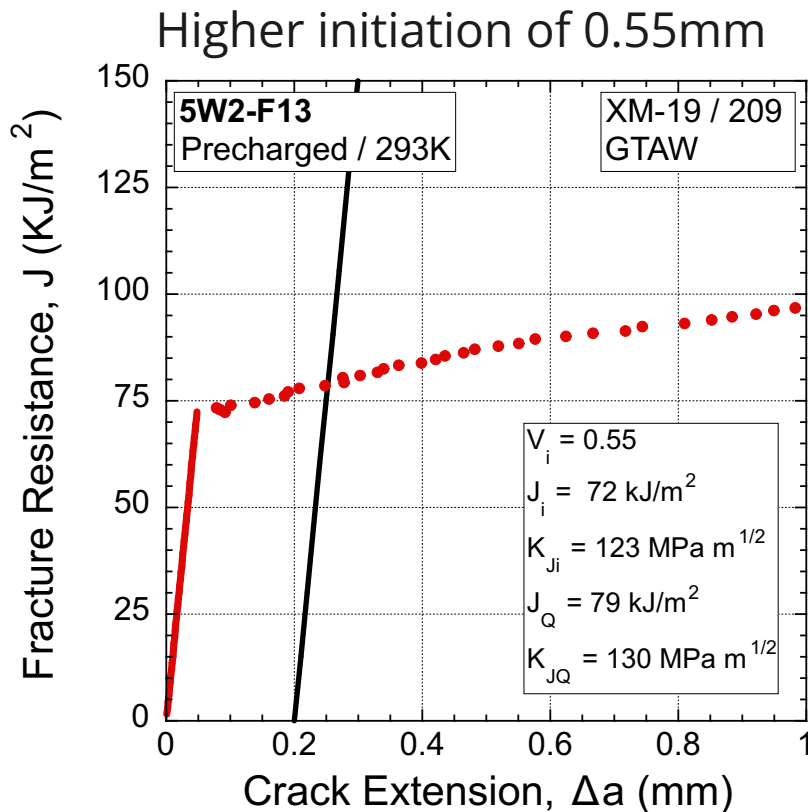


Difficulty with initiation selection in 209 filler weld



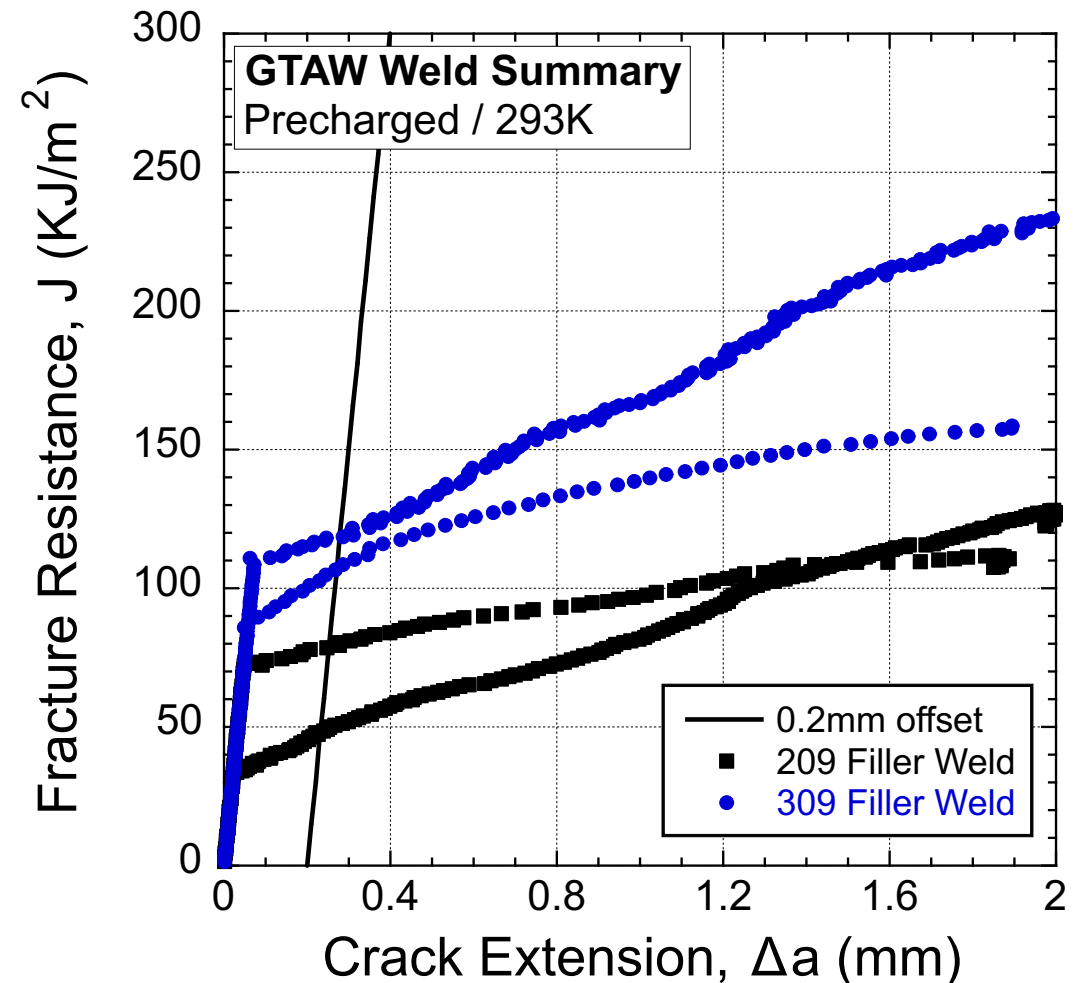
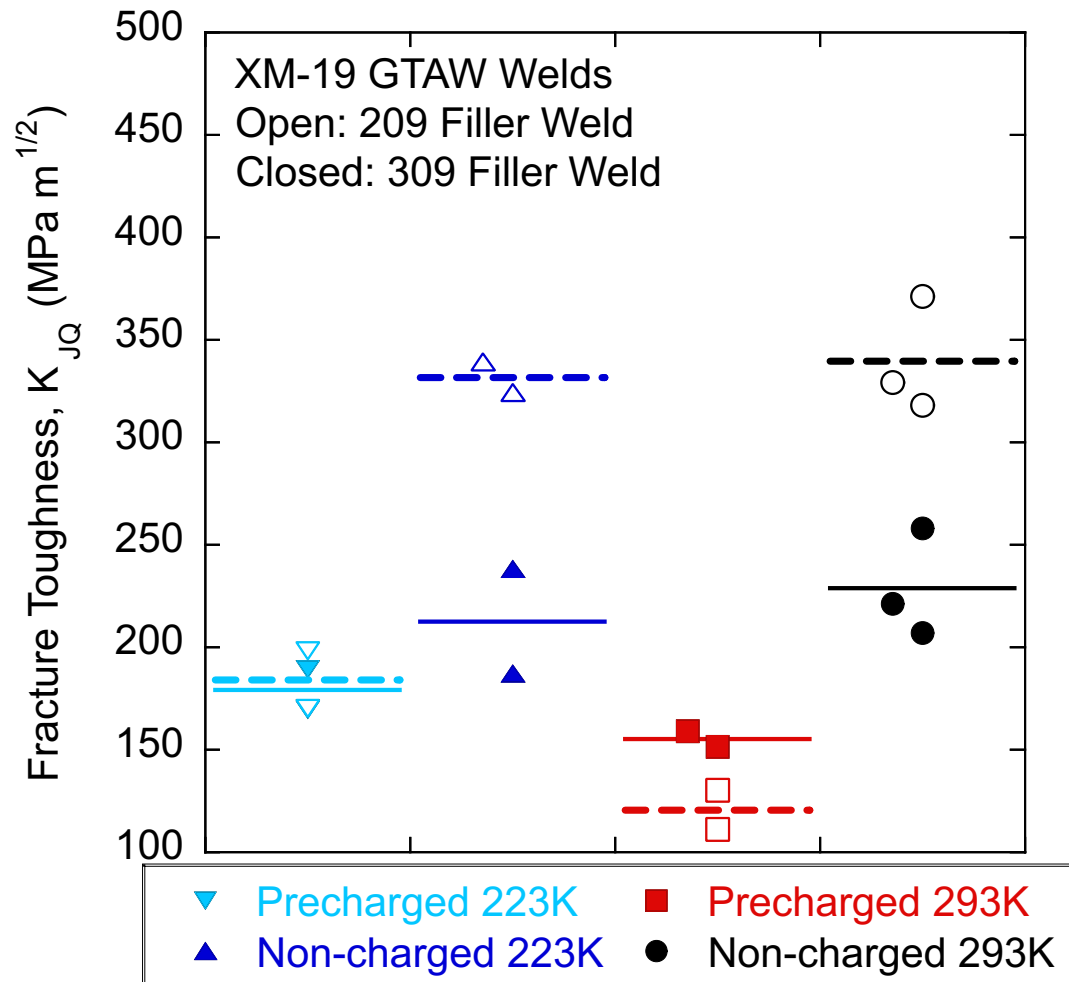
Effect of initiation selection on JR Curve

- Nonuniform crack fronts and material property gradients contribute to the difficulty in initiation selection.



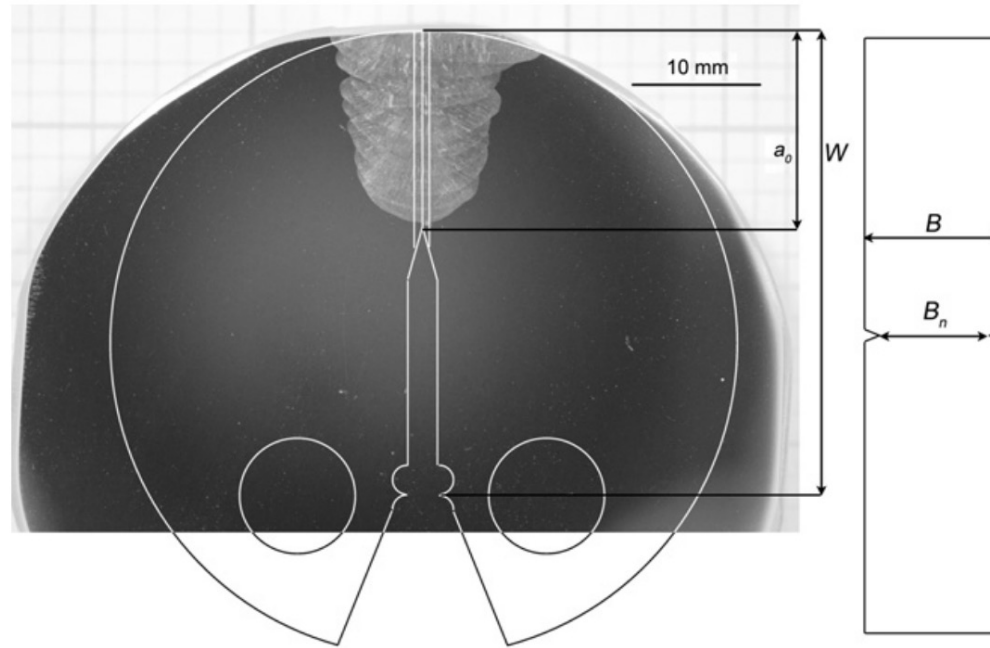
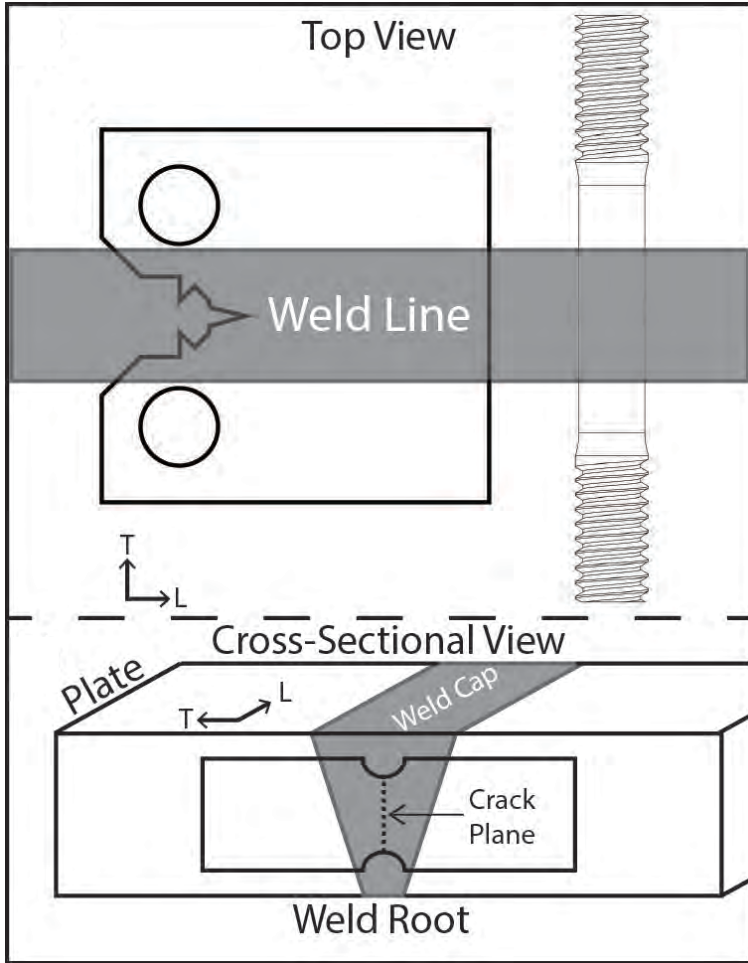
Non-uniform crack fronts produce consistent $K_{0.2\text{mm}}$ values

- The consistency in these results may relate to the small crack extension needed to reach the 0.2mm offset intersection.
- How the JR curves develop after the 0.2mm offset are clearly different and indicate nonuniform behavior.

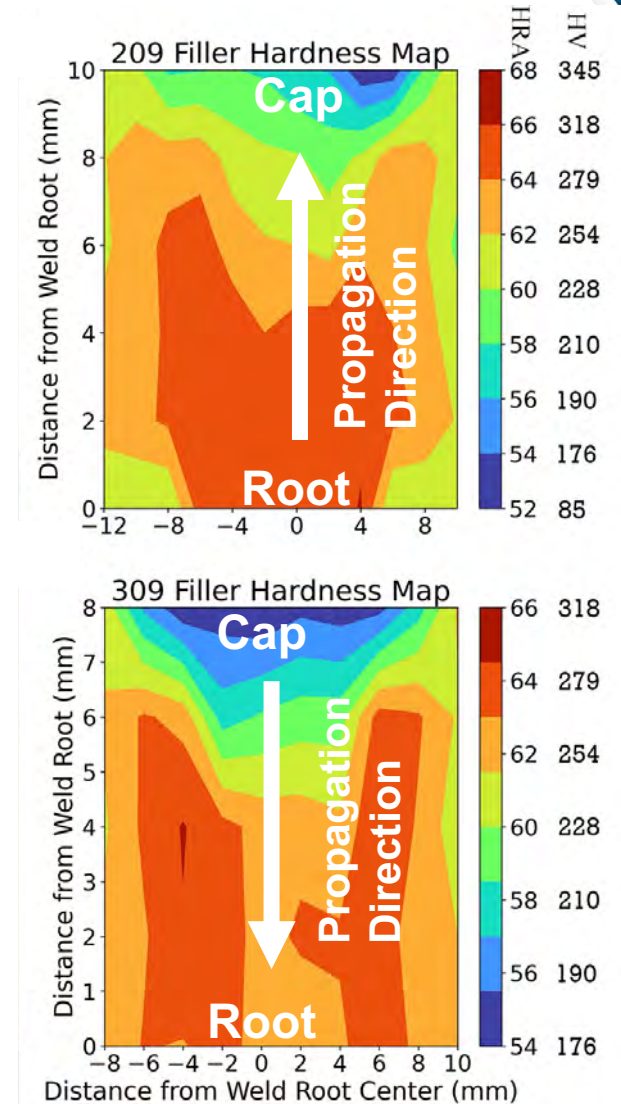


Material property gradients and orientation challenges

- Knowledge of material property gradients and the inability to test the weld in specific orientations highlights a lack of understanding in weld deformation behavior.



H. Jackson et al. Corrosion Science, 2012



Example of strong orientation effect in XM-19



- [1] shows an orientation effect in XM-19 base material that may be present in an XM-19 weld if a different orientation was tested
- The effects of known inhomogeneities and gradients within welds may be exaggerated in different orientations.

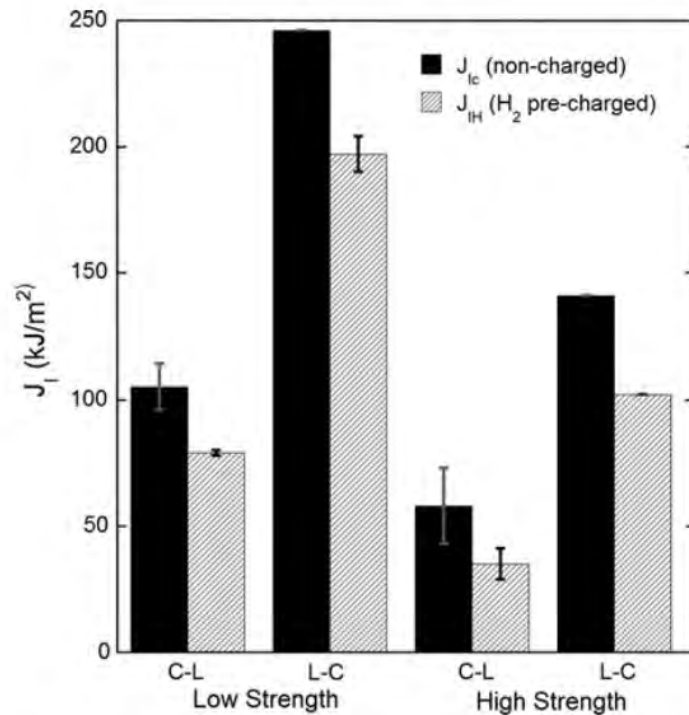


Fig. 3—Average values of J_{IC} and J_{IH} for each specimen condition are plotted. The decreased toughness due to hydrogen precharging is modest relative to the variations associated with strength and crack-growth orientation.

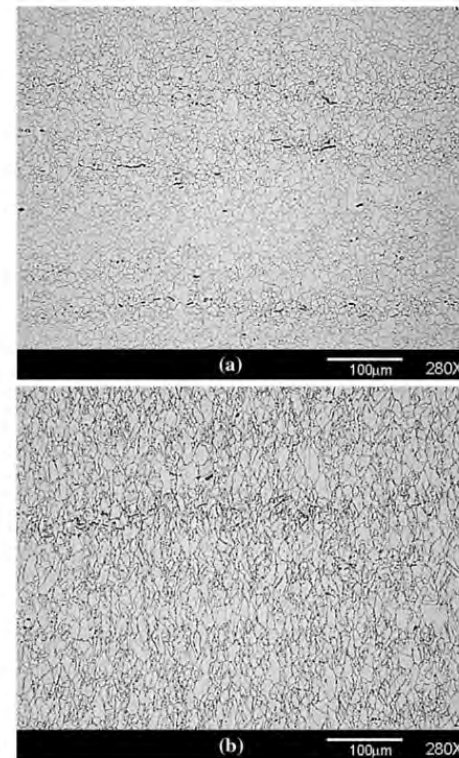


Fig. 2 Optical images of (a) low-strength 22-13-5 forging and (b) high-strength 22-13-5 forging. Each image is taken from the middle of the forging, where the forging axis (and original bar stock axis) is horizontal in each image.

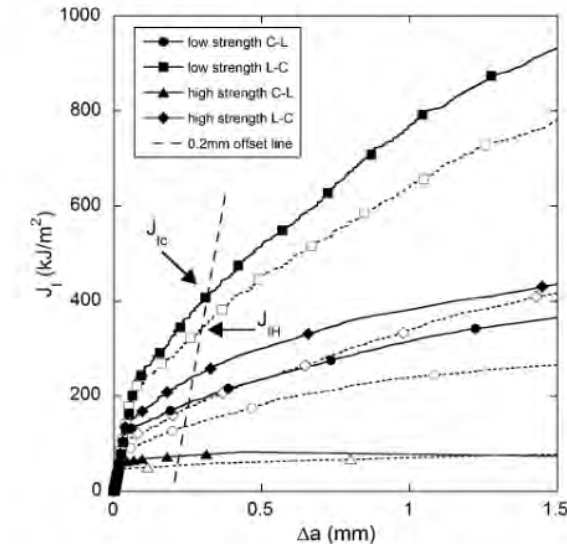


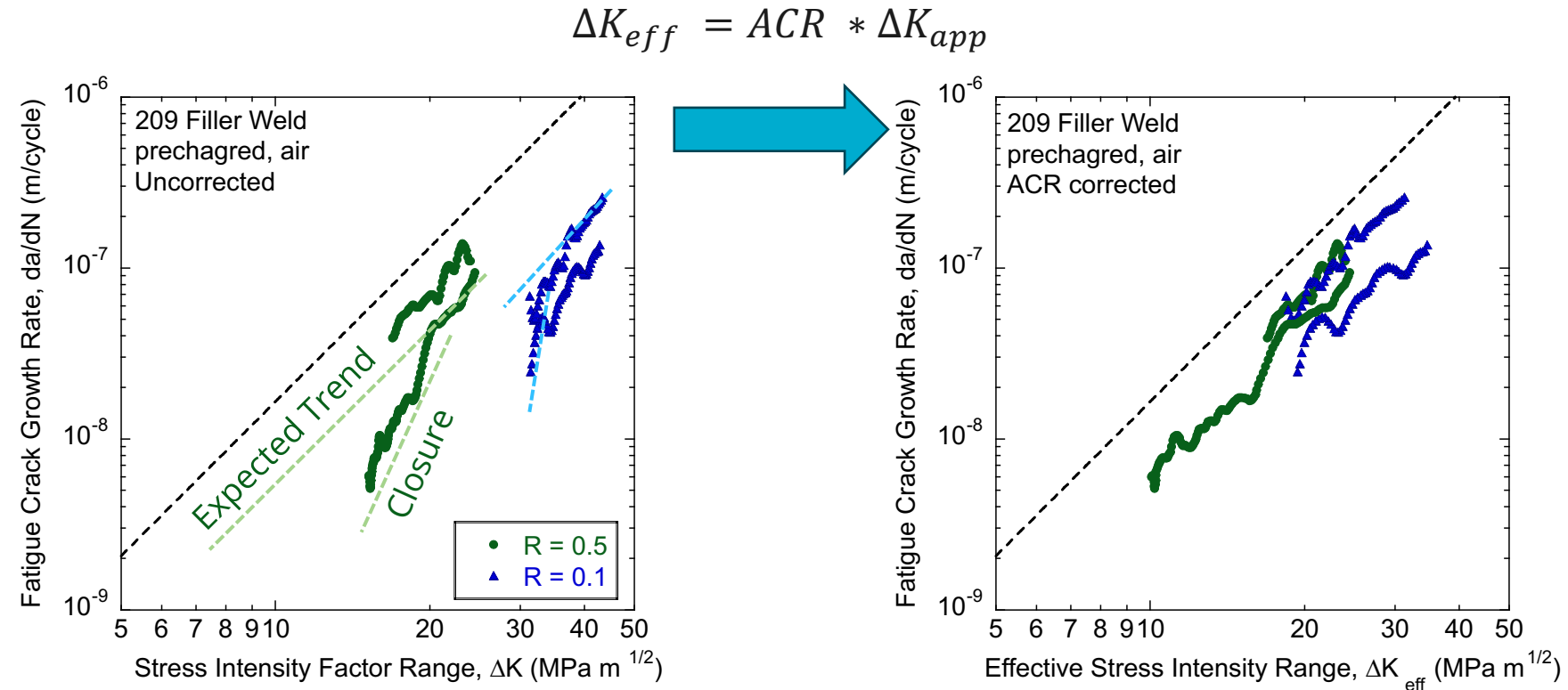
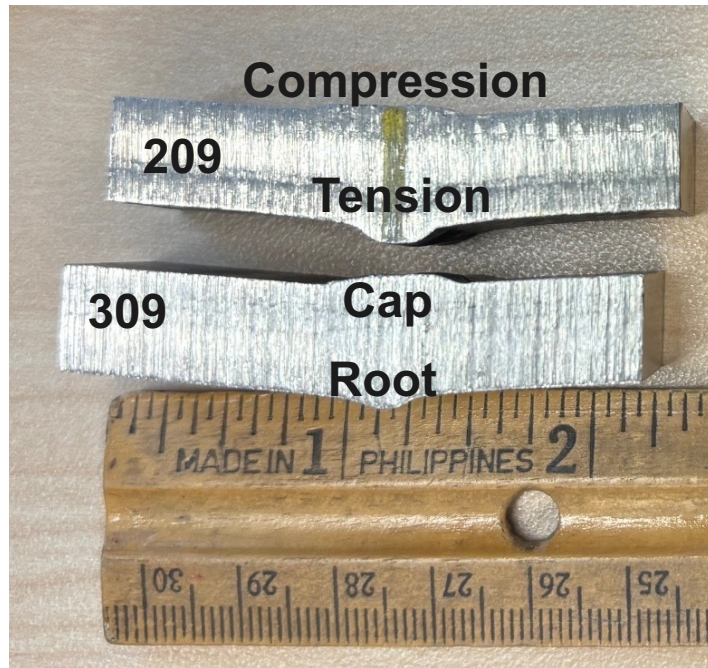
Fig. 4 Representative crack-growth resistance curves for each condition of 22-13-5. Solid lines and solid symbols represent noncharged specimens, while the dashed lines and open symbols represent hydrogen-precharged specimens.

Success with ACR FCGR Corrections



Adjusted Compliance Ratio (ACR)

- By accounting for initial, closure, and loading compliance a more precise measurement of ΔK can be estimated allowing correction for closure.



Lessons and Challenges:

What we have learned:

- ACR works well for correcting closure in weld fatigue data.
- Hardness gradients influence the fracture path and complicate fatigue.
- Results for both fatigue and fracture in XM-19 welds are repeatable, yet J-R curves show larger variance outside of the 0.2mm offset intersection.

Challenges Testing Welds:

- Clearly gradients within the weld effect the results yet the broader implications of these gradients are unclear.
- Additional challenges for testing welds
 - Severity of plastic deformation
 - Residual stress
 - Weld quality
- Testing orientation may exaggerate intrinsic gradients within welds.
- Application must be considered to design appropriate testing methods.





Exceptional service in the national interest

Effect of ultra-low hydrogen partial pressure on hydrogen-assisted fatigue and fracture

Chris San Marchi, Joe Ronevich

Sandia National Laboratories, Livermore, CA, USA

Study Group on Materials Testing and Qualification for Hydrogen Service

Anaheim CA, 24 July 2026



U.S. DEPARTMENT
of ENERGY



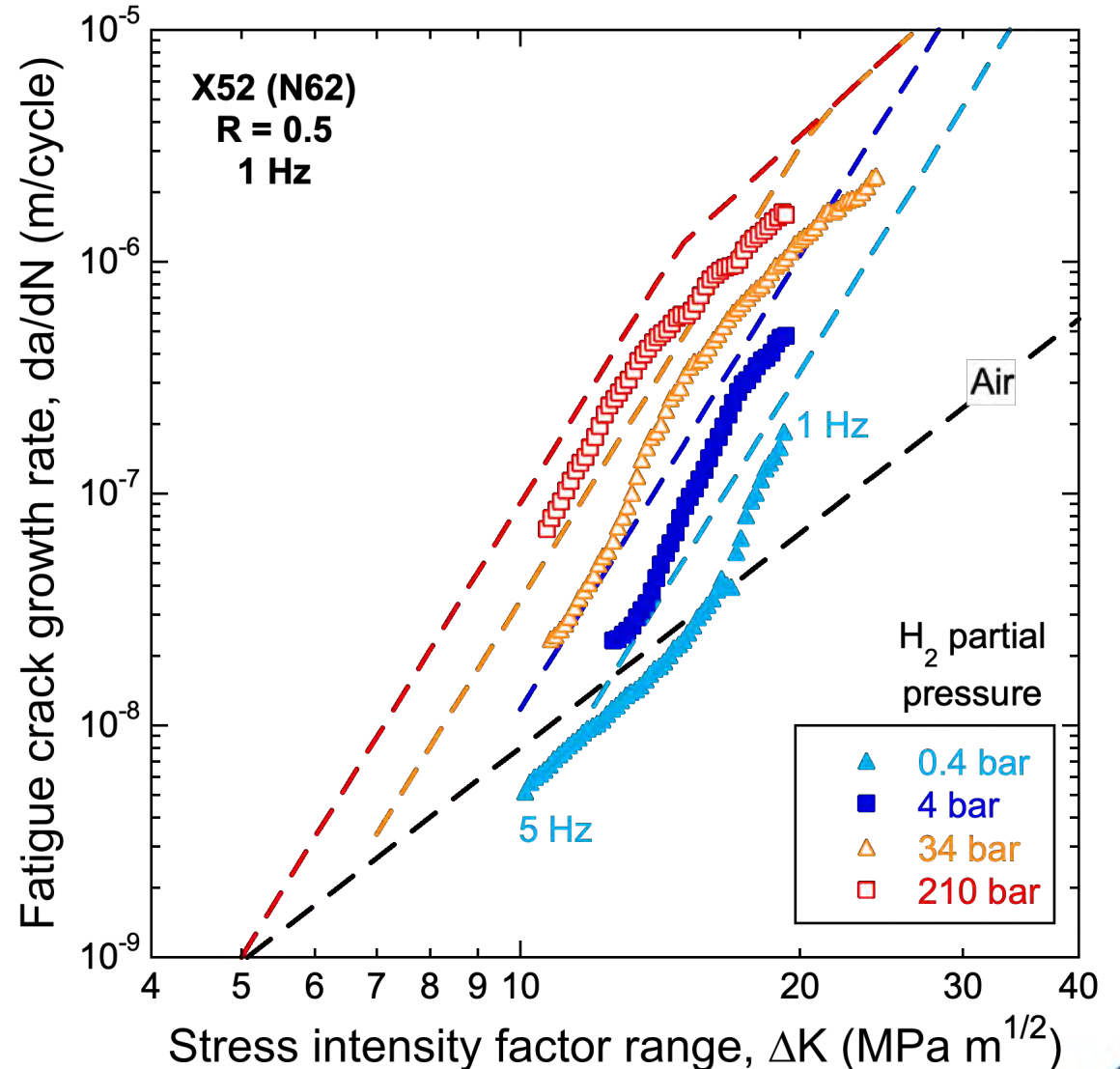
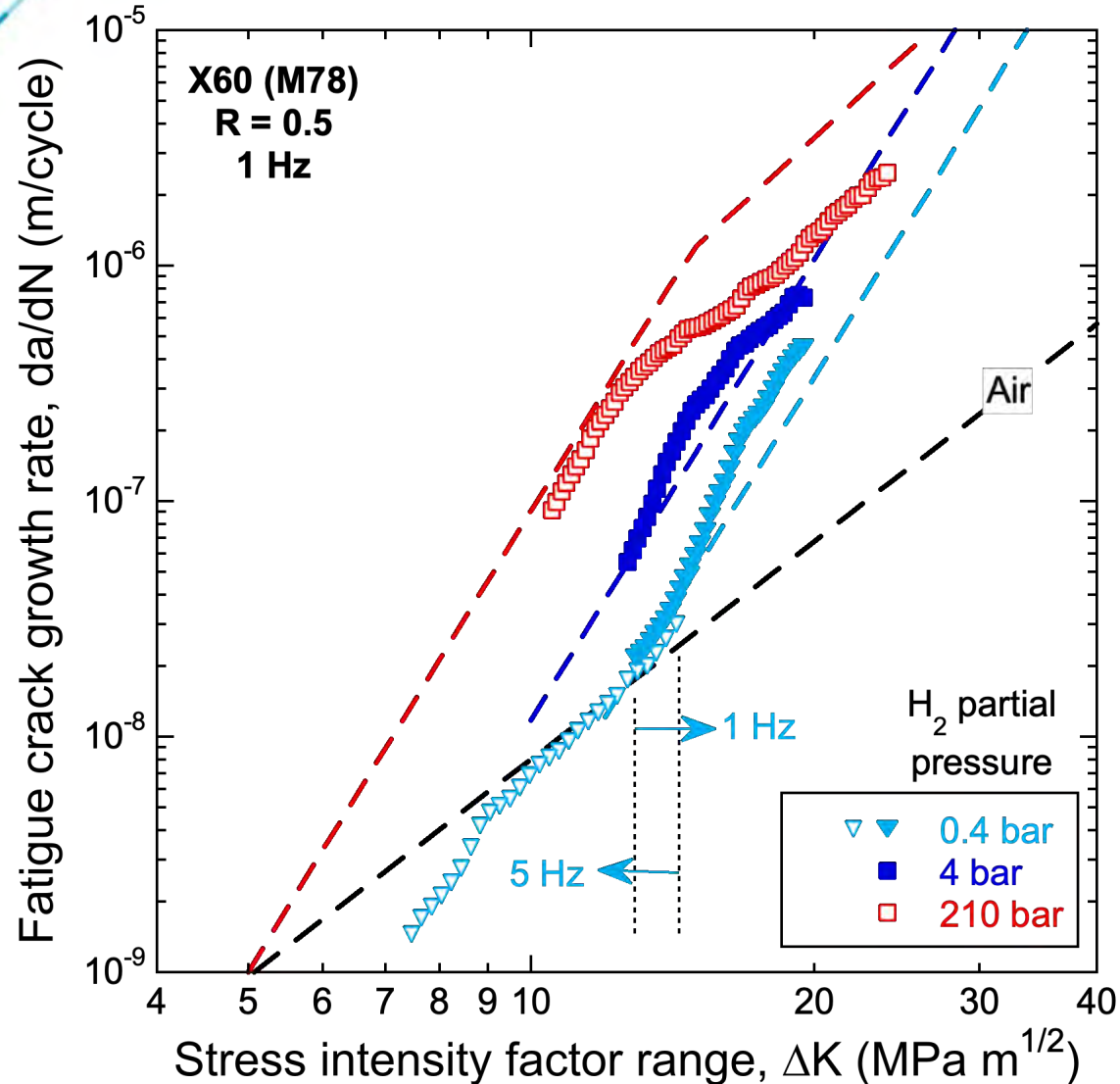
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SAND2026-####



BPVC VIII.3.CC2938 and B31.12.CC220 provide pressure-dependent design curves for hydrogen-assisted fatigue crack growth

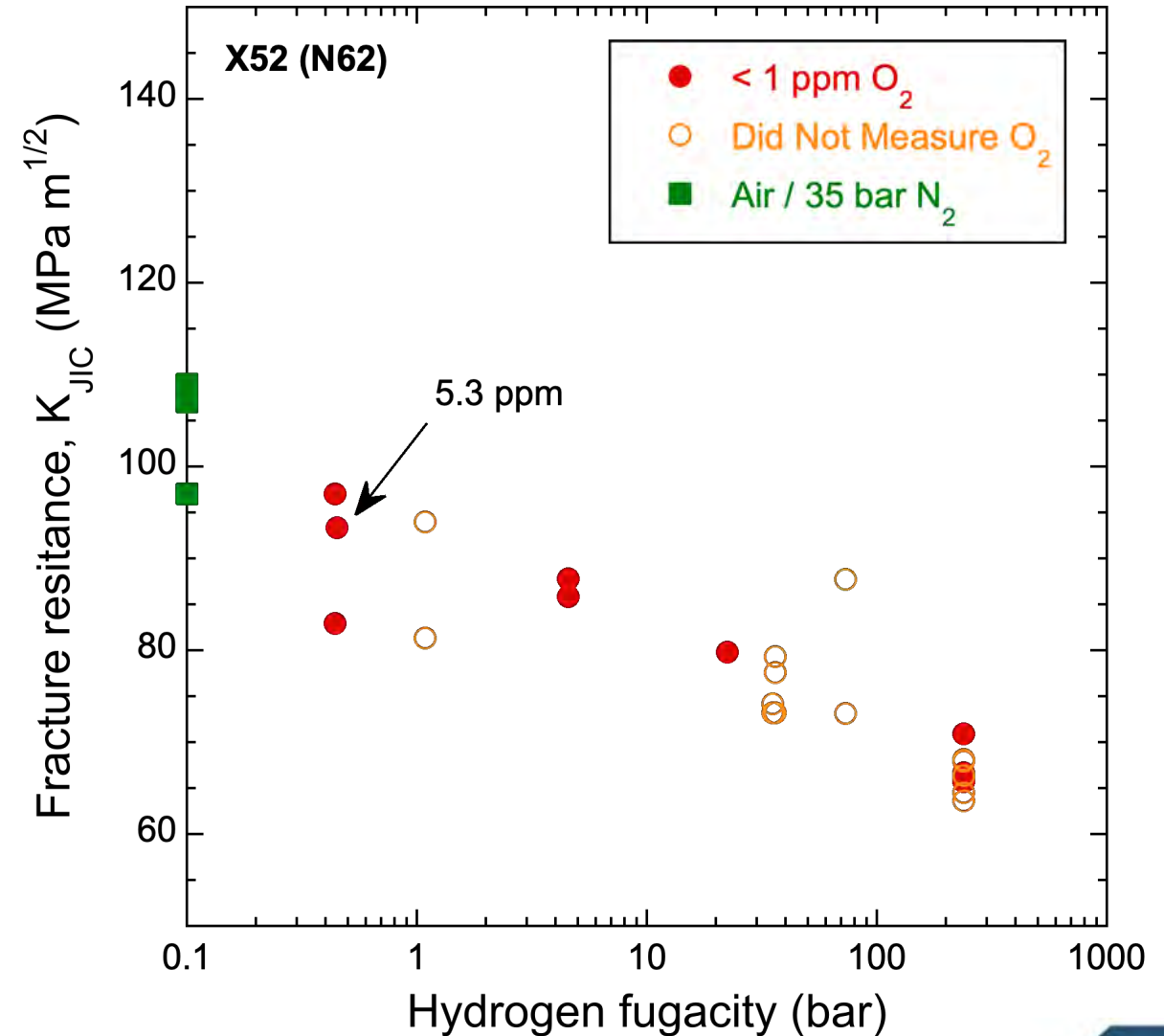
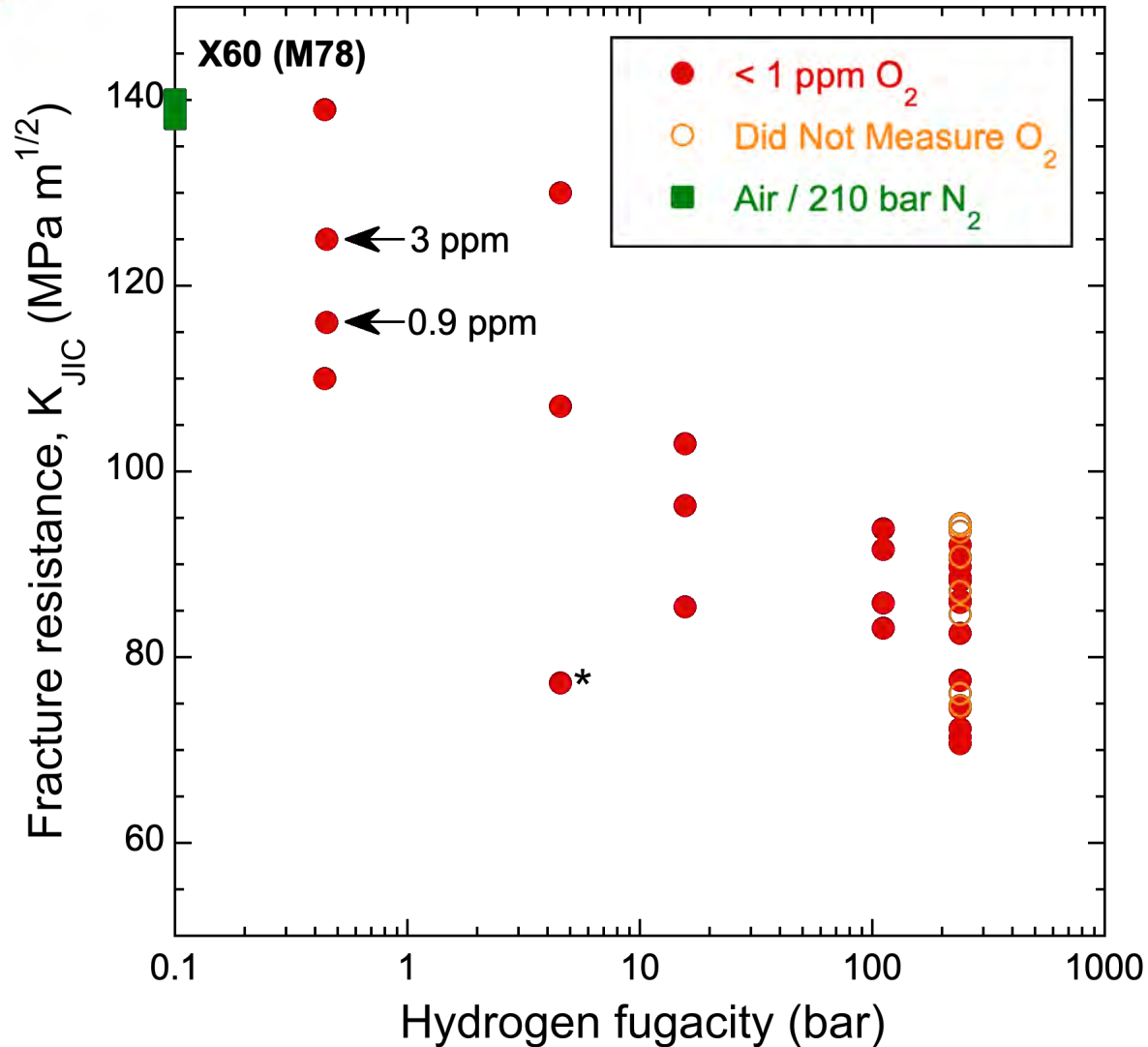
From: ASME IPC2026-186466





Pressure/fugacity dependence of fracture resistance

From: ASME IPC2026-186466





Exceptional service in the national interest

Effects of Temperature on Fatigue and Fracture (and tensile):

- 1) Ferritic-based steels
- 2) Austenitic grades

Joe Ronevich, Chris San Marchi

Sandia National Laboratories, Livermore, CA, USA

Study Group on Materials Testing and Qualification for Hydrogen Service

Anaheim, CA July 19-24, 2026



U.S. DEPARTMENT
of ENERGY



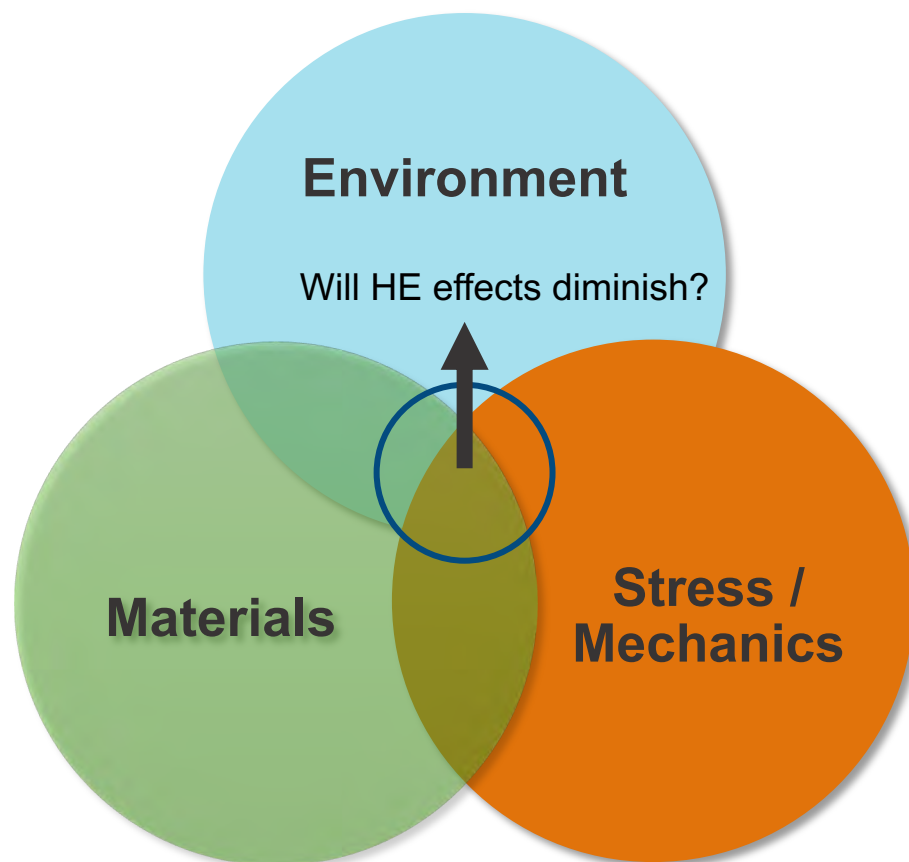
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SAND2026-####



Most hydrogen embrittlement data in literature are at room temperature

→ New uses of hydrogen may extend beyond room temperature



Scarce data available for ferritic steels outside of room temperature for gaseous hydrogen
→ More data on austenitics



FCGR at 0.7 MPa examined at RT $\rightarrow$ 423 K

- JIS-SM490B (low carbon steel)
- Ferrite/pearlite microstructure
- Tested at 25, 90, 150°C
- 0.7 MPa hydrogen exhibited temperature dependence

As temperature increased,
hydrogen accelerated FCG
decreased

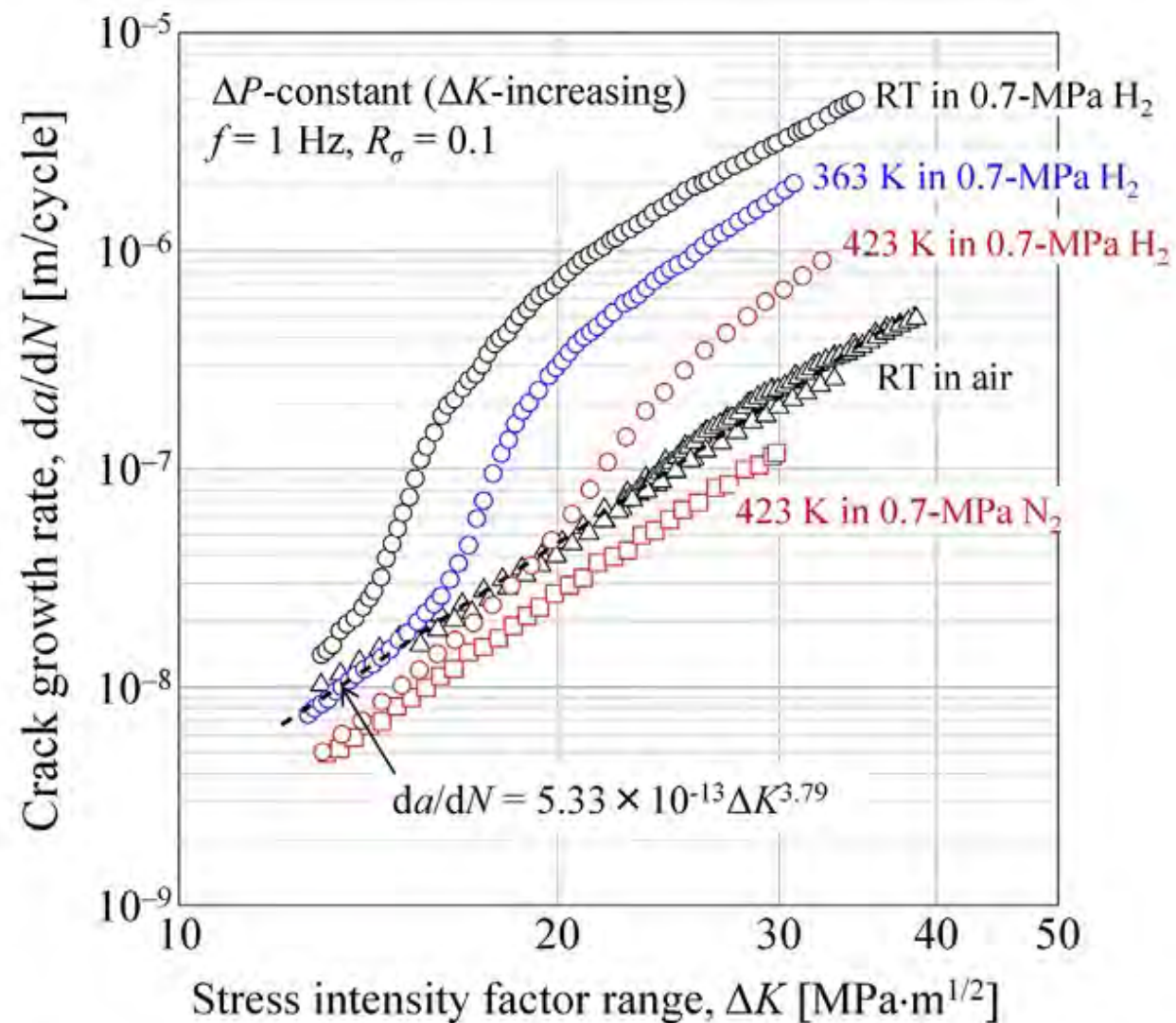


Fig. 12. Relationship between da/dN and ΔK in 0.7-MPa hydrogen gas at elevated temperatures.

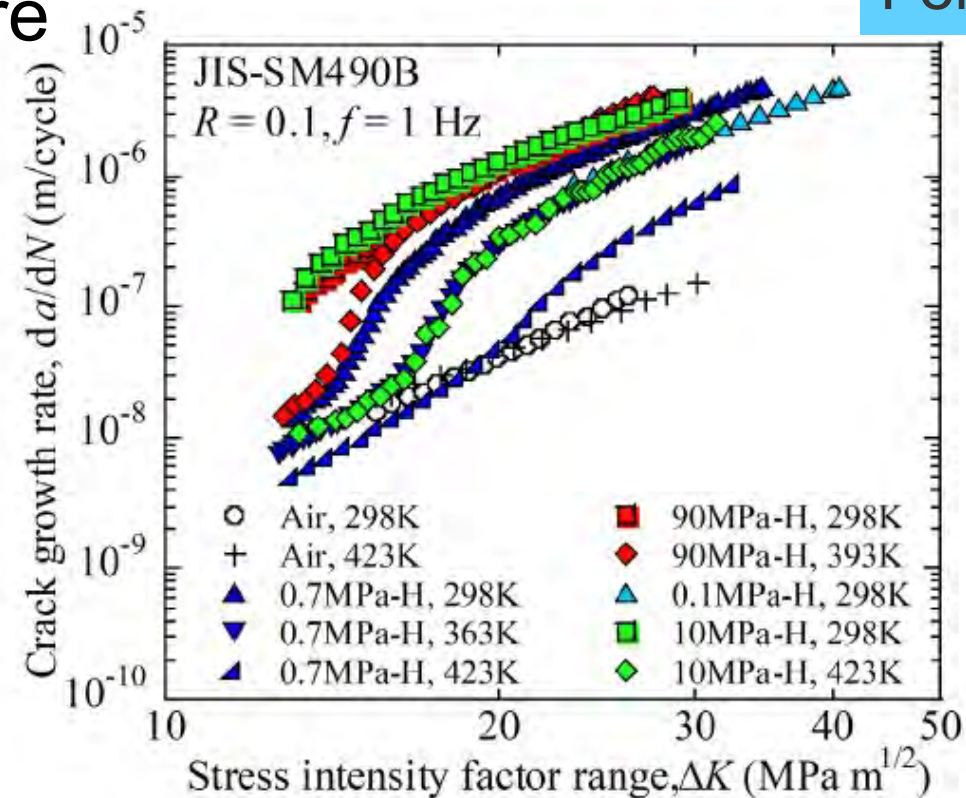


Study was extended to high pressure

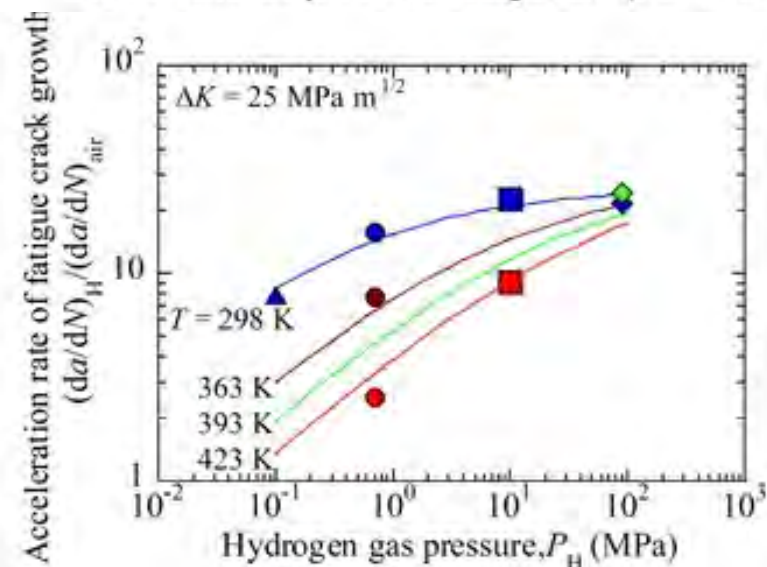
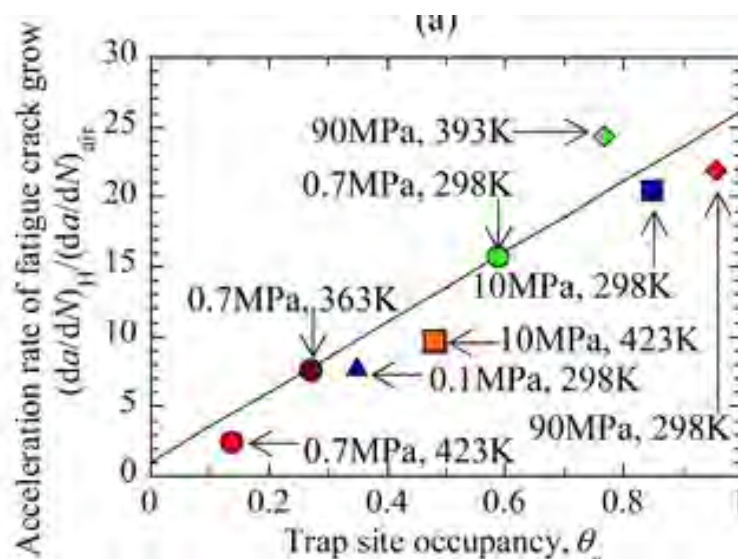
Ferritic

Ref: Matsuoka, Scripta Mat 2018

- Ferrite/pearlite microstructure
- Tested at 25, 90, 150°C
- 0.7 MPa exhibited temperature dependence
- **90 MPa did NOT exhibit temperature dependence**
- Elevated temperature (423K ~ 150°C) showed reduction in da/dN for low pressure environment



- Related temperature dependence to trap site occupancy





Temperature dependence of Pure iron is observed over a variety of pressures

Ref: Ogawa, IJ Fatigue, 2020

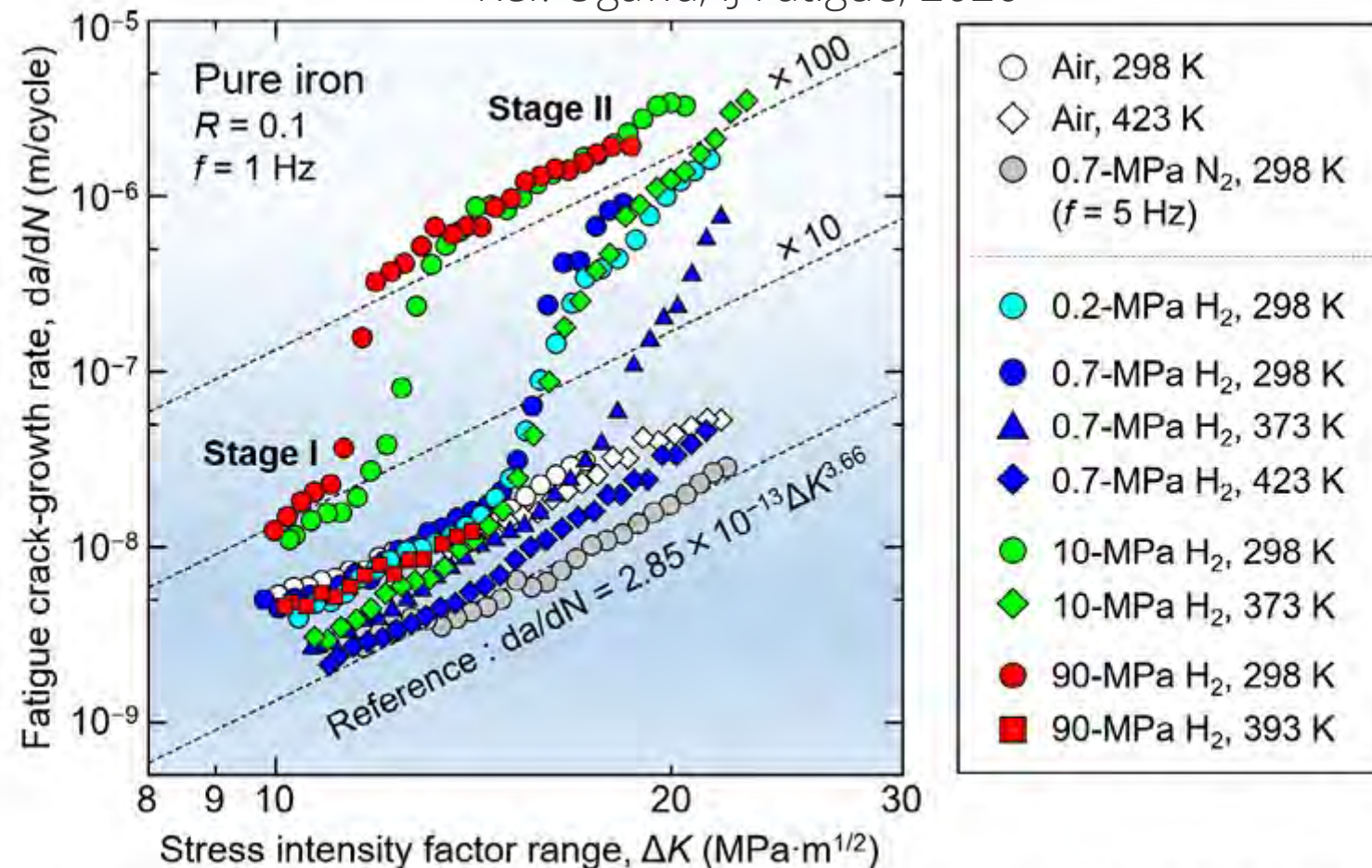


Fig. 2. Relationship between fatigue crack-growth rate (da/dN) and stress intensity factor range (ΔK) of pure iron tested in air, in 0.7-MPa-nitrogen gas, as well as in 0.2–90-MPa-hydrogen gas, within a temperature range of 298–423 K.



Fracture toughness appears to improve with increasing temperature

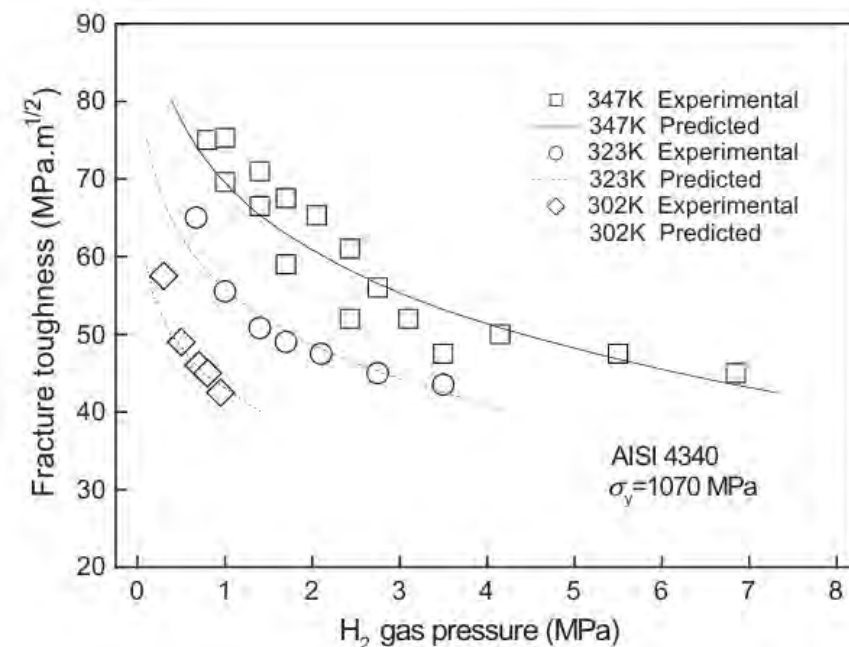
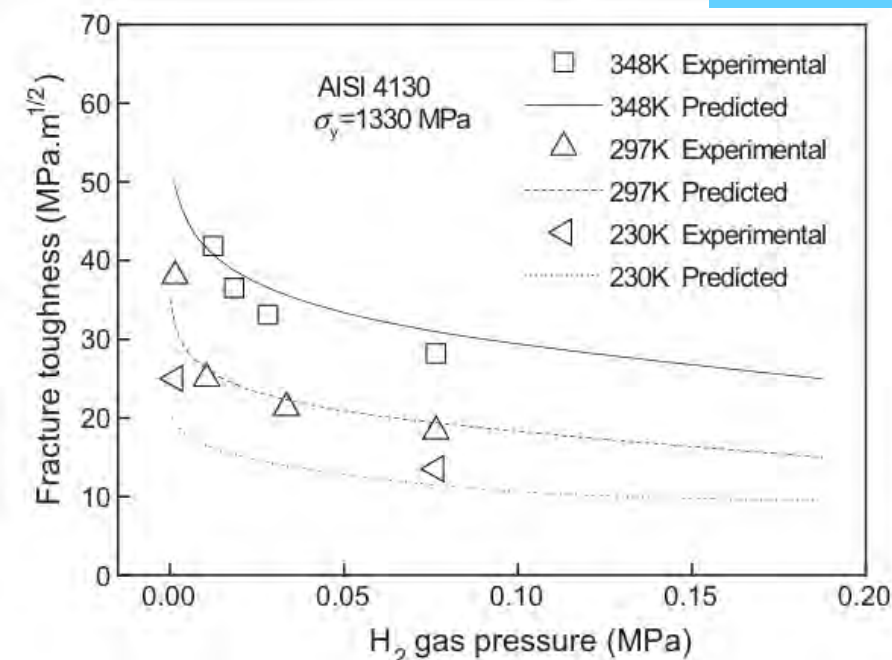
“ Story [13] investigated the effect of temperature (302, 323 and 347 K) on fracture toughness of AISI 4340 steel in hydrogen gas of various pressures (0.1–7 MPa). Their results showed the reduction in fracture toughness of the steel for all three temperatures. Under the same hydrogen pressure, increasing the temperature markedly increased the fracture toughness. In low pressure hydrogen gas, increasing temperature by 20 K increased fracture toughness of the steel by about 30%. Nelson and Williams [14], [15] measured fracture toughness of AISI 4130 steel with different yield strength (1050–1330 MPa) in hydrogen gas at above and below ambient temperatures (230, 297 and 348 K). They also found that fracture toughness increased as temperature increased, but the higher the yield strength, the lower the fracture toughness in both air and hydrogen gas.”

[13] Story GC. Hydrogen assisted cracking of a low alloy steel e pressure, temperature and yield strength effects on the threshold fracture toughness. PhD dissertation. Davis, CA: University of California-Davis; 1980.

[14] Nelson HG, Williams DP. Quantitative observations of hydrogen-induced, slow crack growth in a low alloy steel. NASA TMX-62,253. Moffett Field, CA: NASA Ames Research Center; 1973.

[15] Nelson HG, Williams DP. Quantitative observations of hydrogen-induced, slow crack growth in a low alloy steel. In: Staehle RW, Hochmann J, McCright RD, Slater JE, editors. Stress corrosion cracking and hydrogen embrittlement of iron base alloys. Houston, TX: NACE; 1977. p. 390e404.

Ref: Wang. IIHF 2013





Some additional (and same) fracture data presented as function of temperature → all at low pressures

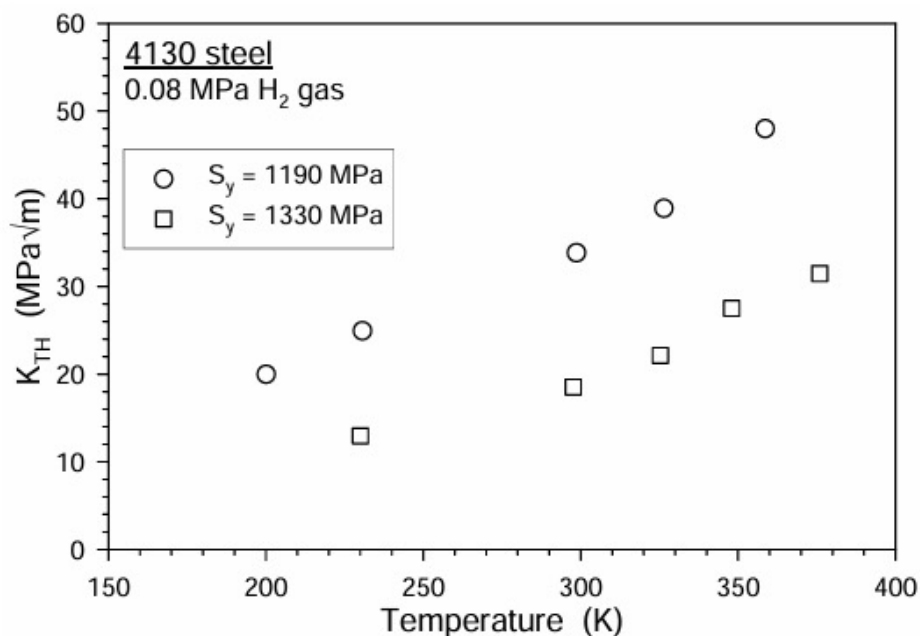


Figure 3.2.2.5. Effect of temperature on threshold stress-intensity factor for crack extension in low-pressure hydrogen gas for 4130 steel [6, 7]. Results are shown for two yield strengths.

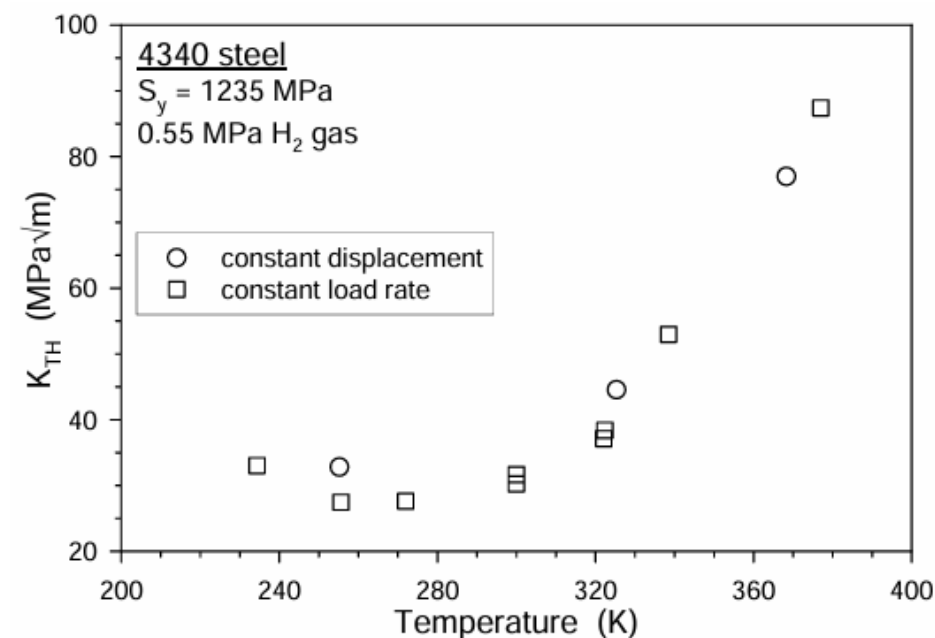


Figure 3.2.2.8. Effect of temperature on threshold stress-intensity factor for crack extension in low-pressure hydrogen gas for 4340 steel [16]. Two loading modes were used to generate the data: constant displacement and constant load rate ($dK/dt = 0.1$ to 0.2 MPa√m/min).

HG Nelson and DP Williams, "Quantitative Observations of Hydrogen-Induced, Slow Crack Growth in a Low Alloy Steel," NASA TMX-62,253, NASA Ames Research Center, Moffett Field CA, 1973.

HG Nelson and DP Williams, "Quantitative Observations of Hydrogen-Induced, Slow Crack Growth in a Low Alloy Steel", in Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, RW Staehle, J Hoch

WG Clark, "Effect of Temperature and Pressure on Hydrogen Cracking in High Strength Type 4340 Steel", Journal of Materials for Energy Systems, vol. 1, 1979, pp. 33-40.



Fracture toughness was evaluated at 6.9 MPa
→ Arguably negligible differences with temperature

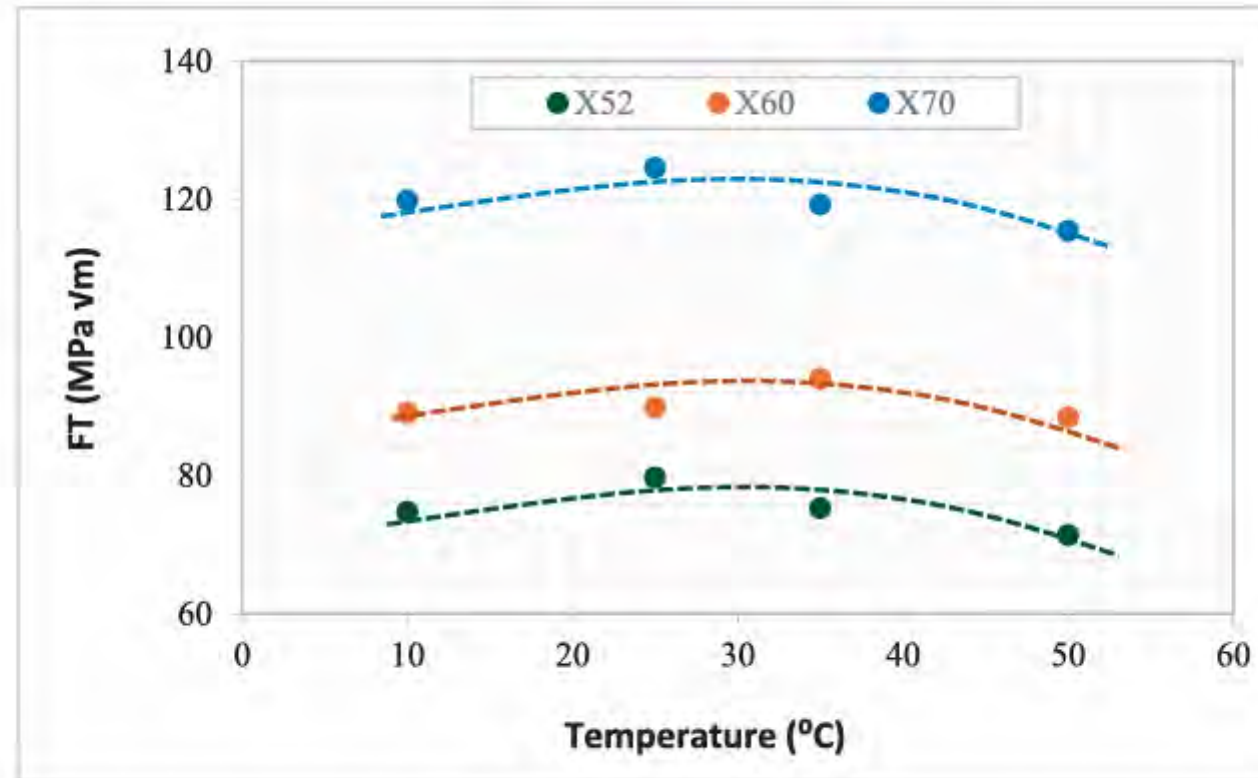
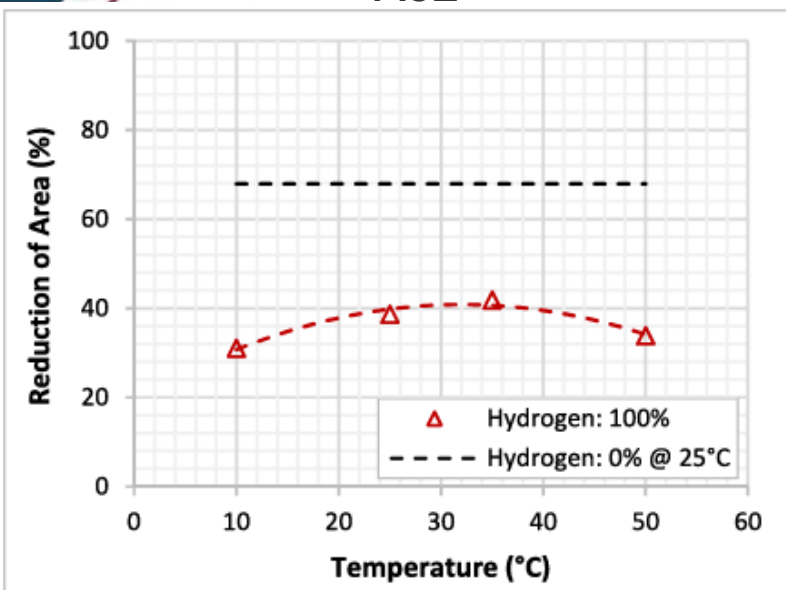


Fig. 12. Temperature effect on FT at 6.9 MPa hydrogen pressure for different materials: X52, b) X60, and X70.

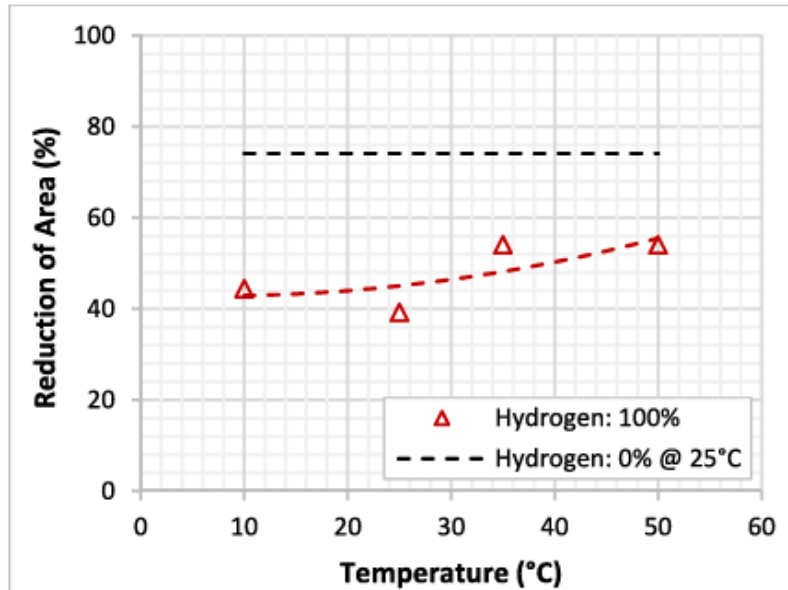


SSRT performed in 6.9 MPa hydrogen gas at different temperatures

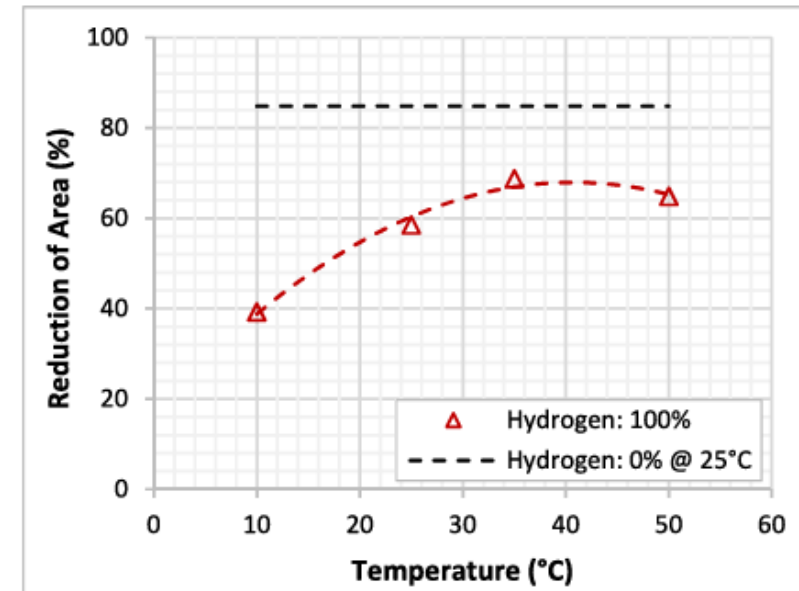
X52



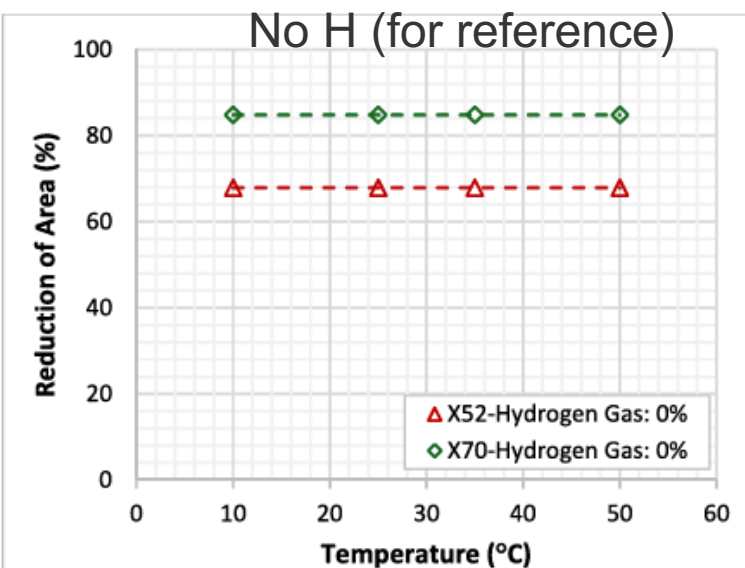
X60



X70



No H (for reference)

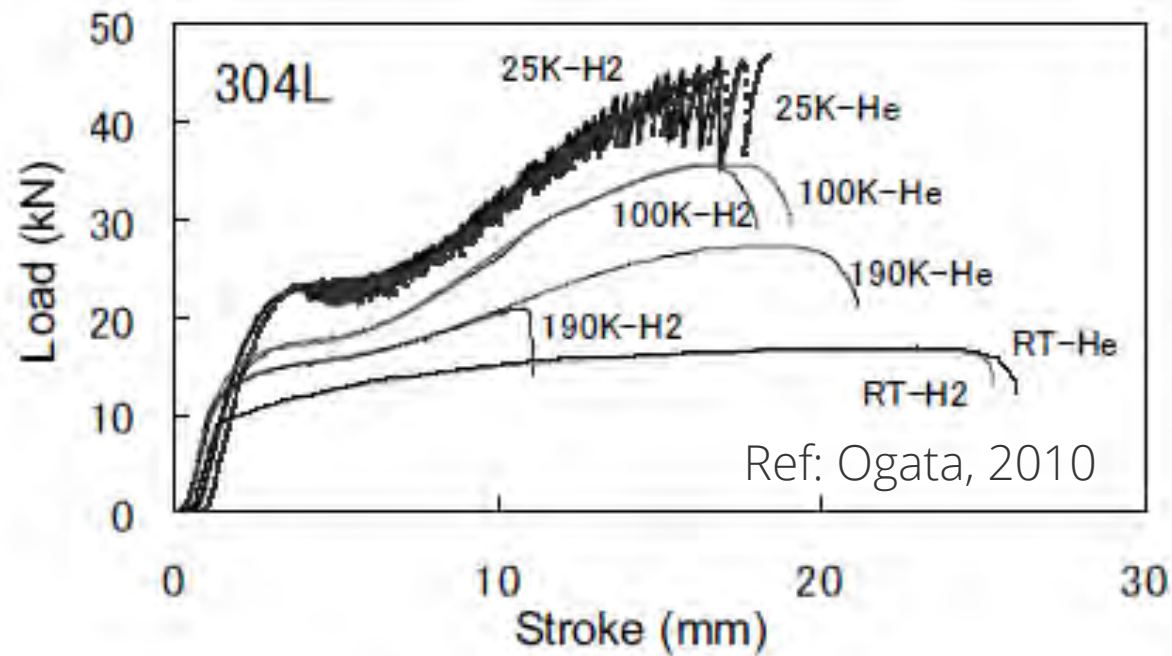


X52 – most influenced by temperature
X70 exhibited highest resistance
10°C showed lowest RA



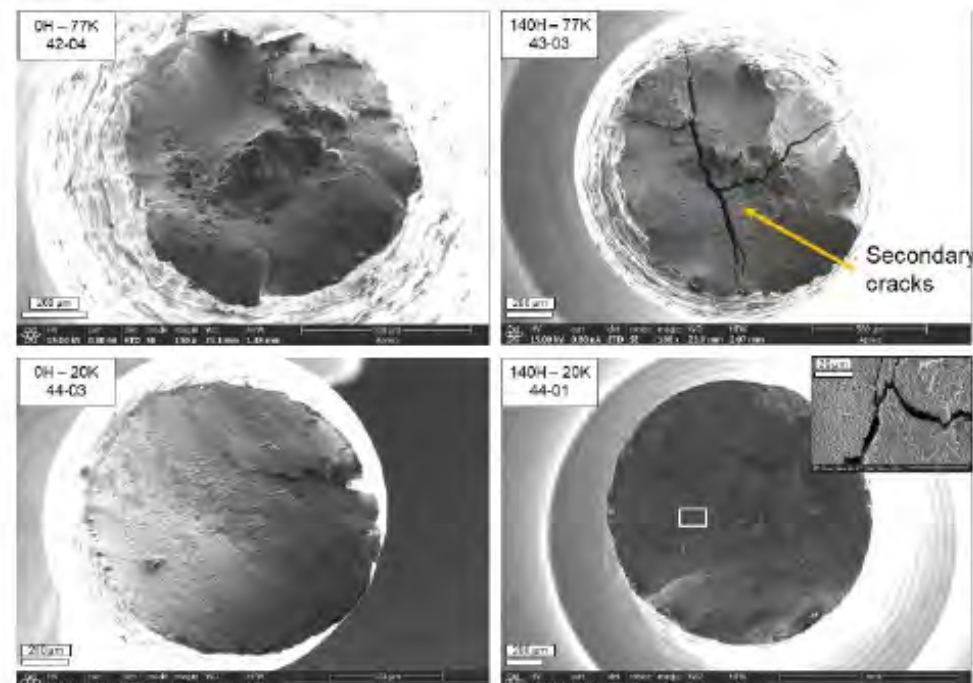
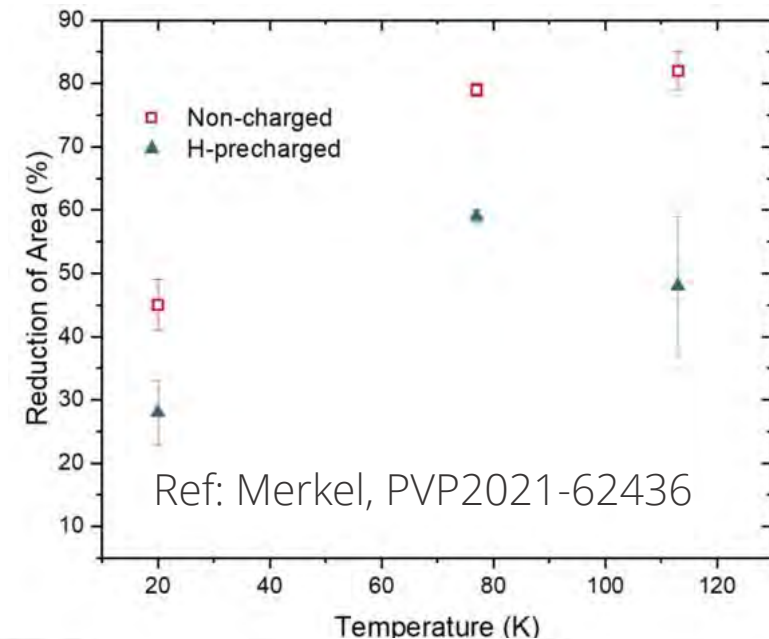
3XX series stainless has been evaluated at low temperatures

Austenitic



Load-displacement curves of SUS 304L at temperatures ranging from 25 K to room temperature in 13 MPa hydrogen gas and 12 MPa helium gas. [1]

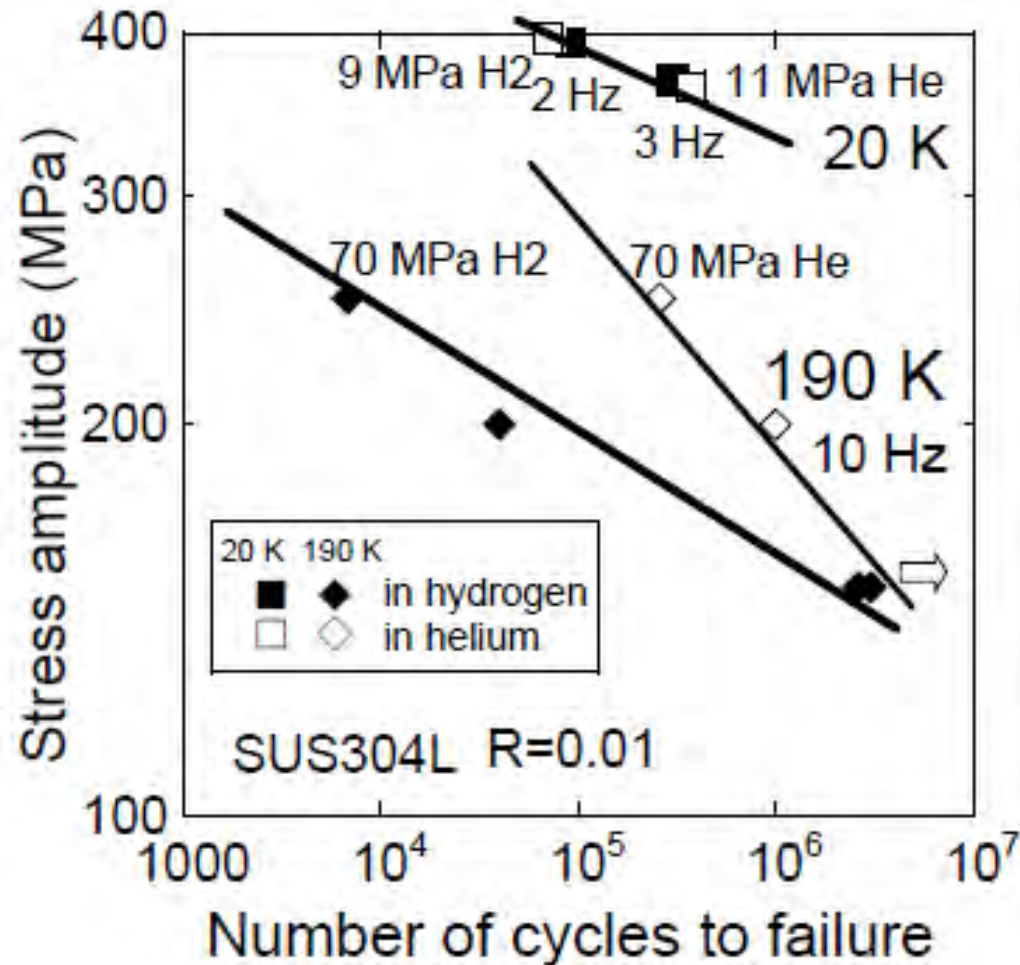
Minimal change in elongation, notable loss in RA
- Secondary cracking at low T with hydrogen





304L has been studied at cryogenic temperatures

Austenitic

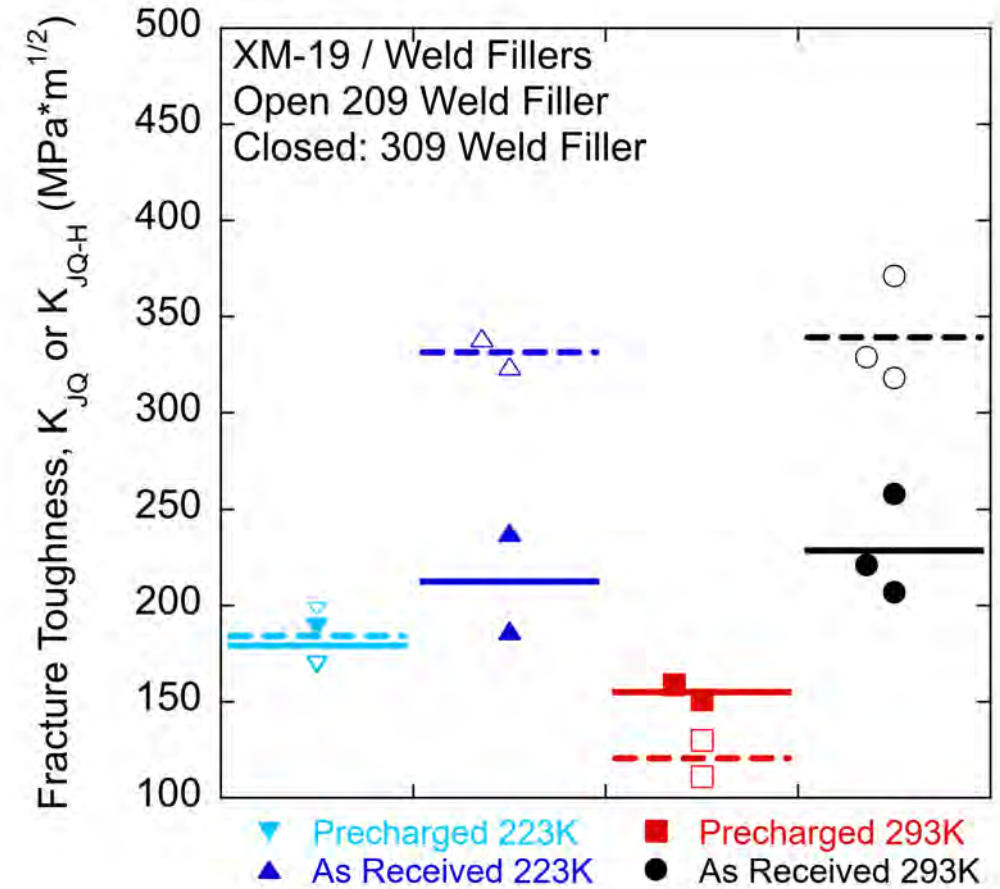
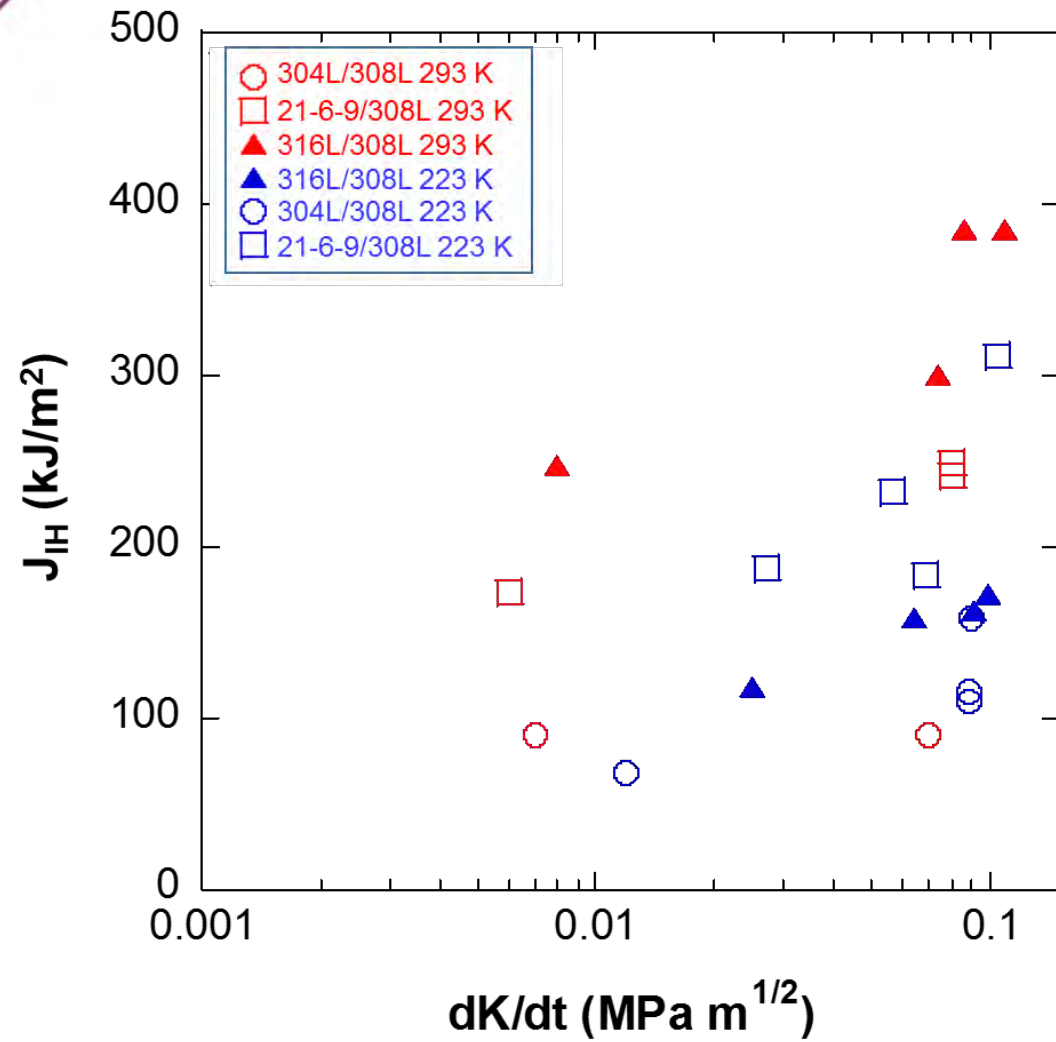


- At 20K, fatigue life is improved due to increase in strength.
- No observed effects of hydrogen



Stainless steel welds have been tested at -50C

Austenitic



Ref: Ronevich, PVP2017

Ref: Yurek, PVP2026



Open questions

- What are relevant temperatures for ferritic steels that are of concern to industry?
- Based on the literature data just presented, where should future efforts on temperature effects be placed?
- What other cryogenic temperature tests for austenitic grades should be done?
- Comment: Rate effects have been well-defined for 20°C (freq, dK/dt), as we examine temperatures above/below 20°C, experiments need to consider that different rate effects or H-trap interactions may be present



Thank you for your attention!

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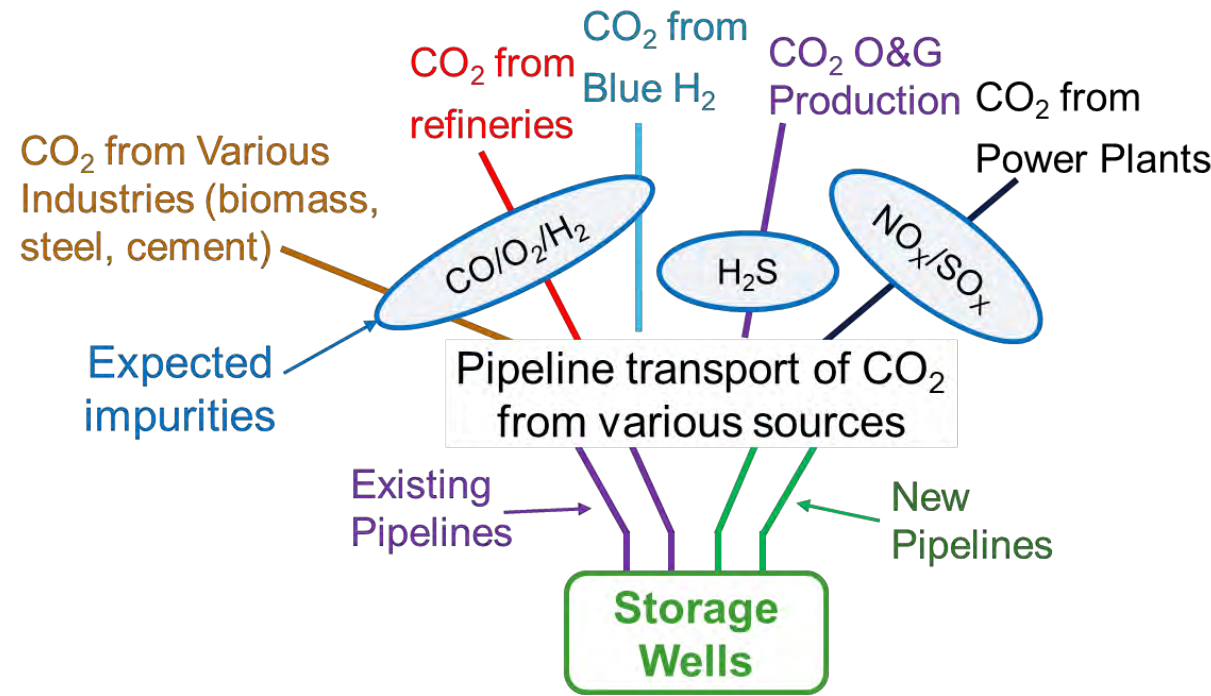
Acknowledgements: Sandia's Hydrogen Effects on Materials Laboratory (HEML) gratefully acknowledges sustained support by the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation (CMEI), specifically the Alternative Fuels and Feedstocks Office (AFFO) . Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

Role of Impurities in CO₂ Streams on Gaseous H₂ Embrittlement of Pipeline Steels

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Feng Gui, Angeire Huggins-Gonzalez

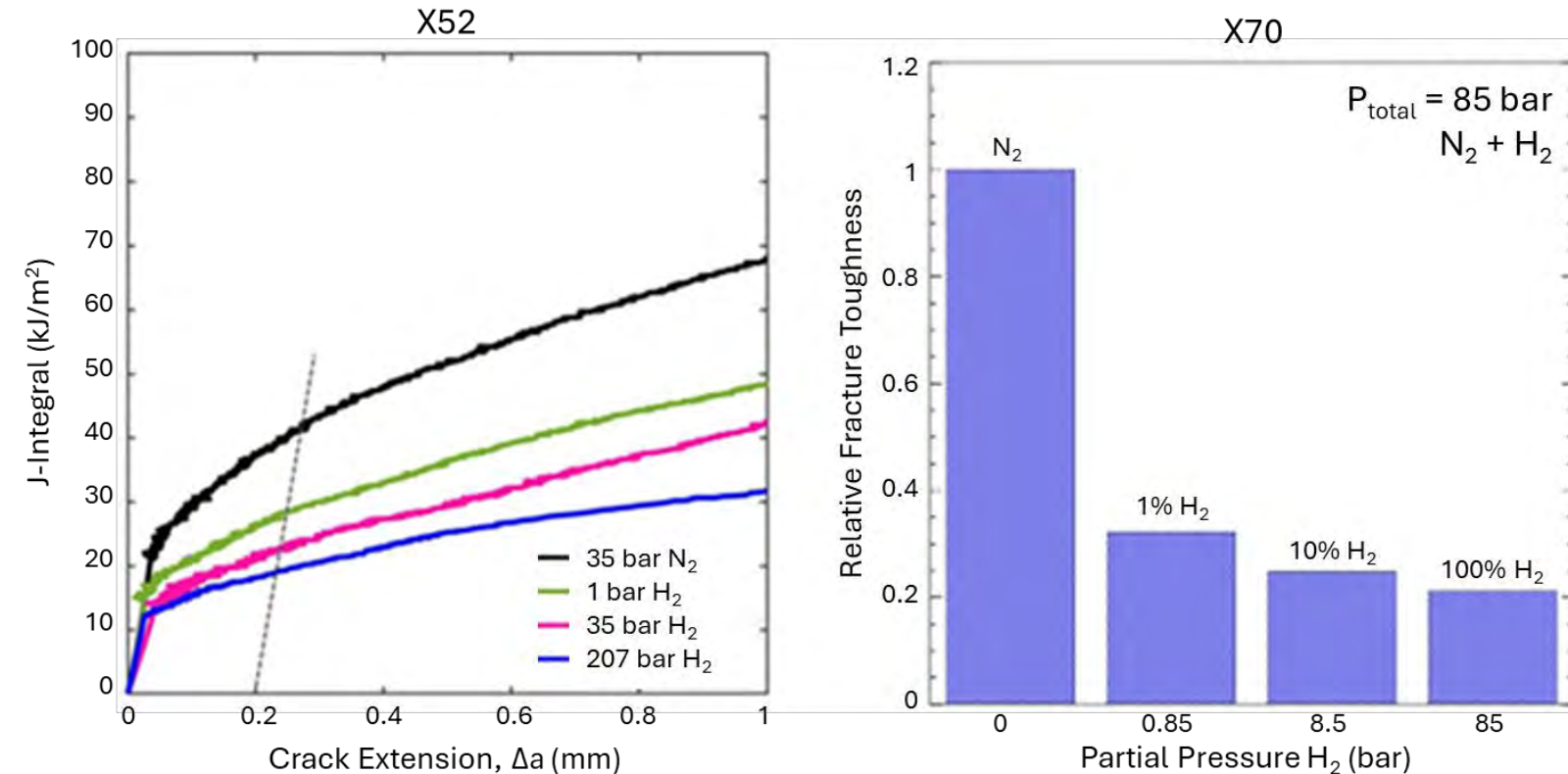
Background - CO₂ Transport

- Experience with CO₂ transport is mainly in anthropogenic CO₂ and under very tightly controlled specifications
- However, for carbon capture utilization and storage (CCUS) applications, the CO₂ streams will likely contain various impurities (post/pre-combustion CO₂) not present in anthropogenic CO₂
- Current focus is on developing impurity specifications from a corrosion and running fracture perspective
- However, recent work indicates that even low hydrogen partial pressures (p_{H_2}) in dense phase CO₂ can lead to hydrogen embrittlement
 - In higher strength/vintage microstructures, the impact of gaseous H₂ appears to be more severe
 - Modern materials appear to perform better
- While pure H₂ effects are being investigated the impact of various impurities in the CO₂ streams on gaseous H₂ embrittlement is not clear



The presence of some impurities (CO, O₂) can mitigate hydrogen embrittlement while others (H₂S) can enhance it.

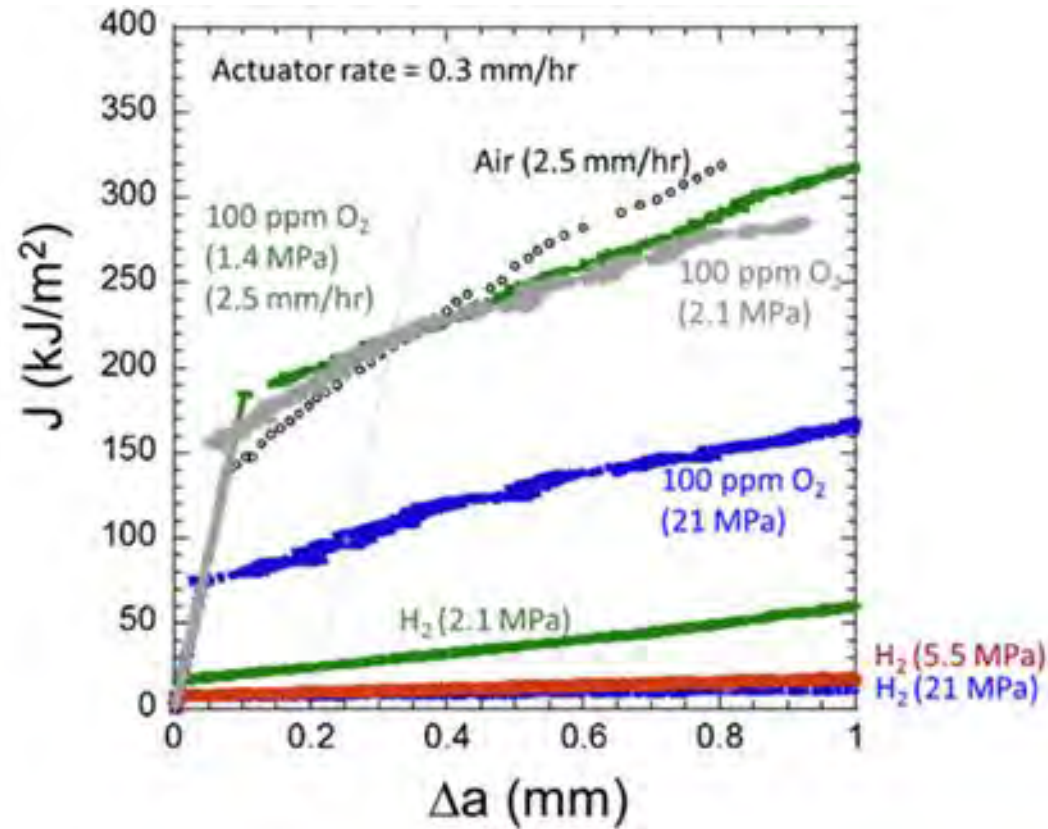
Background → Impact of H₂ on Fracture



- CO₂ streams can have between 0.5 to 2% H₂ in them
- The p_{H2} corresponding to these concentrations is in the range of 1 bara to 6 bara
- Even at these pressures of H₂ there appears to be a significant environmental effect.

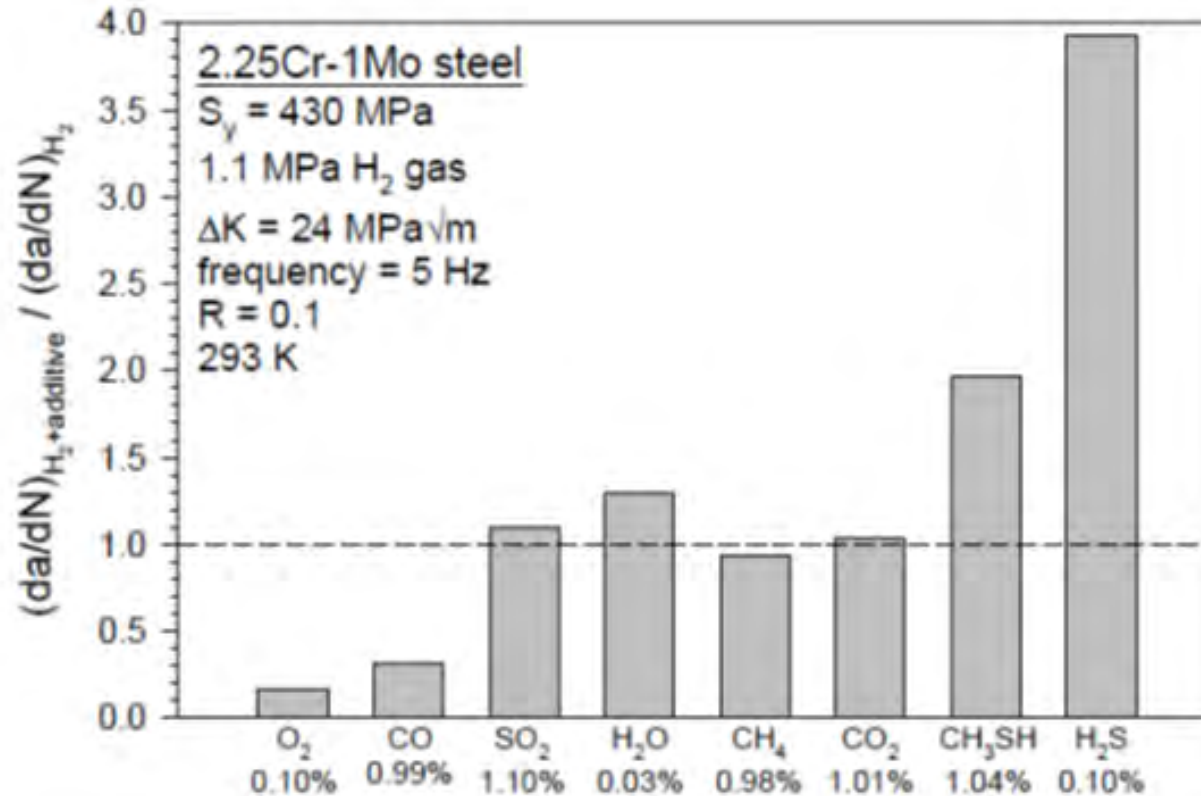
Low pressures of H₂ can lead to a significant decrease in fracture toughness

Impact of Impurities on H Embrittlement → Fracture



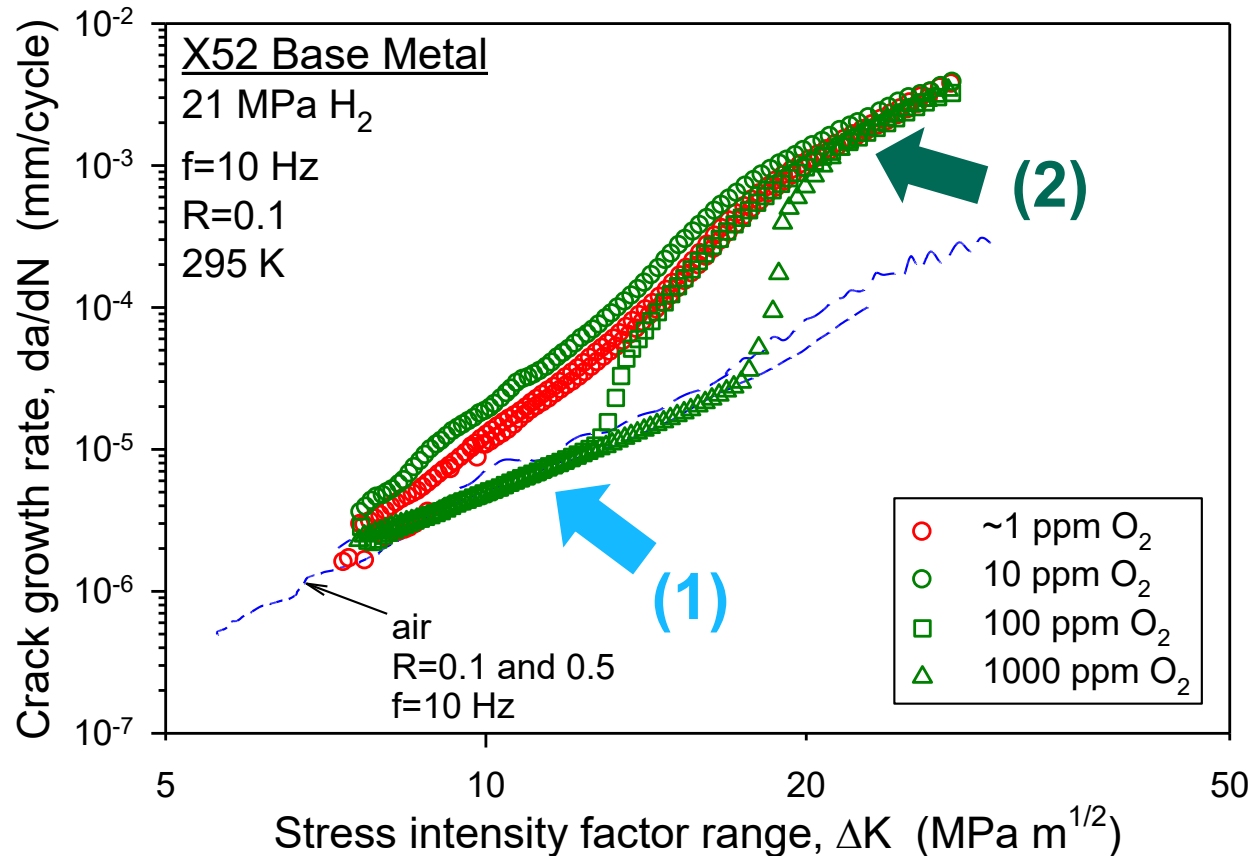
- Addition of O₂ appears to lead to an increase in fracture toughness → However the duration of the tests is short and the reduction is rate dependent

Impact of Impurities on H Embrittlement → Fatigue



- Most impurities seem to have no significant effect
- O_2 and CO appear to have a beneficial effect
 - CO has also been shown to have a beneficial effect in fracture (less than O_2)
- H_2S has a detrimental effect

Impact of Impurities on H Embrittlement → Fatigue

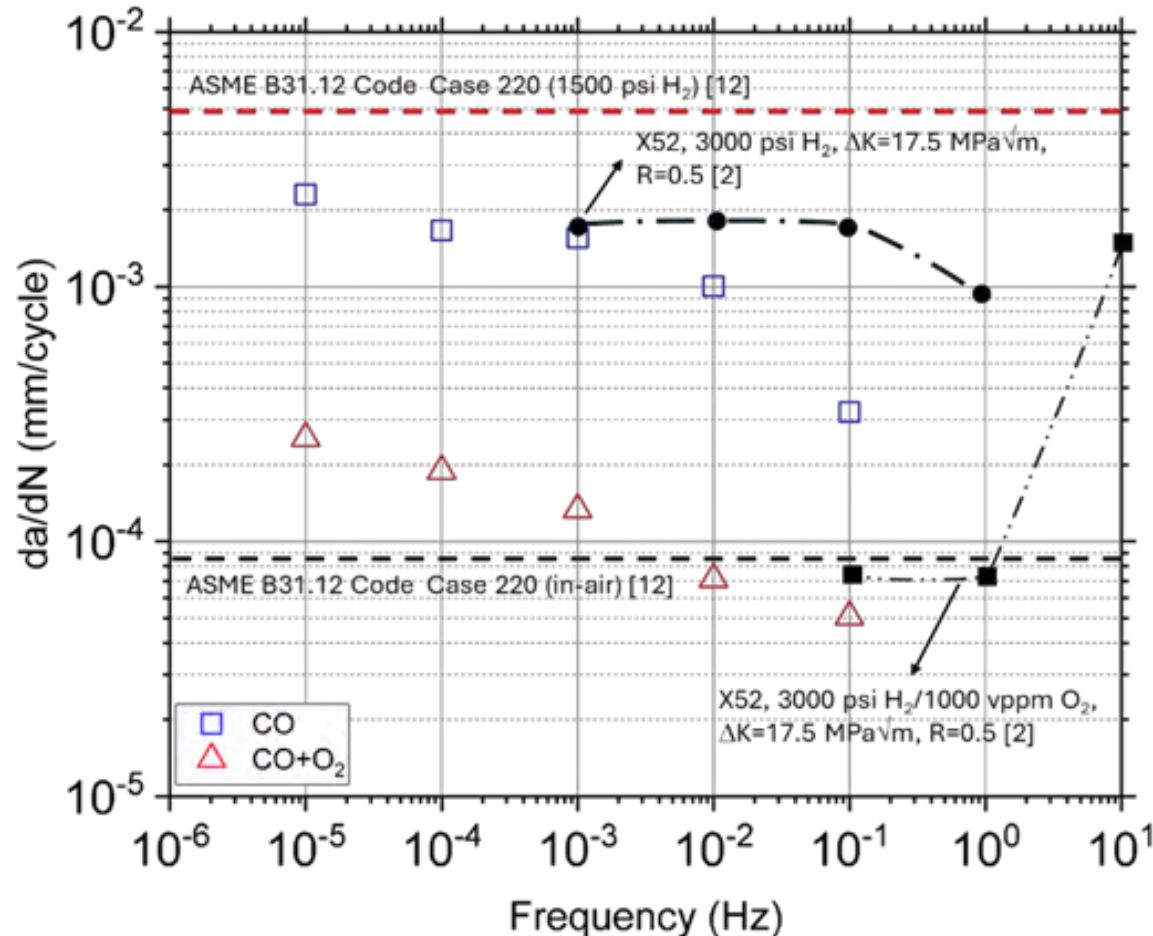


- The effect of O₂ impurities appears to depend on the crack growth rate (CGR):
 - 1) An inhibitive effect at lower $\Delta K \rightarrow$ Lower CGR
 - 2) No effect on FCGR at higher CGR
- CO appears to have an inhibitive effect at high frequencies $\rightarrow$ However at low frequencies there is no effect.
- The combination of CO+O₂ appears to have significant inhibition effect even at low frequencies

Fatigue tests are short relative to the time scales of the operation of the pipeline/Do these effects persist at long time scales?

Most work has been performed at high $p_{H_2} \rightarrow$ How does this translate to low p_{H_2} ?

Impact of Impurities on H Embrittlement → Fatigue

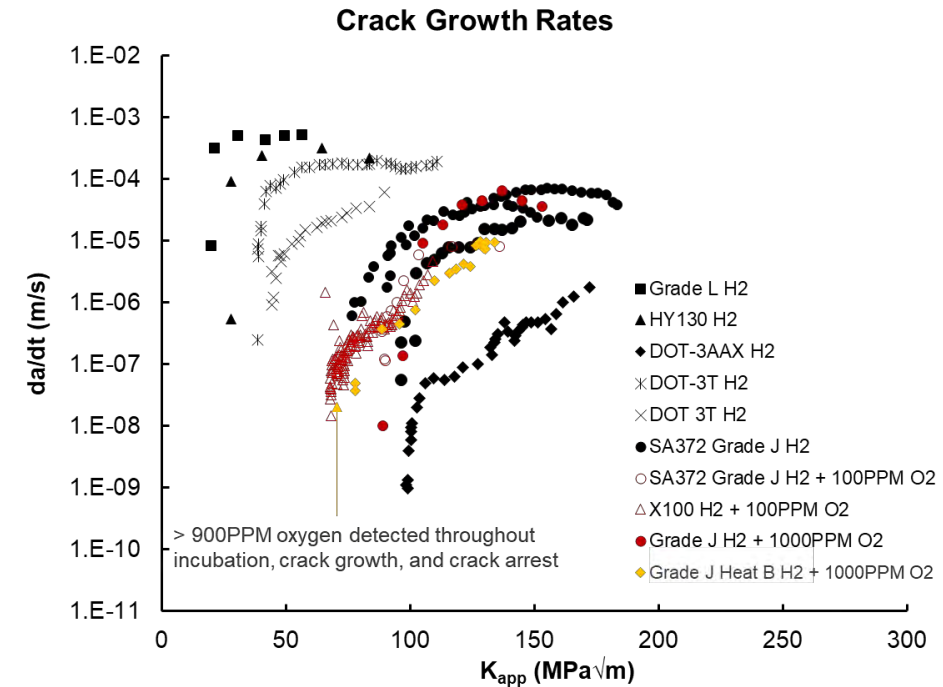
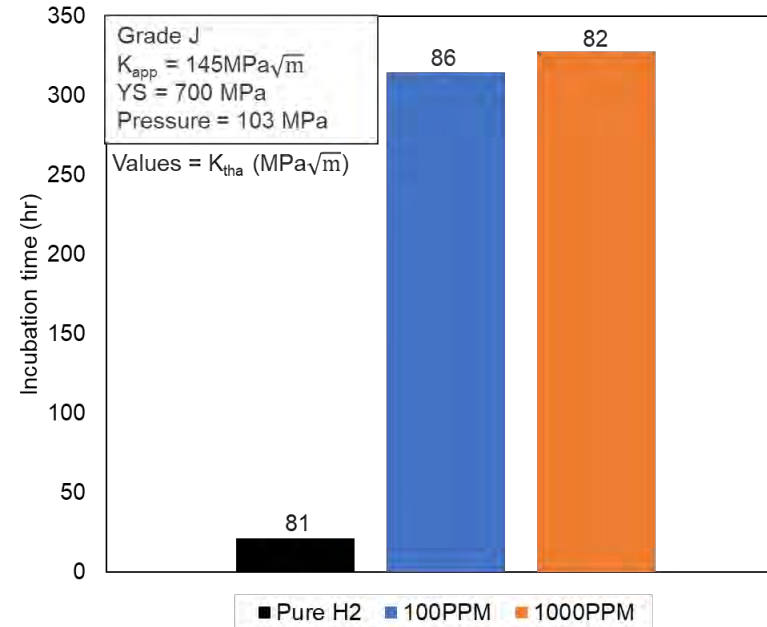
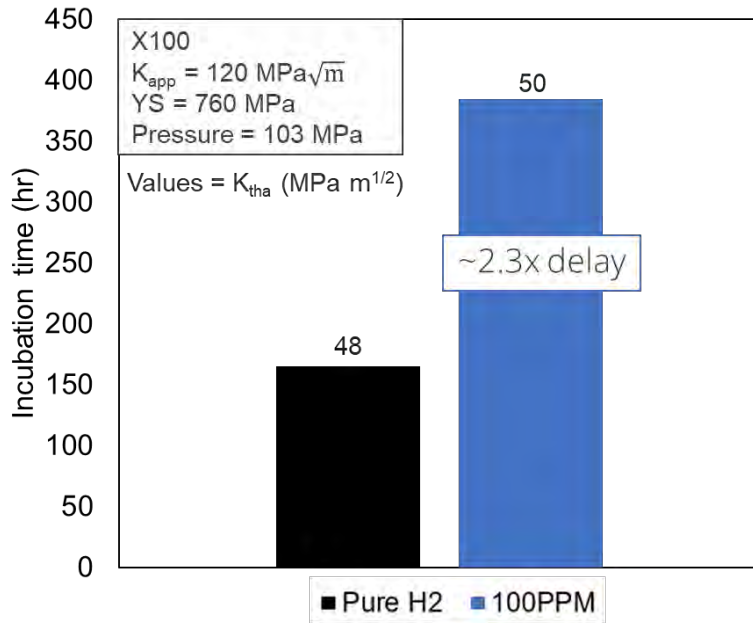


- The effect of O₂ impurities appears to depend on the crack growth rate (CGR):
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Fatigue tests are short relative to the time scales of the operation of the pipeline/Do these effects persist at long time scales?

Most work has been performed at high p_{H2} → How does this translate to low p_{H2}?

Impact of Impurities → Longer Term Tests



- Constant displacement tests performed in $O_2 \rightarrow$ No influence of O_2 content on the K_{tha}
- All the materials tested had very high CGR $\rightarrow$ Possible lack of O_2 effect may be associated with the high CGR and materials that exhibit stress-controlled fracture
- Experiments and atomistic simulations showed that O_2 impeded hydrogen-assisted fracture, but did not prevent it in **high pressure hydrogen environments with 99.9% H_2**

Key Questions

- Do the impurities in the CO₂ stream have an influence on the fracture behavior of typical line pipe steels (X60/X70)
 - Beneficial → CO/O₂
 - Detrimental → H₂S
 - Unknown → NO₂/SO₂
 - Are there synergistic effects of the minor species?
- Most previous work has been based on high pressure H₂ studies with PPM levels of impurities
 - What is the influence of various minor species at low p_{H2}?
- Is the influence of the minor impurities observed in short term tests valid over longer durations associated with pipeline operation?
 - At what time-scales and CGRs do these impurities have beneficial or detrimental effects?

Approach

- **Influence of species**

- Fundamental driver for fracture behavior in high pressure H_2 is the concentration of H in steel
- K_{th} of pipeline steels have an asymptotic dependence on p_{H_2} ($C_H \propto \sqrt{p_{H_2}}$)
- H flux measurements as a function of impurities to obtain long term steady state C_H values
- Change in C_H could result in a change in K_{th} .

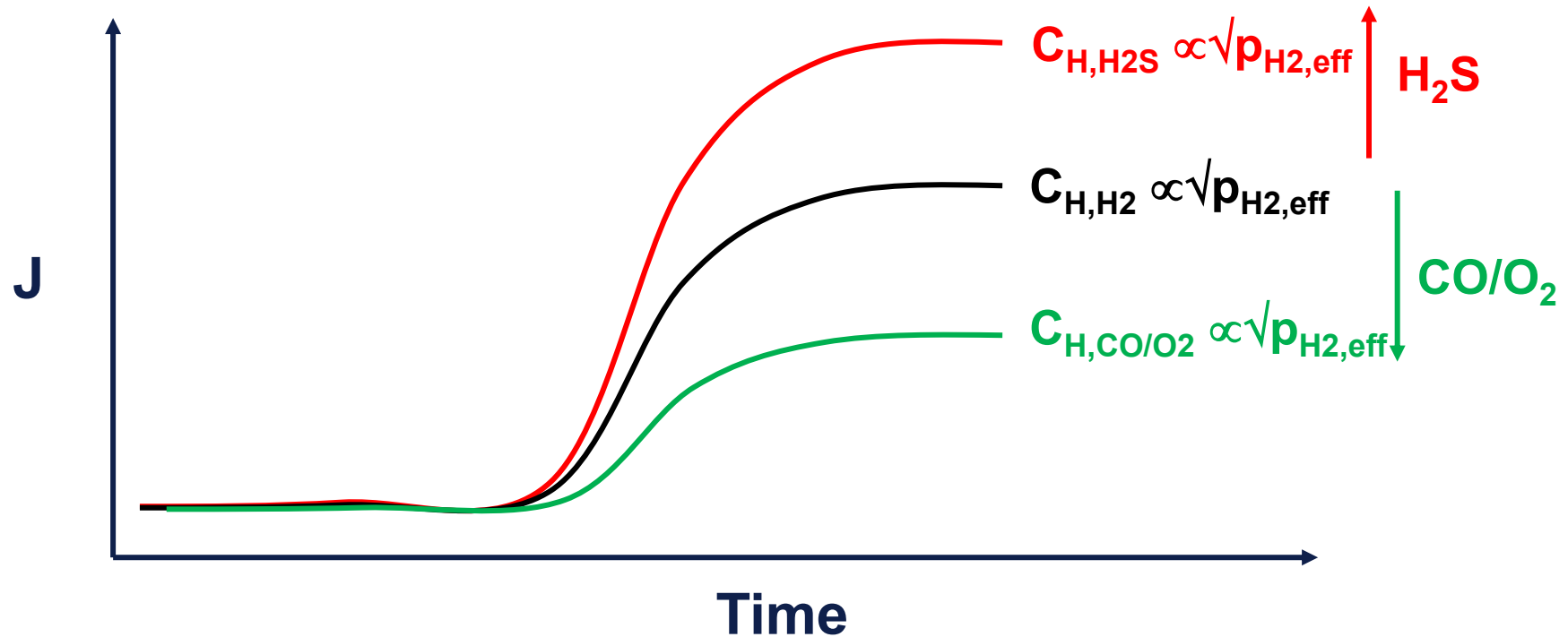
- **Evaluation of Behavior**

- Slow rising K fracture toughness
- Constant Load tests/Low frequency FCGR → Long term behavior

- **Role of microstructure**

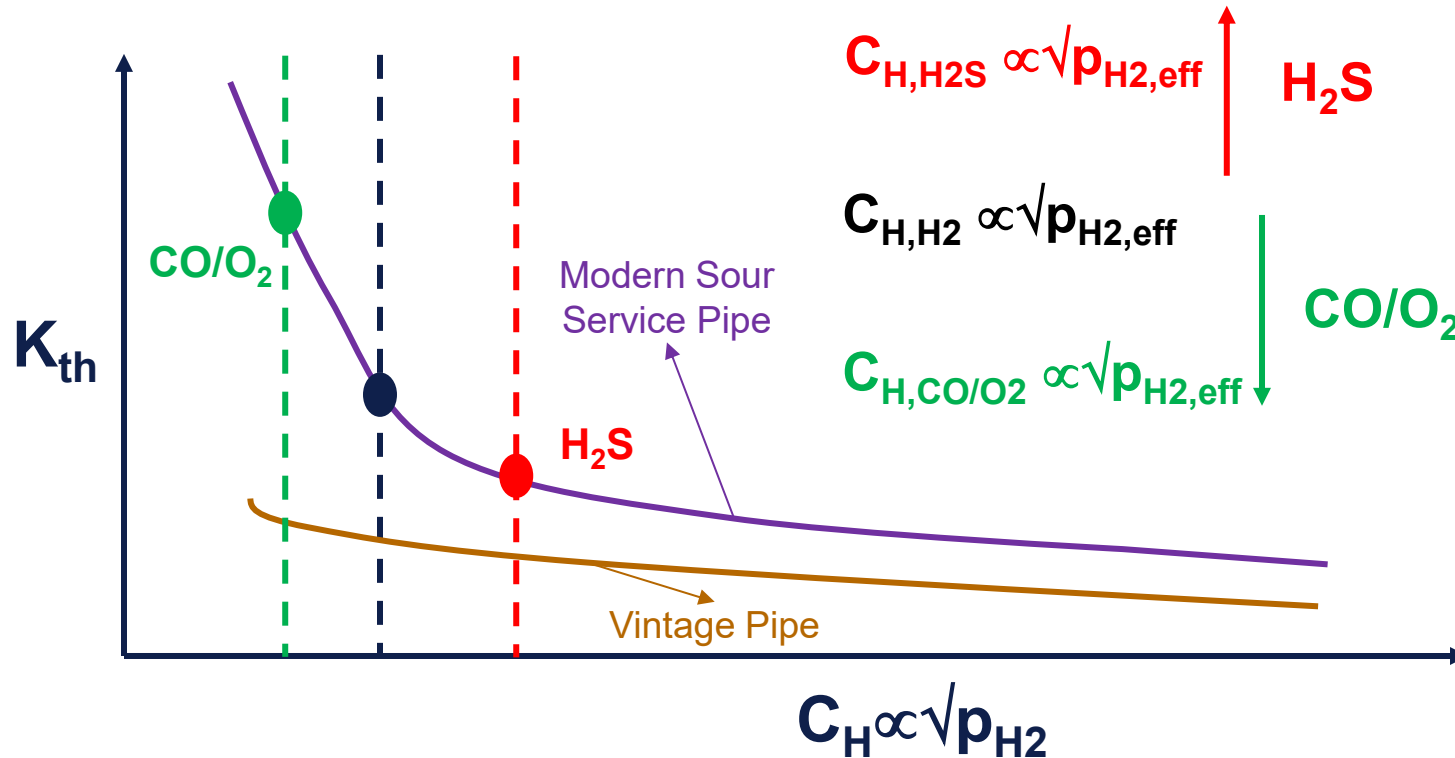
- Modern pipeline grade steels vs Vintage Ferrite/Pearlite

Hydrogen Flux Measurements



Hydrogen flux measurements will be used to establish the influence of species on the hydrogen concentration in the metal.

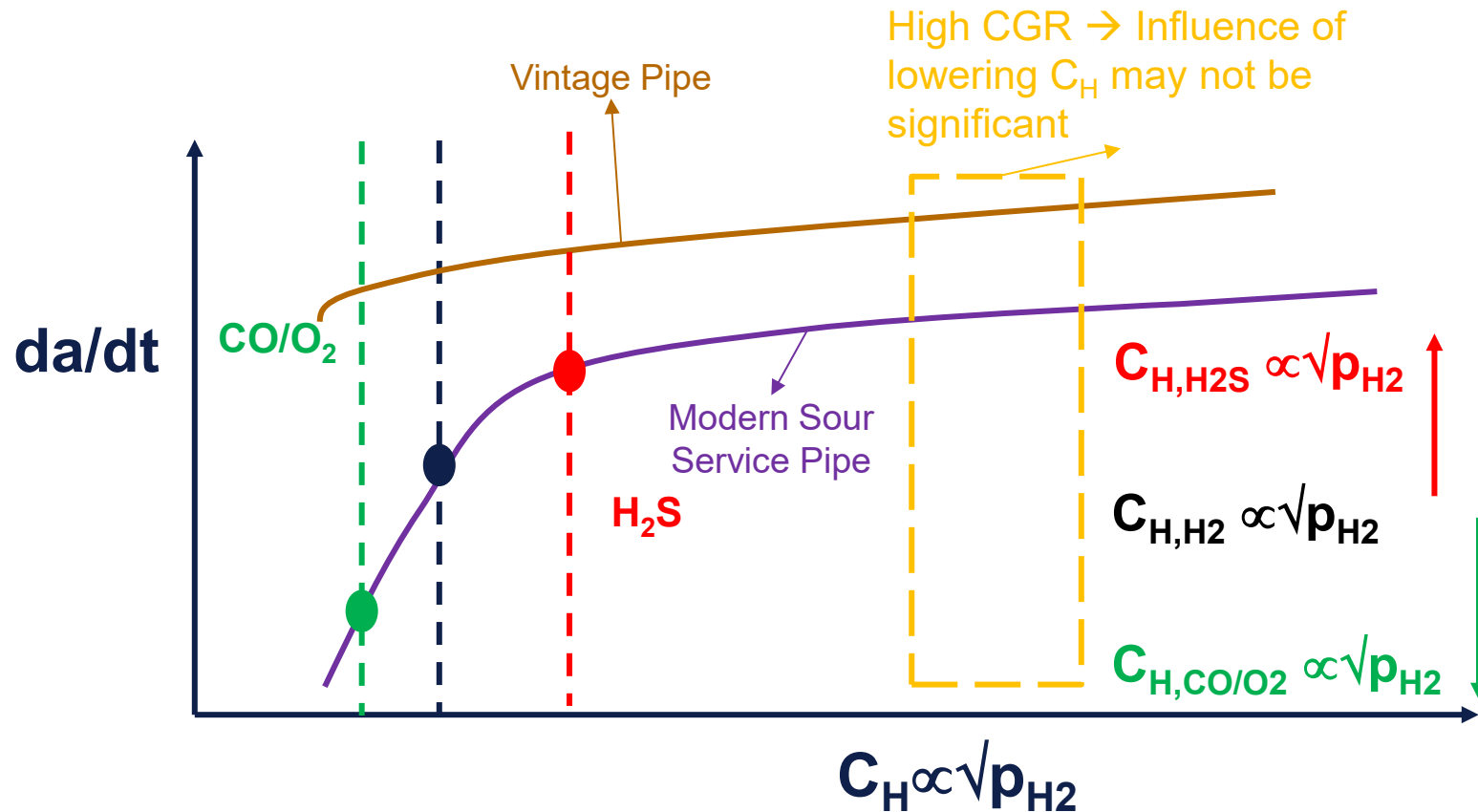
Fracture Toughness Measurements



Explore the influence of species on K_{th} of materials that have differing degrees of susceptibility.

- Slow rising K tests to evaluate the effect of K_{th}/J -R curve behavior in pure H_2 as well as a function of species.
- Presence of species may not change the ability of H to enter the steel but could influence the concentration and therefore the K_{th} .
- Could comparison of da/dt across conditions be useful to understand the rate limiting steps?

Influence of Species on CGR



- High CGR rate $\rightarrow$ typical of high susceptibility conditions does not allow for adsorption of species to influence H uptake.
- However, at lower CGR $\rightarrow$ species can adsorb on the surface and alter the steady state concentration of H.
- The influence of species may be more pronounced at low C_H where the CGR is likely lower.

Characterize influence of species across a range of base line CGR's $\rightarrow$ Range of loading conditions to obtain CGR over a several orders of magnitude $\rightarrow$ Constant Load/Low Cycle Fatigue

Scope of Program

- **Select materials with a large data base of data**
 - Modern X70 → Bainitic Steel
 - Vintage X60 → Ferrite/Pearlite
- **Environments**
 - Two baseline p_{H_2}
 - Individual and combined impurities
- **Evaluation Framework:**
 - Hydrogen Flux Measurements
 - Slow rising K
 - Constant Load/Low Cycle Fatigue

Deliverables

- Determine the role of impurities in CO₂ streams on gaseous H₂ embrittlement
 - Determine which species offer beneficial vs determinantal effects at low p_{H2}
 - Ascertain if the observed behaviour in short term tests can be projected to time scales associated with pipeline operation
 - Determine the behavior of different pipeline grades in the presence of various species

Benefits

- Identify approaches where gaseous H₂ embrittlement can be mitigated for CCS pipelines
- Identify pipeline grades in the infrastructure whose behavior may benefit from the presence of minor species in CO₂ transport streams
- Develop realistic flaw acceptance and inspection intervals for CCS pipelines

Questions or comments?

New program starting in August 2026

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www.dnv.com