Fatigue and Fracture Performance of High Strength Pipeline Steels in High Pressure Hydrogen Gas

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Hydrogen transportation is here!

- FCEVs are on the road
- Fueling station network is growing

Toyota Mirai

- Refueling in 3-5 minutes
- Range up to 500 km

Honda and Mercedes coming soon

Hyundai Tuscon

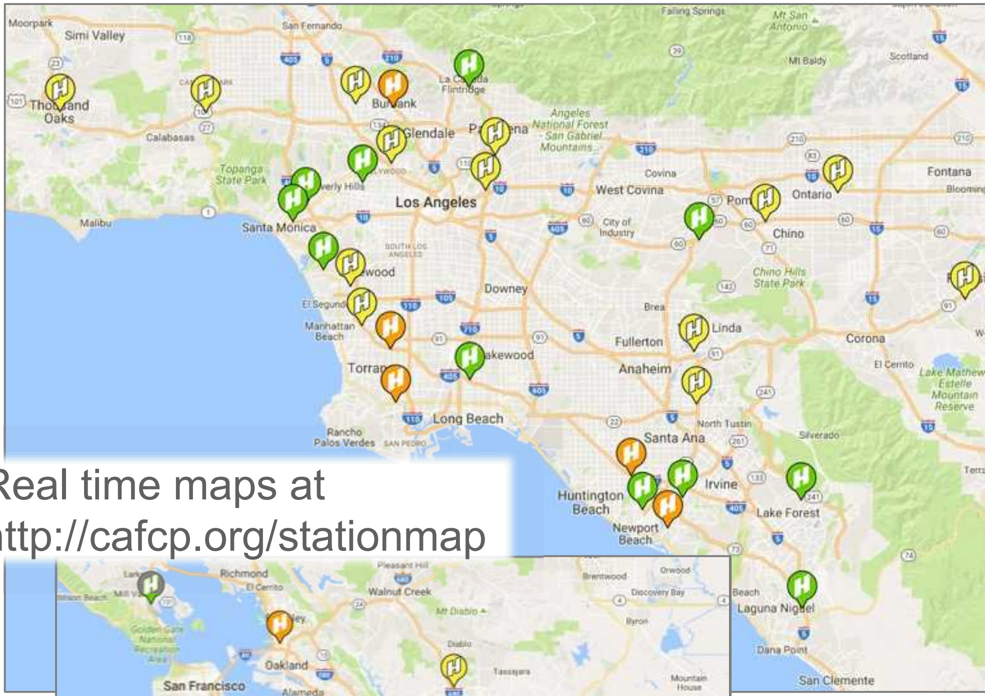
Hydrogen vehicles and fueling stations drive the development of codes and standards in the US


Photo courtesy of GM

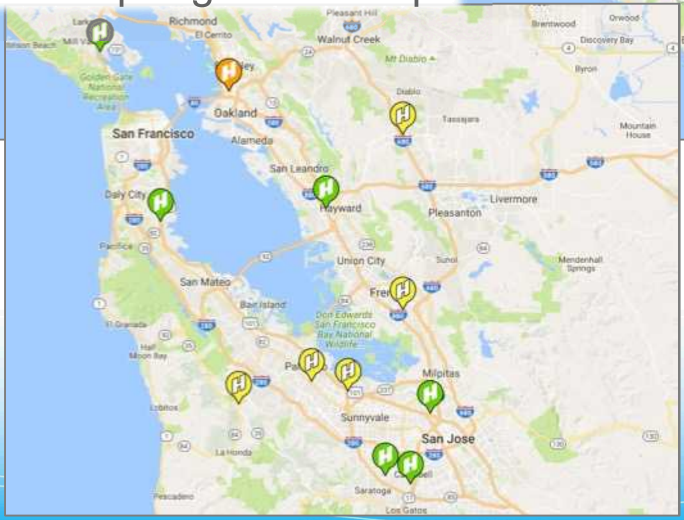
- Growing markets (worldwide estimates)
  - 200-400 light duty vehicles (automobiles on the road)
  - 100-150 heavy duty vehicles (buses, dump-trucks, yard-haulers, etc.)
  - 18,000 industrial trucks (forklifts)
  - >200 fueling stations for buses and automobiles
  - >50 forklift indoor/outdoor fueling sites
- Onboard storage: high-pressure gas at pressure up to 700 bar

H2 fuel infrastructure deployment is a challenge – The State of California is addressing with investments

- CA Governor Signs AB 8
  - programs aimed at reducing auto emissions until 2024
  - Provision to fund at least 100 hydrogen stations
  - Commitment of $20 million/yr
- Cluster Communities
  - South San Francisco Bay Area
  - Santa Monica and West LA
  - Torrance and coastal communities
  - Irvine and southern Orange County
- Similar efforts in Europe, Japan, and Korea

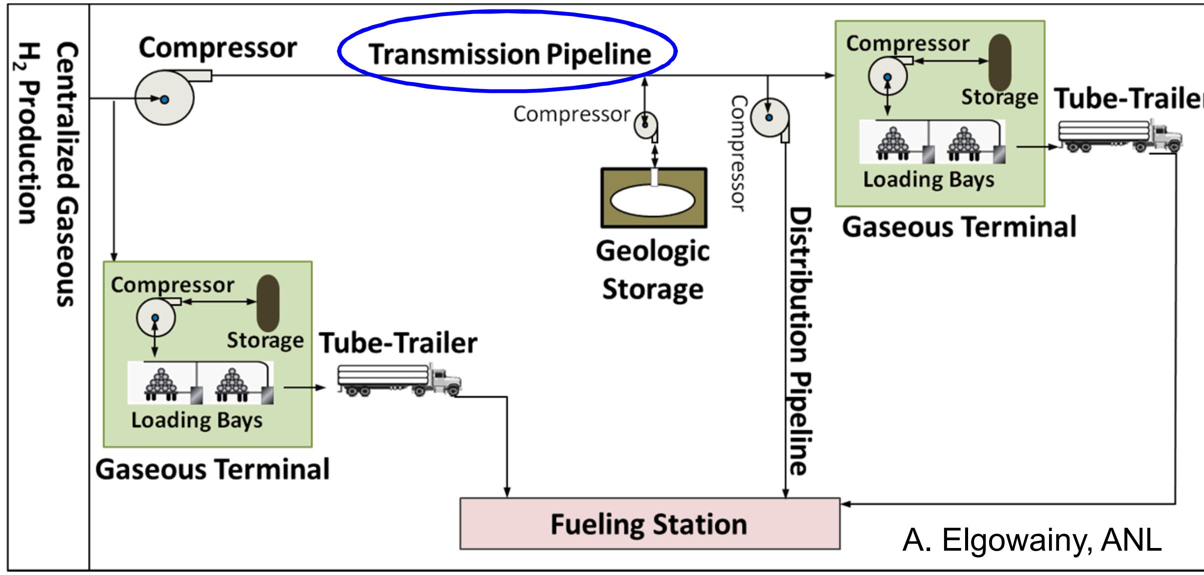


Real time maps at http://cafcp.org/stationmap

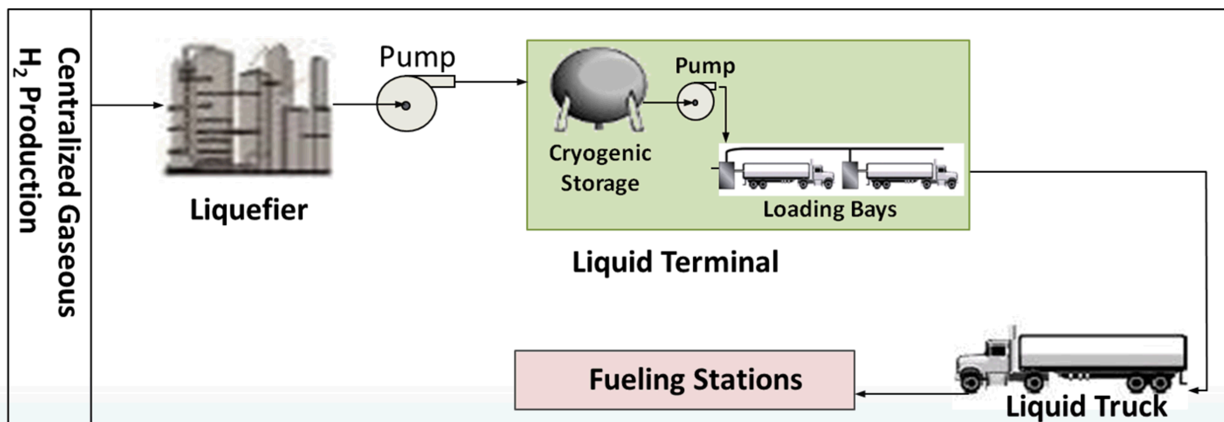


Structural materials are central focus for cost reduction and reliability of H_2 fuel infrastructure

Gaseous Delivery Pathways



Liquid Delivery Pathway



Hydrogen embrittlement recognized as potential reliability issue for steel H_2 pipelines

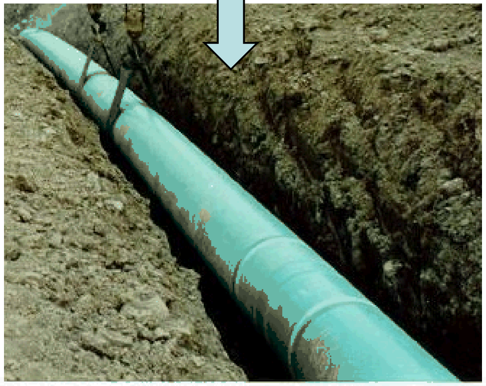
Welds are a potential area of concern for reliability of hydrogen pipelines

X52 or X65 Line Pipe (i.e. base metal)

Microstructure of base metal affects crack growth rates

Welding to join or repair pipe

Welds may be more susceptible to embrittlement



Daily pressure *fluctuations* can result in fatigue loading which can affect embrittlement

Images used with permission from U.S Pipeline, and Canadian Energy Pipeline Association

Objectives/Relevance

Why should steel hydrogen pipelines be used?

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

Project Purpose:

- Assess steel pipeline performance under conditions expected in mature hydrogen market (i.e. *fluctuating pressures = cyclic loading*)
  - Answer specific question: Are welds more susceptible to H_2 accelerated fatigue crack growth compared to base metals?
  - Experimental data and analysis can guide the **optimization of design codes and standards** to lower pipeline cost while maintaining reliability
  - Establish **models that predict pipeline behavior as a function of microstructure** to guide future developments of novel steels

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

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

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

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

F= design factor = 0.72 (Class 1)

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

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

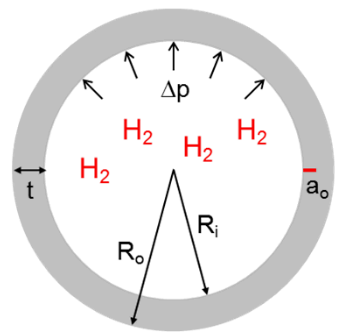
P = design pressure = 3000 psi
S = specified min yield stress
t = thickness
D = outside diameter = 24 in.
F= design factor = 0.5 (Class 1)
E = longitudinal joint factor = 1
T = temp derating factor = 1
H_F=Materials Performance Factor

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

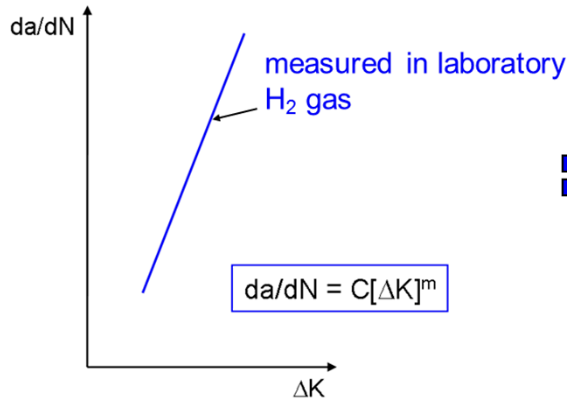
Specified Min. Strength, ksi		System Design Pressure, psig						
Tensile	Yield	≤1,000	2,000	2,200	2,400	2,600	2,800	3,000
66 and under	≤52	1.0	1.0	0.954	0.910	0.880	0.840	0.780
Over 66 through 75	≤60	0.874	0.874	0.834	0.796	0.770	0.734	0.682
Over 75 through 82	≤70	0.776	0.776	0.742	0.706	0.684	0.652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

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

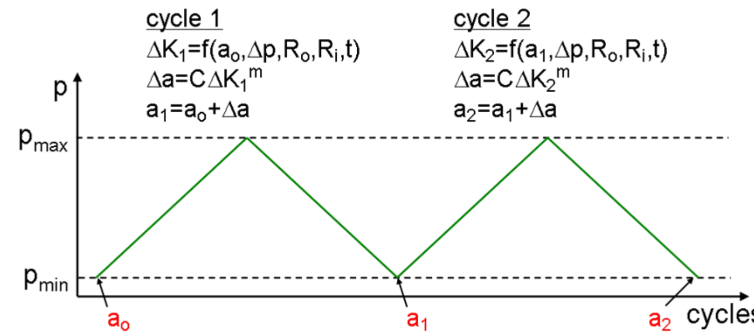
Measured fatigue crack growth laws can be applied to determine appropriate wall thickness for steel H_2 pipelines

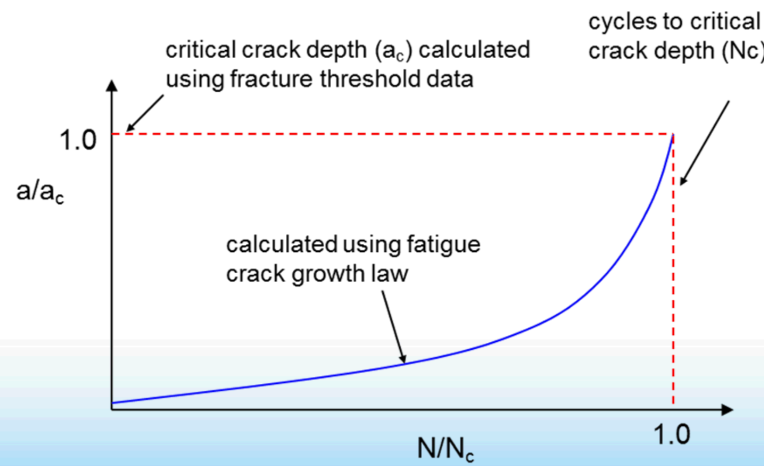


$\Delta K = \Delta p[f(a, t, R_o, R_i)]$



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



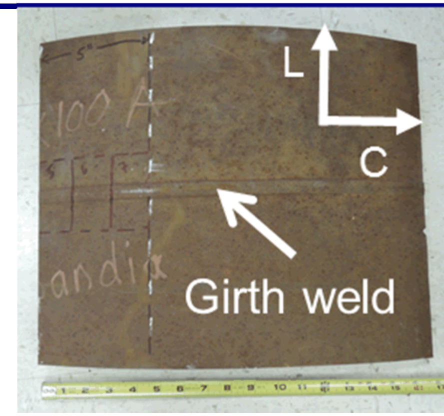


- ASME fatigue life calculation: structural analysis + fatigue crack growth law
- Two fracture properties in H_2 needed
  - Fatigue crack growth law
  - Fracture threshold

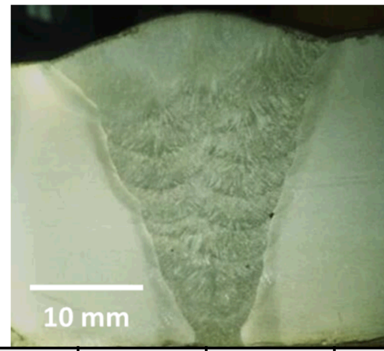
H_2-assisted fatigue crack growth measured for steel pipelines and girth welds

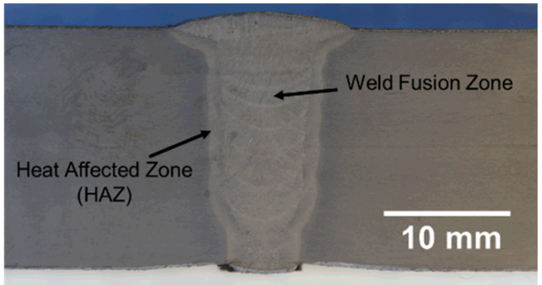
X52
Friction Stir Weld

X65
Gas Metal Arc Weld



X100
Gas Metal Arc Weld



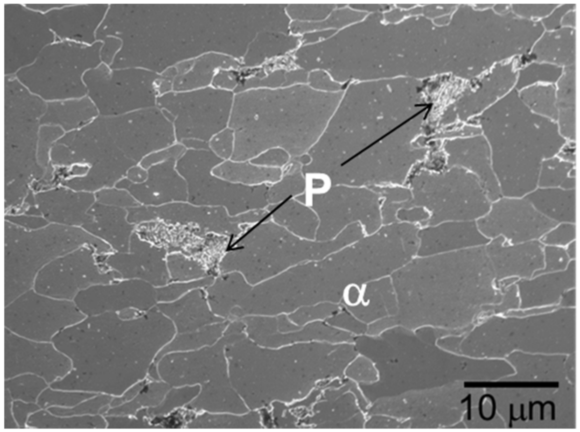


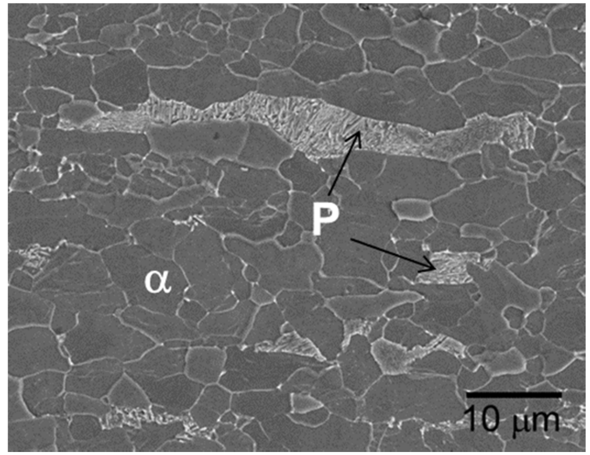
Material	Fe	C	Mn	P	S	Si	Cu	Ni	Nb	Ti	B
X52	Bal.	0.054	1.02	0.009	<0.005	0.16	0.08	0.03	0.02	<0.005	N/A
X65	Bal.	0.08	1.53	0.01	0.001	0.32	0.024	0.038	0.039	0.002	N/A
X100	Bal.	0.085	1.69	0.013	<.001	0.26	0.14	0.24	0.047	0.017	0.0015

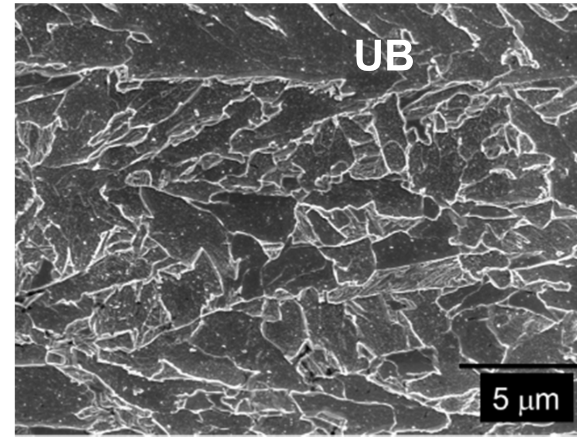
Welding process generates different microstructures and stresses than the base metal.

Microstructures vary quite substantially between welds and base metals

α = ferrite P = Pearlite
UB = upper bainite
AF = acicular ferrite



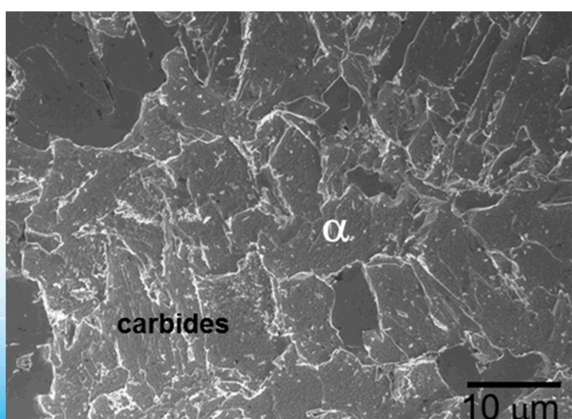


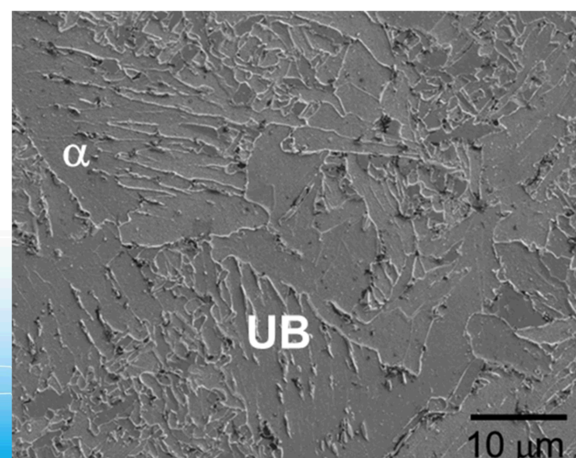


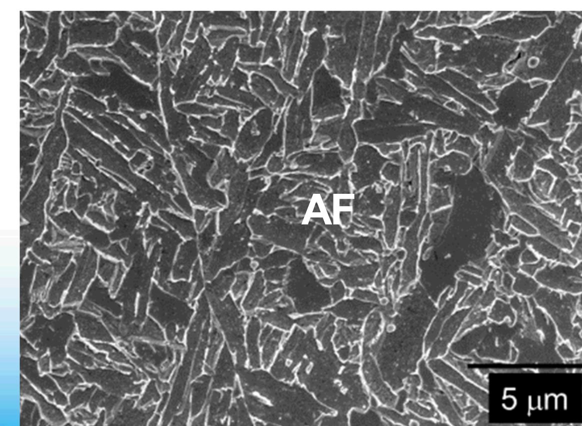
Base Metal
X52
Friction Stir Weld

Base Metal
X65
Gas Metal Arc Weld

Base Metal
X100
Gas Metal Arc Weld

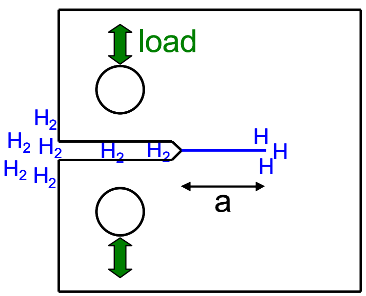




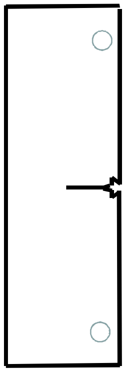


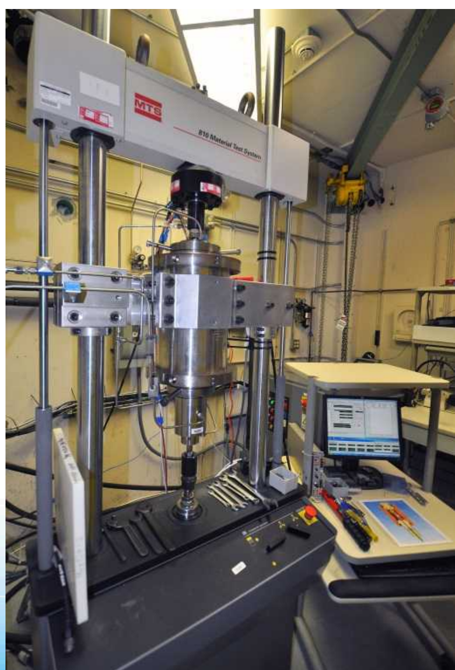
Approach: Fatigue crack growth laws measured in service environment, i.e. high-pressure H_2 gas

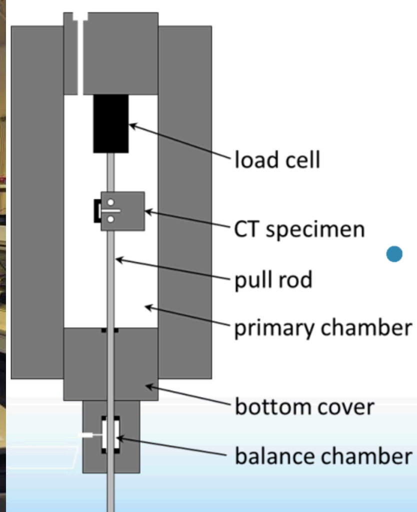
Compact Tension (C(T))



ESE(T)

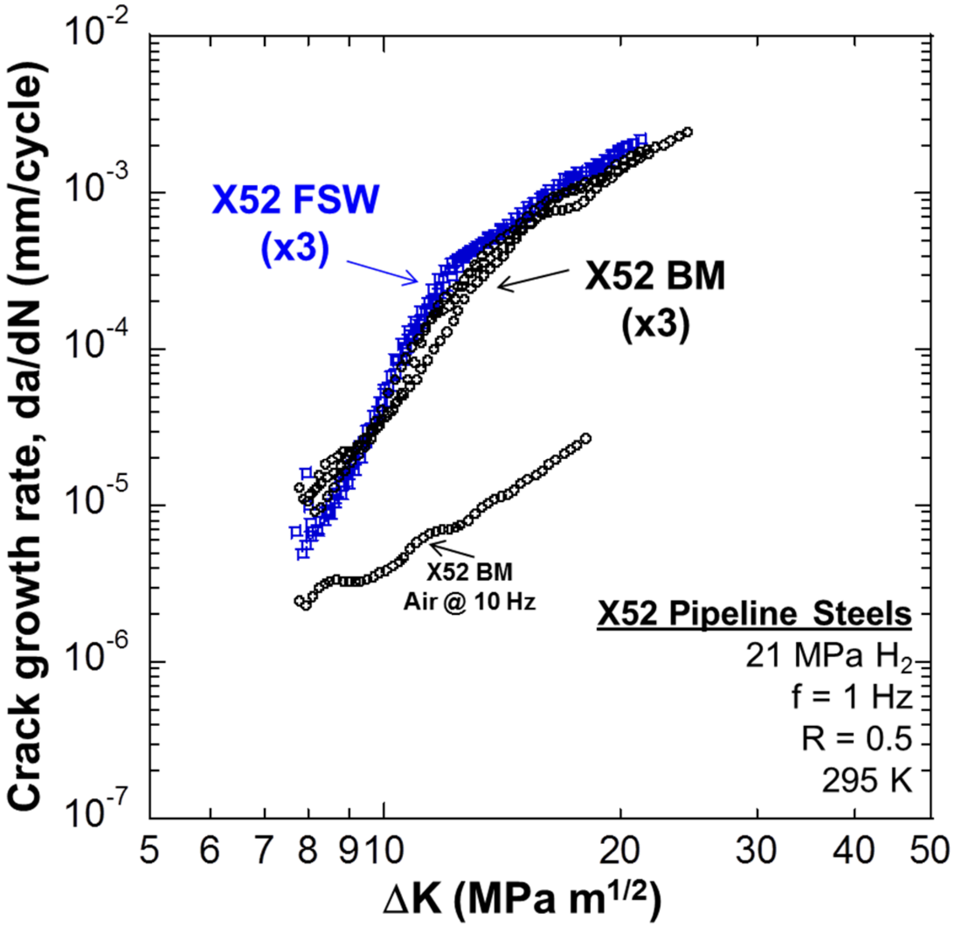


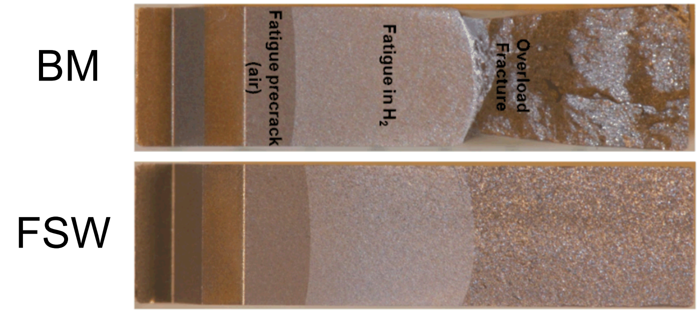


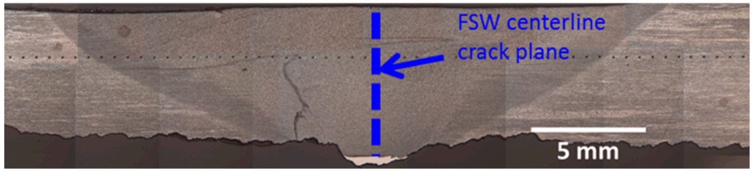


- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT or clip gauge
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude
  - $R = \frac{P_{min}}{P_{max}} = 0.5$ $\quad freq = 1\ Hz$
    - Represents pressure fluctuations to ½ P_{max}
- Environment
  - Supply gas: 99.9999% H_2
  - Pressure = 21 MPa (3 ksi)
  - Room temperature

Triplicate tests on X52 Friction Stir Weld performed in 21 MPa H_2 gas





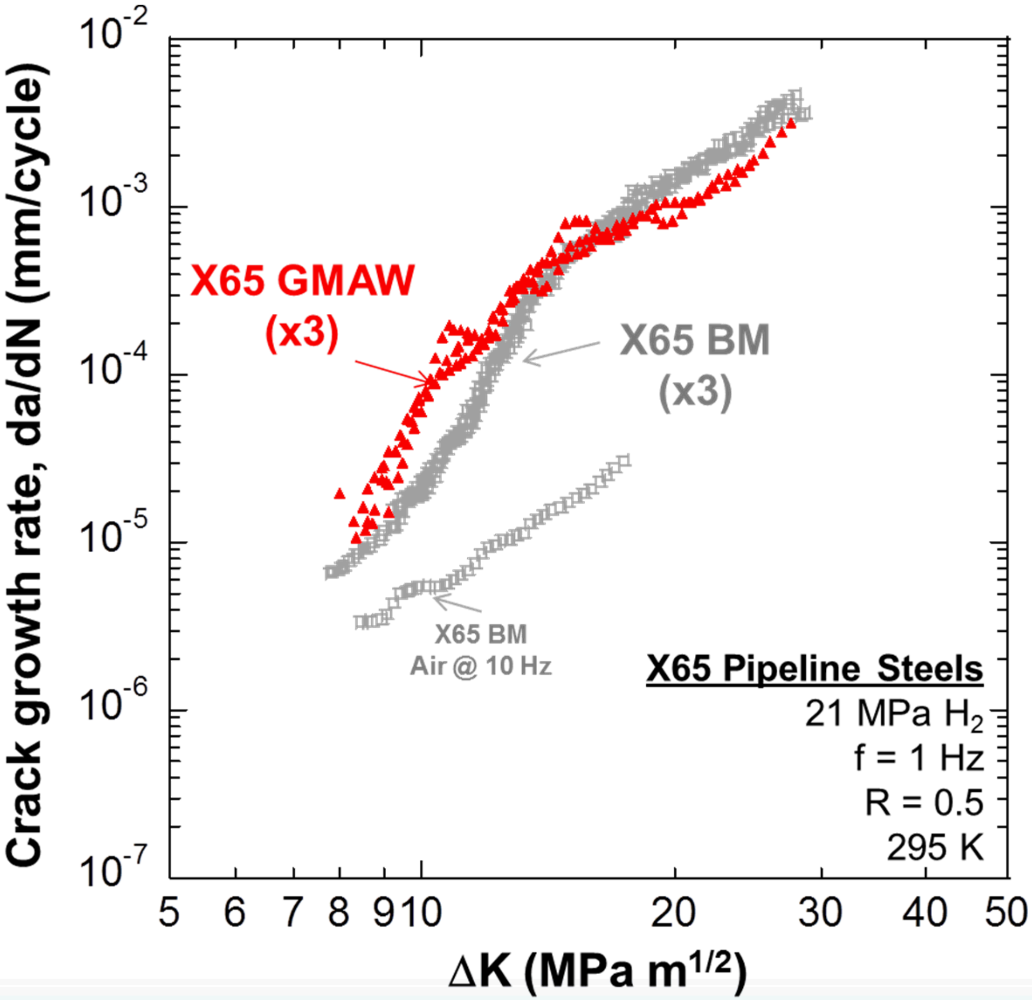


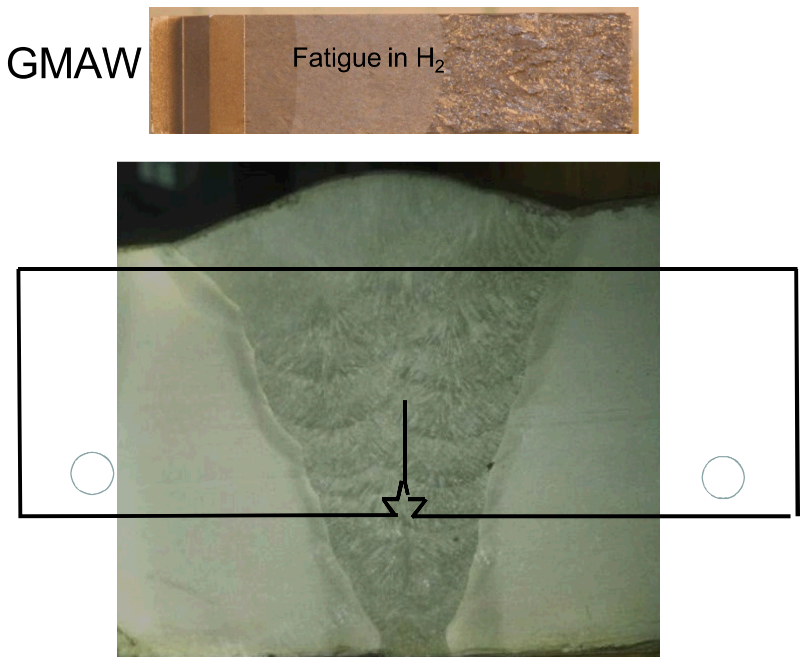
*Crack propagate perpendicular to plane of page

- Crack growth rate measurements in weld and base metal are repeatable

X52 friction stir weld exhibited slightly higher HA-FCG than base metal

Triplicate tests on X65 Gas Metal Arc Weld (GMAW) performed in 21 MPa H_2 gas

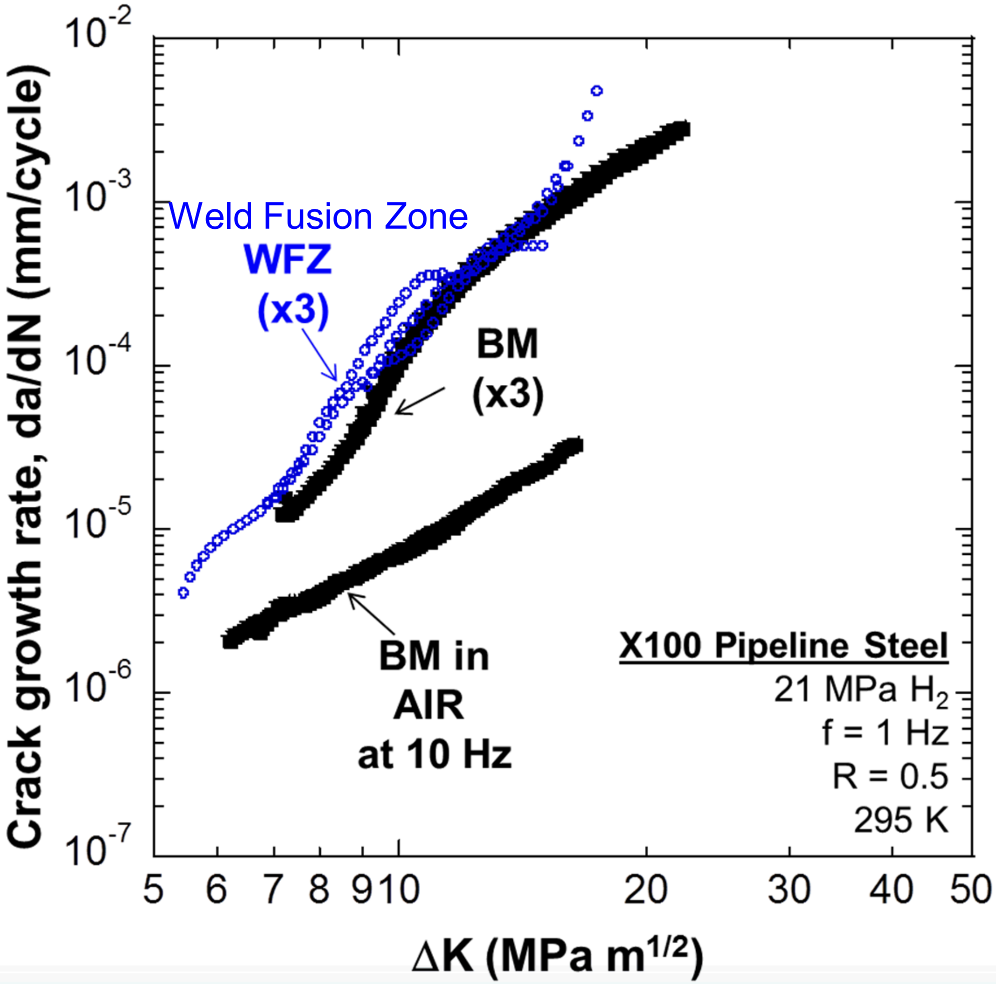




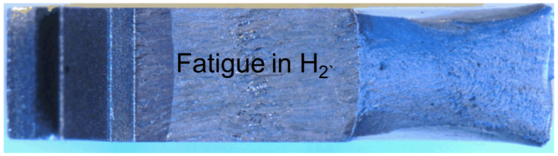
- Crack growth rate measurements in weld and base metal are repeatable

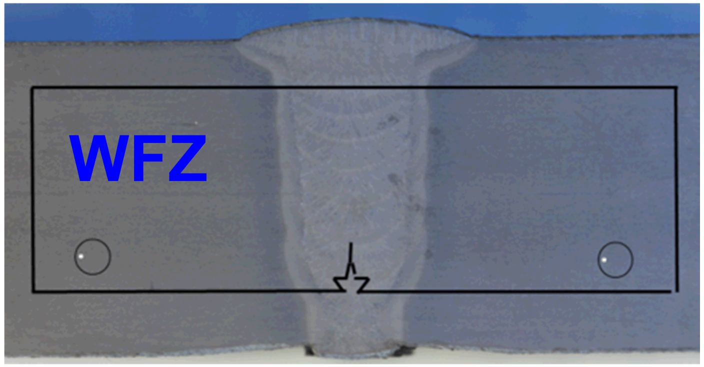
At low ΔK, weld exhibited slightly higher HA-FCG compared to base metal.

Triplicate tests on X100 Gas Metal Arc Weld (GMAW) performed in 21 MPa H_2 gas



WFZ

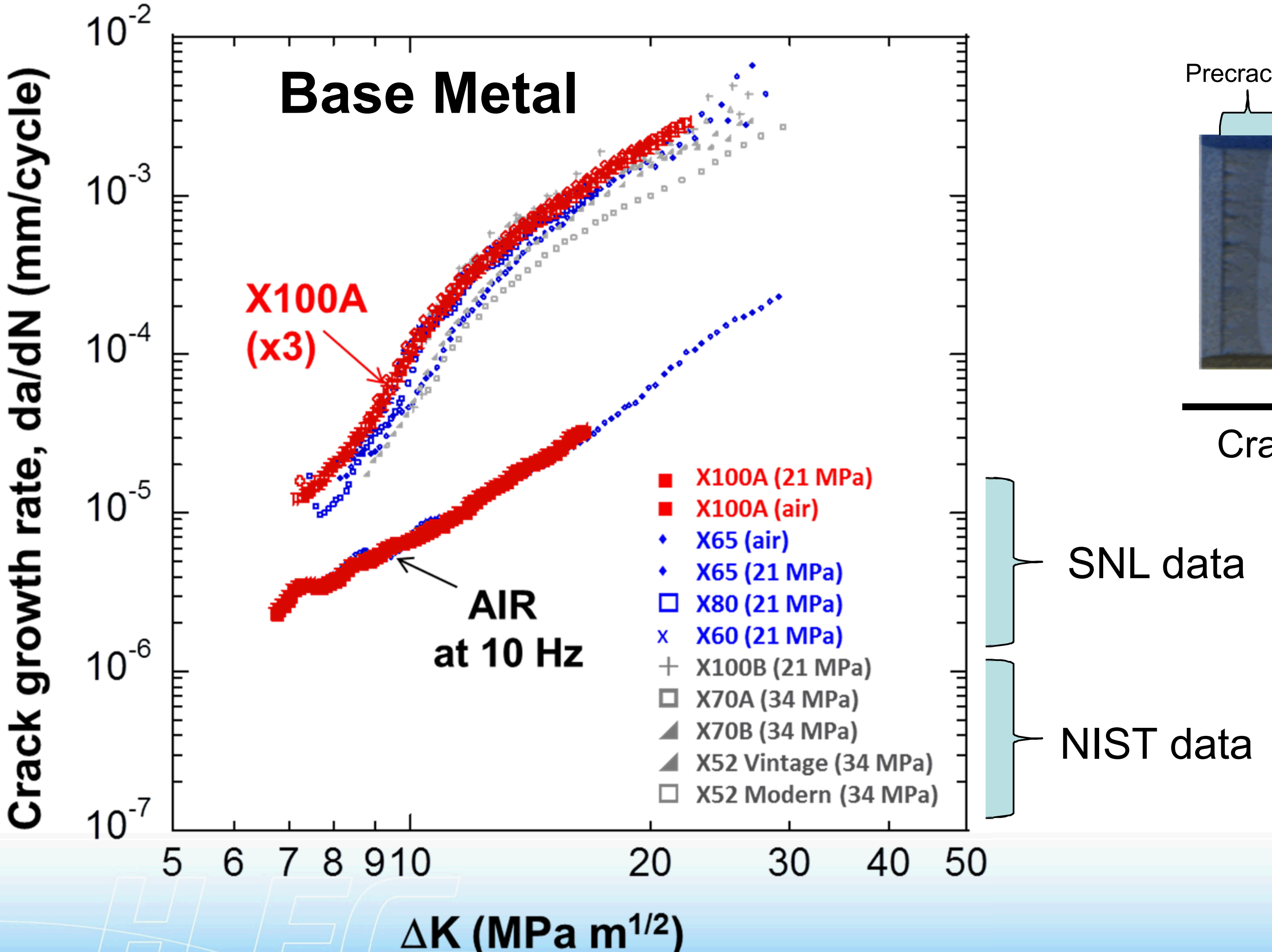


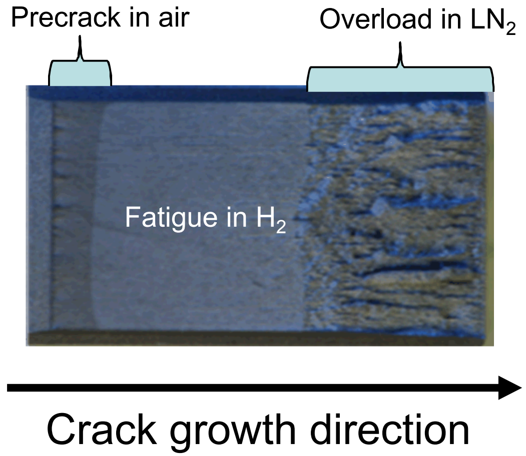


- Crack growth rate measurements in weld and base metal are repeatable

Higher crack growth rates observed at low ΔK range in weld compared to base metal.

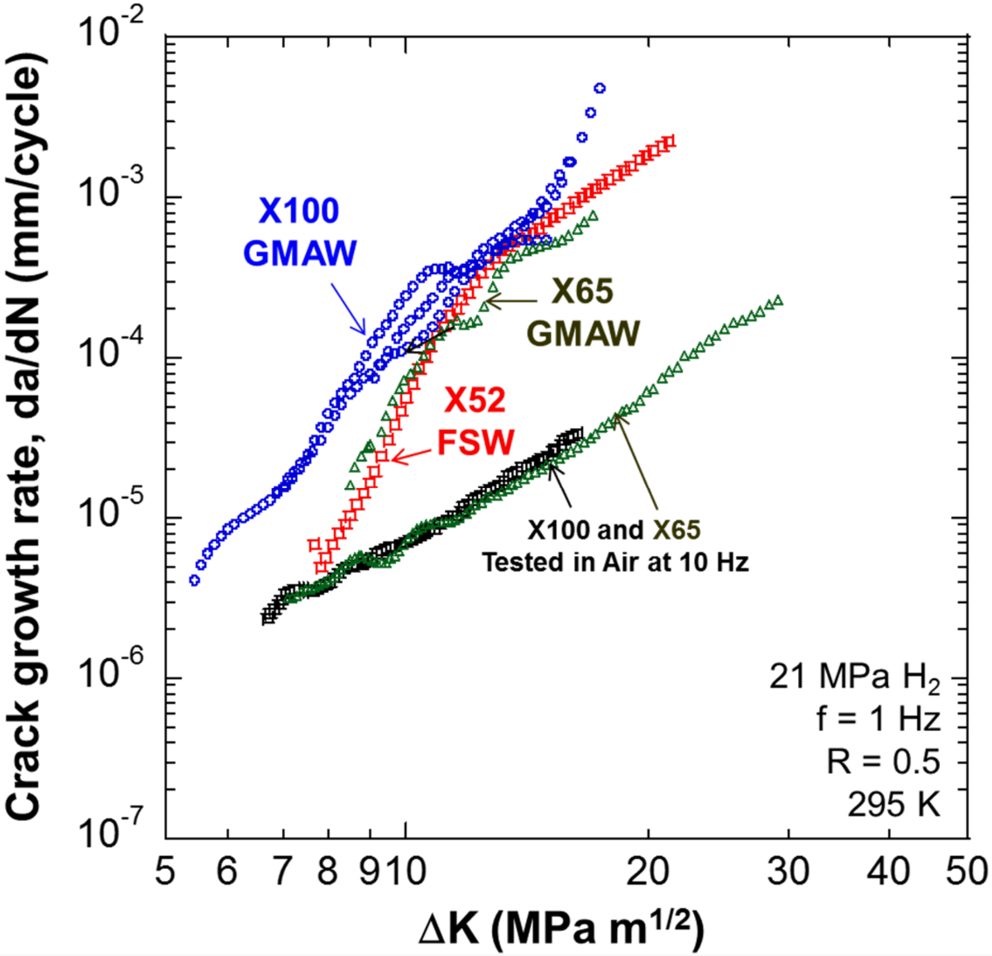
Fatigue crack growth rates of pipelines exhibit similar behavior (SMYS: 358 to 689 MPa)



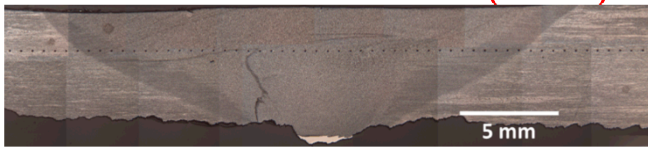


X100A exhibited comparable HA-FCG to lower strength pipelines

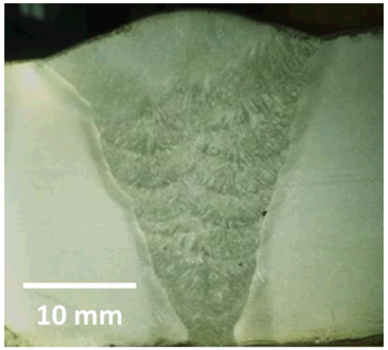
Higher strength pipeline welds exhibit Faster crack growth rates at lower ΔK range



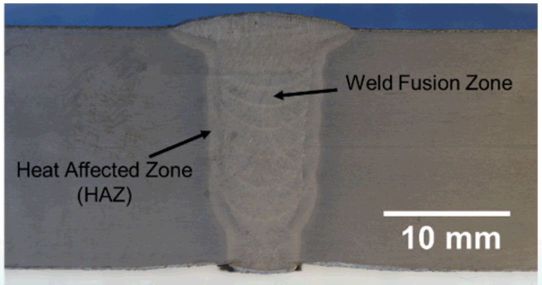
X52 Friction Stir Weld (FSW)



X65 Gas Metal Arc Weld (GMAW)

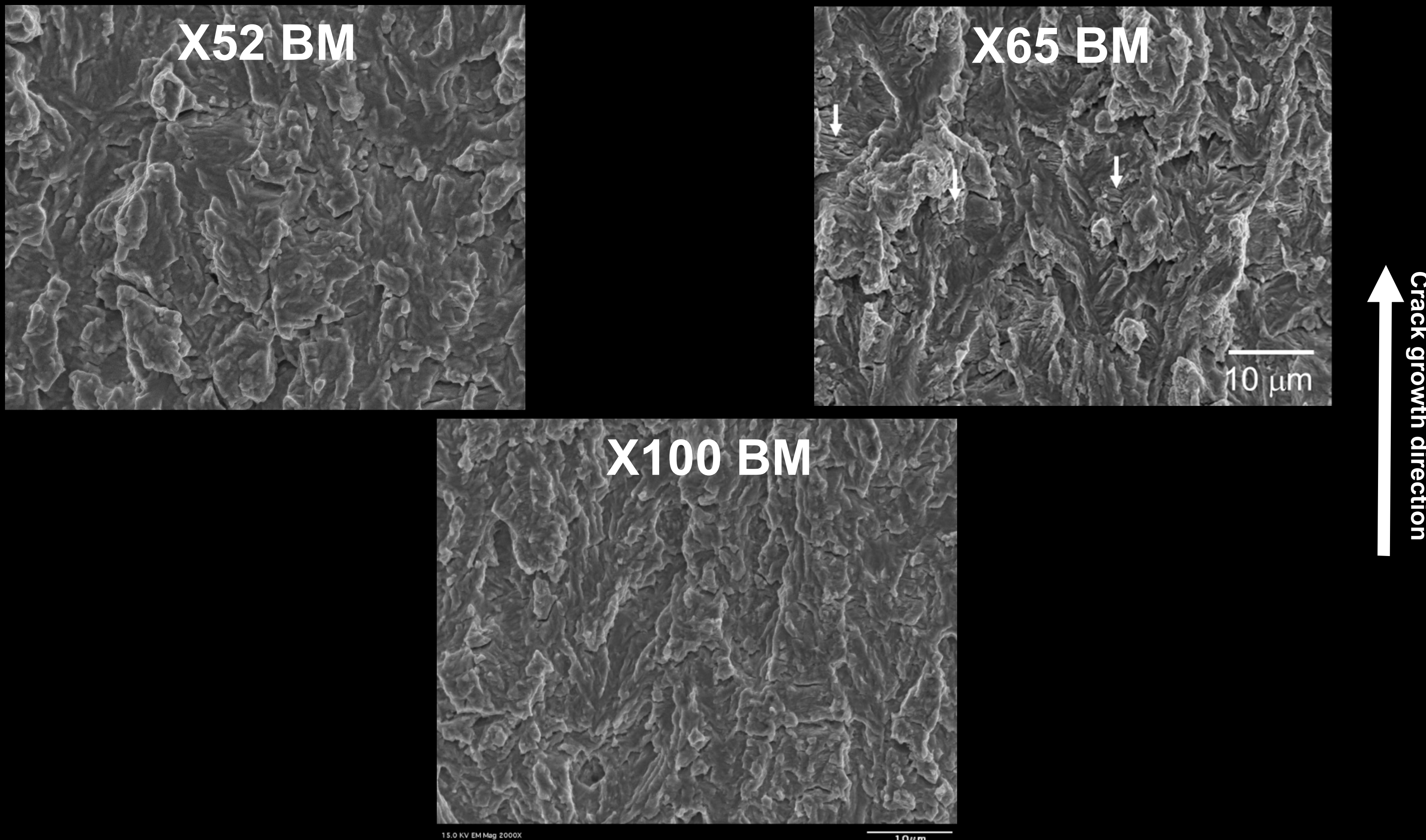


X100 Gas Metal Arc Weld (GMAW)



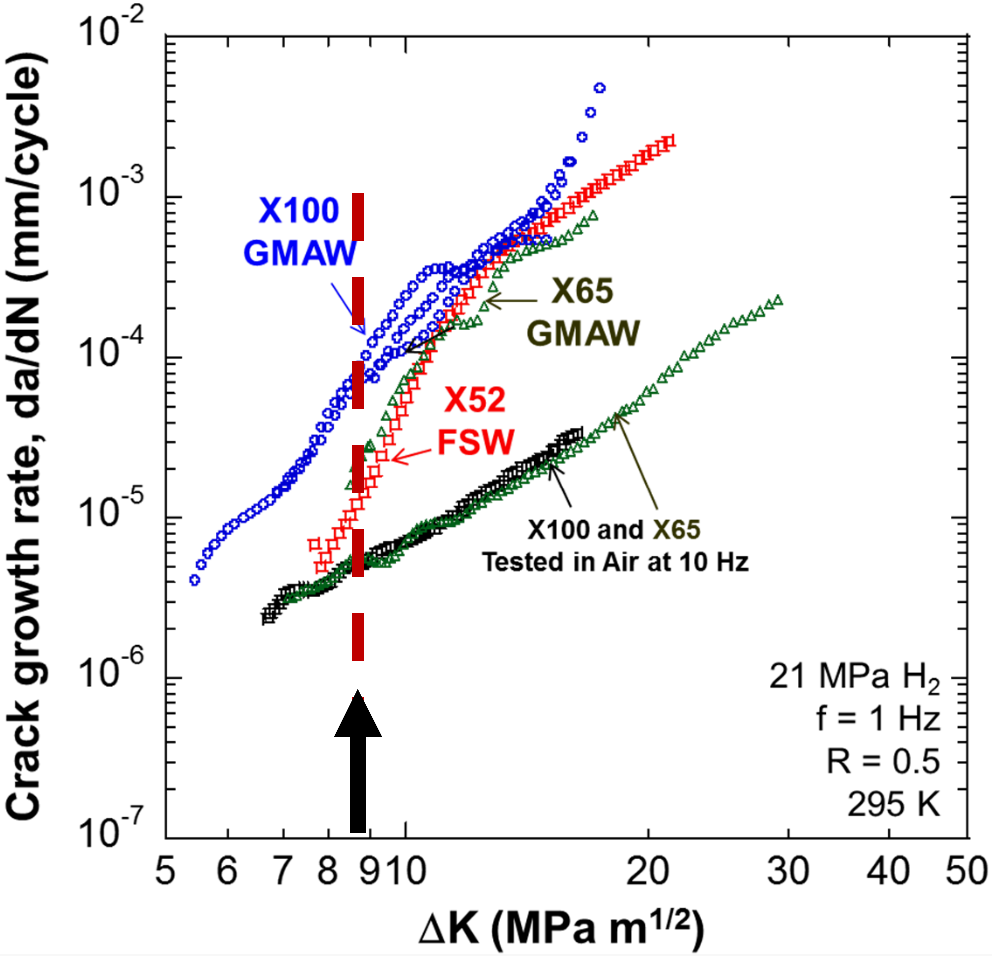
Lower strength welds (X52 and X65) exhibit similar fatigue crack growth rates despite different welding techniques

Fracture surfaces at ΔK = 15 MPa $m^{1/2}$ in ***Air***

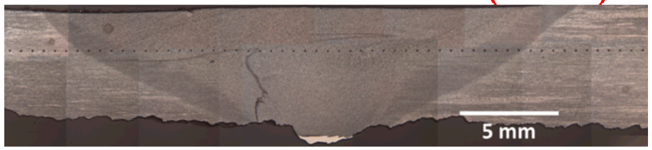


- Predominantly transgranular fracture which appears similar at all ΔK
- Distinct striations on fracture surfaces when tested in Air
  - Due to crack tip blunting/re-sharpening during fatigue

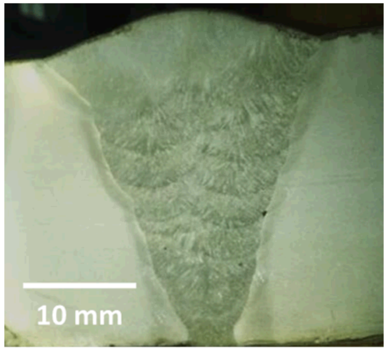
Higher strength pipeline welds exhibit Faster crack growth rates at lower ΔK range



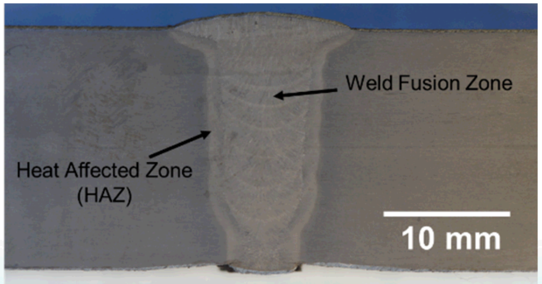
X52 Friction Stir Weld (FSW)



X65 Gas Metal Arc Weld (GMAW)



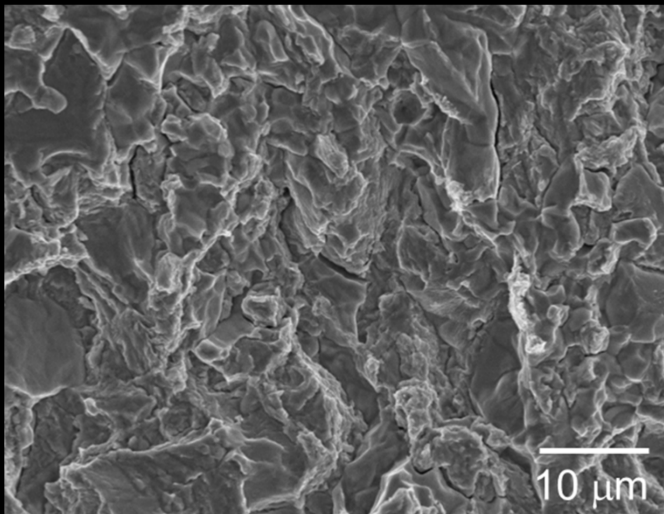
X100 Gas Metal Arc Weld (GMAW)



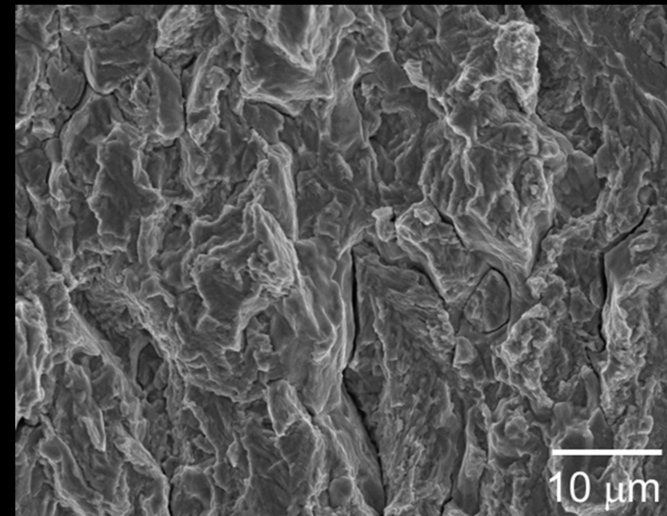
Lower strength welds (X52 and X65) exhibit similar fatigue crack growth rates despite different welding techniques

Base Metal Fracture surfaces at $\Delta K = 8.5$ MPa $m^{1/2}$ in H_2

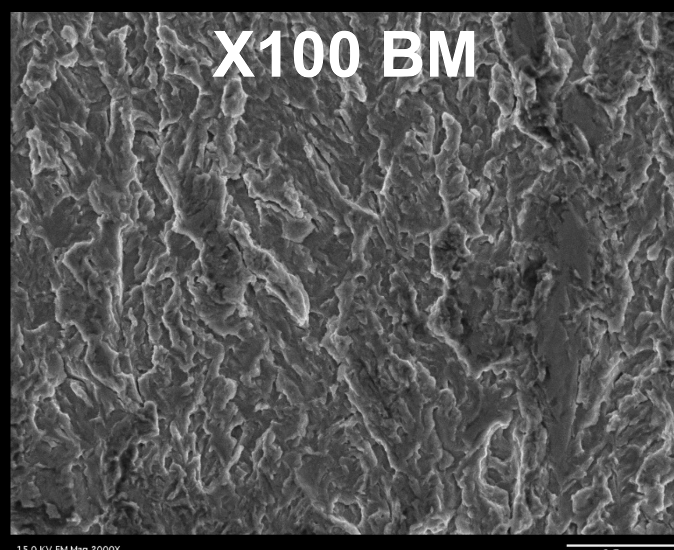
X52 BM



X65 BM

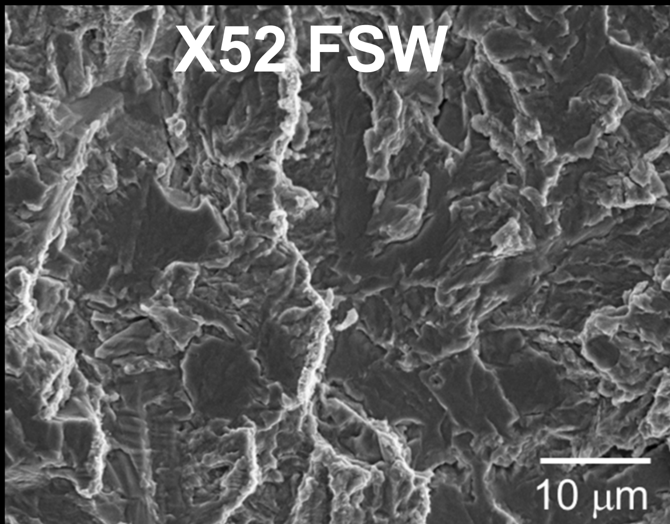


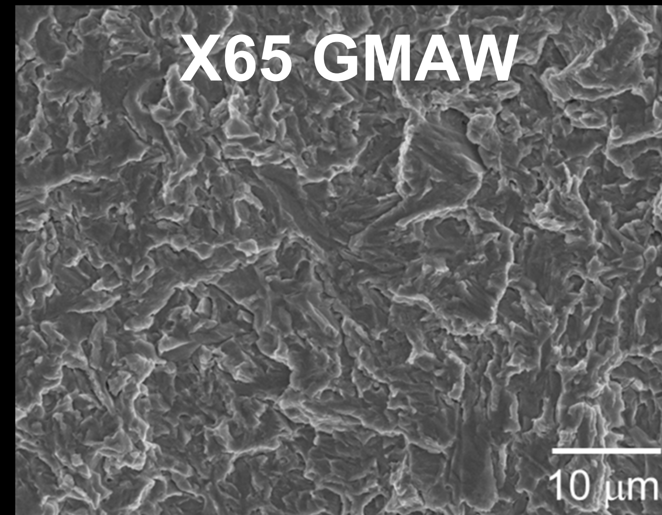
Crack growth direction



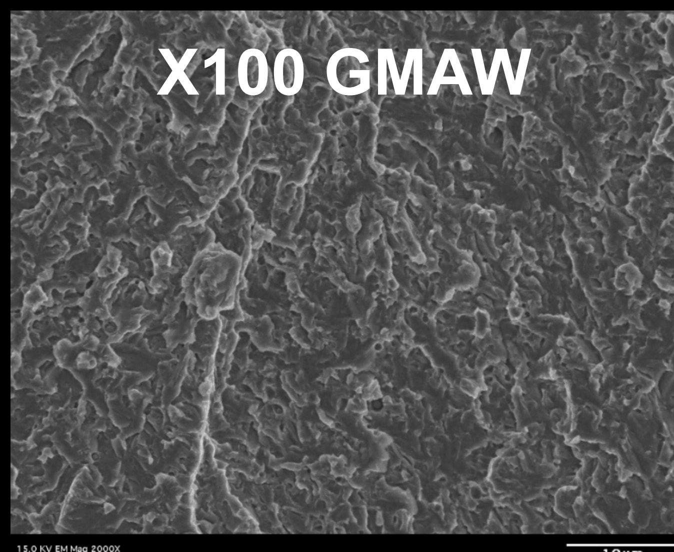
X52 and X65 exhibit some intergranular with transgranular
X100 exhibits only transgranular

Weld Fracture surfaces at $\Delta K = 8.5$ MPa $m^{1/2}$ in H_2



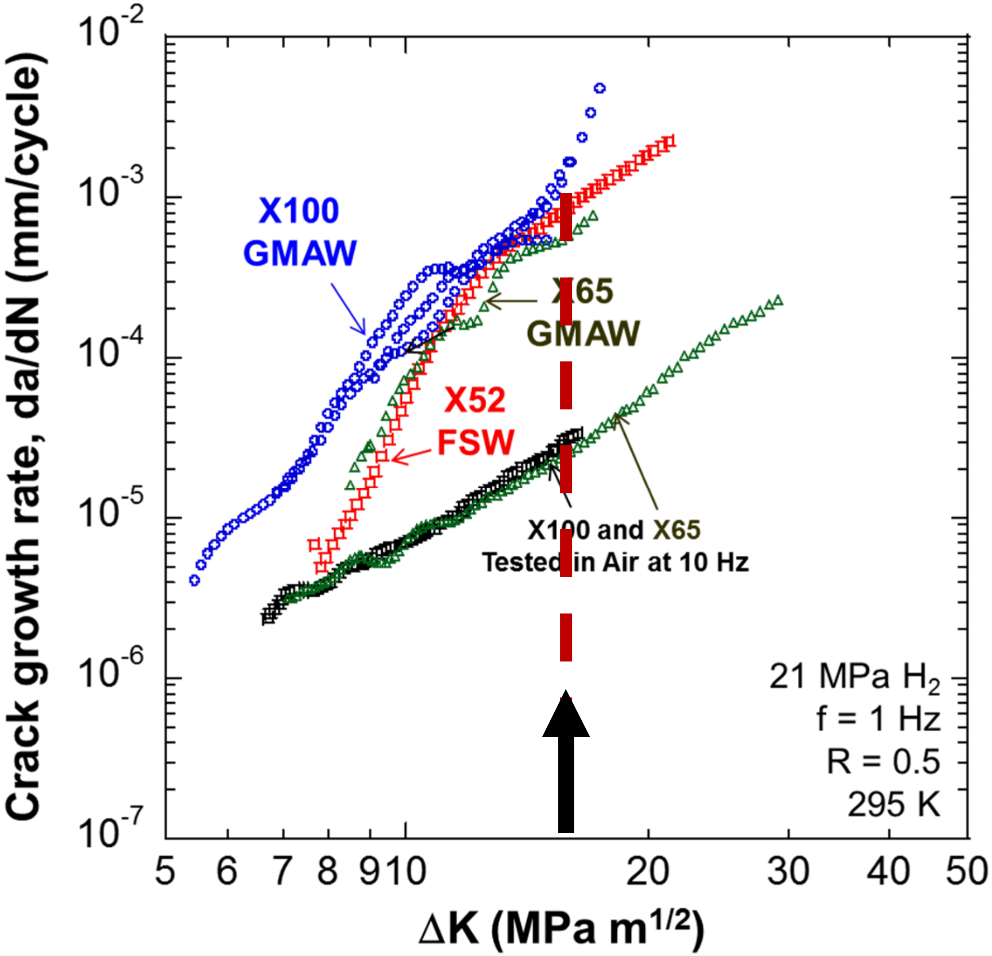


Crack growth direction

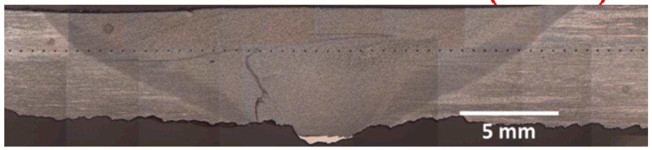


Welds have notable absence of intergranular fracture
X100 weld shows more refined features

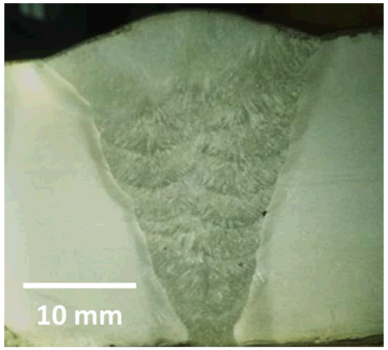
Higher strength pipeline welds exhibit Faster crack growth rates at lower ΔK range



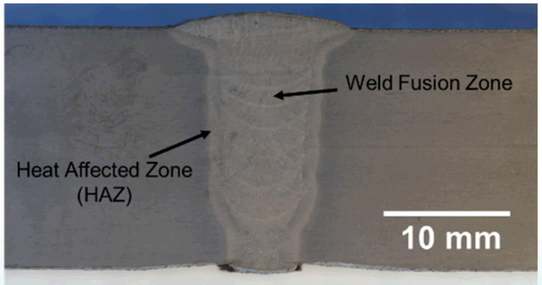
X52 Friction Stir Weld (FSW)



X65 Gas Metal Arc Weld (GMAW)

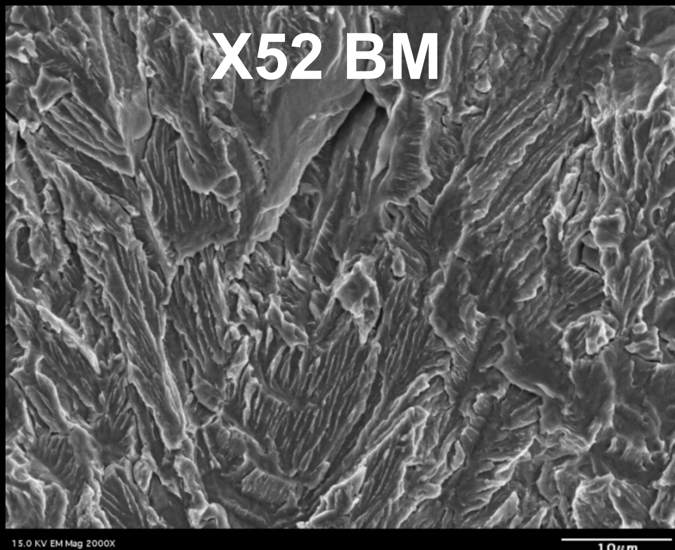


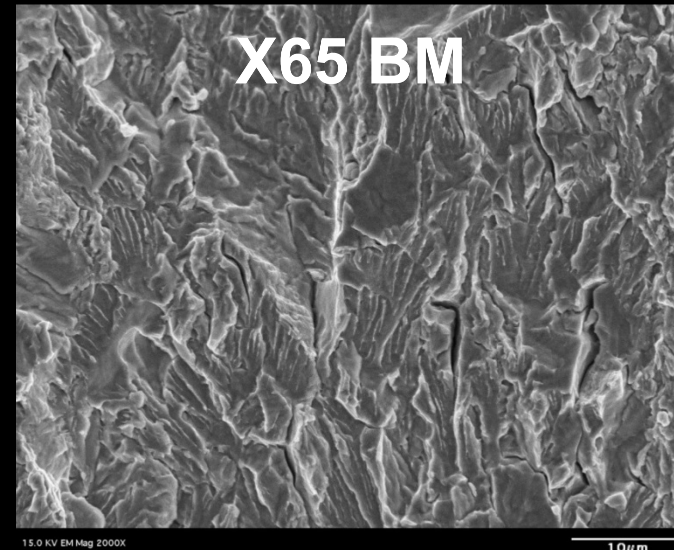
X100 Gas Metal Arc Weld (GMAW)



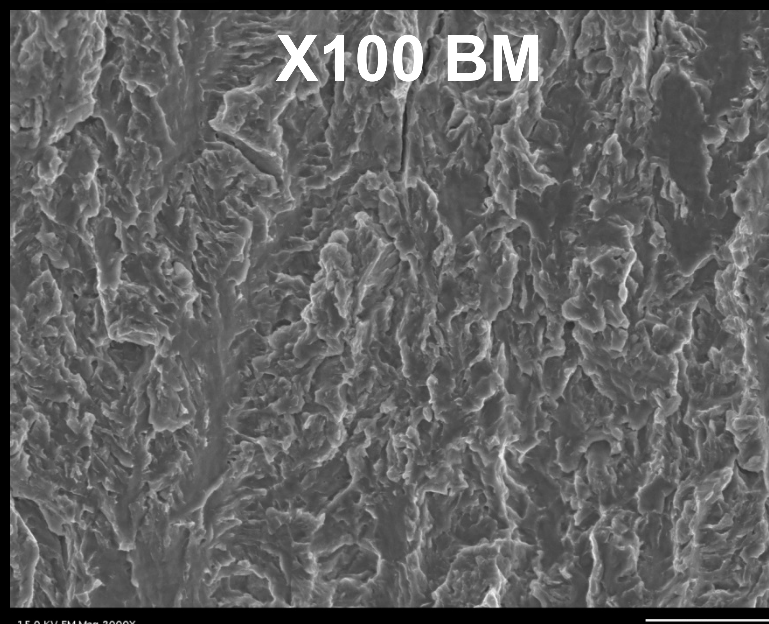
Lower strength welds (X52 and X65) exhibit similar fatigue crack growth rates despite different welding techniques

Fracture surfaces at ΔK = 15 MPa $m^{1/2}$ in H_2





Crack growth direction

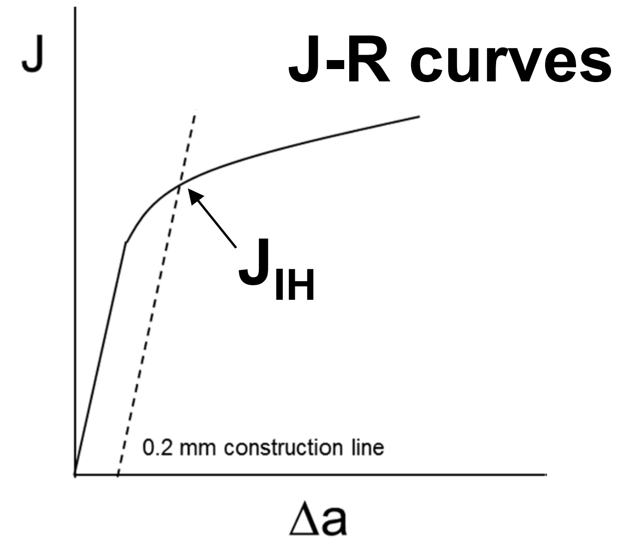


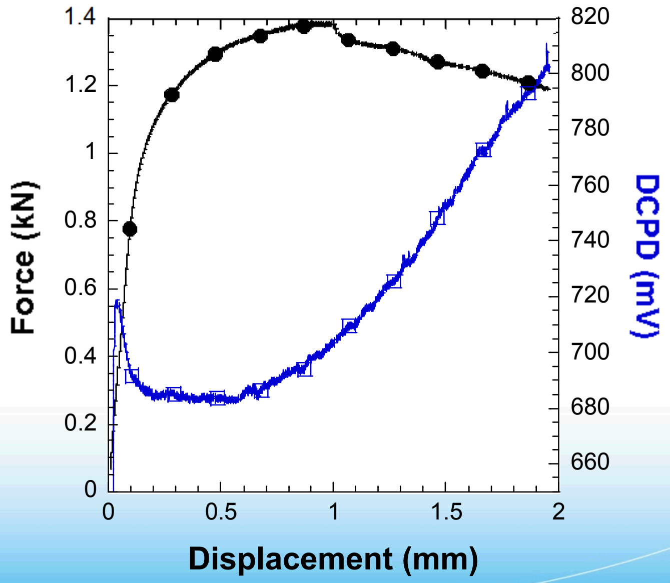
- Similar transgranular features in all materials at ΔK > 15 MPa $m^{1/2}$
- Microstructure plays less role at higher ΔK

Fatigue Life Calculations also require fracture toughness

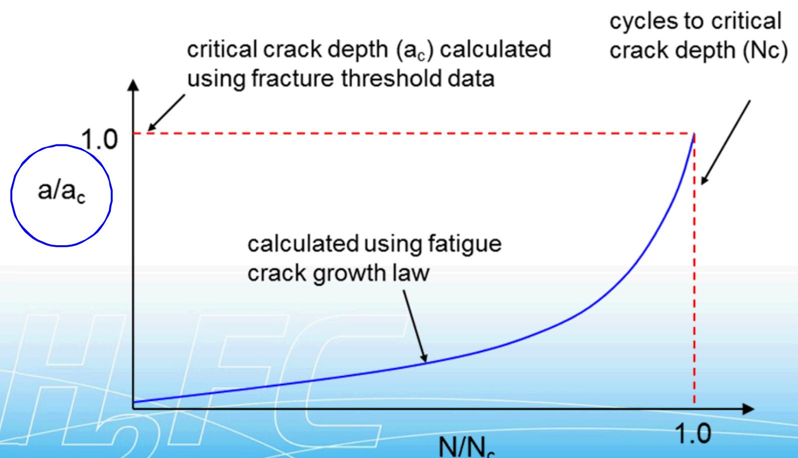
- **Elastic-Plastic Fracture Mechanics (ASTM E1820)**
  - **(J-R curves)**

- **Constant rising displacement test**
- **DCPD signal was used to detect crack initiation**

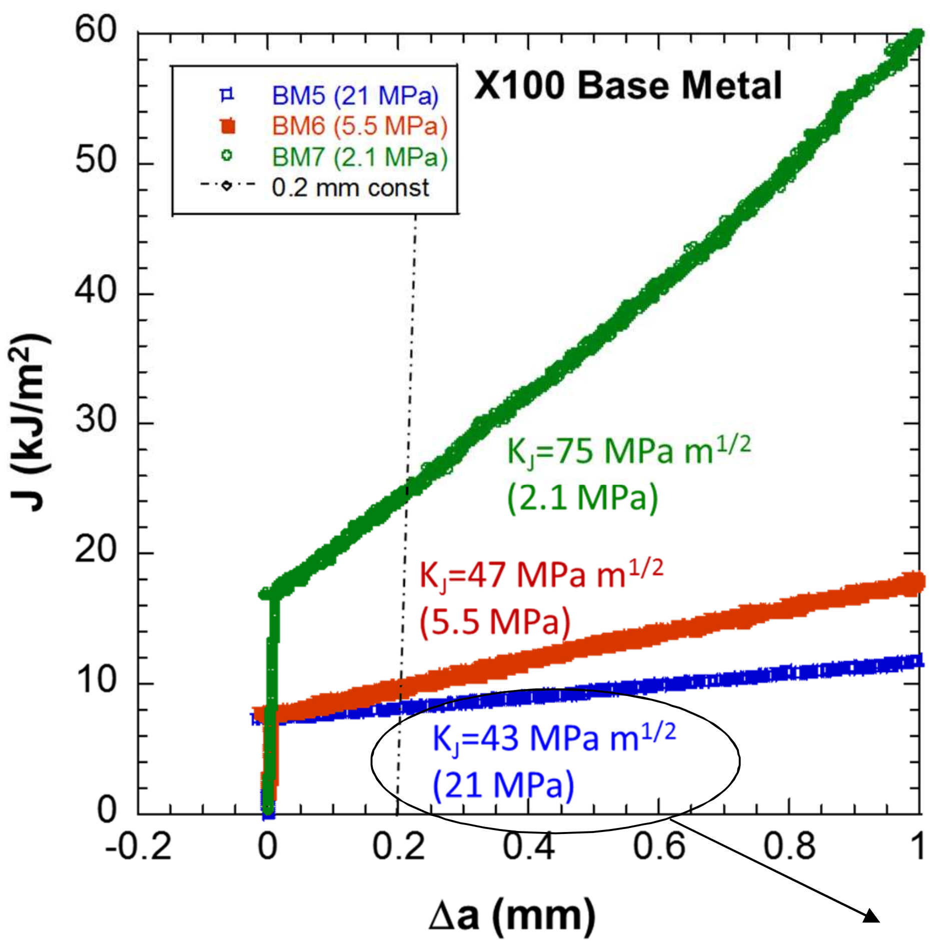


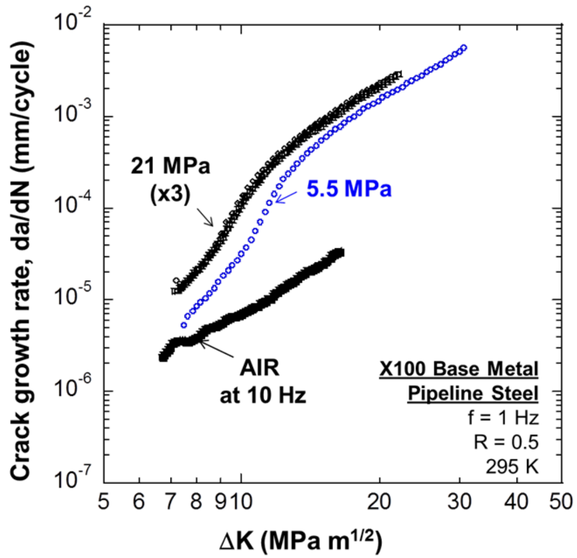


Use Fracture Thresholds → Determine a_{crit}



Fracture toughness degrades with increasing pressure





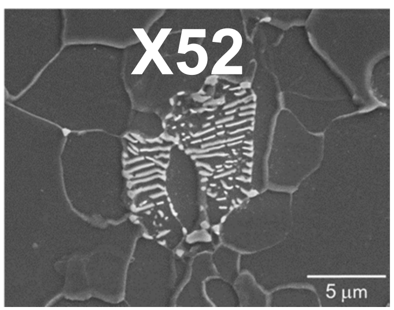
→ Pressure dependence also observed in fatigue

B31.12 requires min K_{IH}= 50 MPa $m^{1/2}$

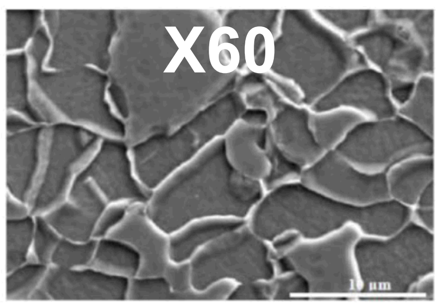
Fracture toughness may be limiting factor in pipeline design for higher strength steel pipes

Different microstructures and properties can be obtained from similar compositions

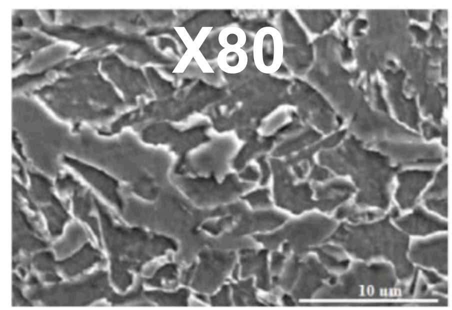
Designation	C	Mn	Si	Cu	Ni	V	Nb	Al	Cr	Mo	Ti	S	P
X52	0.06	0.87	0.12	0.03	0.02	0.002	0.03	0.034	0.03	-	-	0.006	0.011
X60 HIC	0.03	1.14	0.18	0.24	0.14	0.001	0.084	0.034	0.16	0	0.014	0.001	0.008
X80	0.05	1.52	0.12	0.23	0.14	0.001	0.092	0.036	0.25	0	0.012	0.003	0.007
X100	0.085	1.59	0.26	0.14	0.24	-	0.047	0.029	0.19	**0.17**	0.017	<0.001	0.013



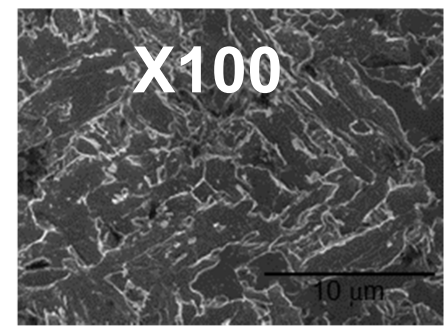
5-7% Pearlite + Ferrite



100% Polygonal ferrite



90% Polygonal ferrite
10% coarse acicular ferrite

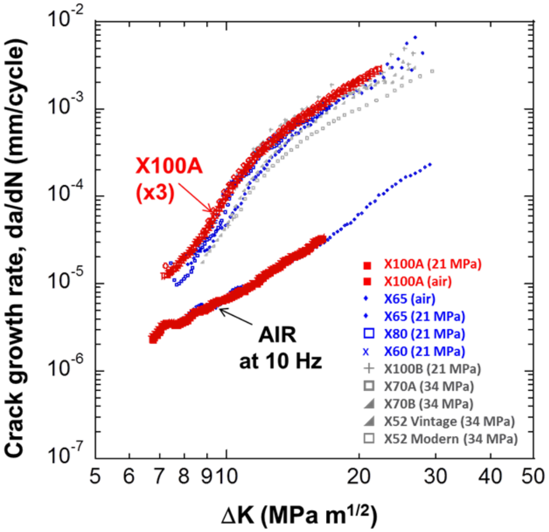


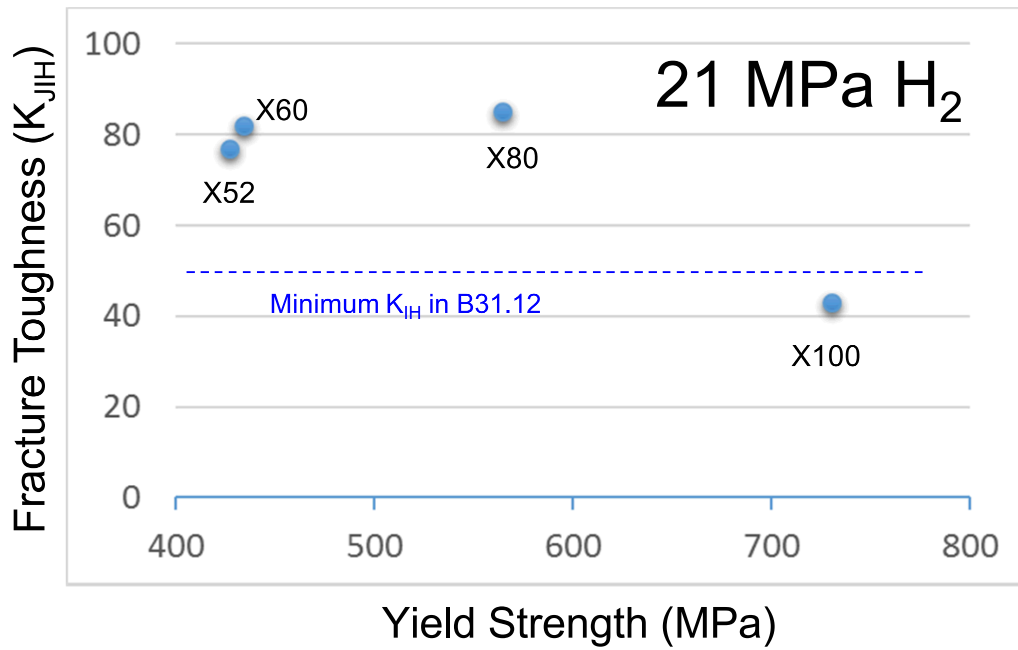
Acicular ferrite
Upper bainite

Alloy ID	S_y (ksi)	S_u (ksi)	S_y (MPa)	S_u (MPa)
X52	62	72	429	493
X60	63	70	434	486
X80	82	87	565	600
X100	106	126	732	868

D. Stalheim *et al.* IPC2010-31301
C. San Marchi *et al.* PVP2010-25825

Similar Fatigue performance but ***Fracture Toughness*** may be limiting factor in high strength pipelines





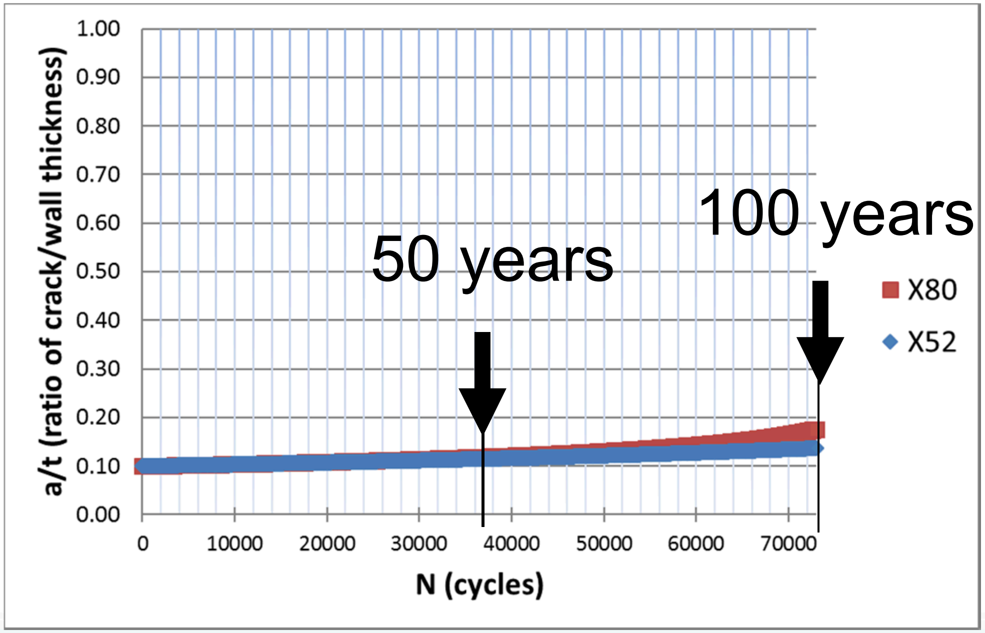
Alloy	H_2 Pressure	K_{JQ} (MPa $m^{1/2}$)
X52	21 MPa	77
X60	21 MPa	82
X80	21 MPa	102
X100	21 MPa	43

- Minimum K_{IH} in ASME B31.12 is 50 MPa $m^{1/2}$

Fracture testing needs to be conducted on weld and base metals to ensure reliability

Thickness premiums might be overly conservative

	Thickness Requirements based on ASME Current Codes	
SMYS	B31.8 - Natural Gas	B31.12 - Hydrogen
X52	0.96 in (24.4 mm)	1.78 in (45.1 mm)
X80	0.625 in (15.9 mm)	1.66 in (42.2 mm)



- ***Design for 50 years of life:***
  - 2 cycles/day, 365 days/ year = 36,500 cycles
- Initial crack: 10% wall thickness
  - semi-elliptical crack
- Load ratio R=0.5
  - *Assumes pressures fluctuate from 3,000 to 1,500 psi twice a day*
- X52 is operated at 68% of YS
- X80 is operated at 39% of YS

1.1” (27.9mm) thick walled pipe would be sufficient for X80 pipe based on fatigue crack growth performance based design

Summary

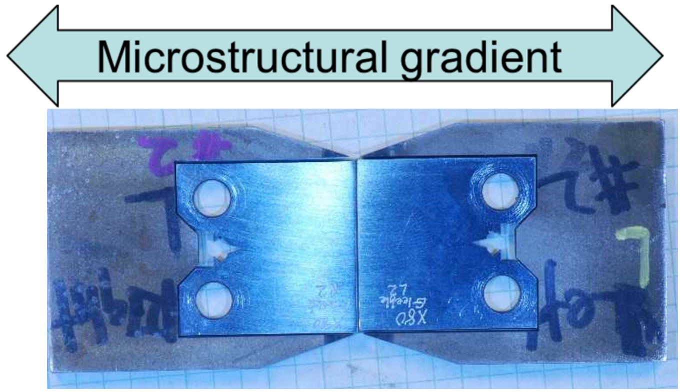
- Fatigue crack growth rates were measured of mild to high strength steel pipelines in 21 MPa H_2.
  - Strength differences did not appear to affect performance of base metals
  - Friction stir welds and gas metal arc welds exhibited similar resistance to hydrogen embrittlement for low strength
    - Friction stir welding could be cost-effective alternative to conventional arc welding
  - X100 GMAW exhibited higher crack growth rates
  - Welds exhibited slightly higher crack growth rates than respective base metals
- Fracture toughness may be limiting factor in high strength pipes
- Thickness premiums might be overly conservative

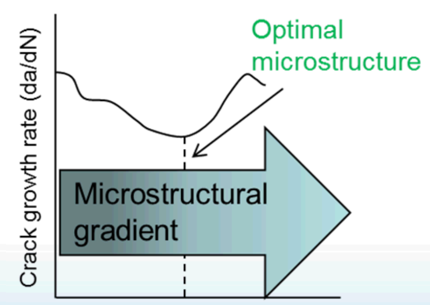
Future Work:
Identify microstructural relationships with HA-FCG

- Use science-based approach to establish models that predict pipeline behavior as function of microstructure in H_2
  - Laboratory controlled microstructural gradients using Gleeble™

Gleeble™

Copper Chill blocks





Provide basic knowledge of relationships between microstructure and HA-FCG

Acknowledgements

- U.S. Dept. of Energy: Fuel Cell Technologies Office
- Hydrogen Effects on Materials Laboratory (SNL)
- Federal Labs: ORNL (supplied FSW pipe), NIST
- Industry: ExxonMobil
- Standards Development Organizations: ASME

Questions

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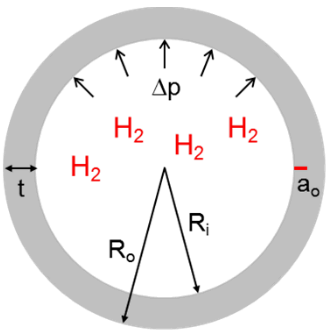
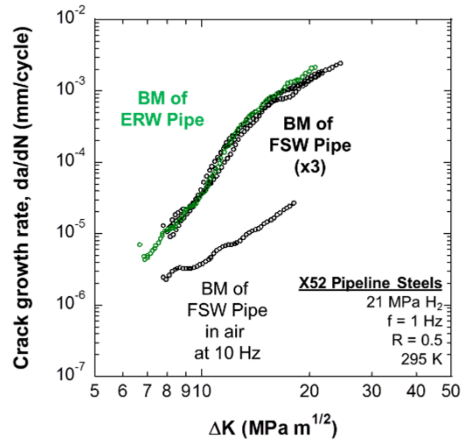
Back-up Slides

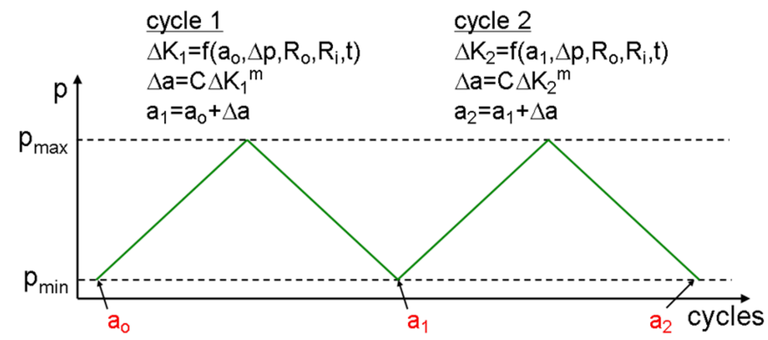
Measured fatigue crack growth laws can be applied to calculate minimum wall thickness for steel H_2 pipelines

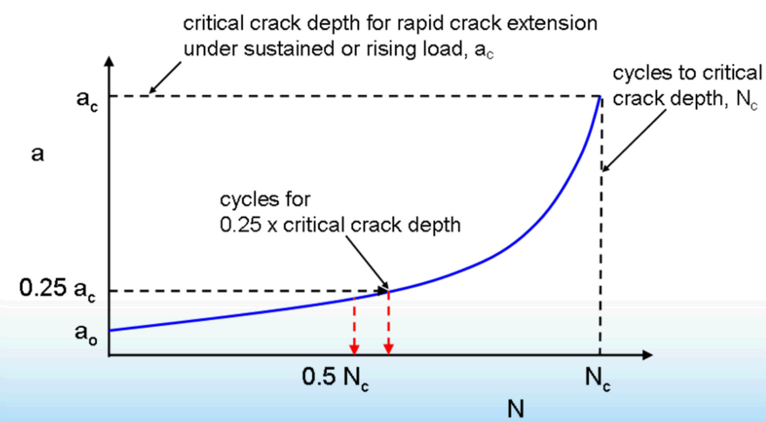


$\Delta K = \Delta p[f(a, t, R_o, R_i)]$



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





- ASME fatigue life calculation: structural analysis + fatigue crack growth law
- Inputs:
  - pressure cycle range (Δp)
  - initial flaw depth (a_o)
  - pipe outer diameter ($2R_o$)
  - fatigue crack growth law ($da/dN = C\Delta K^m$)
- ***Goal:*** Calculate wall thickness (t) required to attain fatigue life of $0.5N_c$

Microstructures vary quite substantially between welds and base metals

Base Metal
X52
Friction Stir Weld

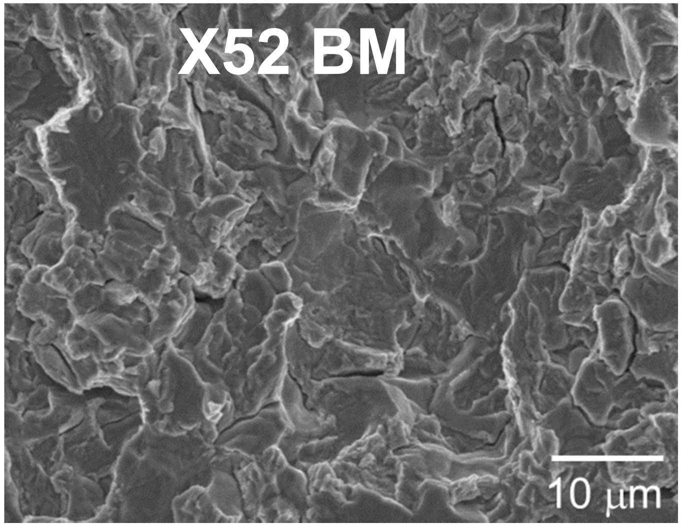
Base Metal
X65
Gas Metal Arc Weld

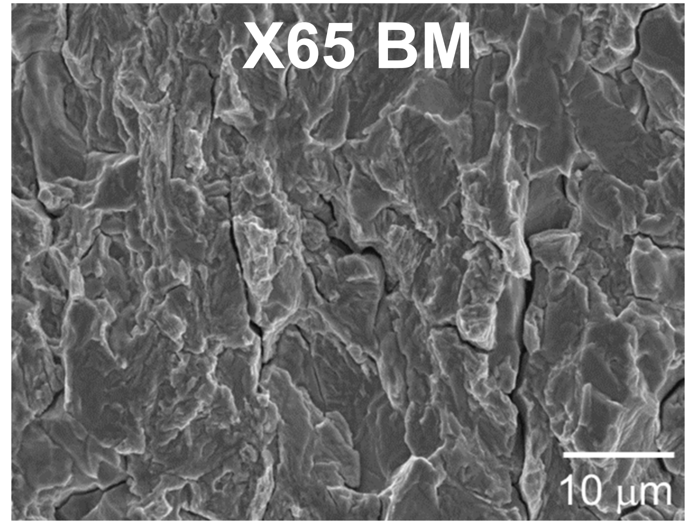
Base Metal
X100
Gas Metal Arc Weld

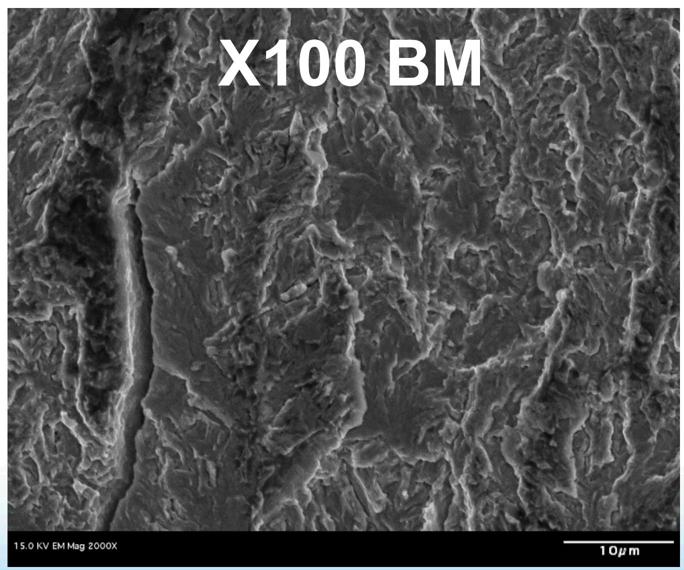
	YS (MPa)	UTS (MPa)
X52	358*	423*
X65	478	564
X100	732	868

Material	Fe	C	Mn	P	S	Si	Cu	Ni	Nb	Ti	B
X52	Bal.	0.054	1.02	0.009	<0.005	0.16	0.08	0.03	0.02	<0.005	N/A
X65	Bal.	0.08	1.53	0.01	0.001	0.32	0.024	0.038	0.039	0.002	N/A

Base Metal Fracture surfaces at $\Delta K = 10.5\ MPa\ m^{1/2}$ in H_2

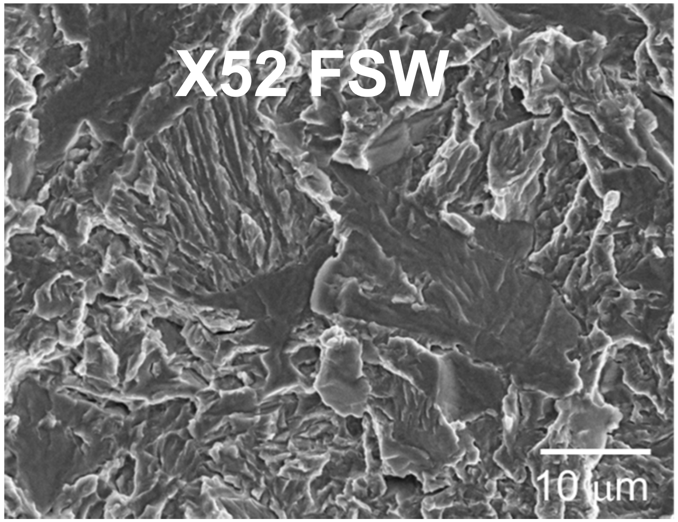


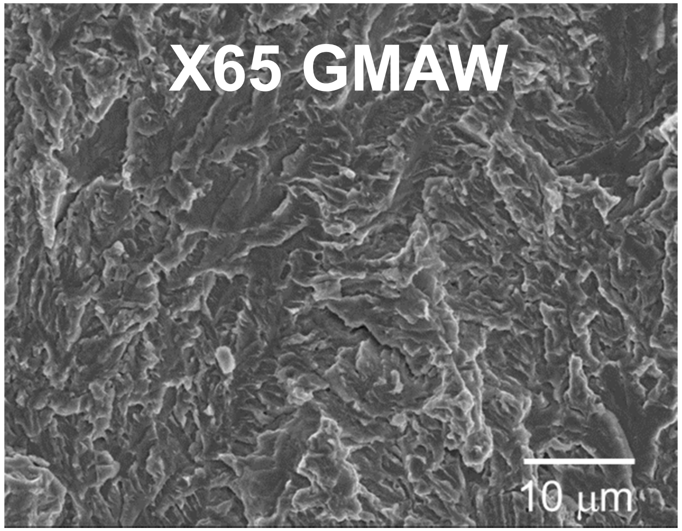


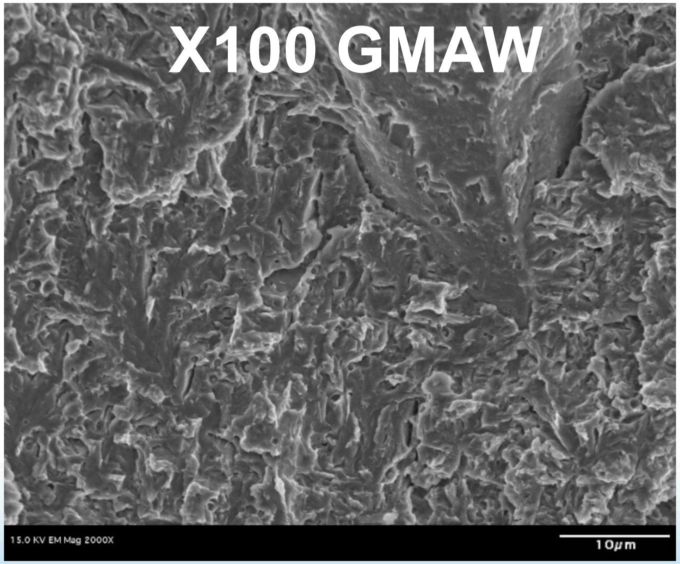


X52 and X65: Less intergranular but similar features

Weld Fracture surfaces at $\Delta K = 10.5$ MPa $m^{1/2}$ in H_2







Fracture surface features appear similar to lower ΔK (e.g. 8.5 MPa $m^{1/2}$)