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Microstructure and Hydrogen Accelerated Fatigue Crack Growth Rates of Pipeline Steel

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Sandia National Laboratories

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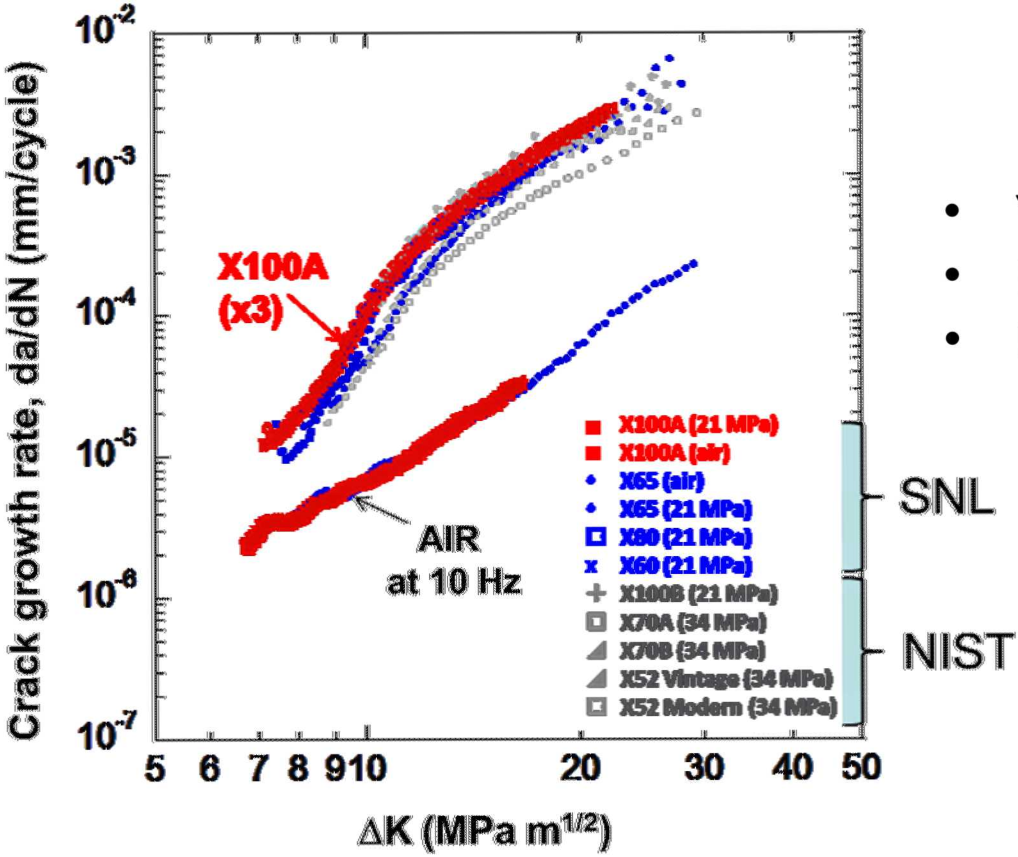
- Fatigue crack growth rates in hydrogen gas
  - Hydrogen accelerated fatigue of **X100**
  - Hydrogen accelerated fatigue of **X60**
  - Hydrogen accelerated fatigue with **graded microstructure**
- Conclusions

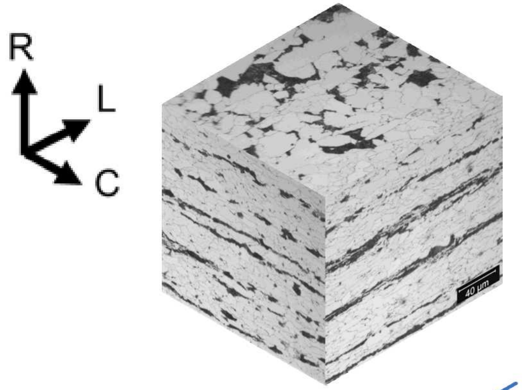
Effects of Strength on Fatigue Crack Growth in H2

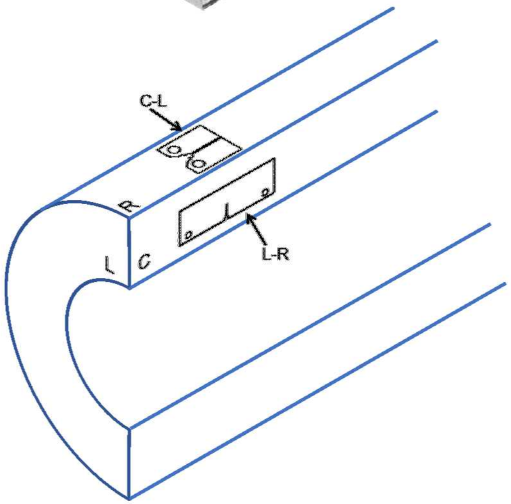


- YS: 364 MPa (X52) ~ 700 MPa (X100)
- H_2 pressure: 21, 34 MPa
- PF, AF, BF, or P but the fraction varies

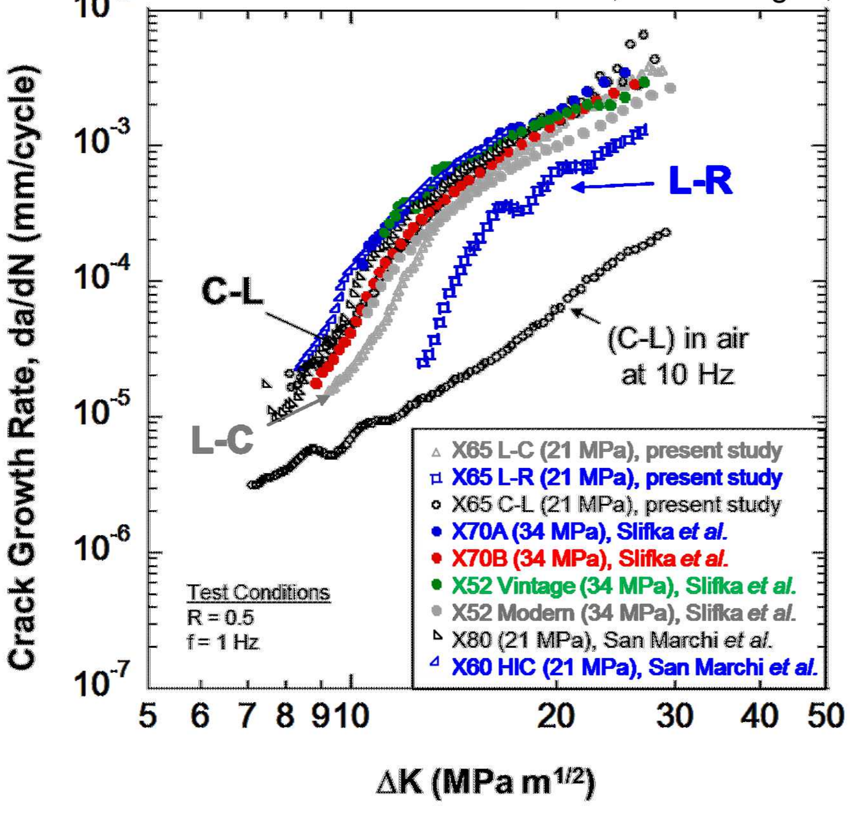
HA-FCGR of pipeline steels is not driven by strength

Previous Study – Orientation Effects of FCGR X65





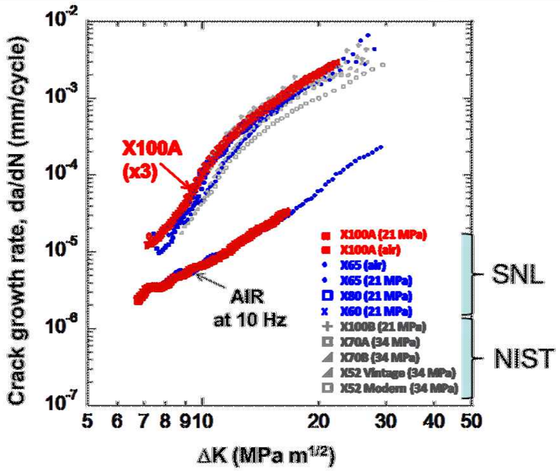
J. Ronevich et al., Int. J. Fatigue, 2015



Lower FCGR with L-R oriented sample

X60 and X80 data: San Marchi et al., ASME PVP, 2010
X52 and X70 data: Slifka et al., ASME PVP, 2014; Drexler et al., Proceedings of SteelyHydrogen, 2014

Objective



Hydrogen assisted fatigue is *not* driven by strength

Higher strength pipe enables both higher pressures and lower costs in Natural Gas Industry

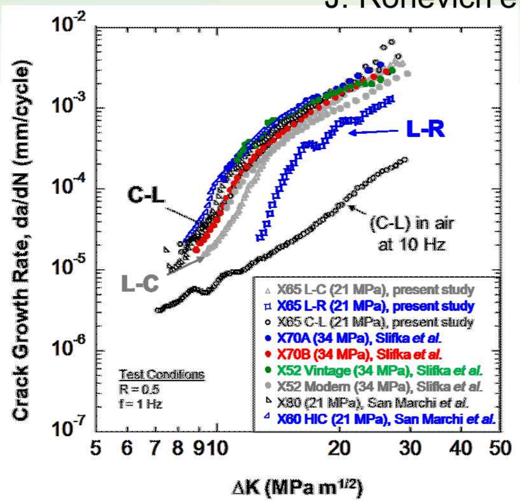
→ Design codes for H_2 (ASME B31.12) place penalties (increased thickness) on higher strength pipes = negligible cost saving

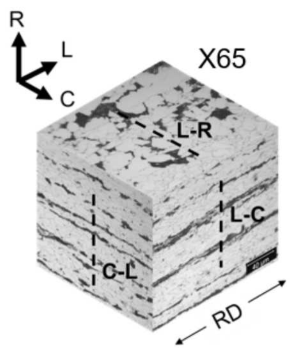
Using X100 (instead of X52) can result in 42% cost reduction for 24" pipe operated at 1600 psi*

* Based on analysis by Amaro from Fekete *et al. 2015 (Int. J of Hydrogen Energy)*

Objective: Microstructure effects

J. Ronevich et al., *Int. J. Fatigue*, 2015.



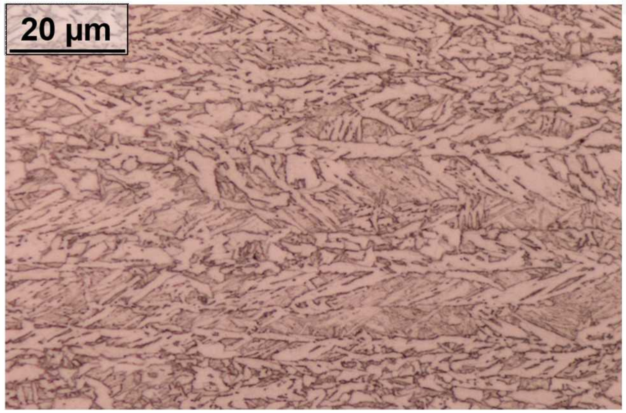


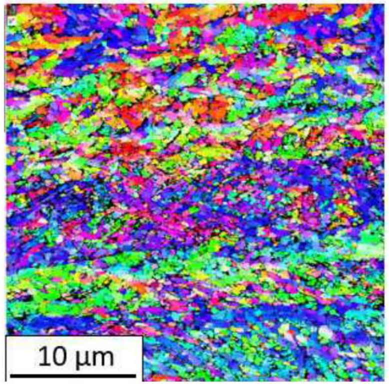
Utilize high-strength pipeline steels for H_2 service to ***<u>cost reduction</u>***

- Determine whether girth welds in high-strength steel pipes exhibit fatigue performance similar to low strength pipes in H_2 gas
- **Determine relationships between microstructure and hydrogen accelerated fatigue crack growth (HA-FCG)**
- Develop predictive models that correlate microstructure to HA-FCG

X100 FCGR Test Method

- Material: X100 base metal (**<u>non-isotropic with orientation</u>**)

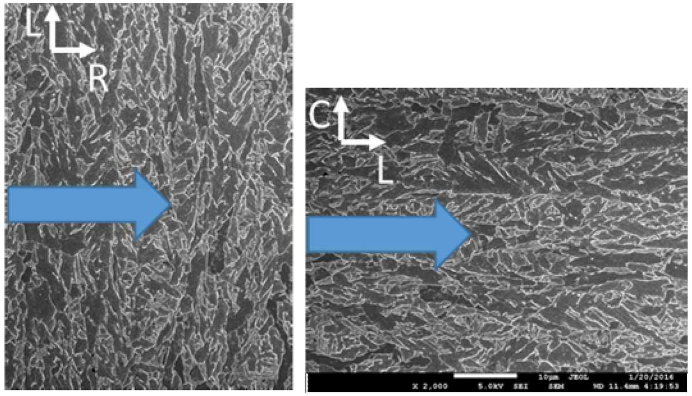




- Fatigue crack growth test in hydrogen gas

  Precracking in air
    f = 10 Hz, R = 0.5, a/W = 0.25 ~ 0.29

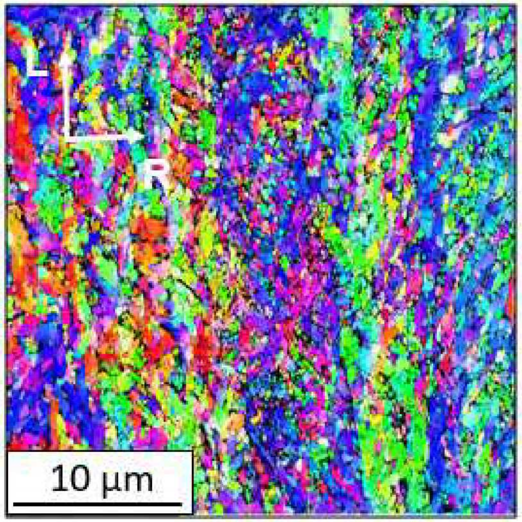
  <u>Constant load amplitude test in hydrogen</u>
    21 MPa, 99.9999% purity
    f = 1 Hz, R = 0.5

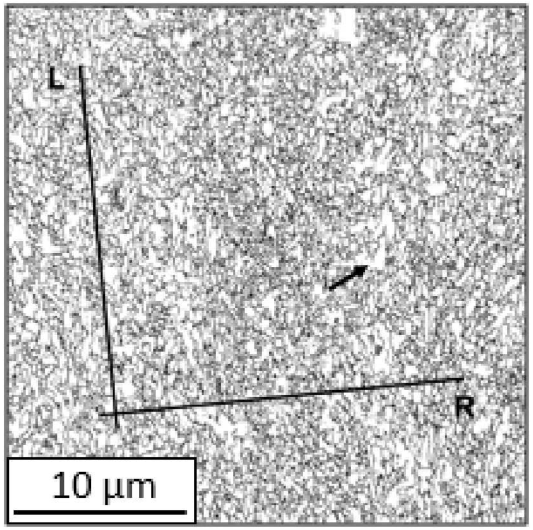


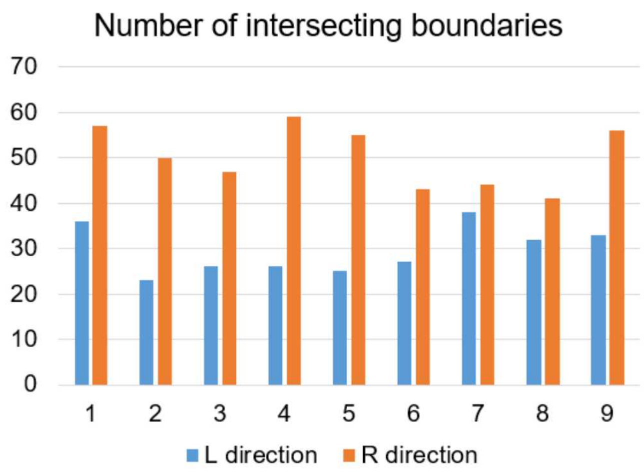
ASTM Standard E647-05

X100 FCGR Test Results

(HAGB: >15°)



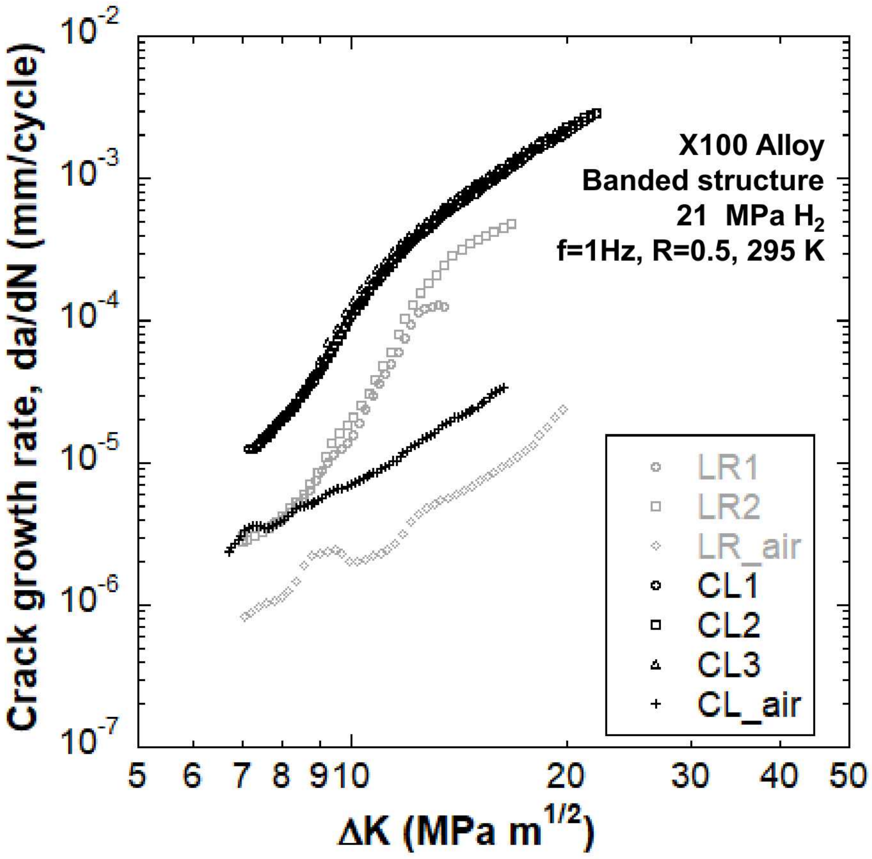


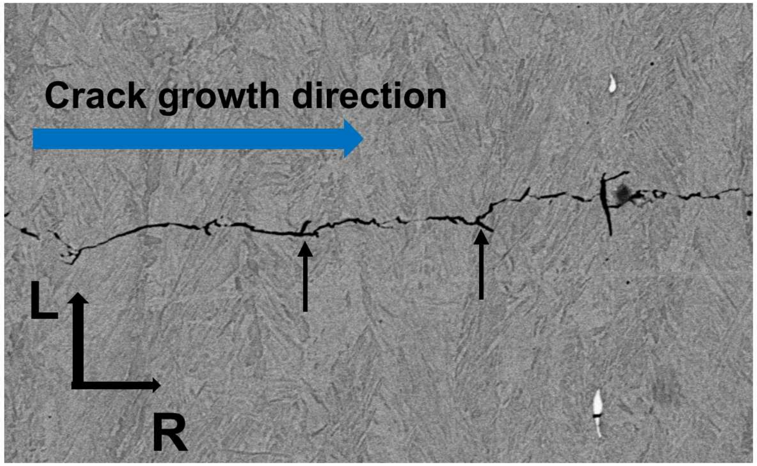


- The intersection of HAGB with 9 lines (~21.2 µm long) were counted
- # of intersection: 1.39/µm (L-direction), 2.37/µm (R-direction)

71% *more* HAGB encountered in R

X100 FCGR Test Results

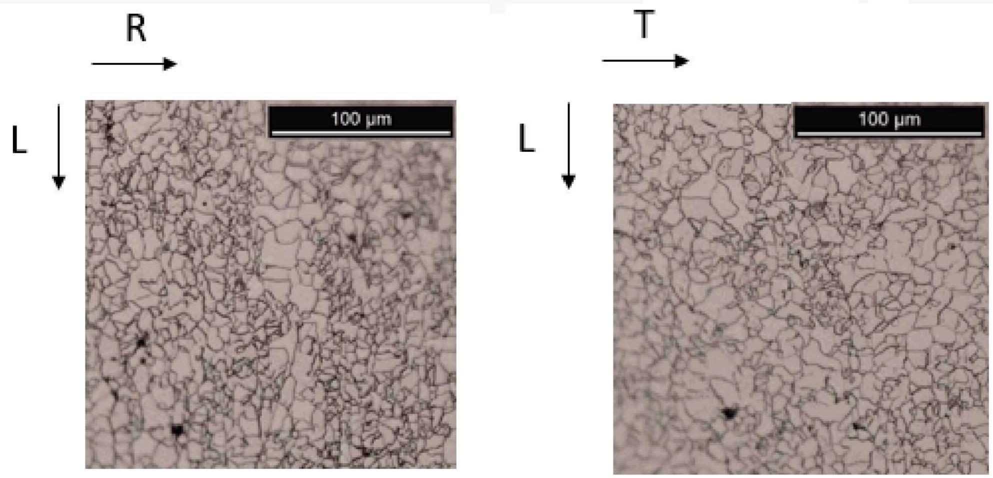




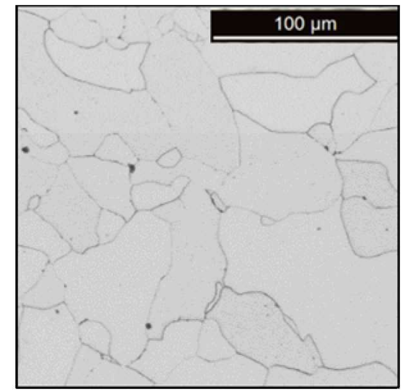
4-5 times lower FCGR with L-R oriented sample

X60 FCGR Test Method

- Material: X60 base metal (100 % polygonal ferrite)



(after HT at 1373 K)



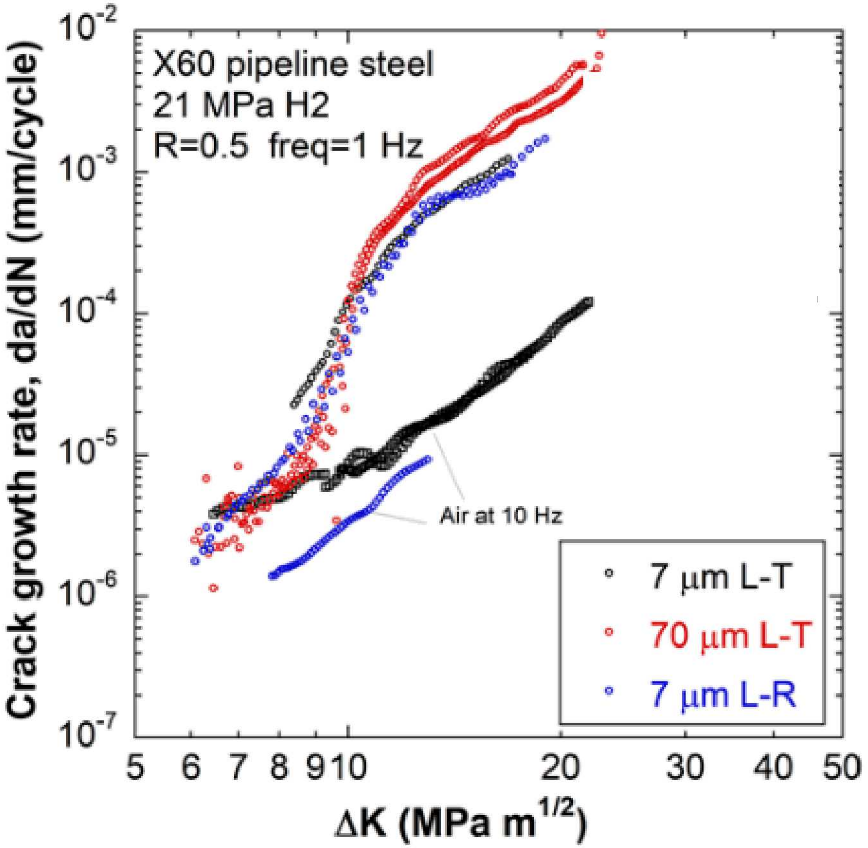
  - # of intersection: 0.14/μm (R-direction), 0.12/μm (T-direction)

- Fatigue crack growth test in hydrogen gas

Precracking in air
f = 10 Hz, R = 0.5, a/W = 0.25 ~ 0.29

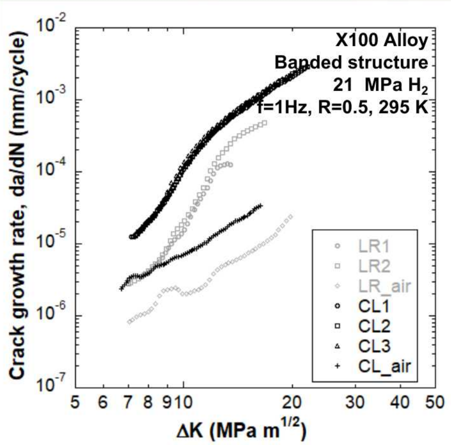
<u>Constant load amplitude test in hydrogen</u>
21 MPa, 99.9999% purity
f = 1 Hz, R = 0.5

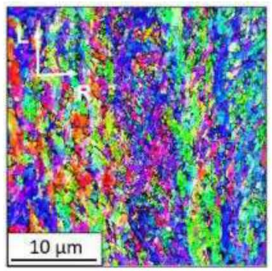
X60 FCGR Test Results

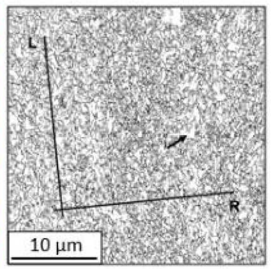


X60 exhibited similar HA-FCG (< 2 difference in da/dN)

Summary



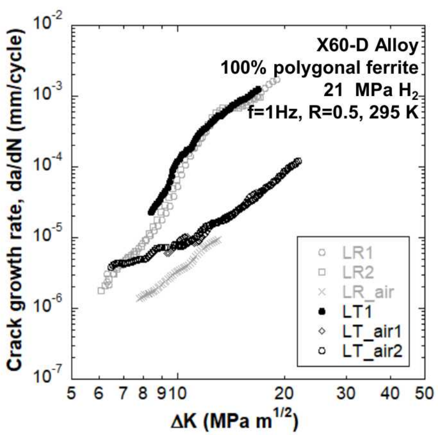


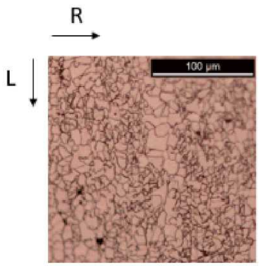


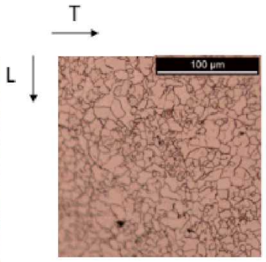
(HAGB: >15°)

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

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





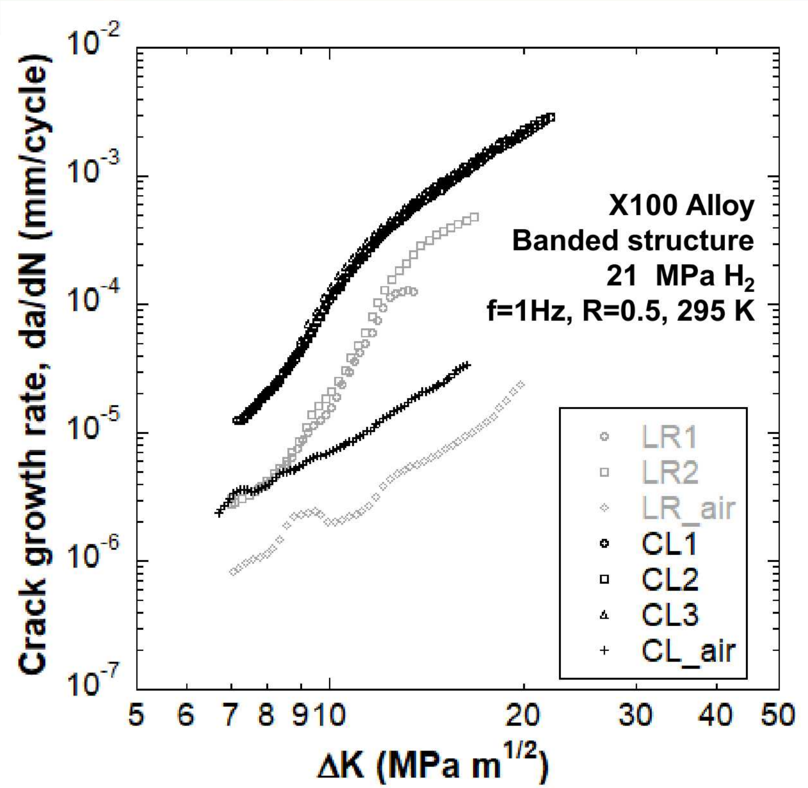


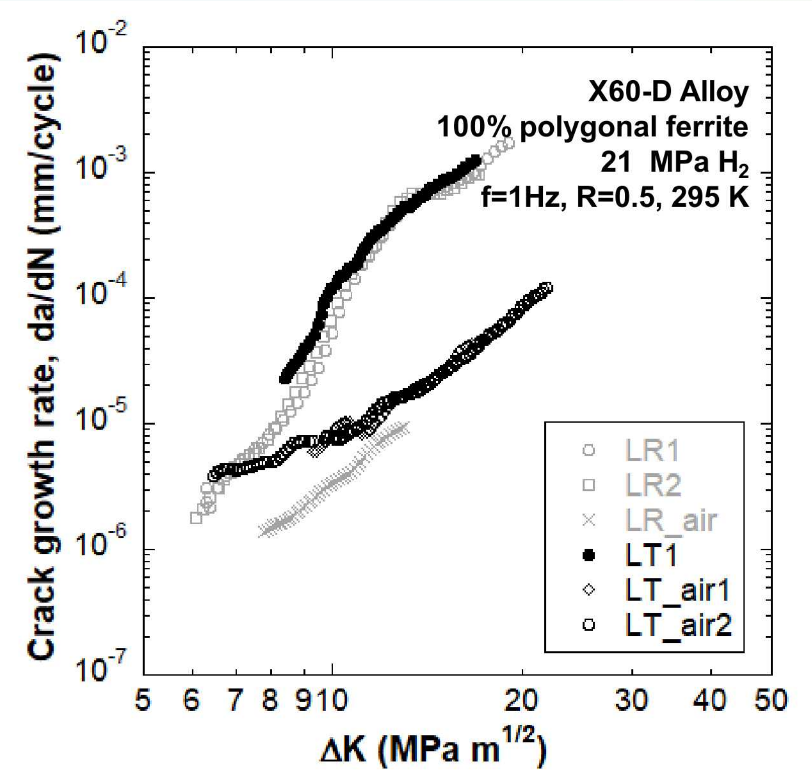
X60 Base metal exhibited similar HA-FCG in both orientations (< 2 difference in da/dN)

- ***13% more*** HAGB encountered in R

Grain boundary interaction has significant effect on HA-FCG

Comparison between X100 and X60





- **HAGB: X100-L ≈ X60-T ≈ X60-R > X100-R**

  1.39/µm 0.12/µm 0.14/µm 2.37/µm

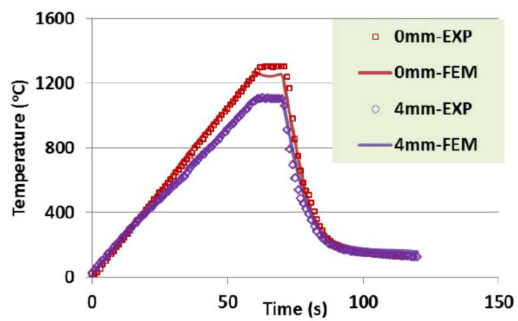
HA-FCG with Graded Microstructure

- Material: X80 base metal

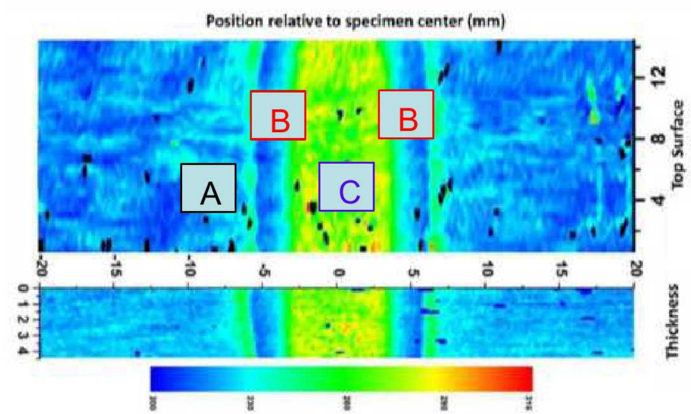
Graded microstructure is produced using Gleeble™

residual stresses removal by a rolling pass (2-5% reduction)

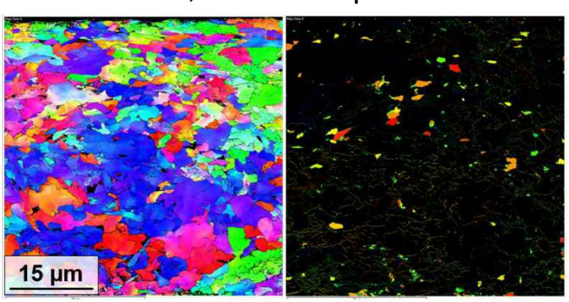
Oak Ridge National Laboratory



Sample thickness = 3.8 mm

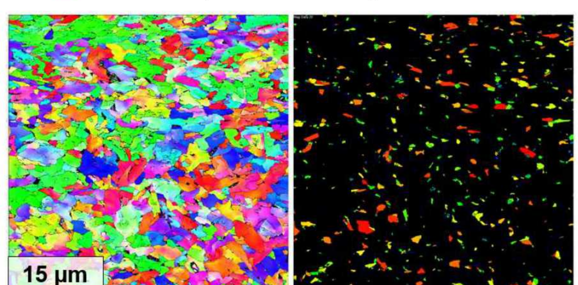


A - bainite, allotriomorphic ferrite



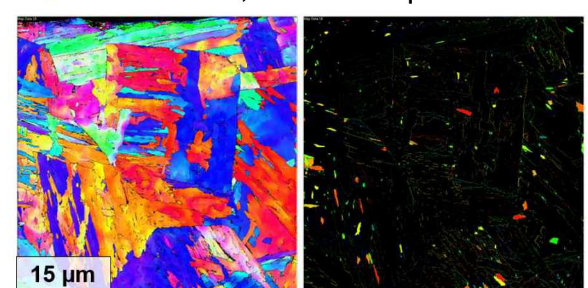
α (8.8%)
misorientations < 1.5°

B - bainite, allotriomorphic ferrite



α (16.2%)

C - martensite, allotriomorphic ferrite

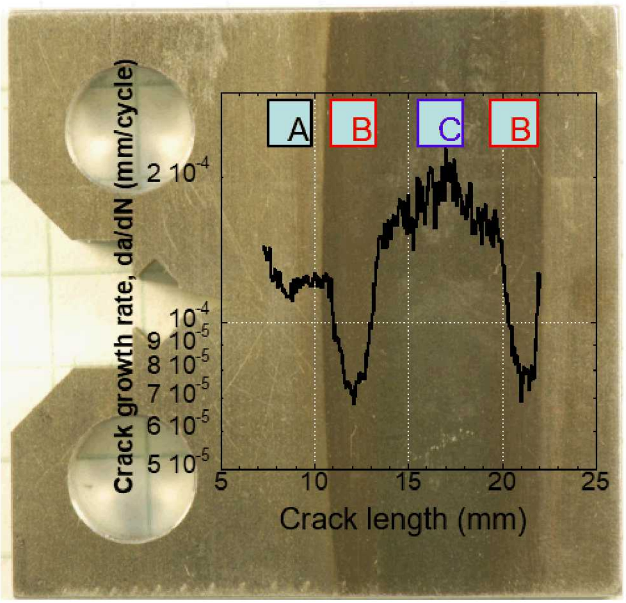


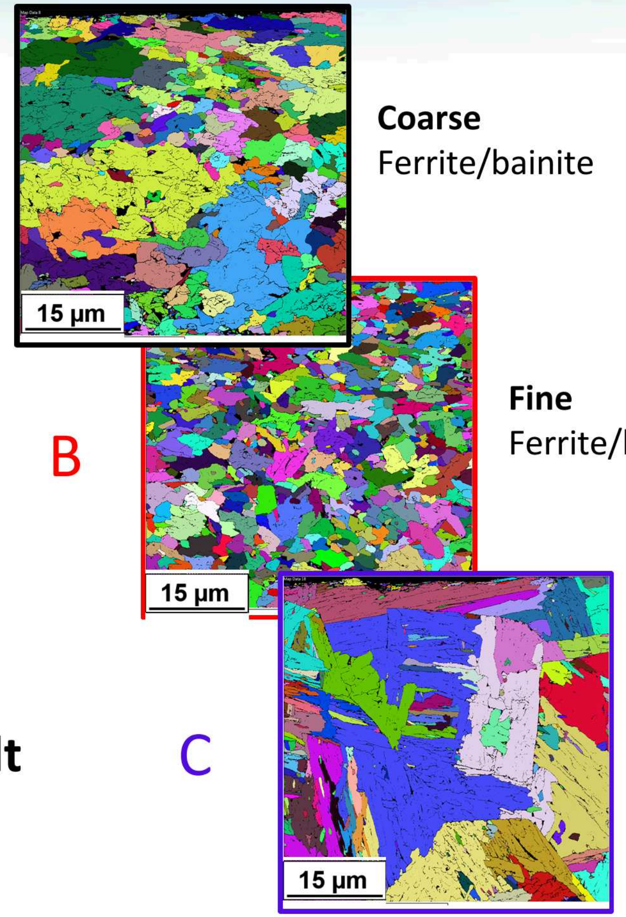
α (4.0%)

HA-FCG with Graded Microstructure

<u>Constant ΔK test in hydrogen</u>

21 MPa, f = 1 Hz, R = 0.5, ΔK = 10 MPa $m^{1/2}$





A **Coarse** Ferrite/bainite

B **Fine** Ferrite/bainite

C Ferrite/ martensite

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

Grain boundary interaction has significant effect on HA-FCG

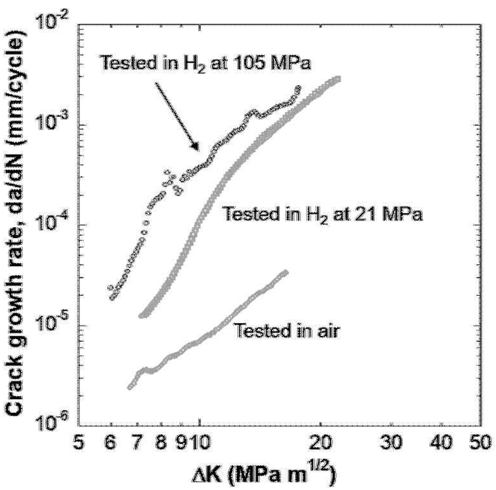
Conclusions

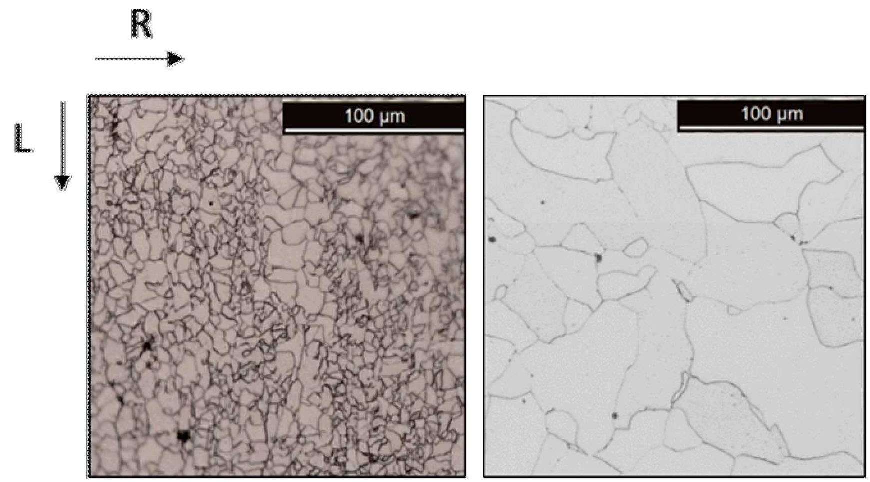
- The effects of microstructure on HA-FCG were studied using X100 BM, X60 BM with different orientations and graded microstructure produced by Gleeble™.

- **Grain boundary interaction** appears to have more or comparably pronounced effect with microstructural constituents.

  - HA-FCG of X100 BM were lower for cracks in R-direction which has more HAGB intersection.

  - HA-FCG of graded microstructure changed by a factor of 2 with varying grain size and constituents.


Tested in H2 at 105 MPa
Tested in H2 at 21 MPa
Tested in air
Crack growth rate, da/dN (mm/cycle)
ΔK (MPa m1/2)
10-2
10-3
10-4
10-5
10-6
5
6
7
8
9
10
20
30
40
50


R
L
100 μm
100 μm