Fatigue and fracture of high-hardenability steels for thick-walled hydrogen pressure vessels

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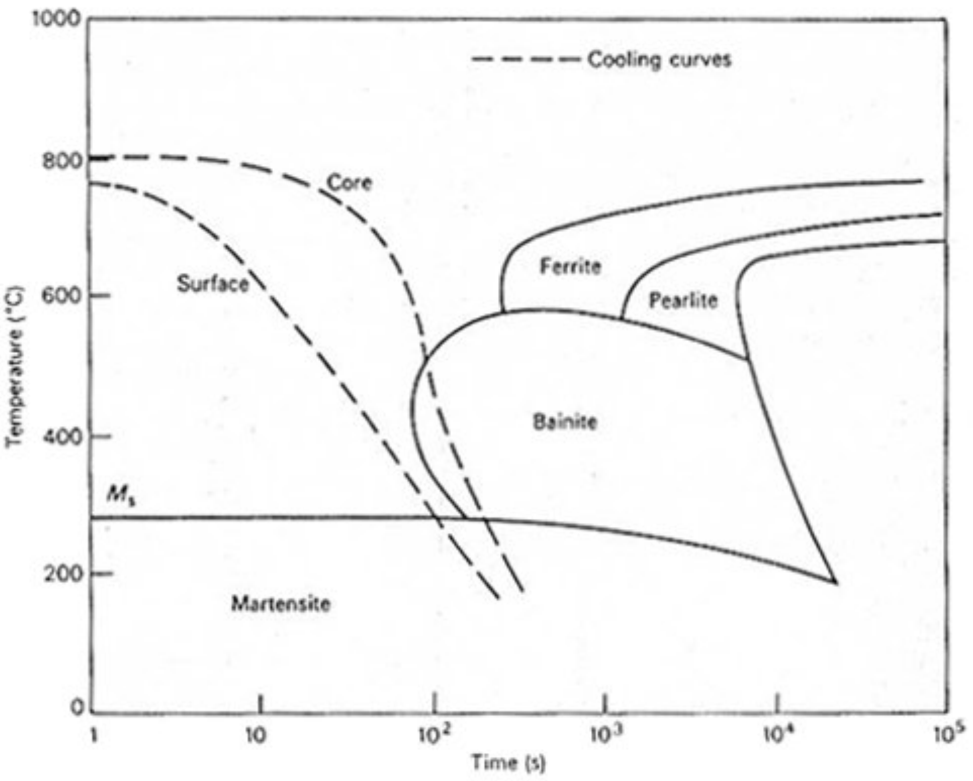
Outline

- Motivate the need to investigate hydrogen compatibility of high-hardenability steels
- Methods and Materials
- Compare fatigue crack growth rates of high-hardenability steels with currently used pressure vessel steels
- Assess the effect of strength on fracture resistance in high-pressure hydrogen

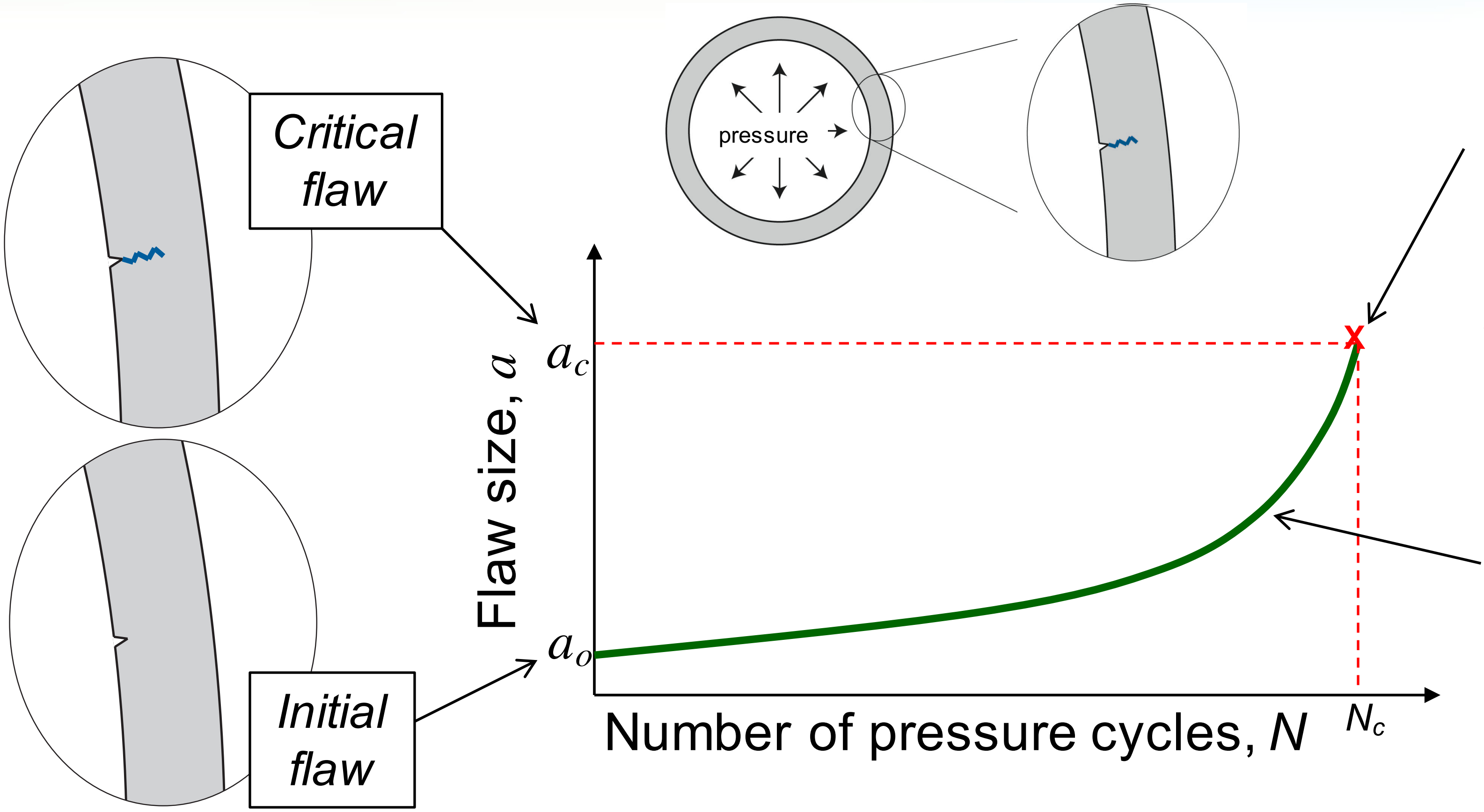
Motivation: industry needs thicker-walled pressure vessels for stationary high-pressure hydrogen storage



- Cr-Mo quench and tempered (Q&T) steels are the standard for high-pressure stationary storage
  - Hardenability limits thickness to less than 35 mm
  - Example: ASME SA-372 Grade J
- Ni-Cr-Mo Q&T steels display higher hardenability than Cr-Mo steels
  - Substantially thicker walls
  - Less property variation through wall thickness
  - Example: ASME SA-723

Question: How do fatigue and fracture properties of Ni-Cr-Mo steels differ from Cr-Mo steels in hydrogen?

Fracture mechanics enables efficient design compared to stress-based methodologies



Rupture determined by *fracture resistance*

Evolution of flaw size determined by *fatigue crack growth*

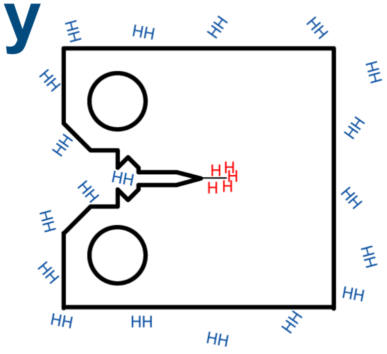
Fatigue basis must be considered for stationary pressure vessels that see frequent pressure cycles

ASME BPVC Section VIII, Division 3, Article KD-10 provides rules for characterization of pressure vessel steels for storage of gaseous hydrogen

Fatigue crack growth

Characterized by *da/dN* = *f*(Δ*K*)

- Typical fatigue crack growth methodology described in ASTM E647



Fracture resistance

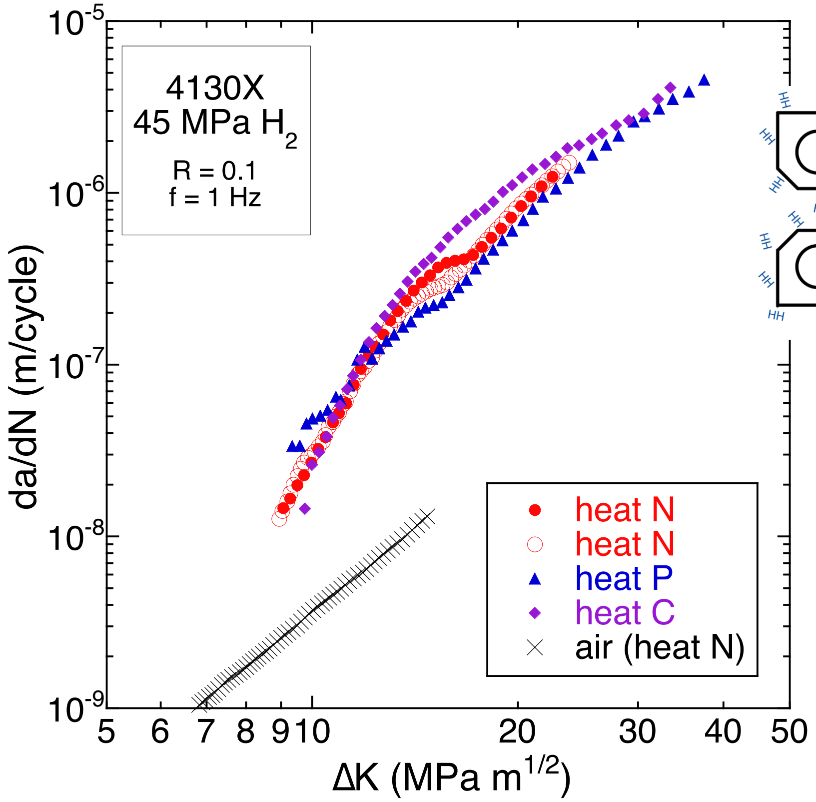
Characterized by K_{IH}

- Threshold stress intensity factor for hydrogen-assisted cracking using ASTM E1681

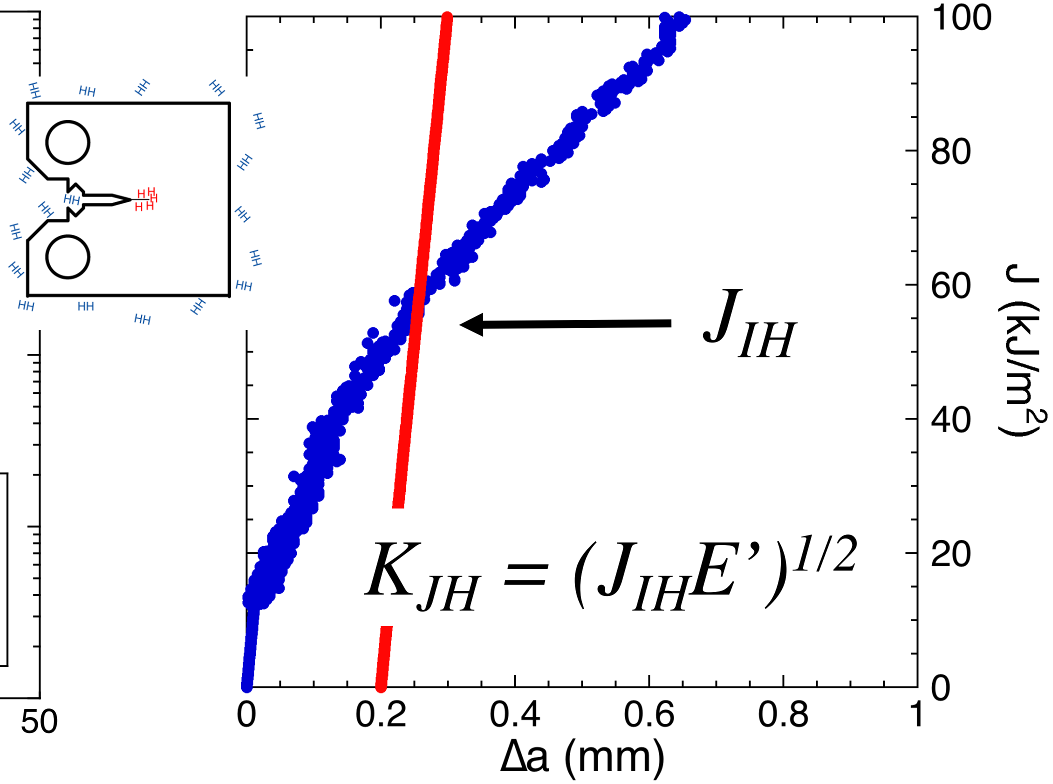
Fracture mechanics parameters must be measured in relevant hydrogen environments

Fracture mechanics measurements can be made in high-pressure gaseous hydrogen

Fatigue crack growth

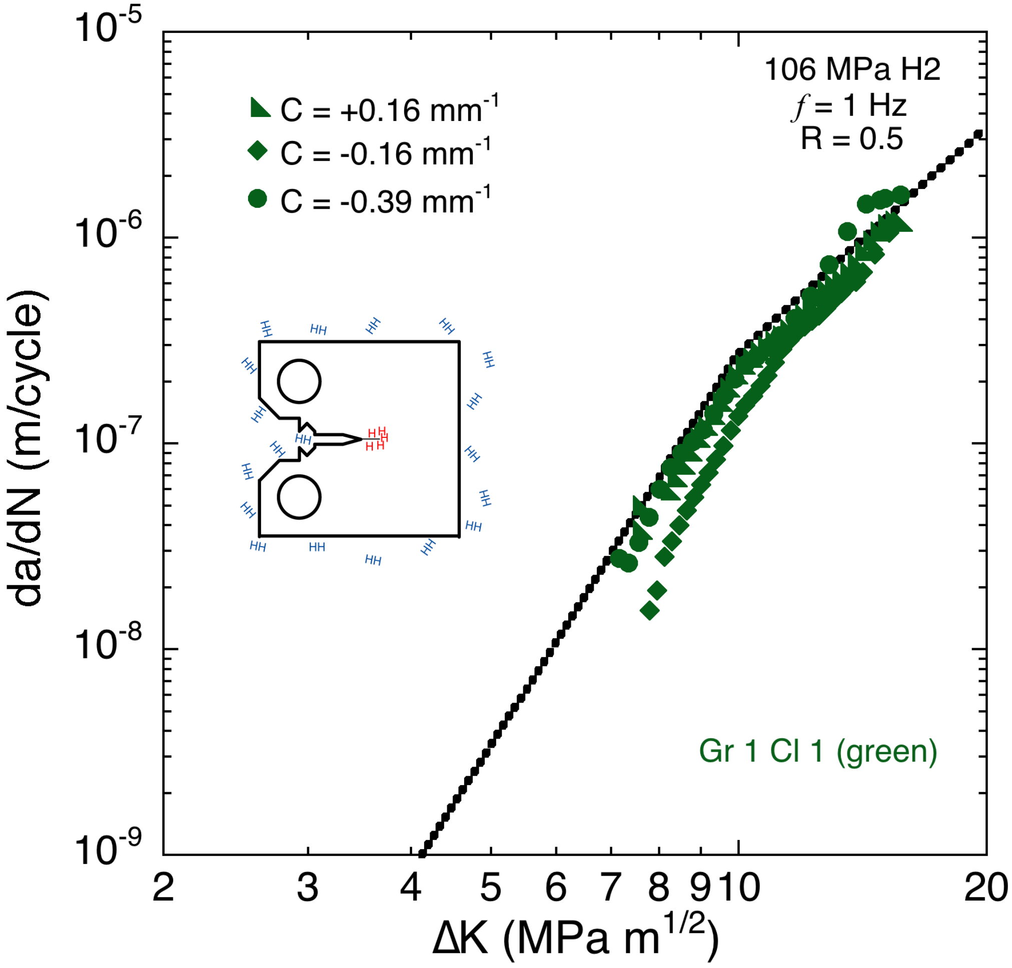


Fracture resistance



- Cracks are extended in fatigue under controlled C or constant load,
- Followed by monotonic fracture resistance measurements, using elastic-plastic, rising load fracture method (ASTM E1820)

Fatigue tests at low ΔK can be greatly accelerated by using negative values of C



- Time to collect data for a given ΔK range scales approximately with C
- For a constant load test C ~ 0.1 mm^{-1}
- For segments shown
  - Constant load is estimated to be 14 ~hr
  - C = -0.16 mm^{-1} is ~8 hr
  - C = -0.39 mm-1 is ~5.5 hr
- For ΔK range of 5–6 MPa m$^{1/2}$
  - C = +0.16 mm^{-1} is ~47 hr
  - C = -0.39 mm-1 is ~27 hr

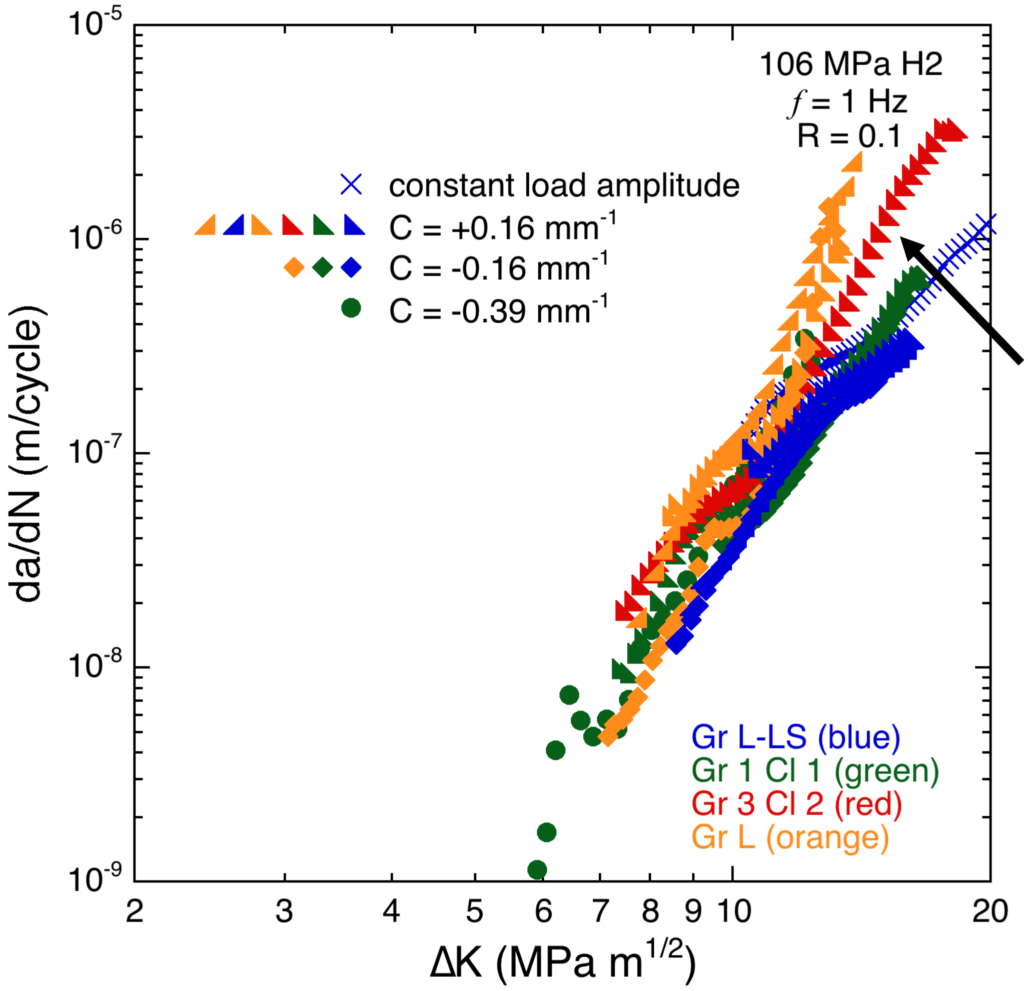
High-hardenability pressure vessel steels: Ni-Cr-Mo quench and tempered (Q&T) steels

Designation	Fe	Ni	Cr	Mo	V	Mn	Si	C	S	P
SA-372 Grade L	bal	1.93	0.82	0.26	nr	0.75	0.28	0.4	0.007	0.006
SA-723 Grade 1	bal	1.5 2.25	0.80 2.00	0.20 0.40	0.20 max	0.90 max	0.35 max	0.35 max	0.015 max	0.015 max
SA-723 Grade 3	bal	3.54	1.72	0.45	0.10	0.30	0.05	0.27	0.0008	0.005

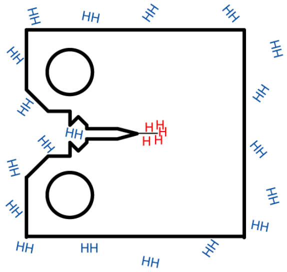
Designation	Tensile strength (MPa)	Yield Strength (MPa)
Grade 1 – Class 1	860	715
Grade L-LS	873	731
Grade 3 – Class 2	978	888
Grade L	1149	1053

Does not meet SA-372 (low strength)

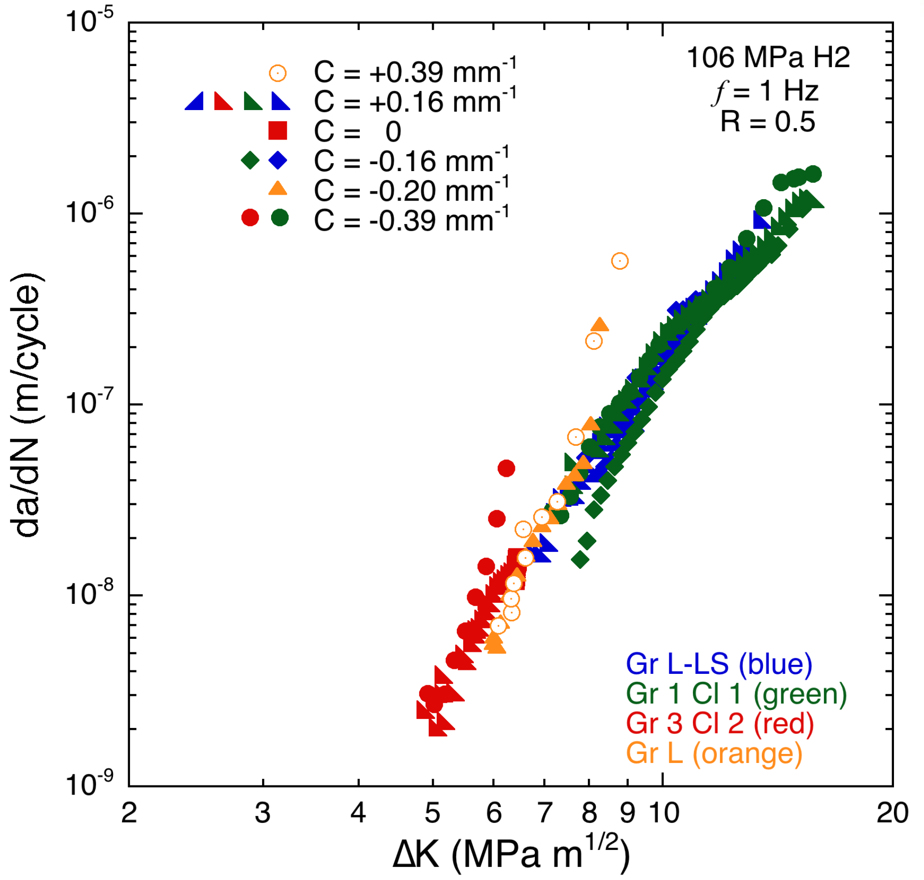
Fatigue crack growth rates of Ni-Cr-Mo Q&T steels are insensitive to strength for low ΔK

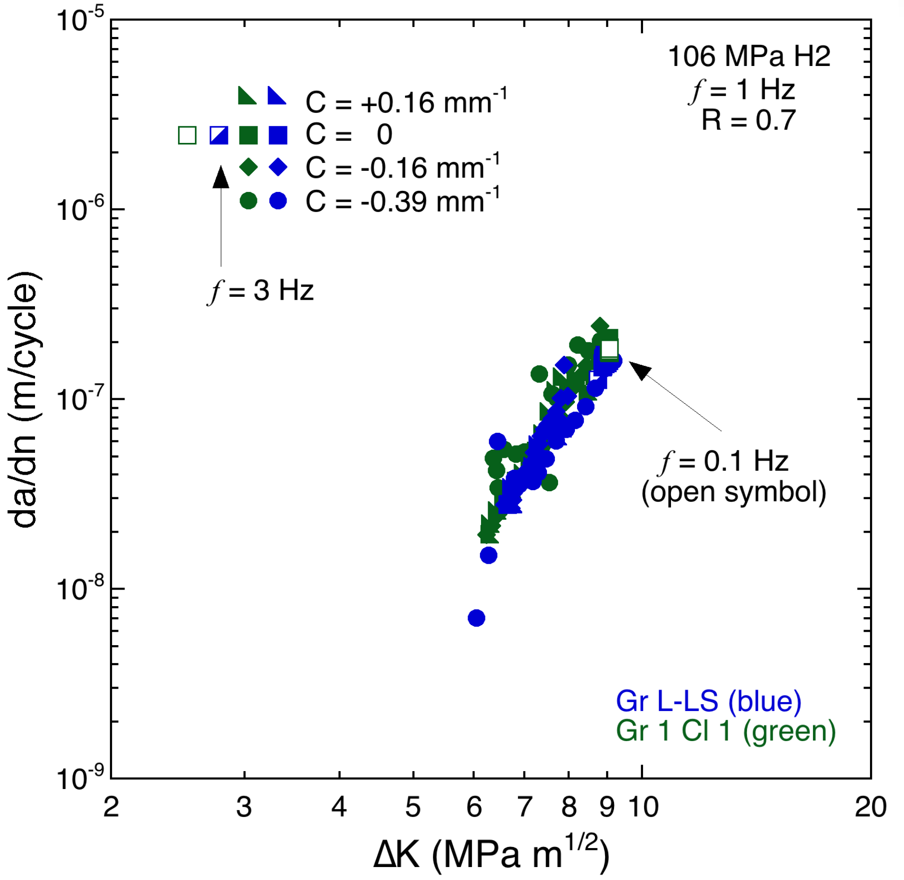


- **These steels represent a wide range of strength and composition for Ni-Cr-Mo PV steels**
- **Deviation from from the basic trend represents K_{max} approaching the fracture resistance (stage III of fatigue crack growth)**
  - **Apparent only for the high-strength steels**
    $K_{max} \rightarrow K_{JH}$



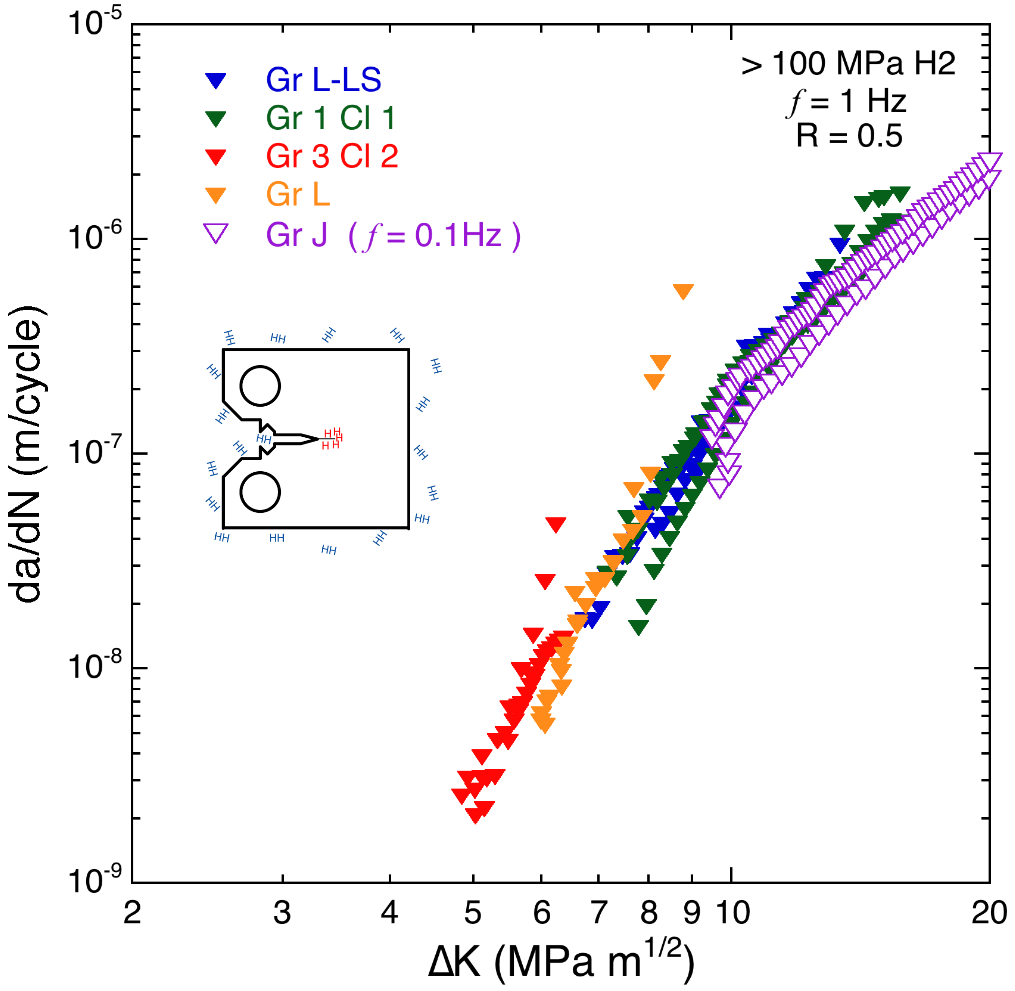
Fatigue crack growth rates for high-hardenability steels are consistent at high load ratio (R)





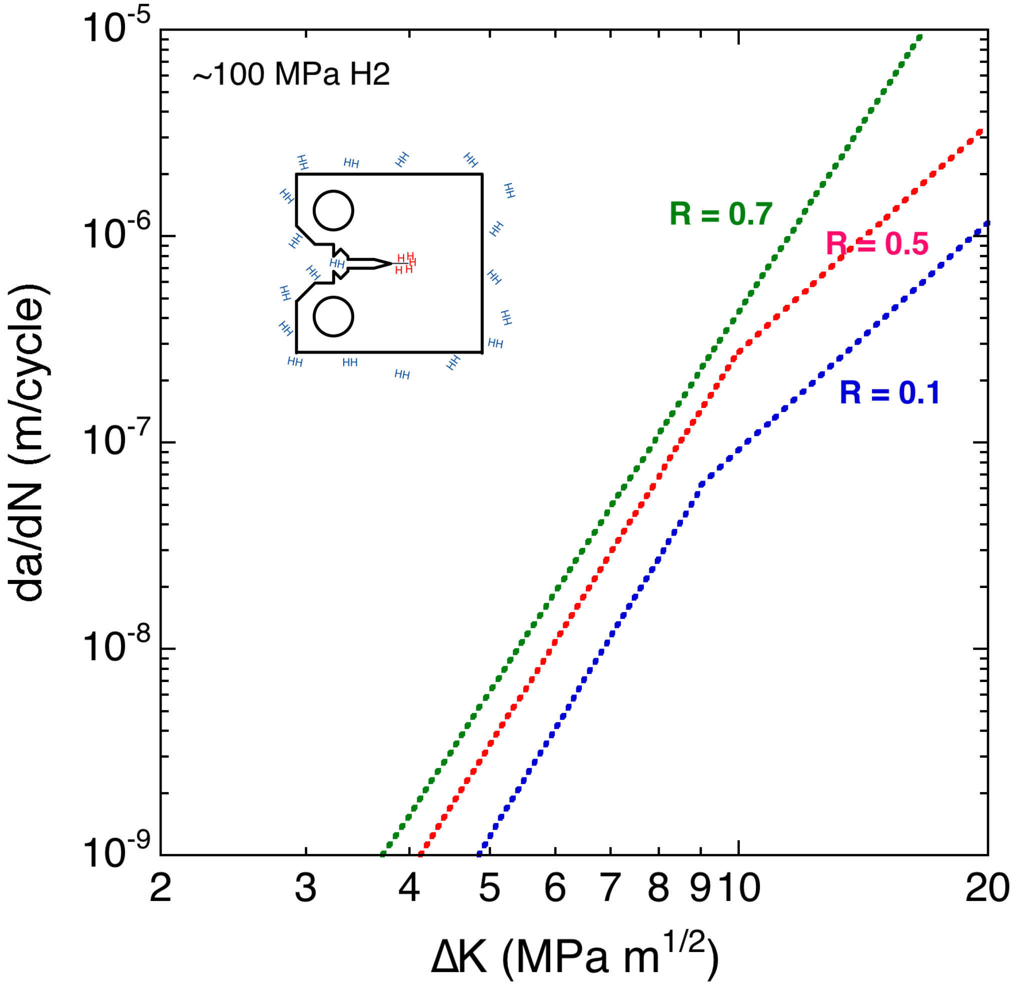
- **Crack growth rates are accelerated at high R (expected)**
- **High-strength material shows transition to stage III at low ΔK for high load ratio (and higher ΔK for lower R)**

Fatigue crack growth rates of Ni-Cr-Mo and Cr-Mo Q&T steels are similar



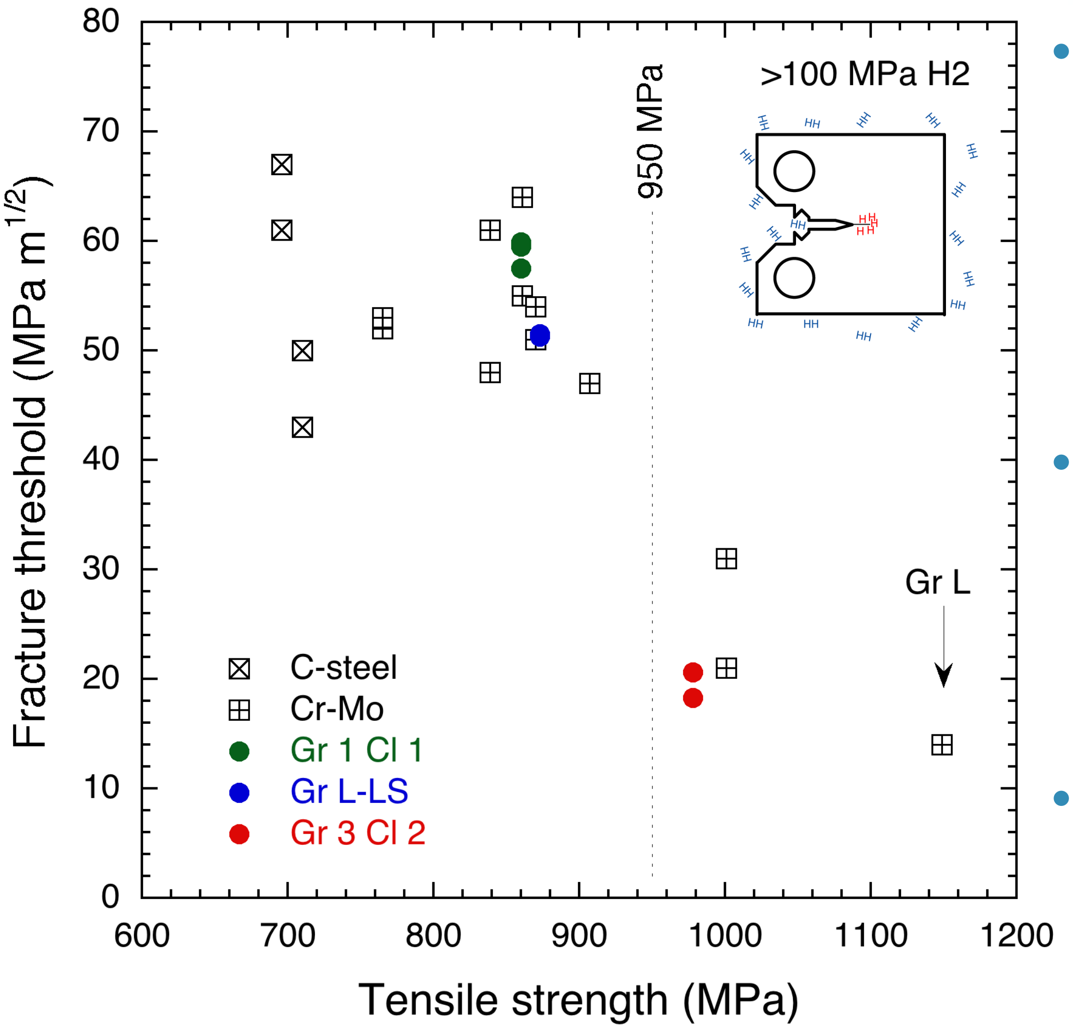
- Cr-Mo and Ni-Cr-Mo steels show similar fatigue crack growth rates in gaseous hydrogen
  - Cr-Mo: SA-372 Grade J
  - Ni-Cr-Mo: SA-723 Grades (SA-372 Grade L also)
- Crack growth rates are not sensitive to frequency between 0.1 and 1 Hz (at least for ΔK > ~9 MPa $m^{1/2}$)
- Single master curve for fatigue crack growth of both Cr-Mo and Ni-Cr-Mo steels appears reasonable

Upper bound fatigue crack growth curves can be estimated for R = 0.1, 0.5, and 0.7



- **Fatigue crack growth curves are approximately parallel for different load ratios**
- **Near ΔK = 10 MPa $m^{1/2}$, the crack growth rates transition to a lower power law slope**
- **In general, these curves intersect air curves near 10^{-9} m/cycle and have similar slope as at high ΔK**

Fracture resistance in gaseous hydrogen is sensitive to tensile strength for Q&T steels



- Ni-Cr-Mo steels show similar fracture resistance (K_{JH}) as other ferritic steels, including Cr-Mo steels
- Fracture resistance of Q&T steels is typically greater than 40-50 MPa m$^{1/2}$ for tensile strength < 950 MPa
- Q&T steels with strength > 950 MPa feature K_{JH} less than 20 MPa m$^{1/2}$

Summary

- Fatigue crack rates of pressure vessel steels in high-pressure gaseous hydrogen are relatively insensitive to composition and strength
  - *A range of Cr-Mo and Ni-Cr-Mo quench and tempered pressure vessels show similar fatigue crack growth rates*
  - *High-strength steels show transition to stage III crack growth rates at K_{max} as low as 12 MPa $m^{1/2}$*
- Fatigue tests can be accelerated by varying the normalized K-gradient (C) in the range +/- 0.4 mm^{-1}
- Fracture resistance is very sensitive to material strength
  - *Rising load fracture measurements on a range of steel strengths show markedly lower fracture resistance for steels with tensile strength >900-950 MPa*