SAND2020-8711PE

SAND2020-XXXX PE

Overview of fatigue of steels in gaseous hydrogen

ASME Code Week

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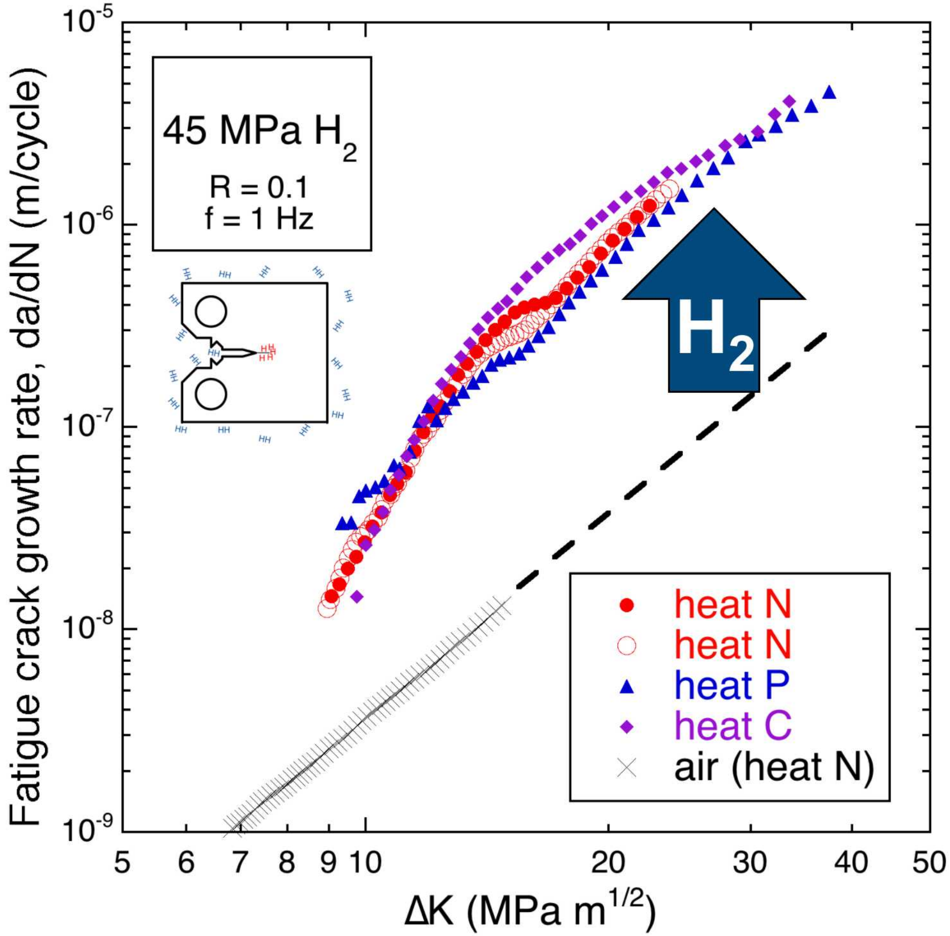
Outline

- When is it necessary to consider the effects of gaseous hydrogen on pressure structures?
- What is the effect of hydrogen partial pressure on fracture mechanics properties?
  - Examples
  - Design curve (ASME Code Case 2938)
  - Pressure correction for design curves
  - Extrapolation to fatigue crack growth threshold
- What are observed trends of fatigue life testing in gaseous hydrogen?
  - Endurance limit
  - High cycle regime / high stress
- Supplementary information

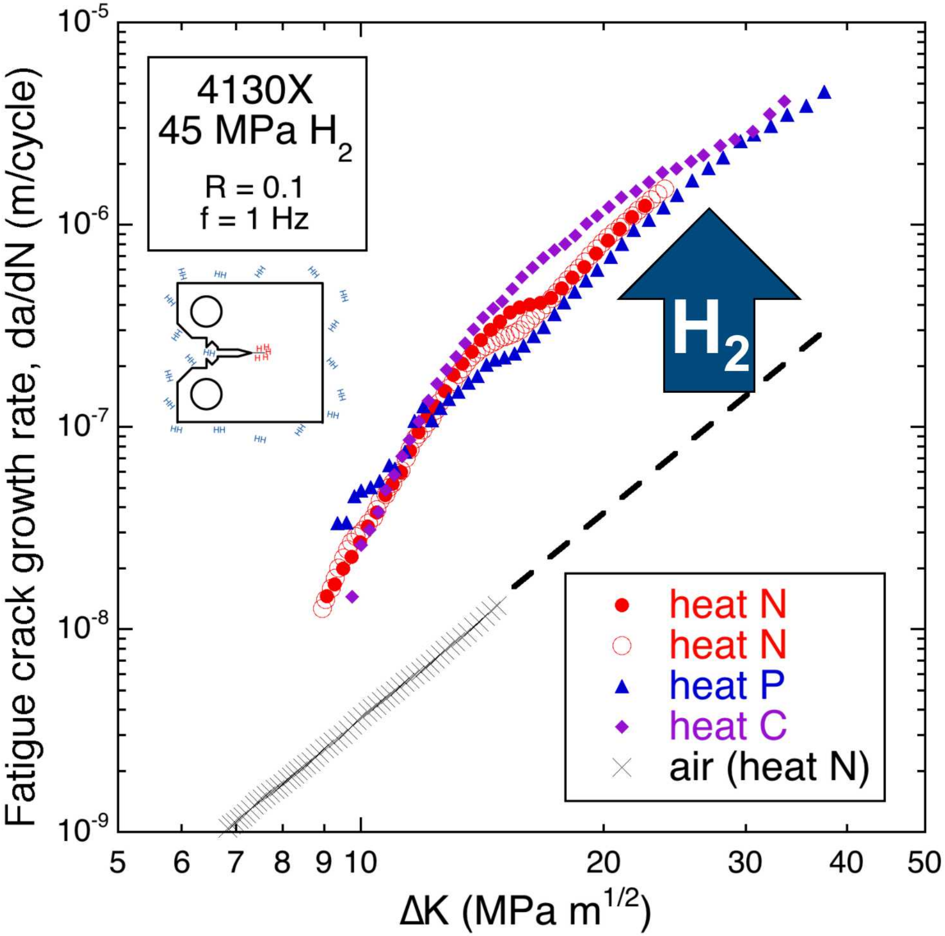
Is this material safe for use in gaseous hydrogen?



Fatigue

- **Fatigue crack growth rate is accelerated by >10X in H2 compared to air**
- **This material is safe for use in gaseous hydrogen?**
  - **(a) True**
  - **(b) False**

Is this material safe for use in gaseous hydrogen?

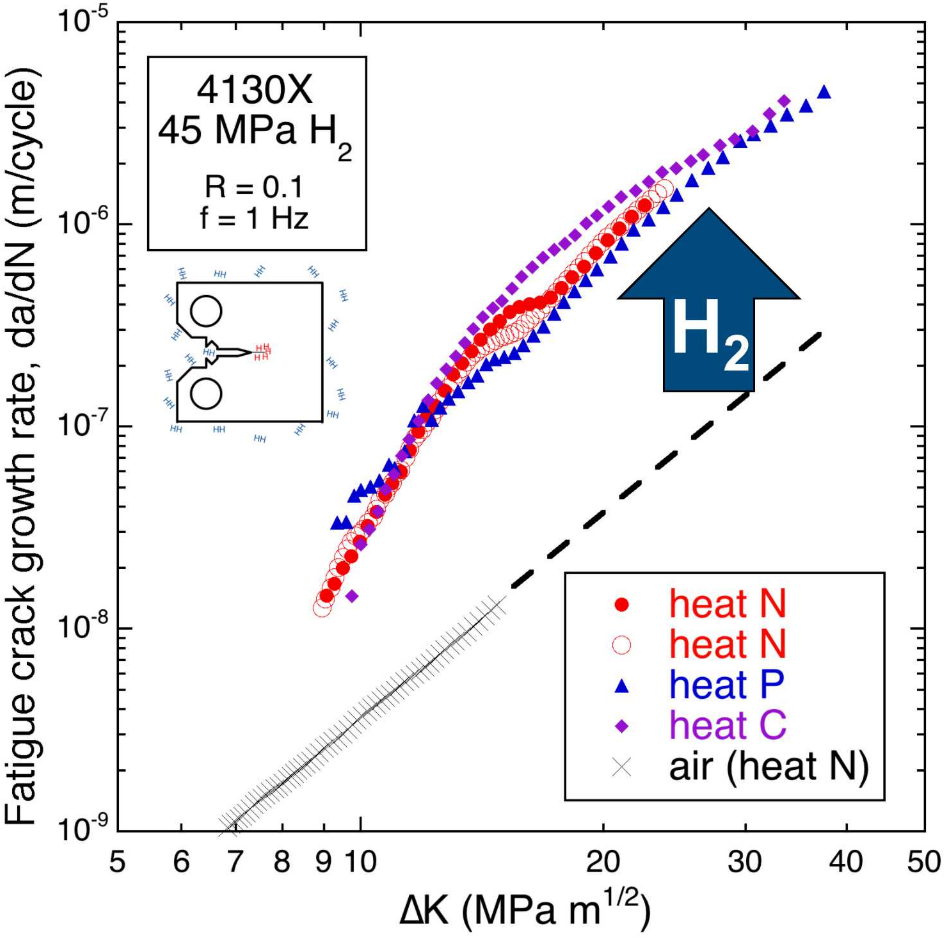


Fatigue

- **Fatigue crack growth rate is accelerated by >10X in H2 compared to air**
- **This material is safe for use in gaseous hydrogen?**
  - **(a) True**
  - **(b) False**

Transportable gas cylinders for H_2 are made of this material

The importance of hydrogen depends on the specifics of the *application* and *design*



The effect of hydrogen is <u>not</u> considered for typical DOT vessels

- **Gas cylinders are made from relatively low strength steels**
- **Wall stresses are relatively low**
- **Number of pressure cycles are modest**
- **Manufacturing defects are well characterized**

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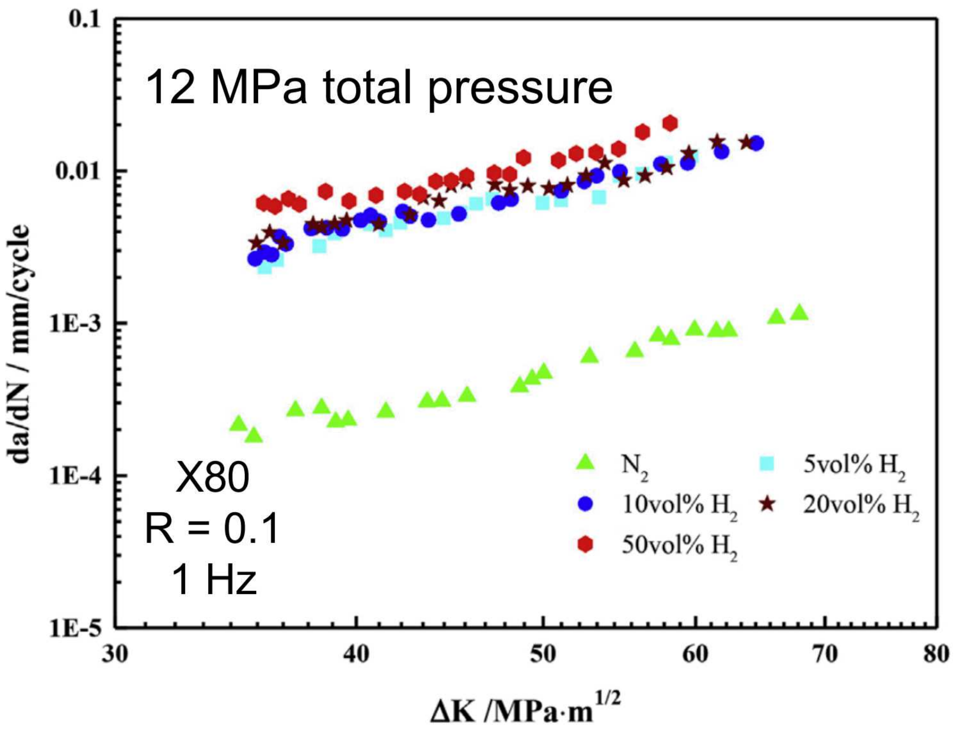
Low pressure H_2 can have a substantial effect on fatigue crack growth rates

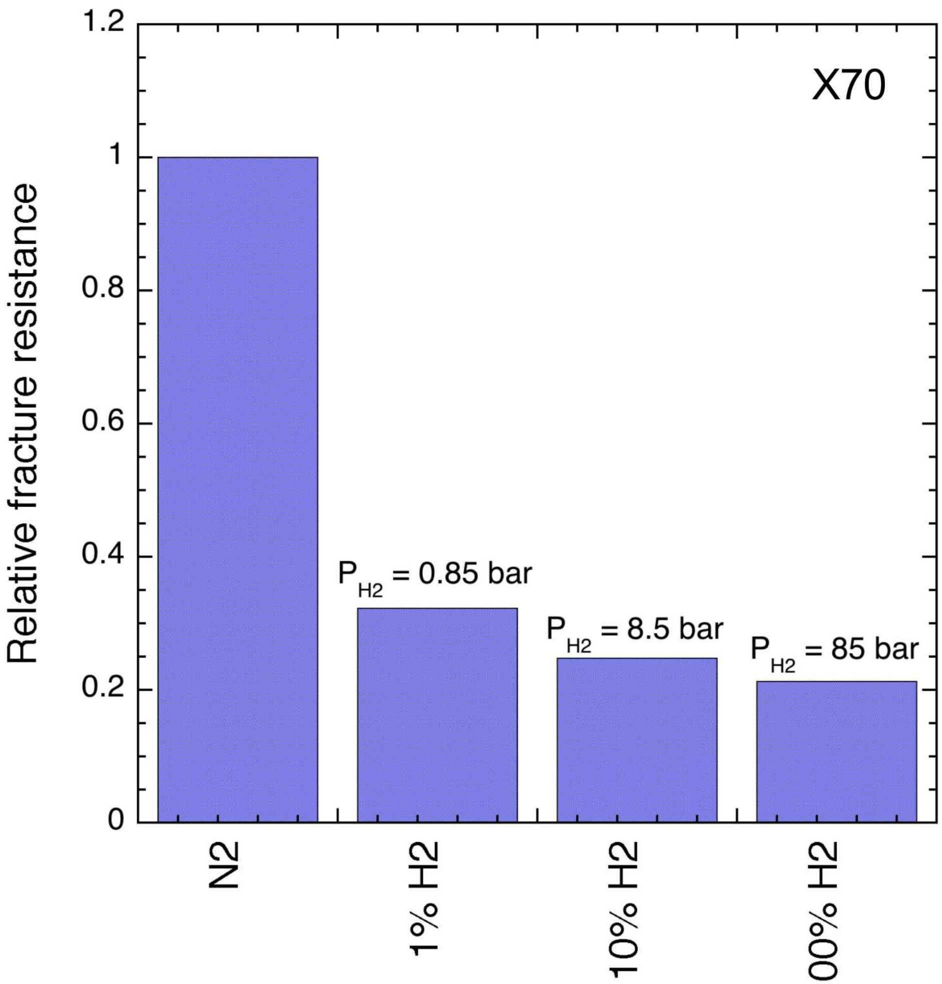


From: Meng et al, *IJ Hydrogen Energy* **42** (2017) 7404.

- **Measurements in gaseous mixtures of H_2 and N_2 show acceleration of fatigue crack growth rate with 5% H_2**
  - **But little additional acceleration with higher H_2 content**

Small amounts of hydrogen can have substantial effect on fatigue

Low partial pressure of hydrogen can have substantial effect on fracture resistance

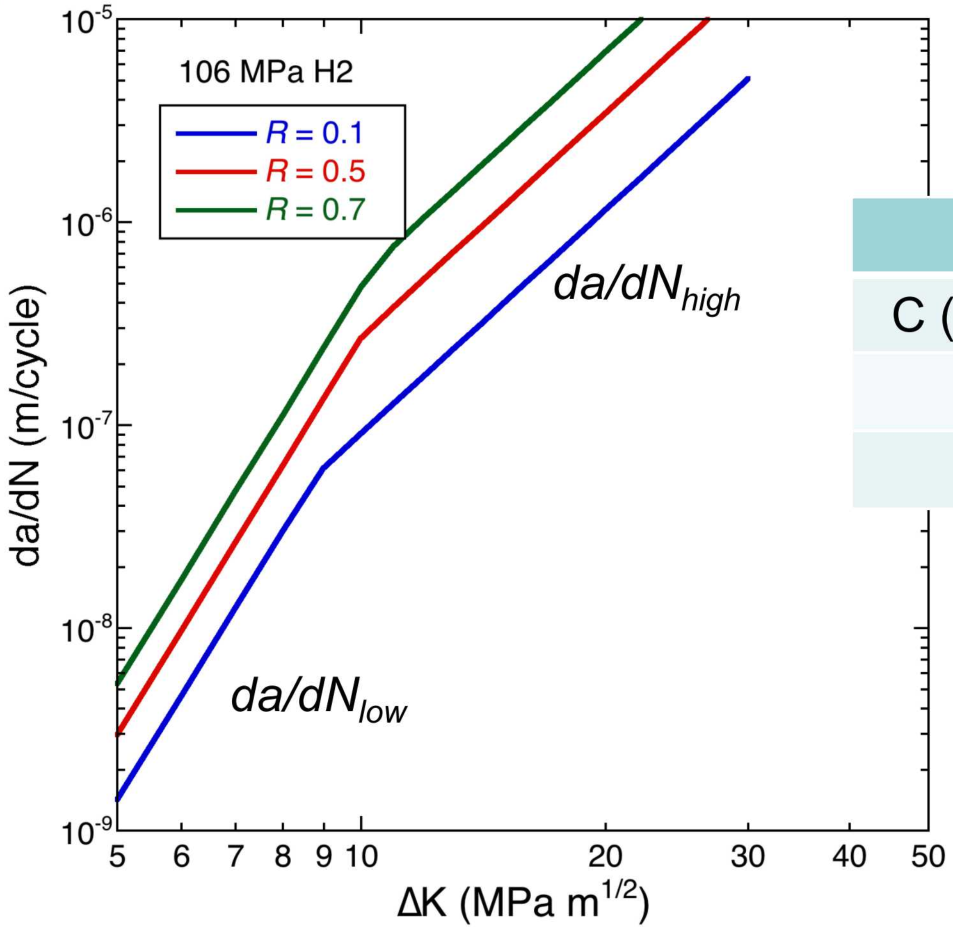


From: Briottet et al, ASME PVP2018-

- Measurements of fracture resistance in gaseous mixtures of H_2 and N_2 show substantial effects of H_2
- 1% H_2 is only modestly different than 100% H_2

<1 bar of H_2 reduces fracture resistance

Formulation of design curves in Code Case 2938



Ref.: San Marchi et al, ASME PVP2019-93907.

$$\frac{da}{dN} = C\left[\frac{1 + C_H R}{1 - R}\right]\Delta K^m$$

	da/dN_{low}	da/dN_{high}
C (m/cycle)	3.5 x10^{-14}	1.5 x10^{-11}
m	6.5	3.66
C_H	0.4286	2.00

$$\Delta K < \Delta K_c: \quad da/dN = da/dN_{low}$$

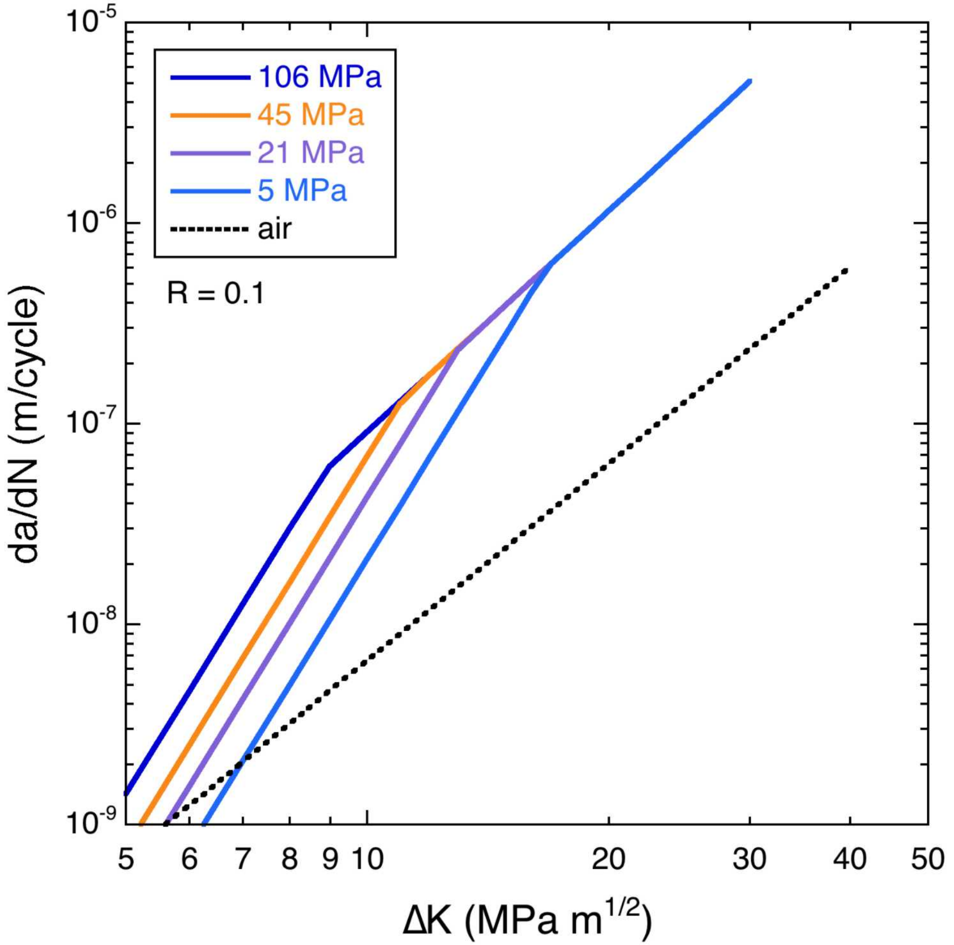
$$\Delta K \geq \Delta K_c: \quad da/dN = da/dN_{high}$$

$$\Delta K_c = 8.475 + 4.062R - 1.696R^2$$

ΔK, ΔK_c units: MPa $m^{1/2}$

Also refer to previous ASME presentations (SAND2018-1098 PE)

Pressure correction for design curves (not included in Code Case 2938)



Ref.: San Marchi et al, ASME PVP2019-93907.

$$\left(\frac{da}{dN}\right)_{low} = C\left[\frac{1+C_H R}{1-R}\right]\Delta K^m \left(\frac{f}{f_{ref}}\right)^{1/2}$$

$$\left(\frac{da}{dN}\right)_{high} = C\left[\frac{1+C_H R}{1-R}\right]\Delta K^m$$

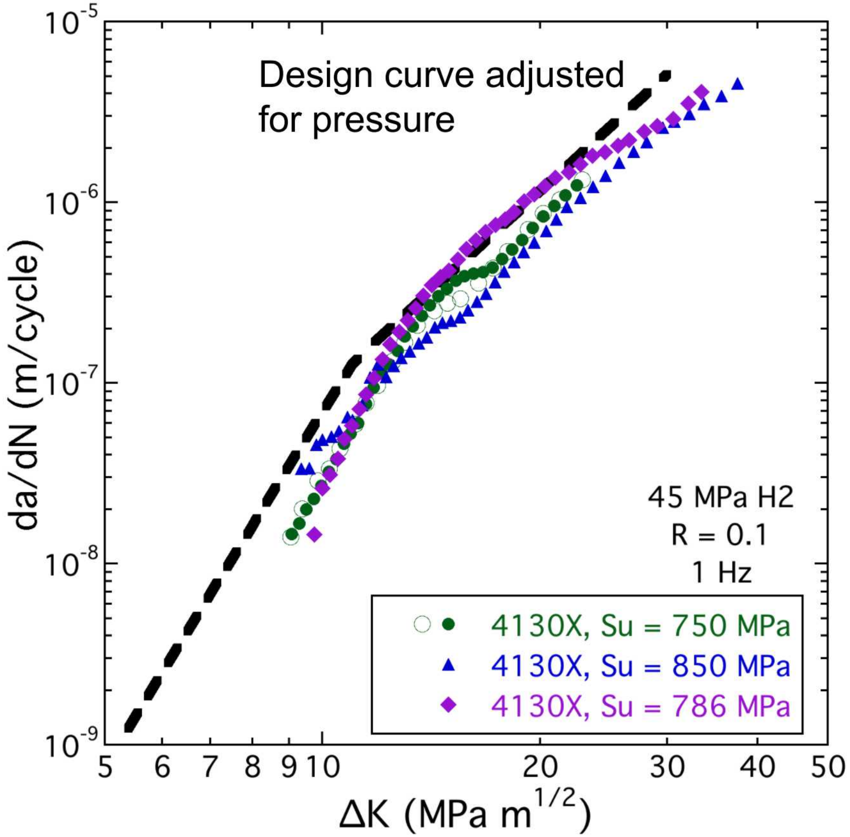
f is fugacity of gaseous hydrogen

$$f = P \exp\left[\frac{Pb}{RT}\right]$$

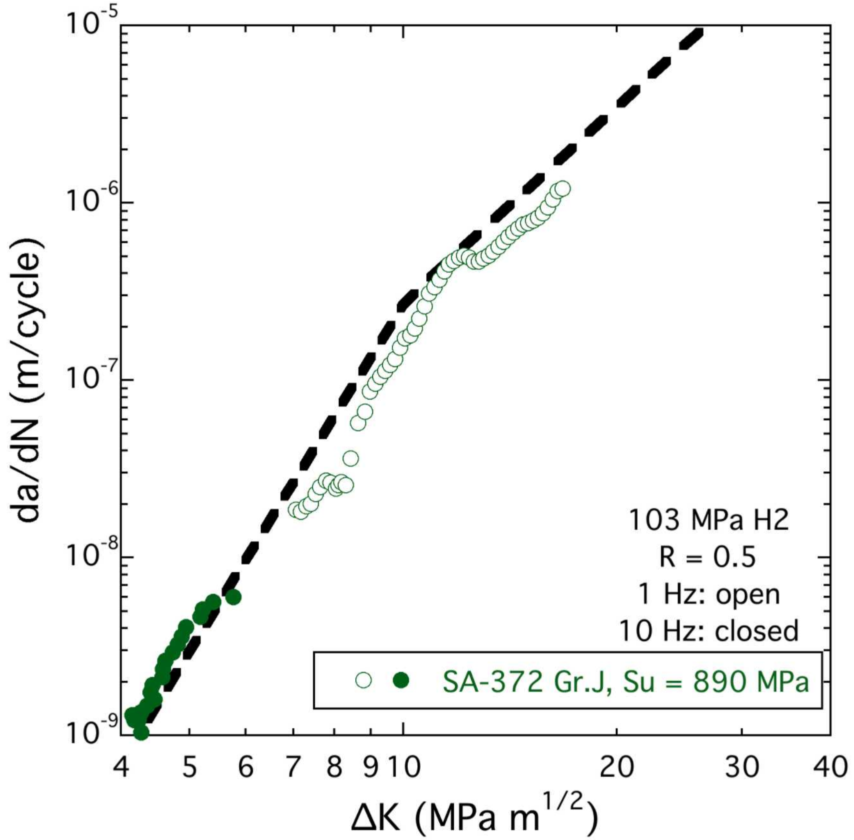
b (H_2) = 15.84 cm^3/mol

f_{ref} = 211 MPa (P_{ref} = 106 MPa)

Design curves can be applied to other Cr-Mo pressure vessel steels and extrapolated to low ΔK



Ref.: San Marchi et al, ASME PVP2019-93907.



Ref.: Ronevich et al, ASME PVP2020-21263.

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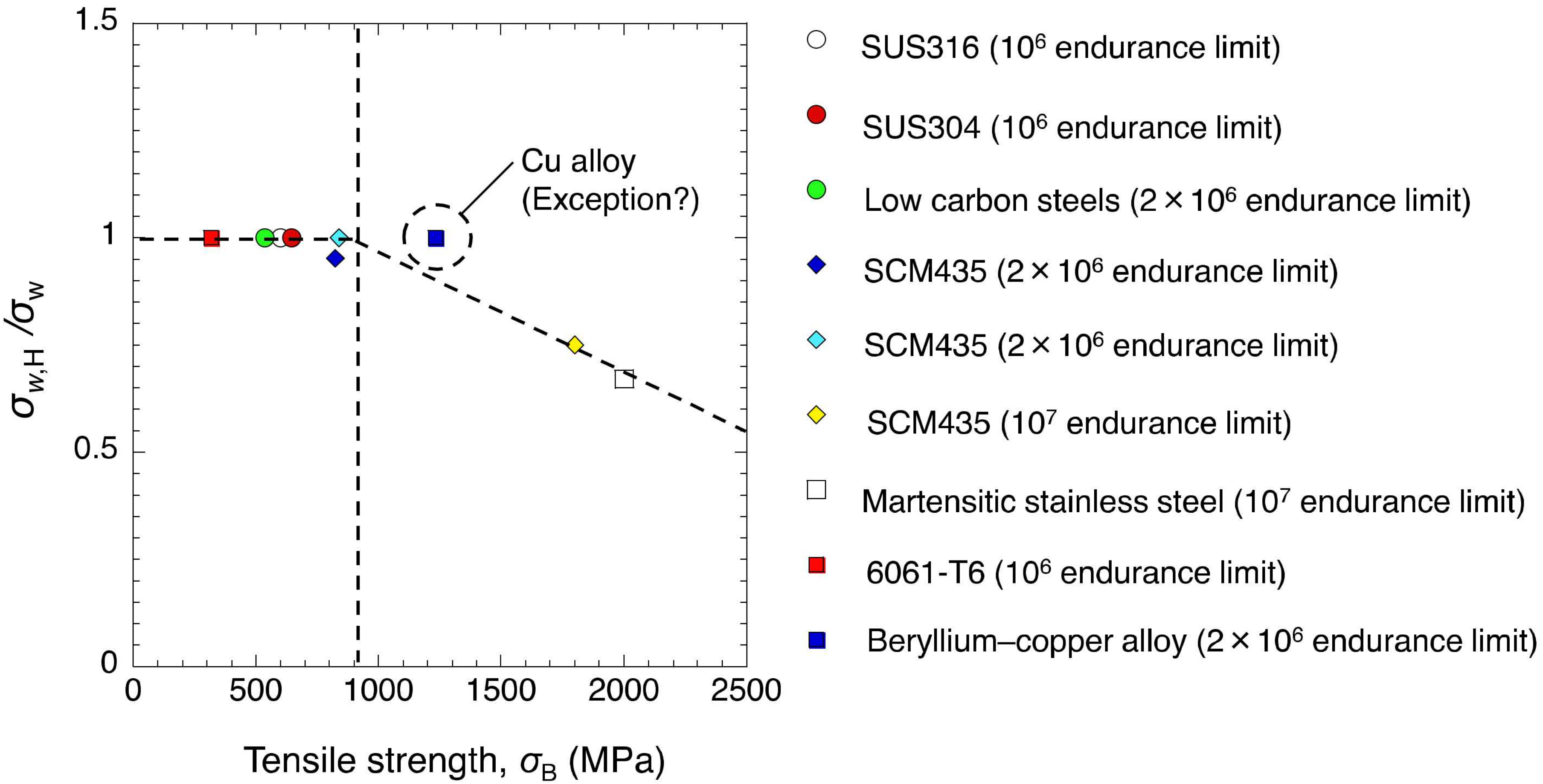
- **What are observed trends of fatigue life testing in gaseous hydrogen?**
  - **Endurance limit**
  - **High cycle regime / high stress**
- Supplementary information

Fatigue endurance limit is unchanged in gaseous hydrogen for materials with tensile strength <915 MPa



Plot courtesy of Matsunaga et al., Kyushu University

Gaseous hydrogen can reduce fatigue life for high applied fatigue stress

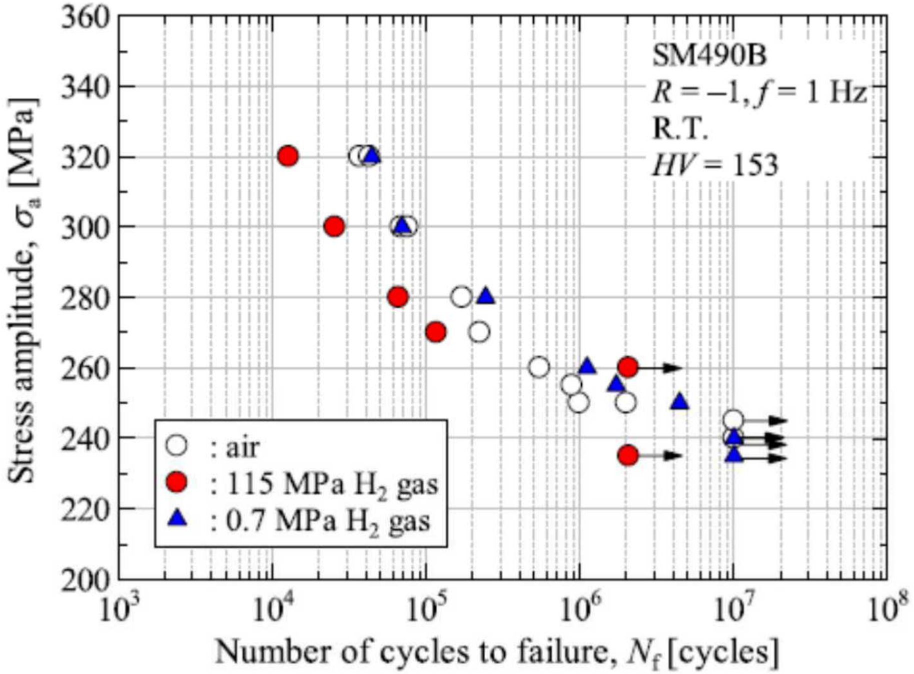
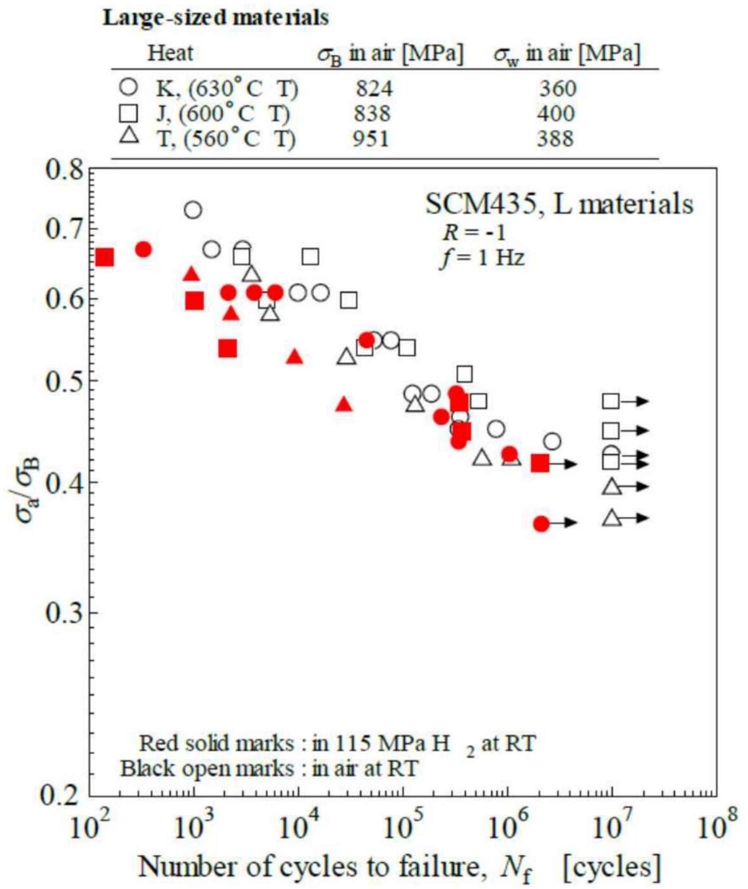


Fig. 4. *S-N* data of JIS-SM490B steel obtained in laboratory air and in the hydrogen gas with pressures of 0.7 and 115 MPa at room temperature.

- **Near endurance limit, fatigue life is not changed by testing in gaseous hydrogen**
  - **For 'low' tensile strength steels**
- **At high stress, fatigue life is significantly reduced**

Ref. Ogawa et al, Intern J Fatigue, v.103 (2017).

Gaseous hydrogen can reduce fatigue life for high applied fatigue stress

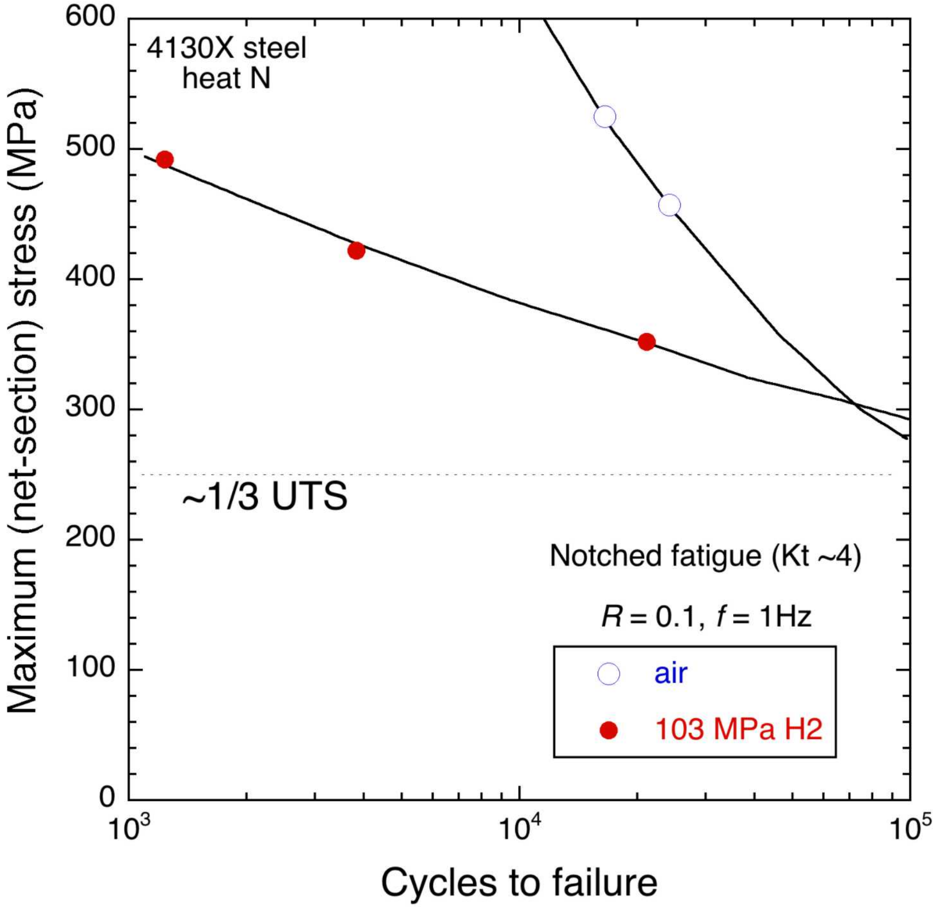


(a) Large-sized materials

- **Hydrogen does not affect the endurance limit of Cr-Mo steels with 'low' tensile strength**
- **At high stress, fatigue life is significantly reduced**

Ref. Matsuoka et al, Trans JSME, v.83 (2017) – in Japanese.

Notched configuration enhances the effect of hydrogen on fatigue life



Ref. San Marchi, unpublished

- **Substantial affects of hydrogen are apparent in notched fatigue configuration in the low cycle regime**
- **Limited data suggest that for (net-section) stress <1/3 tensile strength, fatigue life may be unchanged**

Summary

- Transportable gas cylinders are used for hydrogen successfully and do not directly consider the effect of hydrogen on design
- Low partial pressure of hydrogen can have substantial effects on fatigue and fracture properties
  - Design curves from CC2938 can be applied to evaluate fatigue crack growth and pressure effects for a range of carbon and low-alloy steels
- Fatigue endurance limit appears to be unchanged in hydrogen for steels with tensile strength <915 MPa
  - However, fatigue life can be strongly reduced at high stress

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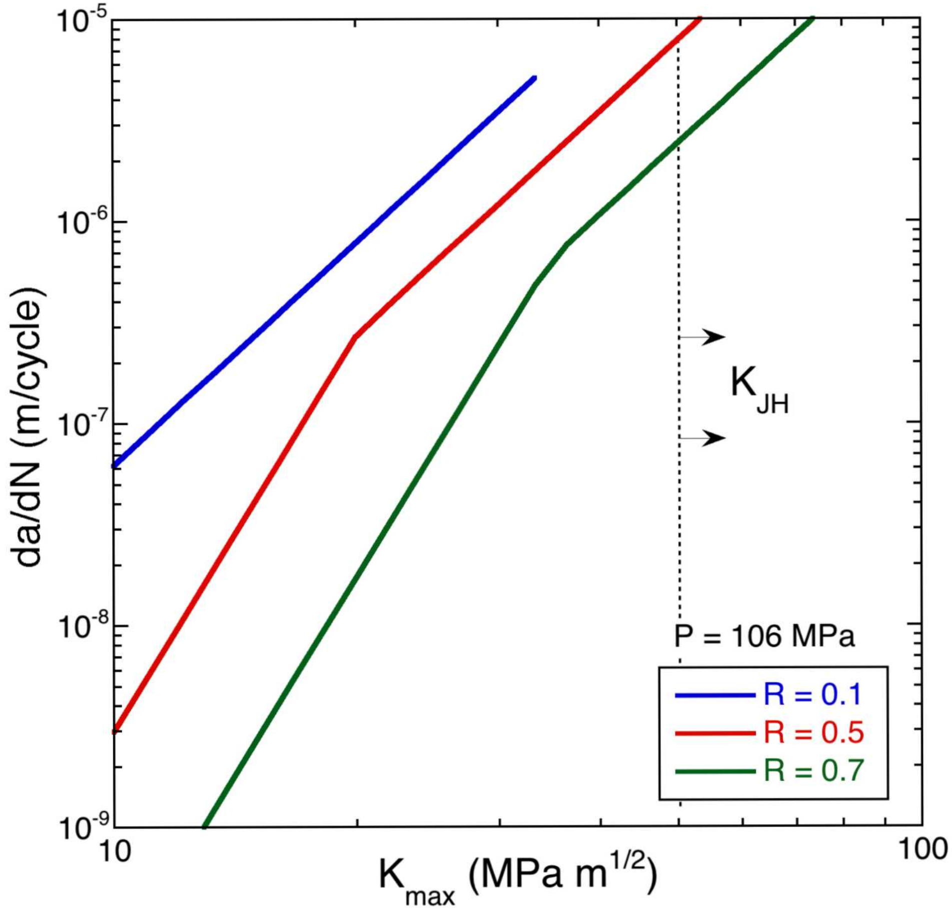
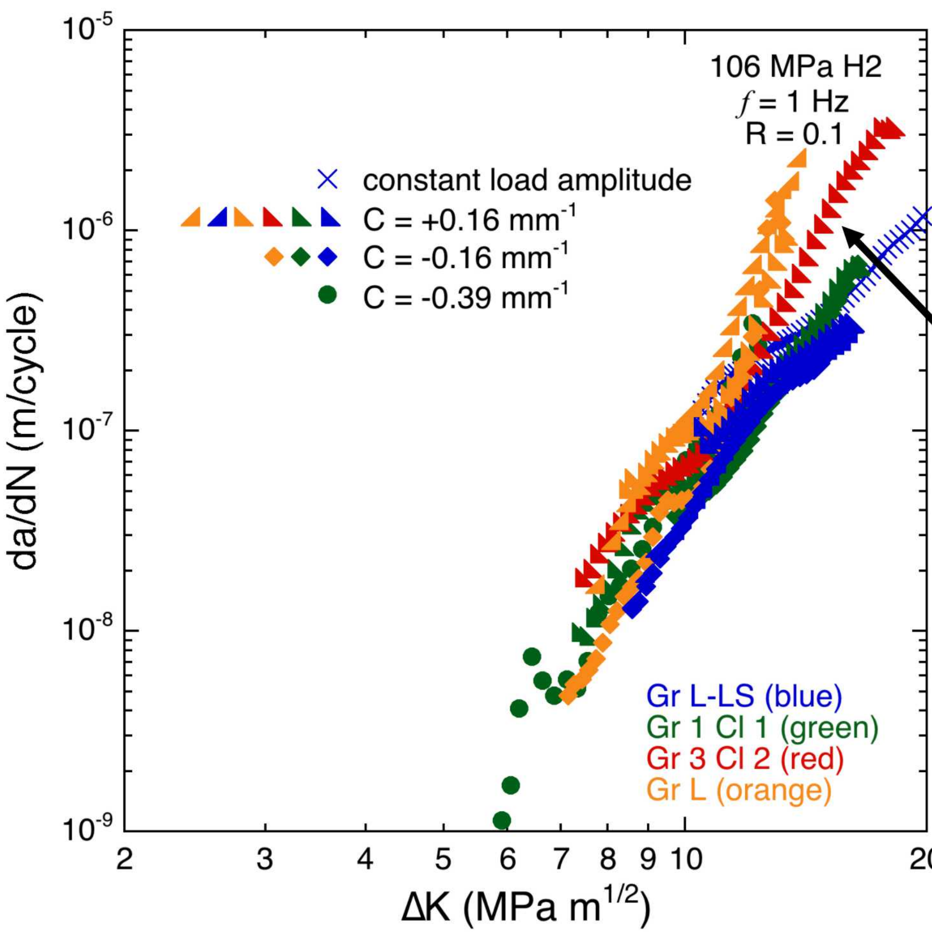
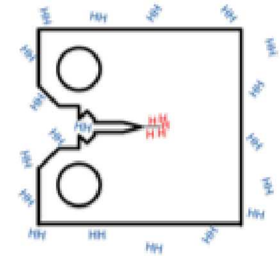
FCGR law formulation (in terms of K_{max})



FCGR data for variable K-gradient



- 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
    $K_{max} \Rightarrow K_{JH}$



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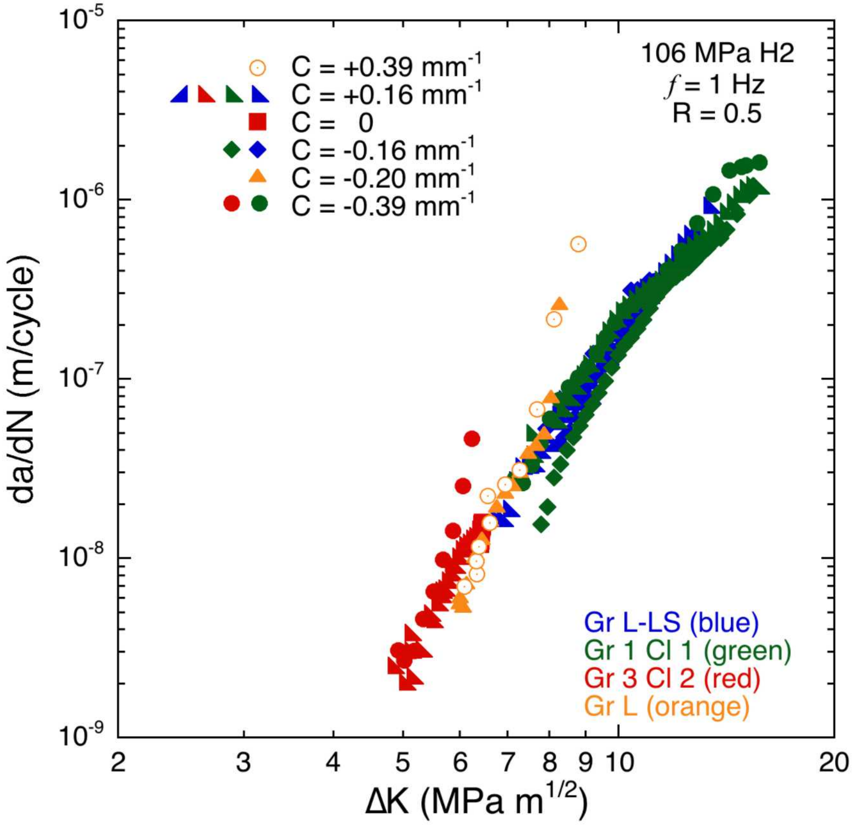
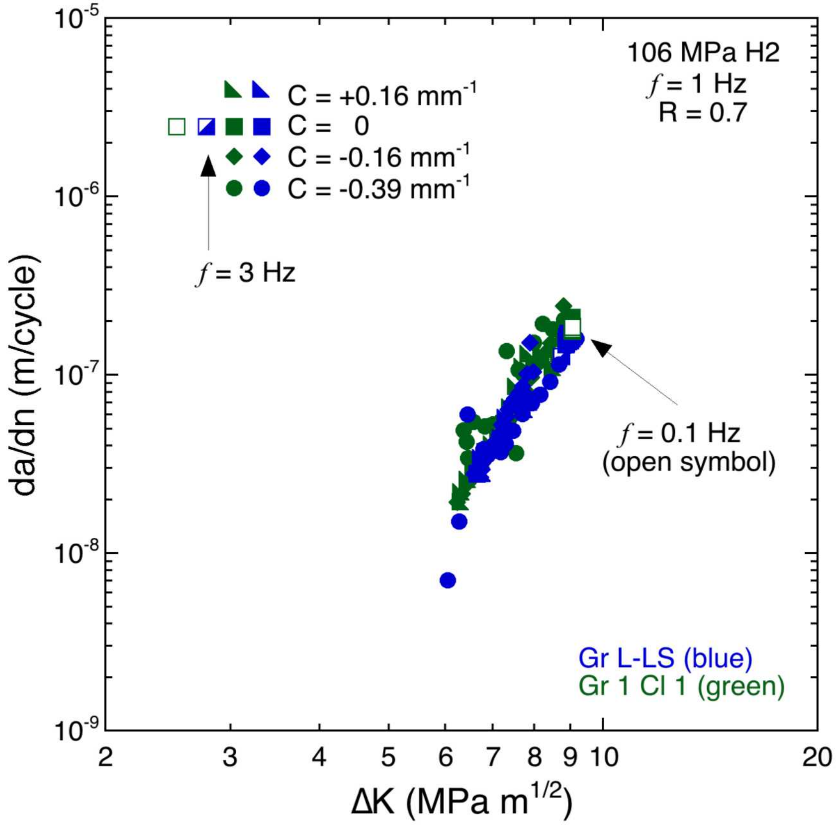
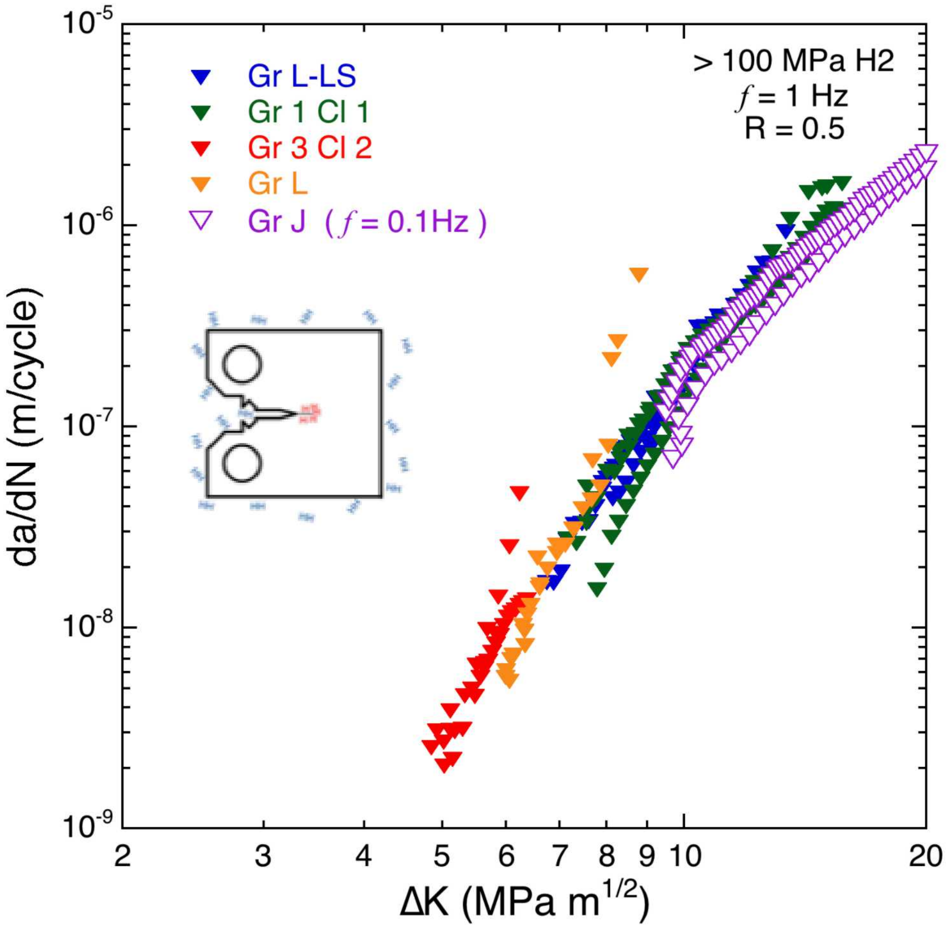


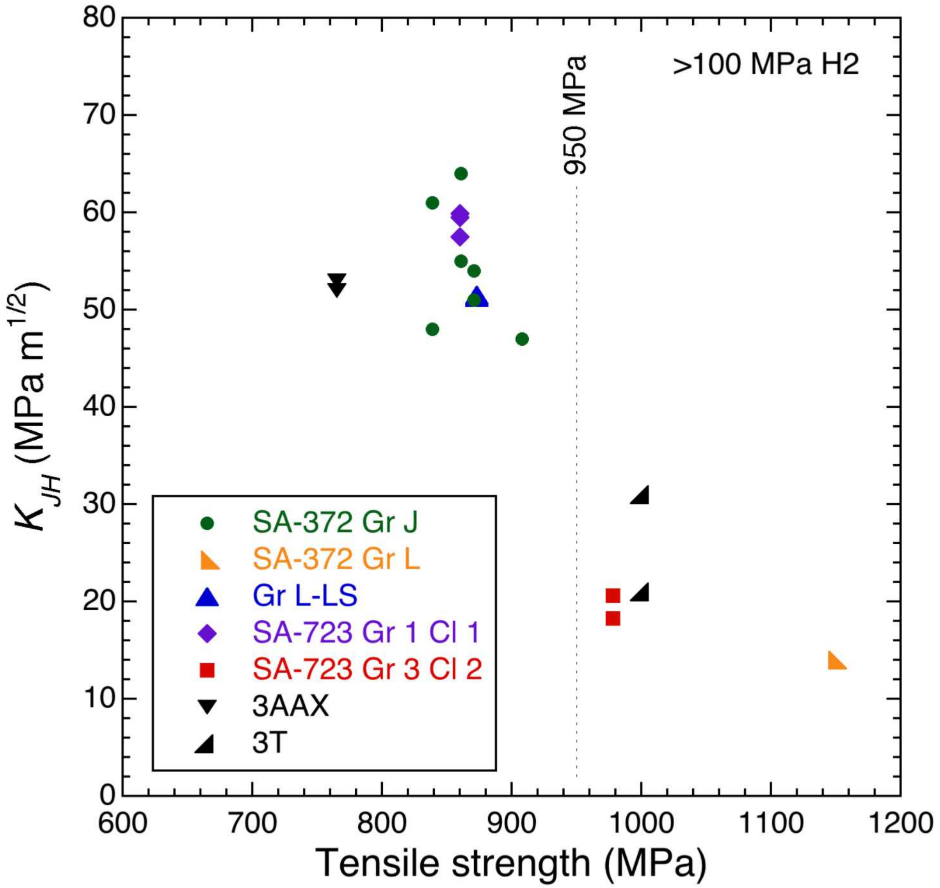


Comparison of Cr-Mo and Ni-Cr-Mo



- **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 $\Delta K > \sim 9$ MPa $m^{1/2}$)**
- **Single master curve for fatigue crack growth of both Cr-Mo and Ni-Cr-Mo steels appears reasonable**

Fracture resistance – rising load (K_{JH})



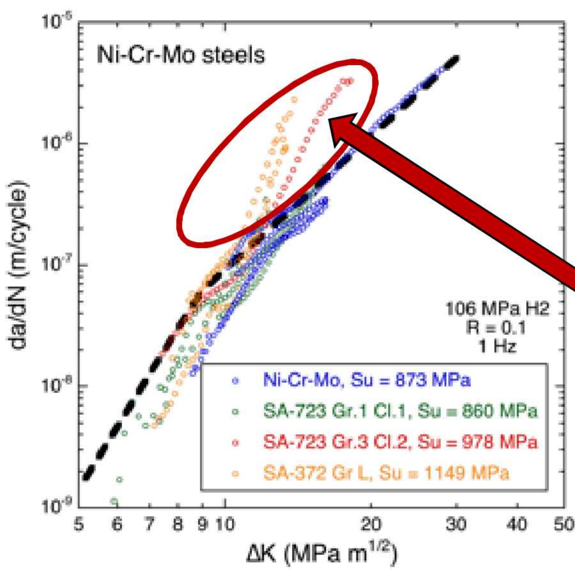
PV steels display low fracture resistance in high strength condition

- **For tensile strength < 950 MPa**
  - **K_{JH} > 45 MPa $m^{1/2}$**
- **For tensile strength > 950 MPa**
  - **K_{JH} < 30 MPa $m^{1/2}$**

K_{JH} = elastic-plastic plane-strain fracture toughness in gaseous hydrogen (ASTM E1820)

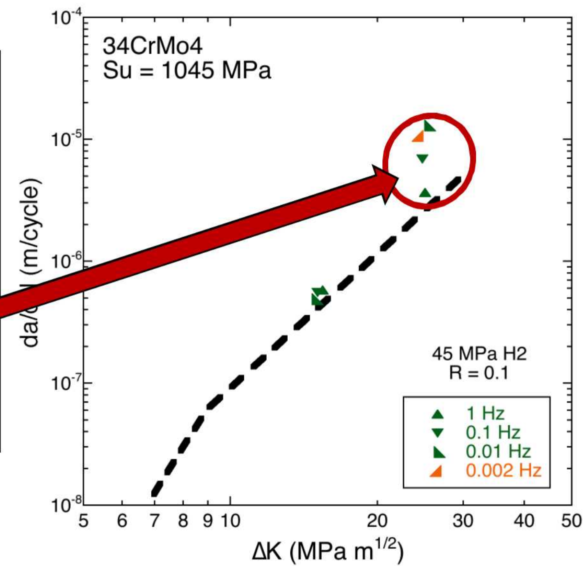
Basis for limiting strength in CC2938

- **High-strength steels show transition to accelerated crack growth related to baseline behavior (*eg*, stage III)**
  - **only observed in tests of high-strength steels: tensile strength > 950 MPa**
  - **Related to fracture resistance: as K_{max} approaches K_{JH} (where K_{JH} is measured as J_{IC} from ASTM E1820 in gaseous hydrogen)**



For PV steels with Su > 950 MPa

- Accelerated fatigue crack growth rate is observed
- K_{JH} < 30 MPa $m^{1/2}$

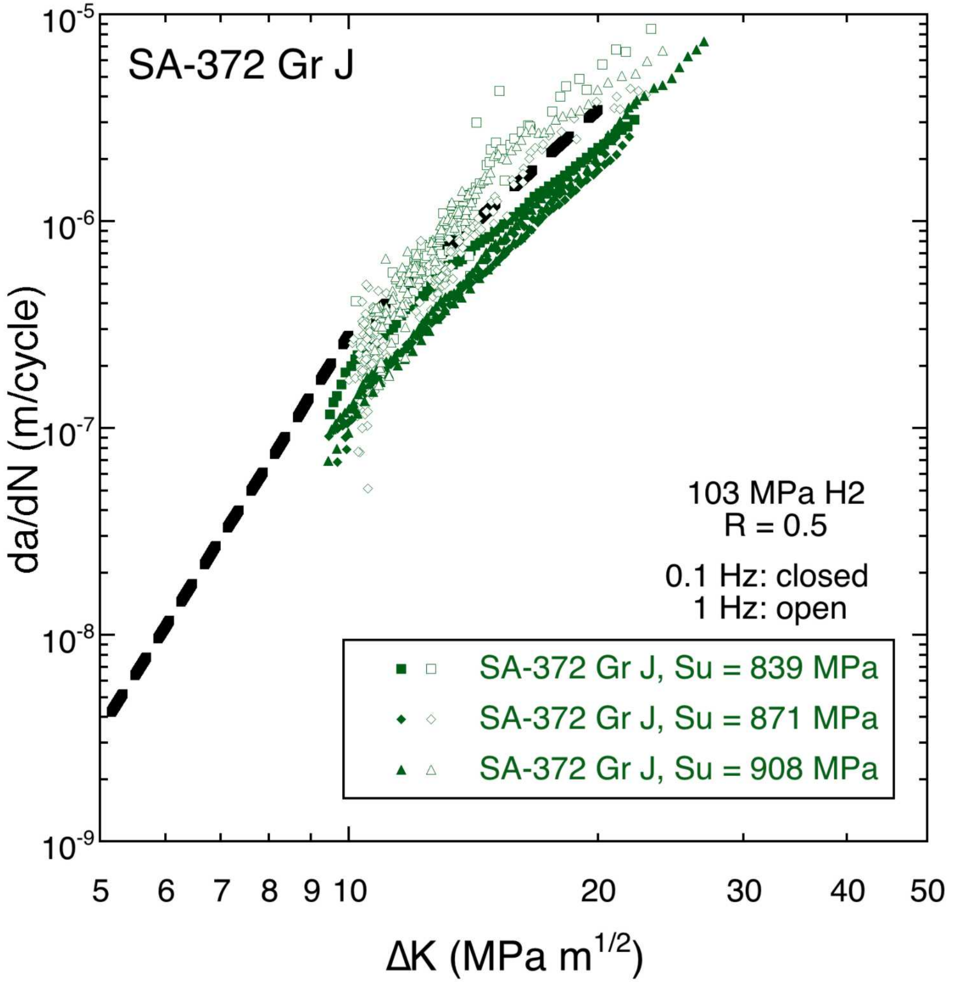


Pressure vessel steels used to formulate fatigue design curves

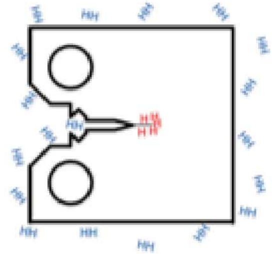
Designation	Tensile strength (MPa)	Yield Strength (MPa)
Cr-Mo steels		
SA-372 Grade J (A71)	839	642
SA-372 Grade J (B50)	871	731
SA-372 Grade J (A72)	908	784
SA-372 Grade J (AV60Z)	890	760
34CrMo4	1045	850
Ni-Cr-Mo steels		
SA-372 Grade L	1149	1053
SA-372 Grade L-LS †	873 †	731 †
SA-723 Grade 1 – Class 1	860	715
SA-723 Grade 3 – Class 2	978	888

† Does not meet SA-372 (low strength)

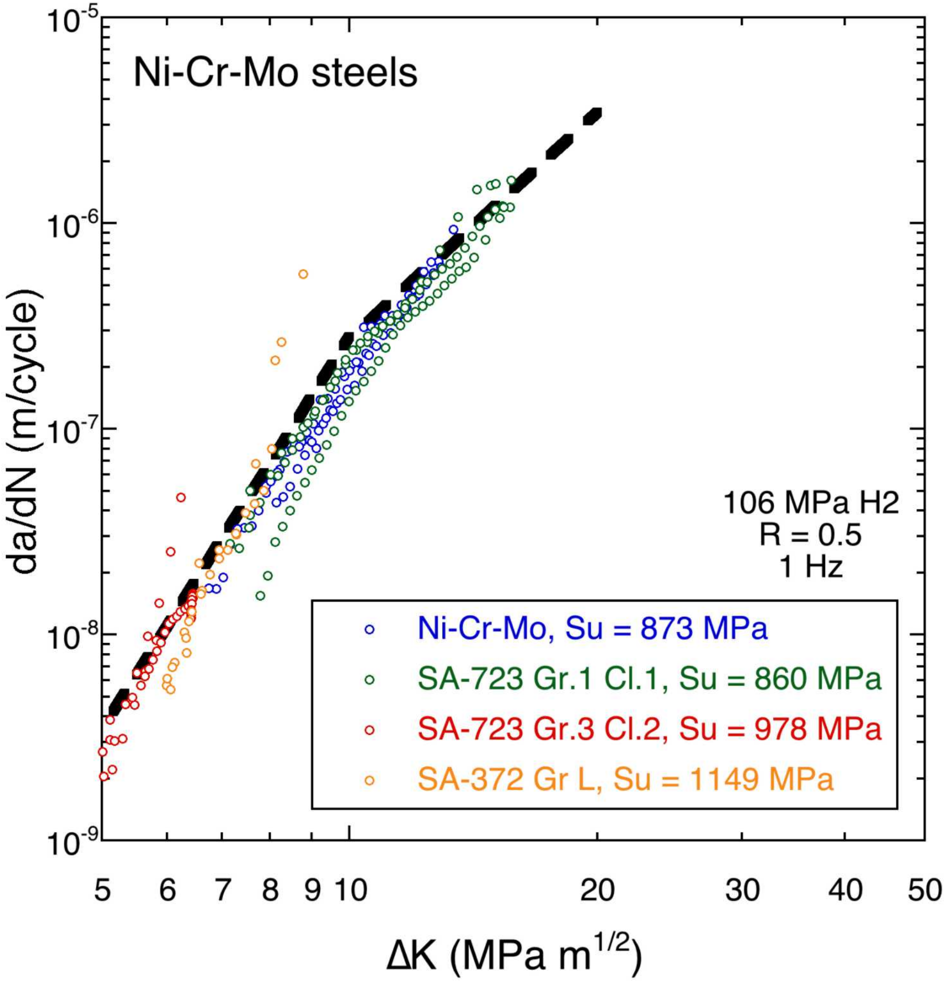
Fatigue crack growth rates of SA-372 Grade J R=0.5



- Gaseous hydrogen at pressure of 103 MPa
- R = 0.5
- 0.1 Hz data from Somerday et al., ASME PVP2013-97455
- 1 Hz data from Somerday et al., International Conference on Hydrogen Safety 2009

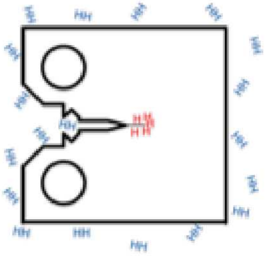


Fatigue crack growth rates of Ni-Cr-Mo steels R=0.5

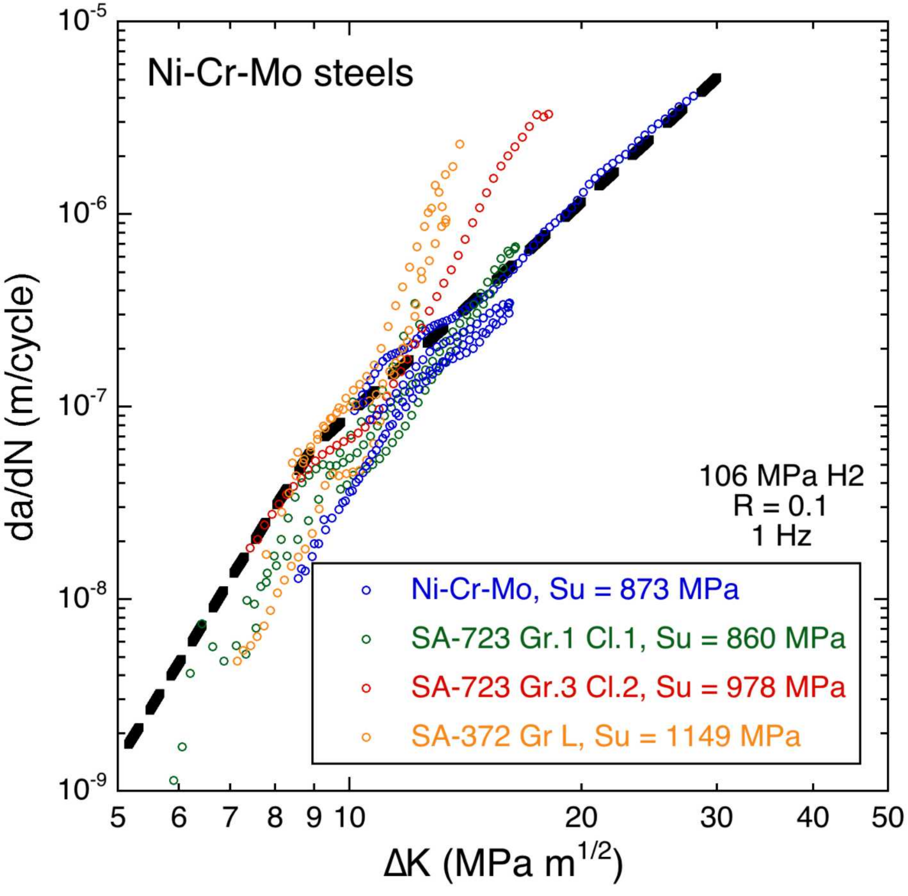


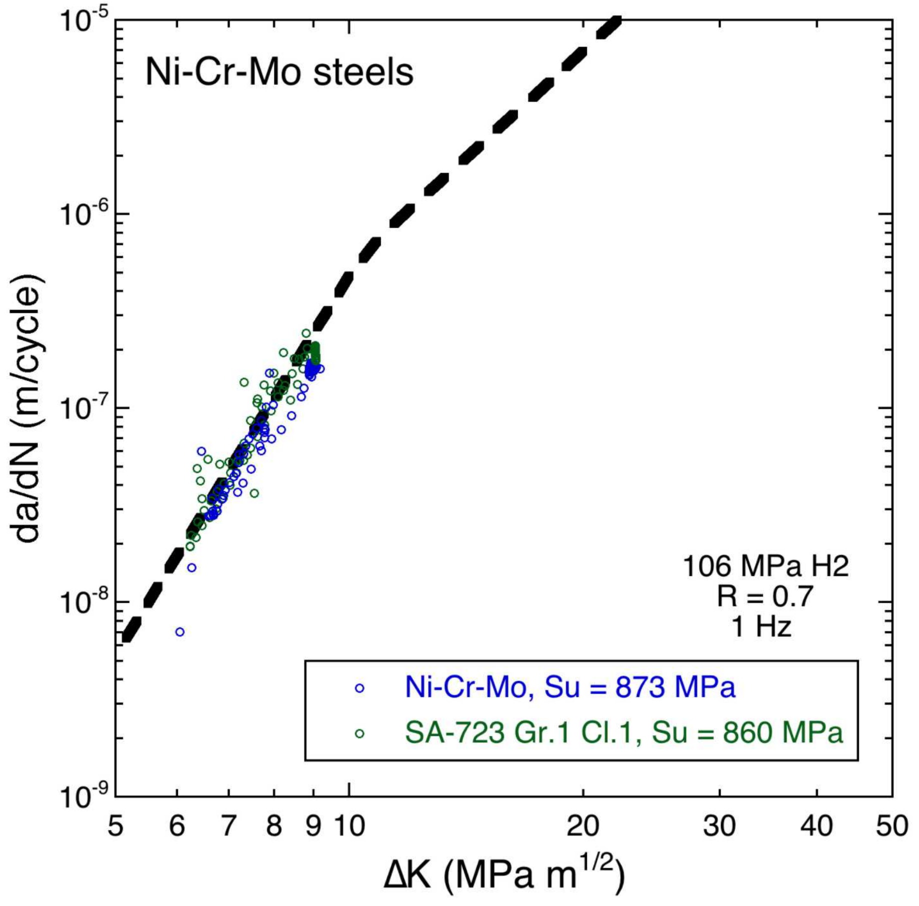
- **Gaseous hydrogen at pressure of 106 MPa**
- **R = 0.5**
- **Frequency of 1 Hz**

Ref.: San Marchi et al, International Conference on Hydrogen Safety 2017.



Fatigue crack growth rates of Ni-Cr-Mo steels



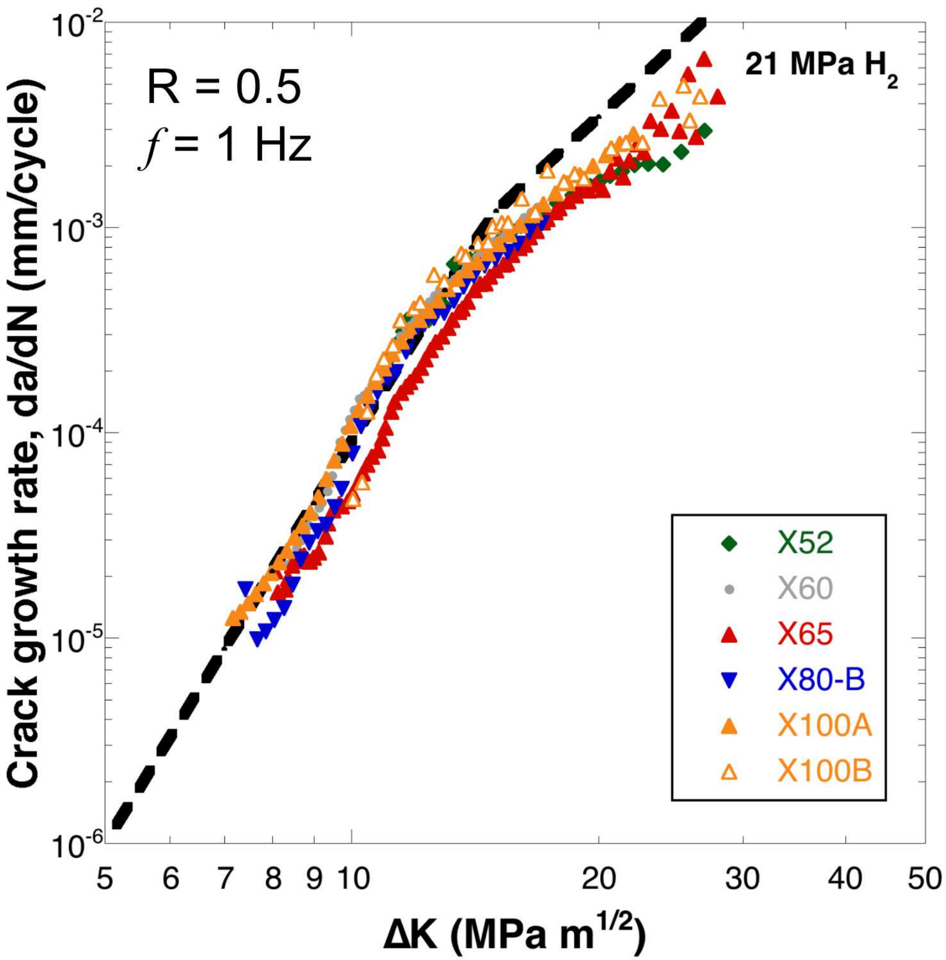


Ref.: San Marchi et al, International Conference on Hydrogen Safety 2017.

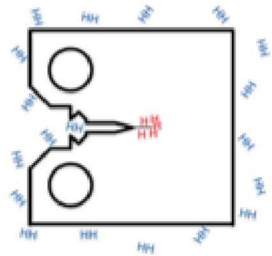
Other common steels, which Sandia has tested in gaseous hydrogen (not complete list)

Designation	Tensile strength (MPa)	Yield Strength (MPa)
Cr-Mo steels		
4130X	750	543
4130X	850	–
4130X	786	–
carbon steels		
SA-516 Gr. 70	503	361
P355 NL2	535	380
API X52	493	429
API X60	486	434
API X80	710	593
API X100	868	732

Design curves can be applied to carbon (pipeline) steels and extrapolated to lower pressure



- Tested steels represent:
  - Wide range of strength
  - Wide range of microstructure
- Design curve is corrected for pressure
- Data from several references



Ref.: San Marchi et al, ASME PVP2019-93907.

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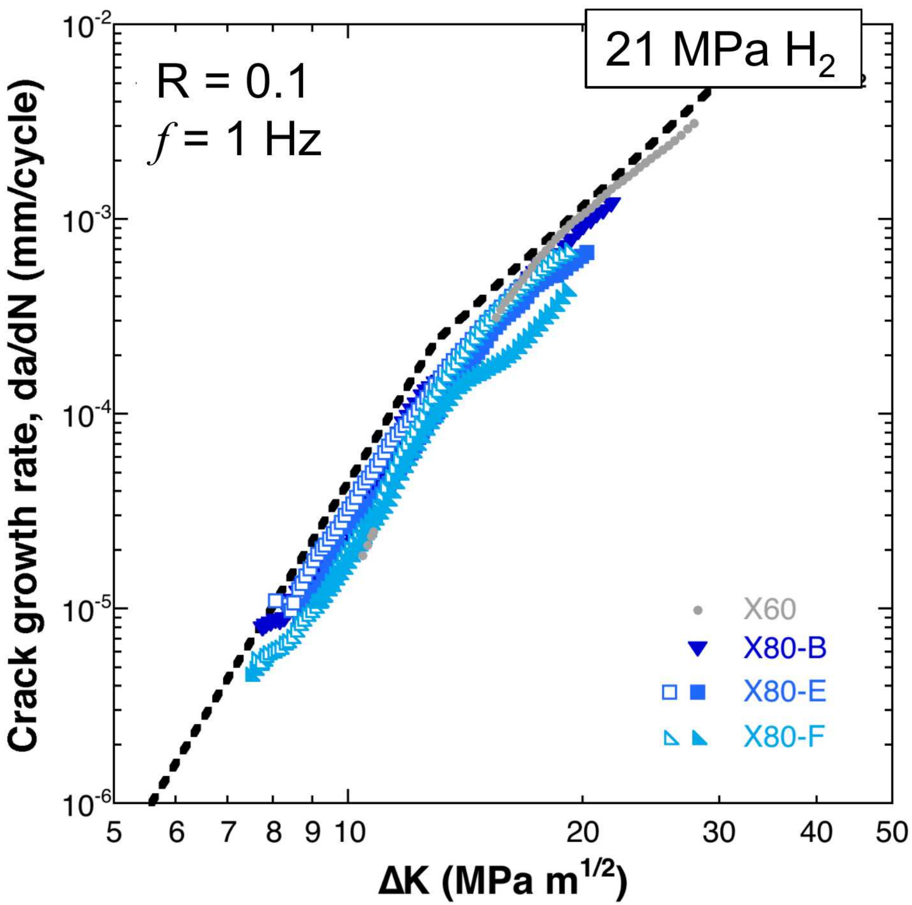
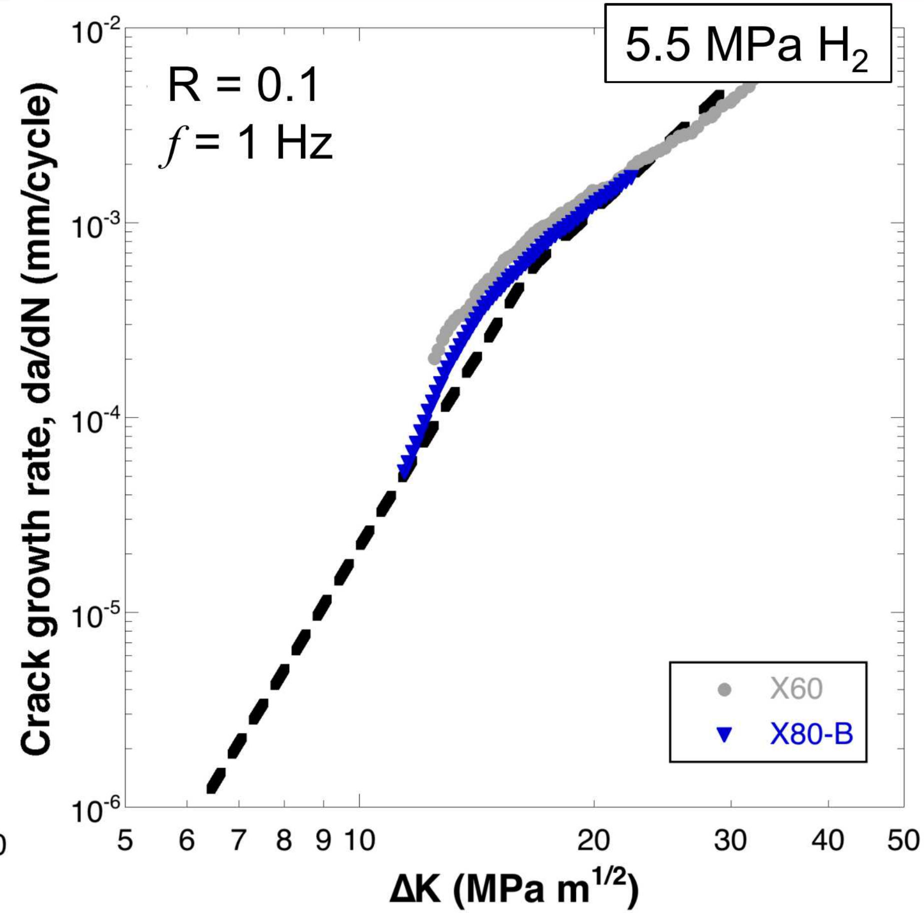
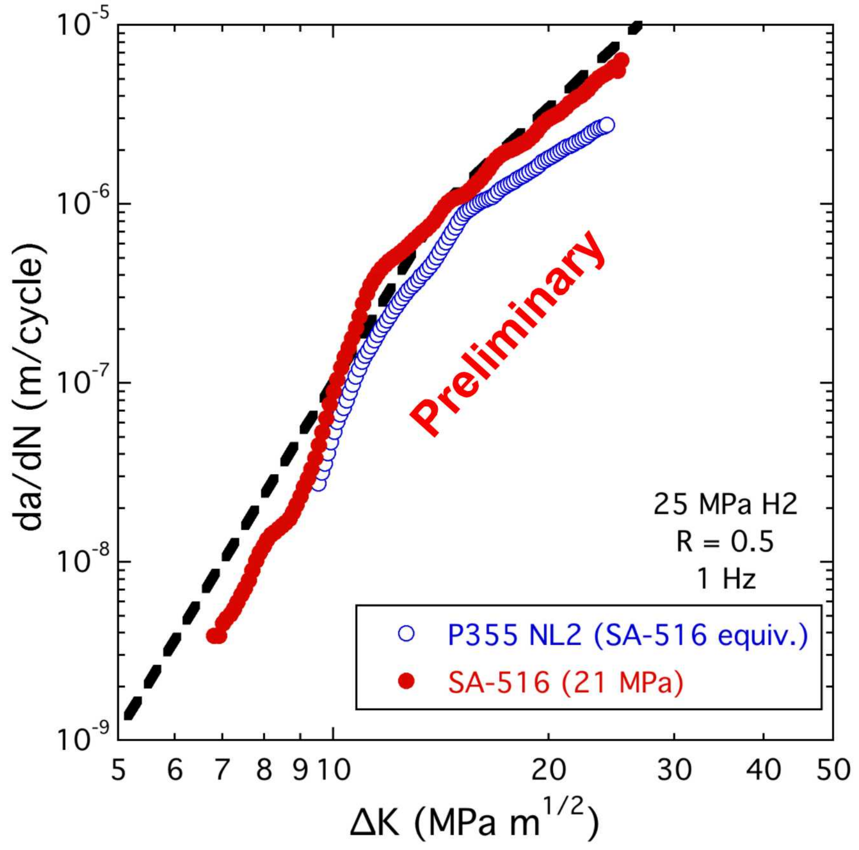


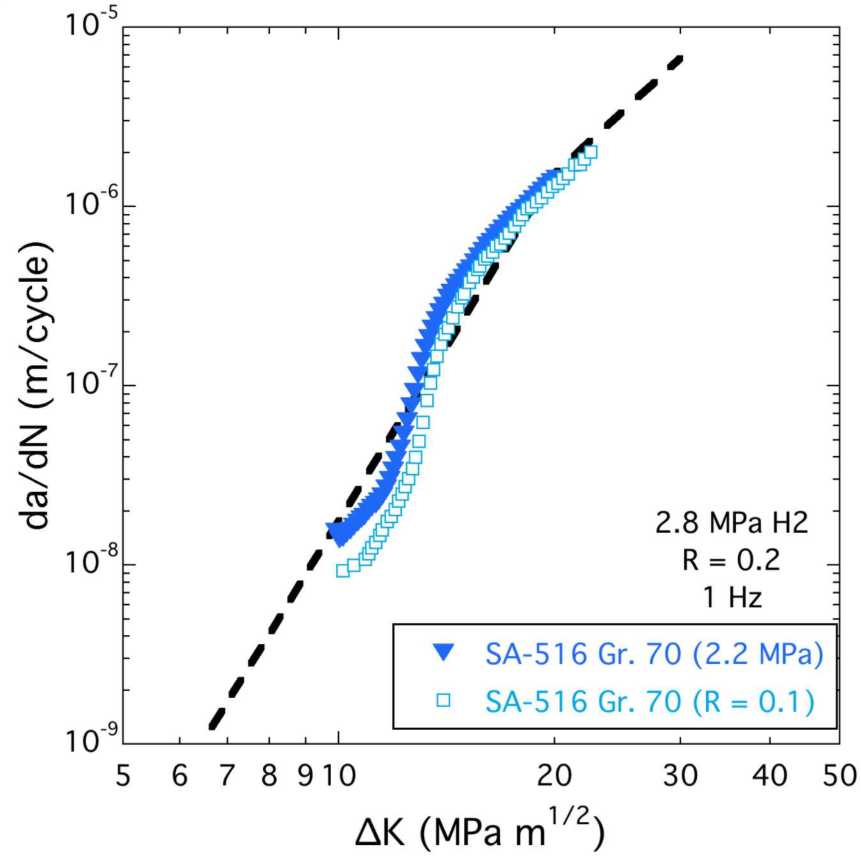


Refs.: San Marchi et al, ASME PVP2010-25825, ASME PVP2011-57684, ASME PVP2019-93907.

Design curves can be applied to carbon steels: for example, SA-516 at lower pressure



Ref.: San Marchi & Ronevich, unpublished

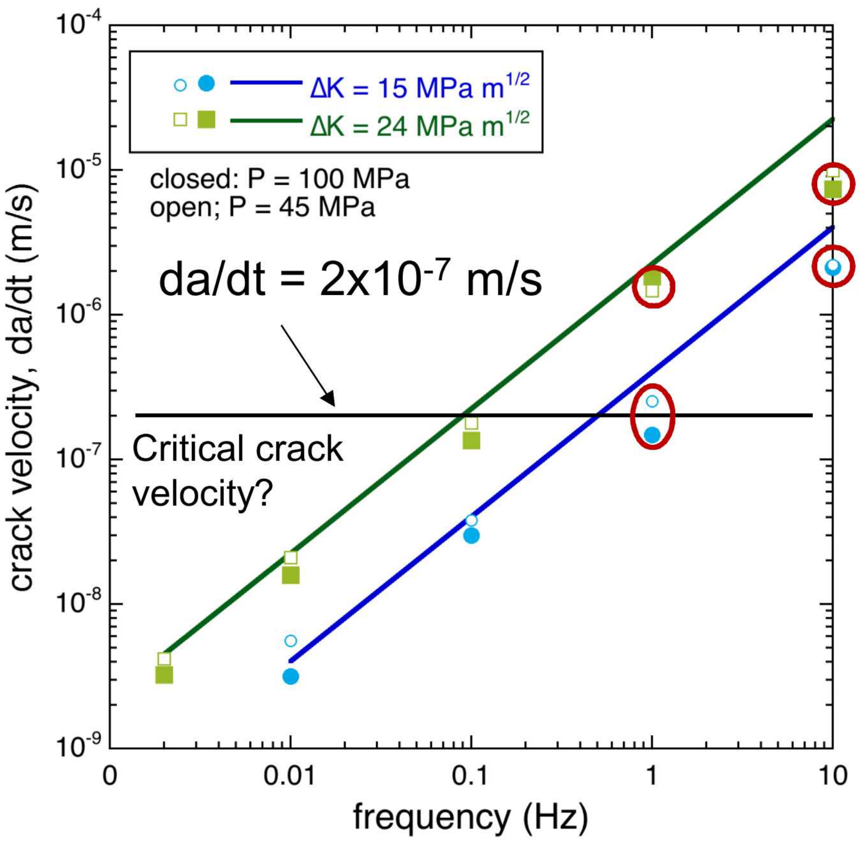


Ref.: Somerday et al, JPVT v.137 (2015).

Test frequency and time

Time scales are important when evaluating hydrogen effects

- because hydrogen is mobile in metals
- but transport can be limited

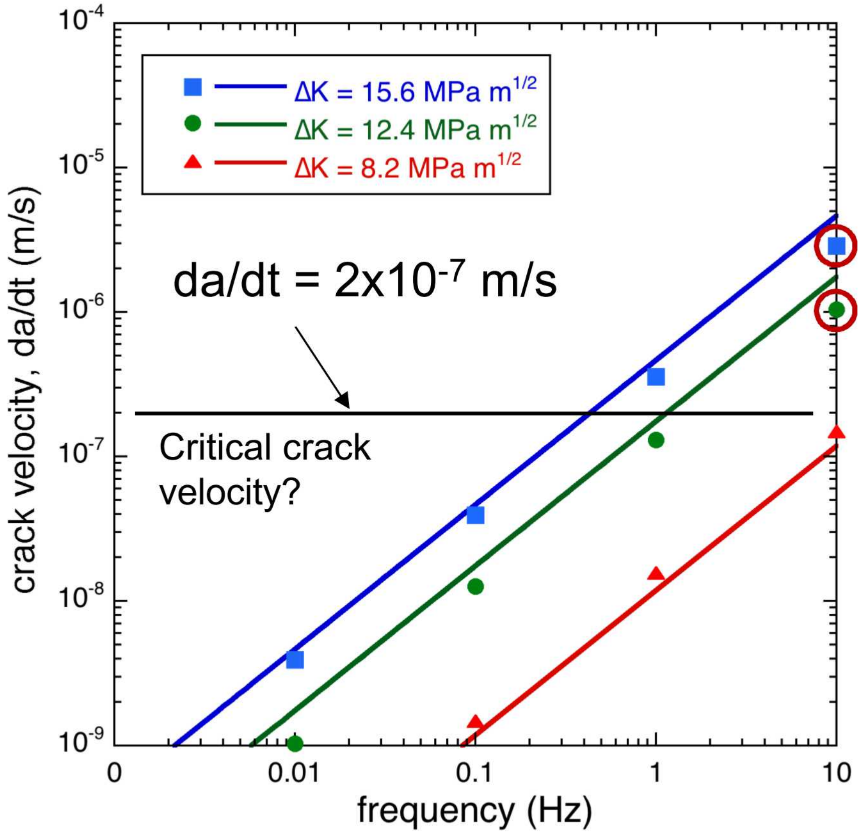


- The relevant time scale in fatigue crack growth is related to the crack velocity
- For a constant da/dN, the crack velocity will depend on the frequency (linear relationship)
- In the plot to the left, the lines represent a constant da/dN and the points represent measurements
- Deviation of the measured data from the limiting behavior (red circles) indicates an effect of time scale

These data show that frequency is important at high da/dN and high ΔK

Waveform and hold time

Waveform and hold times can be considered in the context of the measured crack velocity



- **Literature results related to waveform (hold times) are often biased toward evaluation at high ΔK**
- **Such results will enhance the manifestation of rate effects**
- **Additionally, high K_{max} can induce H-assisted fracture (transition to stage III behavior) as shown above for high-strength steels**

These data suggest that rate effects are less important for low ΔK where da/dt is less than a critical crack velocity