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Technical basis for master curve for fatigue crack growth of ferritic steels in high-pressure gaseous hydrogen in ASME section VIII-3 code (PVP2019-93907)

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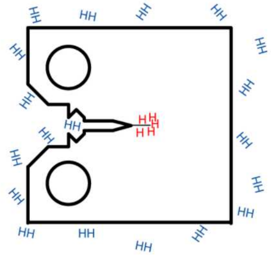
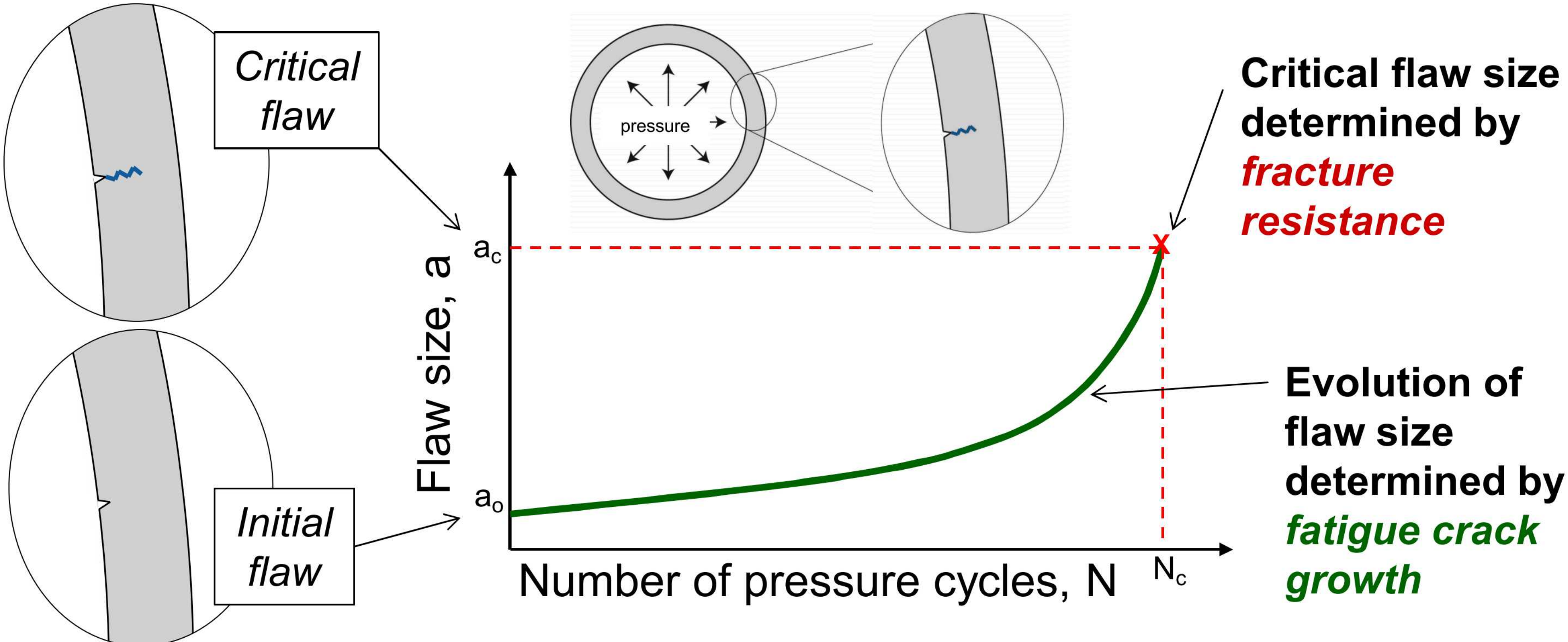
Outline

- Motivation for design equations related to high-pressure gaseous hydrogen storage vessels
  - Code Case 2938
- Fracture mechanics test methods and testing validity
- Basic trends and formulation of master curve for fatigue crack growth in gaseous hydrogen
- Tested materials and review of fracture mechanics data
- Basis of constraints in CC2938
  - Limits on strength
  - Limits on K_{max} range
- Pressure effects (not in CC2938)



Motivation for Code Case 2938 to provide fatigue design curves for hydrogen pressure vessels

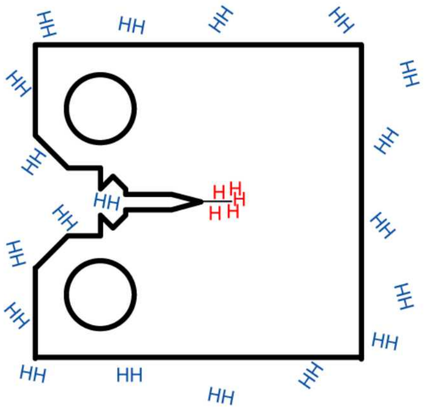
- **Storage vessels for high-pressure hydrogen require fracture mechanics-based design: BPVC VIII.3.KD-10**



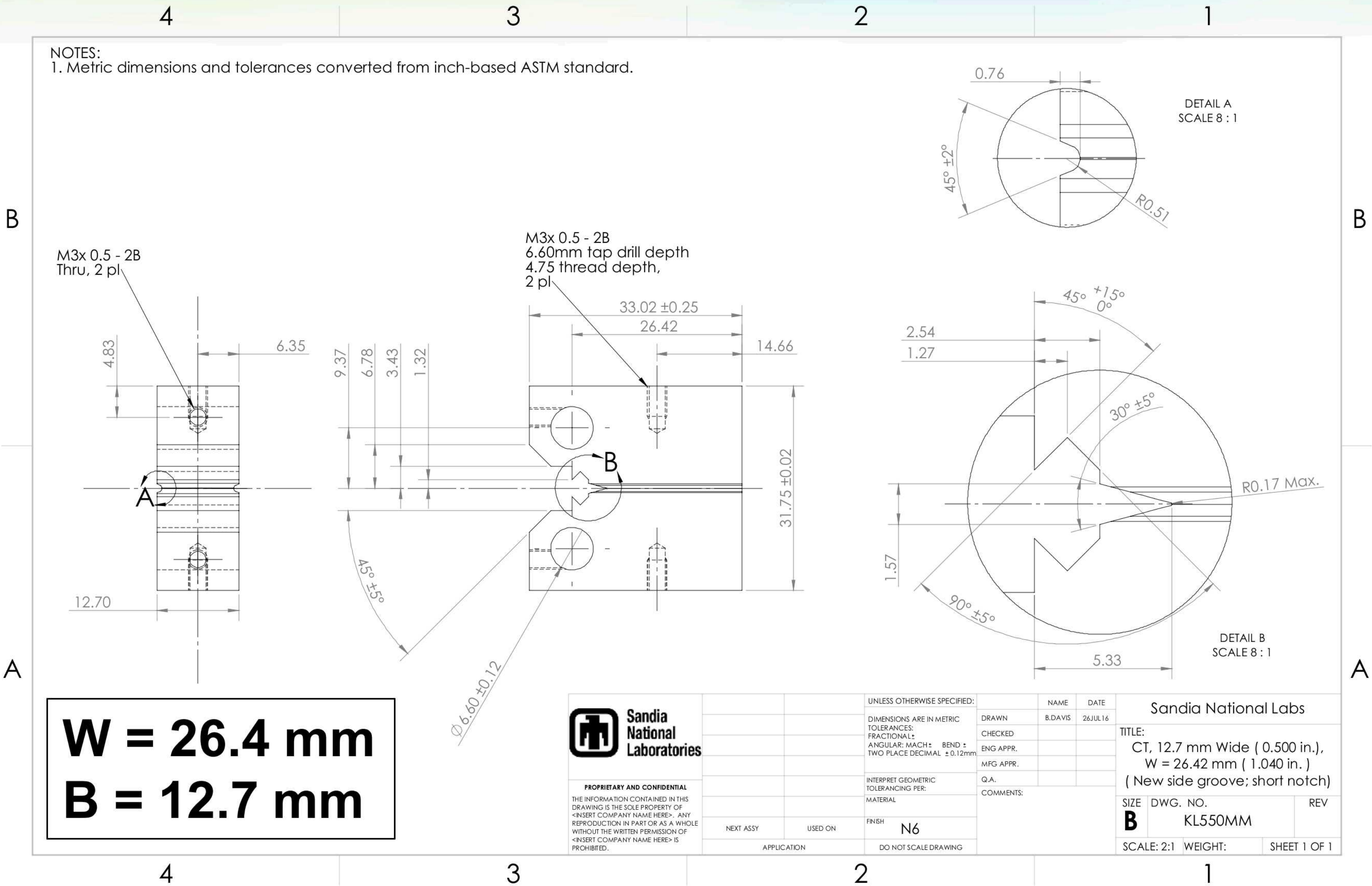
Generation of fatigue and fracture data in gaseous hydrogen is very expensive and time consuming

Fatigue crack growth and fracture toughness were measured in high-pressure gaseous hydrogen

- **Fatigue crack growth rate measured consistent with ASTM E647**
  - **in gaseous hydrogen at pressure of ≥103 MPa**
  - **fatigue typically terminated at *a/W* ~ 0.65**
- **Elastic-plastic fracture toughness evaluated consistent with ASTM E1820 (rising load J_{IC} value)**
  - **in gaseous hydrogen at pressure of ≥103 MPa**
  - **Article KD-10 for high-pressure hydrogen PVs specifies fracture testing in gaseous hydrogen according to ASTM E1681 (K_{IH}), which assumes linear elasticity**



Use same testing geometry – Compact Tension (CT) – for fatigue and fracture testing



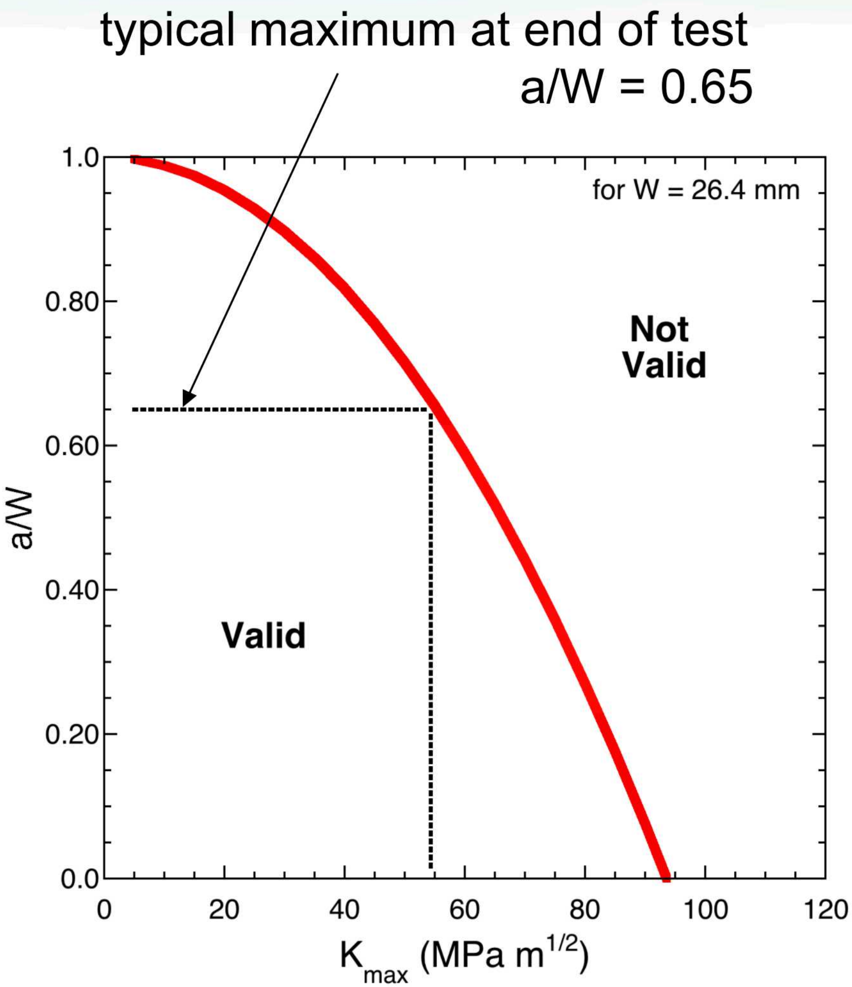
W = 26.4 mm
B = 12.7 mm

Testing validity of fatigue crack growth measurements using ASTM E647: limits on linear elasticity

- **Fatigue crack fronts are uniform unless stated otherwise**
- **Ligament requirements**

$$(W-a) \geq \left(\frac{4}{\pi}\right)\left(\frac{K_{max}}{S_y}\right)^2$$

  - **Satisfied in all cases for data in this report**
  - **Data in other studies may not be valid at high load ratio (R > 0.5)**



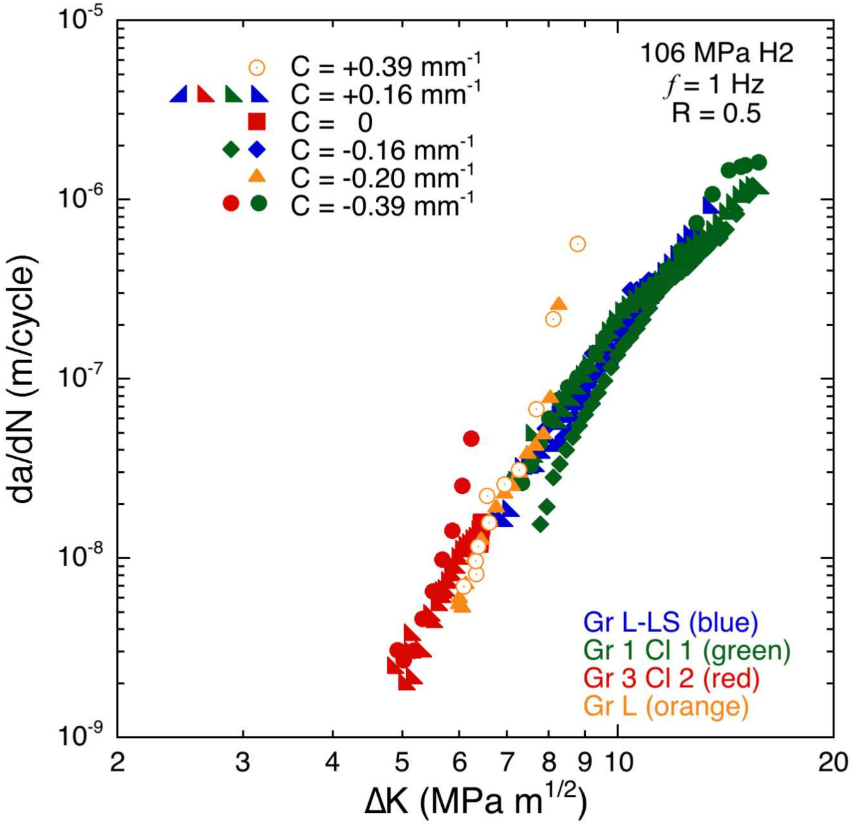
Testing validity of fatigue crack growth measurements using ASTM E647: acceleration of data generation

- **Variation of K-gradient was utilized to accelerate some tests**

$$C = \left(\frac{1}{K}\right)\left(\frac{\mathrm{d}K}{\mathrm{d}a}\right)$$

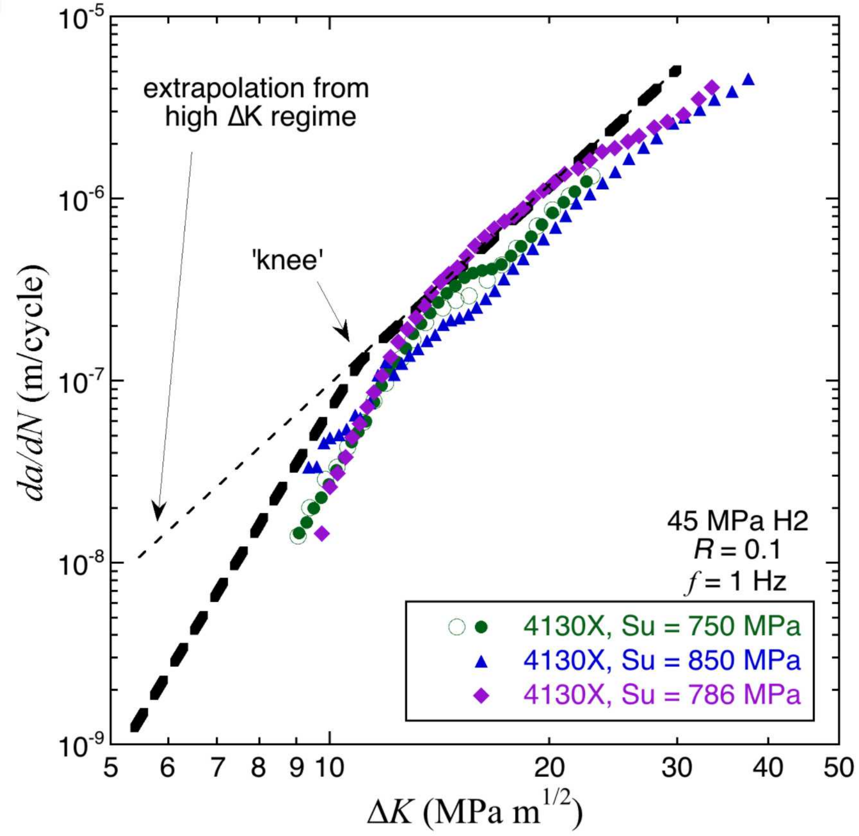
- **No dependence on the K-gradient has been observed in any testing**
  - **K-gradient varied in the range of +/- 0.39 mm^{-1} for several values of R**
  - **Data generally acquired at Δa sufficient to obtain >5 data points per decade of da/dN**
  - **Consistent data for both K-increasing and K-decreasing**

For comparison: constant load test is C ~ +0.1 mm^{-1}



Fatigue crack growth rates in gaseous hydrogen can be characterized by two slopes (or power laws)

- **Fatigue crack growth is characterized by a knee in the *da/dN*–Δ*K* curve**
- **Transition regime at "*low* Δ*K*" with a steep slope and large exponent *m***
- **Crack growth rate at "*high* Δ*K*" with slope similar to air, but significantly higher rate by 10x or more**



Extrapolation to *low-*Δ*K* regime from ΔK > 10 MPa m$^{1/2}$ is overly conservative

Are there simple relationships that capture fatigue crack growth rates in hydrogen and account for load ratio (*R*)?

- Assume two independent regimes, each with a relationship of the form:

$$\frac{da}{dN} = C_R \Delta K^m$$

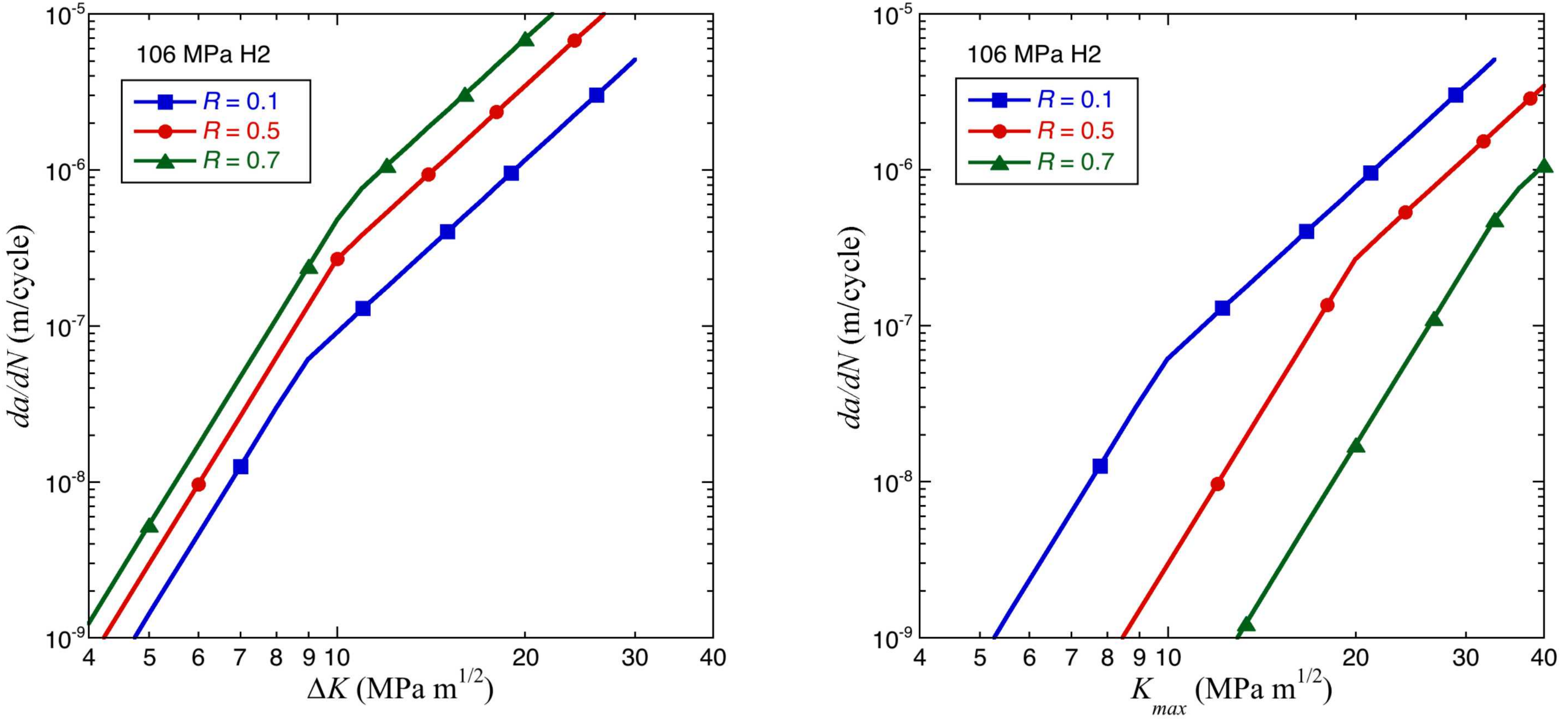
  where C_R is function of *R* and *m* is a constant
- For each ΔK regime and *R*, determine C_R and *m* from power law curve fits
  - Determine best *m* value and adjust C_R to capture data
- Determine common functional form for C_R = f(*R*) in both regimes

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

	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

Relatively simple master curve provides fatigue crack growth estimates as function of ΔK and R

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

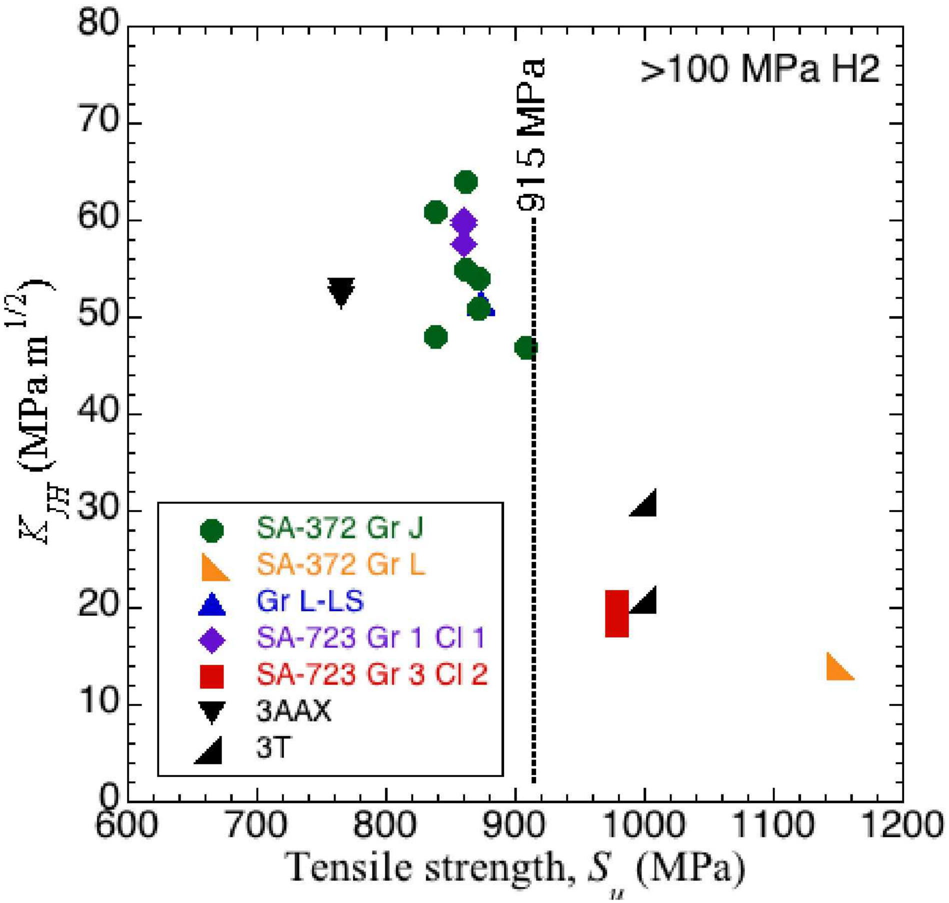


Pressure vessel steels tested at Sandia in gaseous H2 at pressure of ≥103 MPa (15 ksi)

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)

Fracture resistance in gaseous hydrogen is low for high strength PV steels

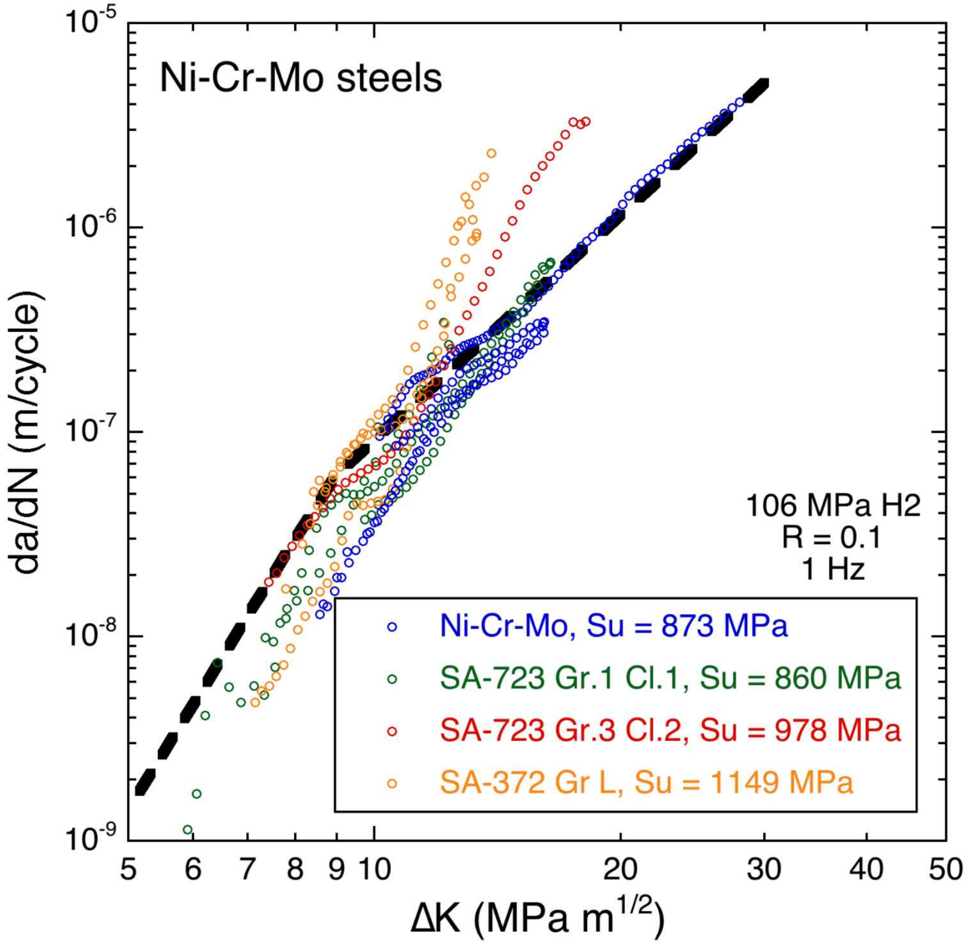


PV steels display low resistance to hydrogen-assisted fracture in high strength condition

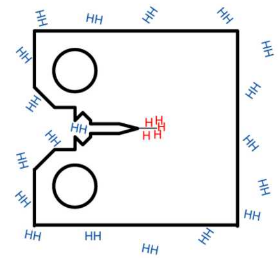
- **For tensile strength < 915 MPa**
  - $K_{JH} > 45$ MPa m$^{1/2}$
- **For tensile strength > 975 MPa**
  - $K_{JH} < 20$ MPa m$^{1/2}$

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

Fatigue crack growth rates of Ni-Cr-Mo steels in 106 MPa H2 and *R* = 0.1

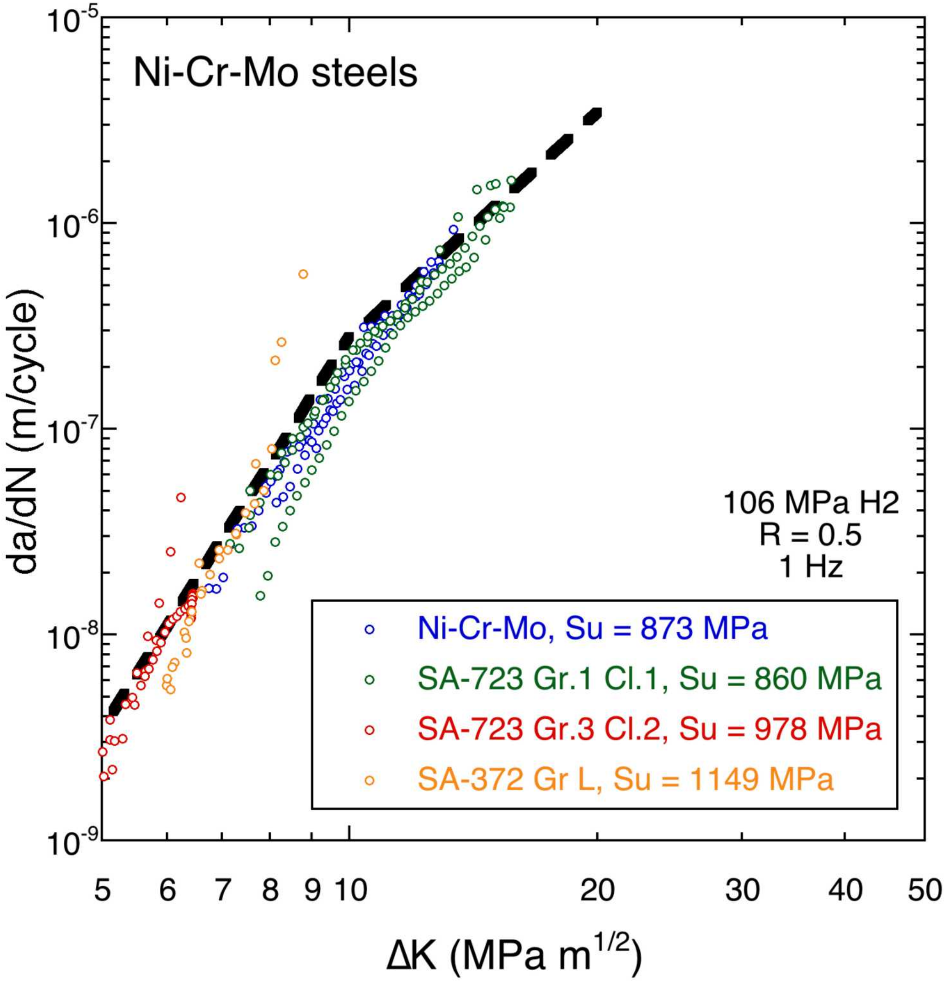


- **Data for different materials are consistent, except for high-strength alloys**
- **Dotted lines represent *master curve***
  - **At ΔK ~ 12 MPa $m^{1/2}$, $K_{max} \rightarrow K_{JH}$ for the high-strength alloys**



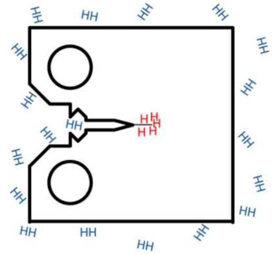
Data from ICHS 2017

Fatigue crack growth rates of Ni-Cr-Mo steels in 106 MPa H2 and *R* = 0.5

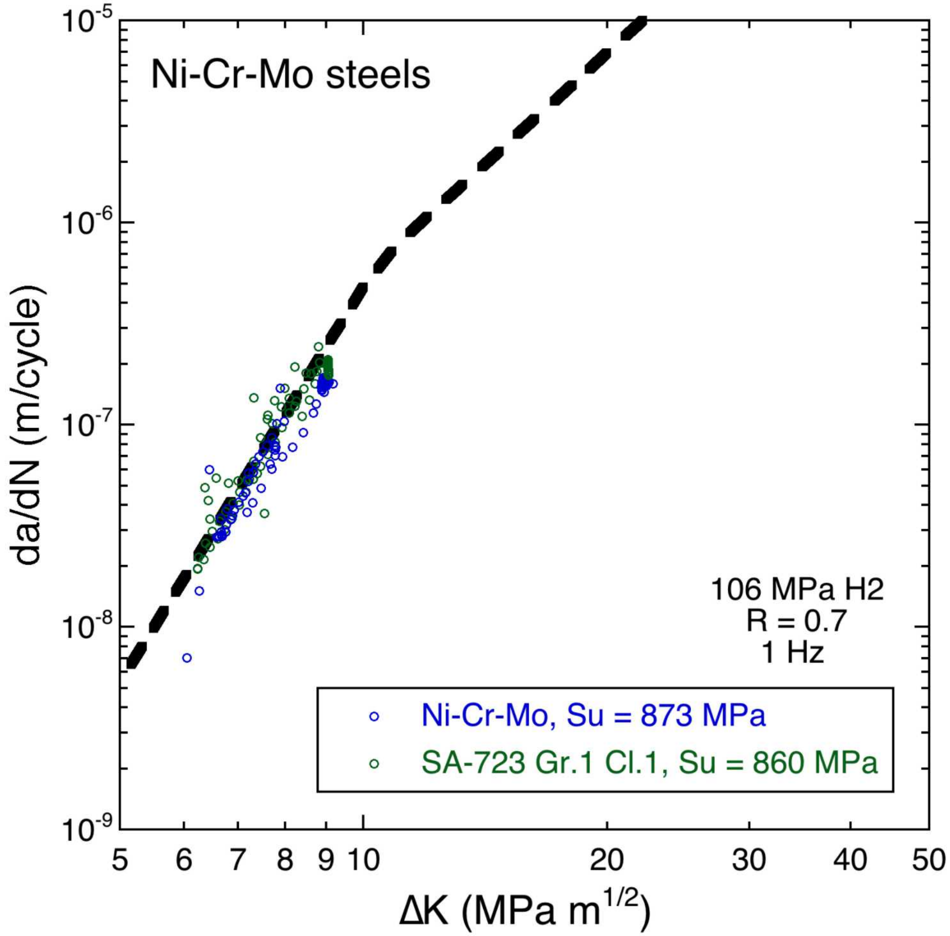


- **Data for different materials are consistent, except for high-strength alloys**
- **Dotted lines represent *master curve***
  - **At ΔK ~ 6 MPa $m^{1/2}$, $K_{max} \rightarrow K_{JH}$ for the high-strength alloys**

Data from ICHS 2017



Fatigue crack growth rates of Ni-Cr-Mo steels in 106 MPa H2 and *R* = 0.7



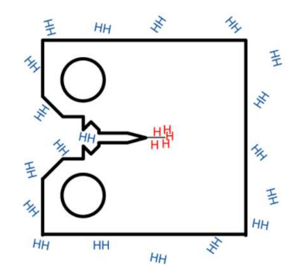
- **Data are consistent for low-strength alloys**
  - **High-strength alloys were not evaluated at *R* = 0.7**

For reference:

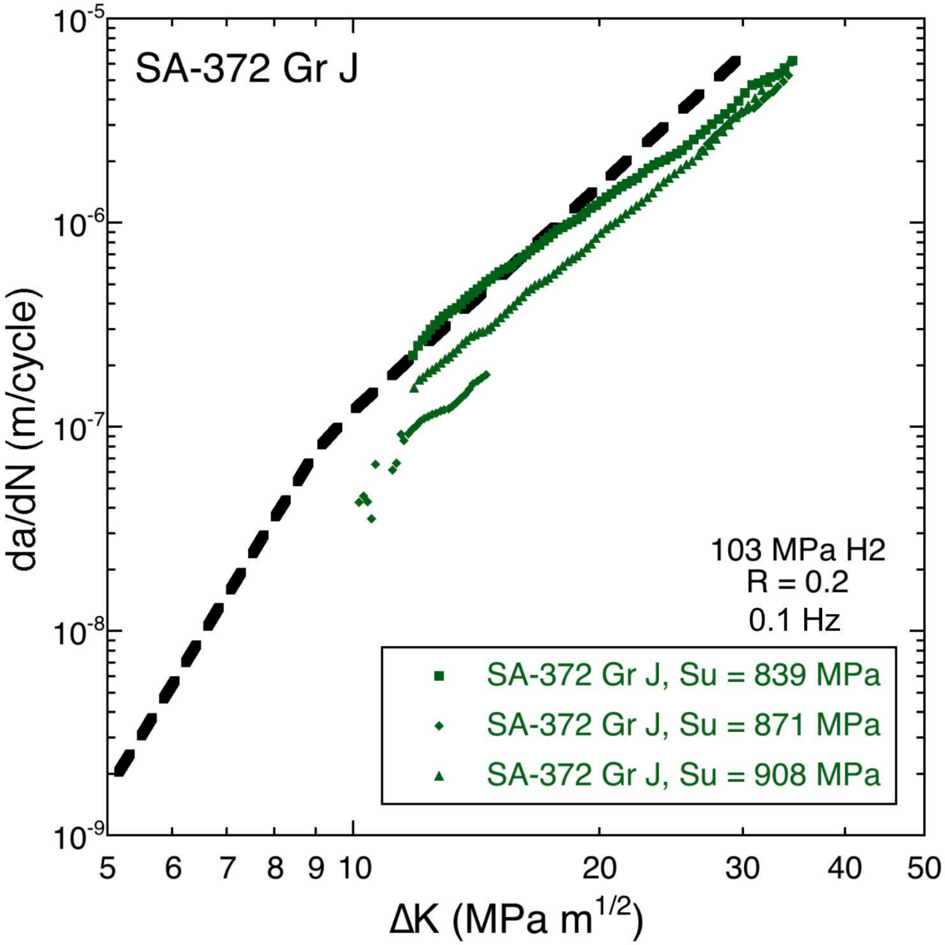
$R = 0.7$ & $\Delta K = 10$ MPa m$^{1/2}$

$K_{max} = 33.3$ MPa m$^{1/2}$

Data from ICHS 2017

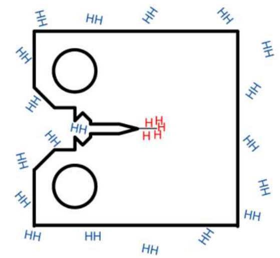


Fatigue crack growth rates of SA-372 Grade J in 103 MPa H2 and *R* = 0.2

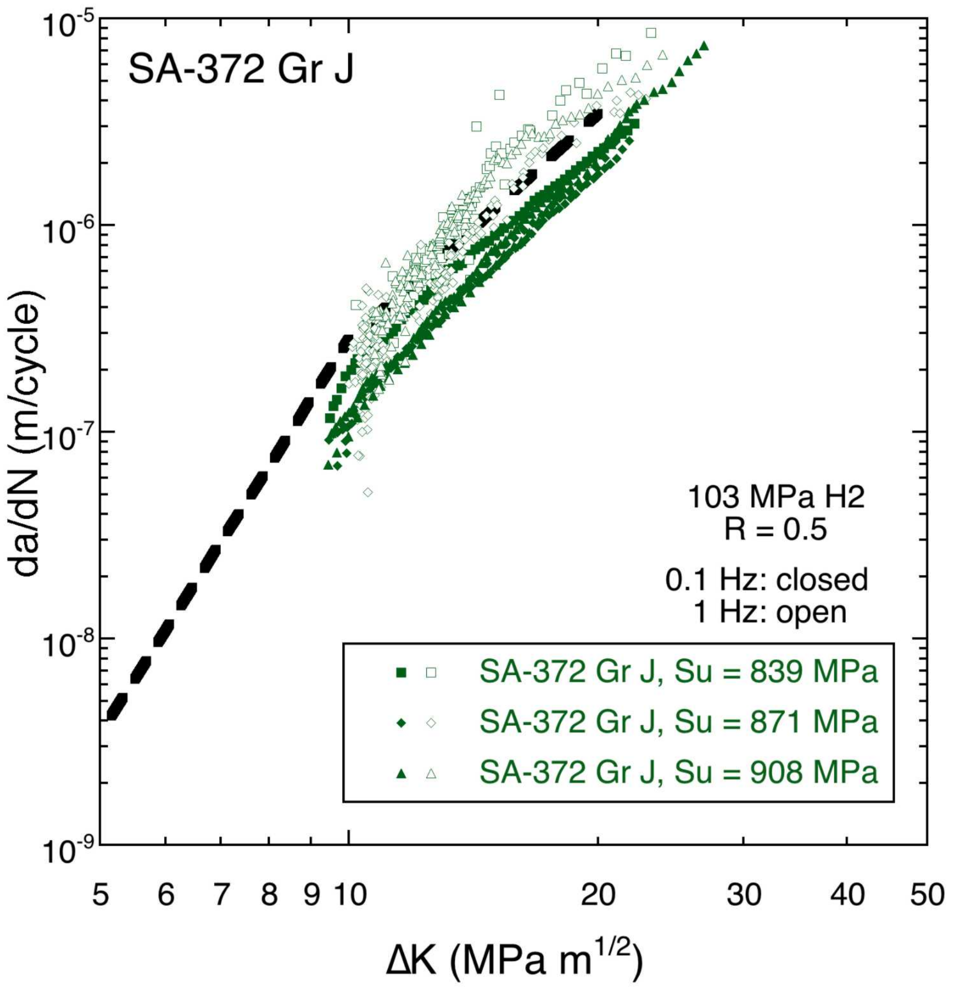


- **Data is relatively consistent for tested alloys**
- **Dotted lines represent *master curve***

Data from PVP2013-97455

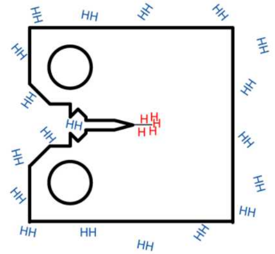


Fatigue crack growth rates of SA-372 Grade J in 103 MPa H2 and *R* = 0.5

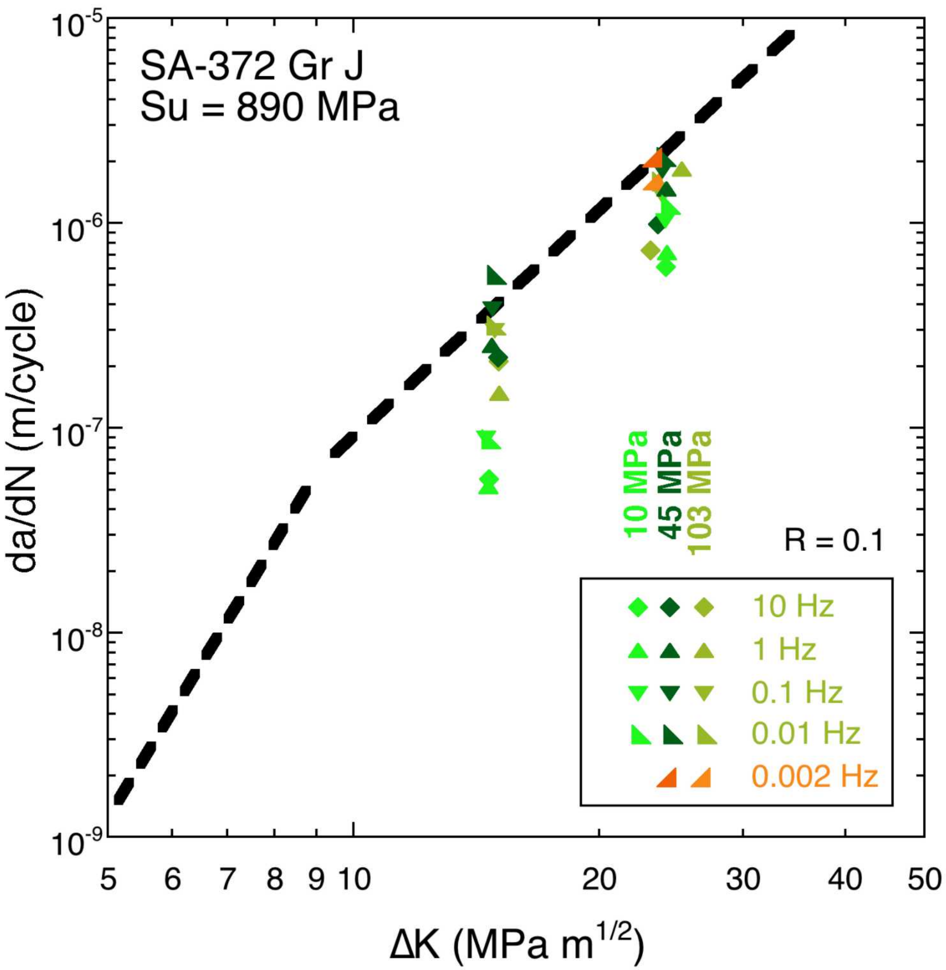


- **Data is relatively consistent for tested alloys**
- **Dotted lines represent *master curve***

Data from ICHS 2009

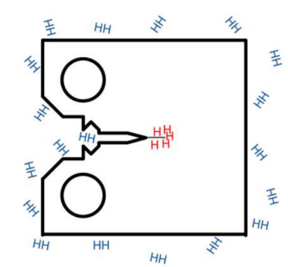


Fatigue crack growth rates of SA-372 Grade J for range of pressure and frequency with *R* = 0.1

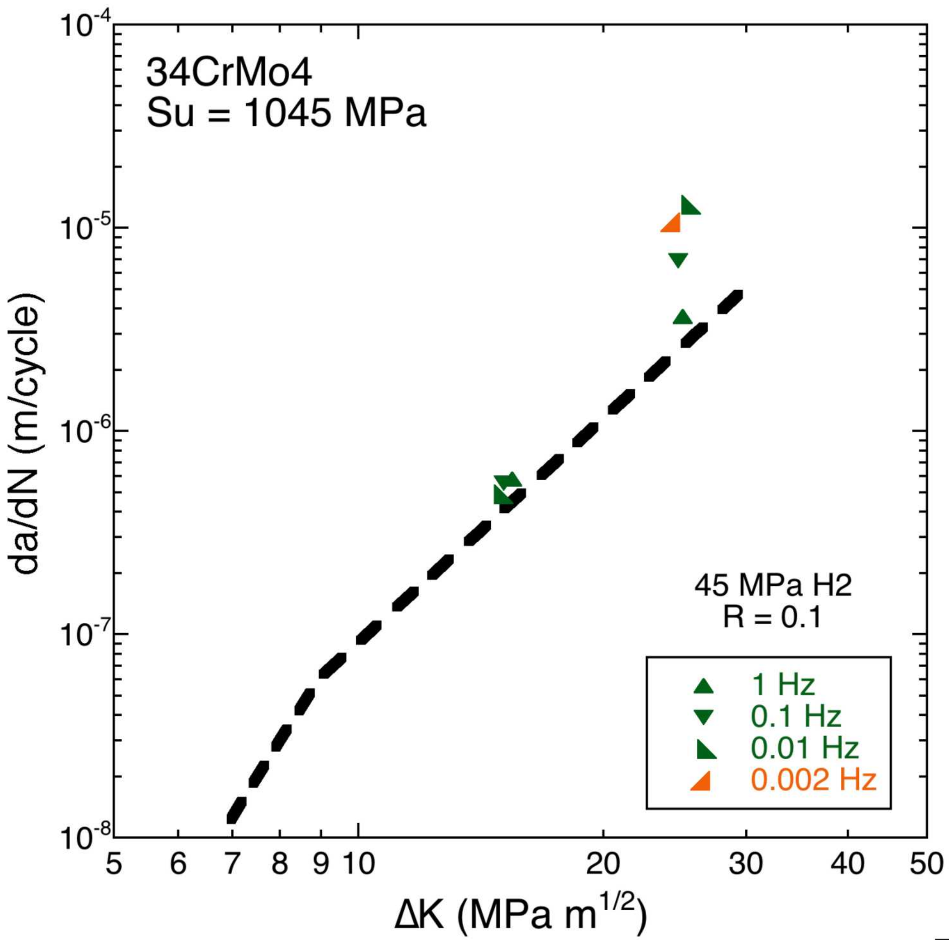


- **Master curve (dotted line) bounds the data for pressure up to 100 MPa and frequency as low 0.002 Hz**

Data from PVP2015-45424



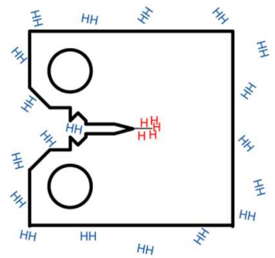
Fatigue crack growth rates of 34CrMo4 steel with tensile strength of 1045 MPa



Note: da/dN axis is different from other plots

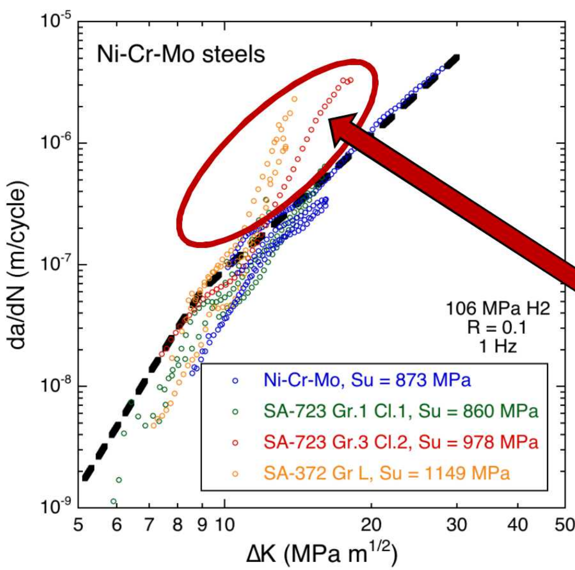
- Master curve (dotted line) approximately bounds the data for low ΔK = 15 MPa m$^{1/2}$
- K_{max} is likely greater than fracture resistance (K_{JH}) at high ΔK = 25 MPa m$^{1/2}$

Data from PVP2015-45424



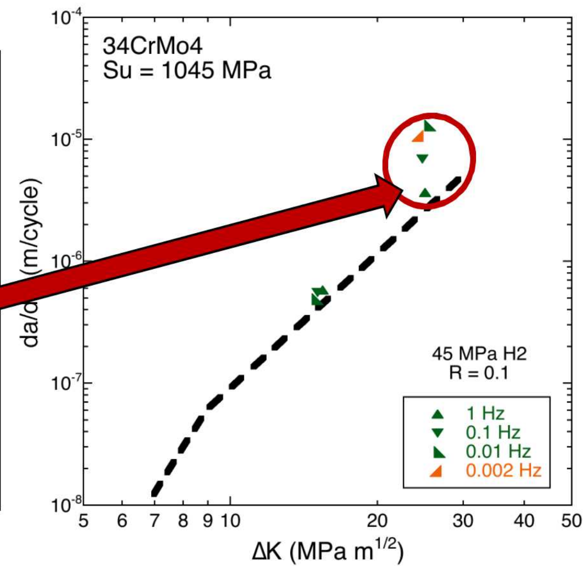
Fracture resistance is basis for limiting strength

- **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 > 915 MPa**
  - **Related to fracture resistance: fatigue crack growth exceeds master curve as $K_{max} \rightarrow K_{JH}$**



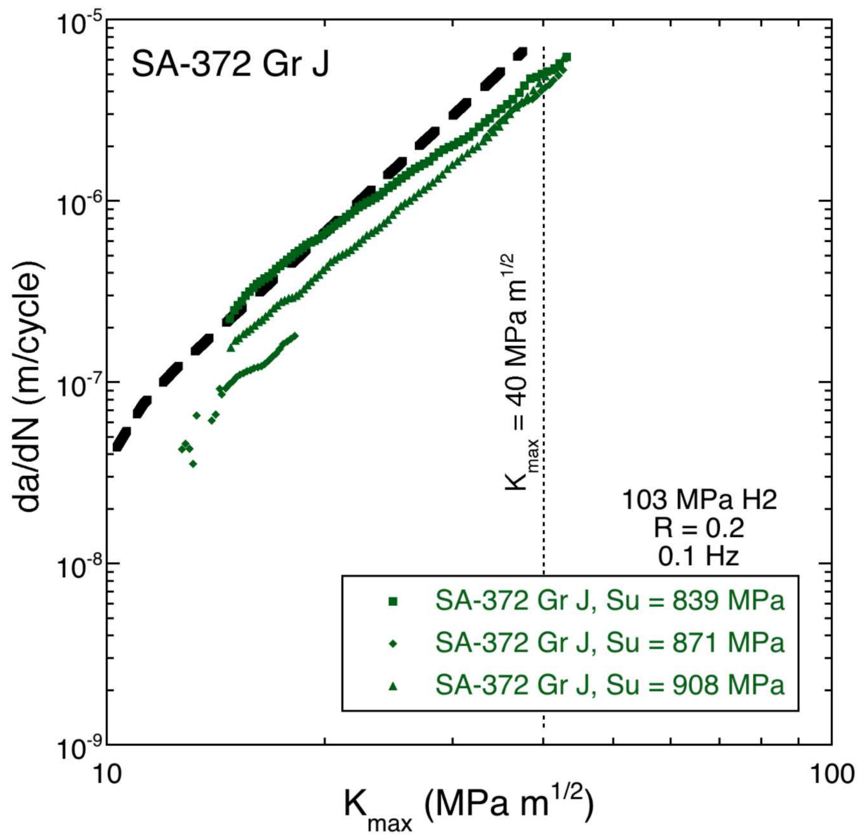
For PV steels with Su > 915 MPa

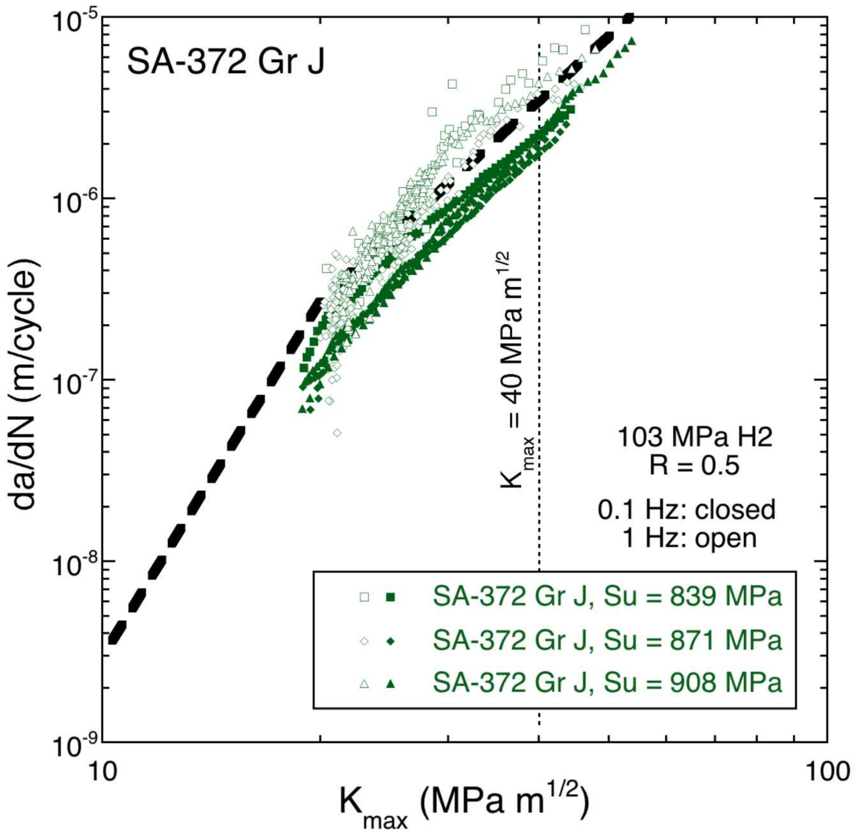
- Fatigue crack growth rate exceeds master curve when ΔK is large
- Associated with K_{JH} < 20 MPa $m^{1/2}$



Basis for limiting K_{max}

- No evidence of transition to stage III for K_{max} up to 40 MPa $m^{1/2}$ in SA-372 Gr J steels
- For steels shown below:
  - Measured K_{JH} values in 103 MPa H2 are within the range of 47-61 MPa $m^{1/2}$ (5 measurements)



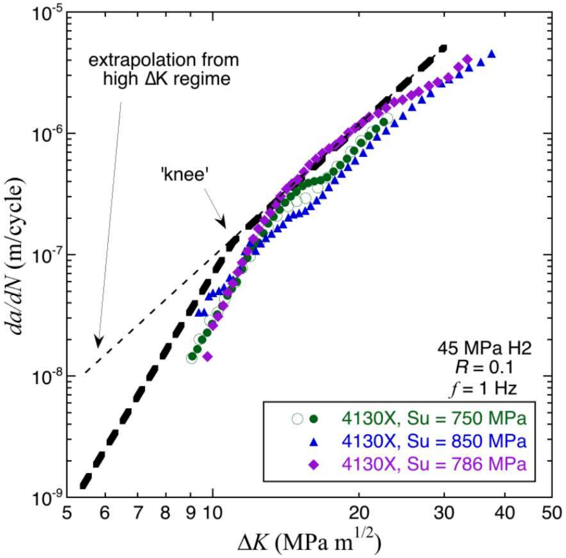


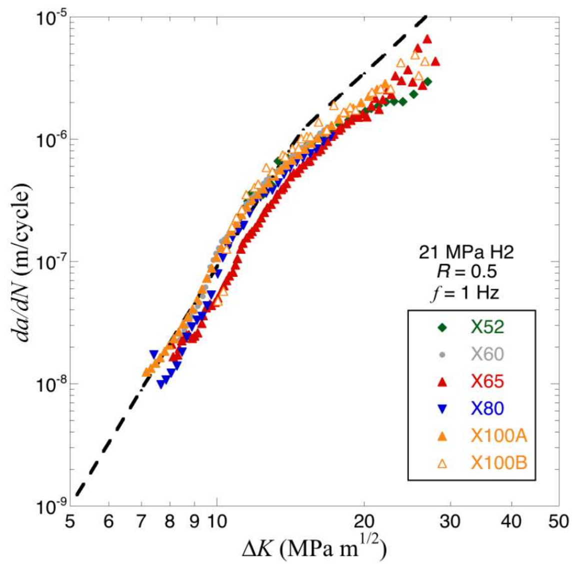
Master curve can also be adjusted for pressure

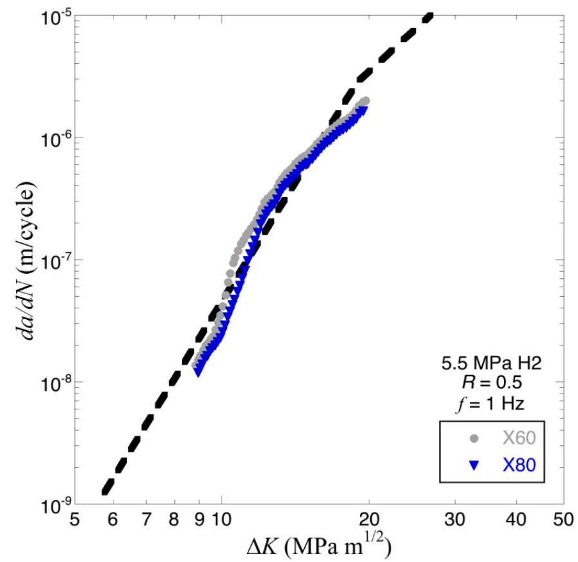
- **Consider the hydrogen effect as proportional to the equilibrium hydrogen concentration**
  - **concentration is proportional to square root of fugacity**

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

  - **However, empirically, the high-ΔK regime appears to be independent of pressure**



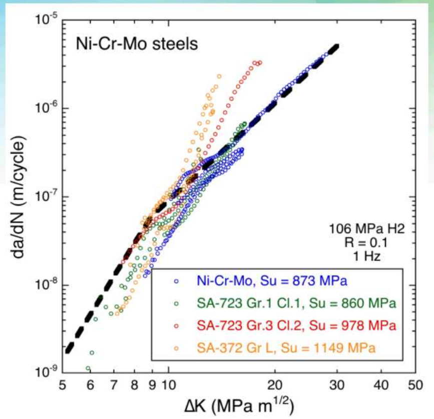




Master curve also applies to carbon steels (eg, pipeline steel)

Summary

- **Review of fatigue crack growth rate for PV steels generally shows consistency of fatigue response independent of alloy and strength**
  - ***Exception*: tensile strength > 915 MPa shows transition to stage III crack growth at low K_{max} (i.e., as $K_{max} \rightarrow K_{JH}$)**



- **Two-part power law was established to bound fatigue crack growth behavior as a function of load ratio, *R***

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

- **Limits on use of master curve:**
  - **Tensile strength < 915 MPa**
  - **$K_{max} \leq 40$ MPa m$^{1/2}$**
- **Pressure effect can also be taken into account (but is not considered in CC2938)**