SAND2018-1098PE

# Basis of FCGR laws for fatigue crack growth of PV steels in gaseous hydrogen

ASME Code Week

Las Vegas, NV, February 2018

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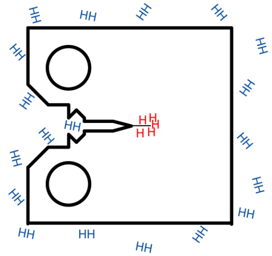
# Outline

- Materials
- Specimen size and ASTM E647 validity
- Environmental variables (pressure and purity)
- Fatigue crack growth data
- Test frequency
- Formulation of proposed FCGR laws
- Basis of constraints
  - Limits on strength
  - Limits on $K_{max}$ range (or $\Delta K$)

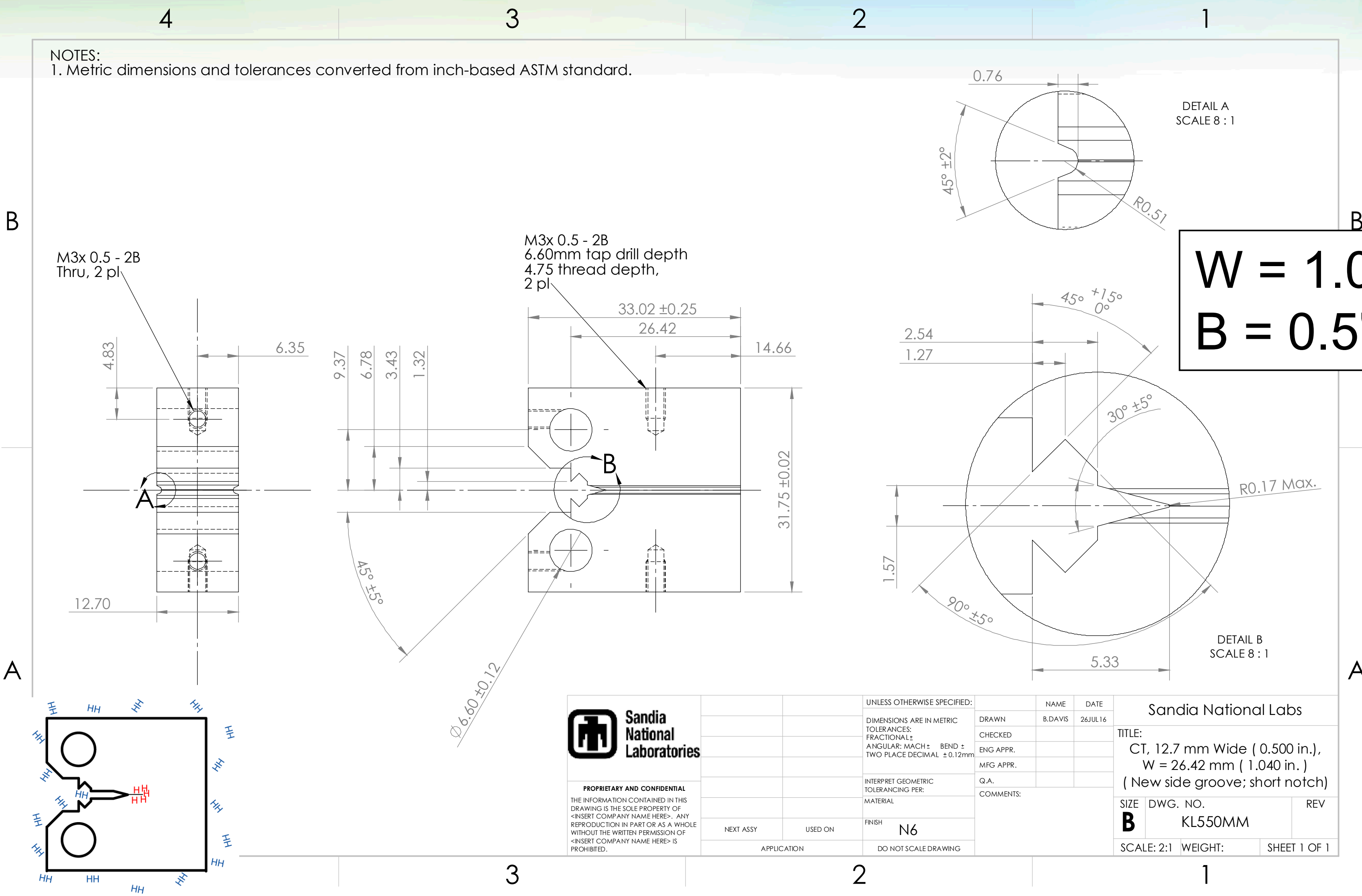


# Pressure vessel steels fatigue tested at Sandia in gaseous H2 at pressure of ≥103 MPa (15 ksi)

| 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)**

# Testing geometry – Compact Tension (CT)




W = 1.04"
B = 0.5"

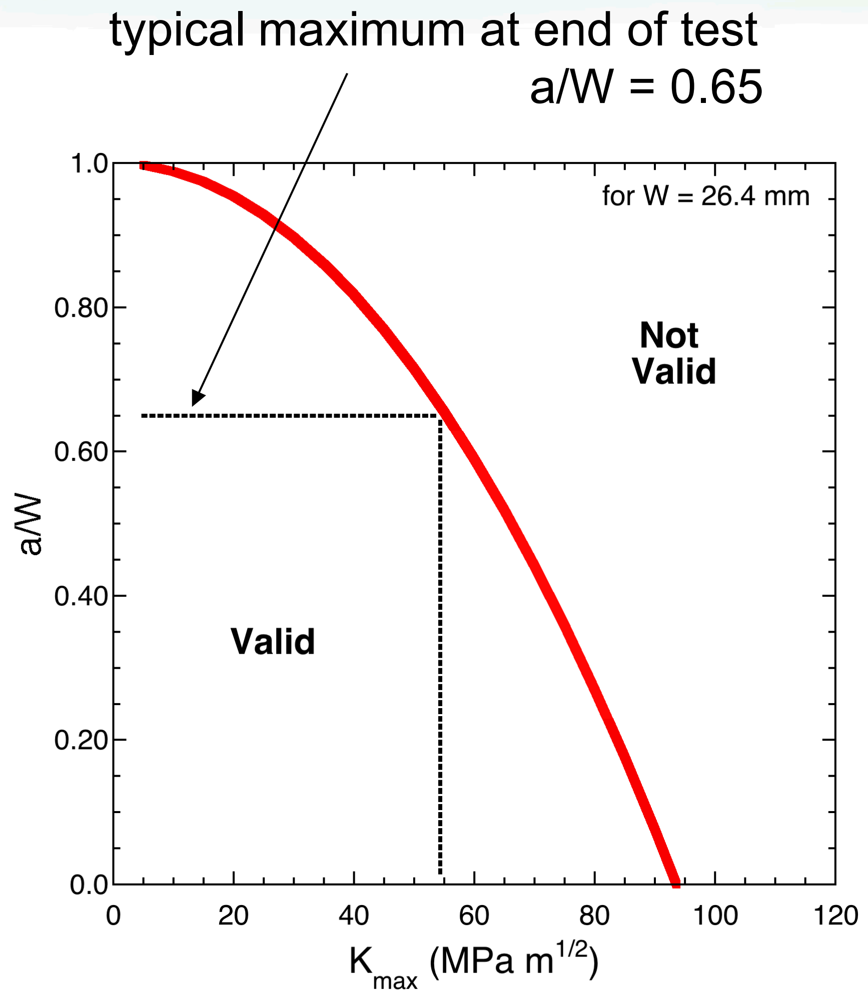
# ASTM E647 testing validity

## For testing at Sandia

- 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 SNL data
  - May not be true of other data at high load ratio (R > 0.5)



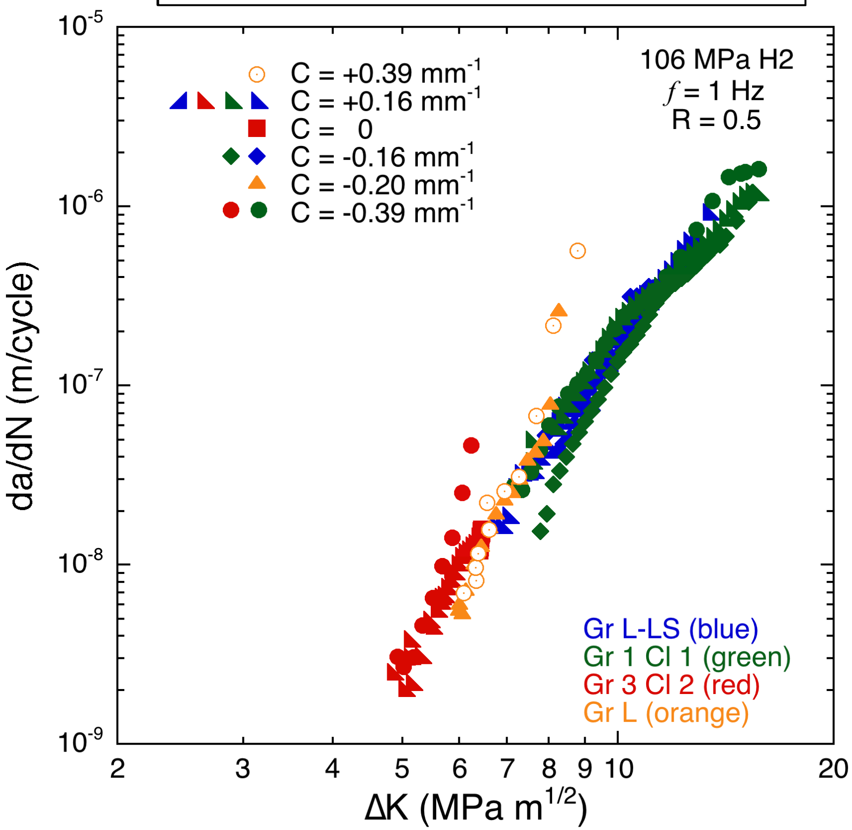
# ASTM E647 testing validity

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

$$C = \left(\frac{1}{K}\right)\left(\frac{dK}{da}\right)$$

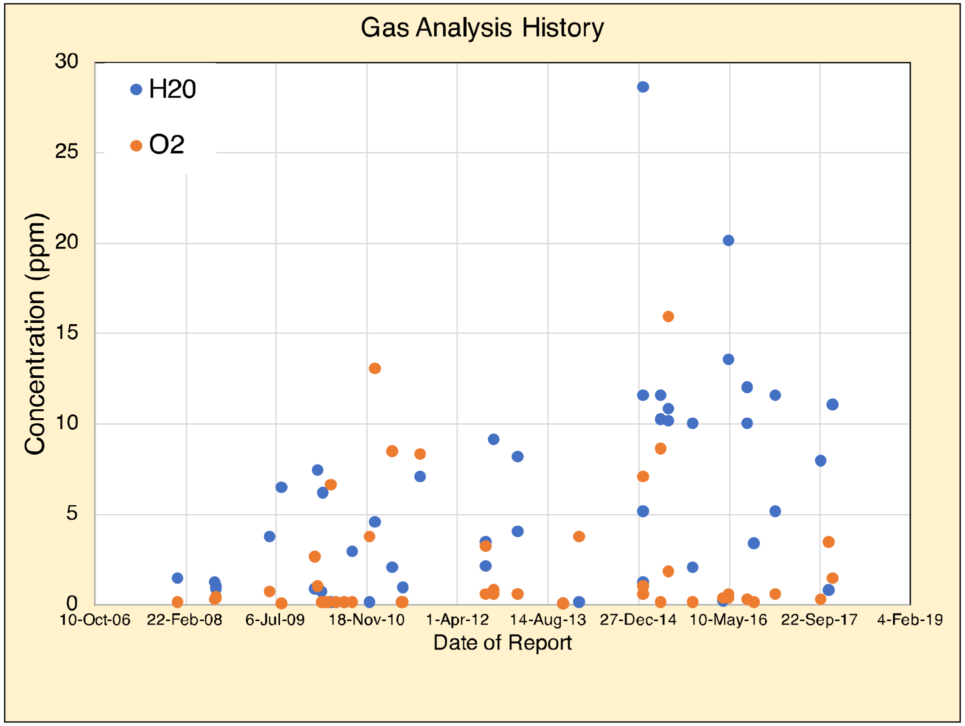
- No dependence on the K-gradient has been observed in any testing
  - K-gradient varied in the range of +/- 0.39 $mm^{-1}$ for several values of R
  - Data generally acquired at $\Delta a$ sufficient to obtain >5 data points per decade of da/dN
  - Consistent data for both K-increasing and K-decreasing

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



# Environmental variables

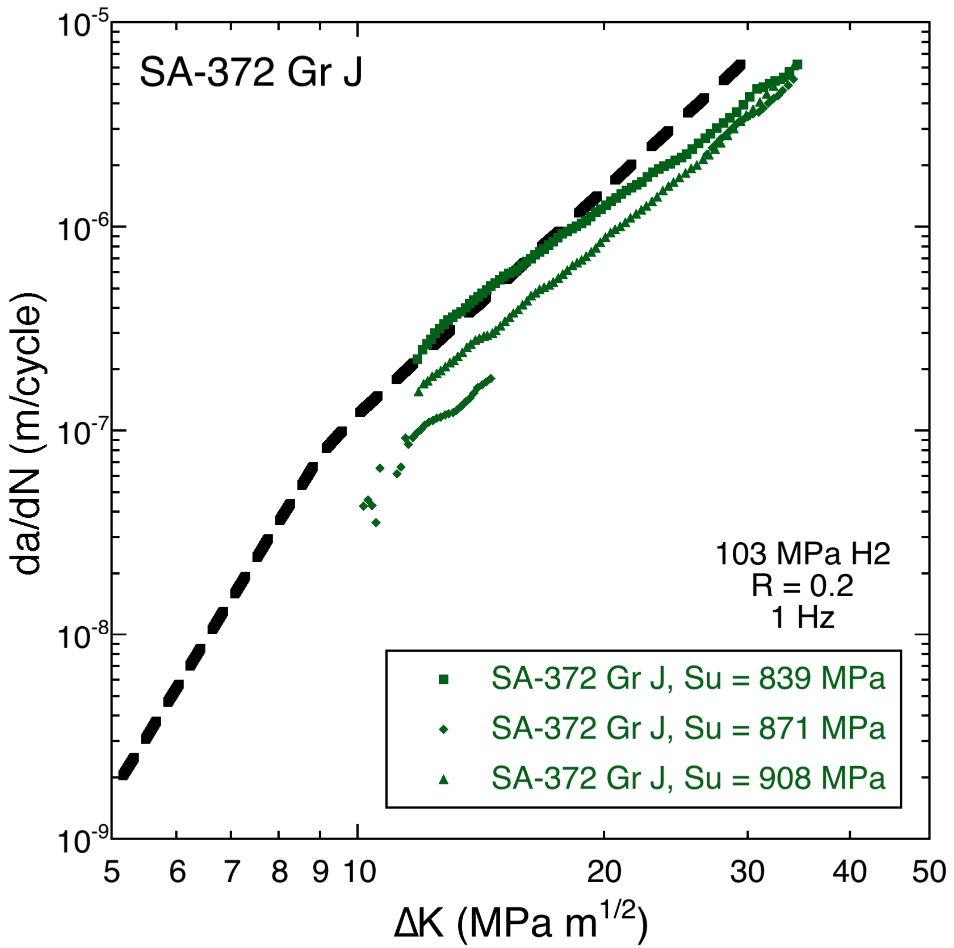
- System pressure is actively maintained at the quoted test pressure (+4% -0%)
- Test temperature is maintained at 22 ±1˚C
- Source gas is research grade hydrogen (99.9999% – 6Ns)



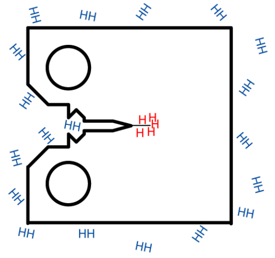

- Analysis is conducted periodically, not every test
- Oxygen content is typically <2 ppm
- Water content is typically <10 ppm
- In some cases, higher content is observed

Data shown for every test of ~10 year period; and includes testing of many types materials

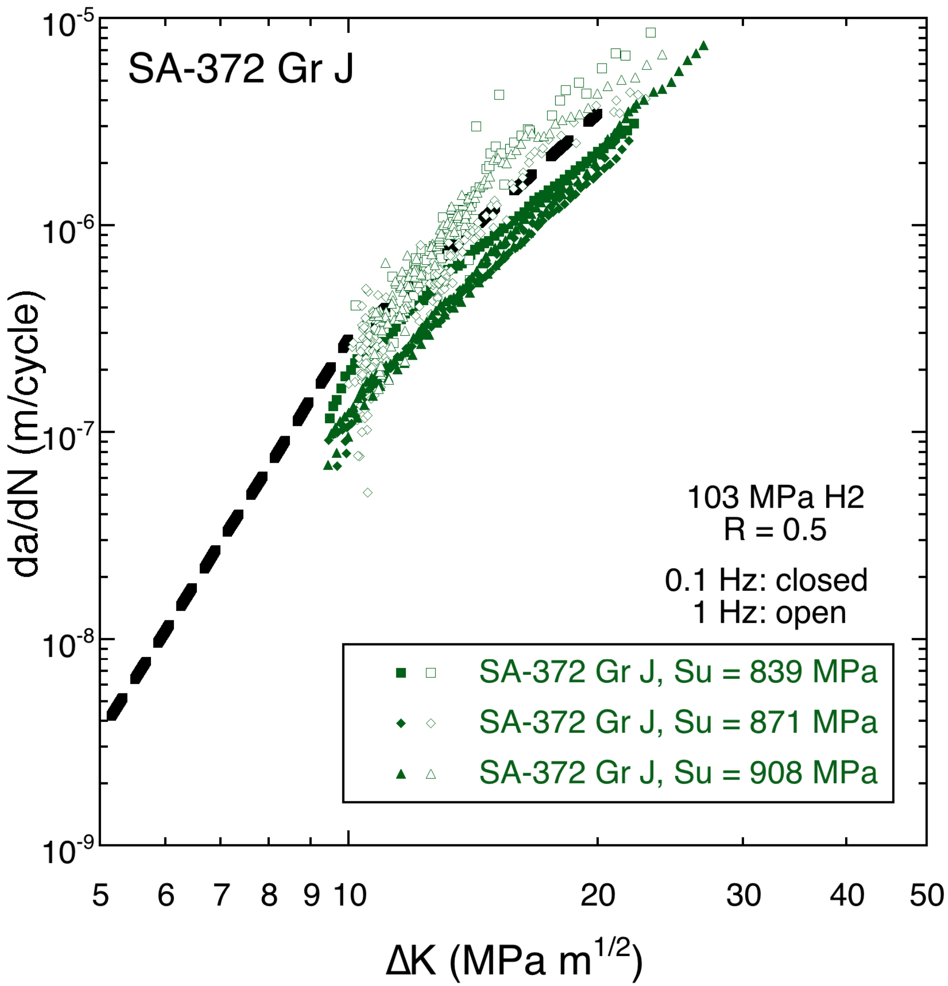
# Fatigue crack growth rates of SA-372 Grade J R=0.2



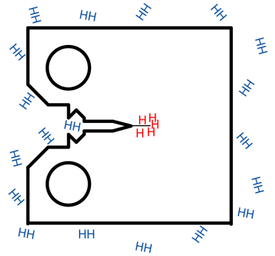

- Gaseous hydrogen at pressure of 103 MPa
- R = 0.2
- 0.1 Hz
- Data from PVP2013-97455



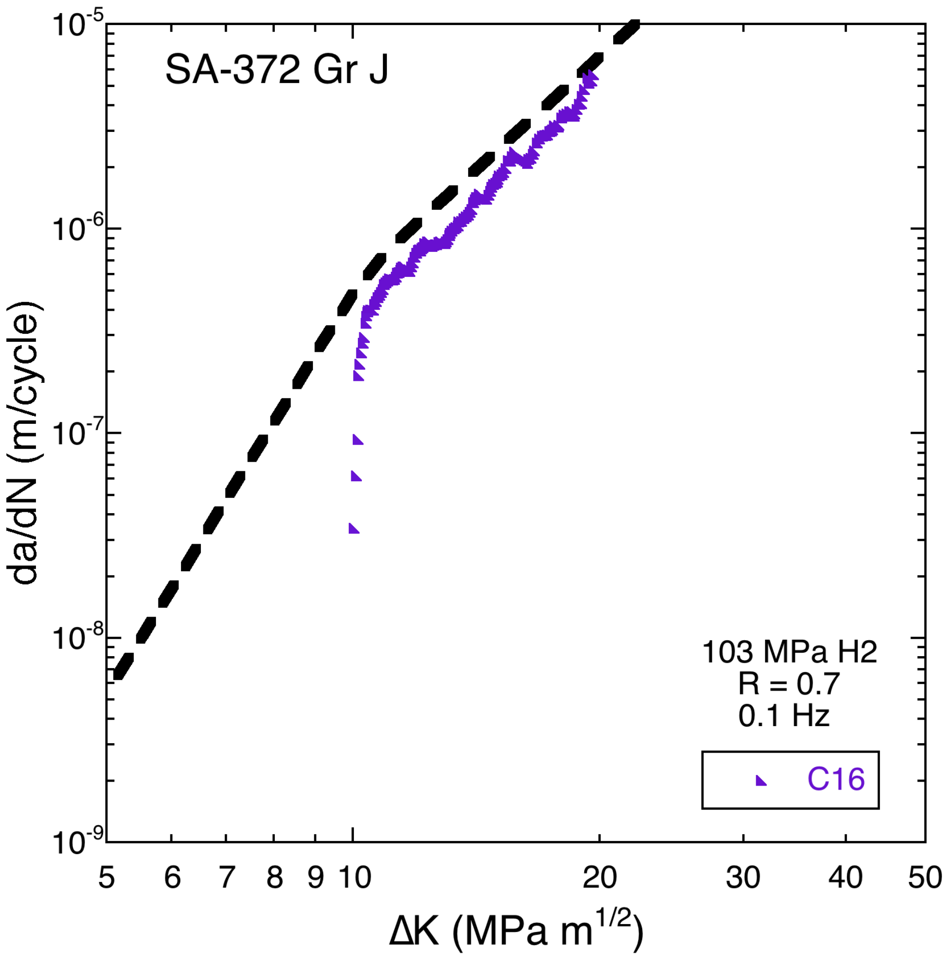
# Fatigue crack growth rates of SA-372 Grade J R=0.5




- Gaseous hydrogen at pressure of 103 MPa
- R = 0.5
- 0.1 Hz data from PVP2013-97455
- 1 Hz data from ICHS 2009



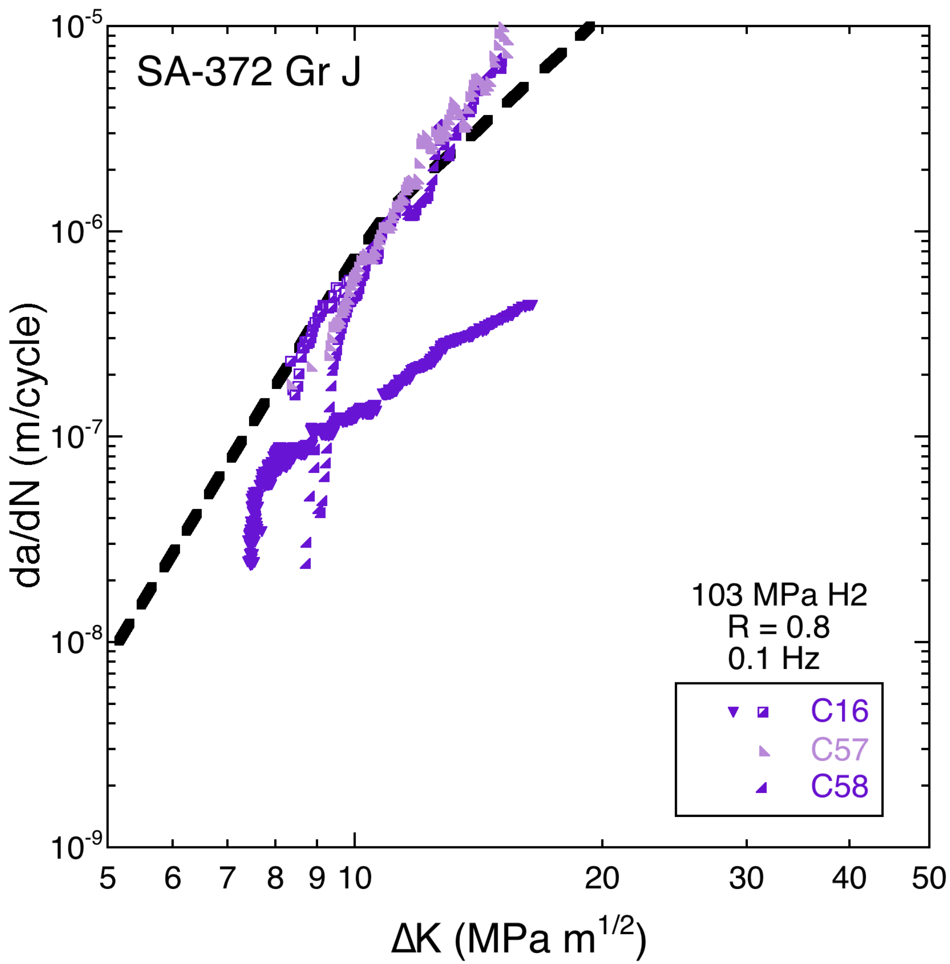
# Fatigue crack growth rates of SA-372 Grade J R=0.7




- Gaseous hydrogen at pressure of 103 MPa
- R = 0.7
- 0.1 Hz
- Data not published?
  - Not from SNL

| Designation | Tensile strength (MPa) | Yield Strength (MPa) |
|---|---|---|
| SA-372 Gr J (C16) | 884 | 711 |
| SA-372 Gr J (C57) | 904 | 787 |
| SA-372 Gr J (C58) | 913 | 764 |

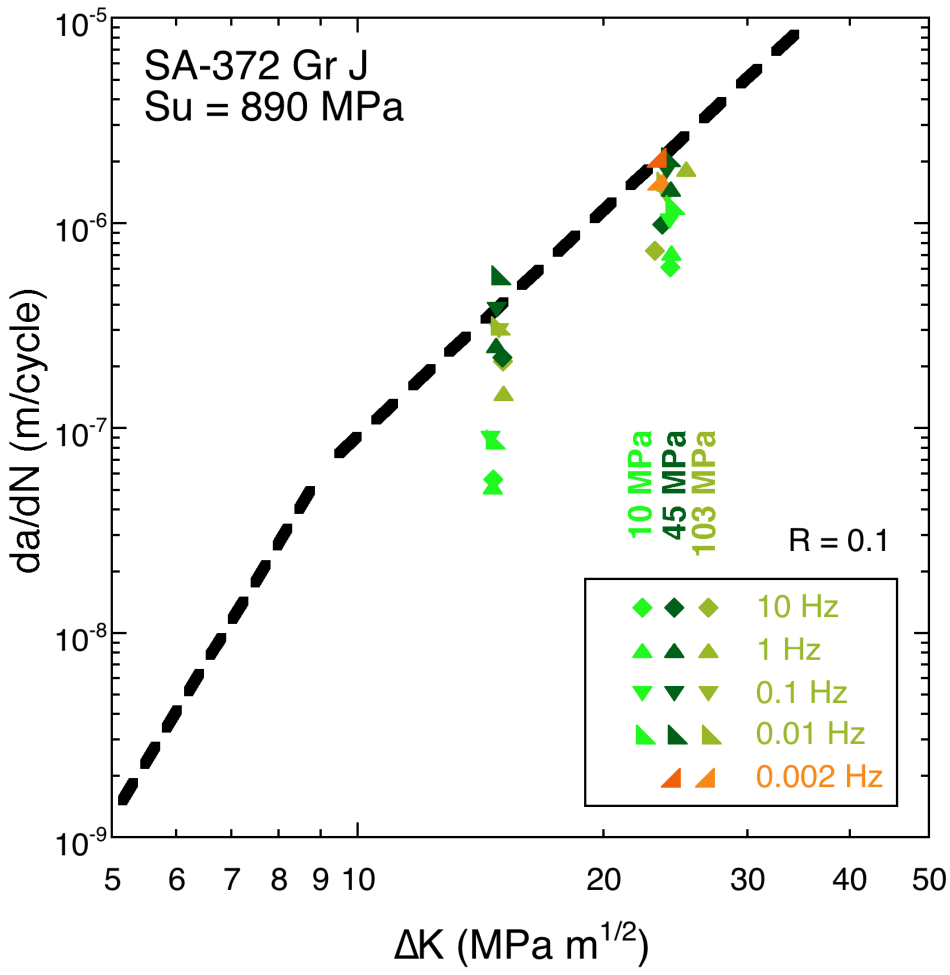
# Fatigue crack growth rates of SA-372 Grade J R=0.8



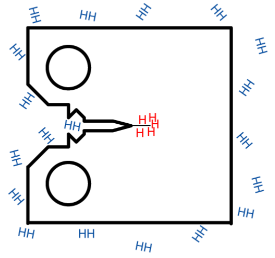

- Gaseous hydrogen at pressure of 103 MPa
- R = 0.8
- 0.1 Hz
- Data not published?
  - Not from SNL

| Designation | Tensile strength (MPa) | Yield Strength (MPa) |
|---|---|---|
| SA-372 Gr J (C16) | 884 | 711 |
| SA-372 Gr J (C57) | 904 | 787 |
| SA-372 Gr J (C58) | 913 | 764 |

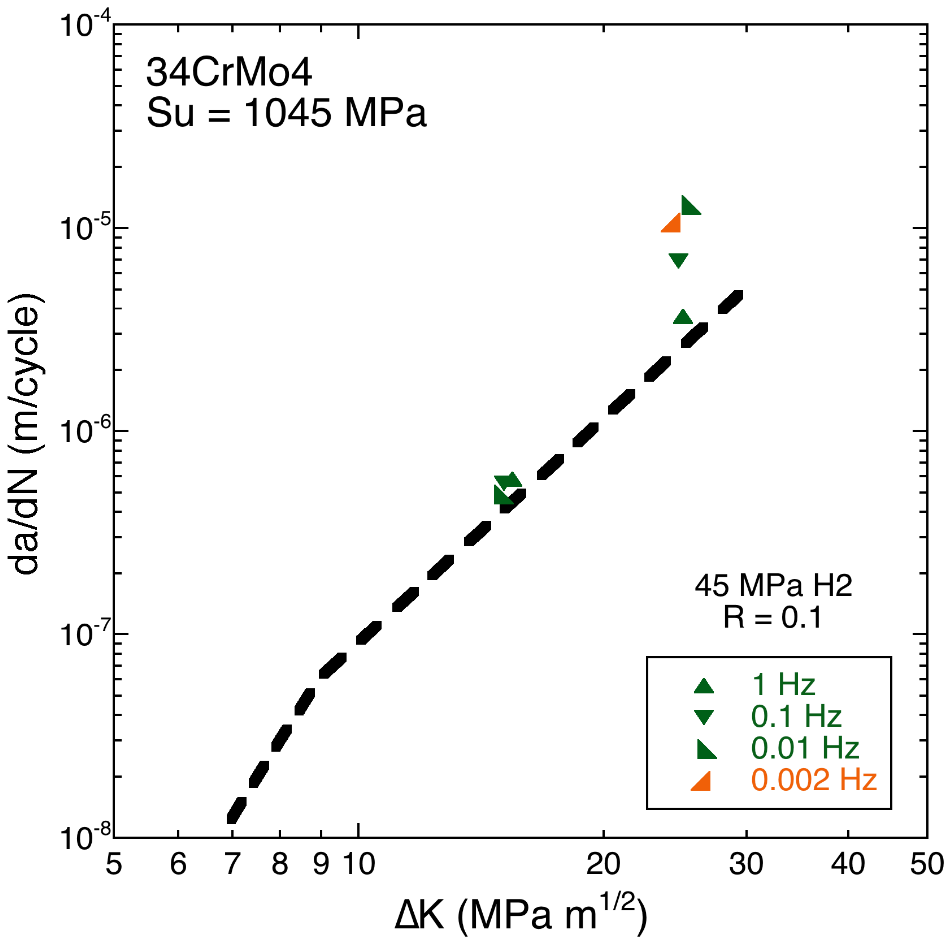
# Fatigue crack growth rates of SA-372 Grade J R = 0.1




- Gaseous hydrogen at pressure between 10 and 100 MPa
- R = 0.1
- Frequency between 0.002 and 10 Hz
- Data from PVP2015-45424

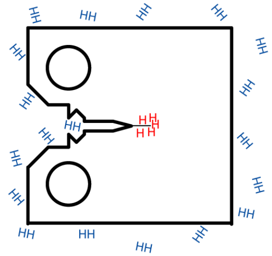


# Fatigue crack growth rates of 34CrMo4 steel R = 0.1

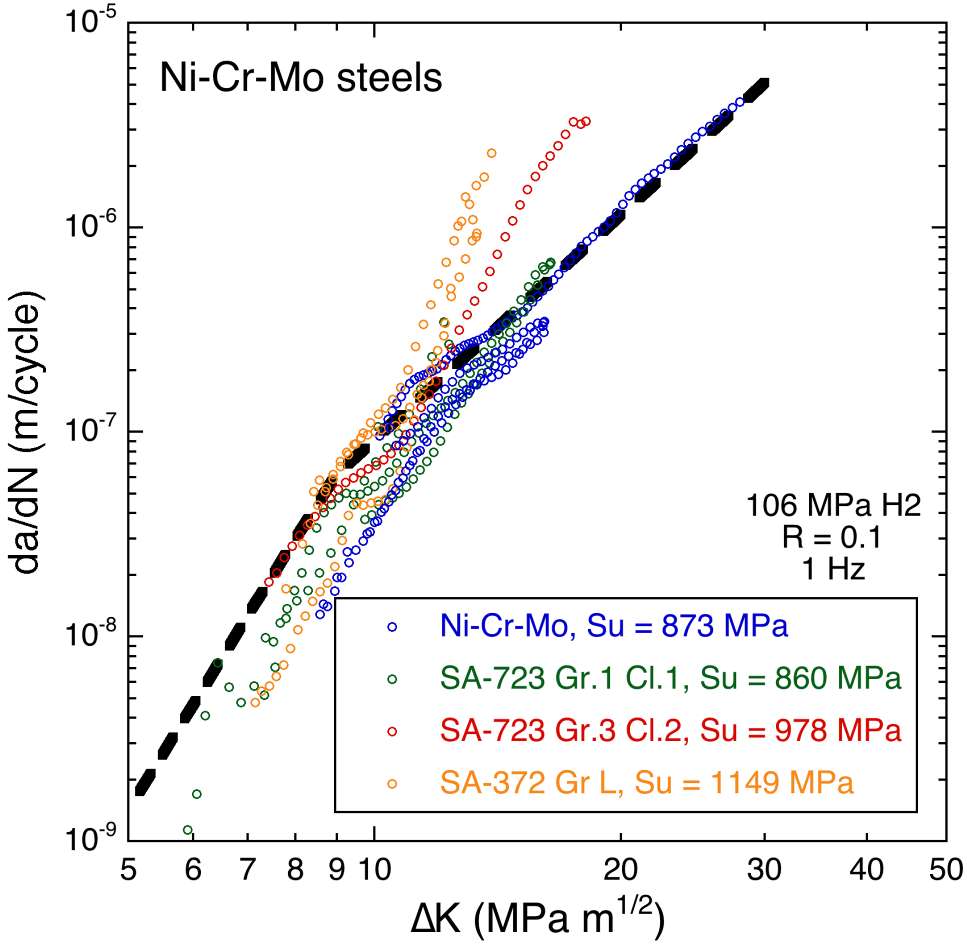



Note: da/dN axis is different from other plots

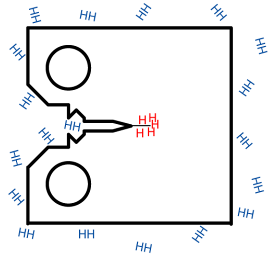
- Su = 1045 MPa
- Gaseous hydrogen at pressure of 45 MPa
- R = 0.1
- Frequency between 0.002 and 10 Hz
- Data from PVP2015-45424



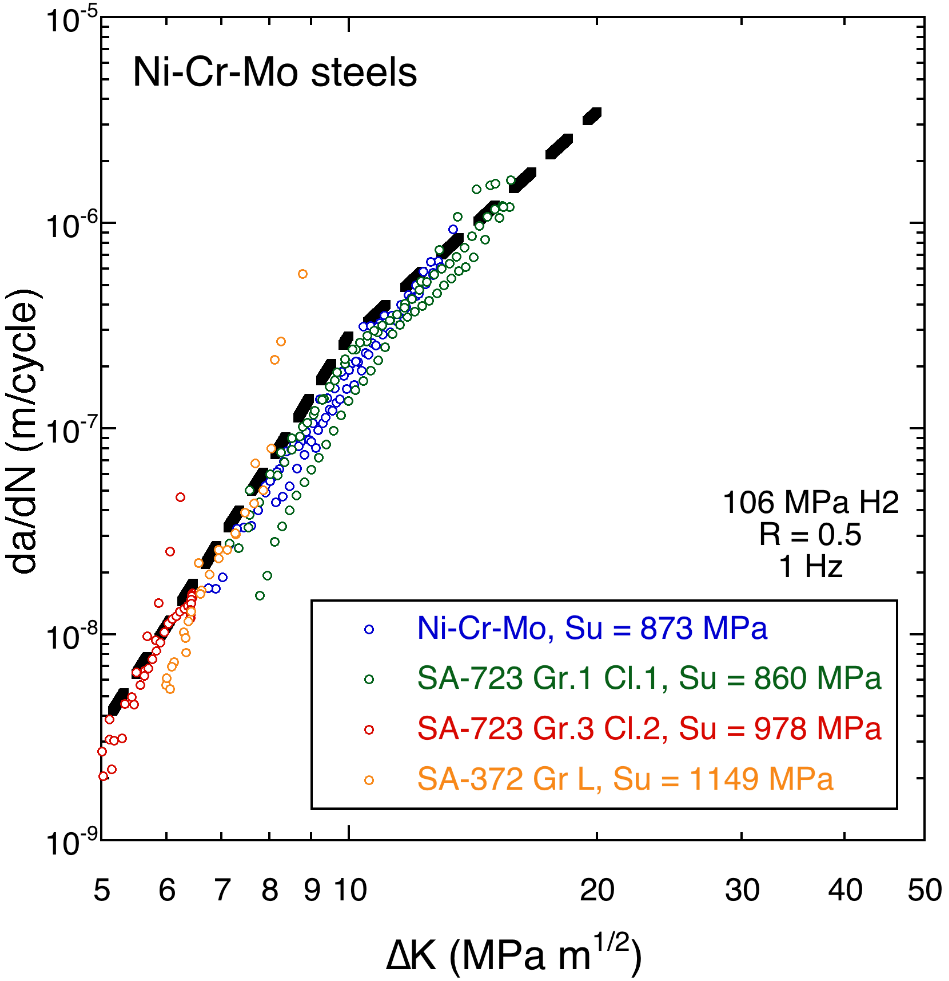
# Fatigue crack growth rates of Ni-Cr-Mo steels R=0.1



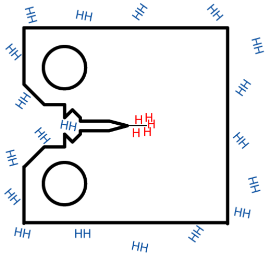

- Gaseous hydrogen at pressure of 106 MPa
- R = 0.1
- Frequency of 1 Hz
- Data from ICHS 2017



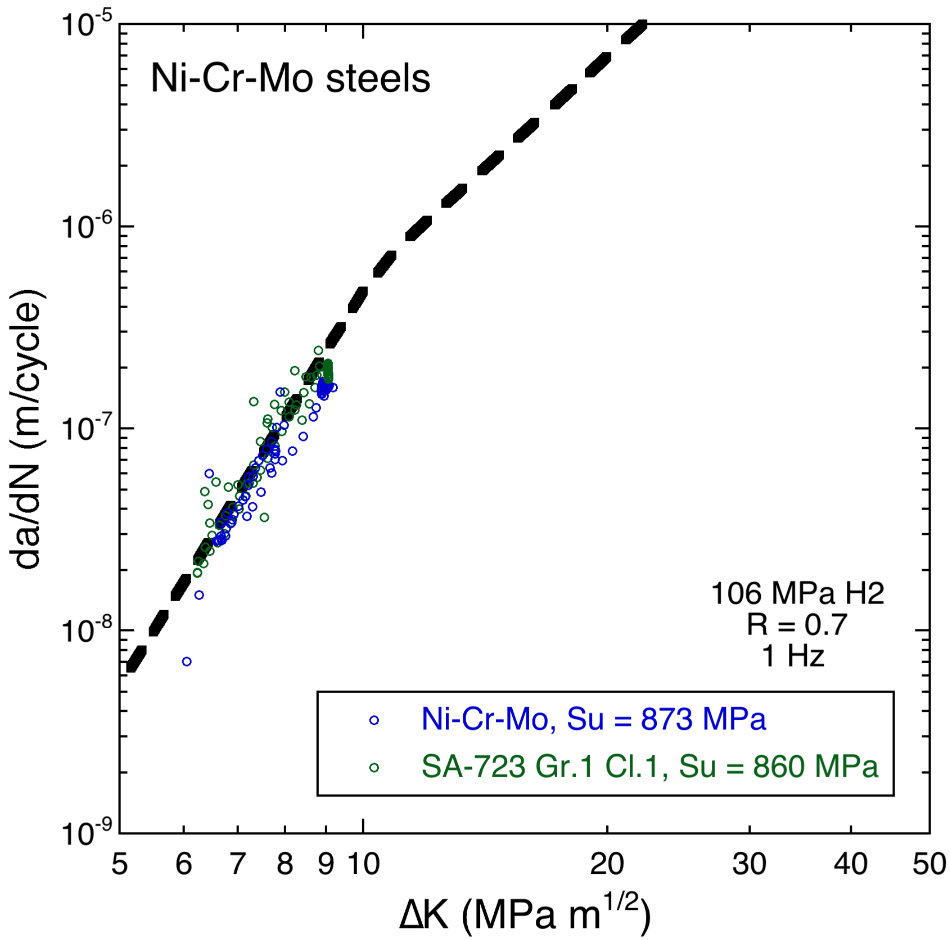
# Fatigue crack growth rates of Ni-Cr-Mo steels R=0.5



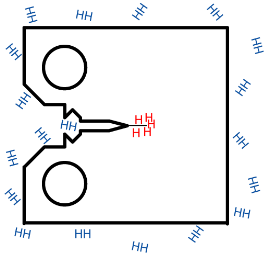

- Gaseous hydrogen at pressure of 106 MPa
- R = 0.5
- Frequency of 1 Hz
- Data from ICHS 2017



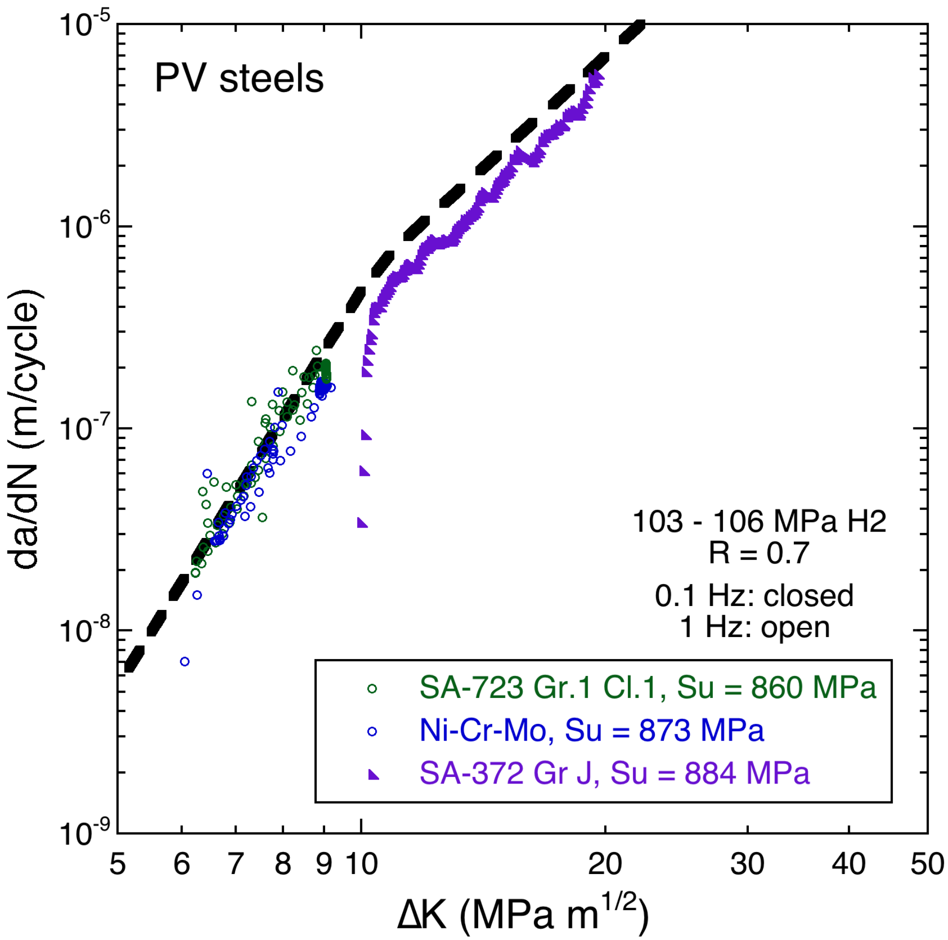
# Fatigue crack growth rates of Ni-Cr-Mo steels R=0.7



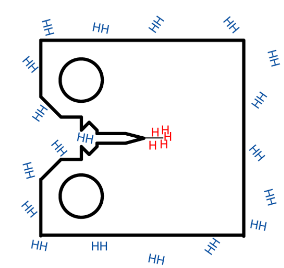

- Gaseous hydrogen at pressure of 106 MPa
- R = 0.7
- Frequency of 1 Hz
- Data from ICHS 2017



# Fatigue crack growth rates at R = 0.7 both Cr-Mo and Ni-Cr-Mo PV steels

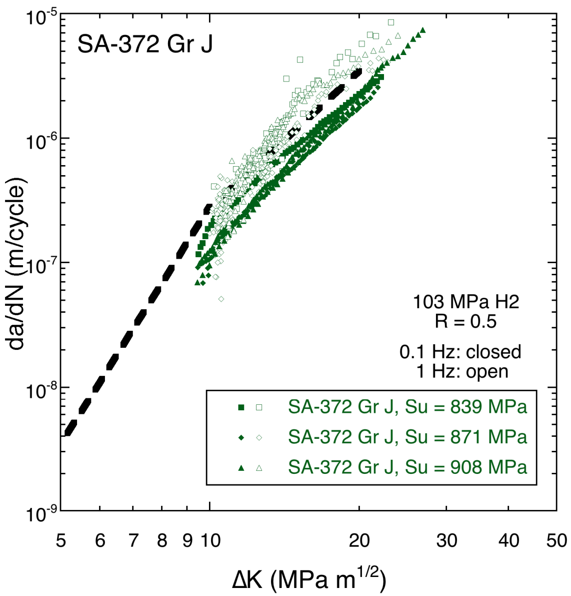


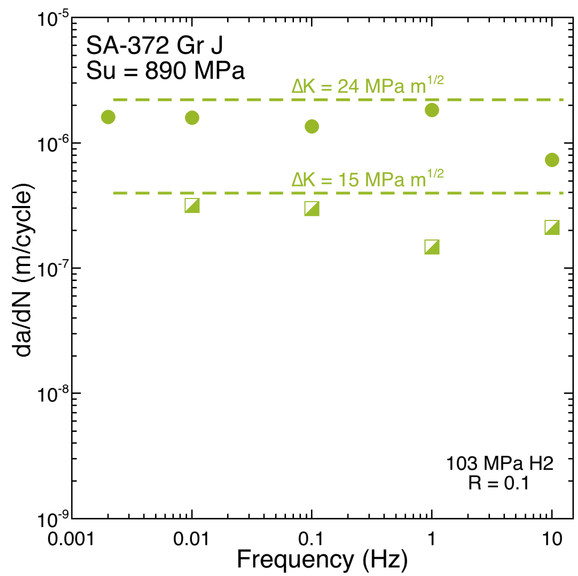

- Gaseous hydrogen
- R = 0.7
- Cr-Mo steel data (0.1 Hz) from NIST (unpublished?)
  - P = 103 MPa
- Ni-Cr-Mo steel data (1 Hz) from ICHS 2017
  - P = 106 MPa

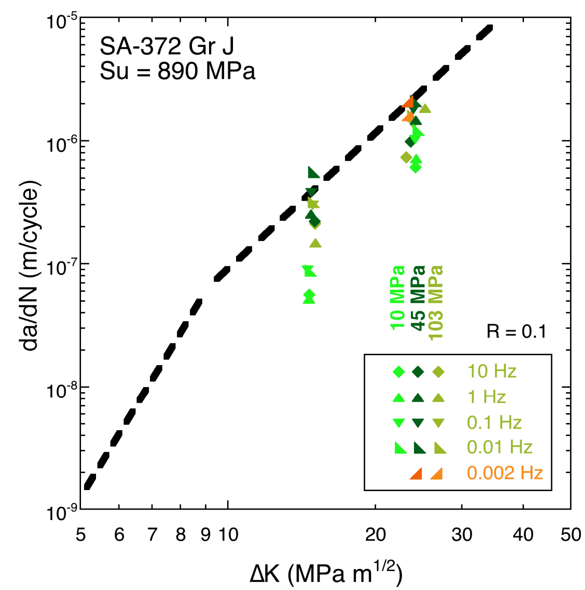


# Test frequency

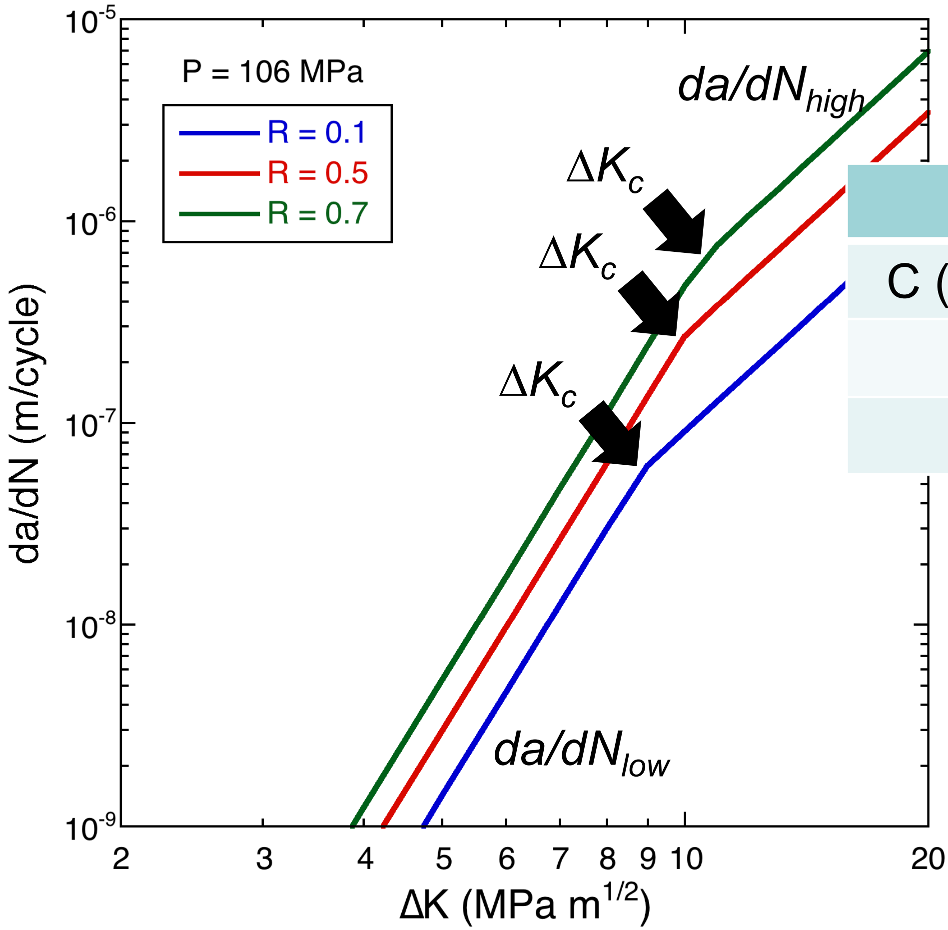
- Frequency in range of ≤ 1 Hz has little, if any, effect on measured fatigue crack growth rates
  - Difference in measured rates with frequency (≤ 1 Hz) is consistent with specimen to specimen variability
  - Dashed lines represent proposed power law relationship



# Formulation of power law relationship for fatigue crack growth




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

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

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

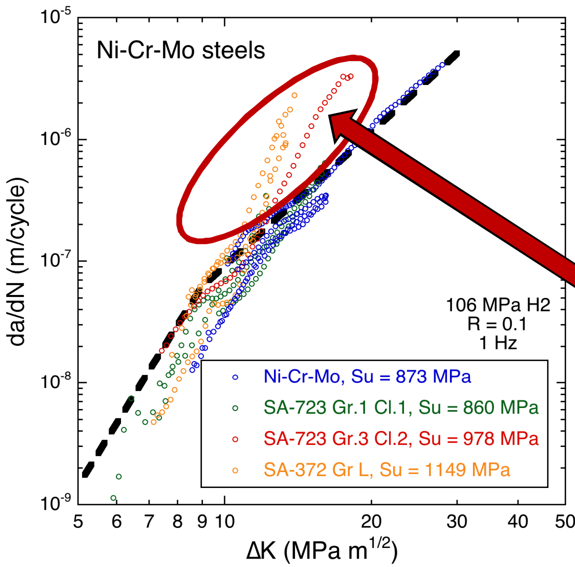
$$\Delta K \geq \Delta K_c: \quad da/dN = da/dN_{high}$$

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

$\Delta K$, $\Delta K_c$ units: MPa m$^{1/2}$

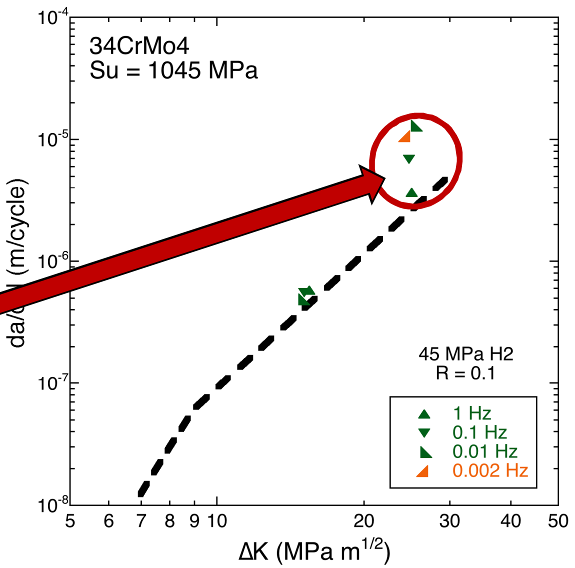
# Basis for limiting strength

- **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 > 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)**

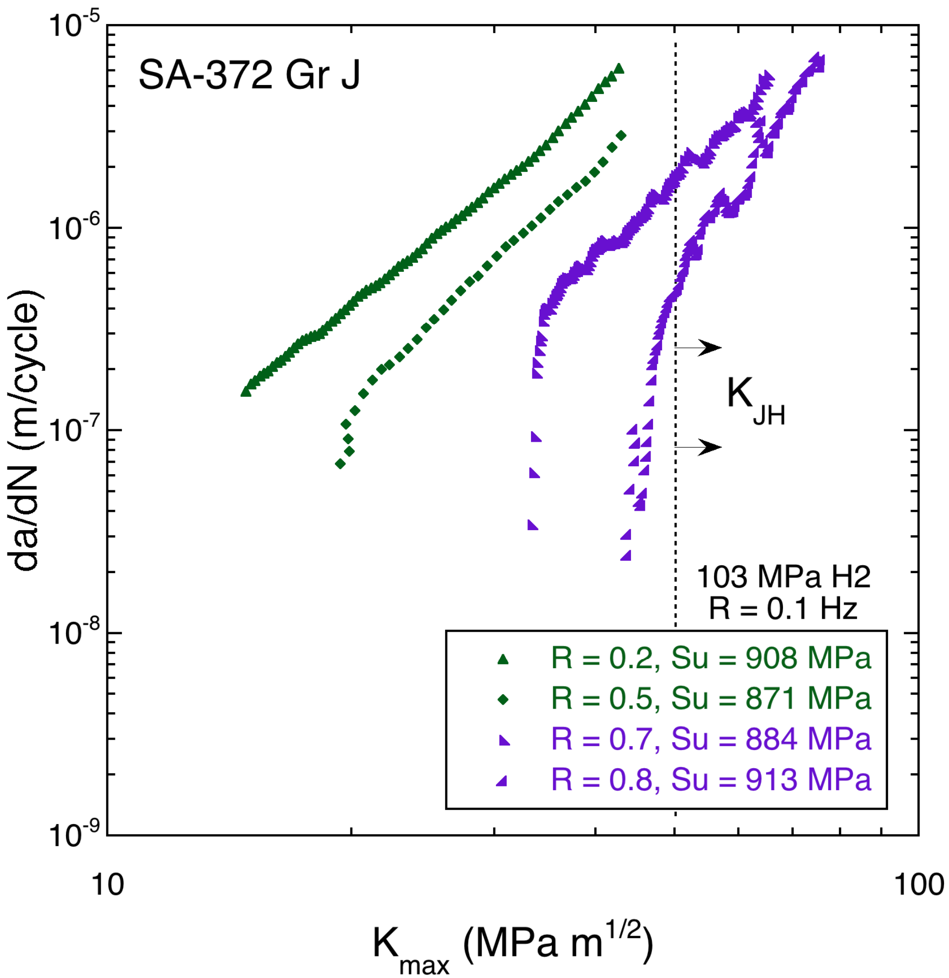



For PV steels with Su > 950 MPa

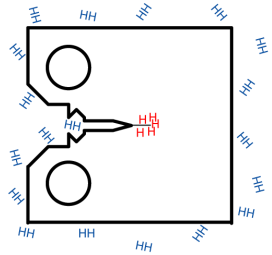
- Accelerated fatigue crack growth rate is observed
- $K_{JH} < 30$ MPa m$^{1/2}$



# Basis for limiting $K_{max}$




- "Stage III" fatigue crack growth begins at $K_{max} < K_{JH}$
  - The the proposed relationships do not capture stage III
- $K_{JH} \geq$ 45-50 MPa $m^{1/2}$ for tensile strength < 950 MPa
- Therefore $K_{max} \leq$ 35 MPa $m^{1/2}$ is a conservative bound on the proposed relationships for tensile strength < 950 MPa



# Summary

- Review of fatigue crack growth rate for PV steels generally shows consistency of fatigue response independent of alloy and strength
  - *Exception*: tensile strength > 950 MPa shows transition to stage III crack growth at low $K_{max}$
- Two-part power law was established to bound FCGR behavior as a function of load ratio, R
  - Transition between "two parts" also quantitatively established

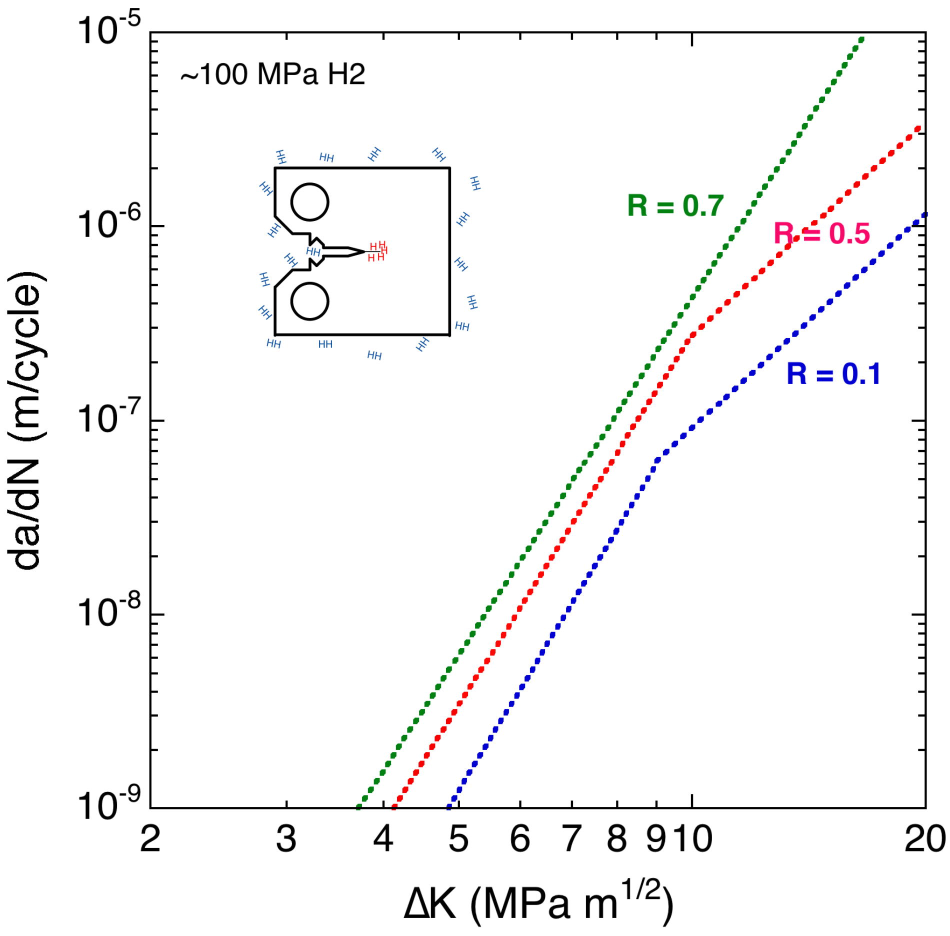
$$\frac{da}{dN} = C\left[\frac{1 + C_H R}{1 - R}\right]\Delta K^m$$

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

- Proposed constraints for use of established relationships
  - Tensile strength < 950 MPa
  - $K_{max} \leq 35$ MPa m$^{1/2}$

# Appendix: FCGR law formulation

**Step 1: establish piece-wise power laws for each load ratio (R)**



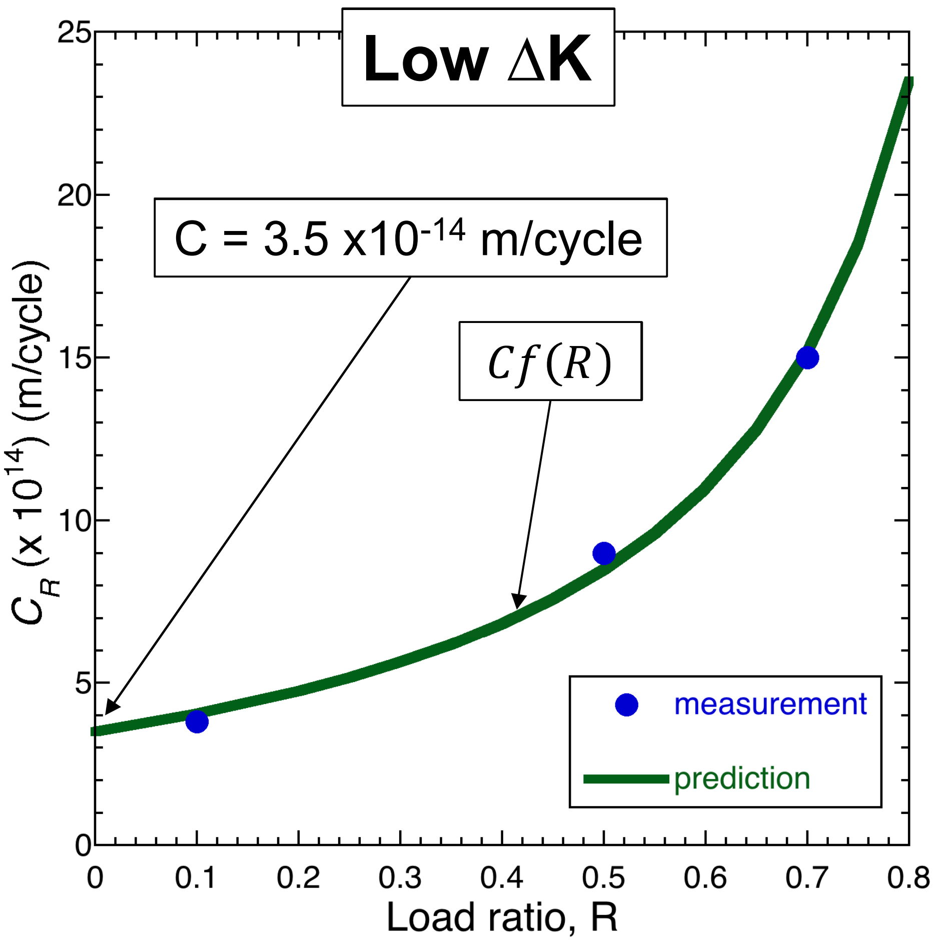

$$\frac{da}{dN} = C_R \Delta K^m$$

| R | $C_R$ (m/cycle) | |
|---|---|---|
| | Low ΔK | High ΔK |
| 0.1 | 3.8e-14 | 2.0e-11 |
| 0.5 | 9.0e-14 | 6.0e-11 |
| 0.7 | 1.5e-13 | – |
| m | 6.5 | 3.66 |

- **For the available data two regimes is sufficient**
  - **Low ΔK (approx. < 10 MPa $m^{1/2}$)**
  - **High ΔK**
- **The power 'm' is defined to be independent of R (simplicity)**

# Appendix: FCGR law formulation

## Step 2A: determine R dependence of $C_R$: low $\Delta K$




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

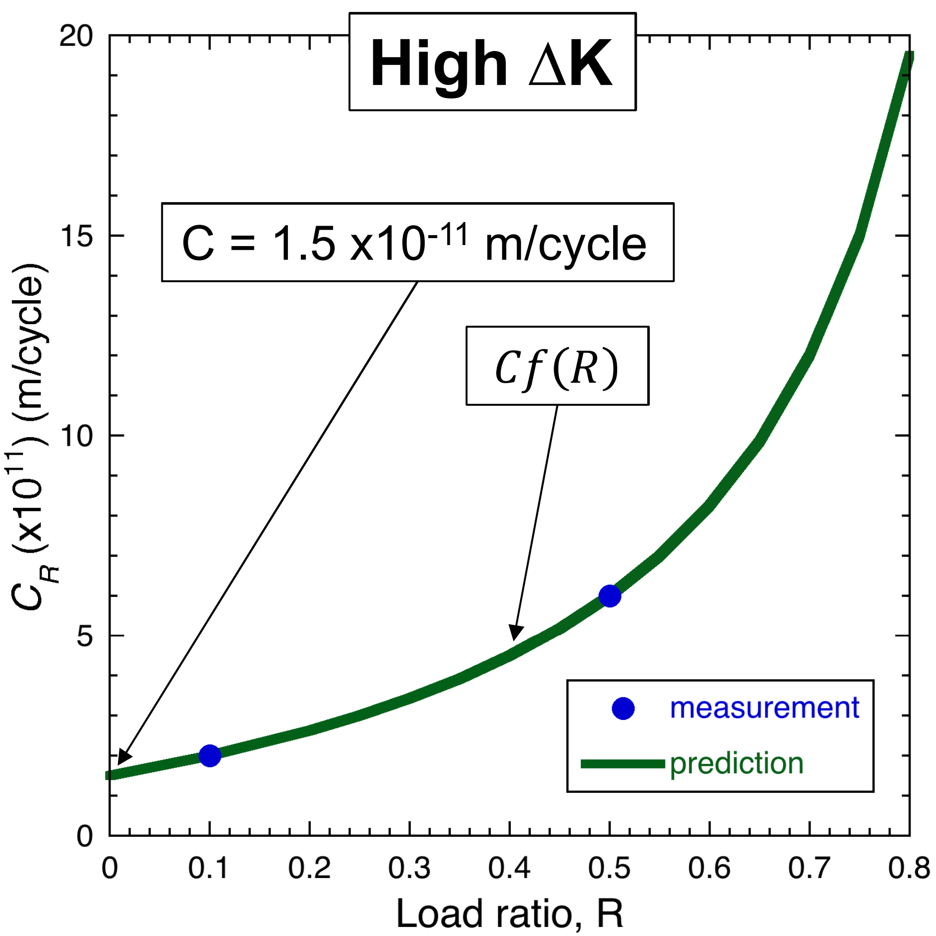
$$\frac{da}{dN} = C[f(R)]\Delta K^m$$

$$f(R) = \frac{1 + 0.4286R}{1 - R}$$

| R | Measurements $C_R$ (m/cycle) | Prediction C * *f*(R) (m/cycle) |
|---|---|---|
| 0.1 | 3.8e-14 | 4.06e-14 |
| 0.5 | 9.0e-14 | 8.50e-14 |
| 0.7 | 1.5e-13 | 1.52e-13 |
| C = 3.5 x $10^{-14}$ | | |

# Appendix: FCGR law formulation

## Step 2B: determine R dependence of $C_R$: high $\Delta K$




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

$$\frac{da}{dN} = C[f(R)]\Delta K^m$$

$$f(R) = \frac{1 + 2.00R}{1 - R}$$

| R | Measurements $C_R$ (m/cycle) | Prediction C * *f*(R) (m/cycle) |
|---|---|---|
| 0.1 | 2.0e-11 | 2.00e-11 |
| 0.5 | 6.0e-11 | 6.00e-11 |
| 0.7 | – | 1.20e-10 |
| $C = 1.5 \times 10^{-11}$ | | |

# Appendix: FCGR law formulation

## Step 3: determine inflection point: defined as $\Delta K_c$

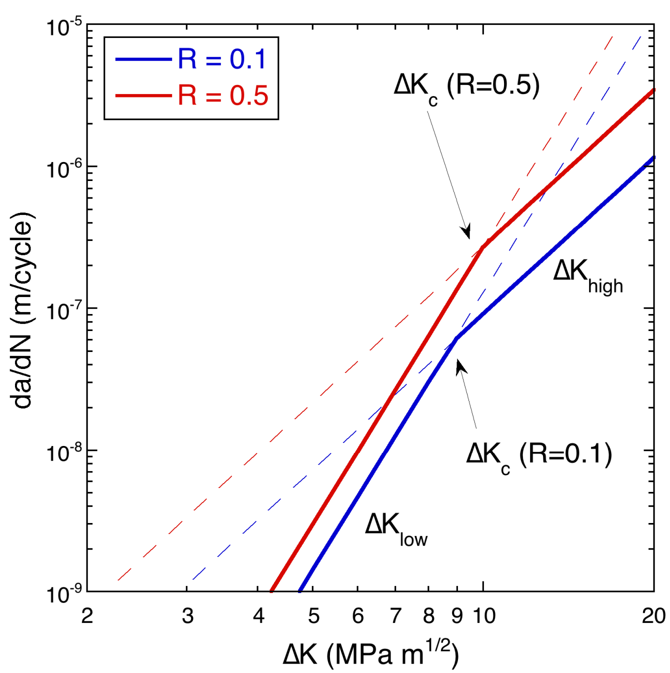
at $\Delta K_c$: $da/dN_{low} = da/dN_{high}$

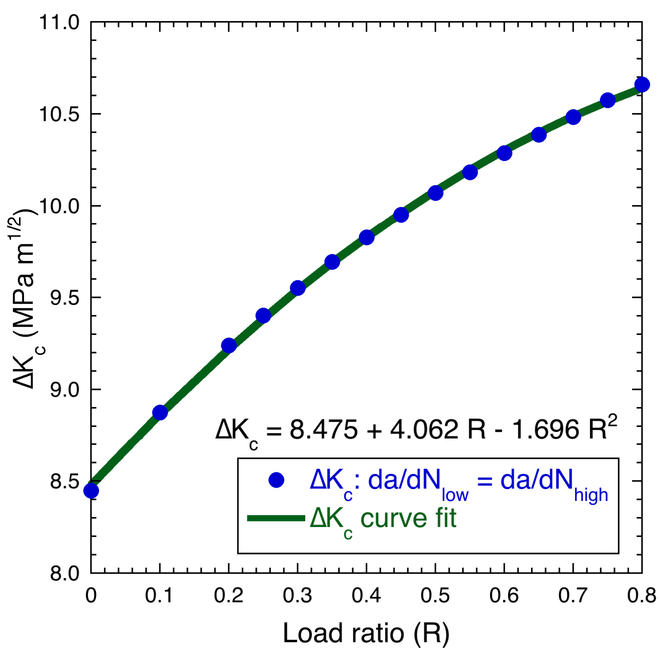
$$\frac{da}{dN} = C_R \Delta K^m$$

$$C_{R,low}(\Delta K_C)^{m_{low}} = C_{R,high}(\Delta K_C)^{m_{high}}$$

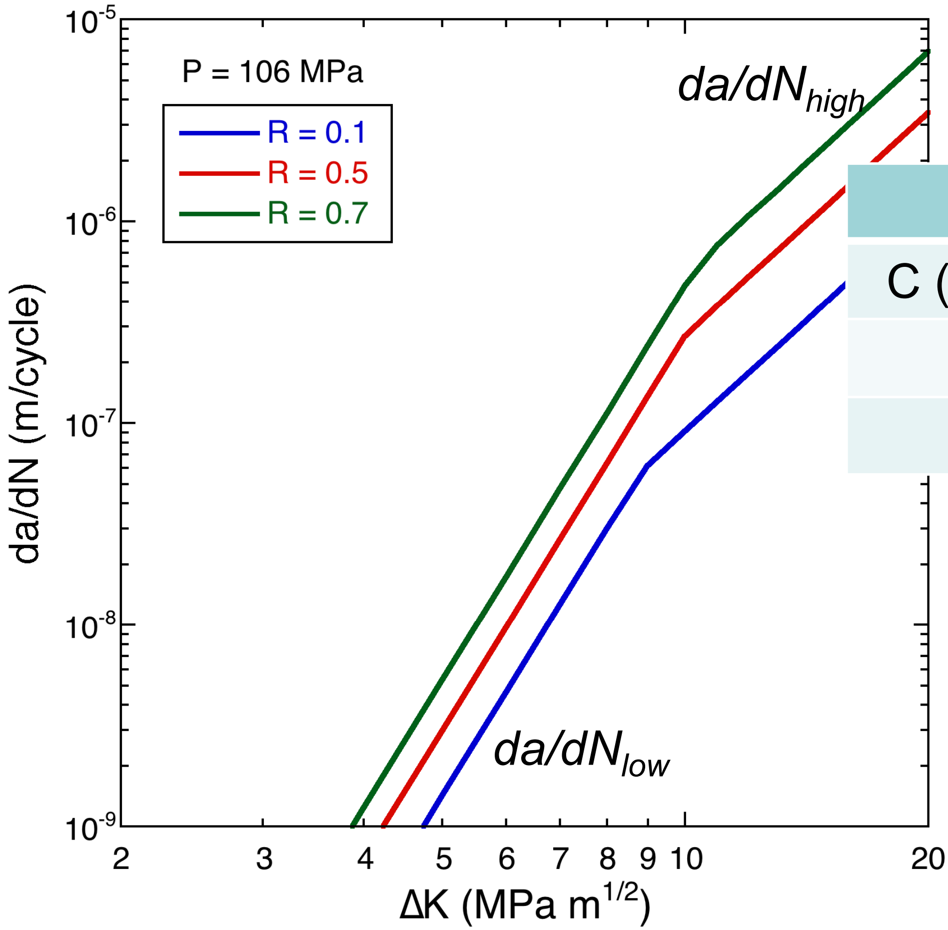
$$\Delta K_C = \frac{ln[C_{R,low}] - ln[C_{R,high}]}{m_{high} - m_{low}}$$

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



# Appendix: FCGR law formulation




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

| | $da/dN_{low}$ | $da/dN_{high}$ |
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| C (m/cycle) | 3.5 x10$^{-14}$ | 1.5 x10$^{-11}$ |
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$$\Delta K < \Delta K_c: \quad da/dN = da/dN_{low}$$

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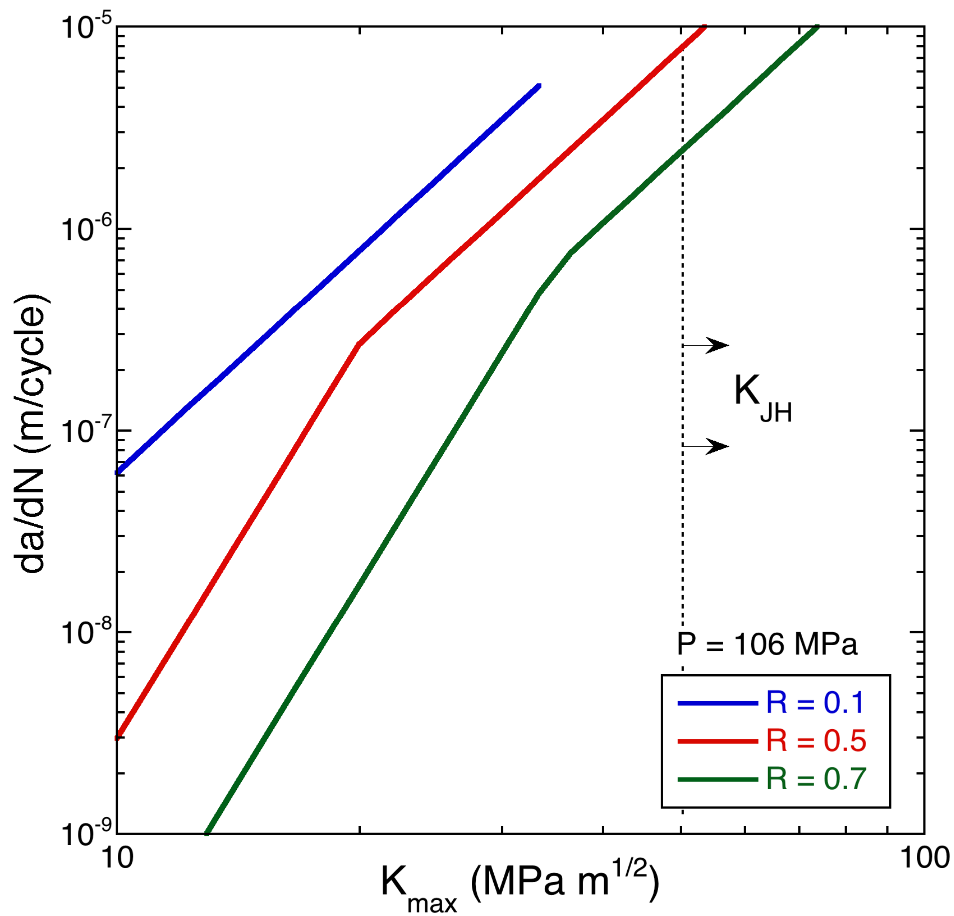
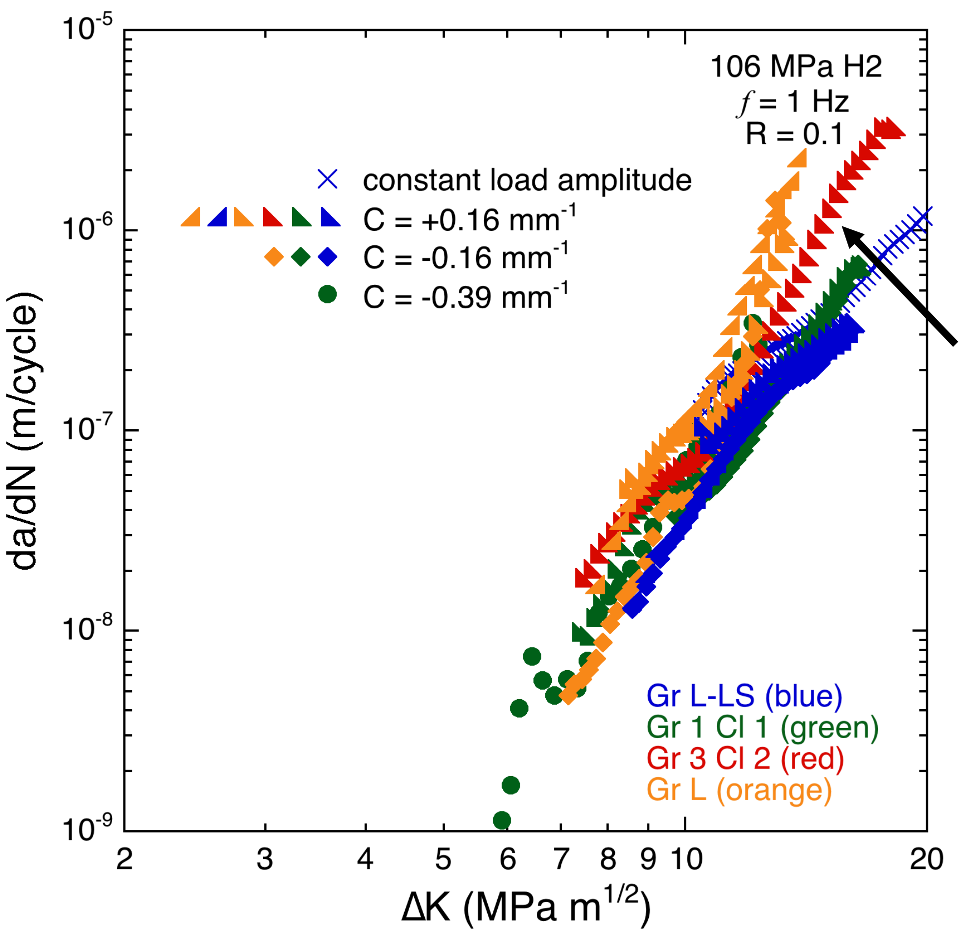
$$\Delta K_c = 8.475 + 4.062R - 1.696R^2$$

$\Delta K$, $\Delta K_c$ units: MPa m$^{1/2}$

# Appendix: FCGR law formulation (in terms of $K_{max}$)

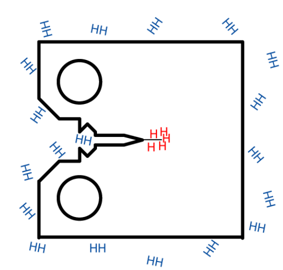


# Appendix: FCGR data for variable K-gradient




- 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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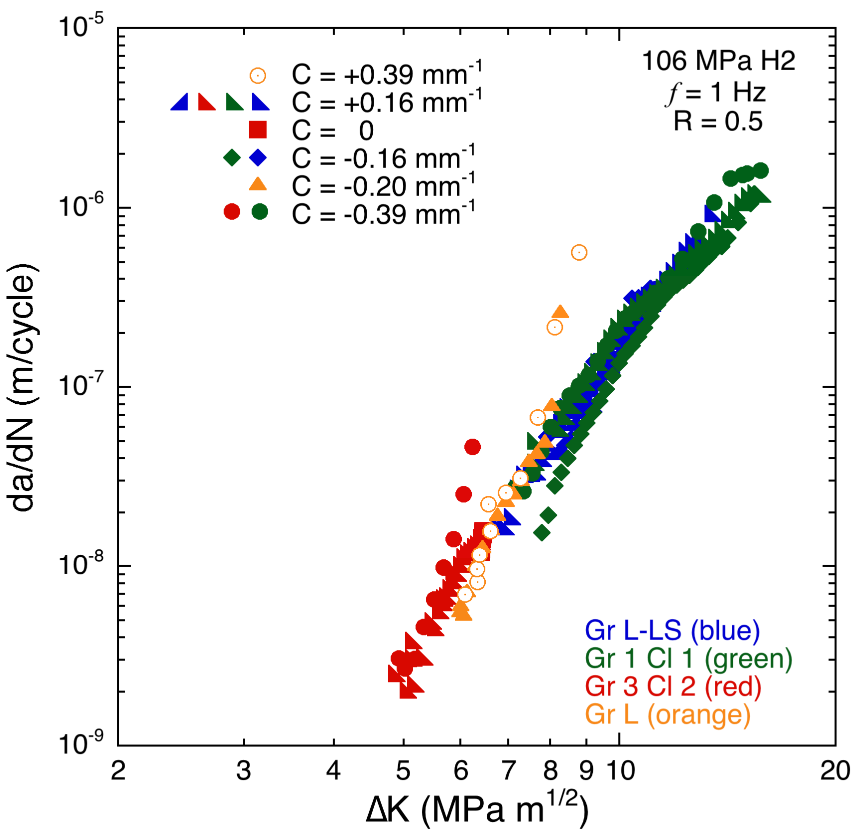
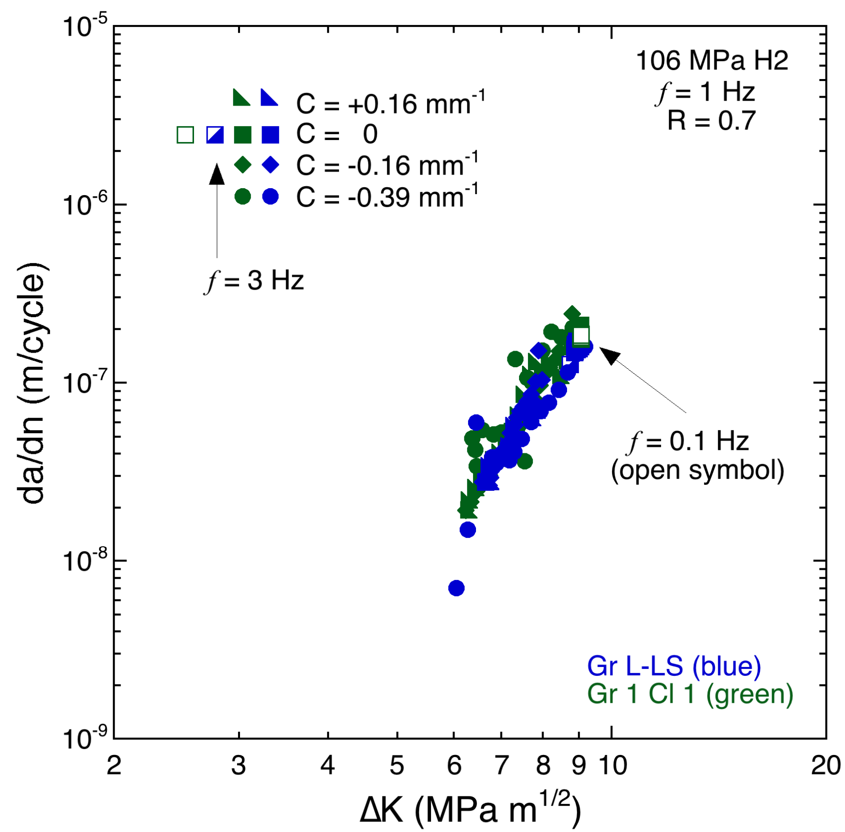
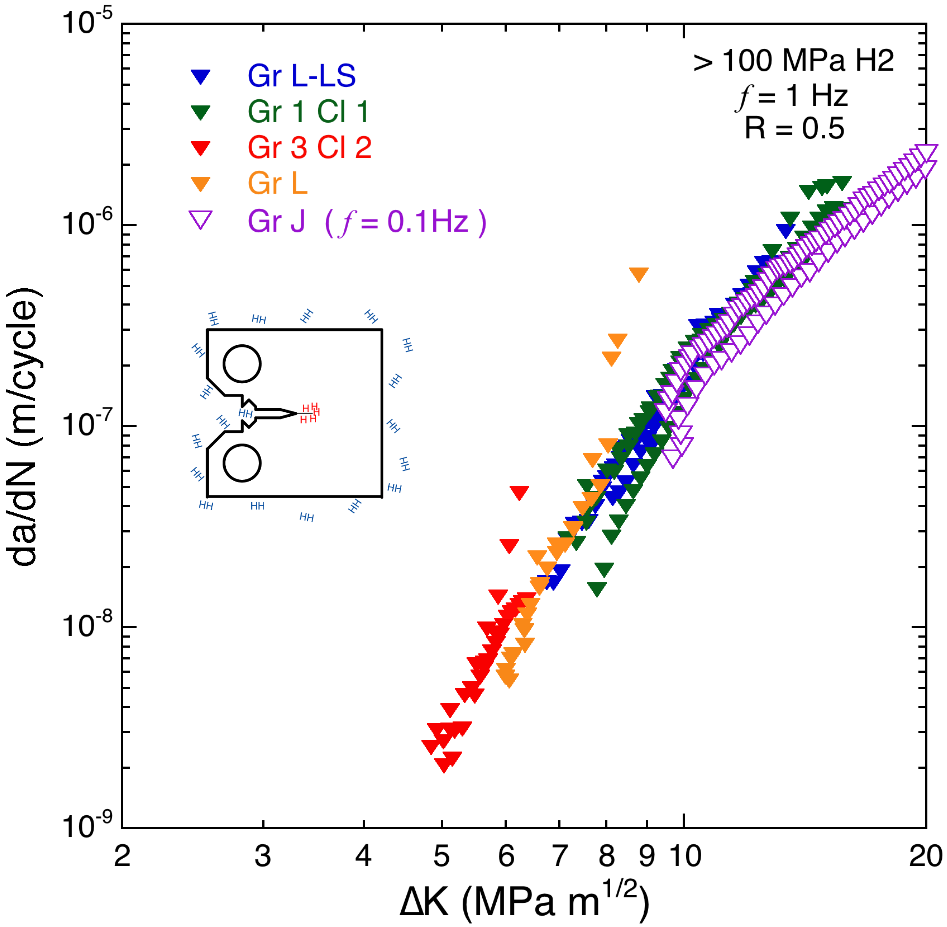


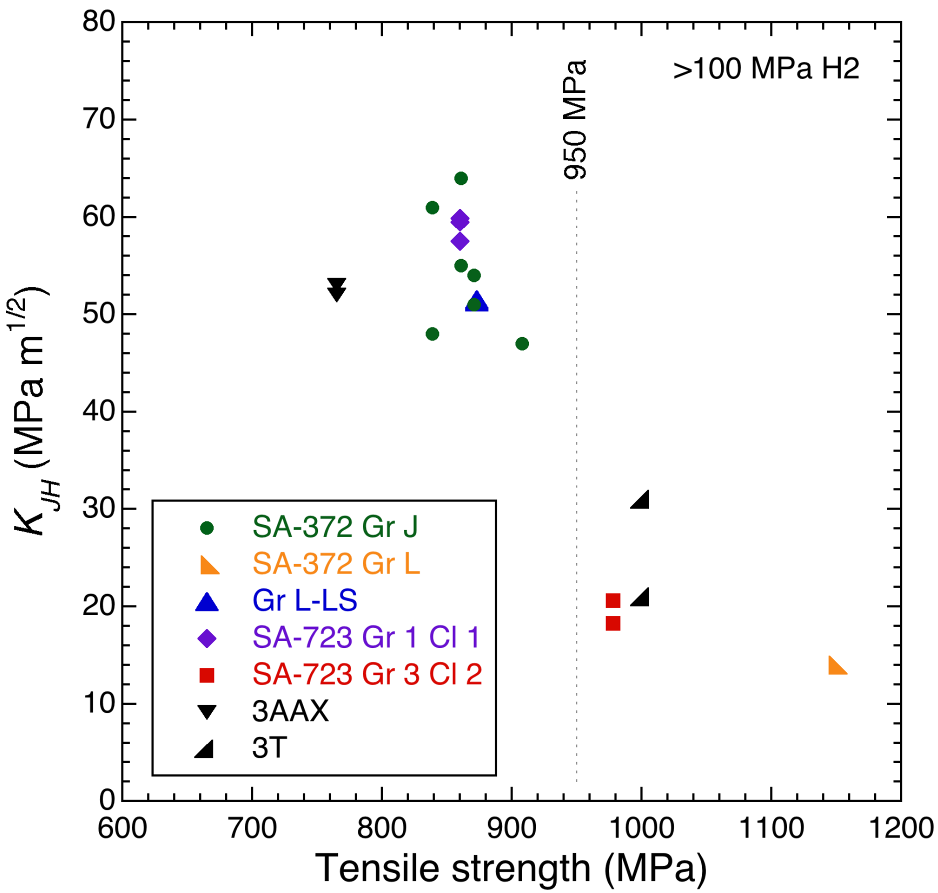



# Appendix: comparison of Cr-Mo and Ni-Cr-Mo




- 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

# Appendix: Fracture resistance – rising load ($K_{JH}$)

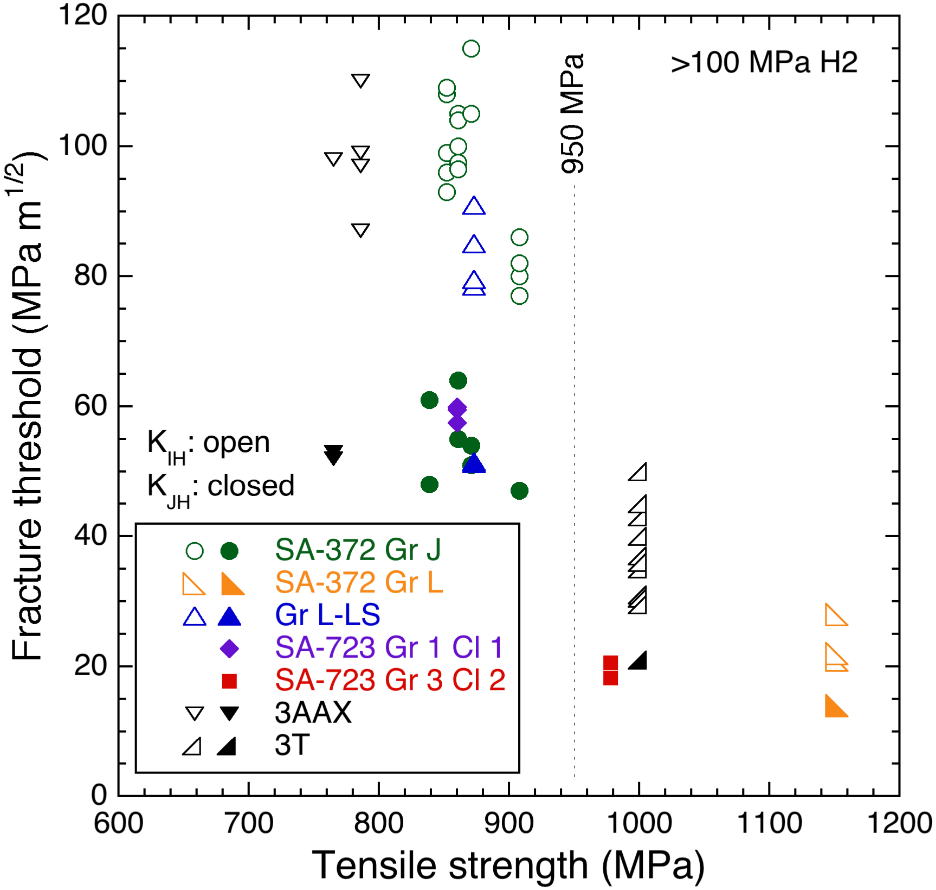



## PV steels display low fracture resistance in high strength condition

- 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)

# Appendix: Fracture arrest threshold ($K_{IH}$) compared to fracture initial threshold ($K_{JH}$ – rising load)

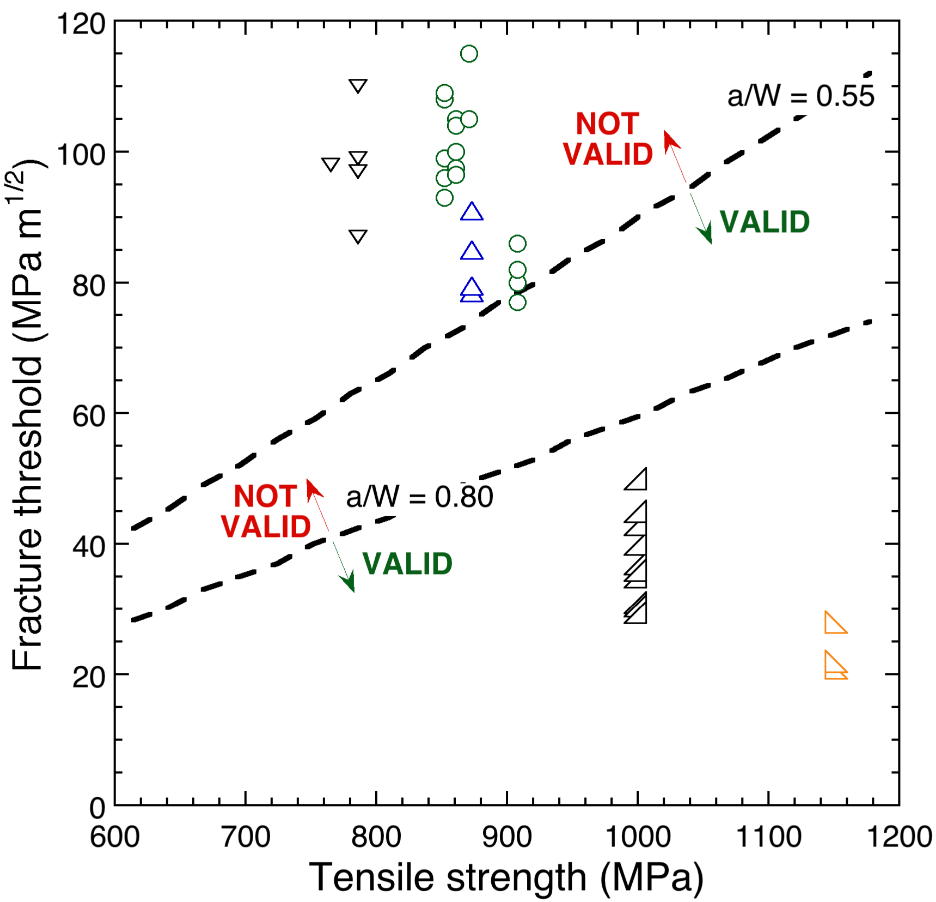



- **For tensile strength < 950 MPa**
  - $K_{JH} > 45$ MPa $m^{1/2}$
  - $K_{IH} >> K_{JH}$
- **For tensile strength > 950 MPa**
  - $K_{JH} < 30$ MPa $m^{1/2}$
  - $K_{IH}$ approaches $K_{JH}$

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

$K_{IH}$ = threshold stress intensity factor in gaseous hydrogen (ASTM E1681) – arrest threshold

# Appendix: Validity of $K_{IH}$ measurements




- **Validity criterion from ASTM E1681**

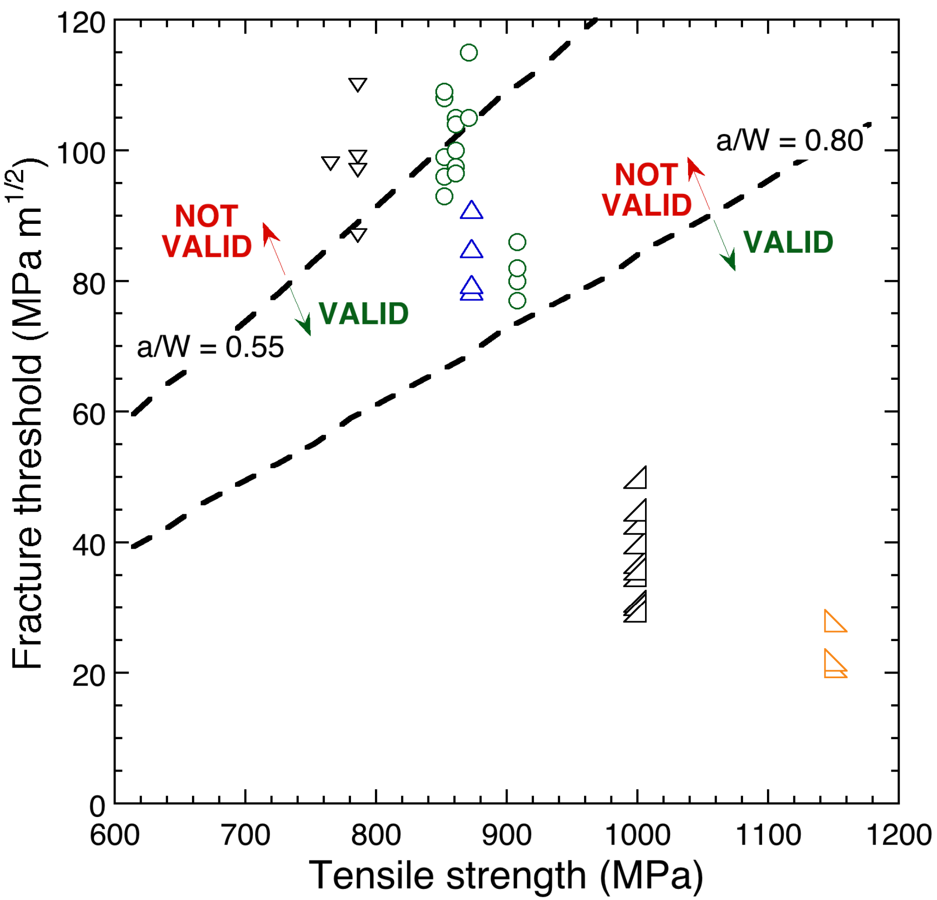
$$(W - a) \geq 2.5 \left( \frac{K_{max}}{S_y} \right)^2$$

  - **Calculated for different ligaments: $b/W = (1 - a/W)$**
  - **$K_{IH}$ is determined at arrest**
  - **Typically at arrest $a/W > 0.8$**
  - **Not valid if the ratio of K to Sy (or Su) is large relative to remaining ligament**

$K_{IH}$ = threshold stress intensity factor in gaseous hydrogen (ASTM E1681) – arrest threshold

Tensile strength is estimated from yield strength (linear relationship)

# Appendix: Validity of $K_{IH}$ measurements




- **Validity criterion from ASTM E1681**

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

  - **Calculated for different ligaments: *b/W* = (1- *a/W*)**
  - **$K_{IH}$ is determined at arrest**
  - **Typically at arrest *a/W* > 0.8**
  - **Not valid if the ratio of K to Sy (or Su) is large relative to remaining ligament**

$K_{IH}$ = threshold stress intensity factor in gaseous hydrogen (ASTM E1681) – arrest threshold

Tensile strength is estimated from yield strength (linear relationship)