SAND2018-3950C

R&D for Safety, Codes and Standards: Materials Compatibility

Chris San Marchi
Sandia National Laboratories

Codes and Standards Tech Team
March 28, 2018

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525

Outline

- Materials Qualification for FCEVs
  - SAE H2 Compatibility Expert Team
  - SAE J2579 Appendix B
    - Summary
    - Justification
- Fatigue crack growth rate (FCGR) laws for high-pressure storage tanks
  - ASME BPVC VIII.3 KD-10
  - Extrapolation to other ferritic steels
  - Effects of pressure

SAE H2 Compatibility Expert Team

- **Representation from nationally funded research programs funded to enable deployment of fuel technologies**
  - **Germany: MPA Stuttgart**
  - **Japan: Kyushu University and AIST**
  - **US: Sandia National Laboratories**
- **Collective learning through so-called "*round robin*" testing campaign**
  - ***Development of capabilities* and *examination of procedures* to execute fatigue tests in high-pressure hydrogen at low temperature**
  - **Demonstrate test methodologies at MPA, KU and SNL**

Collective learning activity ("round robin")

Test	Test conditions	Environment	Number of tests
Slow strain rate tension (SSRT)	$\leq 5 \times 10^{-5}\ s^{-1}$	Control -40˚C	3
		90 MPa H2 -40˚C	3
Notched tension-tension fatigue	Sa = 200 MPa R = 0.1 1 Hz	Control -40˚C	3
		90 MPa H2 -40˚C	3
Smooth tension-compression fatigue	Sa = 320 MPa R = -1 1 Hz	Control -40˚C	3
		90 MPa H2 -40˚C	3

Test criteria for hydrogen compatibility of materials

SAE J2579, Appendix B.3 is essentially a set of generic test criteria for evaluation of structural metals for service in high-pressure gaseous hydrogen

- Part 1: Definition of materials and environment al test conditions
- Part 2: SSRT
- Part 3: Fatigue life test
- Part 4: Welds

In general, CSA CHMC1 is referenced for the test methods (CHMC1 references ASTM standards)

Part 1: Definition of materials and environmental test conditions: test temperature

Table B.3.1.4 from SAE J2579

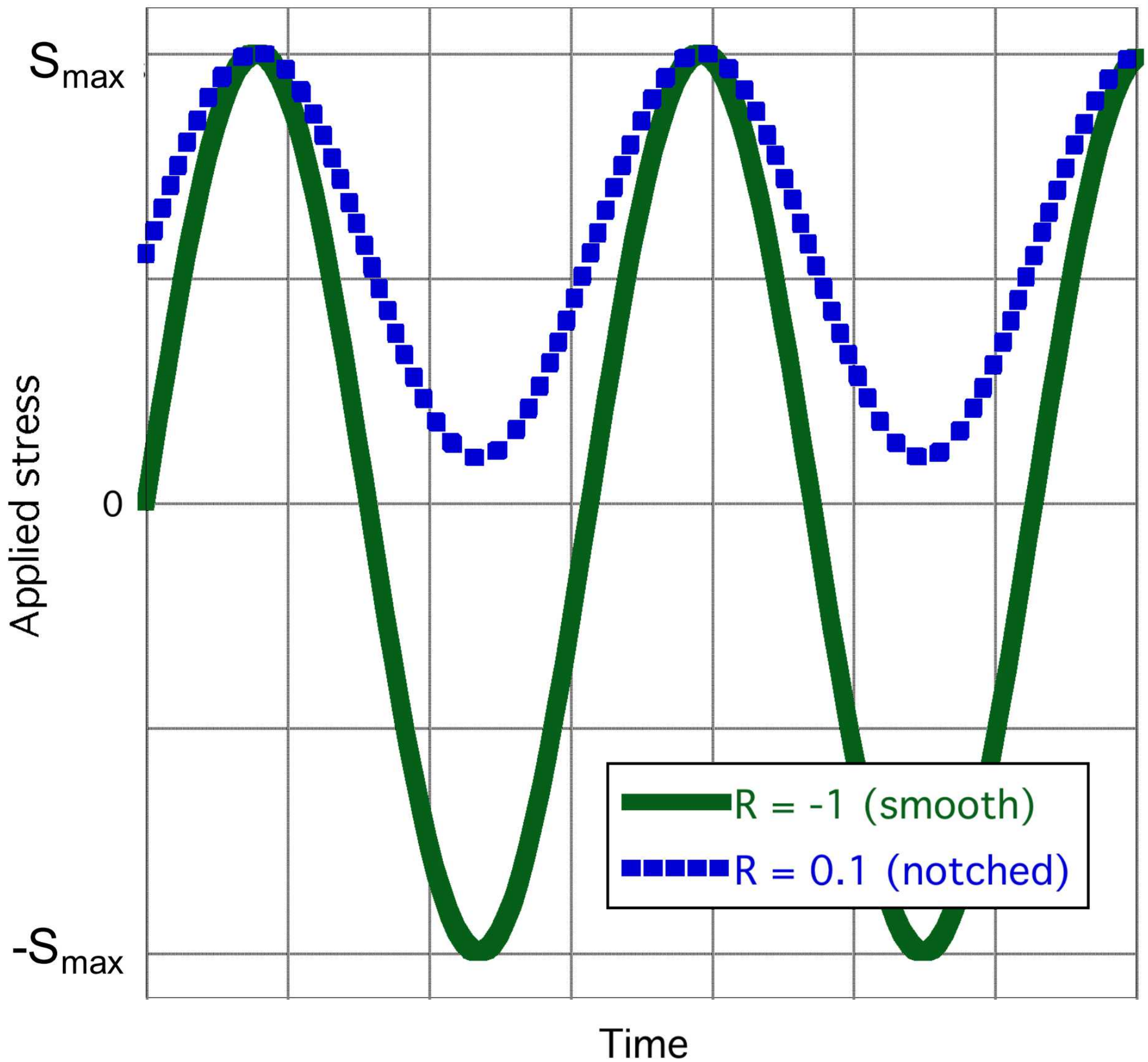
Alloy type	Test method	Test temperature (K)
Austenitic stainless steel	SSRT	228 ±5
	Fatigue life	228 ±5 and 293 ±5
Nickel-based alloys	SSRT and Fatigue life	228 ±5
Aluminum, magnesium and copper alloys	SSRT and Fatigue life	293 ±5
Other alloys	SSRT and Fatigue life	228 ±5 and 293 ±5

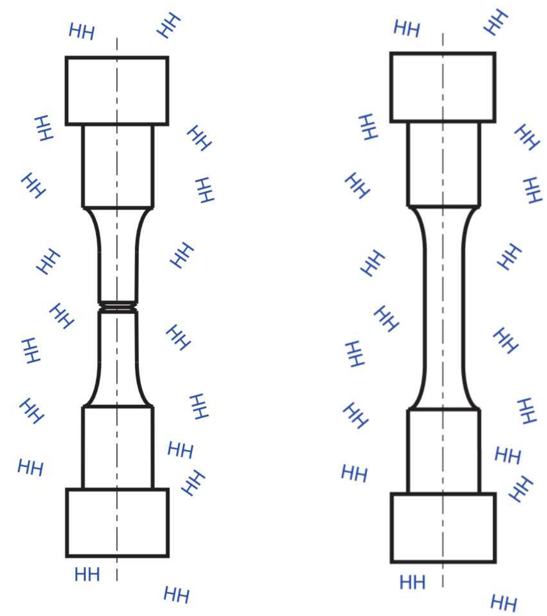
Summary of requirements for compatibility

Test configuration		Evaluation parameter	Requirements of tests performed in H2
Slow strain rate tension tests – SSRT (3 tests)		Yield strength	Average ≥ Sy
		Tensile strength	Average ≥ Su
		Strain hardening capacity	Average > 1.07
		Elongation	Average ≥ 12%
Fatigue life tests (must satisfy 1 of 3 options)	Option 1 **(3 tests)**: **Smooth, R= -1**	Cycles to failure	Each > 200,000 cycles
	Option 2 **(3 tests)**: **Notched, R = 0.1**	Cycles to failure	Each > 200,000 cycles
	Option 3 **(5 tests)**: **Notched, R = 0.1**	Cycles to failure	Each > 100,000 cycles

Note: Sy and Su are specified minimum yield and tensile strength respectively

Part 3: Fatigue life test: stress cycle

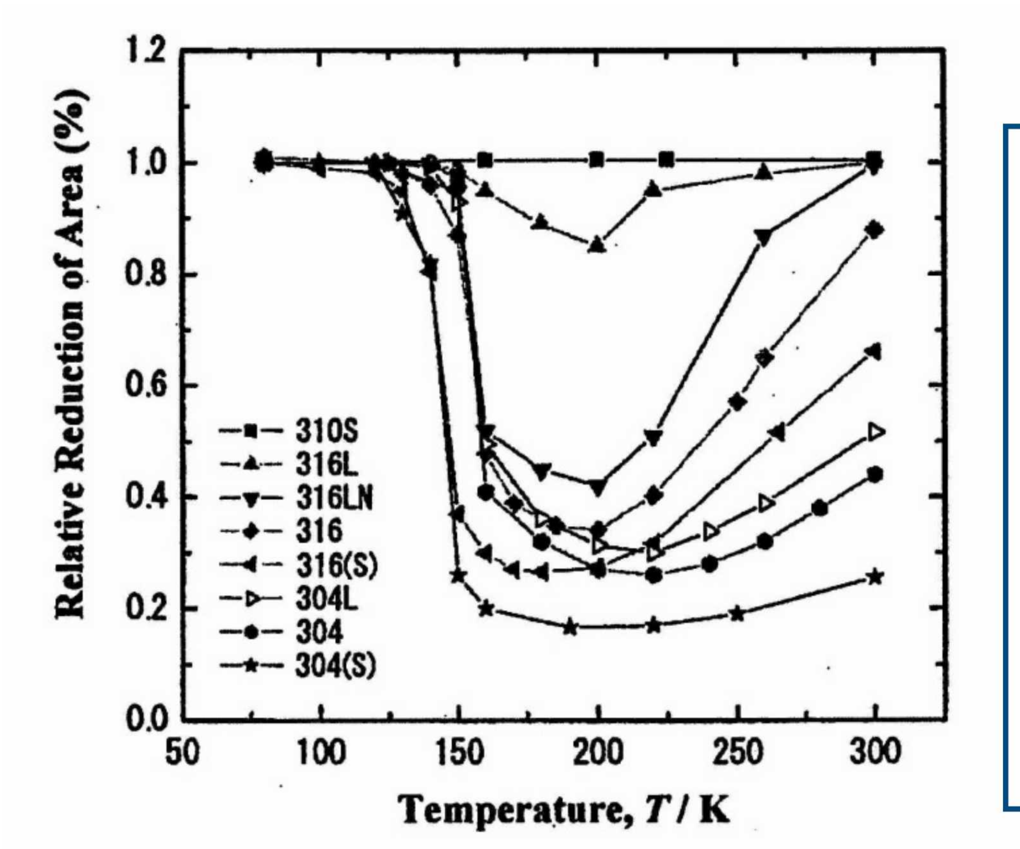




notched tension tension

smooth tension compression

Tensile properties are degraded in gaseous hydrogen especially at low temperature



Data from: Fukuyama et al., *J Japan Inst Metals* 67 (2003) 456-459.

Requirement:

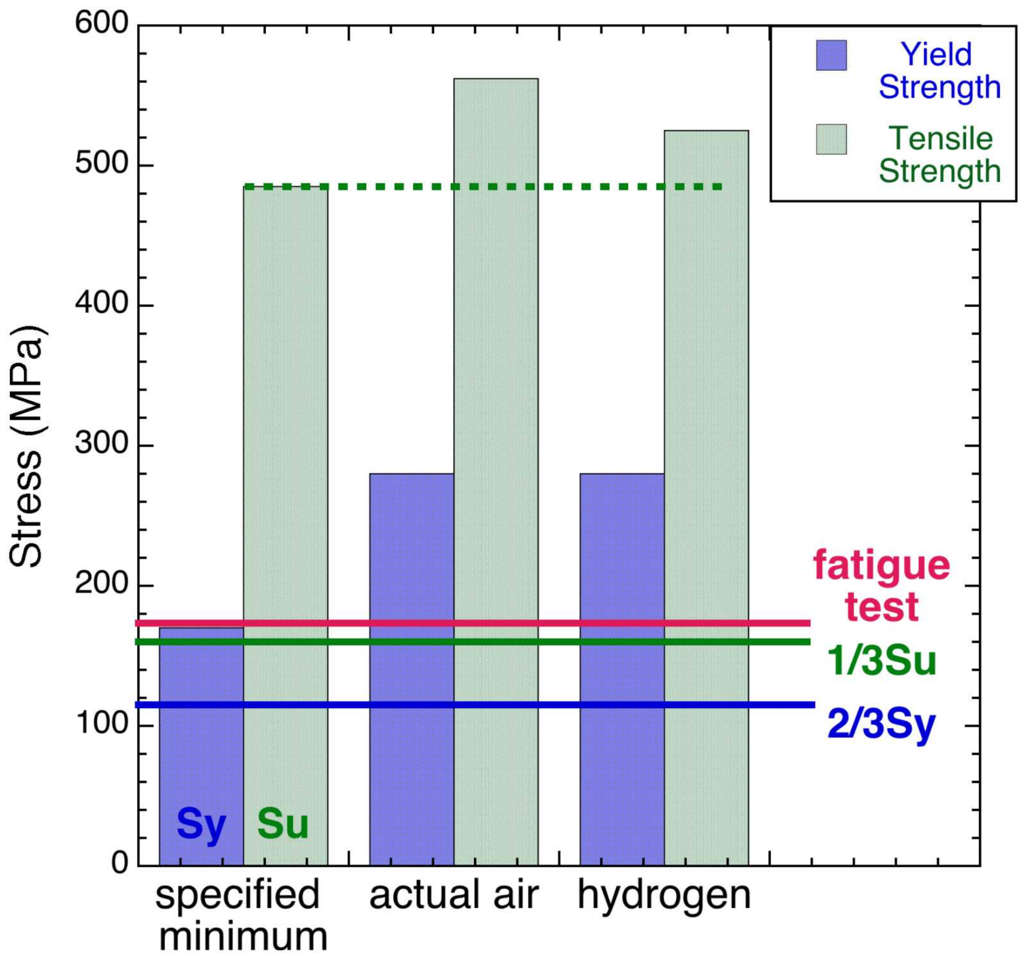
- Minimum specified strength properties are maintained
- Ductility is consistent with pressure applications

Rationale:

- Known and ductile tensile response

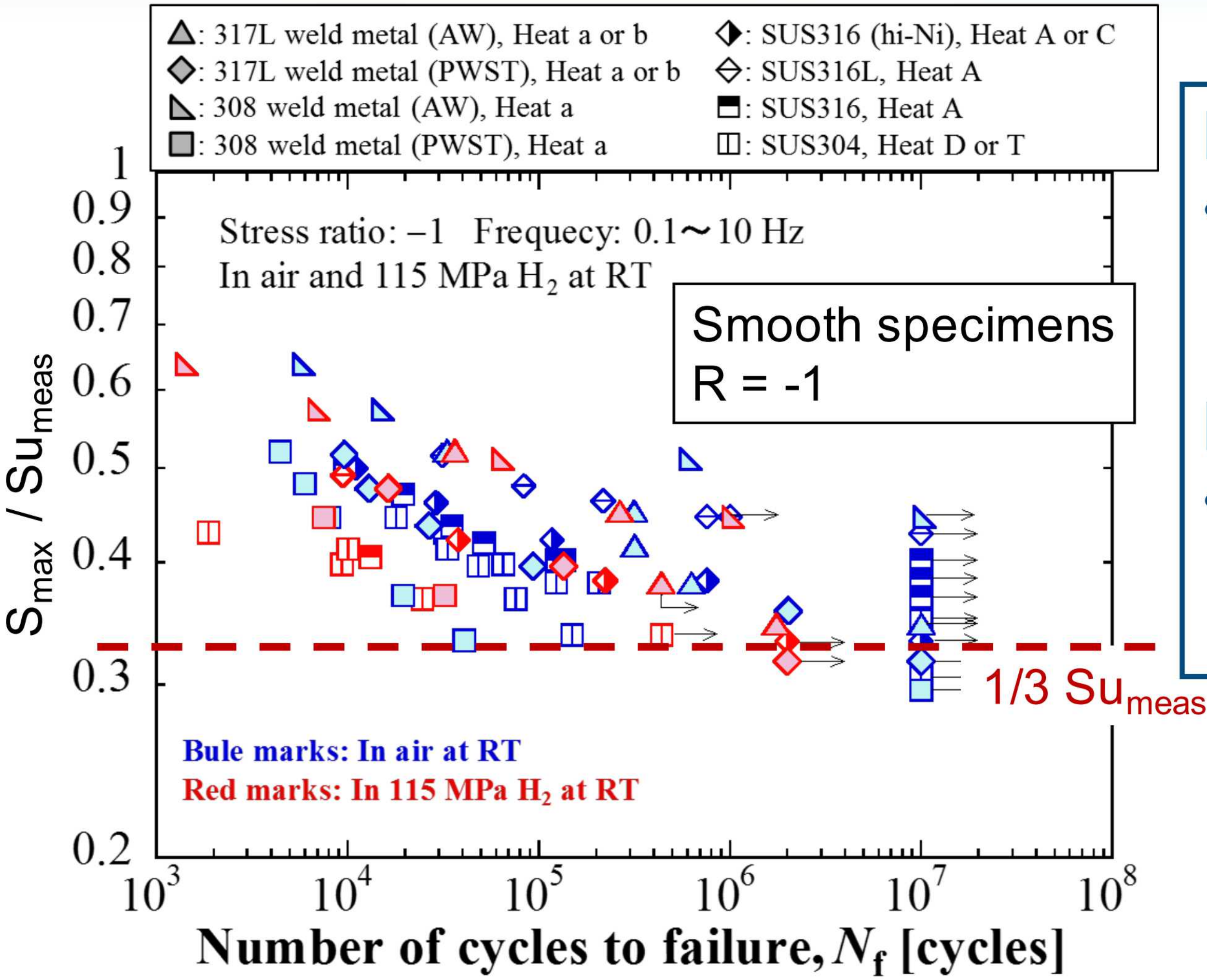
Tensile strength properties are not degraded in gaseous hydrogen for acceptable materials

Annealed austenitic stainless steel



- **Common stress limitations for fatigue design: minimum of 2/3 Sy and 1/3 Su**
- **Yield and tensile strengths are typically not affected by hydrogen**
- **Maximum stress during fatigue testing (J2579) always greater than 1/3 Su**

Fatigue life of smooth specimens is typically infinite at stress of 1/3 Su_{meas}



Requirement:

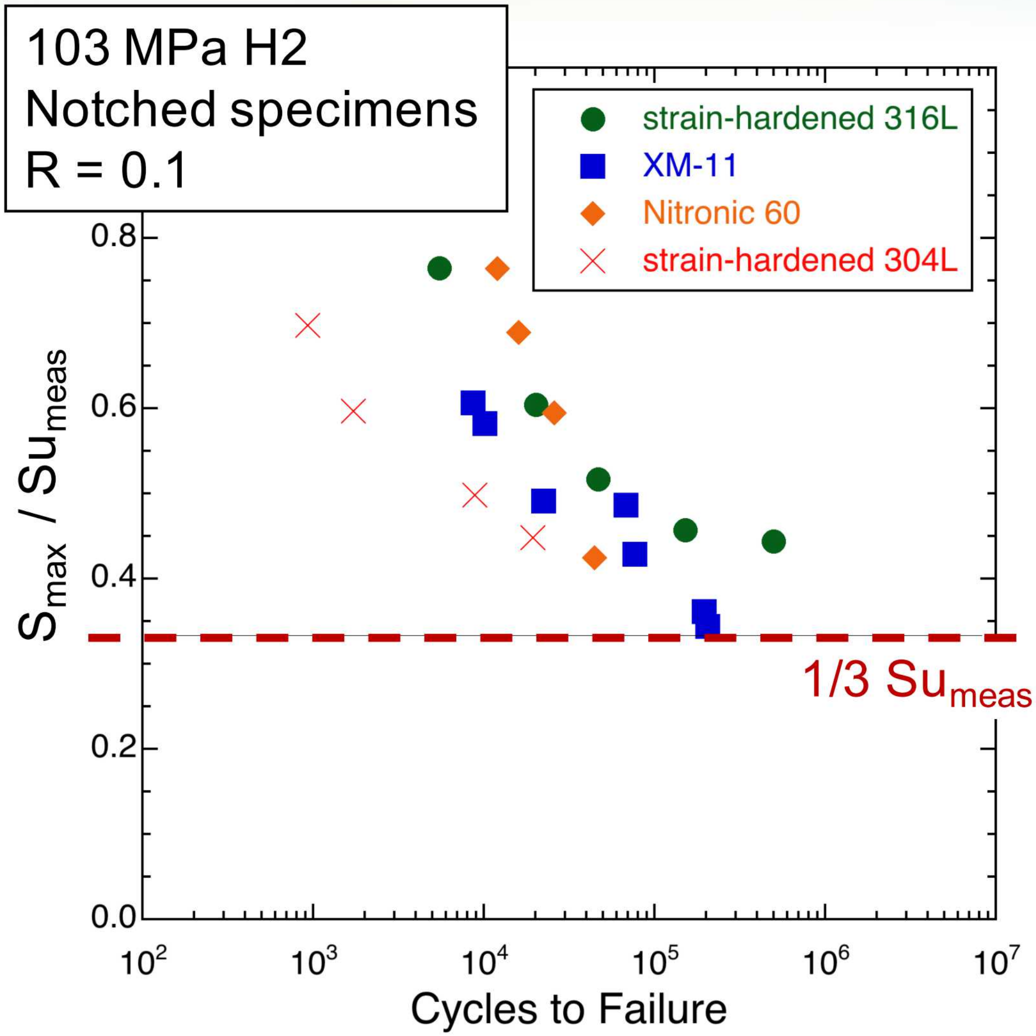
- N_f > 200,000 cycles at S_{max} = 1/3 Su_{meas}

Rationale:

- Ensure fatigue life at high stress is >> than design life

Data from: M. Nakamura et al., M&M2017 conference, 7-9 October 2017, Hokkaido, Japan

Notched specimens assess sensitivity to stress concentration for typical maximum stress (1/3Su)



Requirement:

- **Nf > 100,000 cycles at S_{max} = 1/3 Su_{meas}**

Rationale:

- **Ensure fatigue life at high stress is >> than design life**

Data from: C. San Marchi et al., 43rd MPA Seminar, 11-12 October 2017, Stuttgart, Germany

Diverse range of austenitic stainless steels have been evaluated, including high-strength alloys

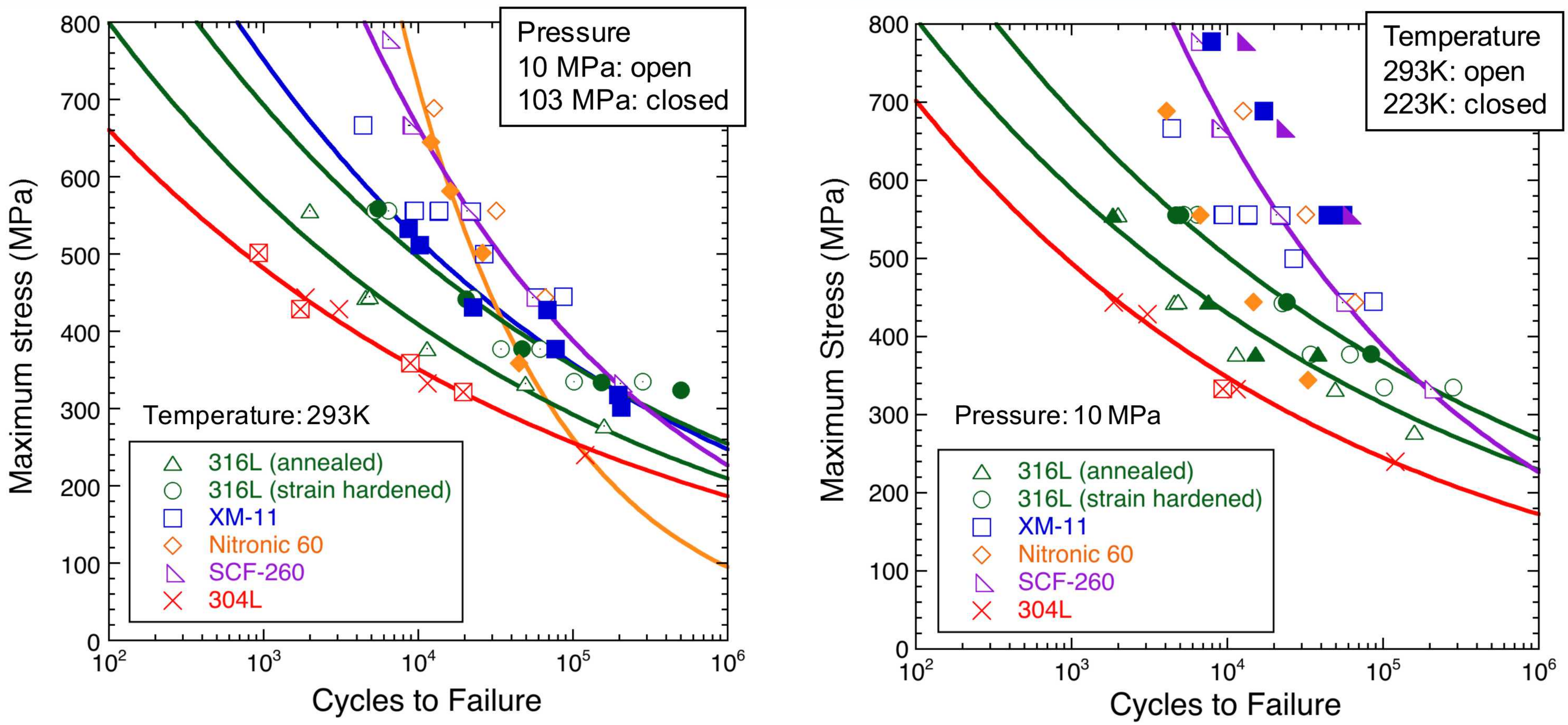
material	Yield (MPa)	Tensile (MPa)	Cr	Ni	Mn	N	Typical allowable stress (MPa)
316L	280	562	17.5	12	1.2	0.04	115
CW 316L	573	731	17.5	12	1.2	0.04	218
304L	497	721	18.3	8.2	1.8	0.56	195
XM-11	539	881	20.4	6.2	9.6	0.26	207
Nitronic 60	880	1018	16.6	8.3	8.0	0.16	218
SCF-260	1083	1175	19.1	3.3	17.4	0.64	333

Wide range of strength

Wide range of Ni/Mn content

Fatigue life at low temperature appears to be greater than at room temperature

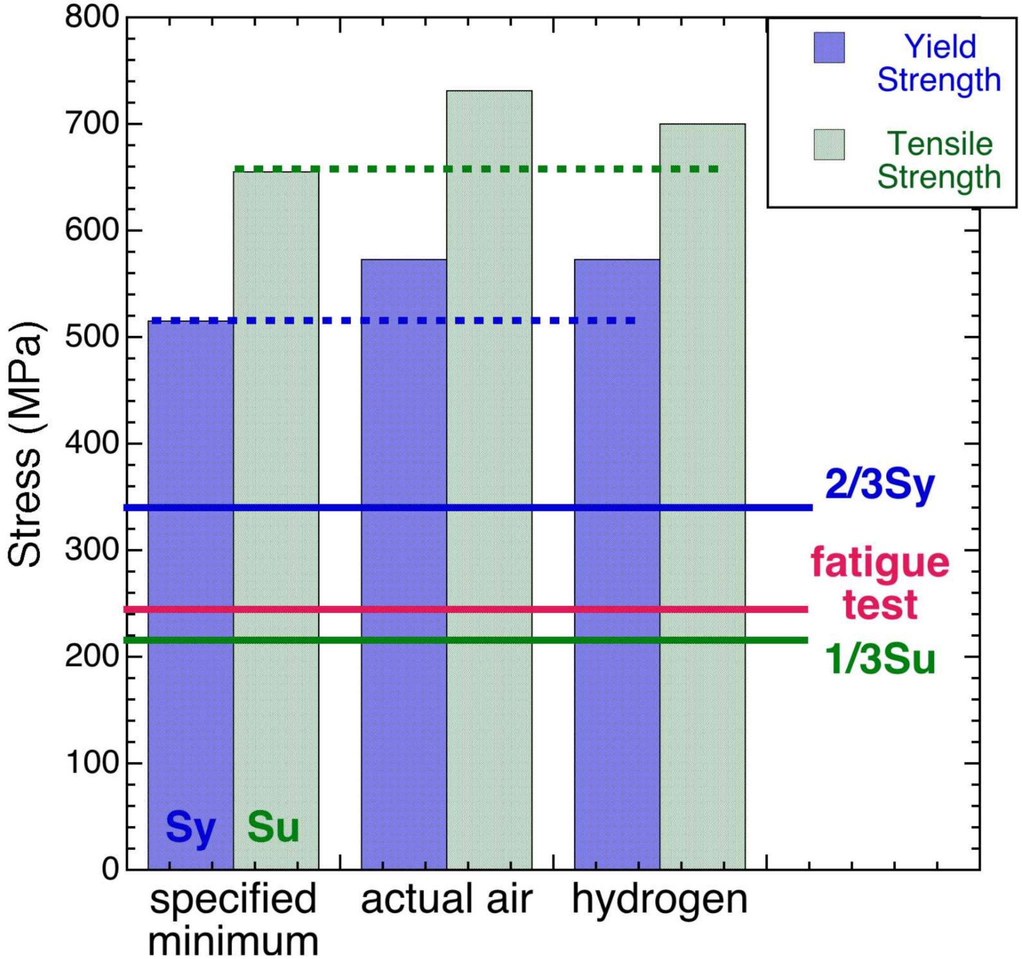
***R* = 0.1, *f* = 1Hz**



- Pressure has modest effect, if any, on fatigue life
- Temperature has either no effect or increases fatigue life
- Nitronic 60 is an exception for both pressure and temperature

High-strength materials can be evaluated by method and enable higher stress designs

Strain-hardened austenitic stainless steel

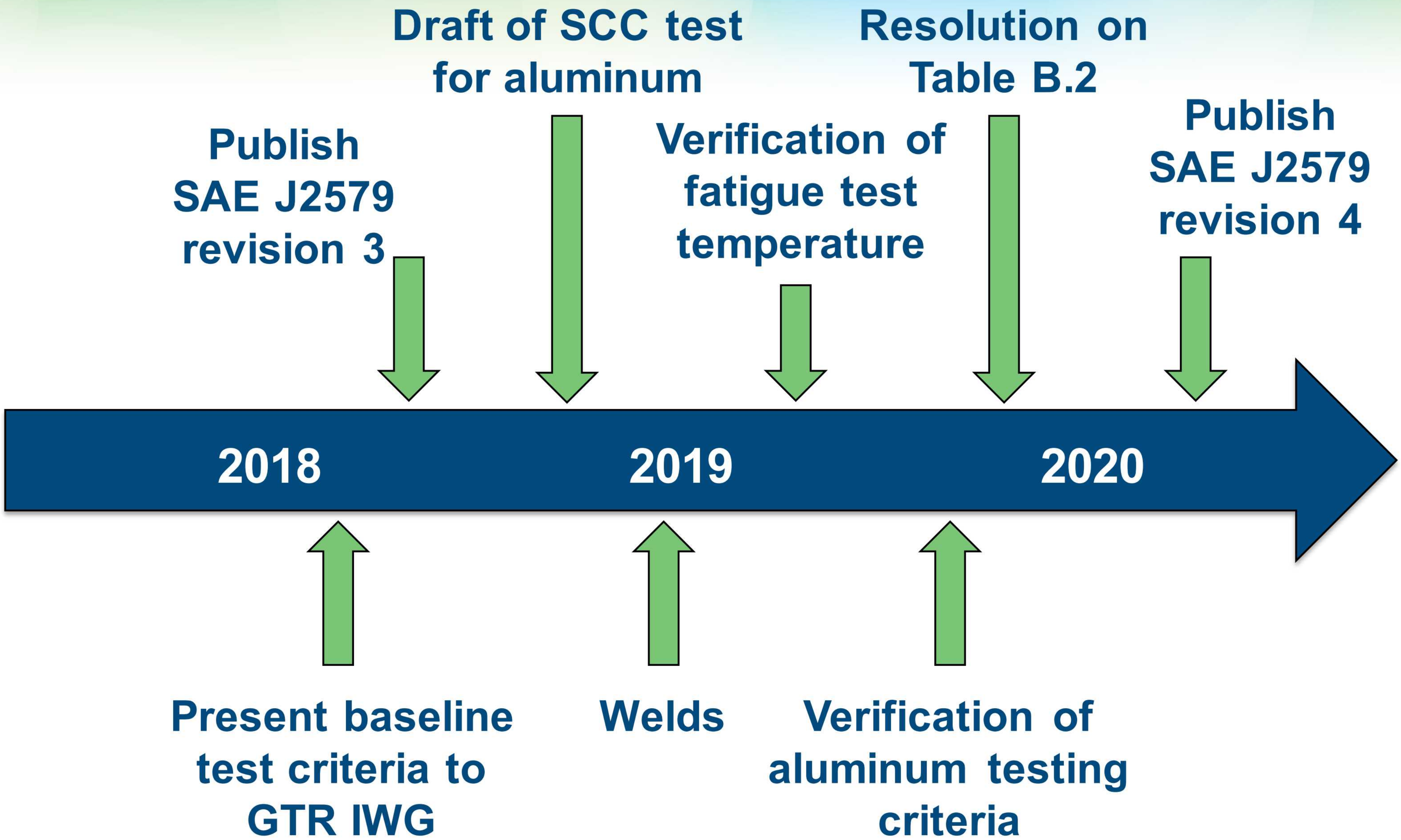


- **1/3 Su of high-strength materials can be more then specified minimum yield strength of annealed material**
- **Implicitly, increase of design stress enables lower weight and lower cost designs without compromising performance**
  - **Justified by fatigue performance**

Open questions

- Temperature for fatigue life testing
  - Most data suggest that austenitic stainless steels show longer fatigue life at low temperature
  - Change temperature of fatigue test to room temperature only?
- Welding
  - Additional requirements?
- Additional testing requirements for aluminum alloys
  - Stress corrosion cracking (SCC) threshold
  - Test method and evaluation criteria for SCC being formulated by High-Pressure Institute of Japan HPIS E 103:2018
    - Method seems equivalent to ISO 7539-6
    - Criteria should be incorporated in SAE J2579
- How to incorporate “new” materials into SAE J2579
  - Replace table B.2 and periodically update with tested materials?

Timeline of SAE activities related to materials



Summary of test criteria in SAE J2579

- Materials compatibility test method in SAE J2579 provides performance-based metrics to evaluate materials for hydrogen service
  - J2579 Appendix B.3 requirements for materials do not purport to generate design data
  - Method consists for 4 parts
    - 1: Materials definition
    - 2: Slow strain rate tensile testing (3 tests)
    - 3: Fatigue life testing (3-5 tests)
    - 4: Evaluation of welds (if welded)
  - Tensile testing (SSRT) in H2 demonstrates that materials satisfy the specified minimum properties consistent with pressure application
  - Fatigue life testing in H2 demonstrates that materials have fatigue performance consistent with baseline materials

Outline

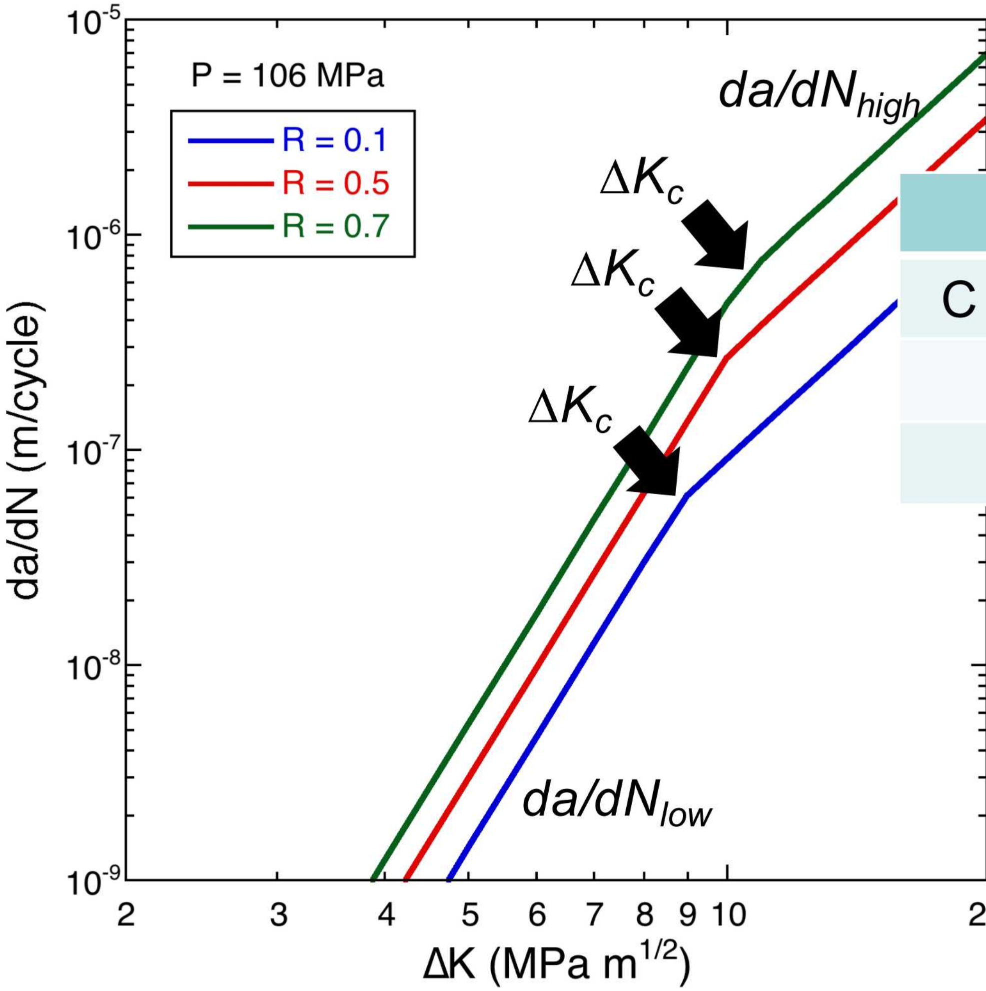
- Materials Qualification for FCEVs
  - SAE H2 Compatibility Expert Team
  - SAE J2579 Appendix B
    - Summary
    - Justification
- Fatigue crack growth rate (FCGR) laws for high-pressure storage tanks
  - ASME BPVC VIII.3 KD-10
  - Extrapolation to other ferritic steels
  - Effects of pressure

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)

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

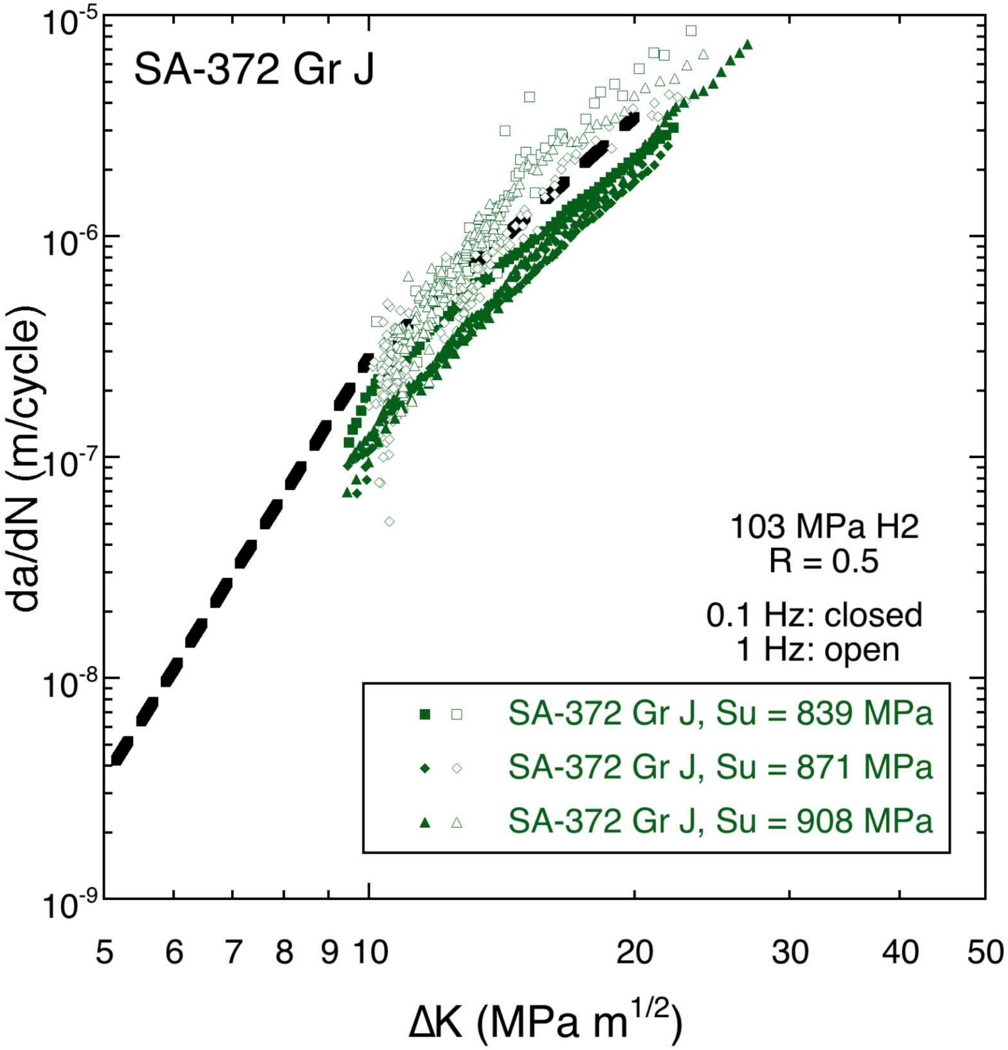
$\Delta K < \Delta K_c$: $\quad da/dN = da/dN_{low}$

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

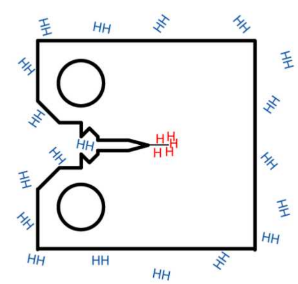
$$\Delta K_c = 8.475 + 4.062R - 1.696R^2$$

ΔK, ΔK_c units: MPa m$^{1/2}$

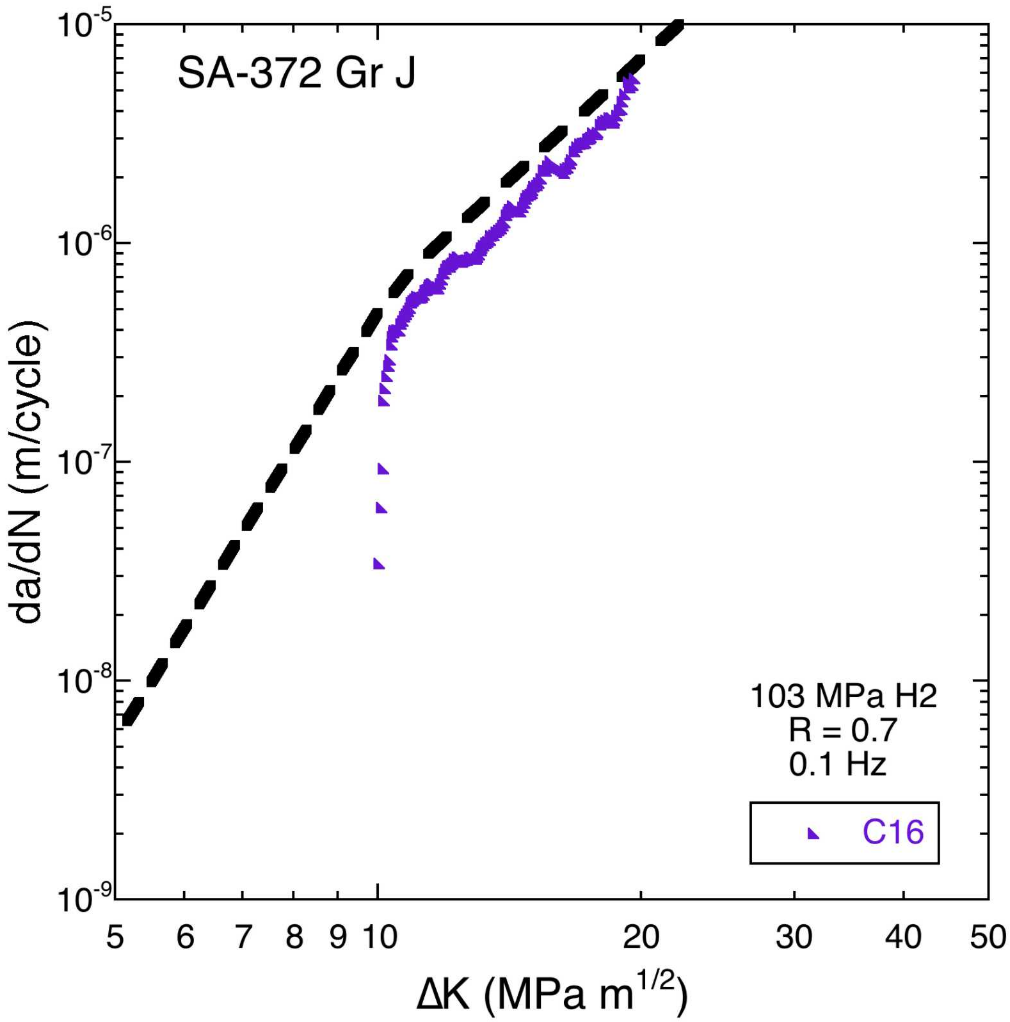
Fatigue crack growth rates of SA-372 Grade J R = 0.5



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



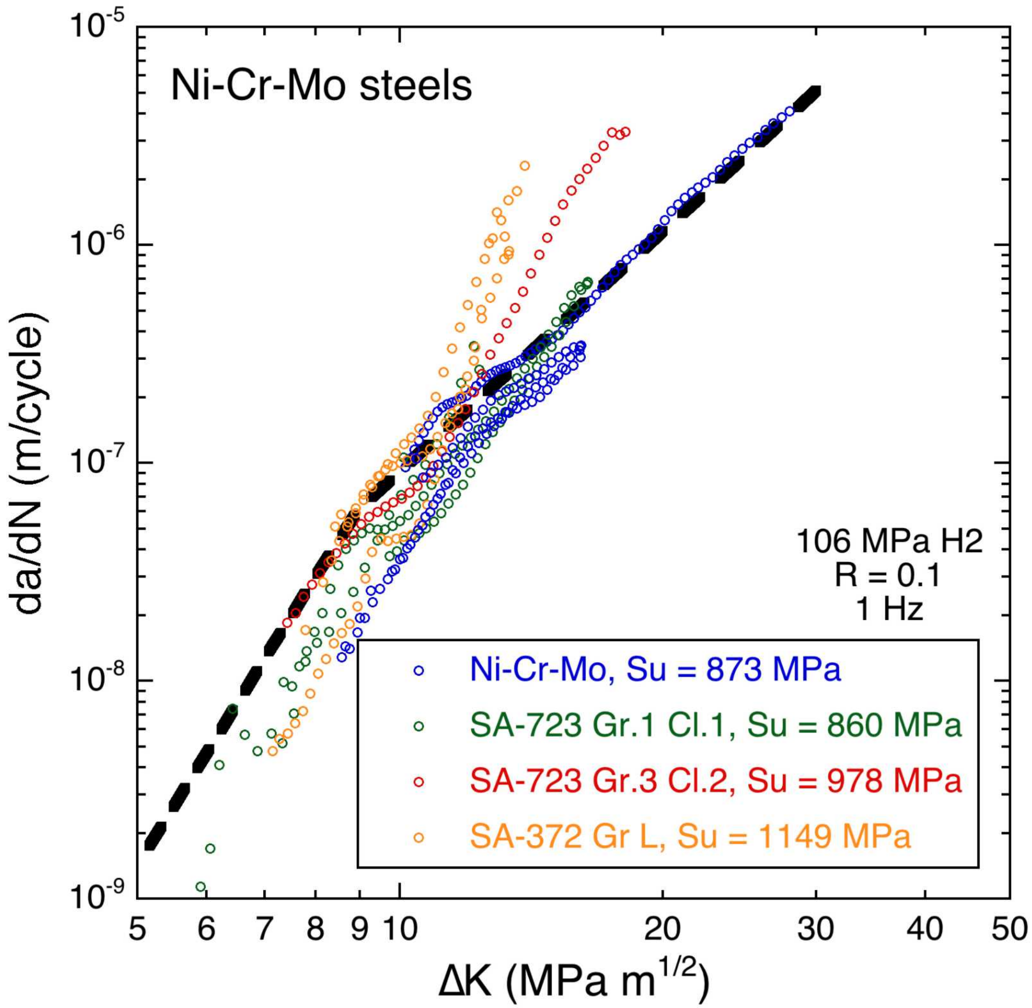
Fatigue crack growth rates of SA-372 Grade J R = 0.7



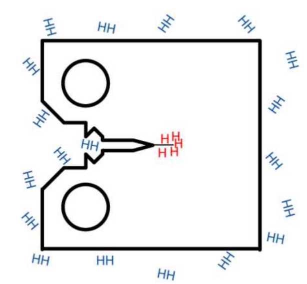
- **Gaseous hydrogen at pressure of 103 MPa**
- **R = 0.7**
- **0.1 Hz**
- **Data not published?**
  - **Not from SNL**

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

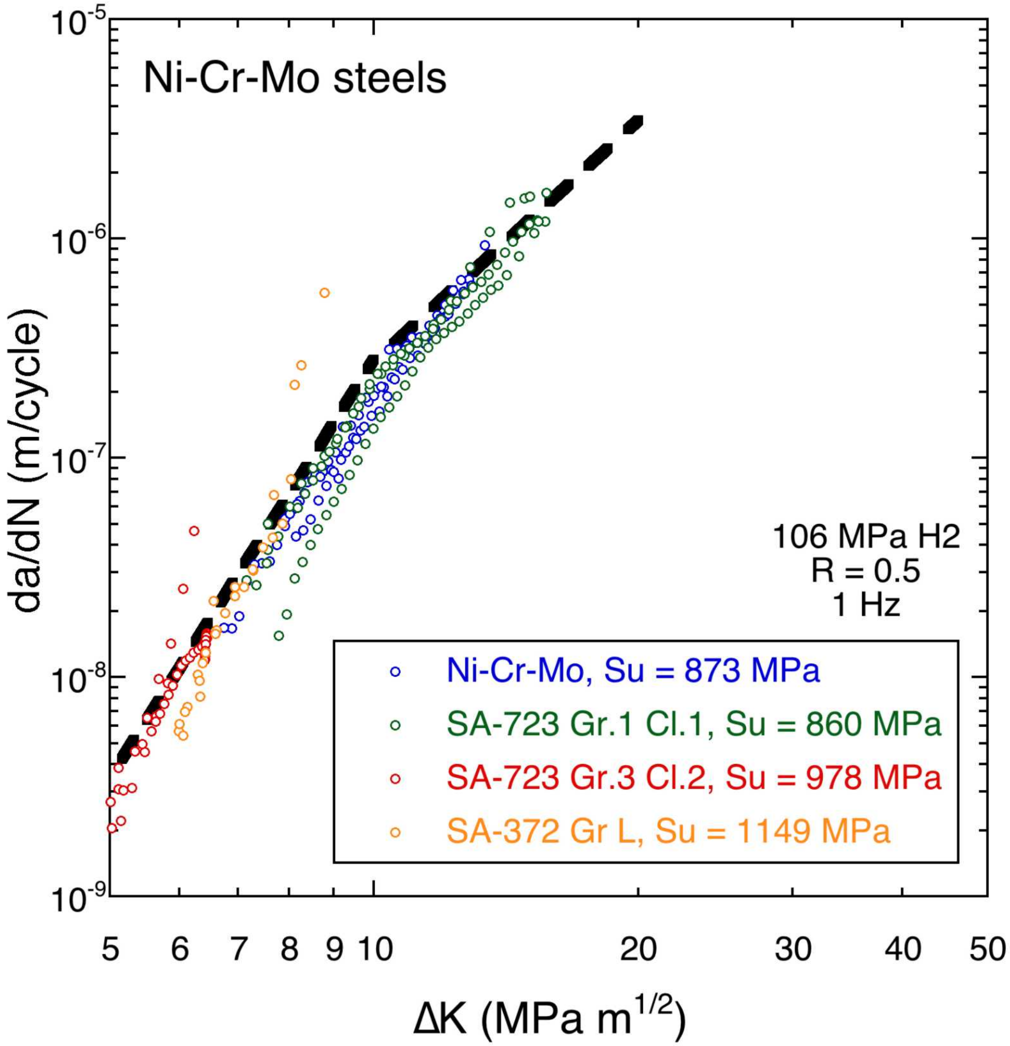
Fatigue crack growth rates of Ni-Cr-Mo steels R = 0.1



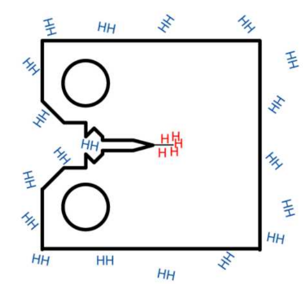
- **Gaseous hydrogen at pressure of 106 MPa**
- **R = 0.1**
- **Frequency of 1 Hz**
- **Data from ICHS 2017**



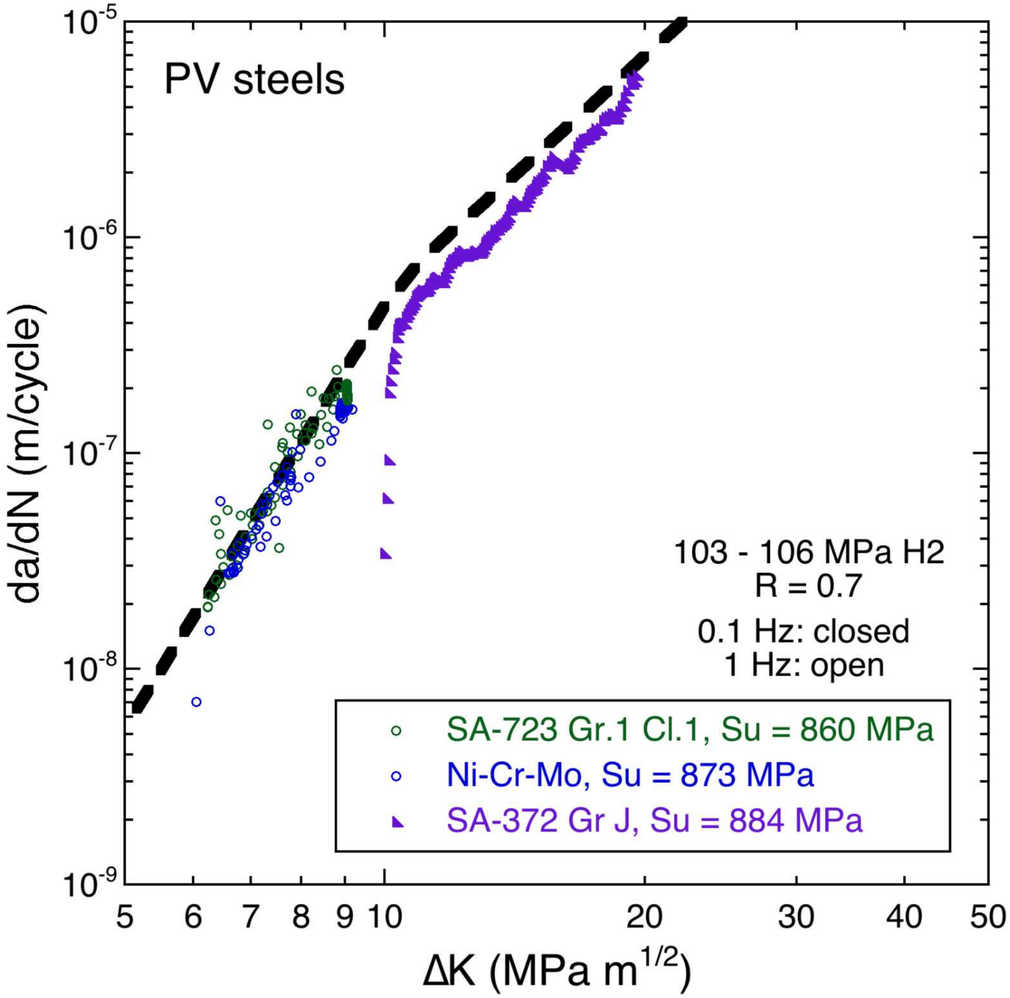
Fatigue crack growth rates of Ni-Cr-Mo steels R = 0.5



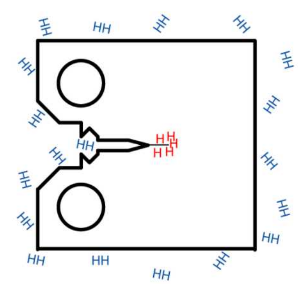
- Gaseous hydrogen at pressure of 106 MPa
- R = 0.5
- Frequency of 1 Hz
- Data from ICHS 2017



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

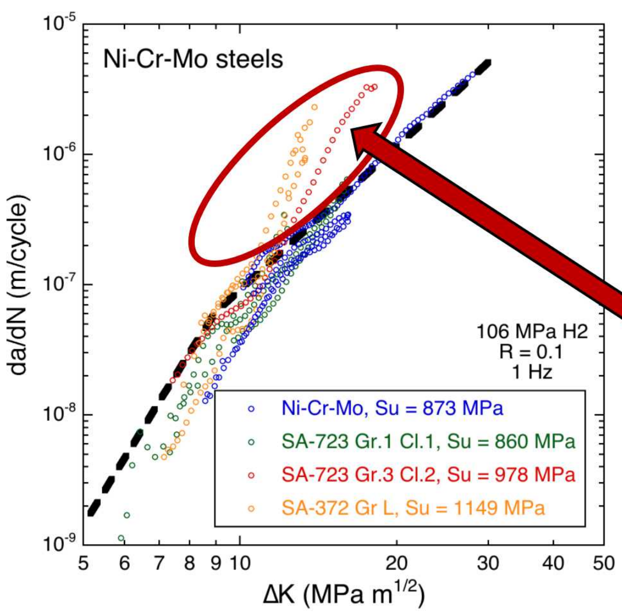


- **Gaseous hydrogen**
- **R = 0.7**
- **Cr-Mo steel data (0.1 Hz) from NIST (unpublished?)**
  - **P = 103 MPa**
- **Ni-Cr-Mo steel data (1 Hz) from ICHS 2017**
  - **P = 106 MPa**



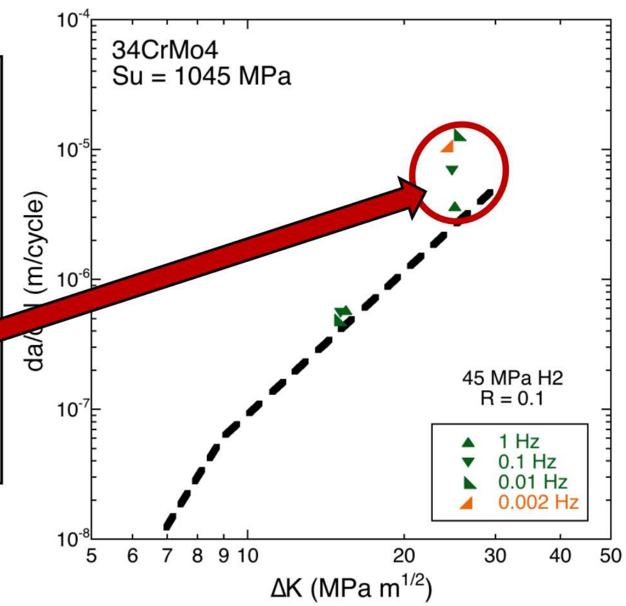
Basis for limiting strength
Hydrogen-assisted fatigue crack growth

- **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)**

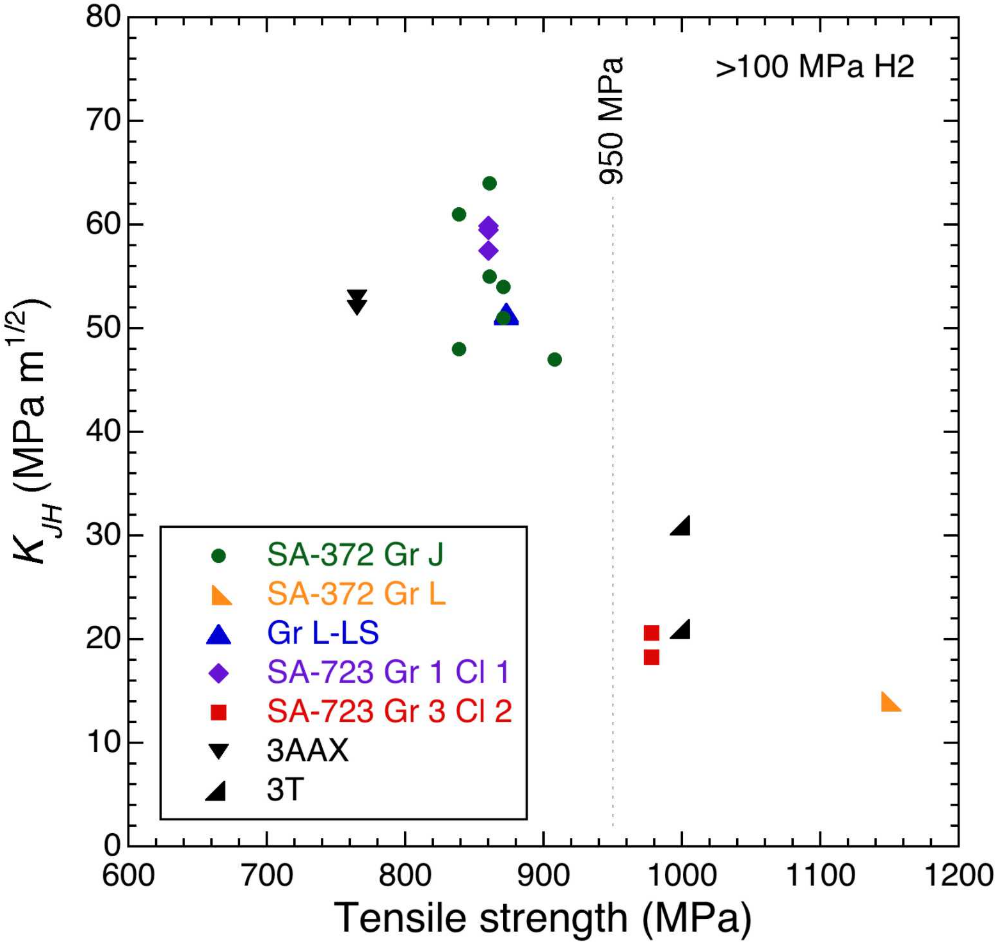


For PV steels with Su > 950 MPa

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



Basis for limiting strength
Fracture resistance – rising load (K_{JH})

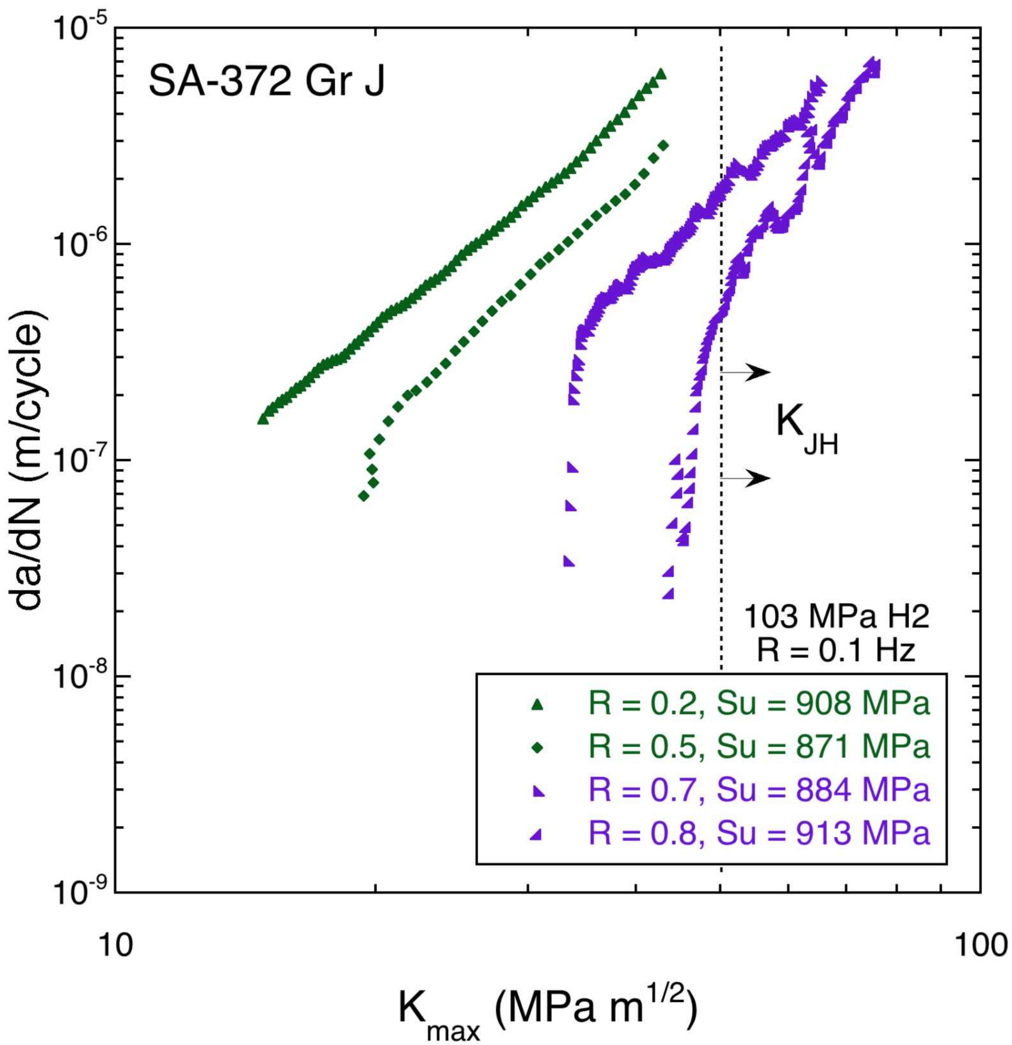


PV steels display low fracture resistance in high strength condition

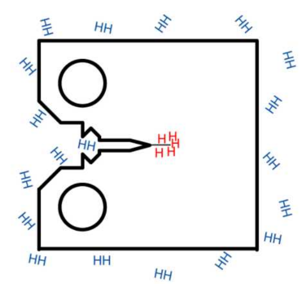
- **For tensile strength < 950 MPa**
  - **K_{JH} > 45 MPa m$^{1/2}$**
- **For tensile strength > 950 MPa**
  - **K_{JH} < 30 MPa m$^{1/2}$**

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

Basis for limiting K_{max}

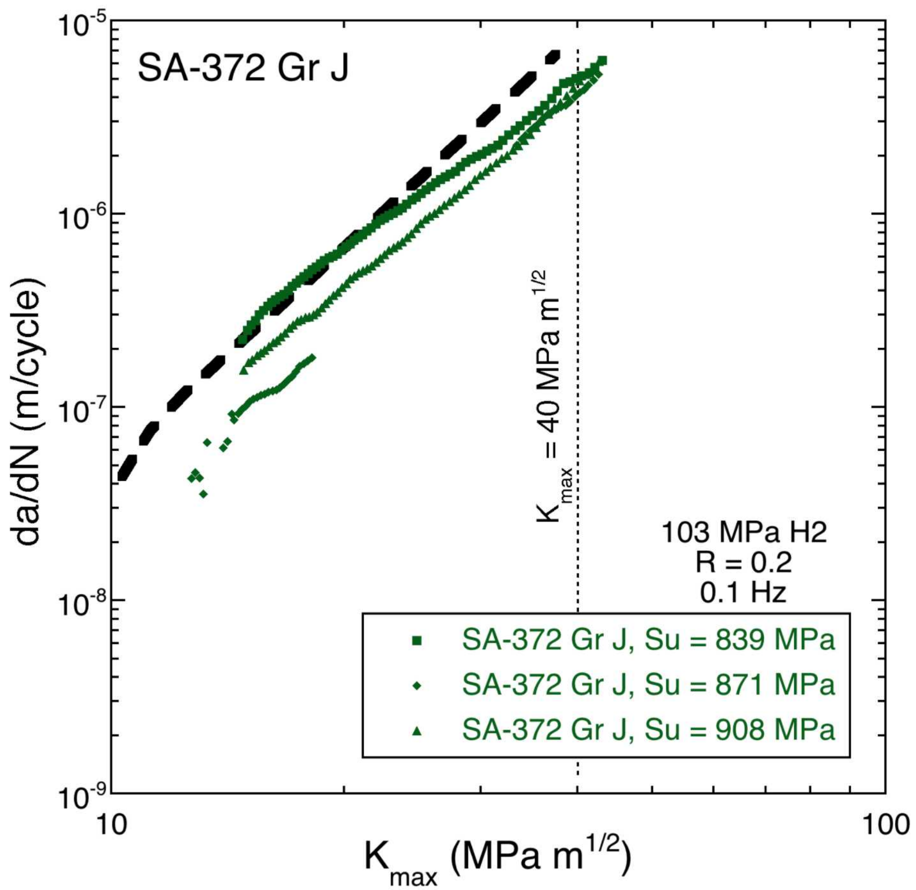


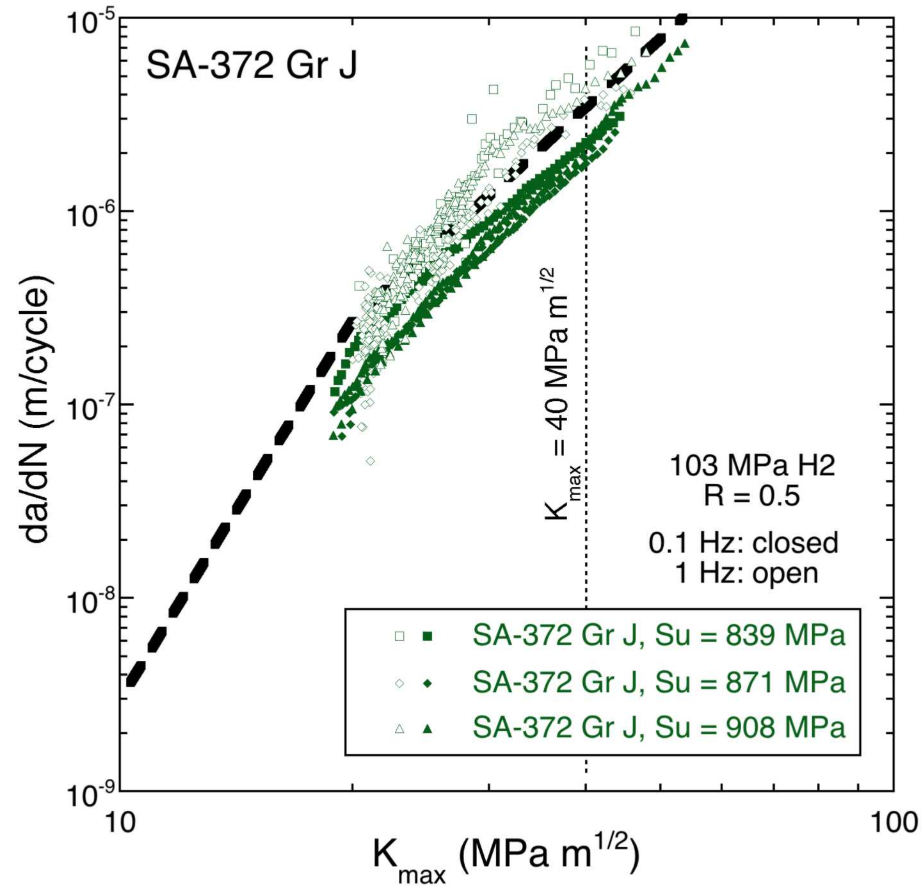
- **"Stage III" fatigue crack growth begins at $K_{max} < K_{JH}$**
  - **The proposed relationships do not capture stage III**
- **$K_{JH} \geq$ 45-50 MPa m$^{1/2}$ for tensile strength < 950 MPa**
- **$K_{max} \leq$ 40 MPa m$^{1/2}$ provides a bound on the proposed relationships to ensure $K_{max} \leq K_{JH}$ for steels with tensile strength < 950 MPa**



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)





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**
  - **$K_{max} \leq 40$ MPa $m^{1/2}$**

Outlook: Pressure term can be added to extend applicability to lower pressure and other steels

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

- f is fugacity (related to pressure) and f_{ref} is the reference fugacity for which other terms were developed