Proposed test method to establish hydrogen compatibility of materials for fuel cell vehicles

GTR no. 13 Phase 2 IWG

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In collaboration with SAE Fuel Cell Safety Task Force

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Motivation: *establish materials compatibility for high-pressure hydrogen service in context of hydrogen fuel cell electric vehicles*

Goals of presentation:

- Briefly summarize activity within SAE Fuel Cell Safety Task Force
  - SAE H2 Compatibility Expert Team
  - Collaborative testing and test criteria development
- Present test criteria developed for SAE J2579
  - Brief justification of requirements for materials compatibility

SAE Fuel Cell Safety Task Force

- Meets quarterly with broad representation from automotive OEMs
- Tasked with developing several standards for fuel cell vehicles in context of safety
  - J2579 - *Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles*
    - Includes requirements for materials in contact with high-pressure gaseous hydrogen
  - SAE H2 Compatibility Expert Team
    - Formed to develop requirements for hydrogen compatibility of materials
    - Includes hydrogen compatibility experts identified by Task Force representation

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

- **Material must be defined by and satisfy requirements for**
  - **Composition**
  - **Tensile properties: specified minimum Sy, Su, El**
- **Environmental test conditions**
  - **Pressure ≥ 1.25 NWP (nominal working pressure)**
  - **Test temperature: 228 K (for most materials)**
  - **Measured gas purity according to CSA CHMC1**
    - **2 ppm O_2, 10 ppm H_2O**

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

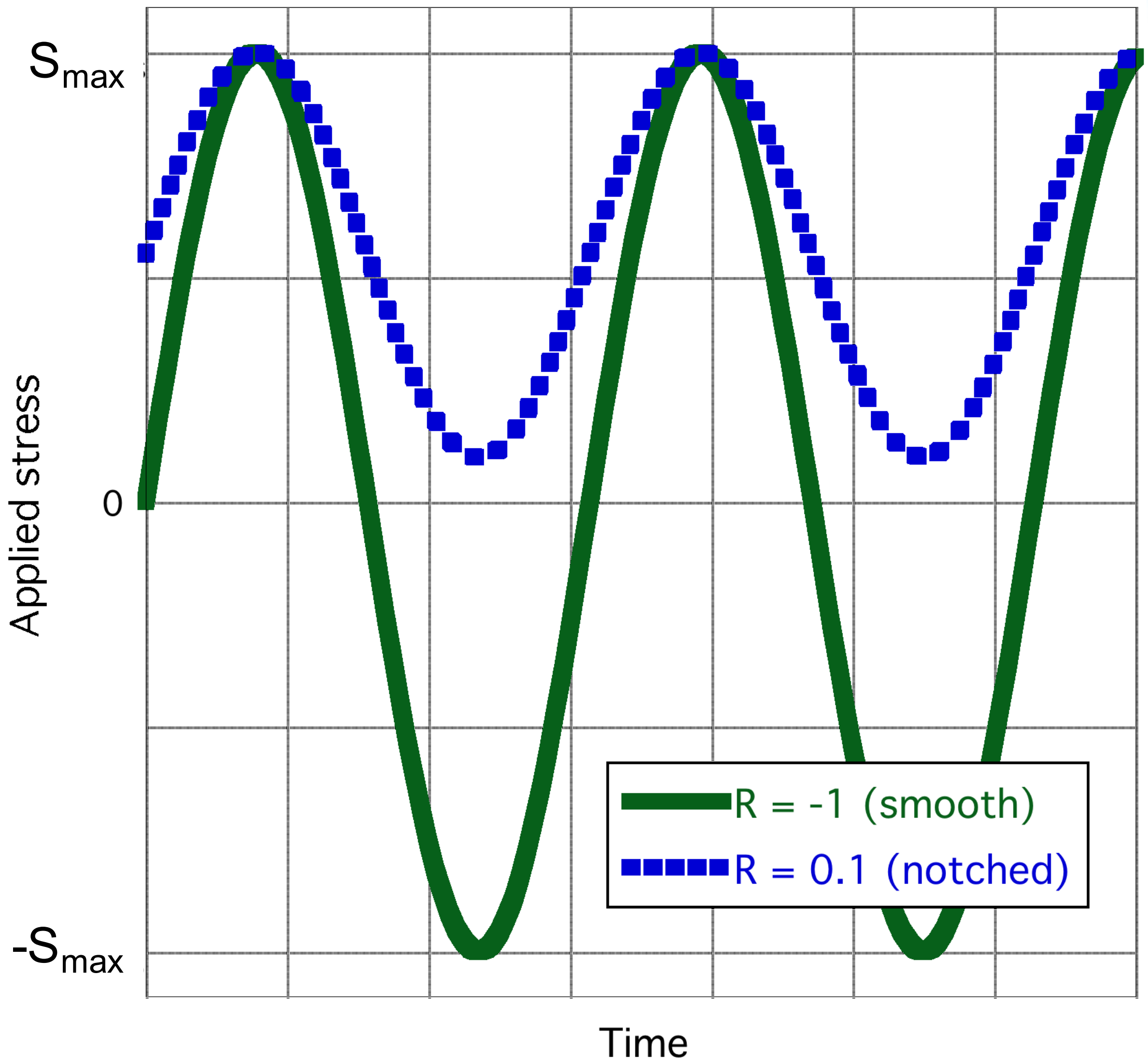
Part 2: Slow strain rate tension test

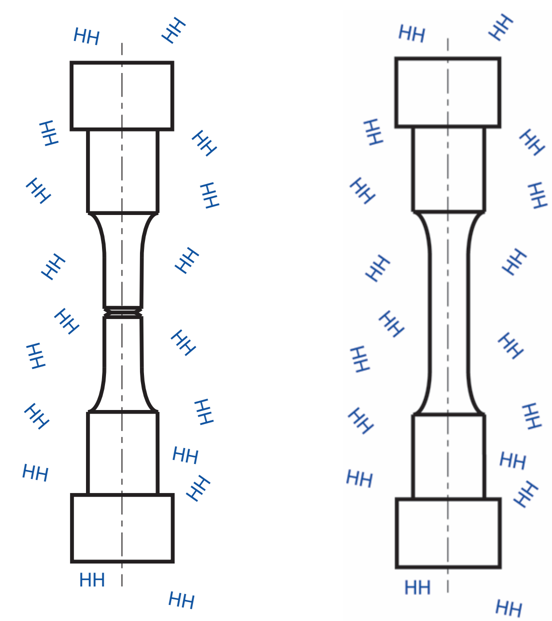
- **Basic tensile test at slow strain rate in the defined hydrogen environment**
- **Minimum of three (3) tests**
- **Average property values must be greater than the specified minimum Sy and Su values respectively**
- **Average elongation (El) > 12%**
- **Additionally, Su/Sy > 1.07**

Part 3: Fatigue life test

- Force-controlled (axially loaded cylindrical) fatigue test in the defined hydrogen environment
  - Frequency of 1 Hz
  - Maximum stress shall be 1/3 of measured Su (air)
- Minimum of three (3) tests
- Two test configuration options
  - Option 1: smooth test specimen with R = -1, or
  - Option 2: notched test specimen with R = 0.1
- Cycles to failure >200,000 cycles for each test
  - Alternatively, cycles to failure >100,000 cycles for each of 5 notched test specimens

Part 3: Fatigue life test: stress cycle





notched
tension
tension

smooth
tension
compression

Part 4: Welds

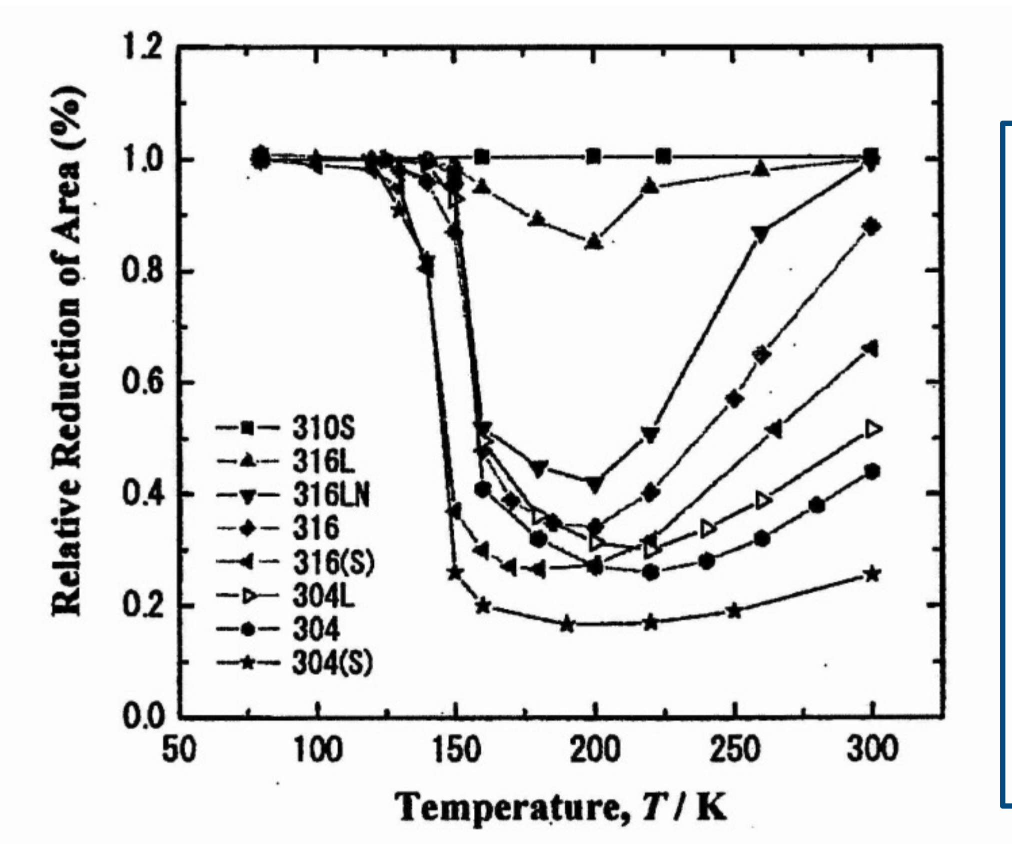
- Prepare representative welded structures
- Same testing requirements as for non-welded materials
  - Specified minimum tensile properties must be defined
  - Weld material must satisfy the minimum specified properties
  - Average values from SSRT tests of weld-material must satisfy minimum specified strength properties, El > 12% and Su/Sy > 1.07
  - Fatigue life must be >200,000 cycles for each of three (3) smooth or notched fatigue tests; or >100,000 cycles for each of (5) notched fatigue tests

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

Tensile properties are degraded in gaseous hydrogen especially at low temperature



Requirement:

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

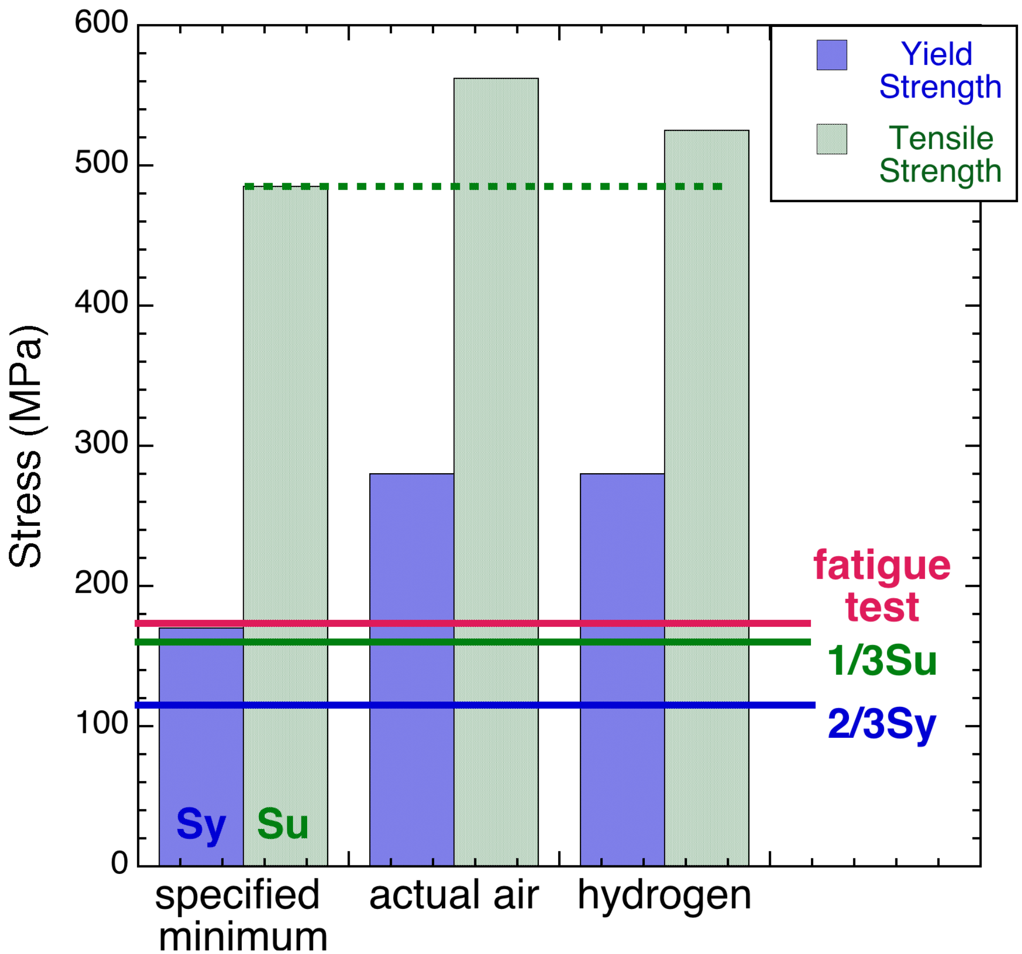
Rationale:

- Known and ductile tensile response

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

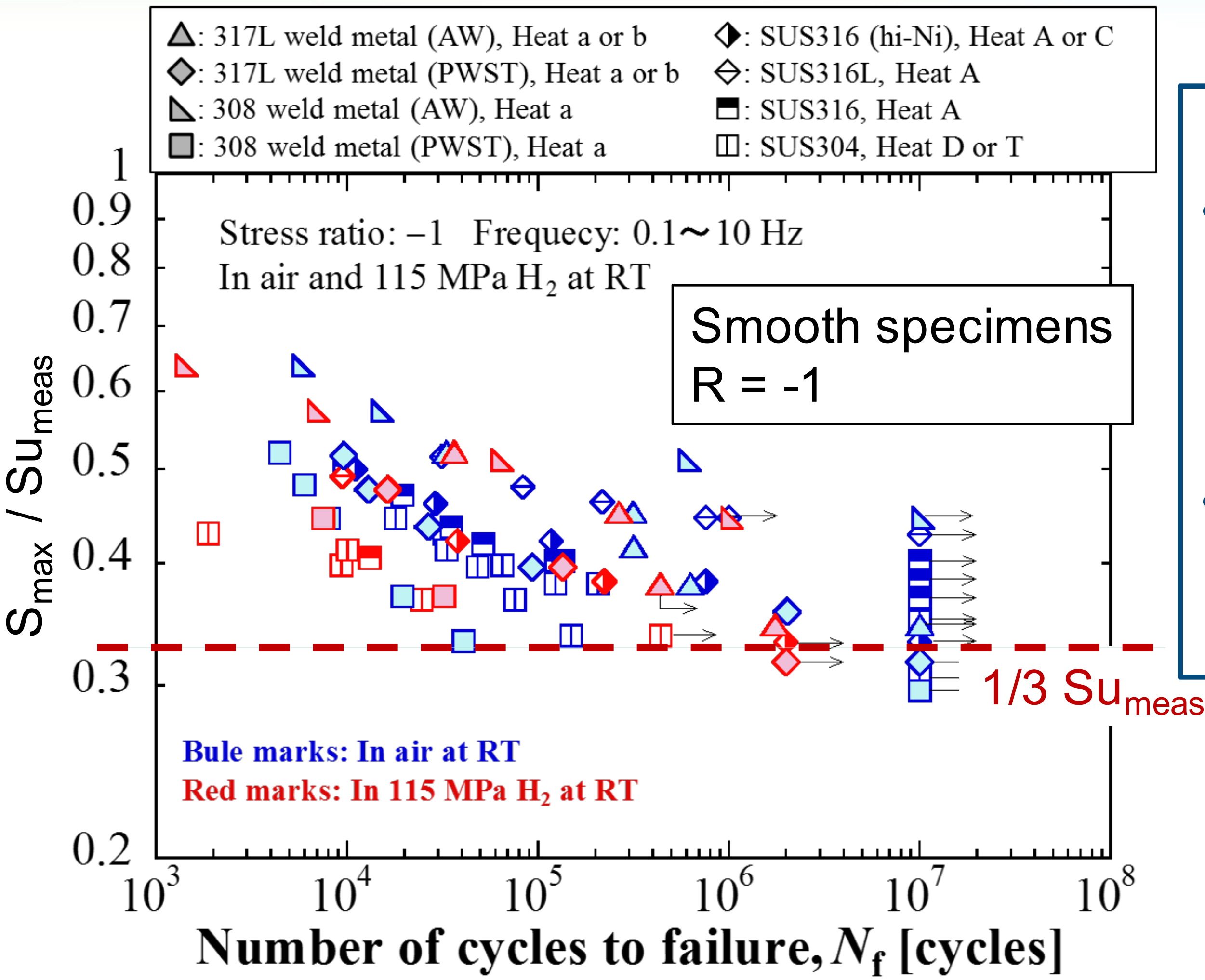
Tensile strength properties are not degraded in gaseous hydrogen for acceptable materials

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:

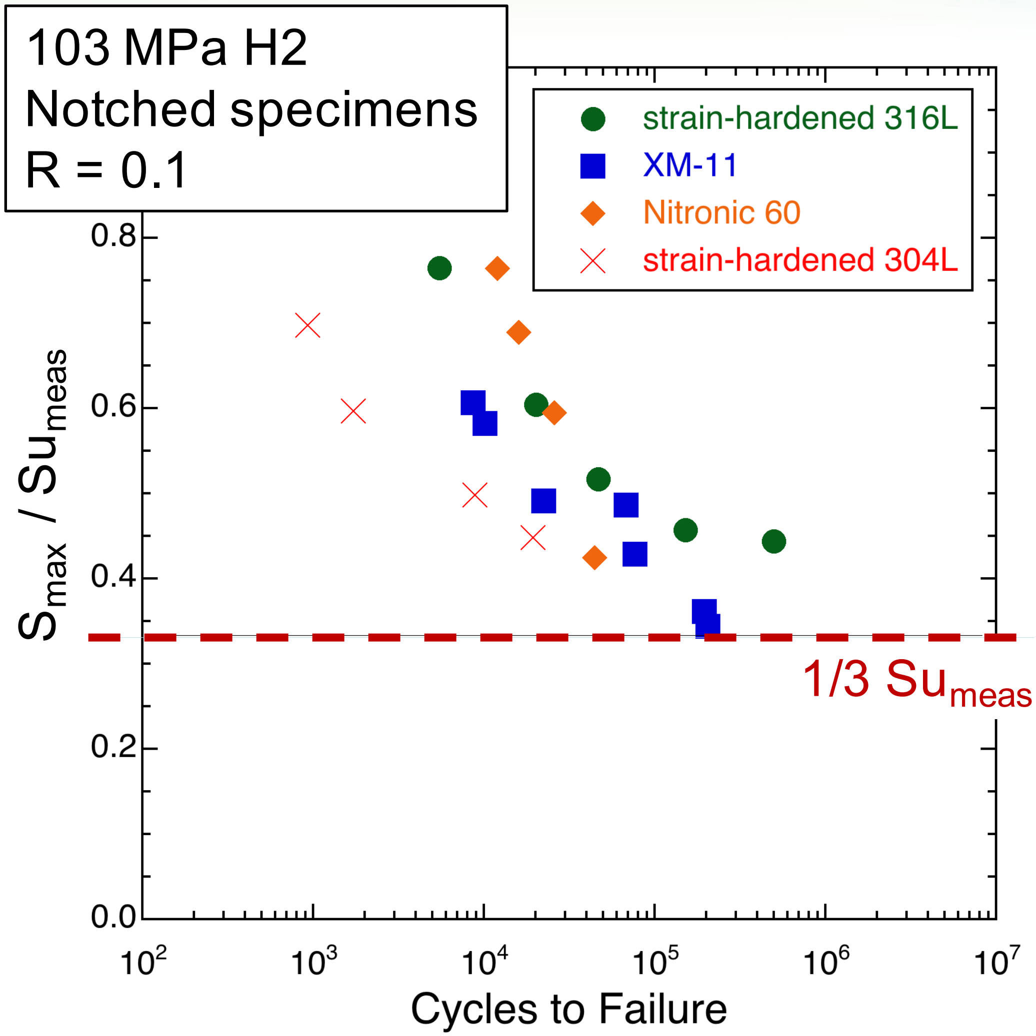
- Nf > 200,000 cycles at S_{max} = 1/3 Su_{meas}

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

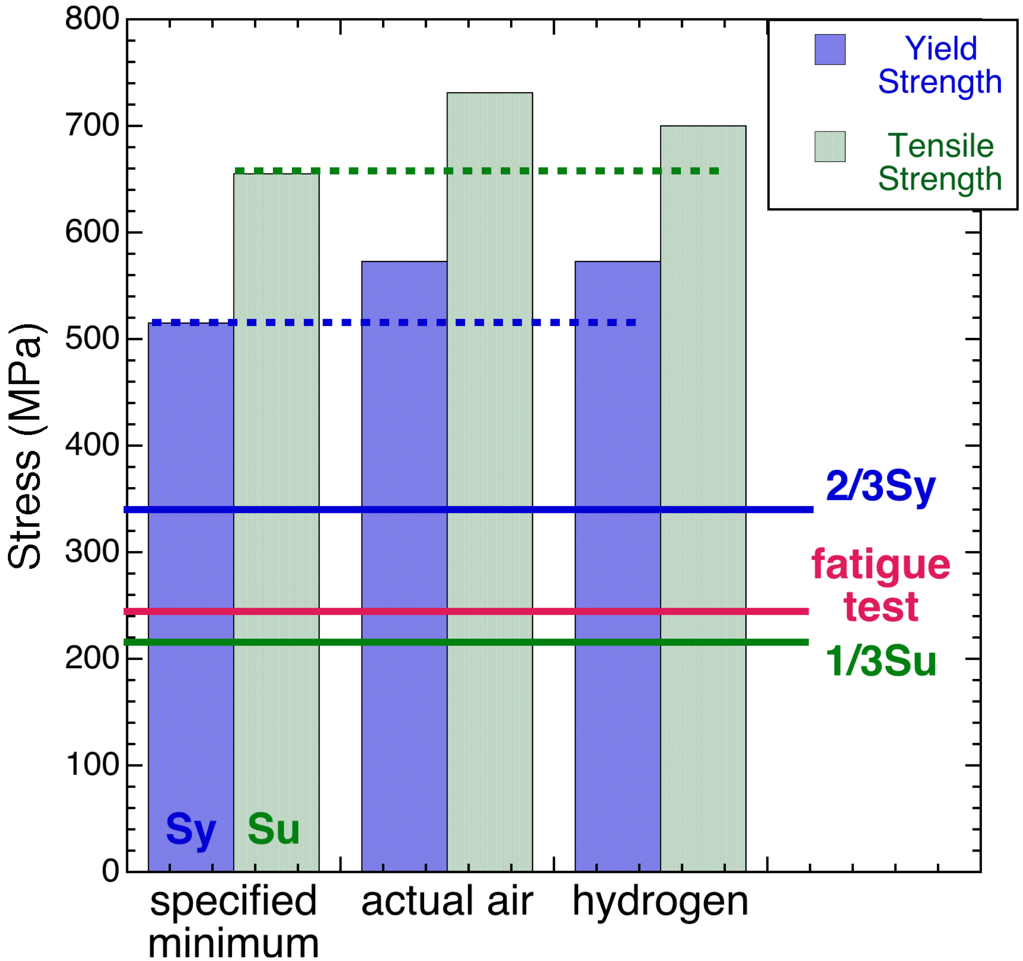
material	Yield (MPa)	Tensile (MPa)	Cr	Ni	Mn	N	Typical allowable stress (MPa)
316L	280	562	17.5	12	1.2	0.04	115
CW 316L	573	731	17.5	12	1.2	0.04	218
304L	497	721	18.3	8.2	1.8	0.56	195
XM-11	539	881	20.4	6.2	9.6	0.26	207
Nitronic 60	880	1018	16.6	8.3	8.0	0.16	218
SCF-260	1083	1175	19.1	3.3	17.4	0.64	333

Wide range of strength

Wide range of Ni/Mn content

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

Strain-hardened austenitic stainless steel

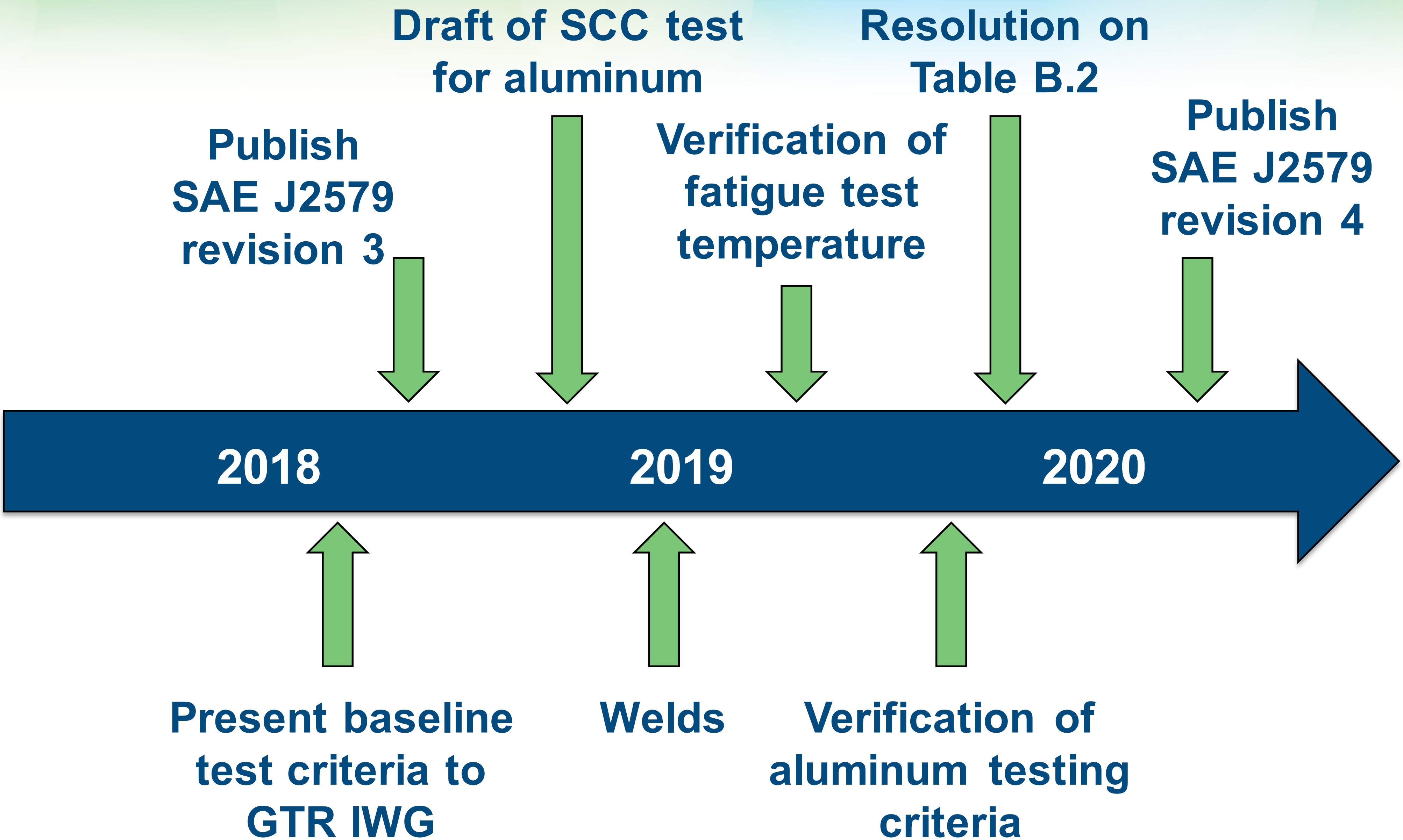


- **1/3 Su of high-strength materials can be more then specified minimum yield strength of annealed material**
- **Implicitly, increase of design stress enables lower weight and lower cost designs without compromising performance**
  - **Justified by fatigue performance**

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


Draft of SCC test for aluminum
Resolution on Table B.2
Publish SAE J2579 revision 3
Verification of fatigue test temperature
Publish SAE J2579 revision 4
2018
2019
2020
Present baseline test criteria to GTR IWG
Welds
Verification of aluminum testing criteria

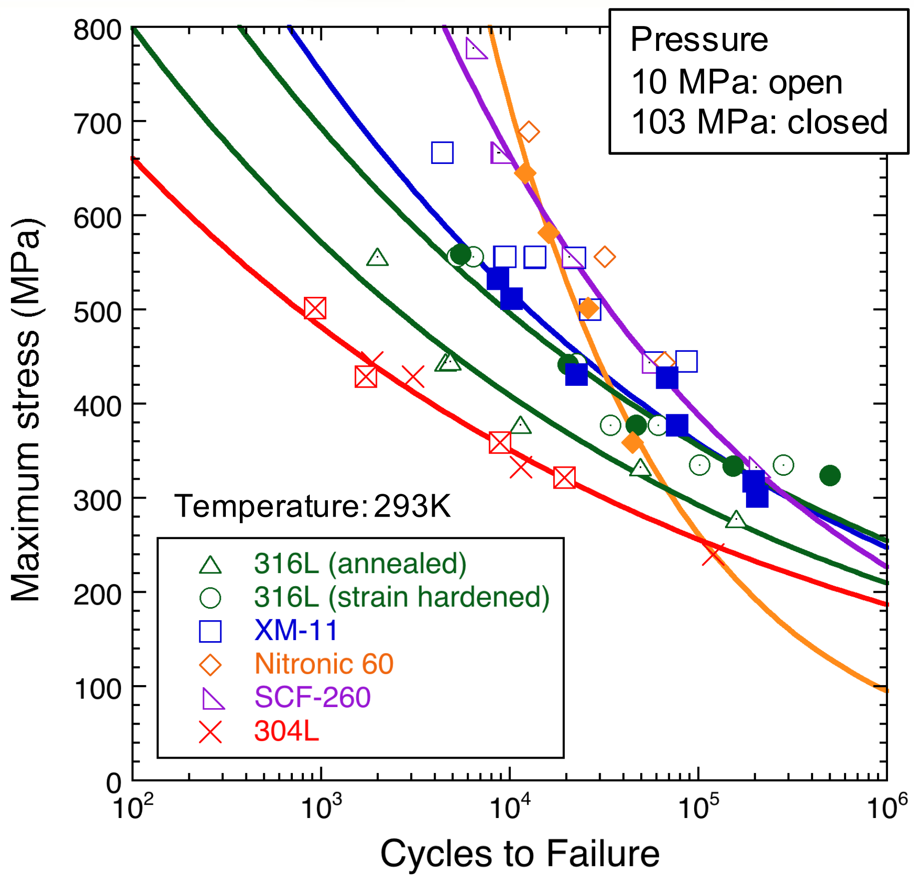
Summary

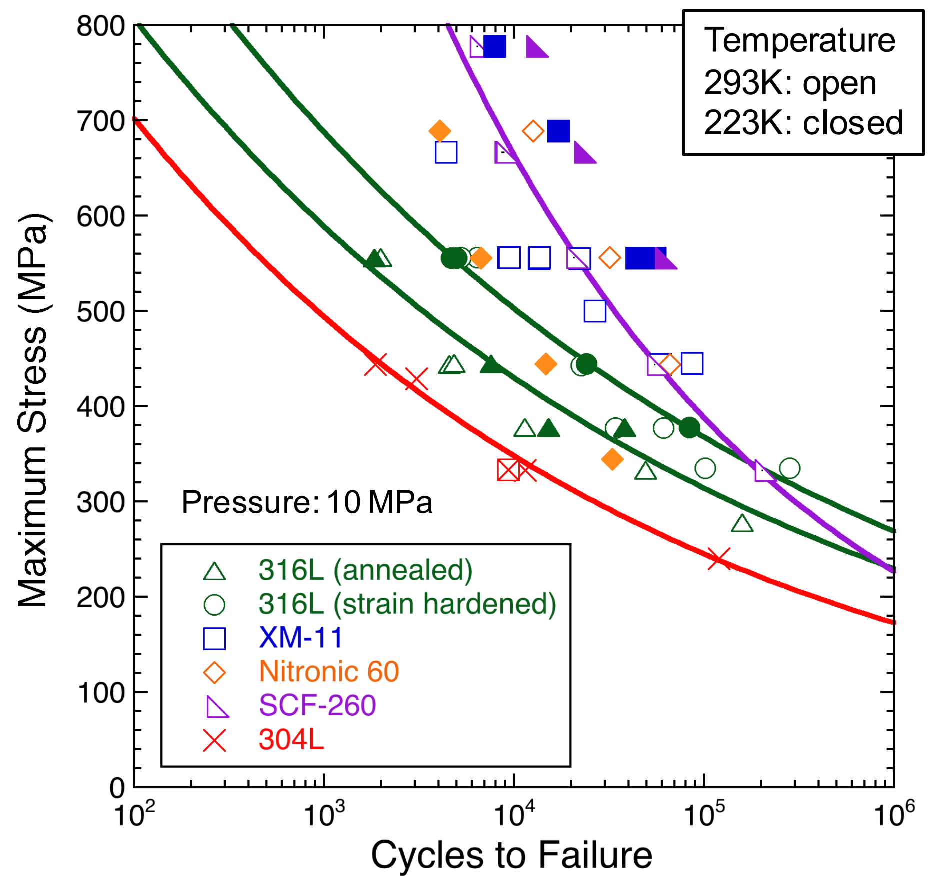
- Materials compatibility test method in SAE J2579 provides performance-based metrics to evaluate materials for hydrogen service
  - J2579 Appendix B.3 requirements for materials do not purport to generate design data
  - Method consists for 4 parts
    - 1: Materials definition
    - 2: Slow strain 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

Backup slides

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