Materials Compatibility

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Overview

Timeline

- Project start date Oct 2003
- Project end date Sep 2015
- Percent complete 33%

Budget

- Total project funding (from FY03)
  - DOE share: $8.3M
- FY06 Funding: $1.5M
- FY07 Funding: $2.9M ($800K for materials compatibility)

Partners

- Collaborators:
  - ASME
  - CSA
  - Swagelok
  - NIST
  - DOE Pipeline Working Group

Barriers & Targets

2006 MYRDDP Section 3.6.4.1 Targets:

- Provide expertise and technical data on hydrogen behavior and hydrogen technologies
- Hydrogen storage tank standards for portable, stationary and vehicular use
- Materials reference guide for design and installation
- Standards for pipelines, delivery and ancillary equipment

2006 MYRDDP Section 3.6.4.2 Barriers:

- J. Lack of National Consensus on Codes & Standards
- K. Lack of Sustained Domestic Industry Support at International Technical Committees
- N. Insufficient Technical Data to Revise Standards

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Objectives

- Safe design of structures for storage and transport of high-pressure hydrogen gas requires material property data that reflects service conditions
  - Identify and document existing data on hydrogen compatibility of materials from technical journals and reports
  - Generate new data through materials testing, emphasizing testing in high-pressure hydrogen gas

- Provide advocacy and technical support for the codes and standards change process
  - ASME Project Team on Hydrogen Tanks
  - ASME Project Team on Hydrogen Piping and Pipelines
  - CSA HGV and HPRD technical committees

Approach

- Compose "Technical Reference for Hydrogen Compatibility of Materials", a compilation of existing data in material-specific chapters (www.ca.sandia.gov/matlsTechRef)
  - ferritic steels (pipelines and pressure vessels)
  - stainless steels (tubing and valves)
  - aluminum alloys (pressure vessels and components)
  - copper (seals)
  - materials not recommended for H_2 service (ferritic stainless steels)

- Conduct materials testing in H_2 gas up to 100 MPa pressure
  - Test relevant structural materials, selected in collaboration with SDOs and industry stakeholders
  - Emphasize fracture mechanics methods
  - Establish procedures for generating reliable design data

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Technical Reference for Hydrogen Compatibility of Materials

- Version 1 completed
  - 14 chapters posted to website (May 2007)
- 4 chapters completed over this past reporting period
  - carbon steels (pipelines)
  - aluminum (pressure vessels and components)
  - duplex stainless steels (tubing and valves)
  - ferritic stainless steels (not recommended for H_2 service)
- New chapters scheduled for Version 2
  - heat treatable aluminum (pressure vessels and components)
  - 310 and 321 stainless steels (tubing and valves)
  - martensitic stainless steels (not recommended for H_2 service)

New chapters in Version 2 motivated by needs and interest communicated by stakeholders

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Testing steels for pressure vessels

- ASME Boiler and Pressure Vessel Project Team on Hydrogen Tanks created Article KD-10 for Section VIII, Division 3
  - "Special Requirements for Vessels in High Pressure Gaseous Hydrogen Service"
  - Specifies need for fracture mechanics-based materials data (i.e., cracking thresholds and fatigue crack growth rates) in high-pressure hydrogen gas up to 100 MPa

- Two objectives for materials testing:
  - Generate benchmark H_2 cracking thresholds for low-alloy steels currently in codes for seamless pressure vessels (SA 372 Gr. J, DOT 3T, DOT 3AAX)
  - Establish best procedures for testing in H_2

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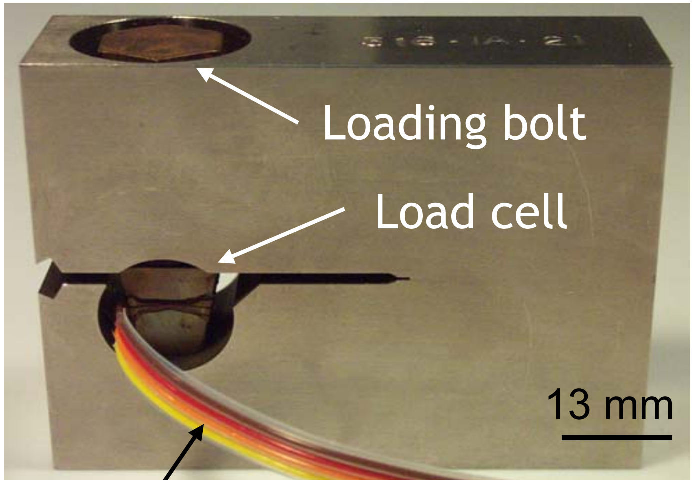
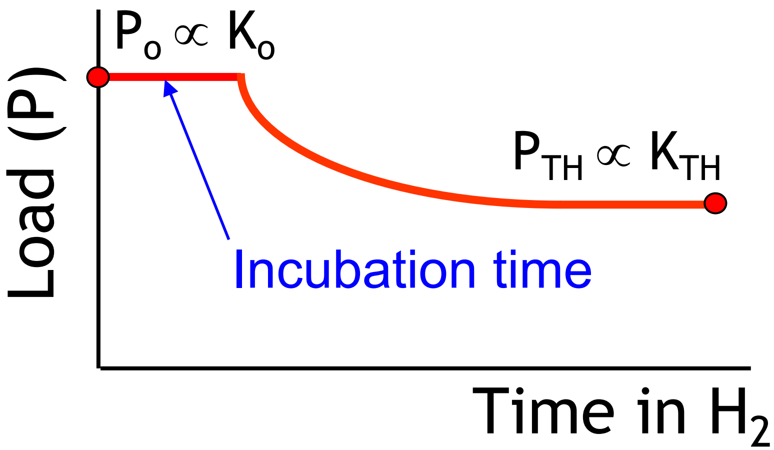
Measuring benchmark cracking thresholds (K_{TH})

wedge opening load (WOL) cracking threshold specimen



strain gage leads (Excitation and DAQ)



- Load applied with bolt, load measured *in situ* with load cell
- Specimen bolted to $K_o > K_{TH}$ in air, then exposed to H_2 gas
- Load cell gives load vs. time: crack advance → load drop
- Crack propagation initiates after incubation time, arrests when $K = K_{TH}$

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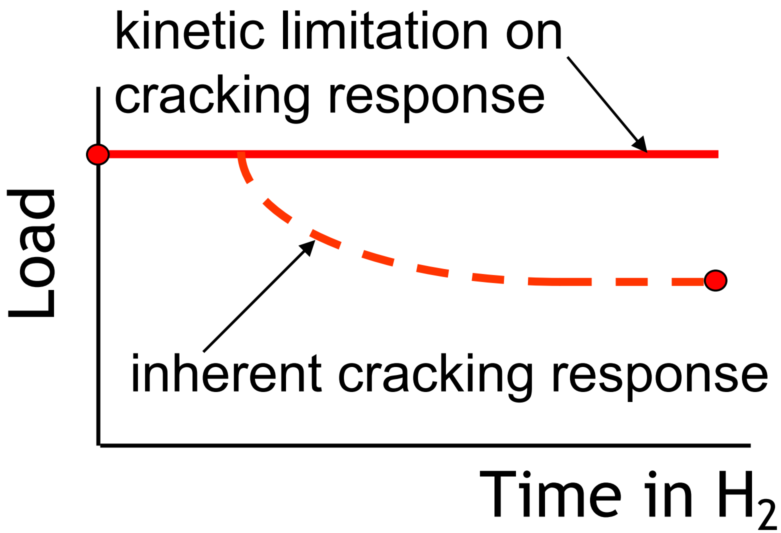
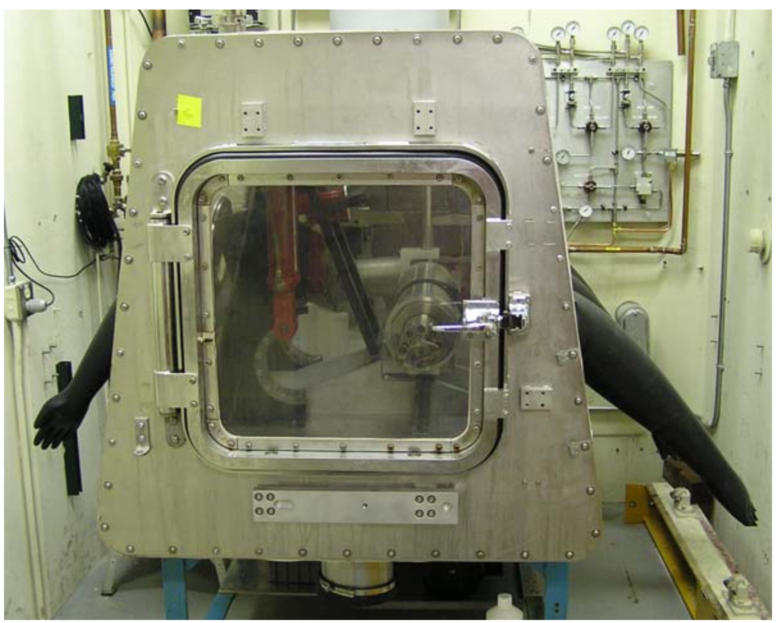
Long incubation times during cracking threshold tests circumvented with glove box





- Initial tests on steel specimens loaded in air had extended incubation times
  - Incubation times could be > 5000 hr
  - Can give false indication of "immunity" to cracking in H_2
- Designed custom glove box with internal fixtures for loading specimens in 1 ppm O_2 environment
  - Incubation times < 24 hr

Environment control procedures included in ASME Article KD-10

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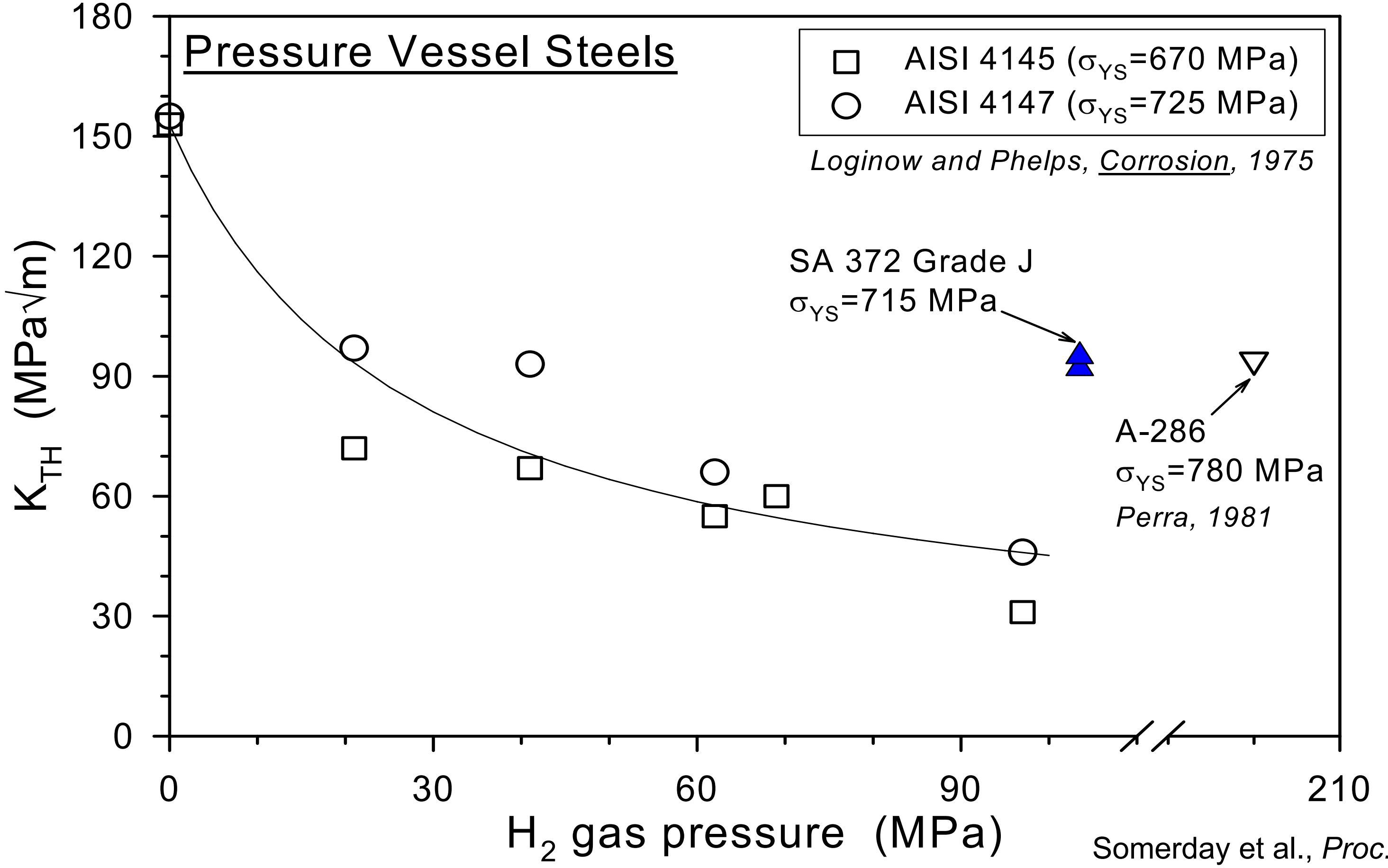
Cracking threshold (K_{TH}) measured for SA 372 Gr. J in 100 MPa H_2



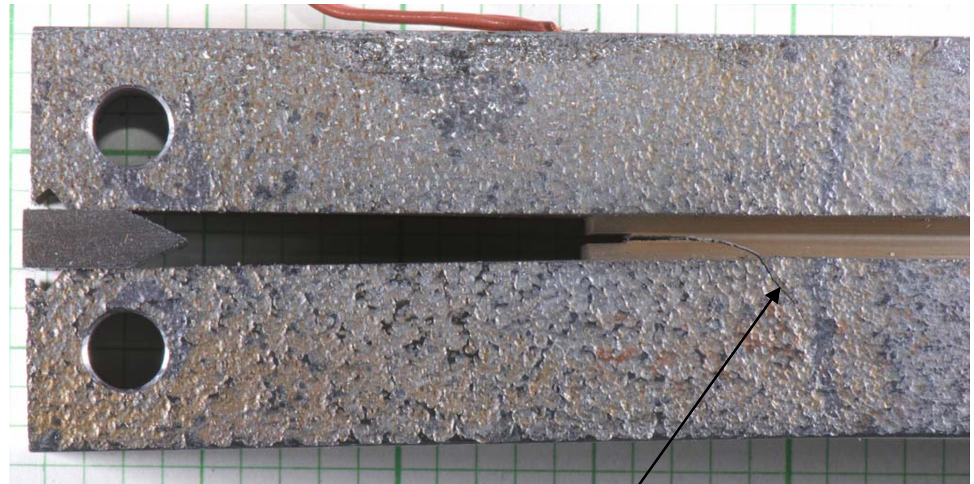
Somerday et al., *Proc. International Hydrogen Energy Development Forum & Workshop*, 2007

K_{TH} values for SA 372 Gr. J higher than historical values and approach values for stainless steel A-286

Cracking threshold specimen design must be selected judiciously

steel panel from vessel

double-cantilever beam (DCB) specimen of DOT 3T steel



deflected crack

- DCB specimen geometry may not yield successful results for materials with high H_2 cracking thresholds
  - Solution: design curved WOL specimen for testing materials from vessel/pipe walls

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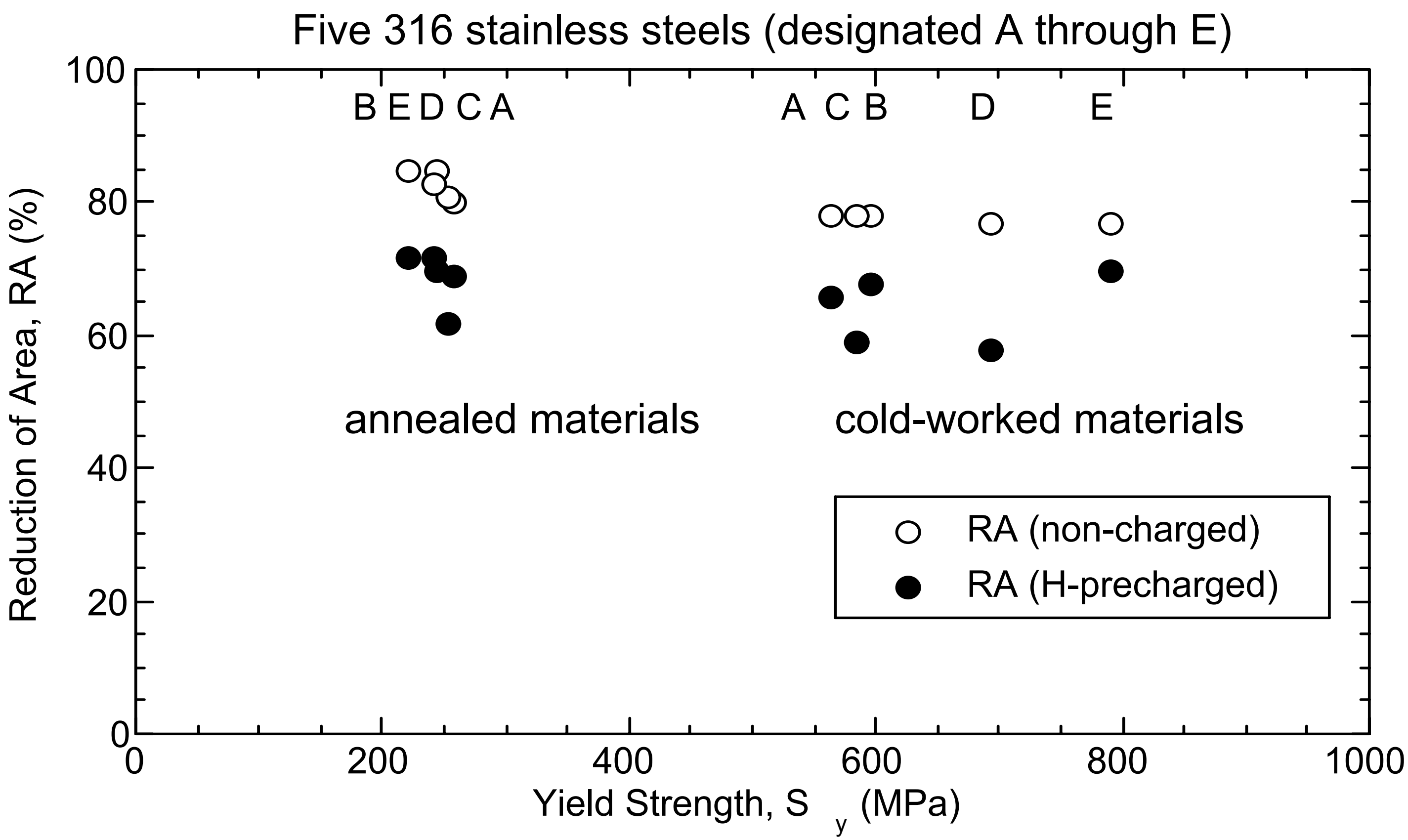
Testing stainless steels for piping

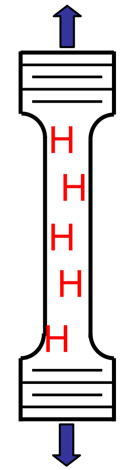
- ASME Project Team on H_2 Piping and Pipelines creating new code B31.12
  - Need material property data for 316 stainless steel exposed to high-pressure hydrogen gas

- Sandia role guided by Materials for the Hydrogen Economy Coordinating Group and DOE Pipeline Working Group

- Generate benchmark tensile fracture data of 316 stainless steel after hydrogen gas exposure
  - Emphasize cold-worked microstructures, varying test temperature, and effect of stress concentrations

Tensile fracture of H_2-exposed 316 stainless steels as a function of cold work



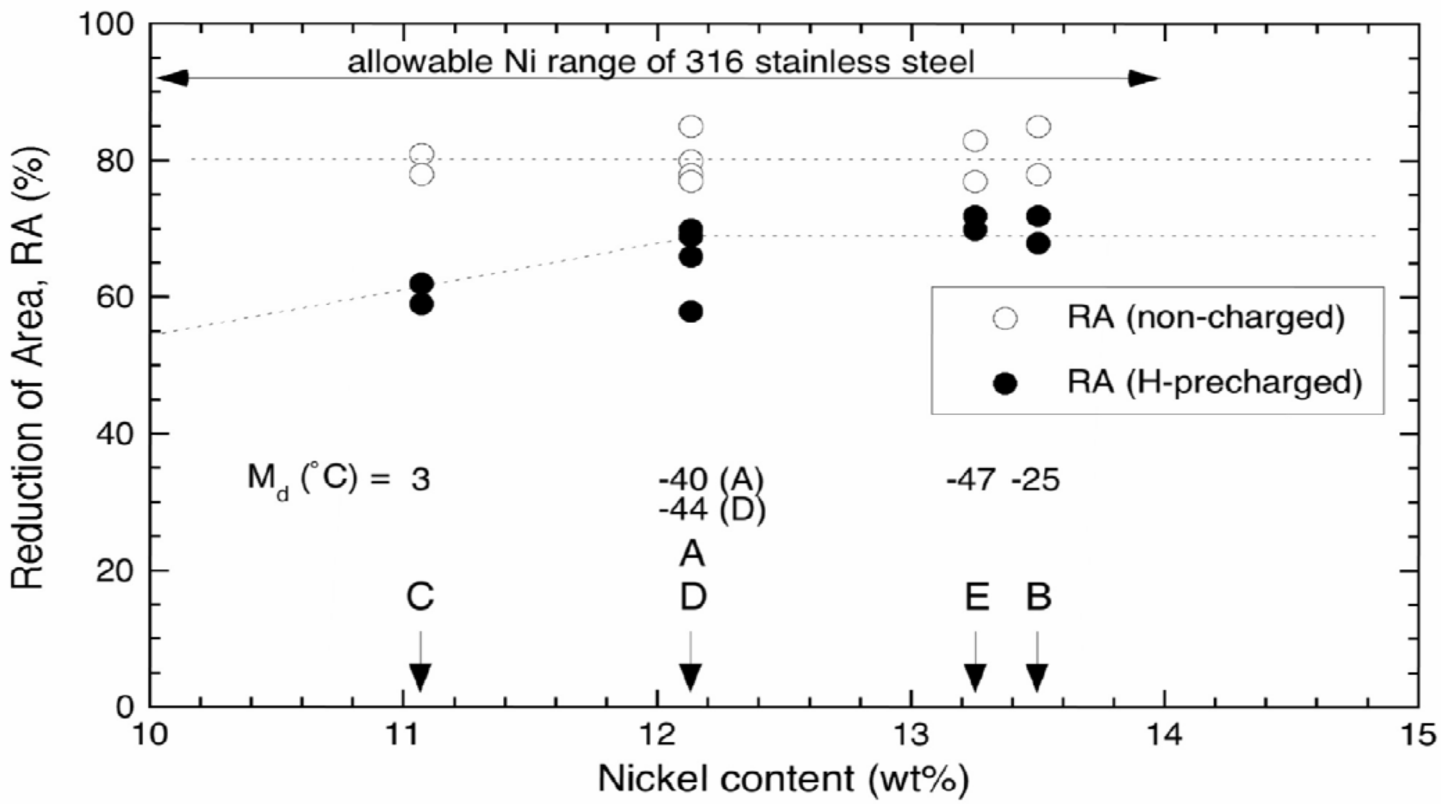


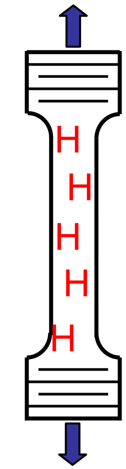
~140 wppm H

San Marchi et al., submitted to *Int J Hydrogen Energy*, 2007

Tensile fracture resistance of cold-worked (high-strength) 316 similar to annealed material

Tensile fracture of H_2-exposed 316 stainless steels as a function of Ni content





~140 wppm H

San Marchi et al., submitted to *Int J Hydrogen Energy*, 2007

H_2 compatibility of 316 stainless steel can be optimized by controlling composition, particularly nickel

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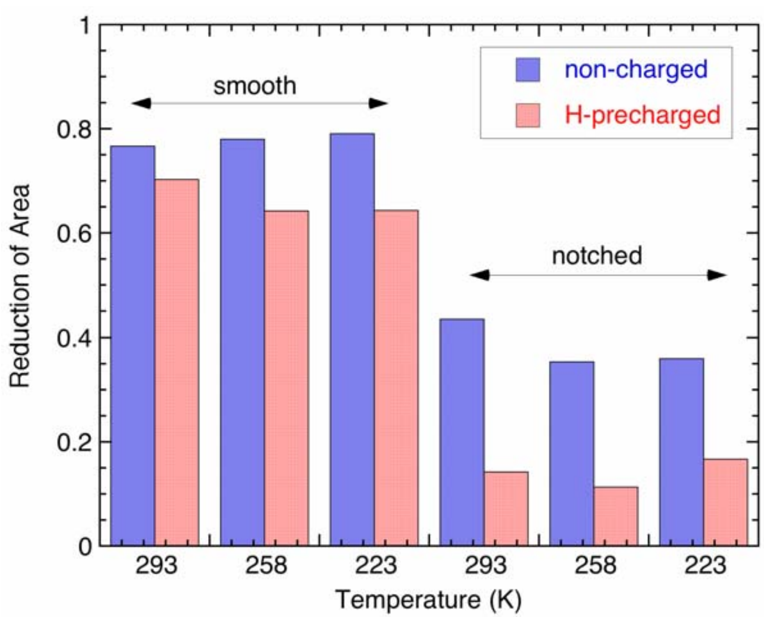
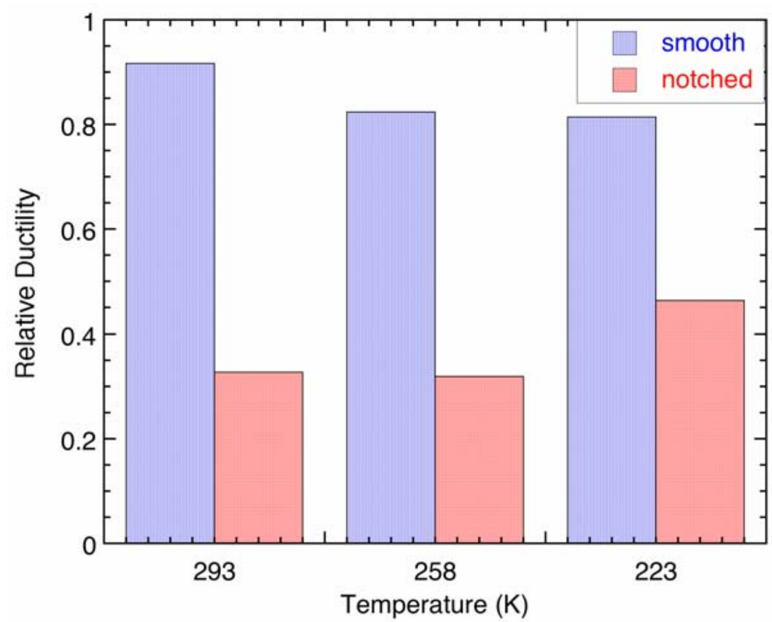
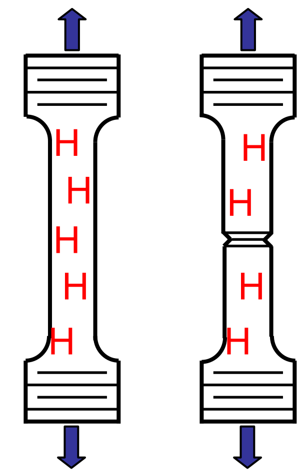
Tensile fracture of 316 as a function of temperature and stress concentration

Cold-worked 316 stainless steel Alloy E



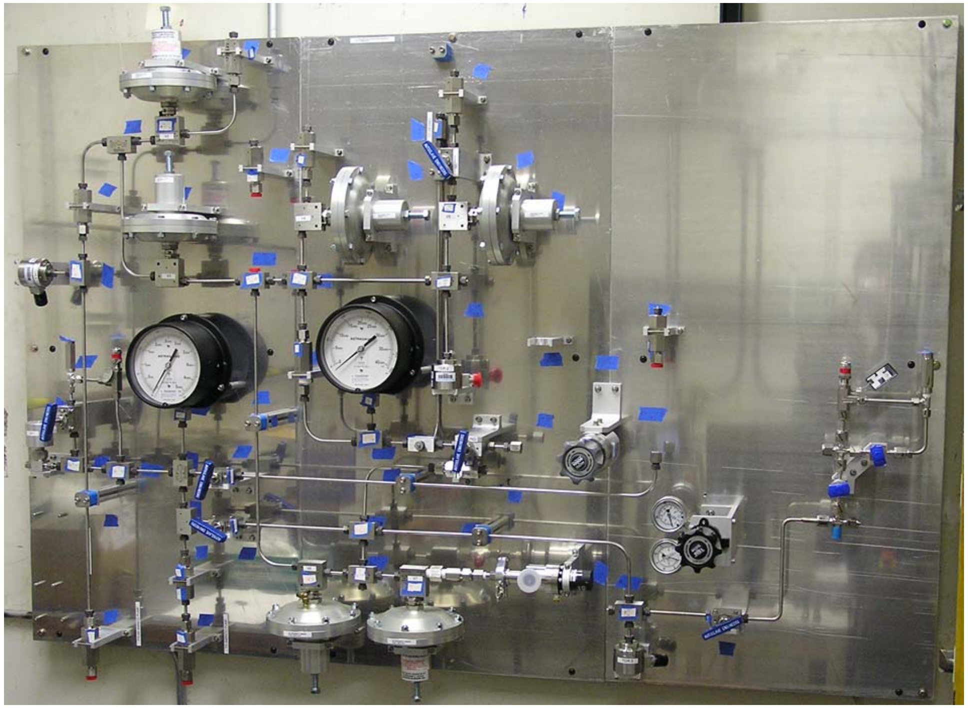


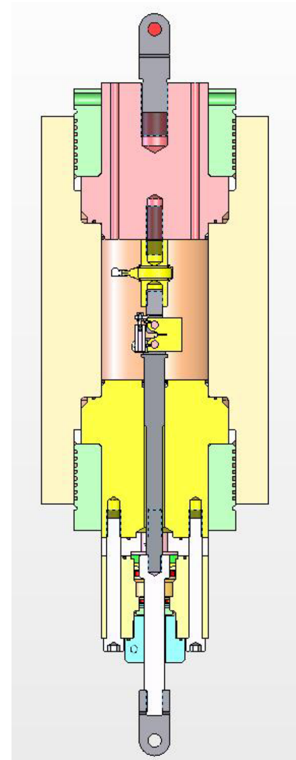


~140 wppm H

H_2 compatibility of 316 stainless steel depends mildly on temperature but strongly on stress concentration

Design of system for fatigue crack growth tests in high-pressure H_2 gas





- ASME Article KD-10 requires fatigue crack growth rate data for hydrogen containment structure design
- Pressure vessel delivery delayed by feed-through subcontractor
- Only system in U.S. for conducting fatigue tests in 100 MPa hydrogen gas

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Future Work

Remainder of FY07

- Measure cracking thresholds of DOT 3T and DOT 3AAX steels in 100 MPa H_2
- Complete data set for SA 372 Gr. J steel in 100 MPa H_2 to satisfy Article KD-10 (i.e., measure fatigue crack growth and cracking thresholds at low temperature)
- Initiate next phase of 316 stainless steel testing in collaboration with industrial partner
- Start work on version 2 of Materials Technical Reference

FY08

- Create data set for Cr-Mo-Ni steel (e.g., SA 372 Gr. M) in 100 MPa H_2 to satisfy Article KD-10 (i.e., fatigue crack growth and cracking thresholds)
- Continue testing of 316 stainless steels (e.g., testing in fatigue, testing of welds)
- Compose new chapters for version 2 of Technical Reference (e.g., stainless steels 310, 321, 17-4 PH)

Summary

- Completed Technical Reference Version 1 containing existing data on high-priority structural materials
- Measured fracture properties of hydrogen-exposed steels used in pressure vessels and piping
  - cracking threshold of SA 372 Gr. J in 100 MPa H_2 gas about three times higher than historical data
  - tensile fracture of 316 not affected by cold work, but can depend on nickel content and stress concentration
- Finalizing laboratory infrastructure for fatigue crack growth testing in high-pressure H_2 gas

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