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Hydrogen compatibility of austenitic stainless steel tubing and orbital welds

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Materials selection for hydrogen service includes diverse range of product

Hydrogen delivery

- e.g., hydrogen pipelines: carbon steels
- Challenge: cyclic pressure

Mobile storage (fuel tanks)

- e.g., hydrogen forklifts: Cr-Mo ferritic steels
- Challenge: cycling ~6/day

Pressure manifold components

- ***Austenitic stainless steels***
- Challenges: low temperature, lower-cost alternatives (e.g., aluminum), alloy content, ***welding***

Motivation

- Tubing and piping are important components of hydrogen energy infrastructure
  - Relatively little work has been devoted to evaluation of tubing materials
- Orbital tube welding is an effective joining strategy for gas handling and dispensing manifolds
  - H-assisted fracture of welds has not been extensively characterized

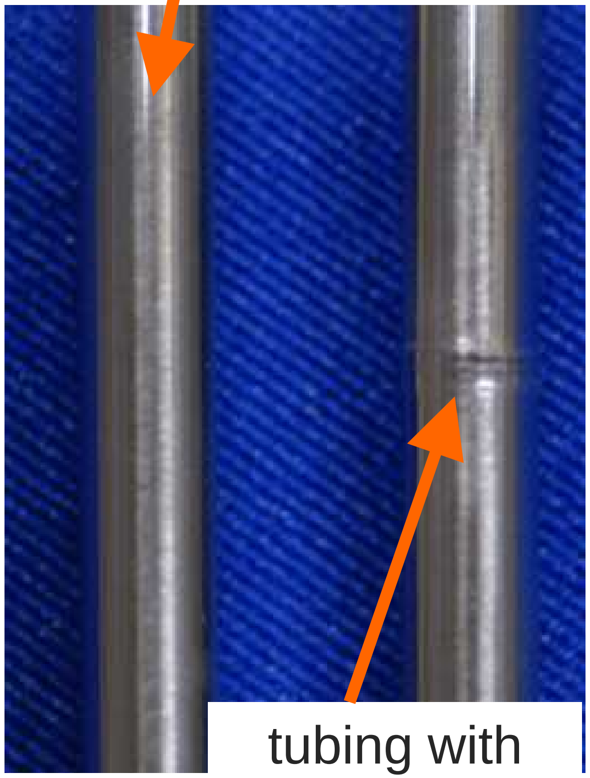
Conclusion from *Workshop on Hydrogen Compatible Materials* at SNL/CA (November 2010):

- Evaluation of welded structures is critical to deployment of hydrogen infrastructure and technology.

Tensile properties of tubing and orbital tube welds were evaluated

Testing scope: Uniaxial tension

- As-received tubing
- *Internal hydrogen* (~140 wtppm)
  - Produced by thermal precharging (573K in 140 MPa H2)
  - Simulates hydrogen at stress concentrations
- *Orbital tube welds*
- Effect of subambient *temperature*
  - 293 K (room temperature)
  - 223 K (-50˚C)



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A range of alloy compositions and material strength have been evaluated

Alloy type	ID	Yield strength (MPa)	Cr (wt%)	Ni (wt%)	C (wt%)	S (wt%)
316L	316L	286	16.7	12.4	0.018	0.006
304L	1	n/m	18.2	9.1	0.020	0.004
304L	2	656	18.6	11.7	0.021	0.0004
304L	3	296	18.7	11.6	0.015	0.026
304	4	627	18.3	10.2	0.04	0.002
304L	5	359	18.4	10.2	0.01	0.007
304L	6	763	18.4	8.2	0.024	0.003

Low nickel

High carbon

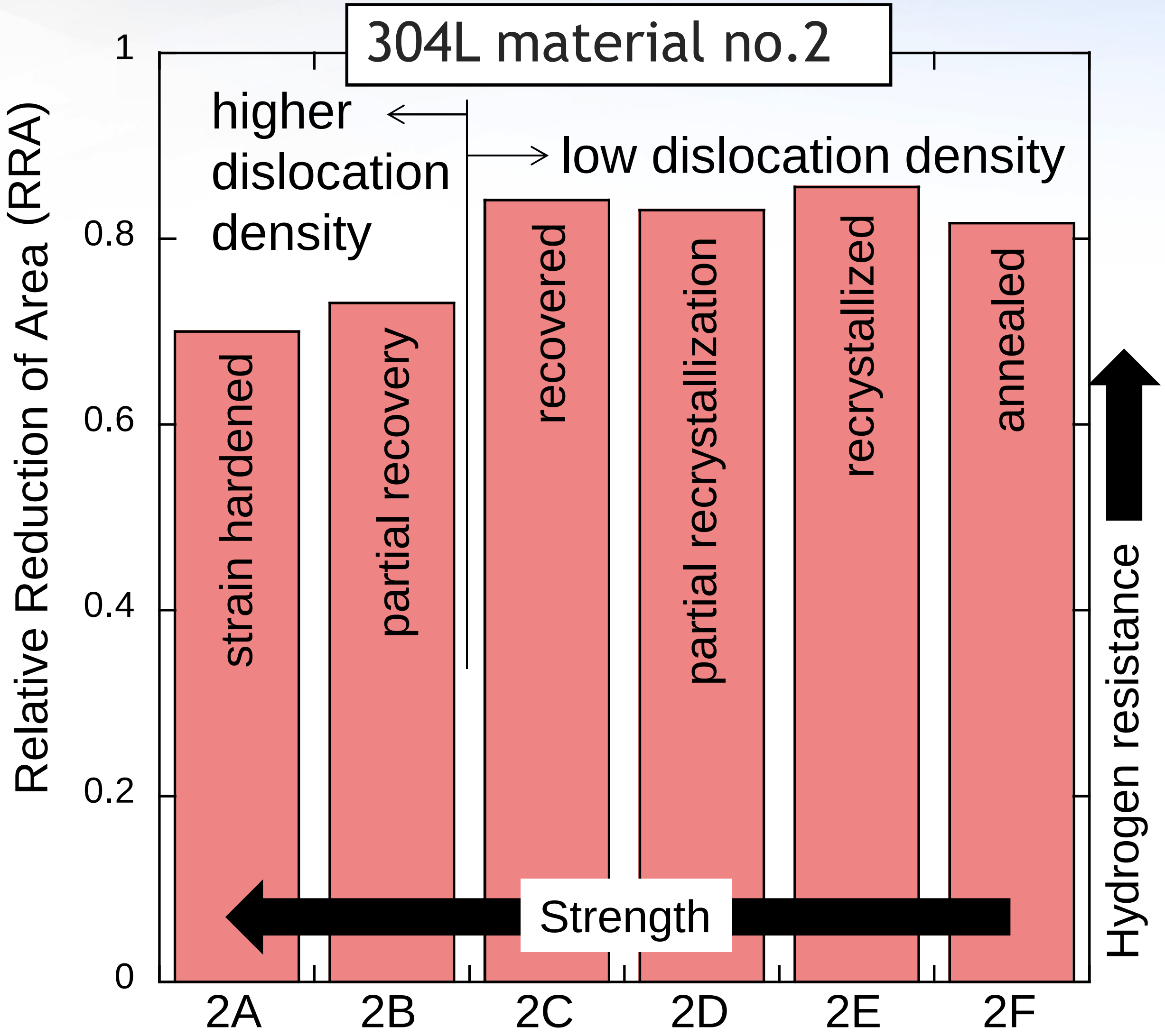
High sulfur

Thermal treatment was used to vary microstructure

Material/ Condition	Temperature (K)	Time (min)	Yield strength (MPa)	Target microstructure
2A	n/a	n/a	697	Strain-hardened (as-received)
2B	866	60	678	Partially recovered
2C	1000	30	576	Full recovery
2D	1033	30	377	Partially recrystallized
2E	1116	60	228	Fully recrystallized
2F	1311	60	179	Annealed
*x*S	998	240	varies	Sensitized

- Heat treatments applied to only alloy no. 2 (304L)
- Sensitization is used to evaluate susceptibility to stress corrosion cracking (not evaluated for the 316L alloy)

Strength and microstructure show only modest effect on hydrogen resistance

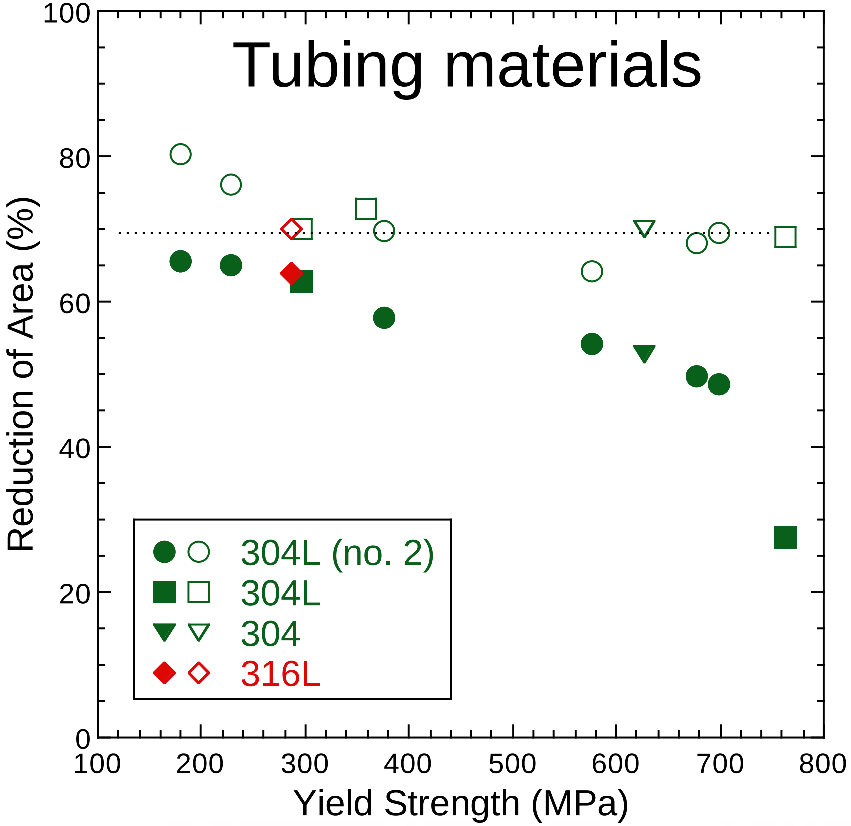


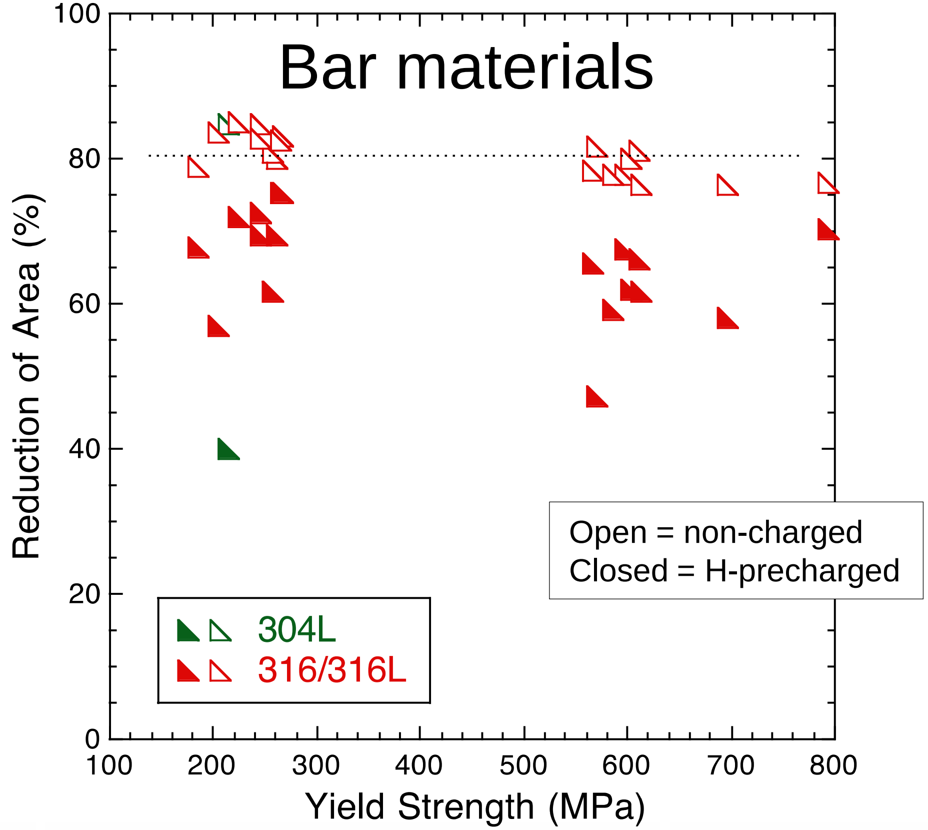
- Hydrogen resistance dependence on yield strength is relatively small for strength in range of 180 to 700 MPa
- RRA > 0.8 for low dislocation microstructures
- RRA ~ 0.7 for high dislocation microstructures

RRA = RA(H)/RA(air)

Austenitic stainless steel tubing behaves similarly to bar materials

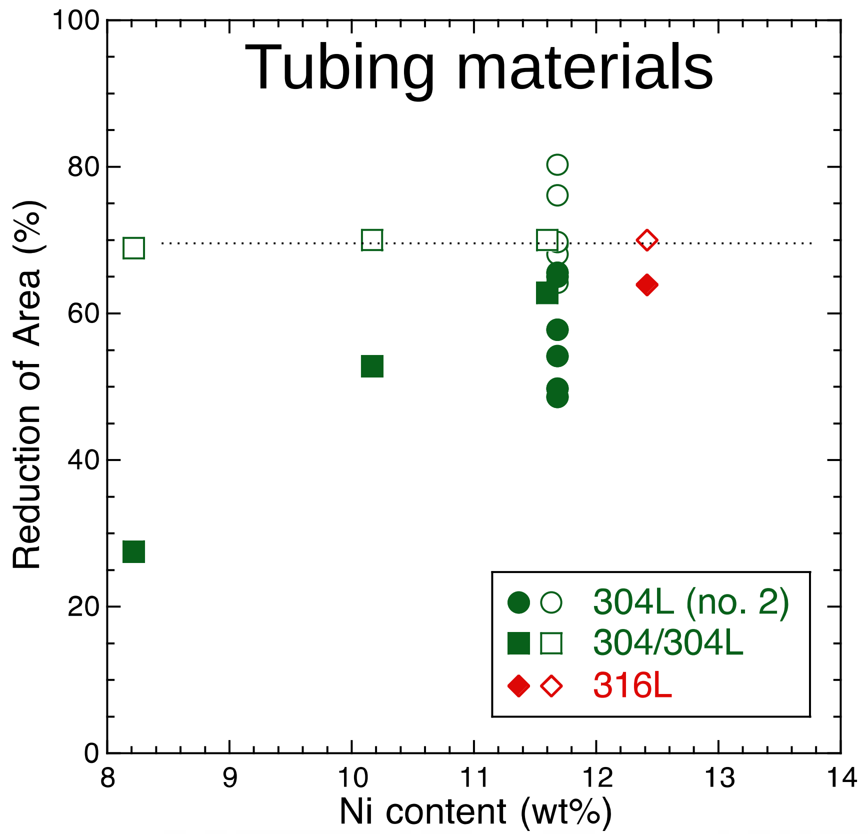
- Higher yield strength results in lower tensile ductility in the presence of hydrogen for both tubing and bar
- Other material variables can dominate effects

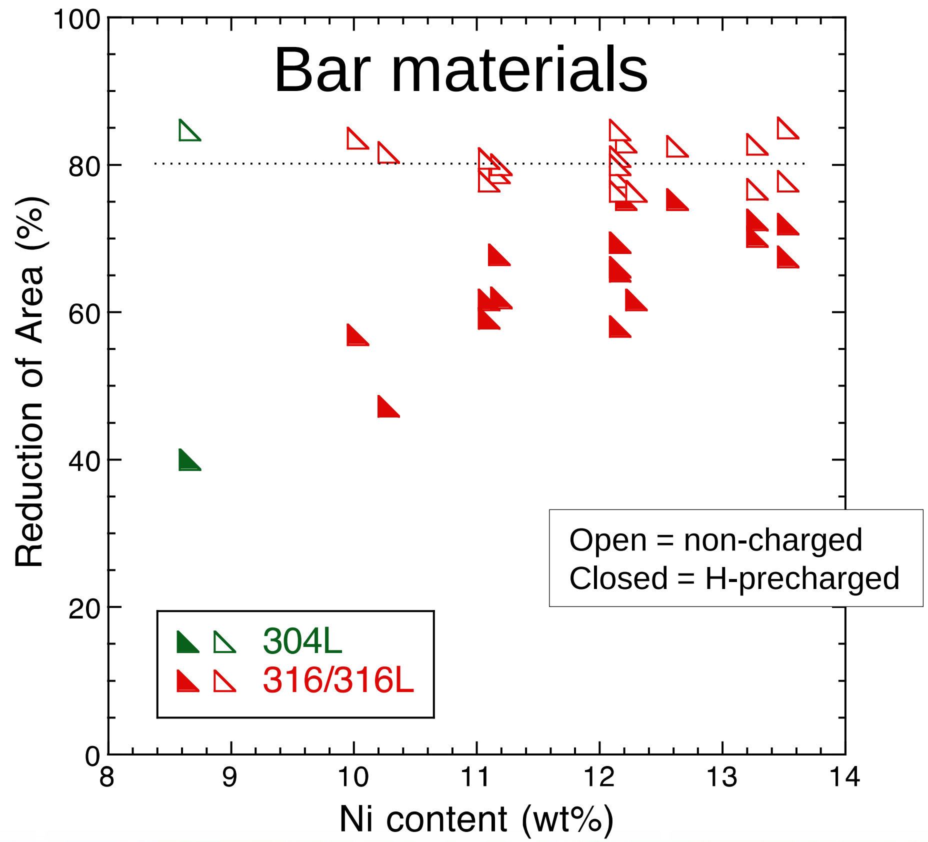




Compositional trends are also similar for tubing and bar

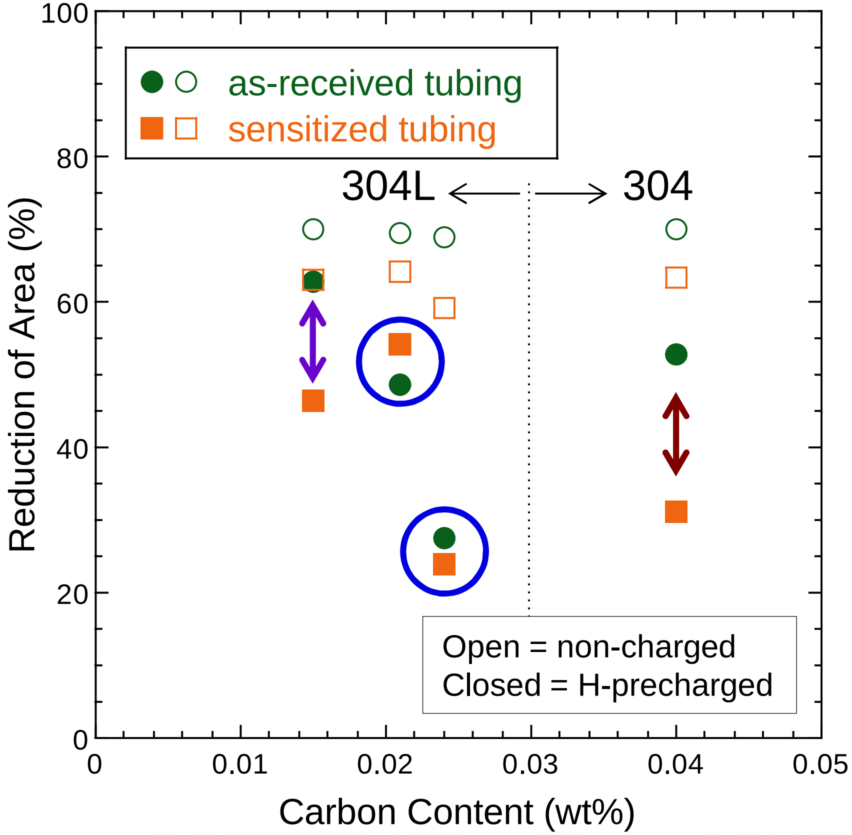
- Nickel composition is an important variable in hydrogen-assisted fracture of austenitic stainless steels





Carbon content has indirect consequences for hydrogen resistance

- There is no direct trend of hydrogen ductility loss with carbon content
- However, carbon content can indirectly influence the effects of H
- Sensitization evaluates the sensitivity of austenitic stainless steels to microstructural segregation, which affects resistance to H

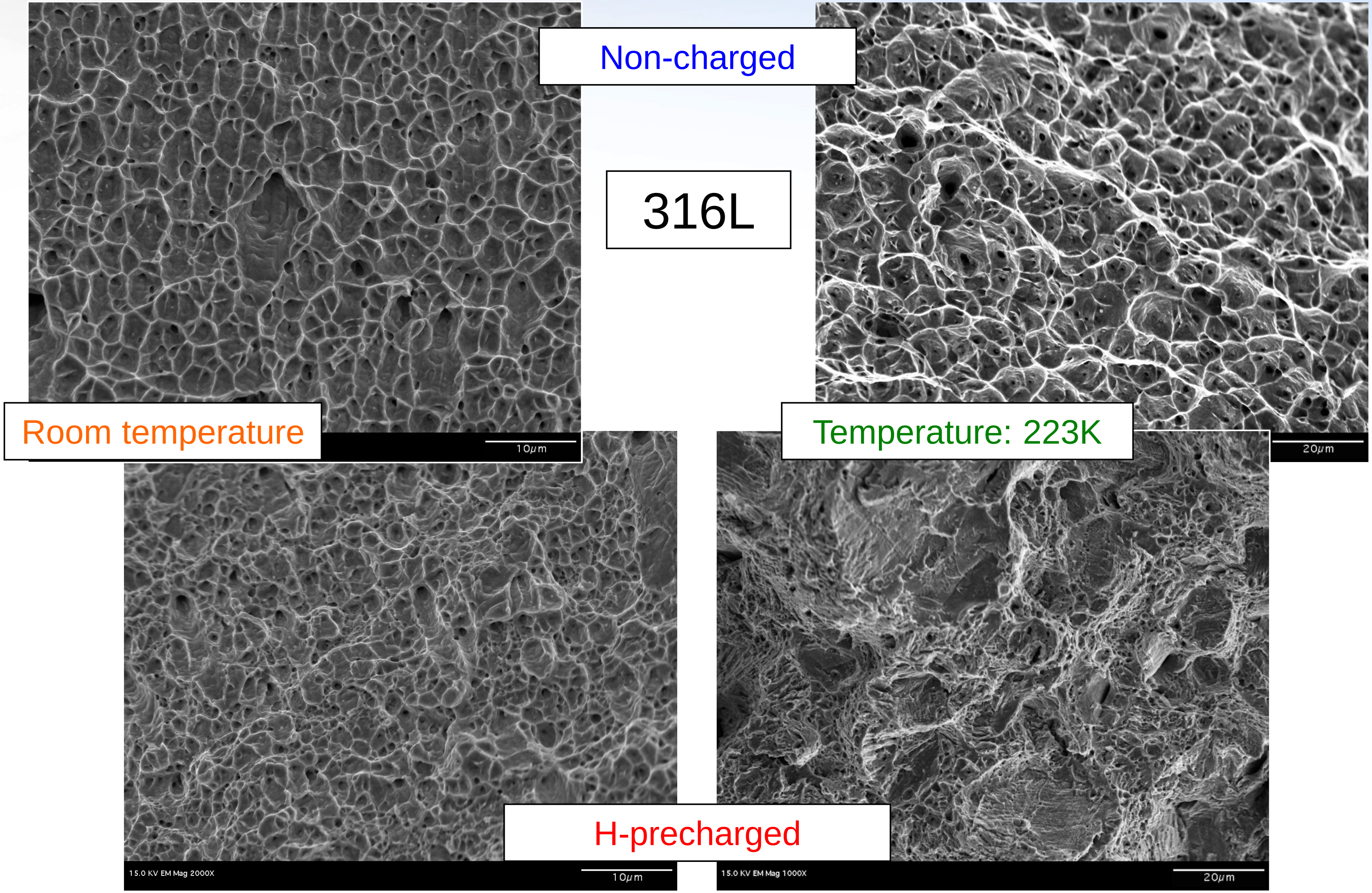


- For type 304L: sensitization does not strongly impact hydrogen effects

- For type 304 (high carbon): sensitization enhances effects of hydrogen

- Effect of high sulfur?
  - Material no. 3 has ~5x more sulfur than the other alloys

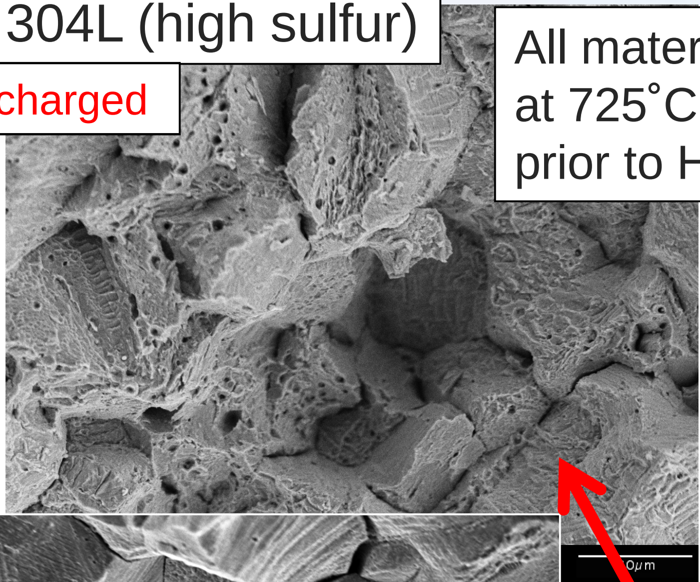
Fractography of tubing is similar to base materials



Compositional segregation (S & C) appear to enhance the effects of H

Type 304L (high sulfur)

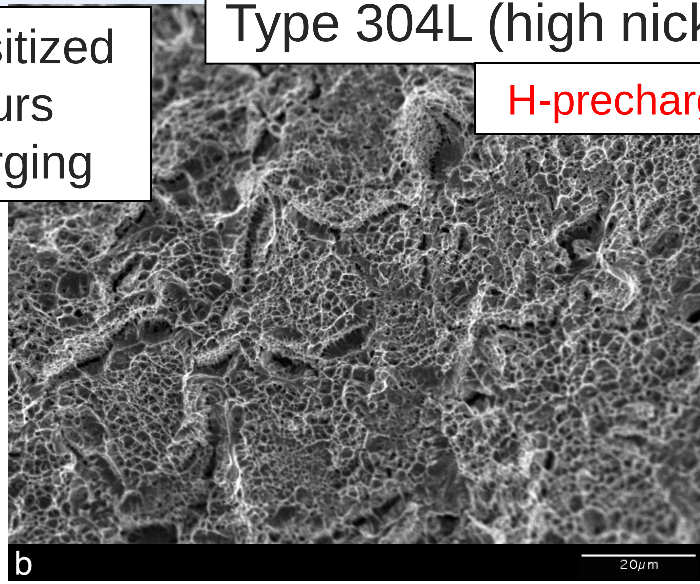
H-precharged

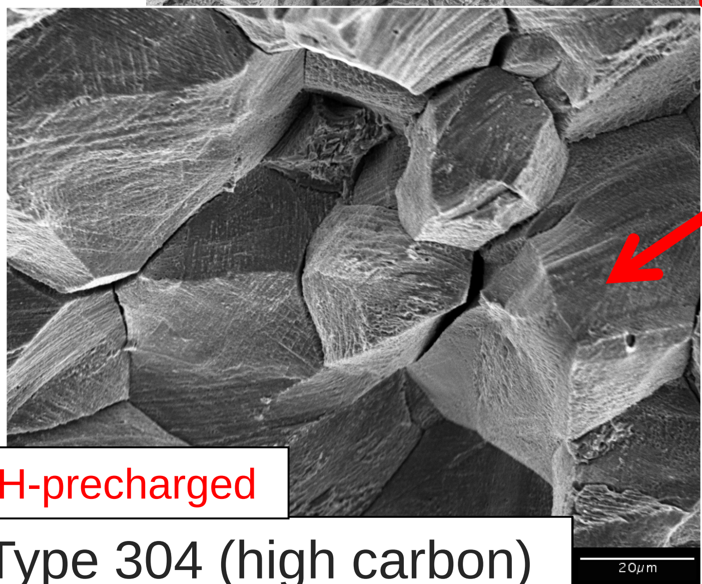


All materials sensitized at 725˚C for 4 hours prior to H-precharging

Type 304L (high nickel)

H-precharged





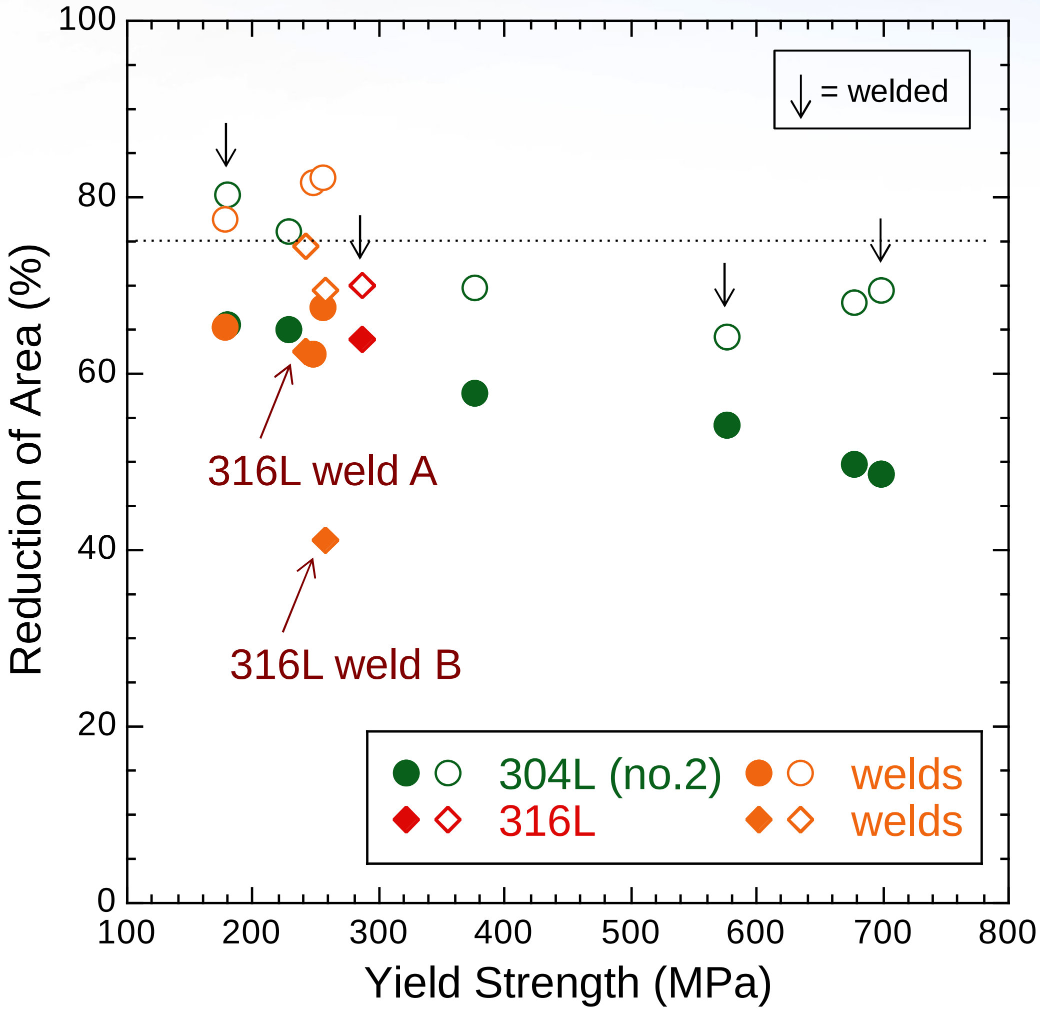
H-precharged

Type 304 (high carbon)

Undesirable “embrittled” fracture features

- Alloys with high carbon and sulfur show large reductions of ductility
  - Presumably due to the combined effects of segregation (sensitization) and hydrogen

Orbital tube welds behave similarly to the tubing materials



- The yield strength of the welded specimens are similar to annealed tubing
- Tensile ductility H-precharged welded specimens can be similar to tubing

- Two sets of 316L welds (A and B) produced independently, resulted in different effects of H
  - Weld B is still very ductile

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Summary

- Hydrogen effects evaluated in austenitic stainless steel tubing and orbital tube welds
  - Tensile testing shows similar tensile ductility in tubing as in annealed and strain-hardened bar
  - Effect of internal hydrogen on tensile ductility in tubing is similar to previous work on bar materials
  - Welded specimens generaly display similar tensile ductility as the tubing of the same strength
  - Welded specimens remain very ductile after hydrogen precharging

- Conclusion: Orbital tube welds in austenitic stainless steels can display similar resistance to hydrogen embrittlement as the tubing from which the welds are manufactured