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Effect of microstructural and environmental variables on ductility of austenitic stainless steels

Chris San Marchi,
Sandia National Laboratories

Joe Ronevich, Julian Sabisch, Josh Sugar, Doug Medlin (Sandia)
Brian Somerday (Somerday Consulting, LLC)

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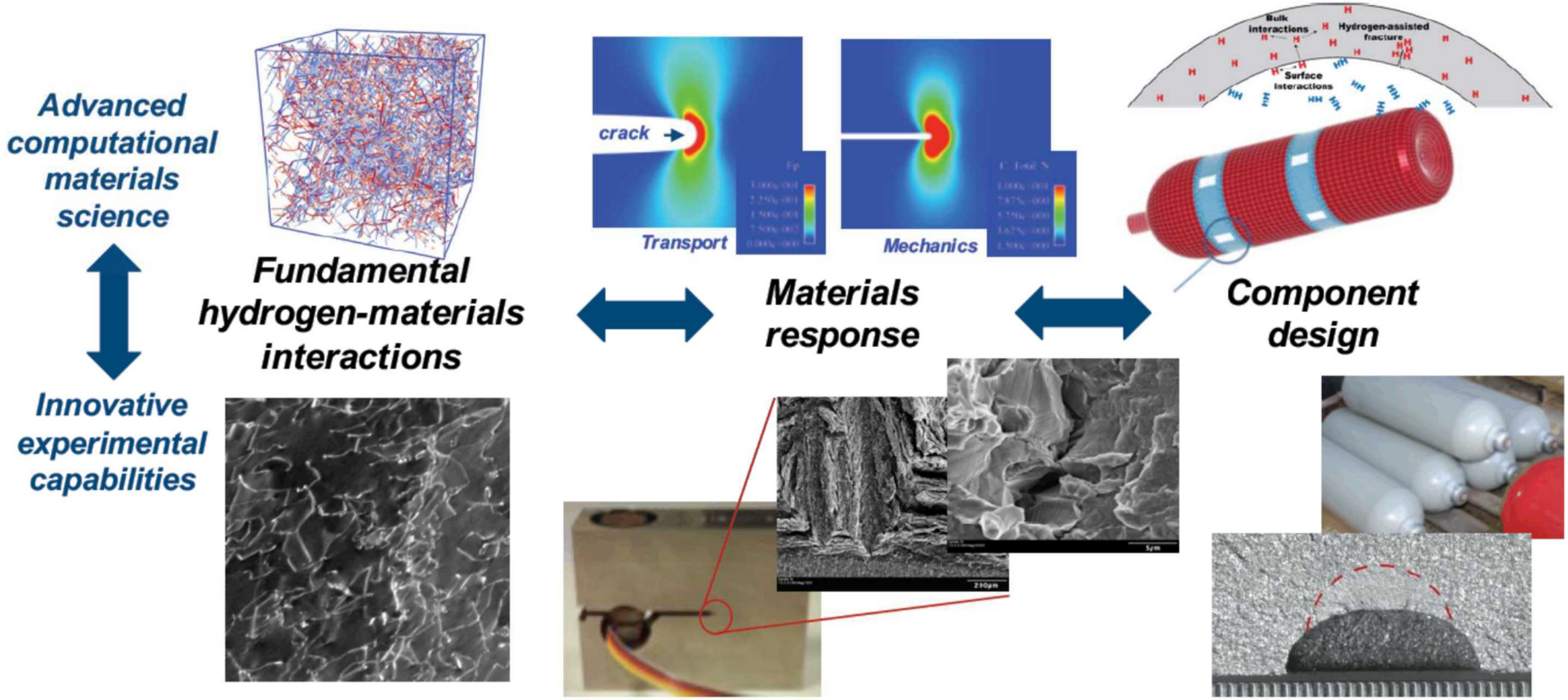
H-Mat – Hydrogen Materials Compatibility Consortium:

Science-based advancement of materials for hydrogen technologies

H-Mat addresses the challenges of hydrogen degradation by elucidating the mechanisms of hydrogen-materials interactions with the goal of providing science-based strategies to design materials (micro)structures and morphology with improved resistance to hydrogen degradation.

Six new projects with universities and industry currently being negotiated with DOE for inclusion under the H-Mat umbrella

H-Mat approach: integrate innovative computational & experimental activities across length scales



Thermodynamics of H-interactions at nm-scale

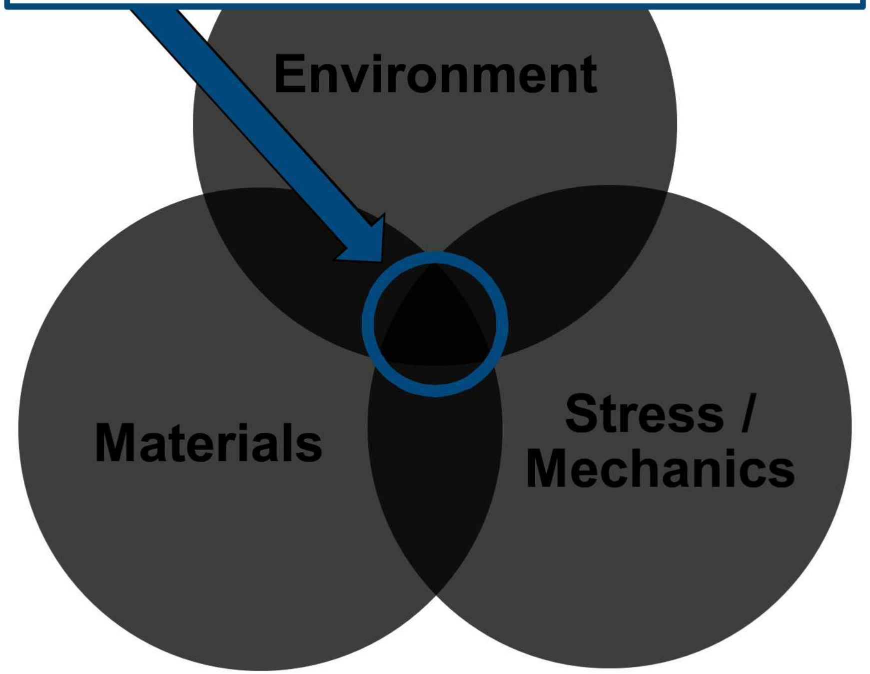
Micromechanisms of materials behavior at μm-scale

Structural performance at the engineering scale

Microstructural and environmental variables are considered in this study

- **Microstructural variables**
  - Composition
    - 304L – 316L (nickel)
    - XM-11 (nickel-manganese)
  - Alloy stability
    - Metastable (304L, 316L)
    - Stable (XM-11)
  - Strength
    - Forged – Annealed (XM-11)
- **Environmental variables**
  - Hydrogen concentration
    - 0 to 140 wt ppm H (to 220 wt ppm H in XM-11)
  - Temperature
    - Room temperature (293 K) and low temperature (223K)

*Hydrogen embrittlement occurs in **materials** under the influence of **stress** in hydrogen **environments***



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Austenitic stainless steels in this study

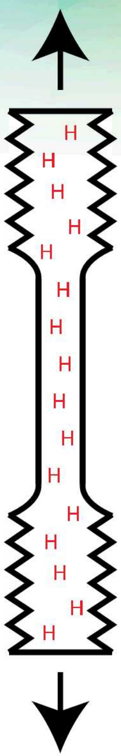
Designation	Fe	Cr	Ni	Mn	Mo	Si	C	N	S	P
304L - F	Bal	19.6	10.6	1.6	–	0.65	0.028	0.04	0.0042	0.02
316L - F	Bal	16.7	12.7	0.64	2.8	0.62	0.020	0.04	0.0023	0.008
XM-11 - F	Bal	21.1	7.2	9.1	–	0.53	0.031	0.28	0.001	0.015
XM-11 - A	Bal	19.3	6.8	9.0	–	0.39	0.022	0.25	<0.001	0.017

F= forged; A = annealed

Designation		Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)
304L - F	Metastable	436	611	69	85
316L - F	Metastable	422	571	70	84
XM-11 - F	Stable	674	830	48	76
XM-11 - A	Stable	457	755	65	83

H-precharging is used to simulate hydrogen service environment

- **Thermal H-precharging**
  - **Exposure to gaseous hydrogen until specimen is saturated with hydrogen**
    - **Pressure: varied to achieve target [H] (up to 138 MPa)**
    - **Temperature: 300˚C**
- **Testing in air after precharging with hydrogen**



- **Mechanical testing in H-precharged condition (internal H) is similar to *in situ* testing in high-pressure gaseous hydrogen (external H) for tension, fatigue and fracture**
- **Conditions simulate the high concentration anticipated under high triaxial stress (i.e., near crack tip) in gaseous hydrogen**

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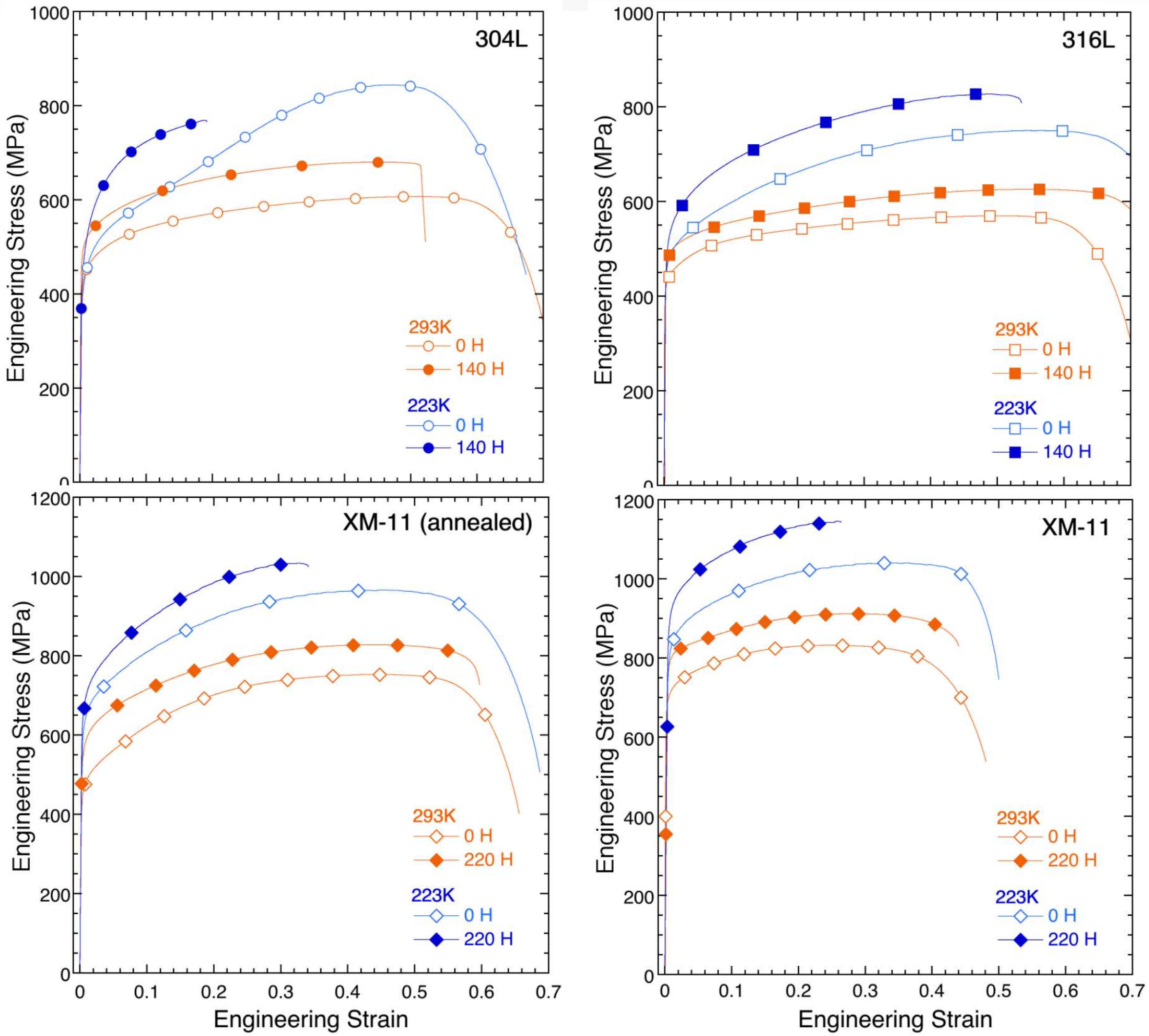
Tensile stress-strain curves show similar behavior for all materials in general



Elongation

- **Type 304L shows the lowest elongation to failure**
- **Low temperature has the greatest effect on tensile elongation of 304L**

Strength

- **Temperature seems to have a greater effect on strength properties of XM-11 compared to 304L and 316L**
- **In general, temperature strengthens austenitic stainless steels**
  - **Exception: Type 304L**

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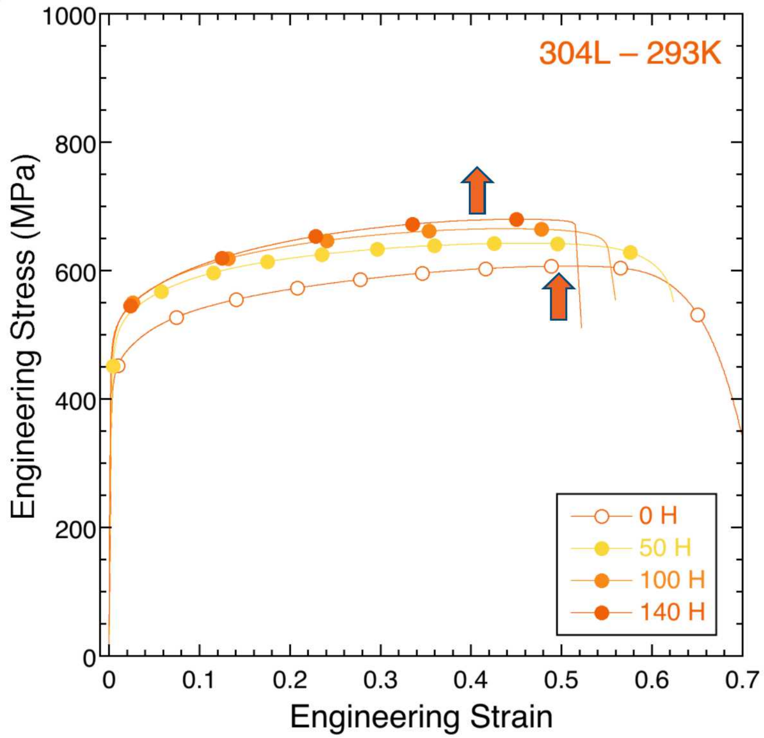
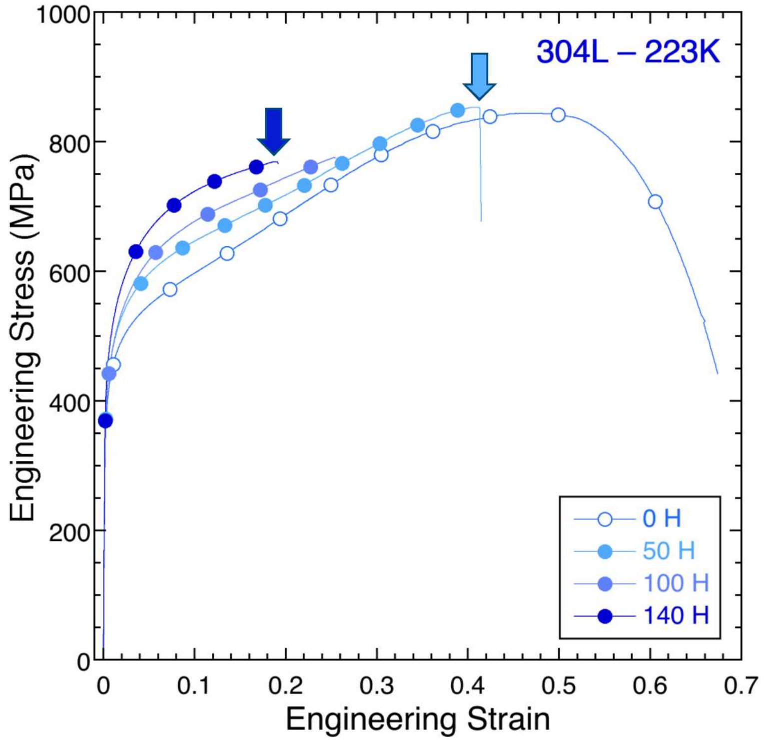
Tensile stress response roughly scales with hydrogen concentration for type 304L





- **Hydrogen acts similar to a solid-solution strengthening element**
- **Hydrogen substantially reduces tensile ductility in 304L**
  - **At low temperature, reduction of ductility results in decreased tensile strength**

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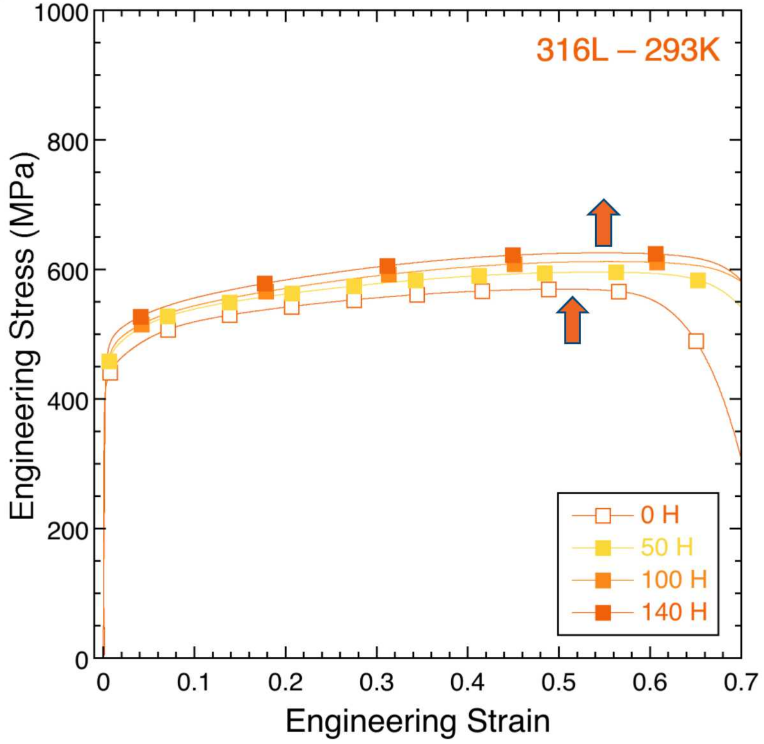
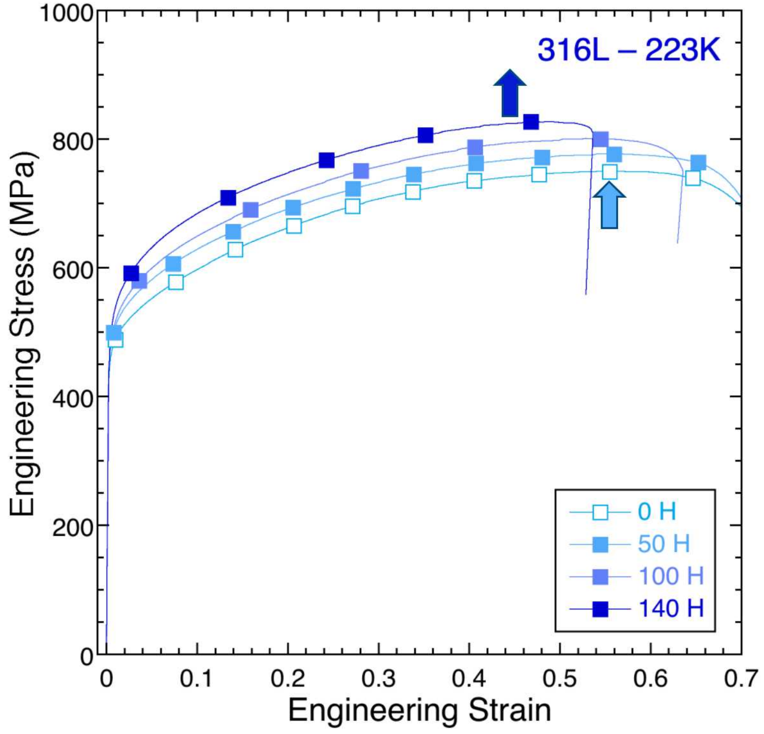
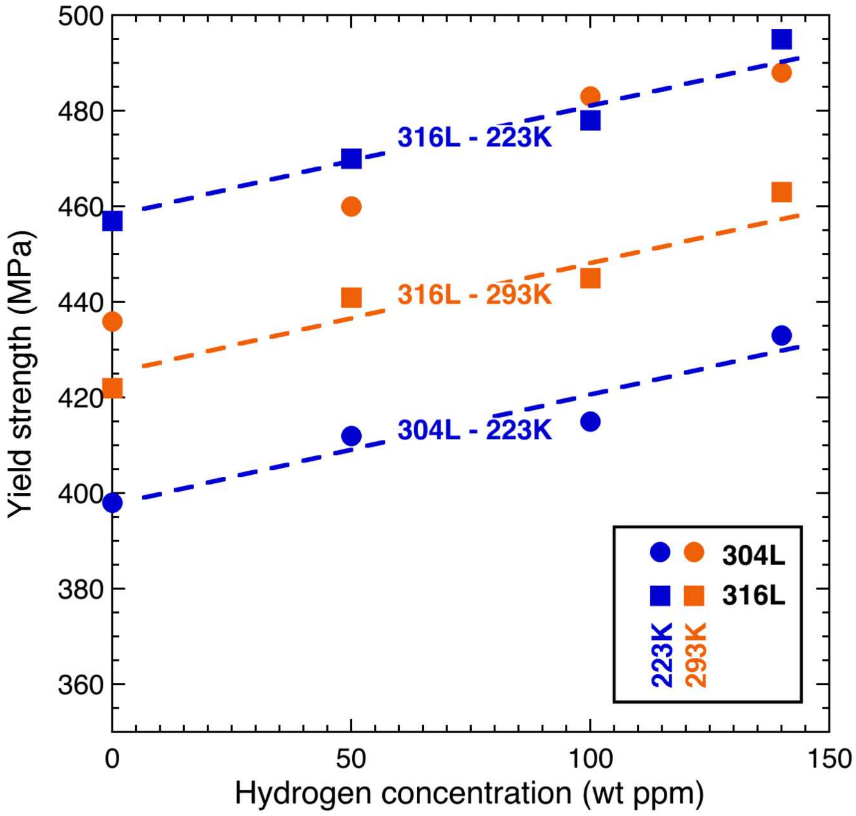
Tensile stress response roughly scales with hydrogen concentration for type 316L

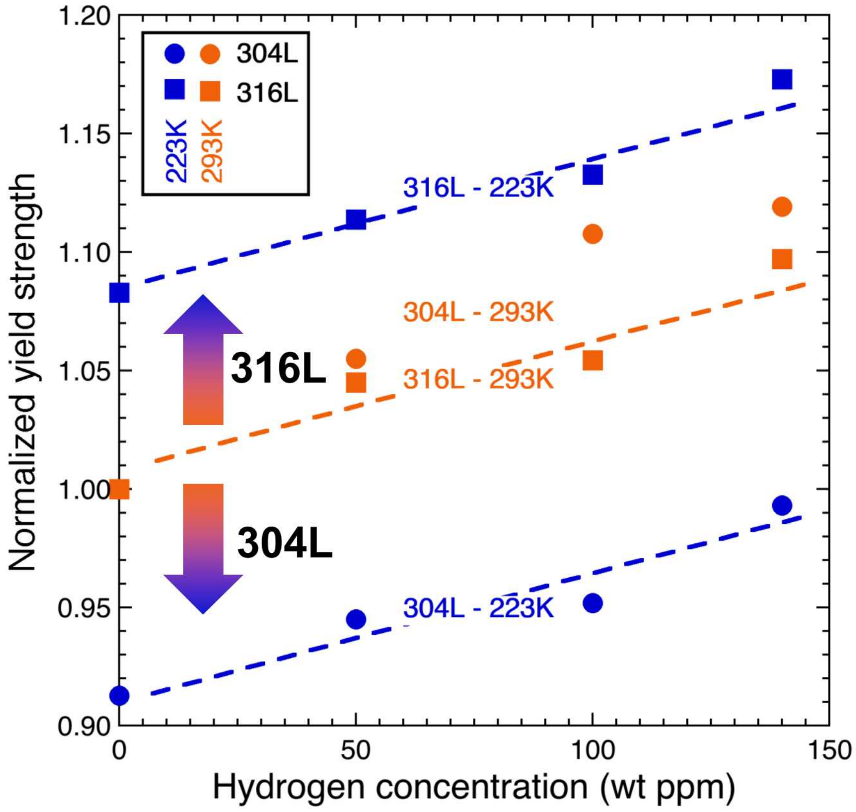




- **Hydrogen acts similar to a solid-solution strengthening element**
- **Hydrogen has modest effect on tensile ductility**
  - **At low temperature, tensile ductility remains high and tensile strength with hydrogen is greater than without hydrogen**

Yield strength increases approximately linearly with hydrogen concentration for types 304L & 316L

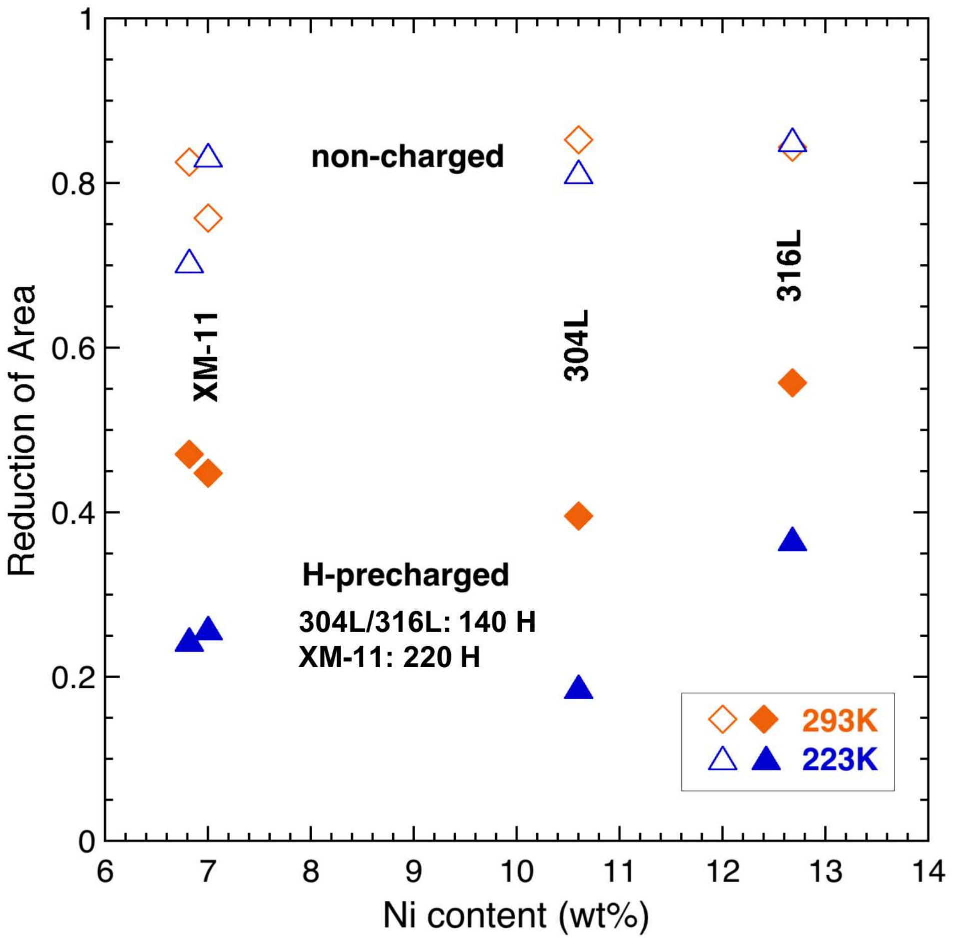




- Low temperature reduces yield strength of 304L while strength of 316L increases at low temperature
- Effect of hydrogen concentration, however, remains constant

Compositional effects are not straight forward when both stable and metastable alloys are considered

- All materials show a substantial loss of ductility with high concentration of hydrogen
- H-precharging reveals that even high-Ni 316L shows substantial loss of ductility
- Metastable 304L and stable XM-11 show similar loss of ductility
  - Despite much lower nickel content of XM-11



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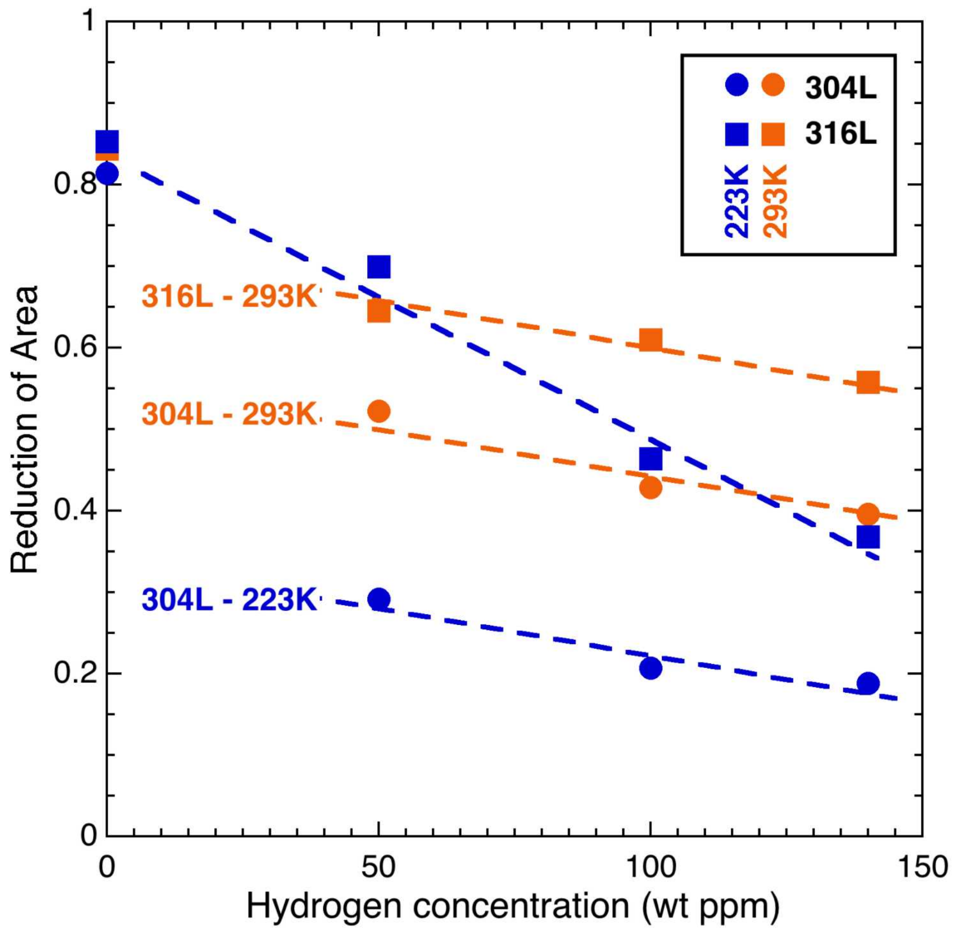
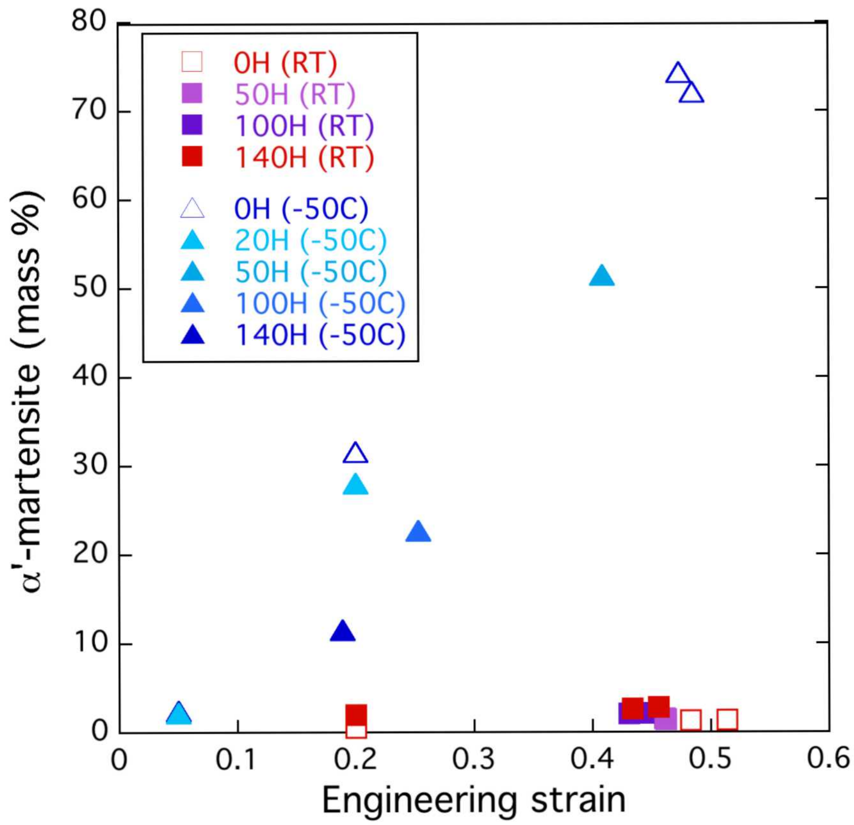
Ductility loss is nominally a linear function of hydrogen concentration for type 304L & 316L



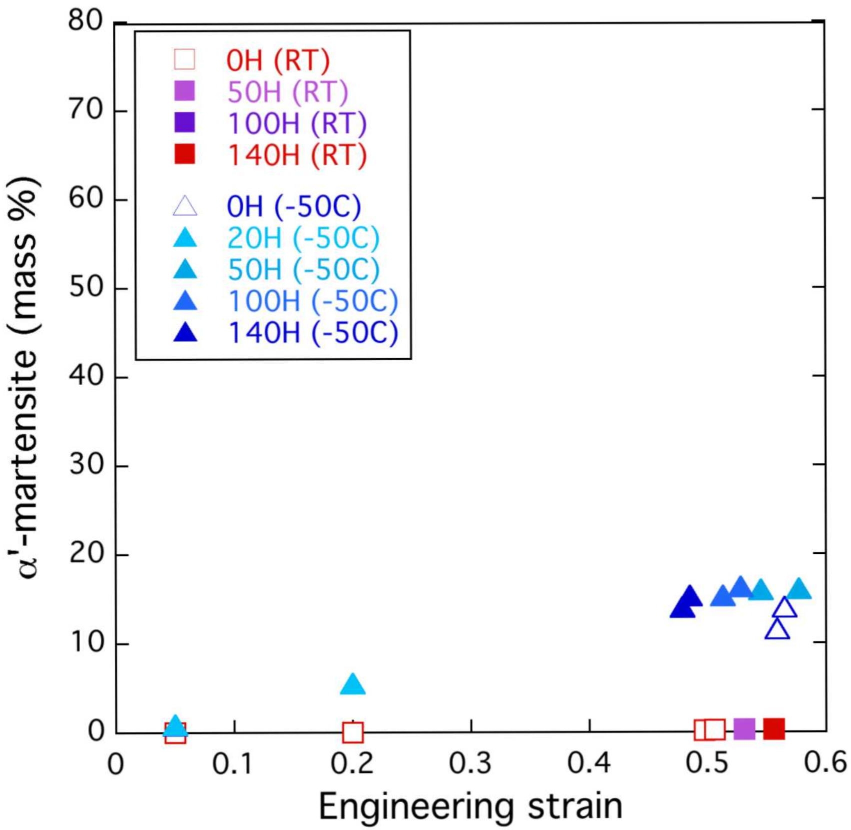
- **'Offset' of ductility with hydrogen depends on composition and temperature (i.e., extrapolated value of RA)**
- **Dependence on hydrogen concentration ('slope') is similar for type 304L at both temperatures and type 316L at room temperature**
- **Slope of ductility loss with hydrogen concentration is significantly greater for type 316L at low temperature**
  - ***Results suggest that high-Ni 316L is not as resistant to hydrogen as generally assumed***

Strain-induced α'-martensite transformation in metastable austenitic stainless steels depends on composition

304L: 10.6% Ni



316L: 12.7% Ni



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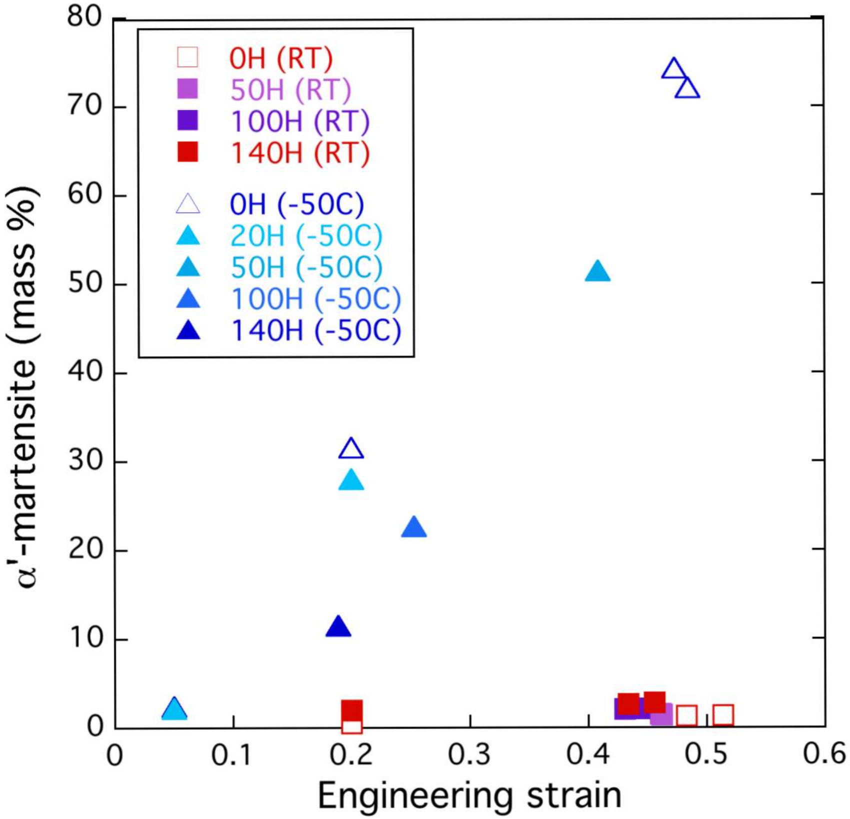
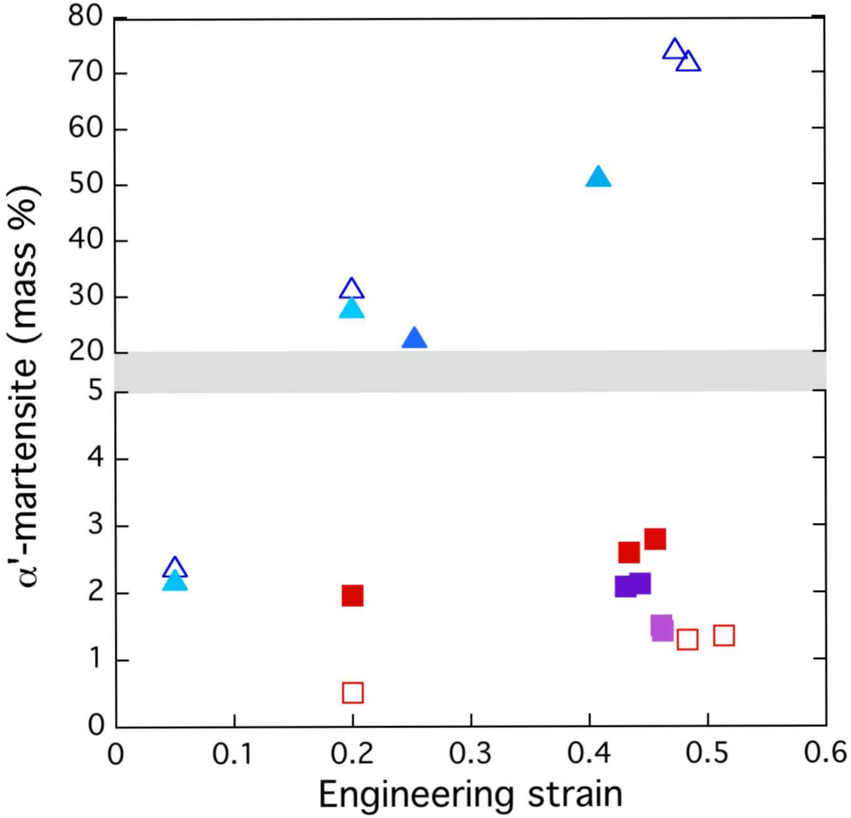
Strain-induced α'-martensite transformation in 304L





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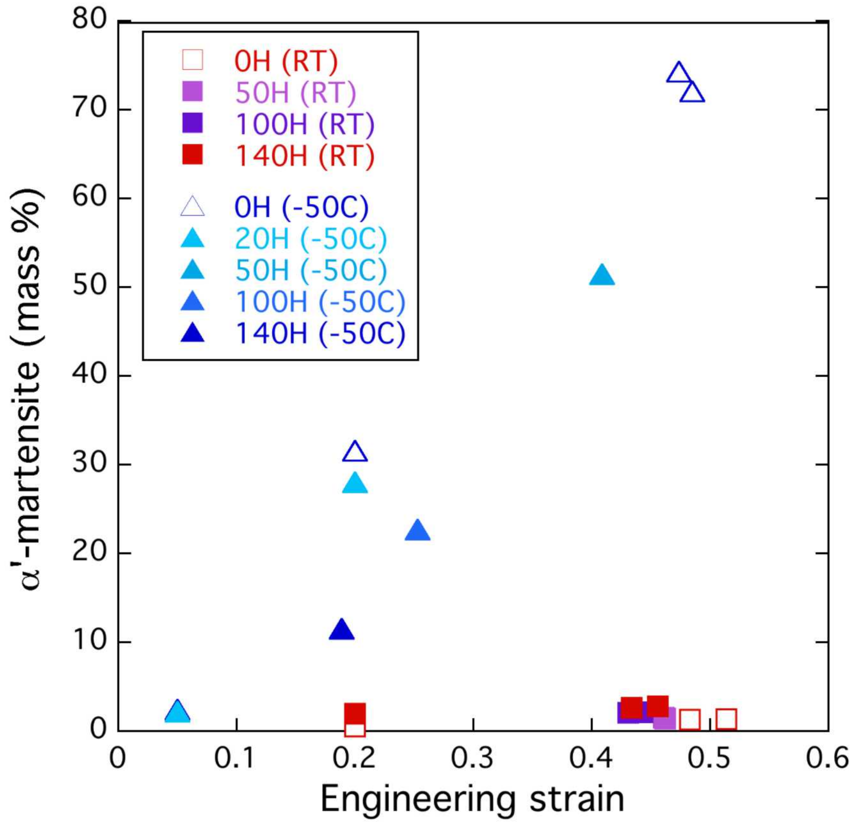
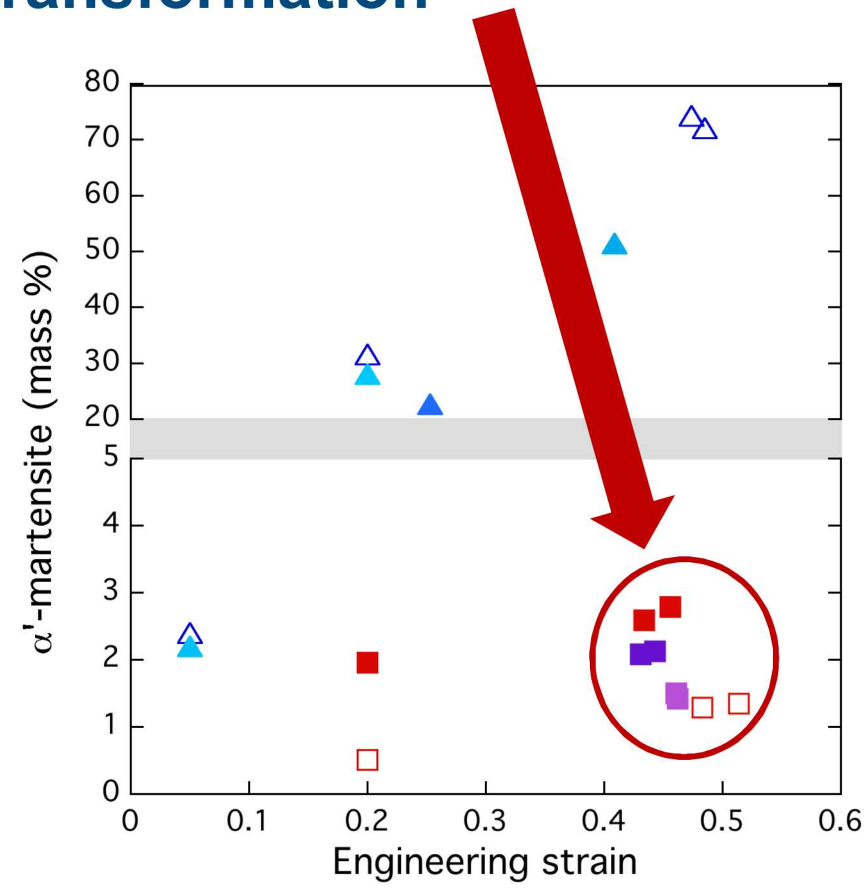
Strain-induced α'-martensite transformation in 304L

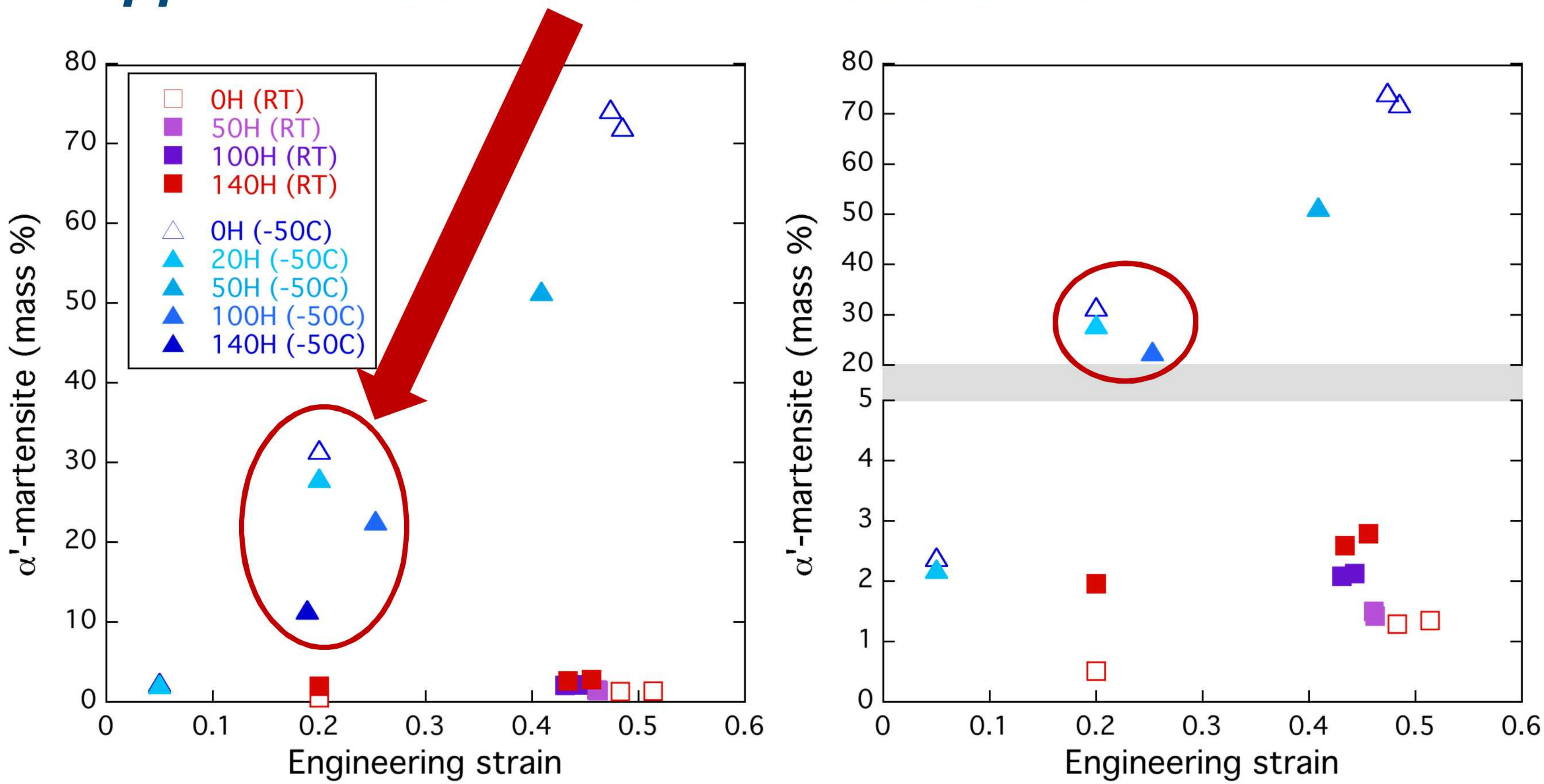
At *low* volume of transformation, hydrogen *promotes* strain-induced transformation



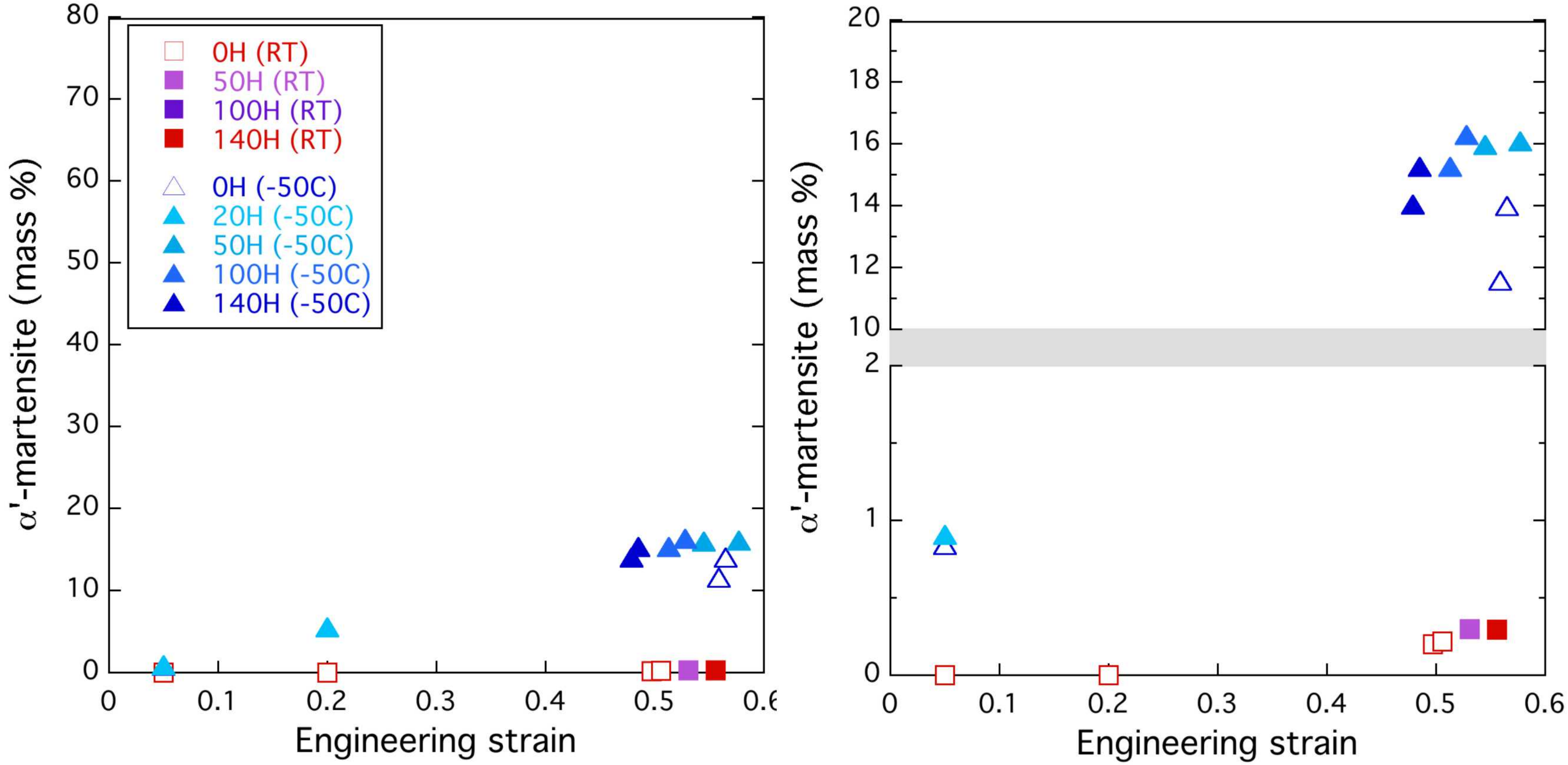


Strain-induced α’-martensite transformation in 304L

At *high* volume of transformation, hydrogen *suppresses* strain-induced transformation

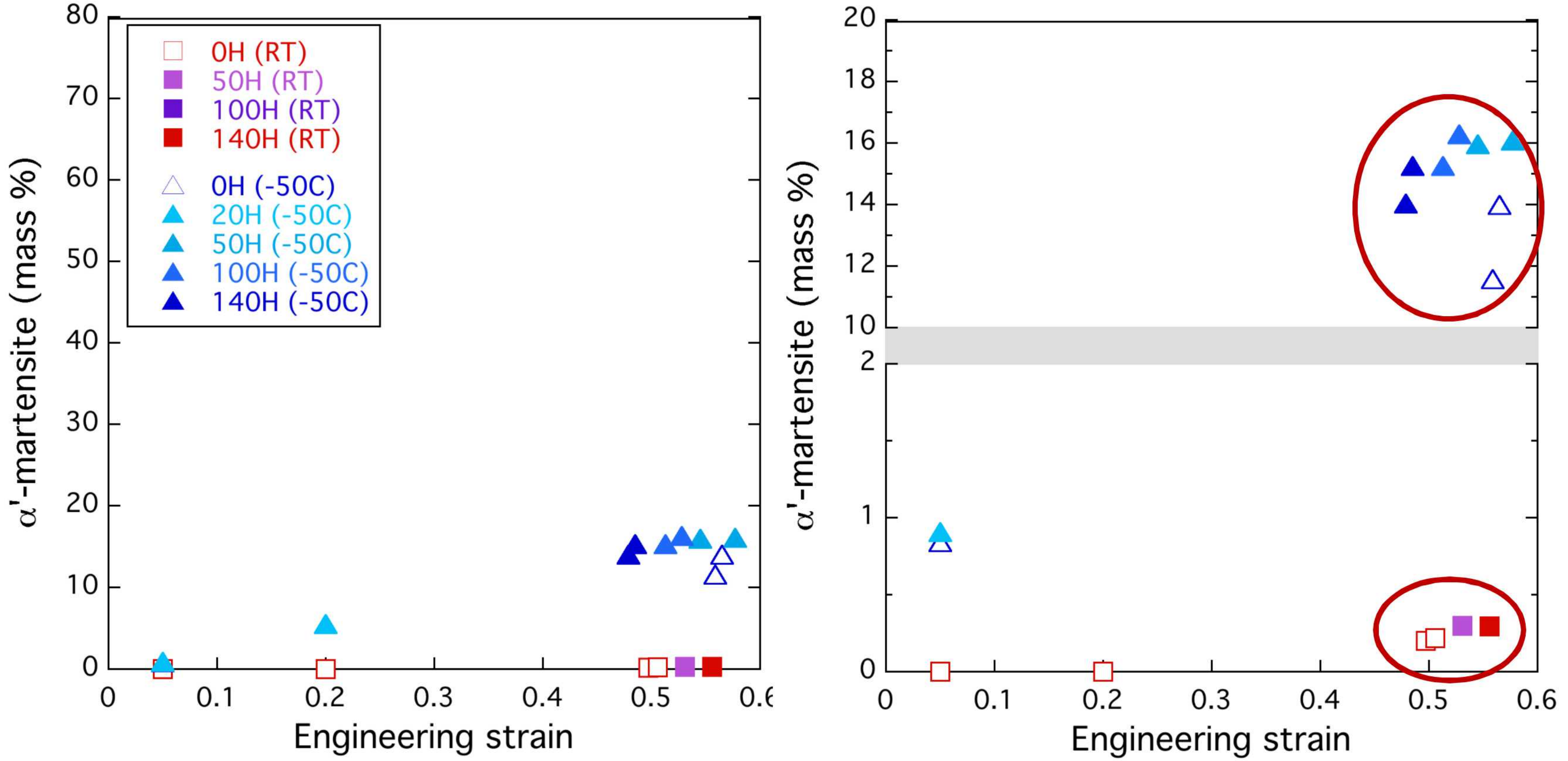


Strain-induced α'-martensite transformation in 316L

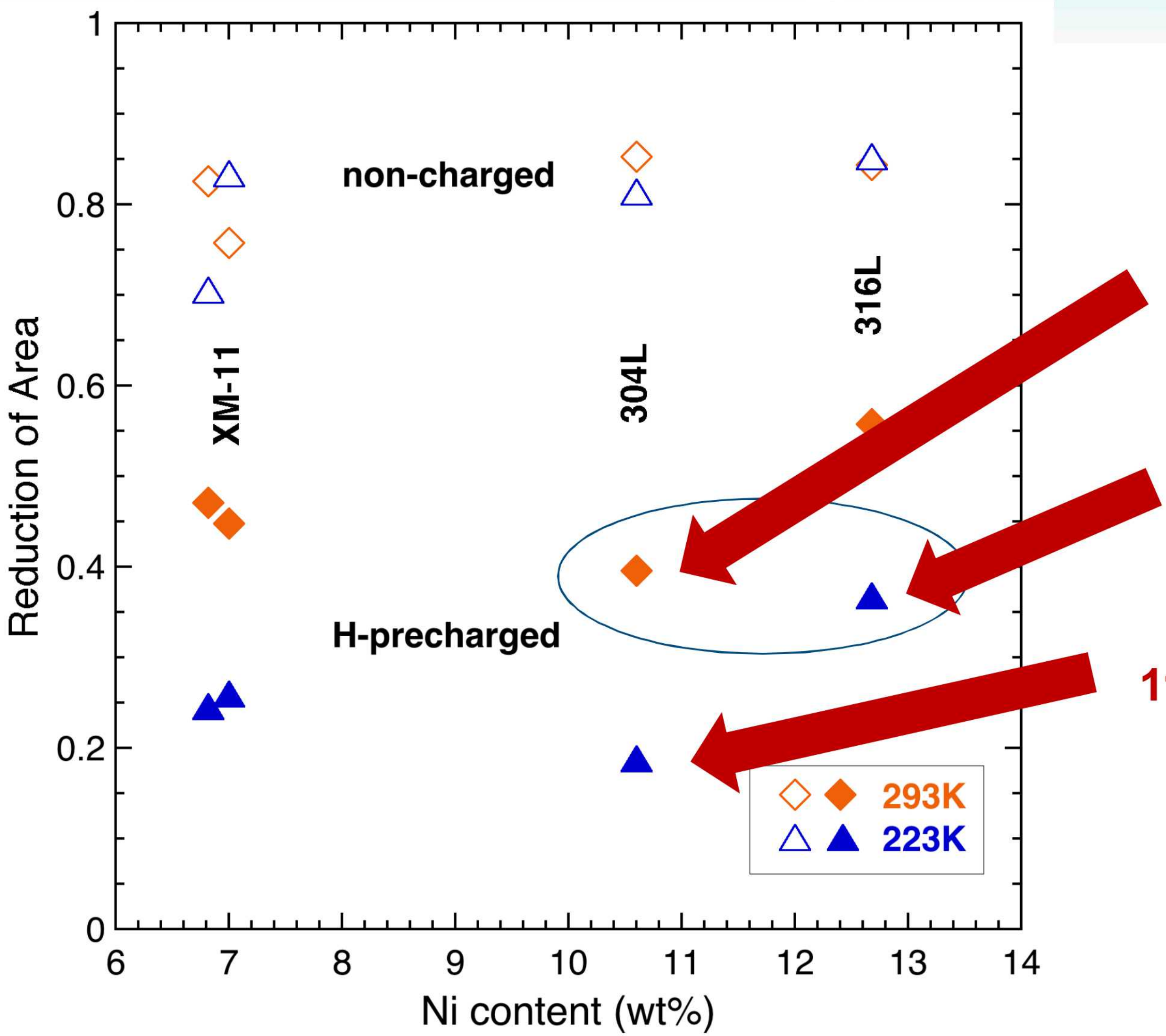


Strain-induced α'-martensite transformation in 316L

At *low* volume of transformation, hydrogen *promotes* strain-induced transformation



Ductility loss in austenitic stainless steels with internal hydrogen does NOT correlate with α'-martensite



3% α□– martensite

14% α'-martensite

11% α'-martensite

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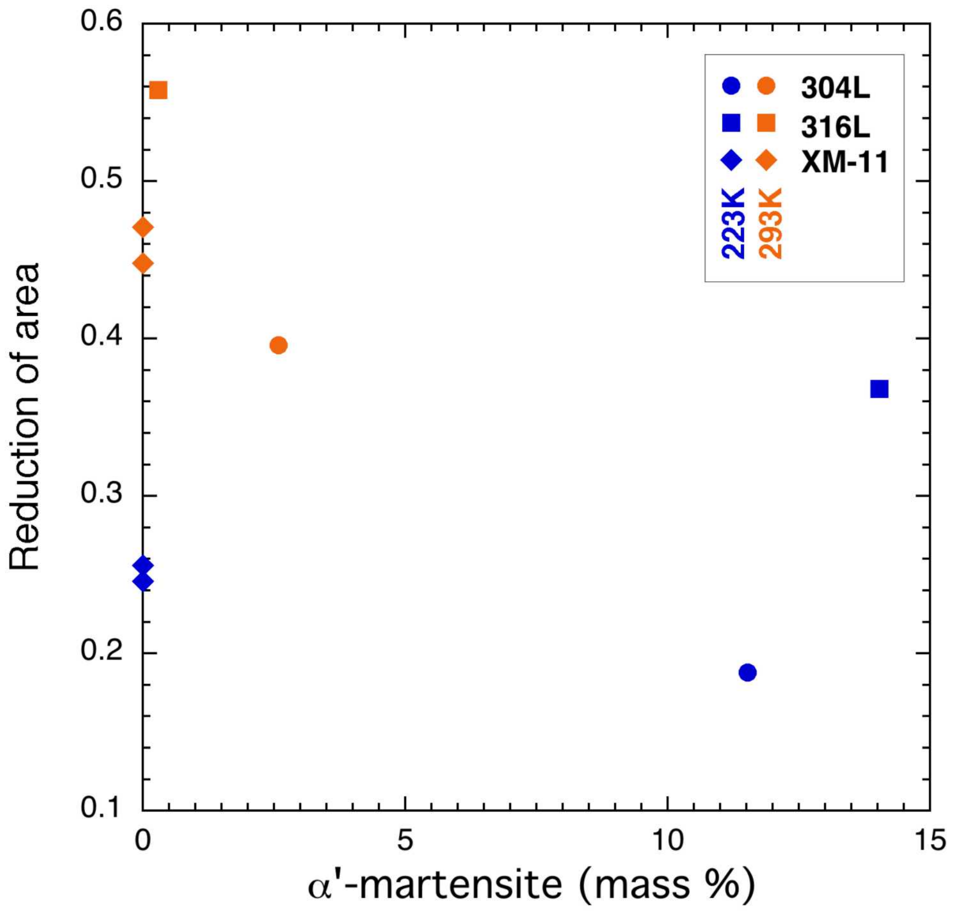
Ductility loss in austenitic stainless steels with internal hydrogen does NOT correlate with α'-martensite



- Low ductility with hydrogen is observed in both stable and metastable alloys
- Moderate ductility with hydrogen is observed with both low and high martensite transformation

- Promotion of martensite formation at low martensite content is likely related to greater nucleation sites due to hydrogen-promoted planar slip
- Suppression of martensite formation at high martensite content is likely related to stabilization of austenite by interstitial hydrogen

Summary and conclusions

- Internal H strengthens alloys approximately linearly with hydrogen content
- Internal H reduces tensile ductility
  - Temperature reduces RA by about the same amount for all alloys
- Internal H promotes strain-induced α'-martensite when volume of martensite is small (<20%)
- Internal H suppresses strain-induced α'-martensite when volume of martensite is large (>20%)
- No apparent correlation between α'-martensite and ductility with internal H

- ***Hydrogen has strong effects on ductility of all stainless steels (which are not always captured by tests in external H)***
- ***Hydrogen-assisted fracture cannot be understood by hydrogen-induced fracture of strain-induced martensite***