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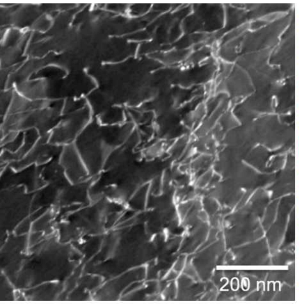

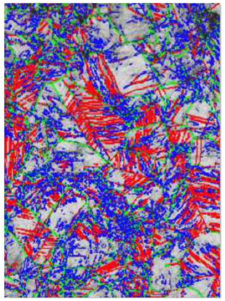

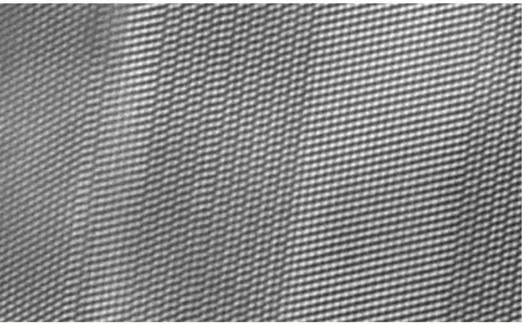

Strain localization and martensitic transformations at shear bands in a low SFE austenitic stainless steel.

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U.S. DEPARTMENT OF ENERGY

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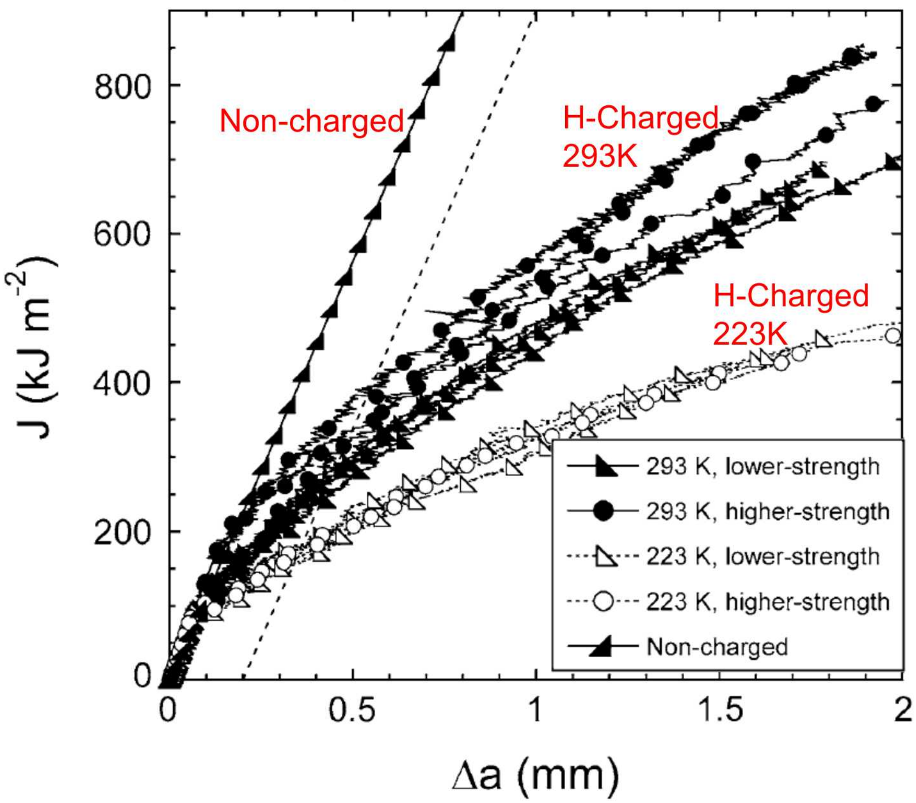
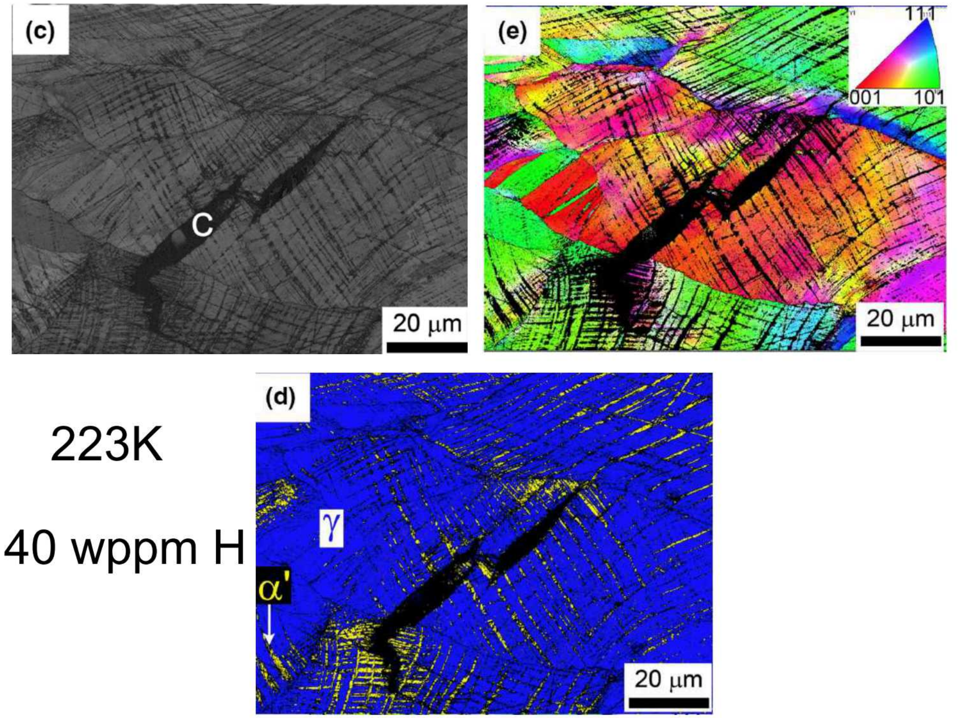
Hydrogen degrades fracture toughness

Crack Growth Resistance (J-R) Curve



Microvoid initiation at intersecting deformation-bands



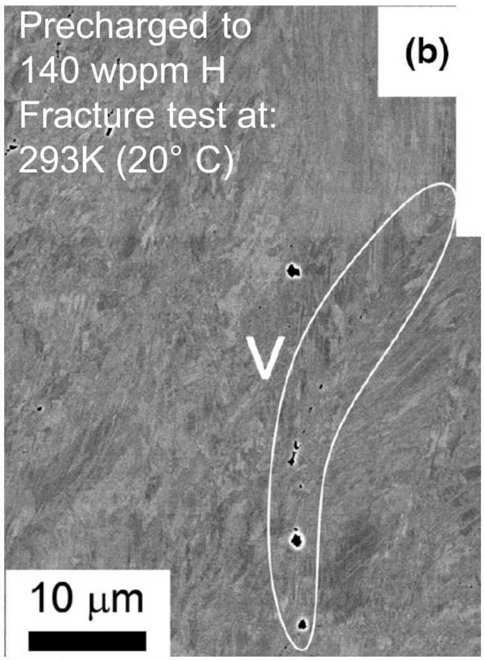
223K

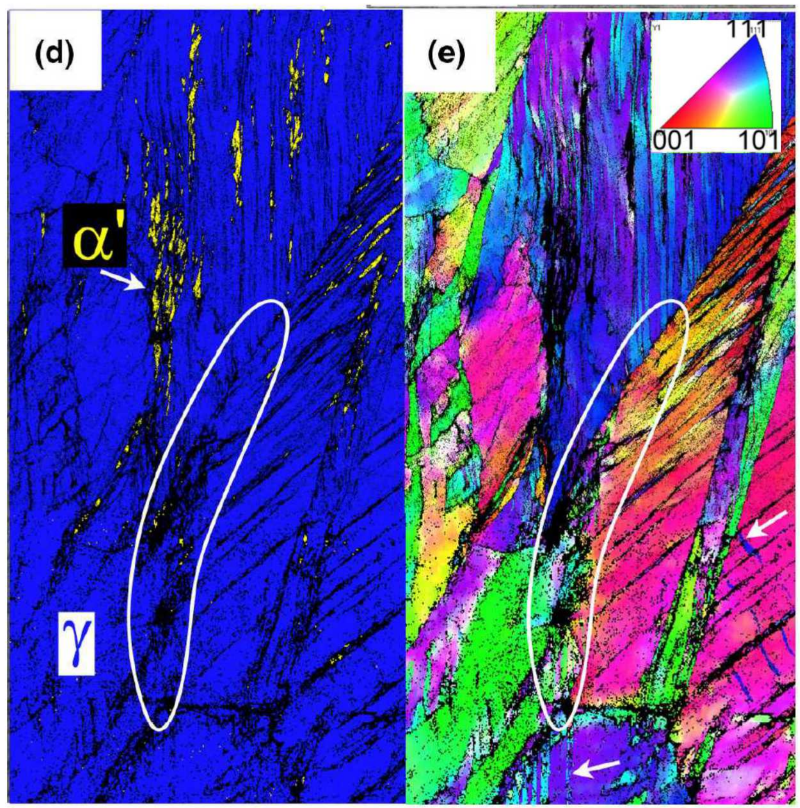
140 wppm H

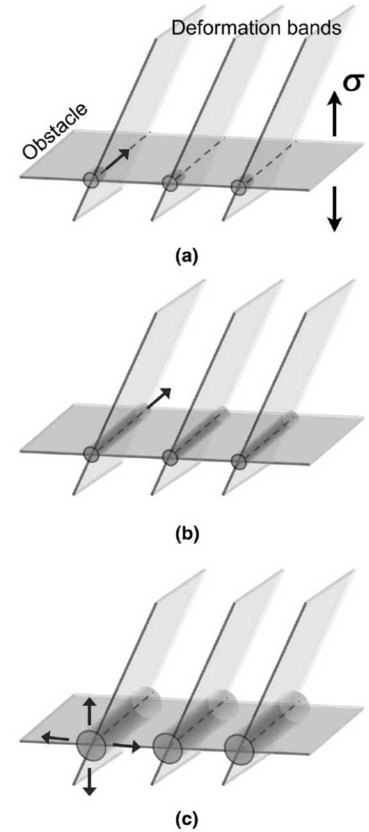
H. Jackson, C. San Marchi, D. Balch, B. Somerday, J. Michael, Metallurgical and Materials Transactions A, 2016

Microvoid nucleation at intersection of planar deformation bands with GBs

Fracture processes in H-Charged 304L associated with void nucleation







H. Jackson, C. San Marchi, D. Balch, B. Somerday, J. Michael, Metallurgical and Materials Transactions A, 2016

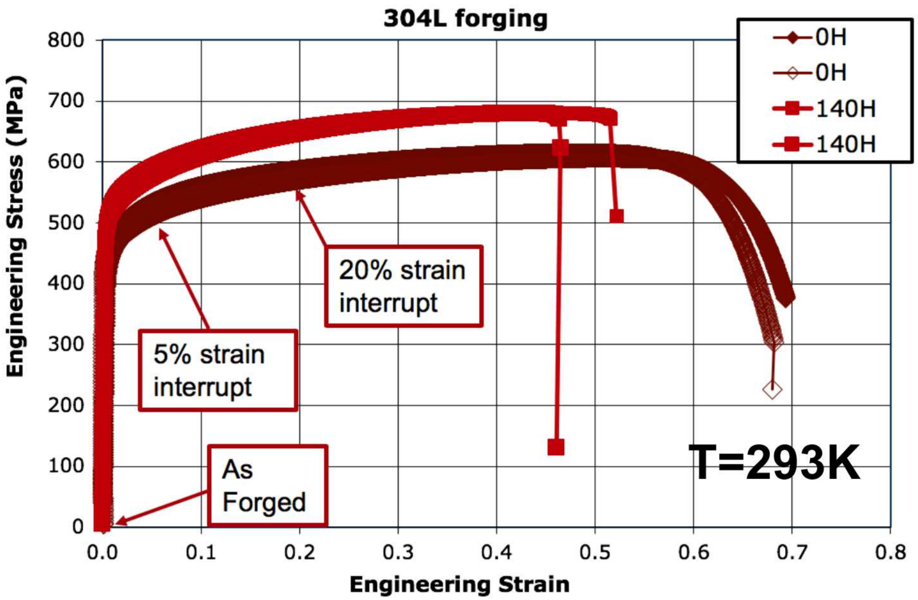
What are the deformation bands and how do they depend on hydrogen?

Focus for this talk:

- **Structure of the planar deformation bands**

  -Microstructure in specimens from interrupted Tensile Tests.

  -Same forged 304L material as in Jackson 2016 study



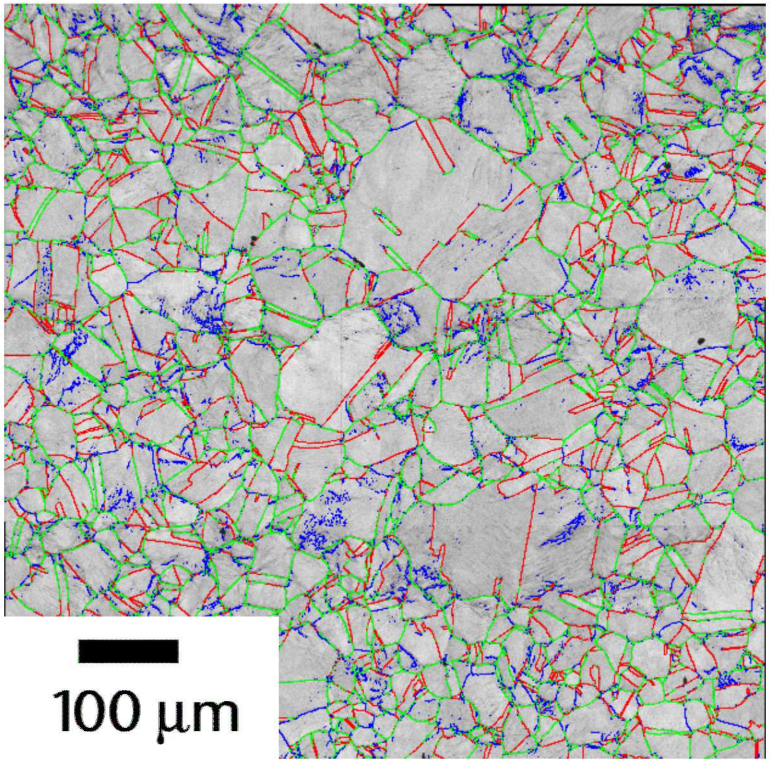
- **Relationship of the bands to α' martensite nucleation**

  -Influence of hydrogen on ε-martensite formation

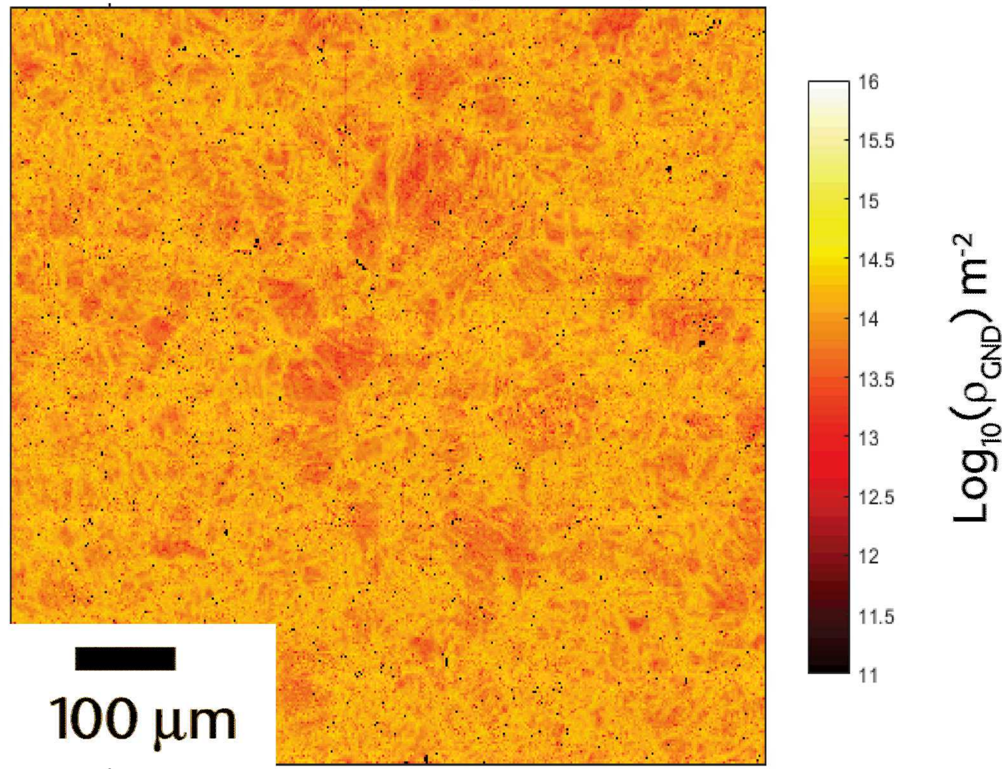
Initial As-forged microstructure

EBSD Measurements

GB Misorientations



Geometrically Necessary Dislocation (GND) Density

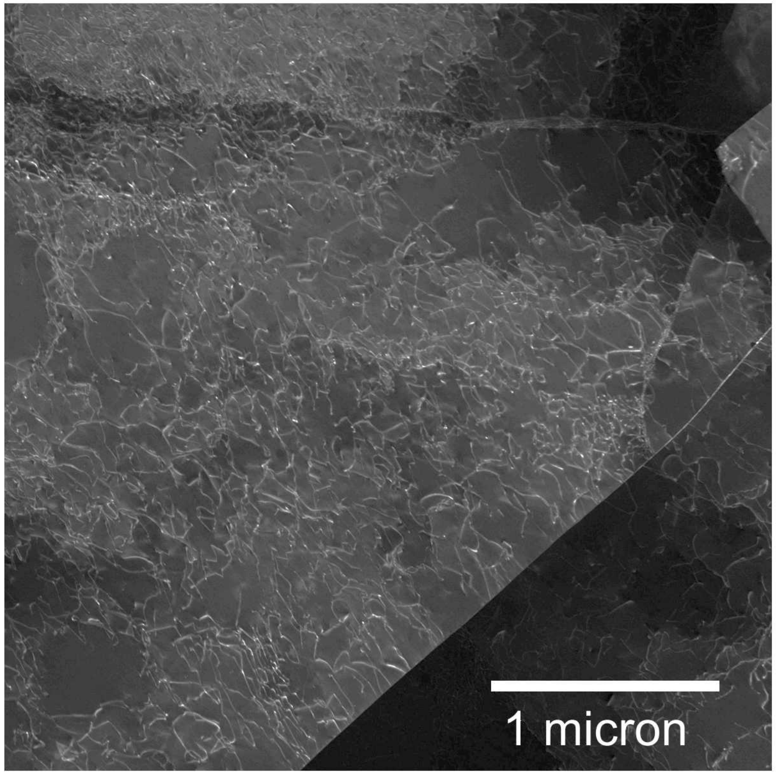


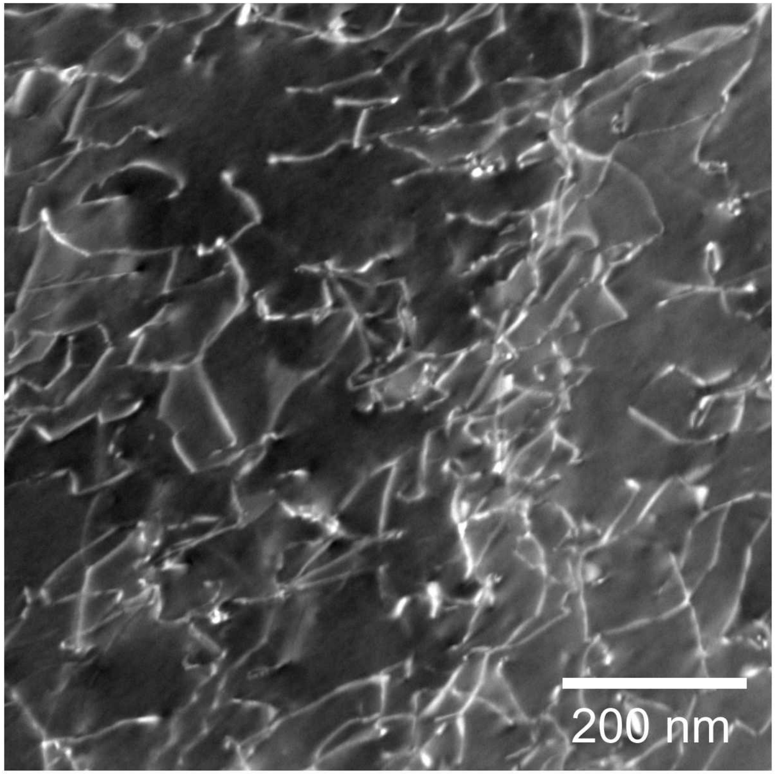
Misorientation
5-20° (blue)
20°-55° (green)
55°-60° (red)

- Some pre-existing twins within the microstructure
- Dense distribution of geometrically necessary dislocations (GNDs)

As-forged microstructure: dense dislocation network

Diffraction Contrast Scanning Transmission Electron Microscopy
(DC-STEM)





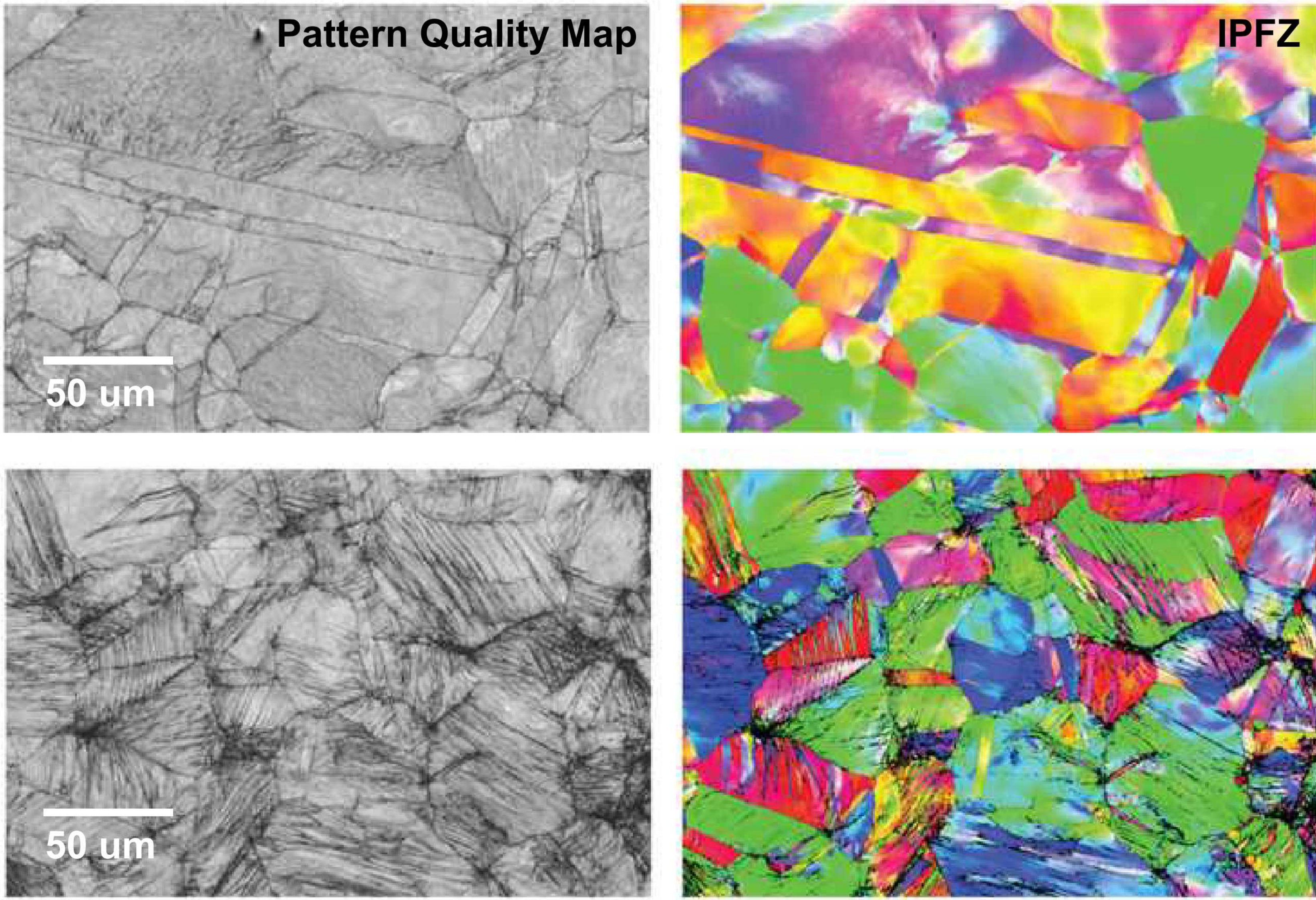
How does this microstructure evolve with plastic strain?

H increases density of deformation bands

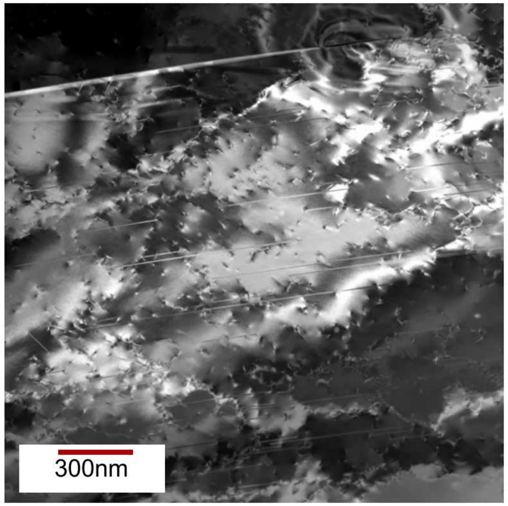
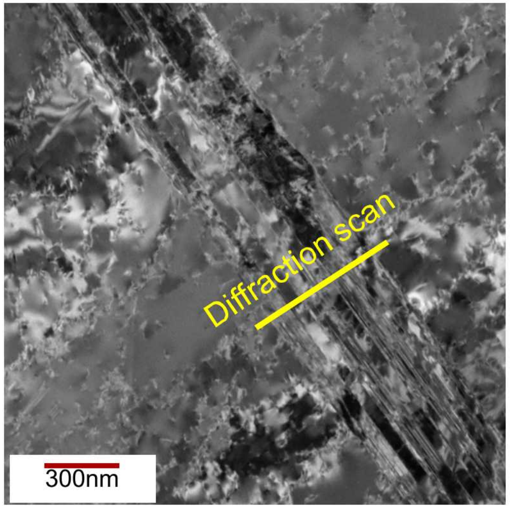
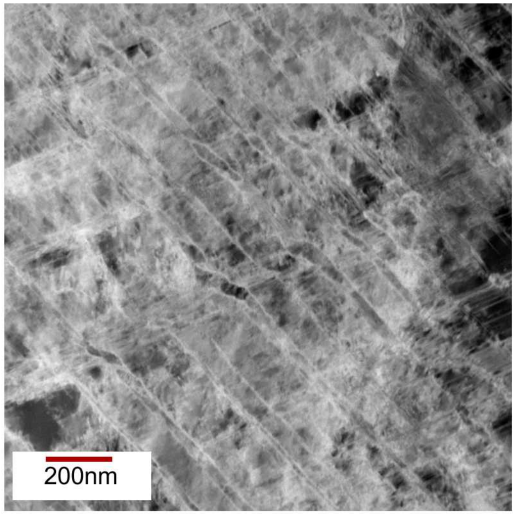
EBSD - 20% Strain

Non-Charged

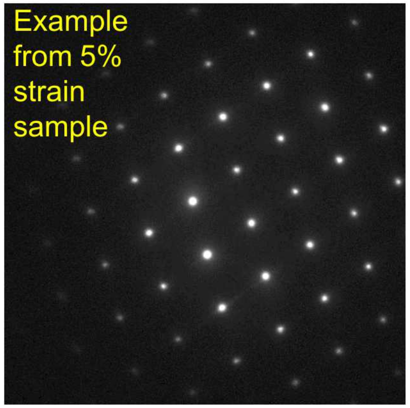
Hydrogen Charged



STEM: Insight to Development of Shear Bands

As-forged and H-charged (140 ppm H)	5% strain (140 ppm H)	20% strain (140 ppm H)
		
Dislocation cells and extended stacking faults	Parallel bands of deformation twins and ε-martensite (no α'-martensite observed)	Intersecting shear bands (twins, ε-martensite) α' – martensite at intersections

Scanning diffraction to determine interphase crystallography at nanometer-scale resolution



Key techniques:
- -Diffraction-Contrast STEM
- -Scanning nano-beam diffraction
- -Atomic-resolution STEM

Orientions and phases in shear-bands can be distinguished through nanobeam diffraction

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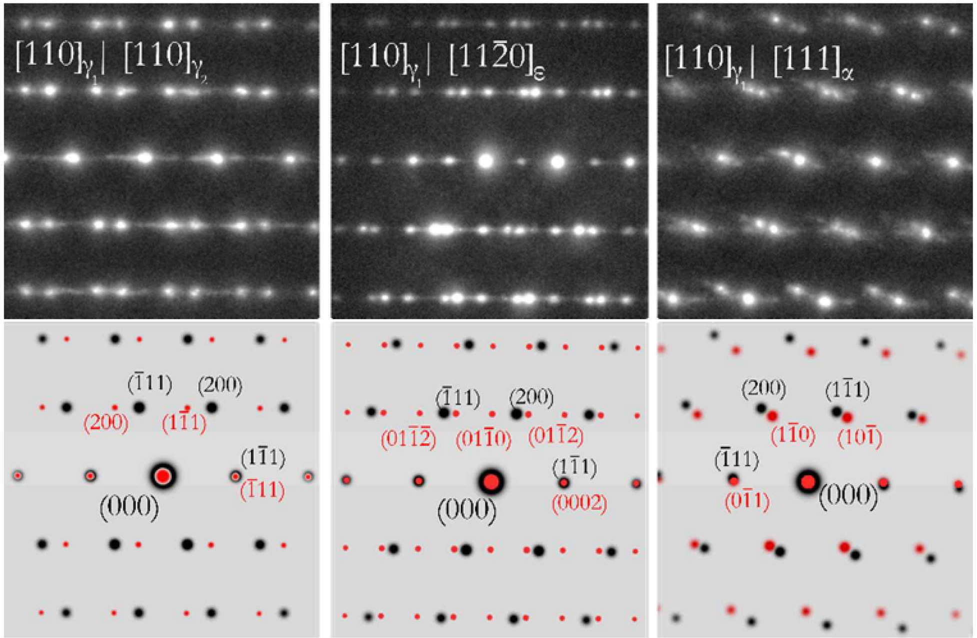
Austenite:
face-centered cubic (fcc)

ε-martensite:
hexagonal close packed (hcp) structure

α'-martensite:
body-centered cubic (bcc) (or bct depending on C-content)

Austenite: matrix & twin | Austenite & ε-martensite | Austenite & α'-martensite

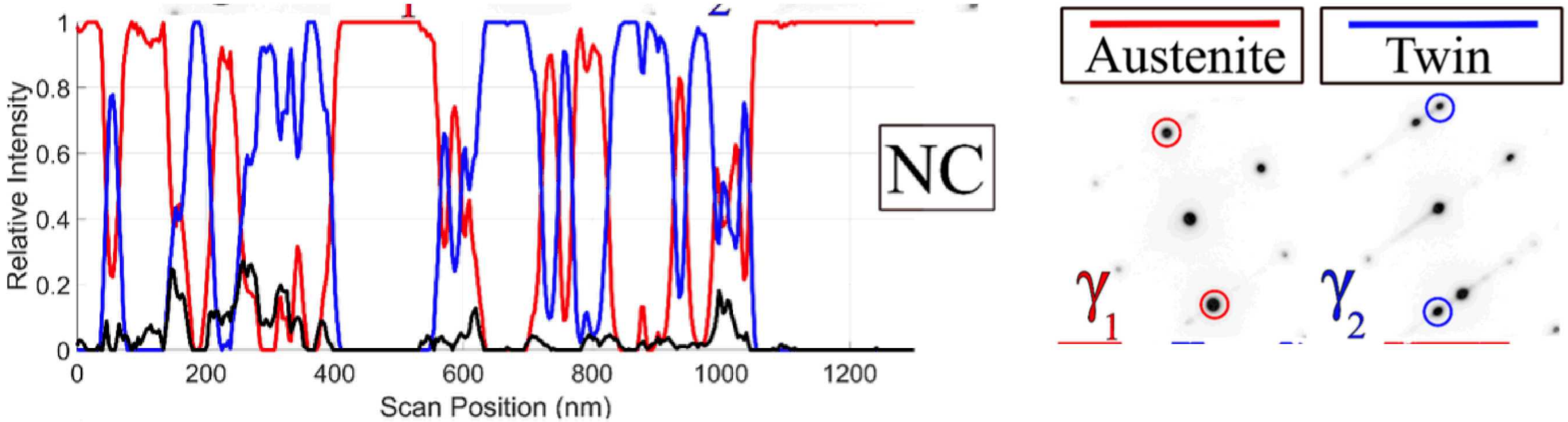


Orientations align close-packed planes and directions:
- Austenite//ε-martensite: Burgers relation
- Austenite//α'-martensite: Kurdumow-Sachs relation

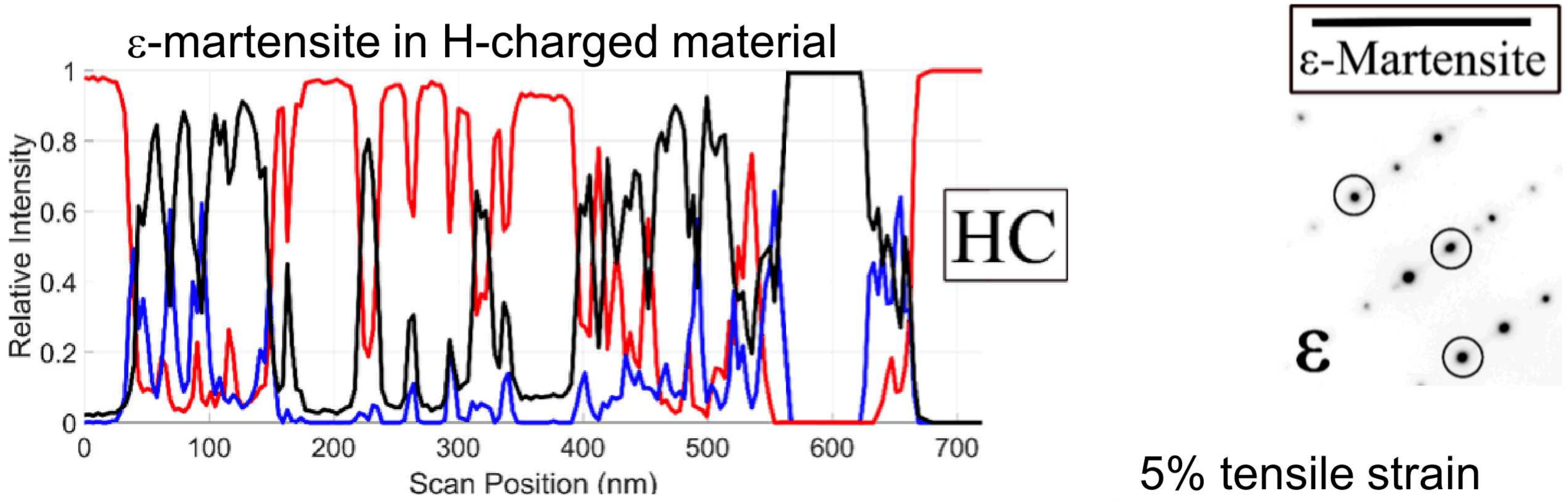
Hydrogen charging promotes ε-martensite formation in shear bands

Nanobeam diffraction line-scan analysis

Twinning in non-charged material



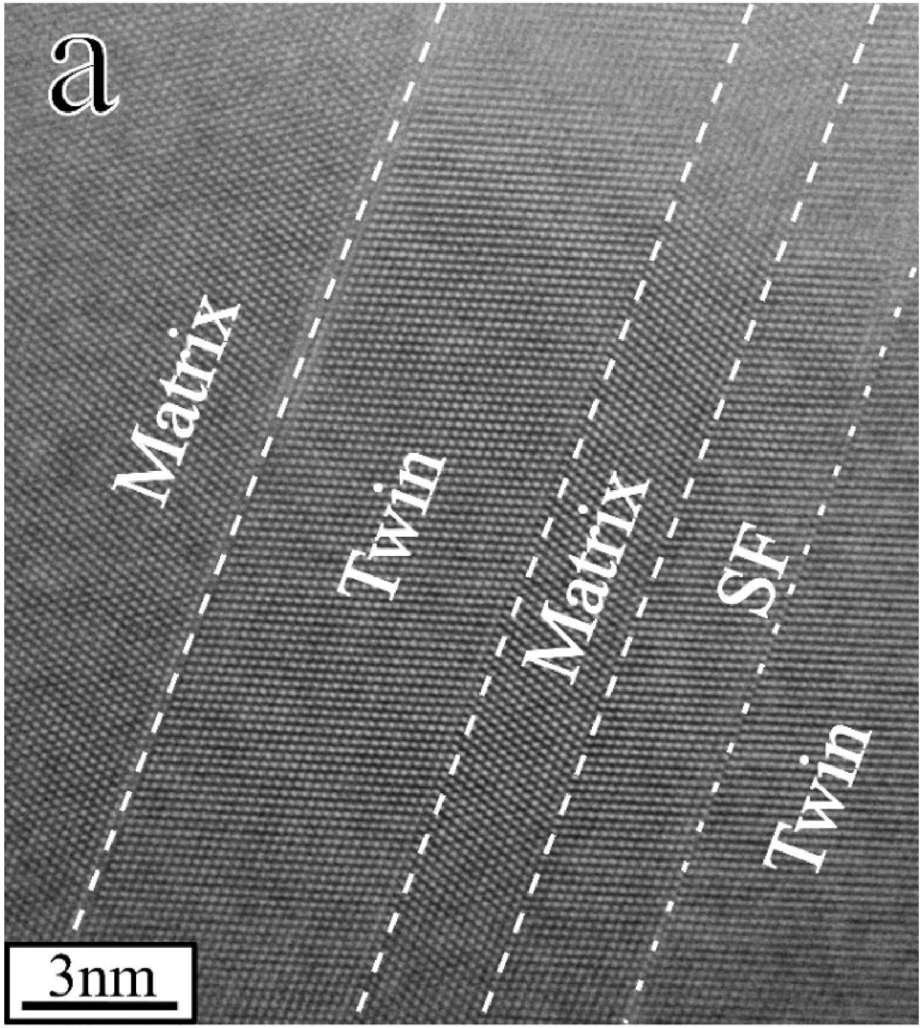
ε-martensite in H-charged material

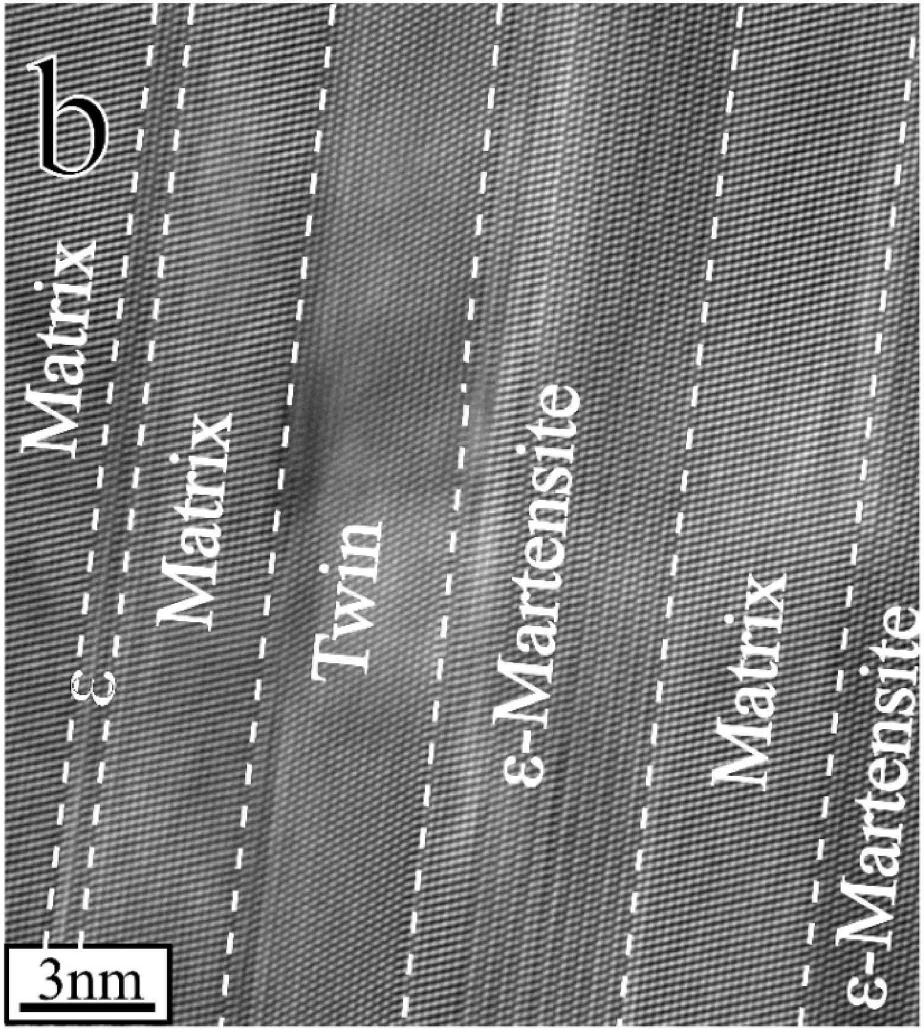


5% tensile strain

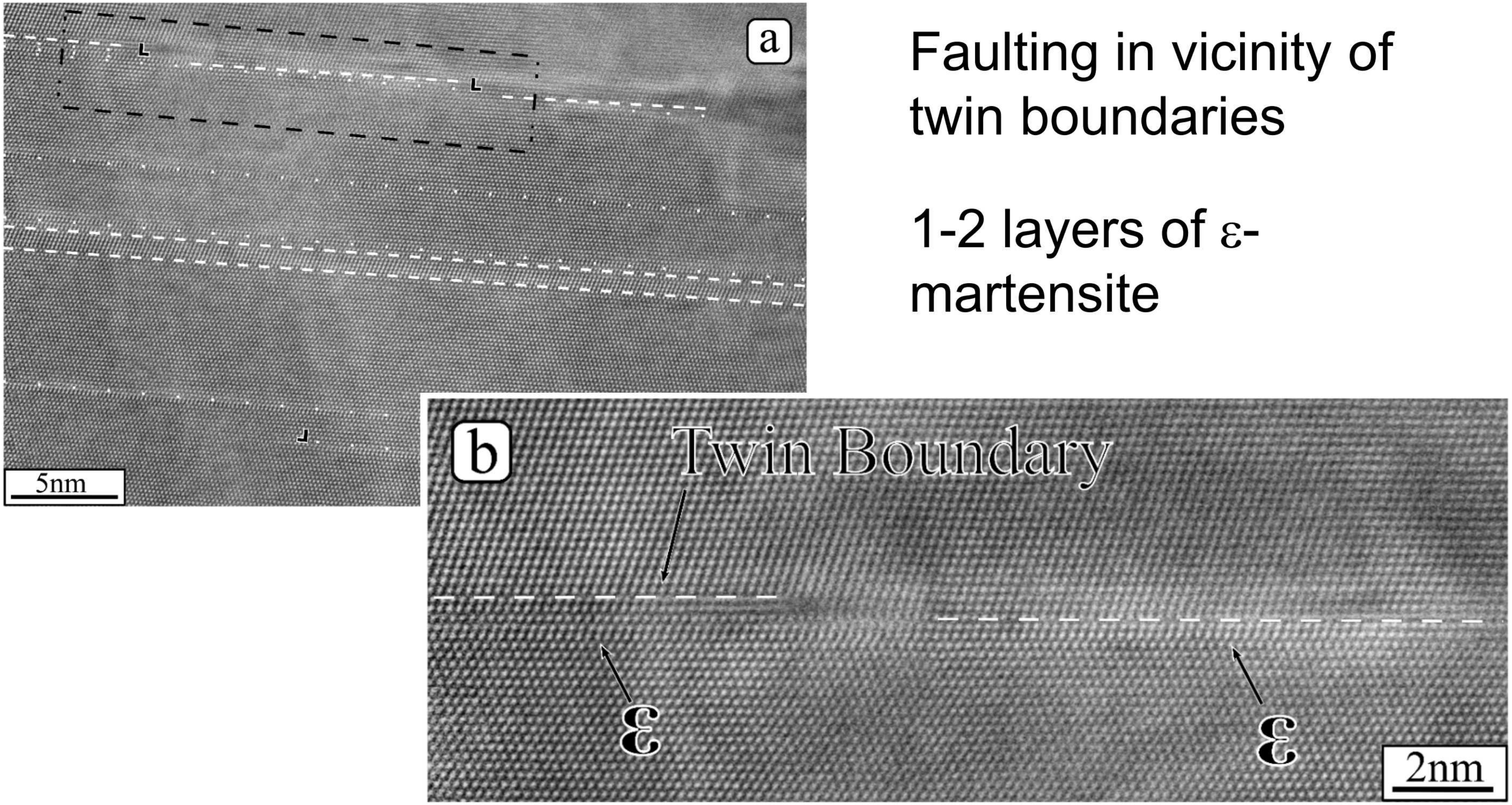
HRSTEM: detail of deformation bands

5% strain





20% Strain: limited initiation of ε-martensite in non-charged material



Faulting in vicinity of twin boundaries

1-2 layers of ε-martensite

Promotion of ε-martensite by hydrogen: an open mechanistic question

Understanding relationship to stacking fault formation and partial dislocation motion is critical

-Reduction in SFE is often invoked as explanation H-influence on shear localization.

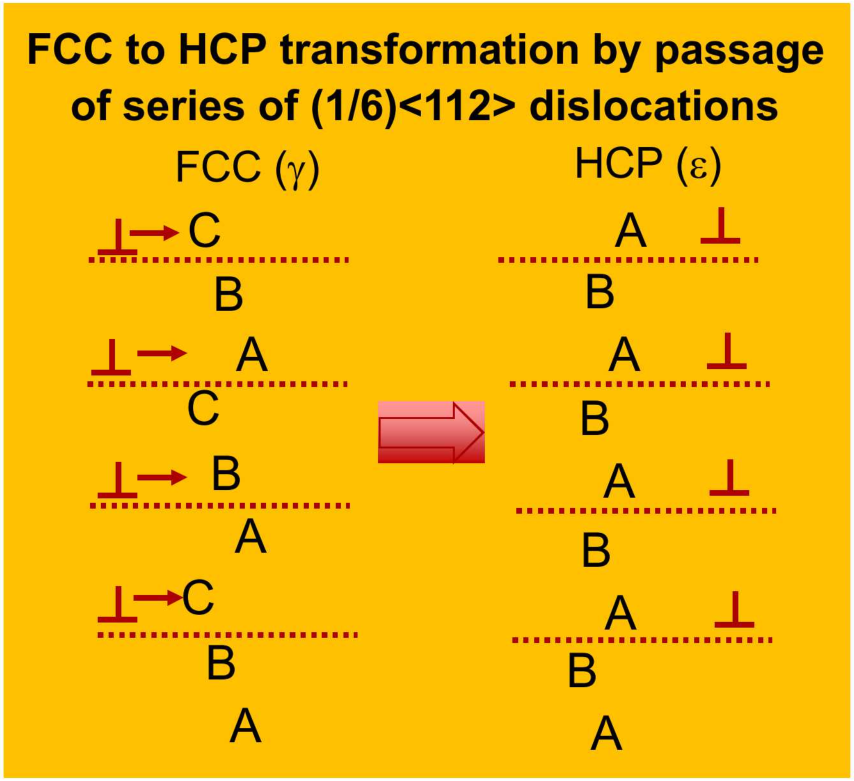
Existing experimental literature shows small reductions in SFE with H.

(e.g., Ferreira, Mat Sci Forum 1996, Pontini, Scripta Mat 1997)

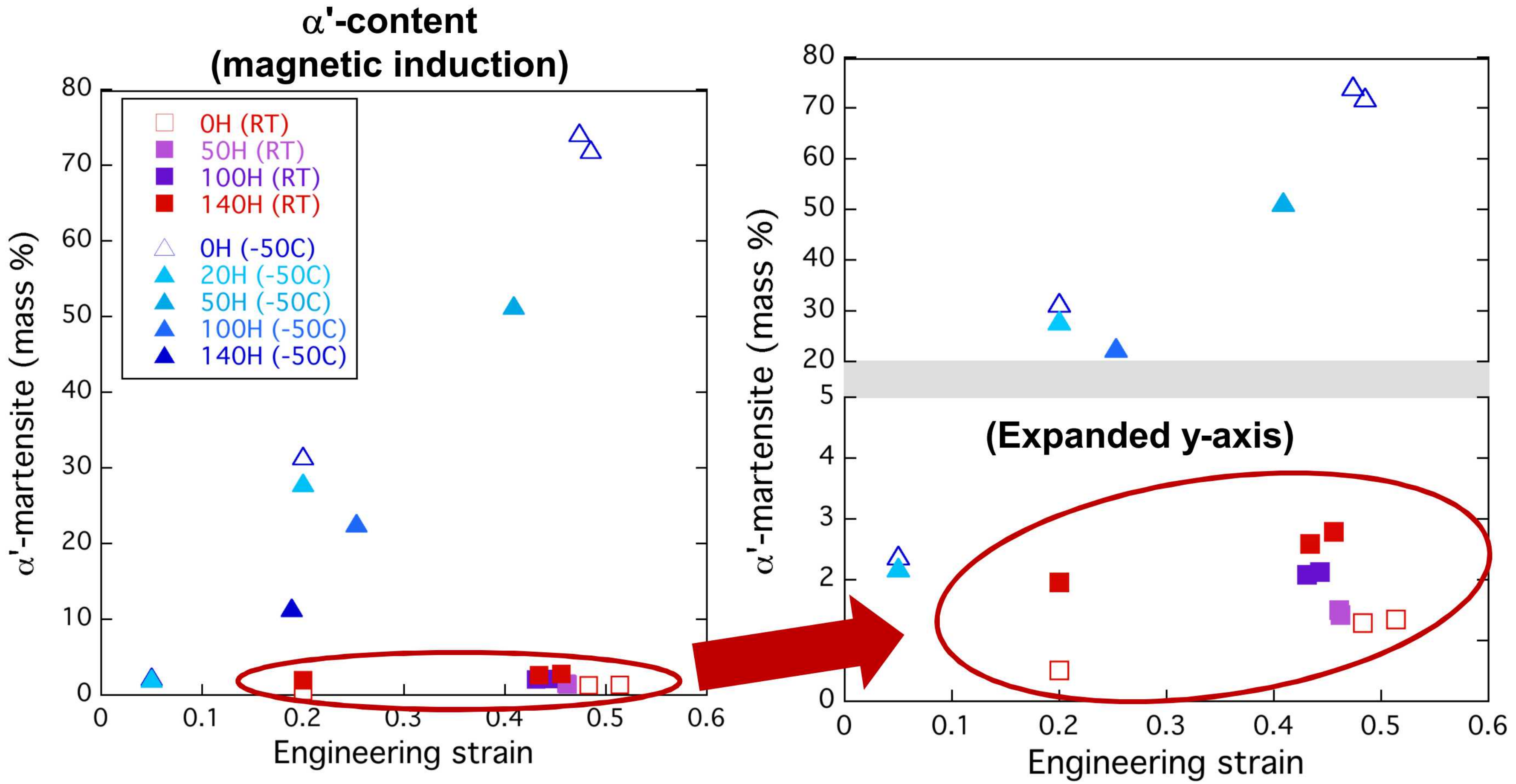
-Solute drag effects:

Preferential pinning of trailing partials by hydrogen gives kinetic mechanism for fault extension. (e.g., Sills et al., 2016)

-Does not explain how faults would order into required ABAB... stacking sequence



Strain-induced α'-martensite transformation in 304L



At *RT* and *low* volume of transformation, hydrogen *promotes* α'-martensite

C. San Marchi et al. 2019

Strain-induced α'-martensite transformation in 304L

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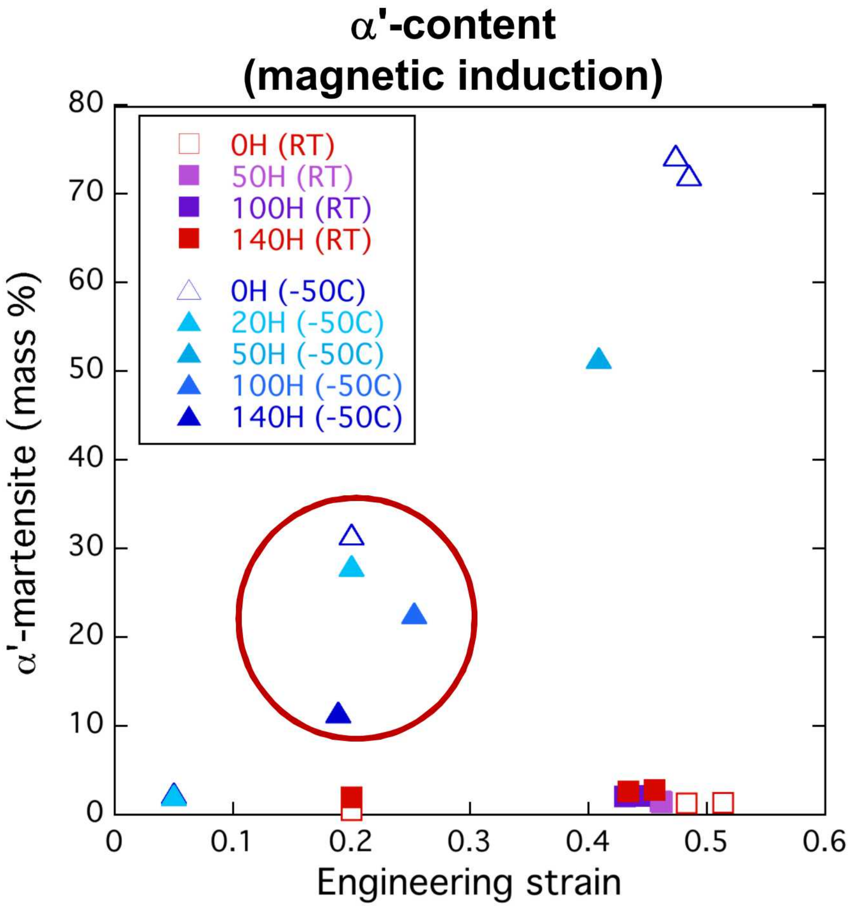
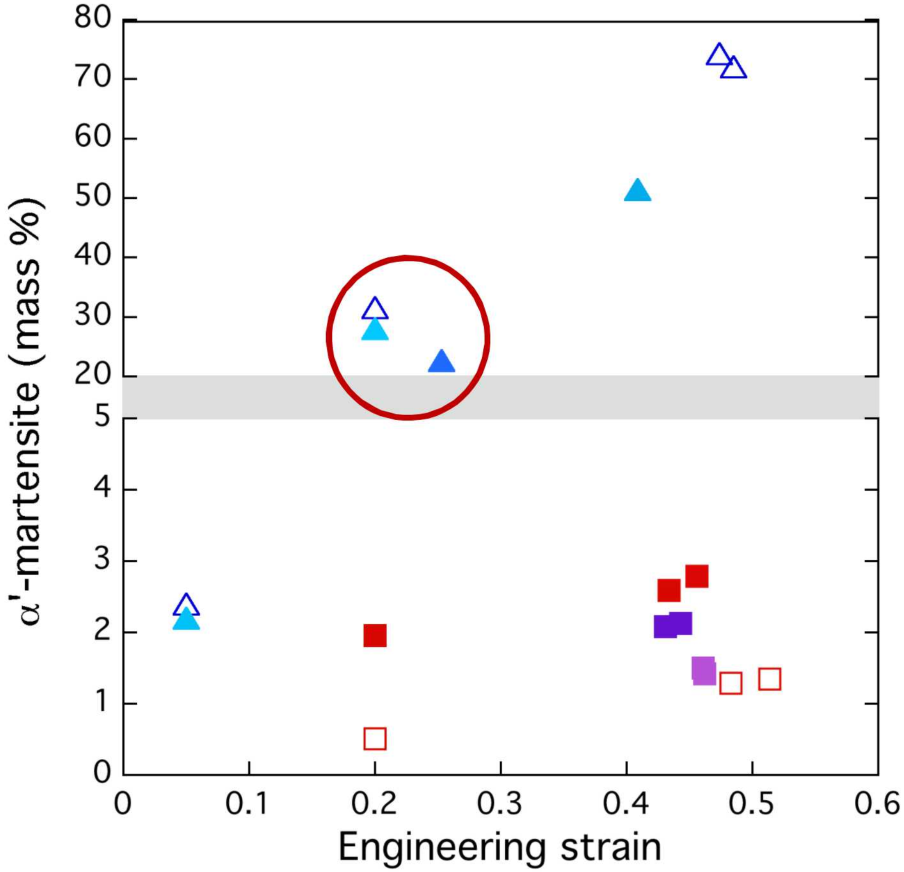
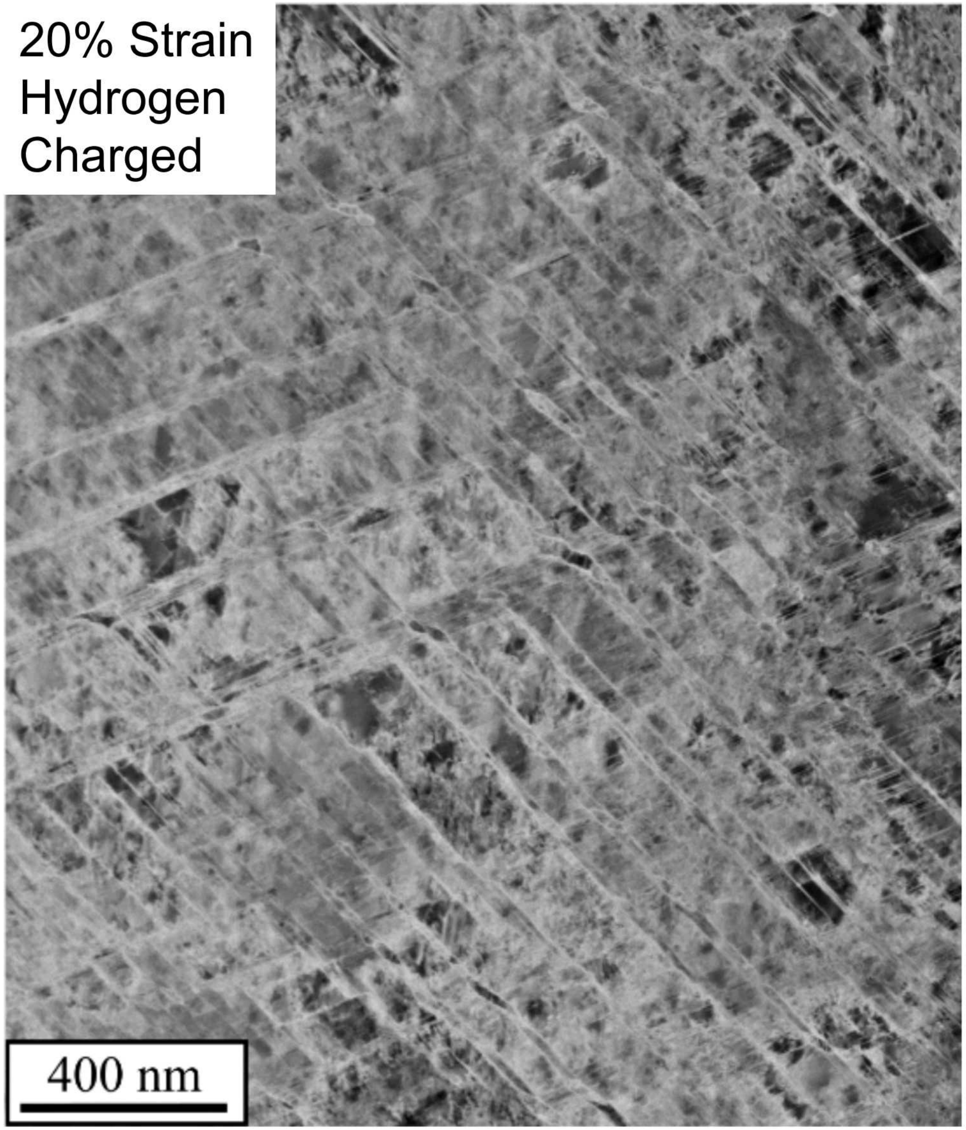




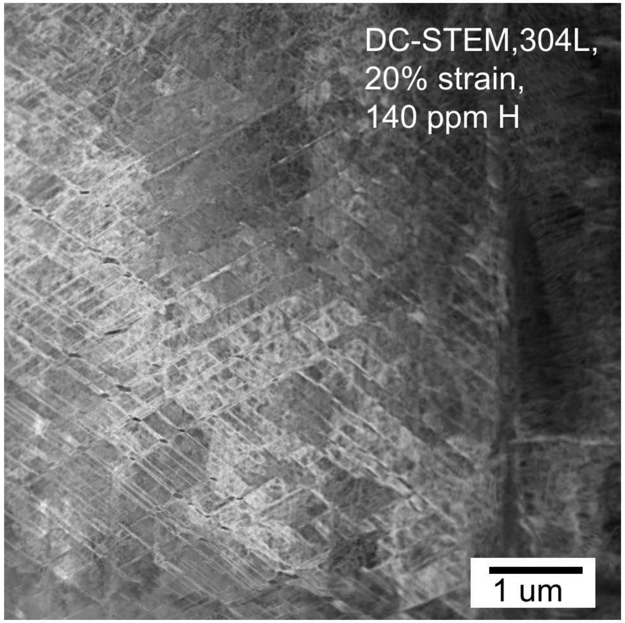
At *-50°C* and *high* volume of transformation, hydrogen *suppresses* α'-martensite

C. San Marchi et al. 2019

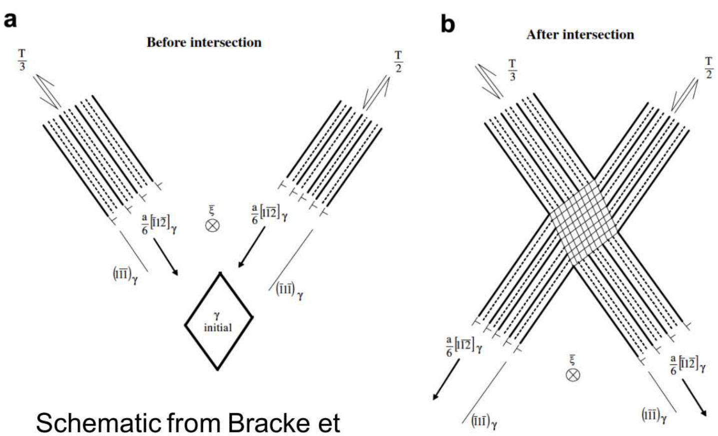
Higher Strain: Activation of multiple slip gives cross-hatched microstructure



α' martensite at shear band intersections



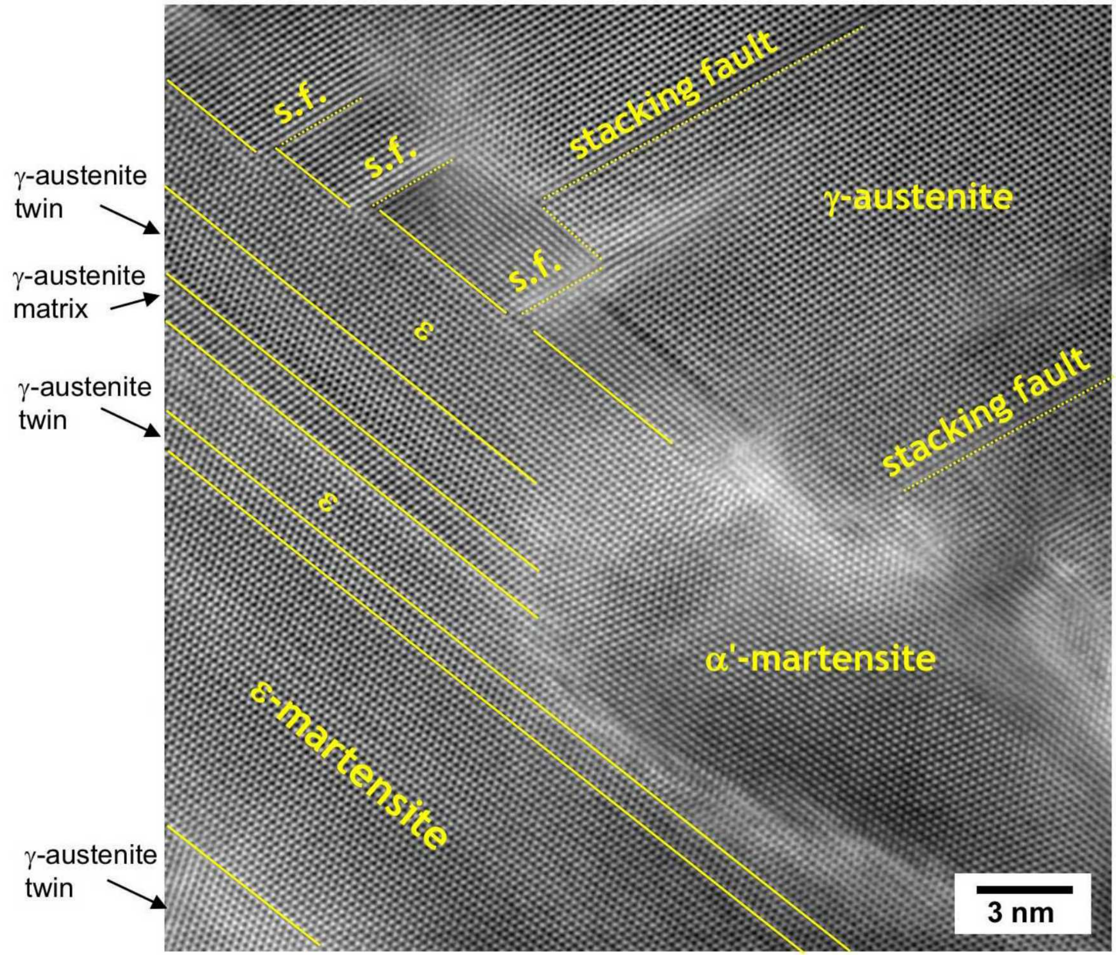
Olsen & Cohen model for α'-martensite nucleation at shearbands



Schematic from Bracke et al. Scripta Materialia 2007

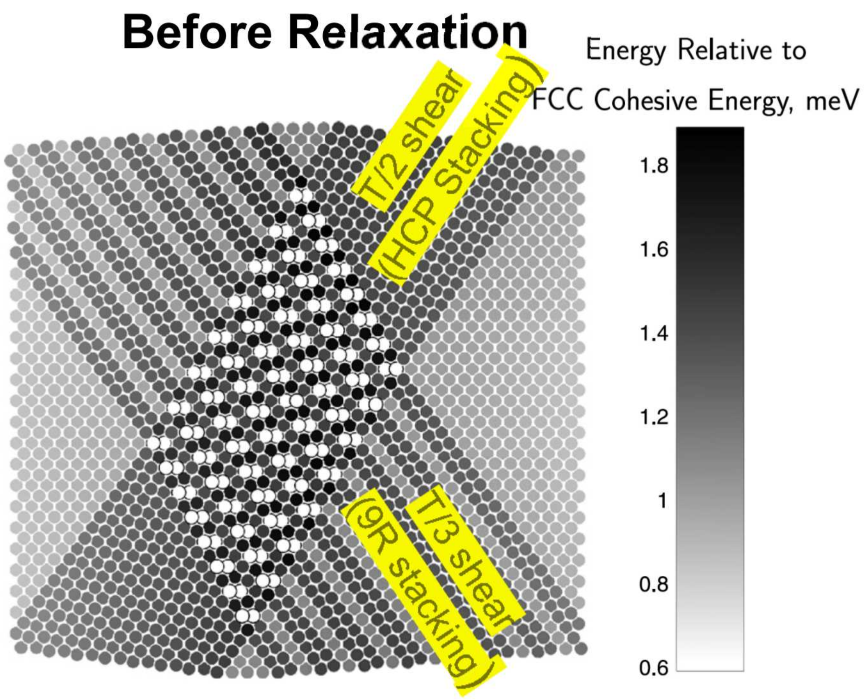
ε- and α'-martensite at shear bands in tensile-strained 304L stainless steel

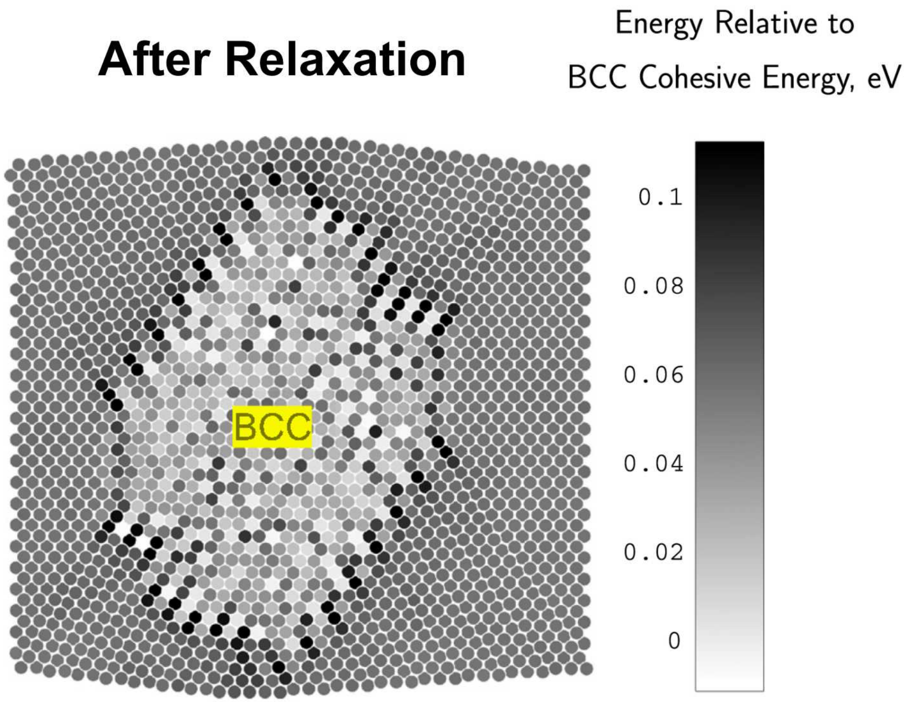
(20% strain, 140 ppm H)



Atomistic calculations:
α' nucleation at ε-martensite intersection

C.W. Sinclair and R.G. Hoagland, Acta Materialia 2008





Increased potency for α' nucleation at intersections of ε-martensite

Increase of BCC α'-martensite with internal hydrogen may be a secondary effect of hydrogen increasing ε-martensite formation

Conclusions

• Complex, multiscale evolution of microstructure under tensile strain in forged austenitic stainless steel.

• Microstructure affected by presence of internal hydrogen

-Strain localization into planar deformation bands

-Twinning in non-charged 304L

-Both twinning and martensite formation in H-charged 304L

ε –martensite in shear-bands

α'-martensite at intersections of shear-bands

-ε martensite provides a favorable pathway to α'.

-Likely that the initial increase in α' with H is a secondary effect of hydrogen promoting ε-martensite formation, aiding α' nucleation

• Open mechanistic questions:

-Promotion of ε-martensite formation by H?

-Low T reduction of α' by presence of H?

Acknowledgements

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Mark Homer (Sandia)

Transmission Electron Microscopy
Julian Sabisch

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