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Effects of Hydrogen on Deformation Evaluated with EBSD of Single Crystal Austenitic Stainless Steel

Brian Kagay[1,2]

Coleman Alleman[1], Brandon Talamini[1], Chris San Marchi[1]

[1]Sandia National Laboratories

[2]Now at MPA University of Stuttgart

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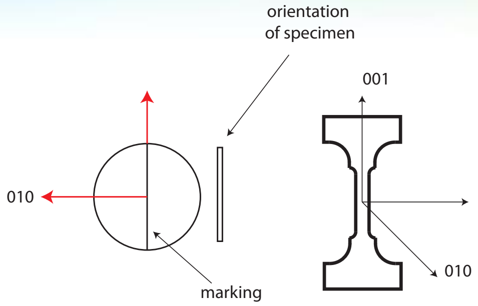
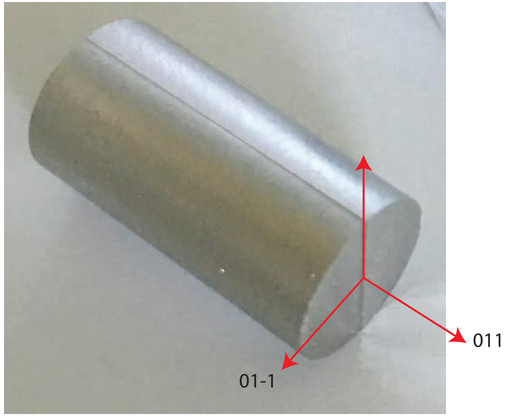
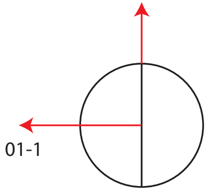
Evaluated hydrogen effects on deformation mechanisms of 316L single crystals

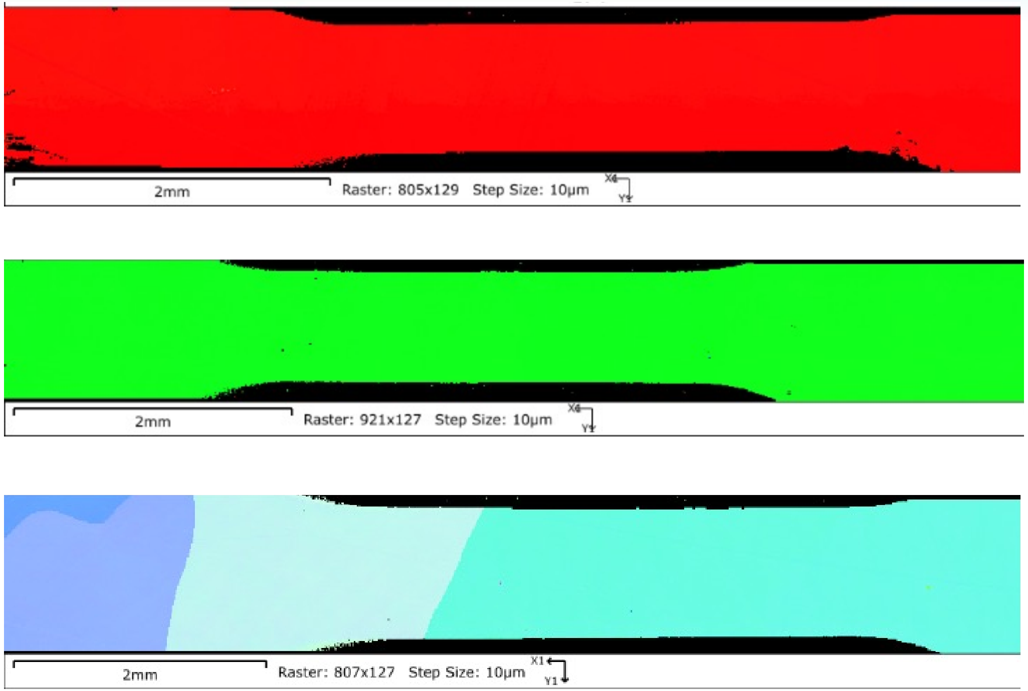
- Mini-dogbone tensile samples extracted from 316L single crystal cylinders with three different orientations
- Samples polished prior to testing to enable EBSD
- Half of the tensile samples pre-charged with hydrogen
- Strains measured with DIC and laser extensometer
- Interrupted testing to evaluate evolution of deformation
- Stress-strain curves and EBSD observations used to inform crystal plasticity modeling (yielding, hardening rate, grain rotation, etc.)





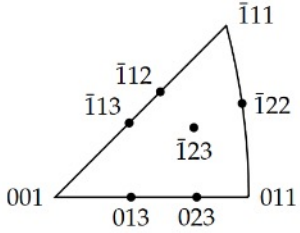


3 orientations parallel to tensile axis : <001>, <011>, <123>



<001>
4 initial active slip planes

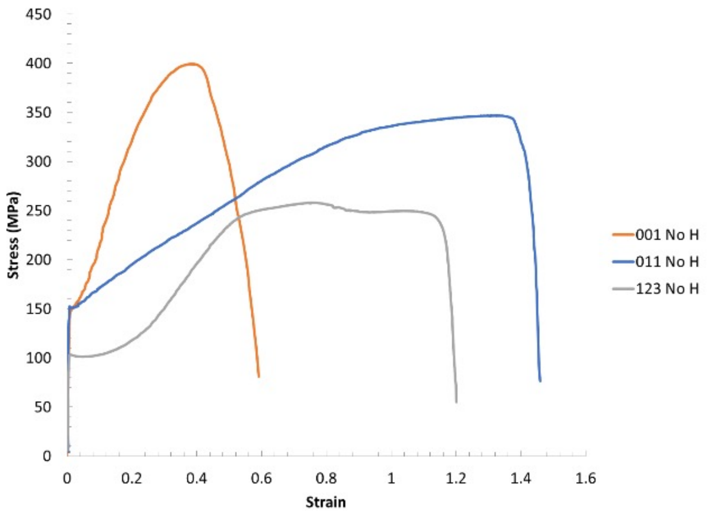
<011>
2 initial active slip planes



<123>
1 initial active slip plane

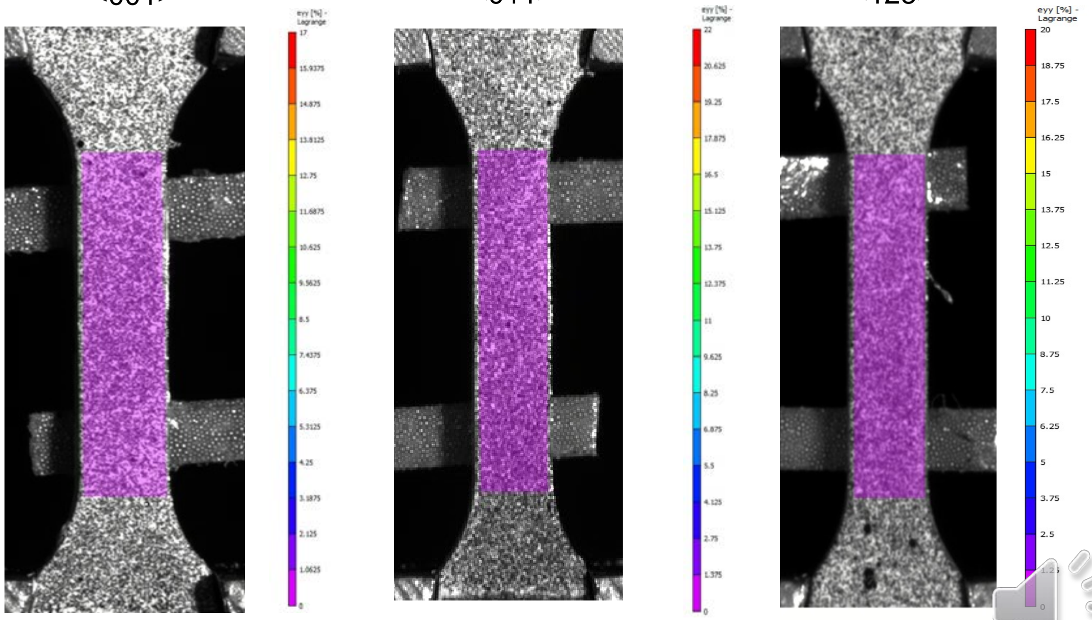
Differences in stress-strain behavior due to orientation and number of active slip planes

No H Tensile Curves



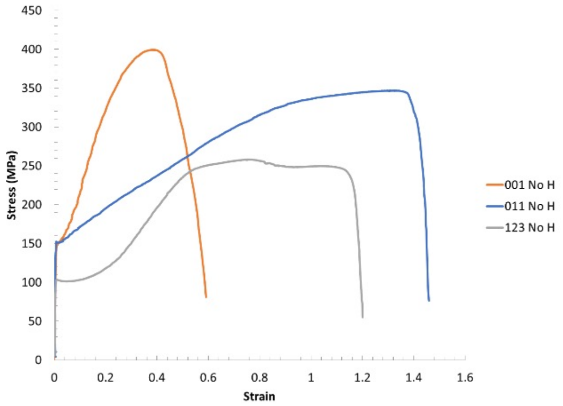
DIC videos for first 10% strain from interrupted tests

<001> <011> <123>

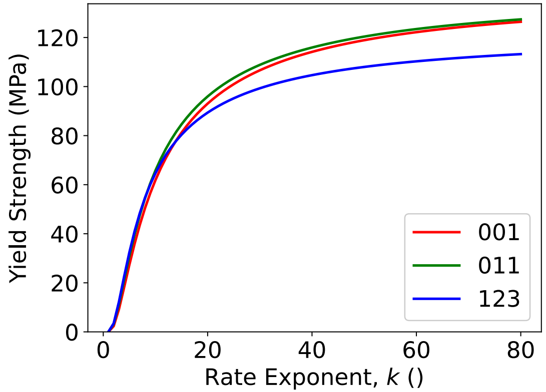


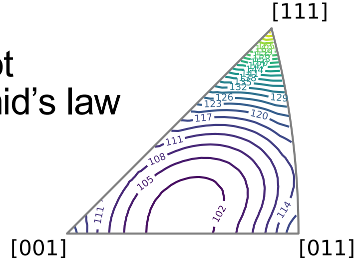
Yield stress, stages of hardening, hardening rate, and necking behavior are dependent on orientation and hydrogen content

No H Tensile Curves



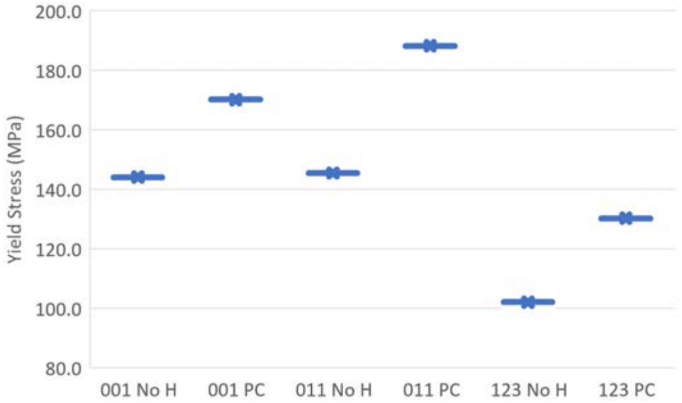
Yield behavior based on Schmid's Law





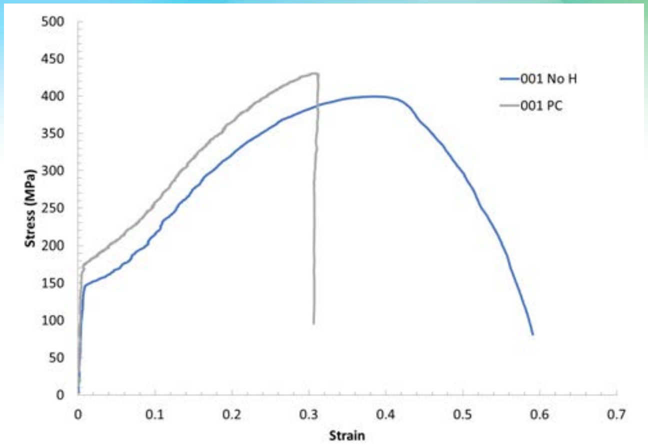
Yield stress does not correspond to Schmid's law

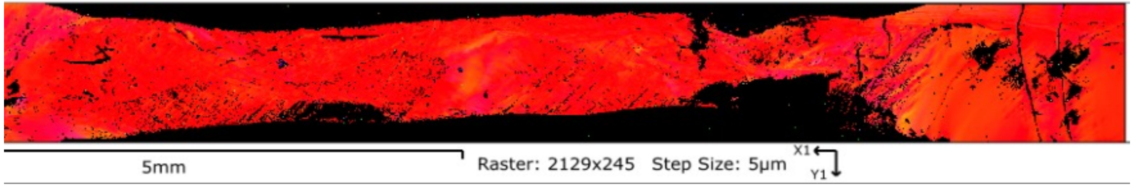
Amount of increase in yield stress due to hydrogen is dependent on orientation



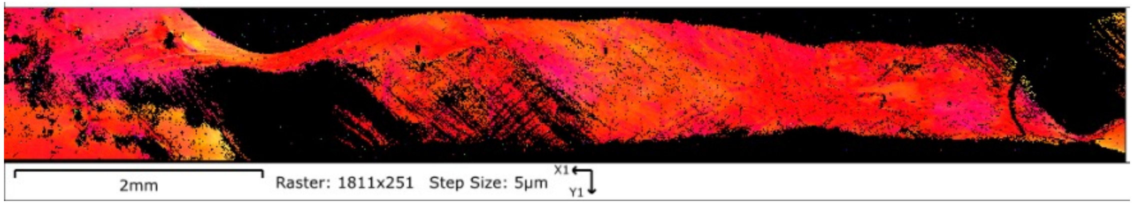
For <001> orientation hydrogen increased flow stress and decreased reduction of area

No significant twinning, martensite formation, or grain rotation observed through EBSD





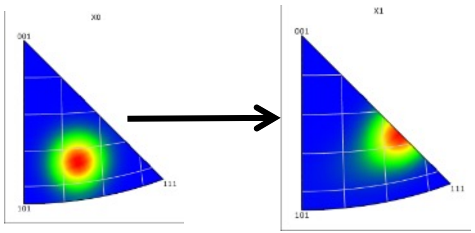
<001> No H
Interrupted at onset of necking

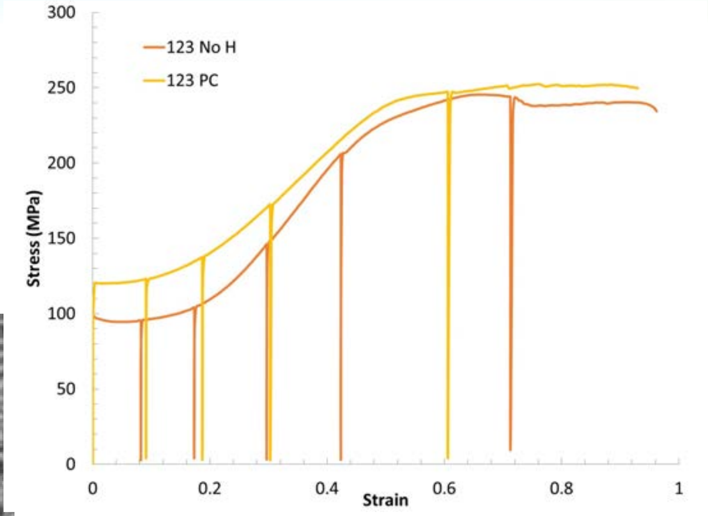


<001> PC
Interrupted at onset of necking

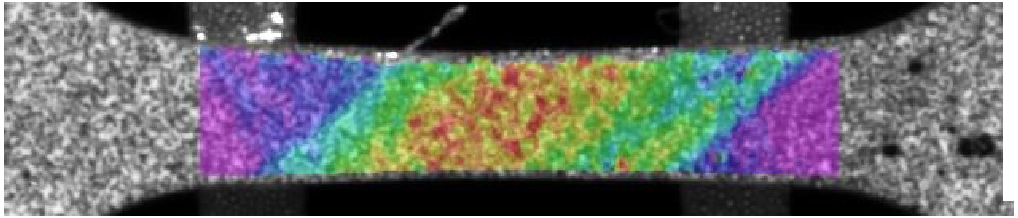
For <123> orientation hydrogen increased flow stress, decreased total hardening, and decreased load drop at onset of diffuse necking

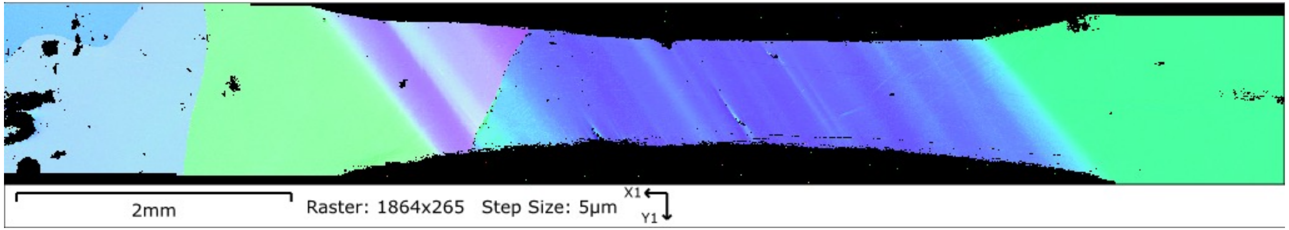
- Grain rotated to <001>-<111> line and a second slip system activates
- No significant twinning or martensite formation observed through EBSD





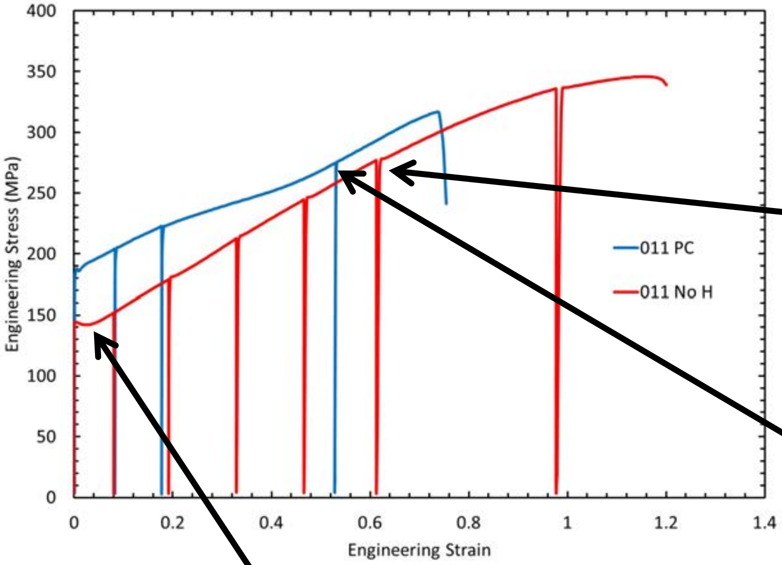
DIC and EBSD at 10% strain





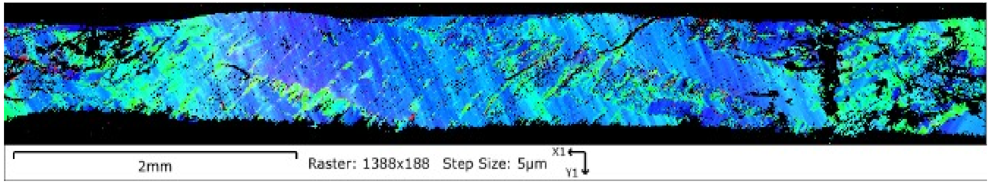
Hydrogen affects deformation of <011> orientation prior to necking

For <011> orientation, hydrogen
- decreased hardening rate between 20% and 50% strain
- caused twinning to occur at lower strains
- increased flow stress
- decreased uniform elongation
- decreased reduction of area

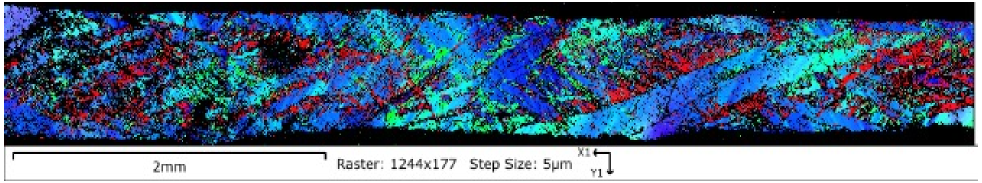


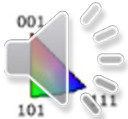
Small single slip stage I

<011> No H



<011> PC

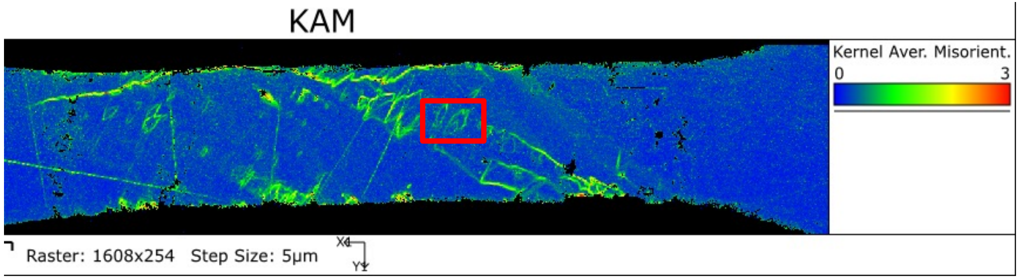


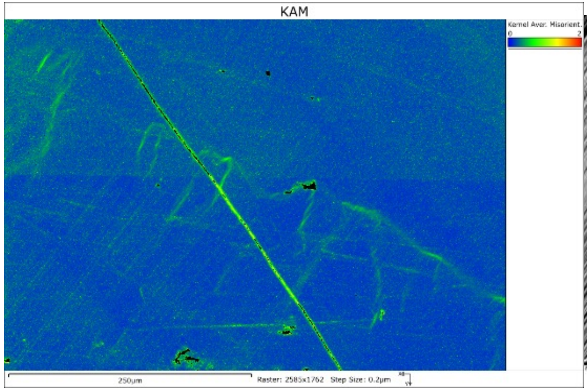


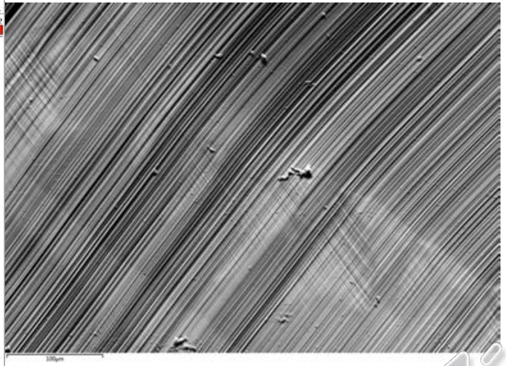
Significantly more twinning at 50% strain when hydrogen is present

For <011> at low strains the highest local misorientations (GNDs) are at edges of regions with slip lines in multiple directions

- Initially slip occurs primarily on one slip plane
- Shortly after yielding slip begins to occur on a second slip plane
- Dislocation interactions occur which can form obstacles to dislocation motion (Lomer-Cottrell locks)
- Geometrically necessary dislocations (GNDs) accumulate where slip is blocked at the obstacles



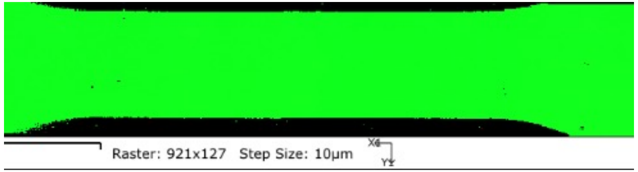




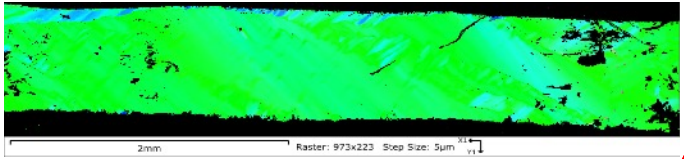
With further straining tensile axis of <011> rotates towards <111> direction

<011> No H

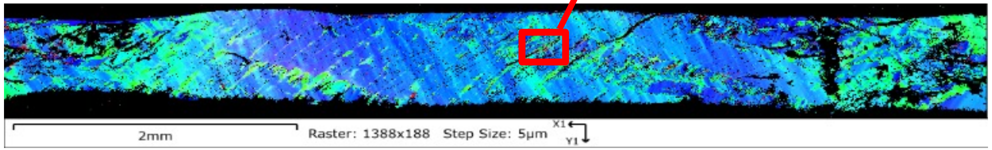
Pretest

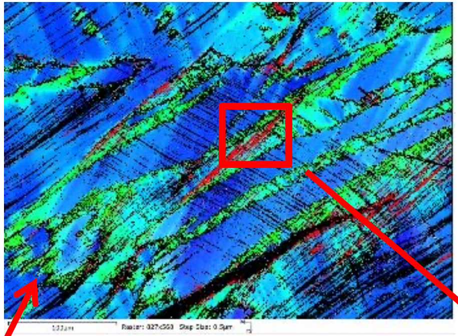


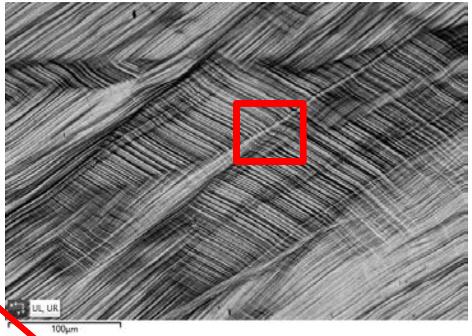
20% Strain
Some regions rotating to <111>



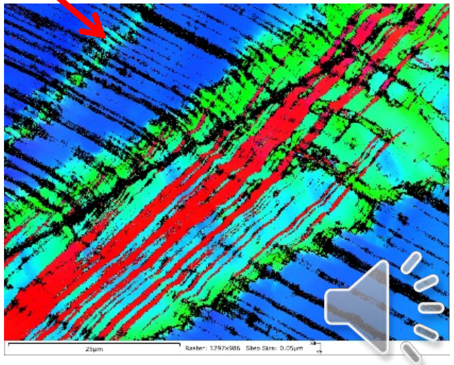
60% strain
Most of crystal rotated to <111>
Twinning is visible







Twinning initially occurs at low angle boundaries and where rotation is not complete

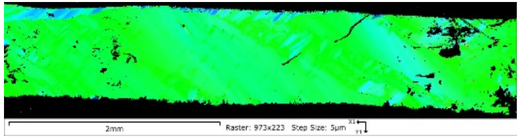


Hydrogen affects grain rotation and twinning planes for <011>

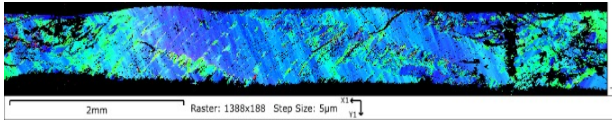
- For no H tensile axis rotates mostly towards a single <111>, but <011> PC rotates towards two different <111>.
  - These are rotations in the direction of the leading partial dislocations on the active slip plane
- Twinning occurs primarily on one plane with no H, but with H significant twinning occurs on two different planes

<011> No H rotates mostly to a single <111>

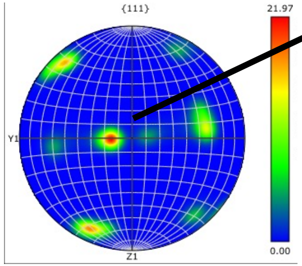
20% strain

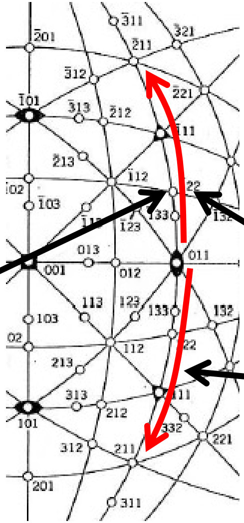


50% strain



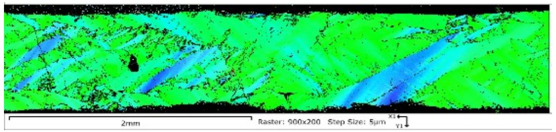
50% strain
<111> pole figure
in tensile direction



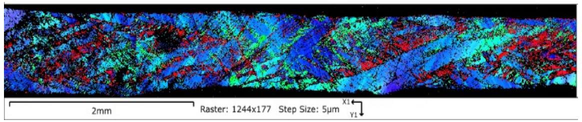


<011> PC rotates towards two <111>

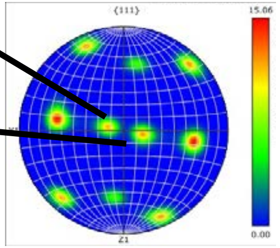
20% strain



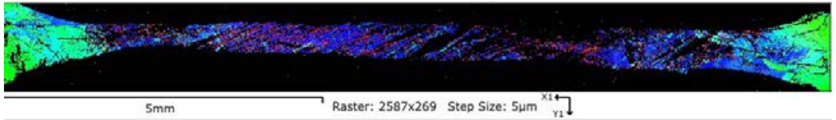
50% strain



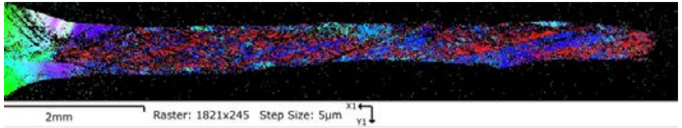
50% strain
<111> pole figure
in tensile direction



Necked. Twinning
mostly on one plane

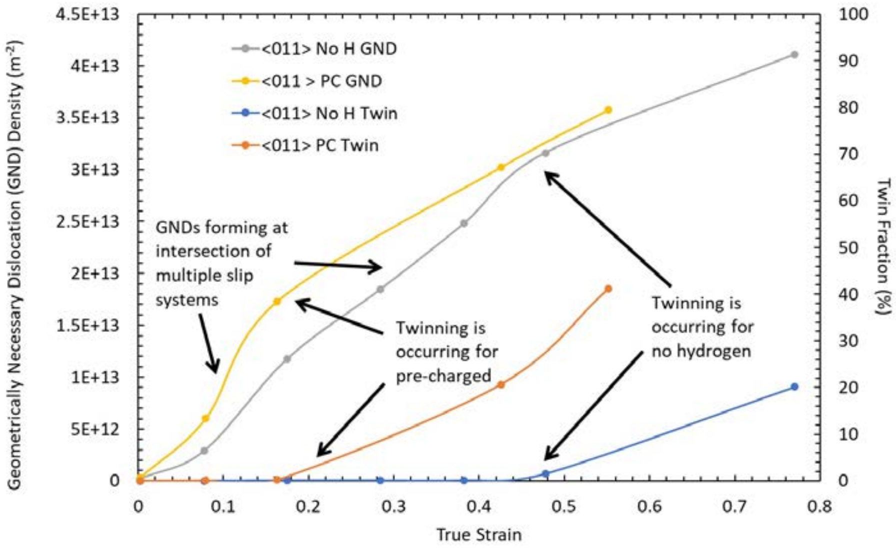


Failed. Twinning
on two planes

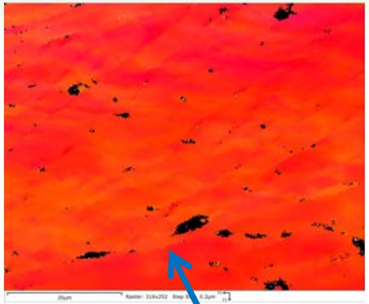


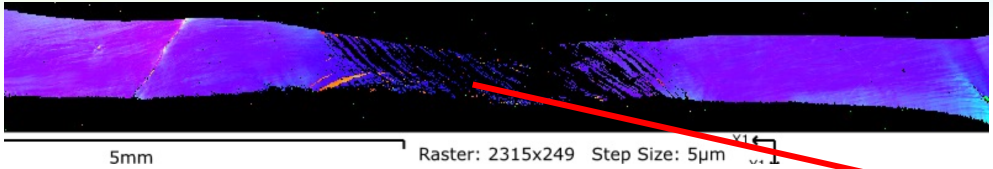
For <011> hydrogen causes twinning to occur at a lower GND density

- GND density estimated from kernel average misorientation maps
- Twinning fraction is fraction of cells that are indexed as twinned orientation
- GND density increases more at lower strains with hydrogen
- Twinning commences at lower GND density and lower strain with hydrogen
- Hydrogen may cause obstacles to dislocation motion to form at lower strains which increases dislocation density and results in twinning due to blocking of movement of partial dislocations

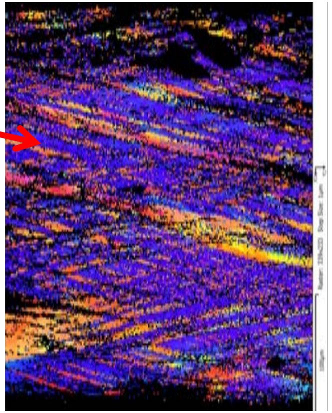


Twinning in necks of <011> and <123> specimens but not <001>
No ε-martensite observed, even in neck of <011> PC specimen



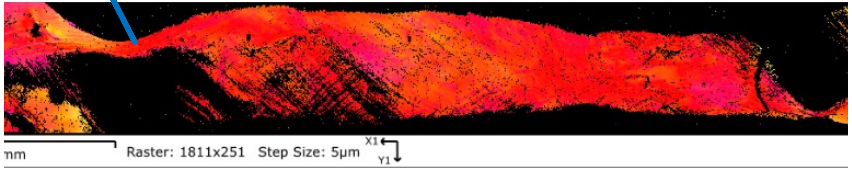


<123> PC

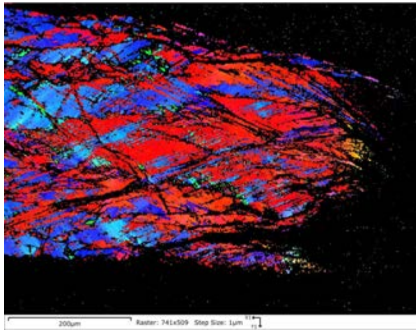


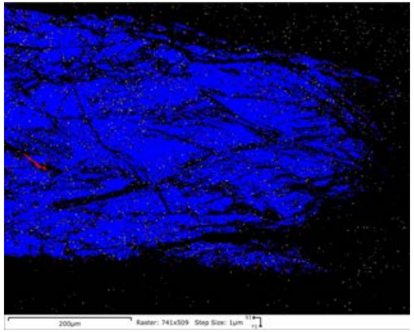
Two twinning directions in neck of <123> specimens

<001> PC



<011> PC
Small amount of α‘-martensite in <011> specimen

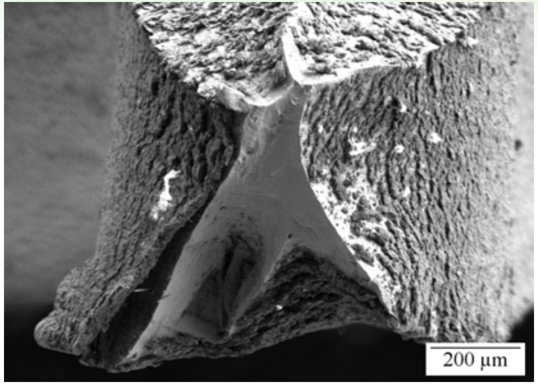




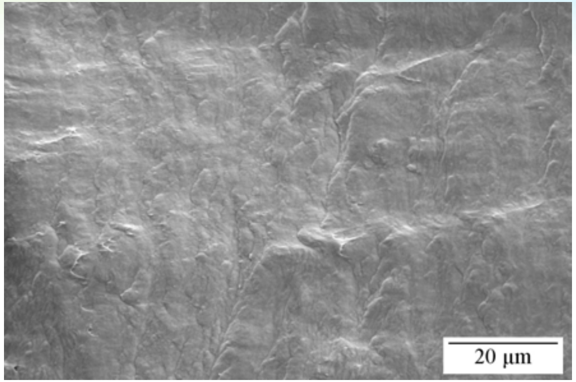
Phase Map
Blue = γ-austenite
Red = α‘-martensite
Yellow = ε-martensite

Fracture morphology dependent on orientation and presence of hydrogen

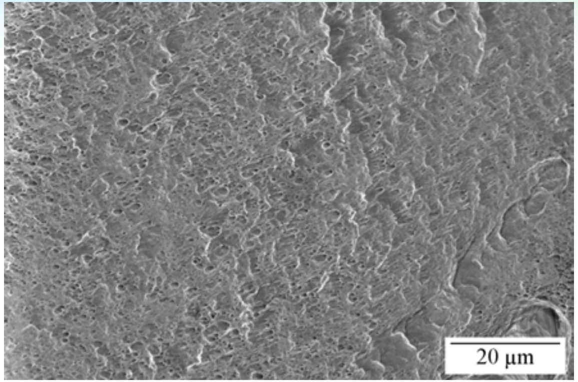
001 No H



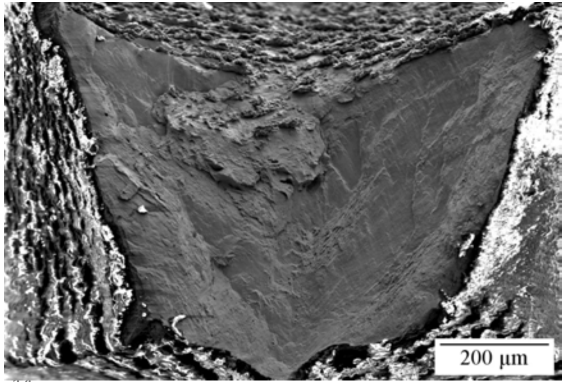
011 No H



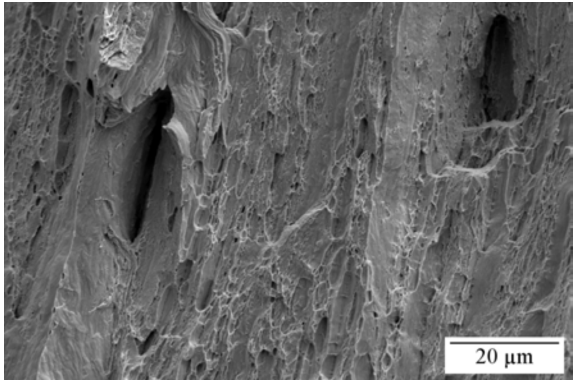
123 No H



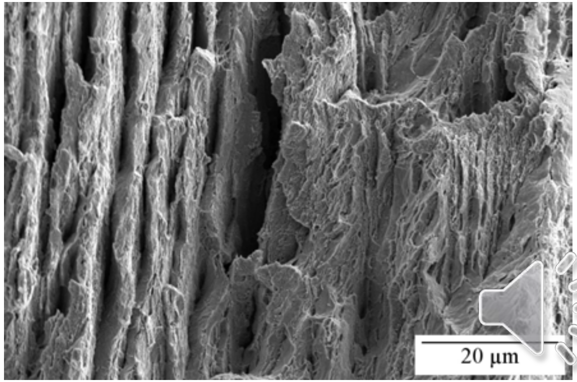
001 PC



011 PC



123 PC



Summary

- Tensile testing and EBSD of single crystal specimens with three different orientations parallel to the tensile axis (<001>, <011>, or <123>) and with and without hydrogen was performed
- The yielding behavior of the three tested orientations did not correlate to Schmid’s law and the increase in yield stress with hydrogen was dependent on orientation
- Hydrogen affected the flow stress and failure mechanisms of the <001> and <123> oriented single crystals, but did not significantly alter the deformation mechanisms prior to necking
- Hydrogen affected the stress-strain response and deformation mechanisms of the <011> specimen prior to necking
- For the <011> oriented specimen twinning occurred at lower strains and a lower GND density when hydrogen was present
- Twinning was observed in the necks of the <011> and <123> specimens, but not the <001> specimen, and no ε-martensite was observed
- The observed stress-strain behavior and deformation phenomena are being used to inform crystal plasticity modeling

Questions?

brian.kagay@MPA.uni-stuttgart.de