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An Investigation of Microscale Damage Evolution in High-Strength Al Alloy

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Background: Failure Modeling

- Many micromechanics-based failure models were developed to predict the ductile failure of materials.
  - typically employ the isotropic void evolution model.
  - are inadequate to model the anisotropic damage in rolled material.
- Motivations:

→ Perform experiments to gain a fundamental temporal and spatial understanding of the failure process.

→ Include the anisotropy of damage to accurately model the behavior of rolled materials.

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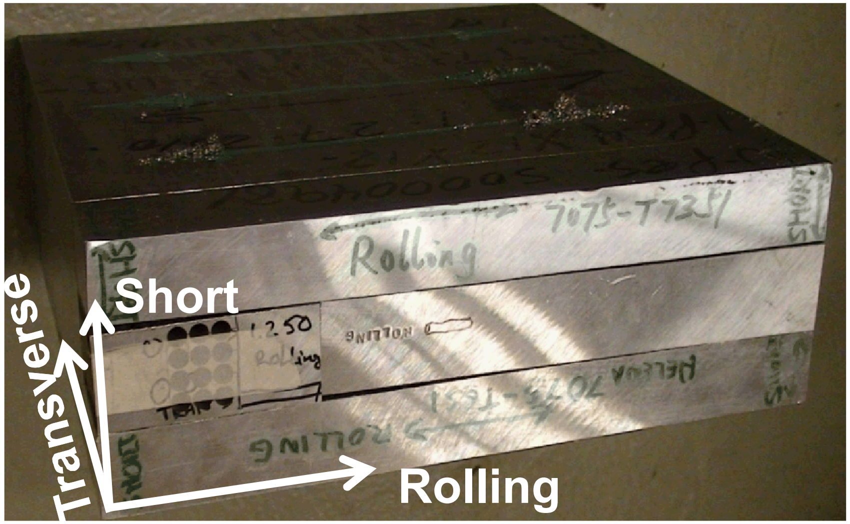
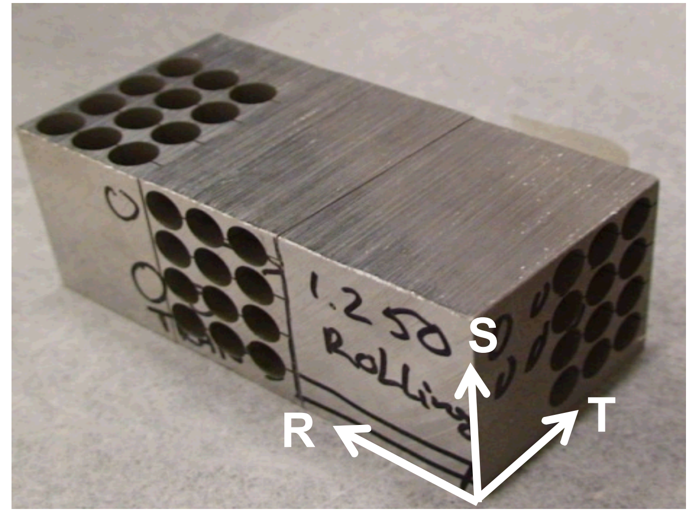
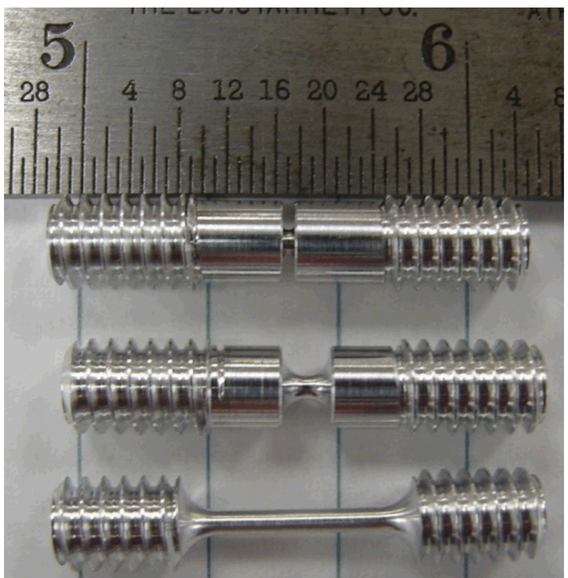
Material of Interest







- Rolled aluminum alloy 7075-T7351
- Uniform tension and notched tension with notch width of 0.75 & 3.0 mm (0.03 & 0.12 in)
- Same diameter of 1.5 mm;
- Same specimen length of 25 mm;

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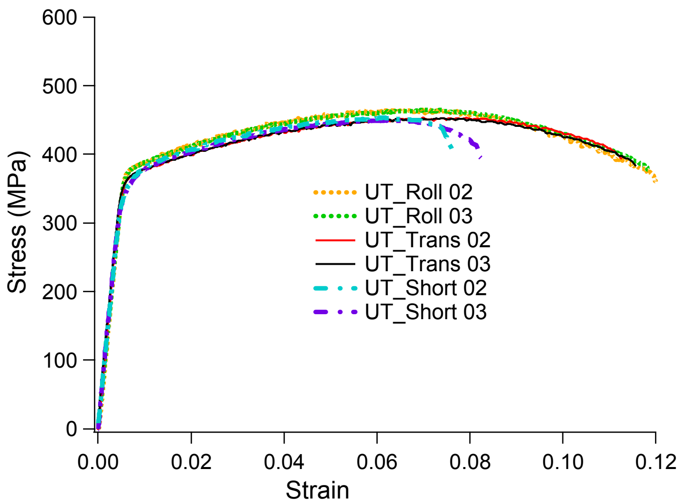
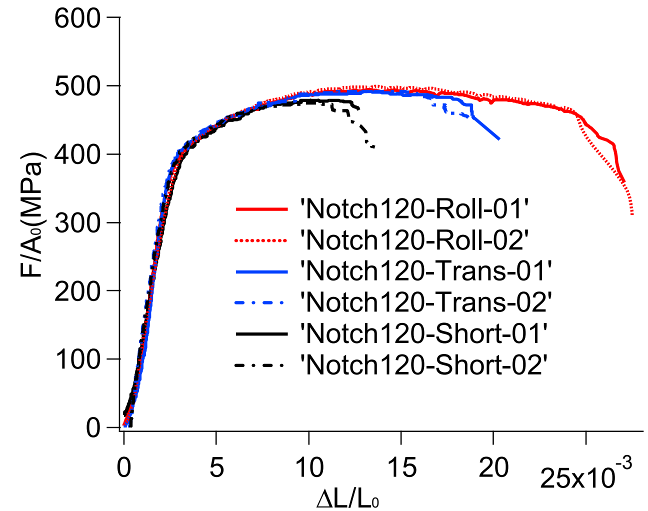
Anisotropy of Ductility in Rolled Material

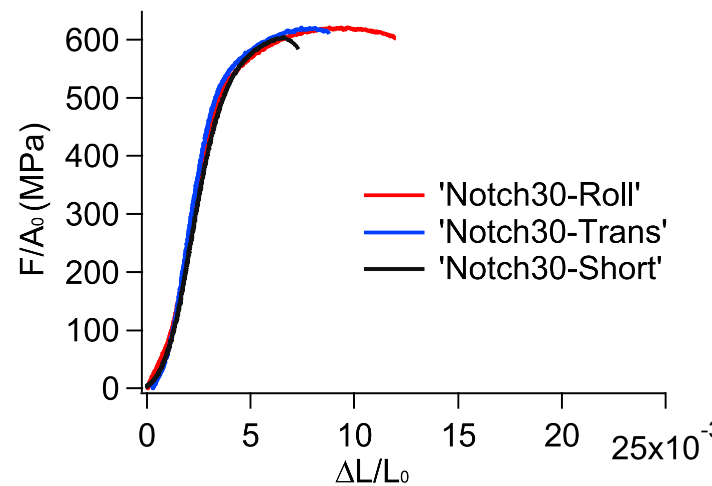


uniform tension



notch width of 3.0mm (0.12 inch)

- No apparent difference in modulus, yield stress and maximum stress.
- Large difference of ductility in different orientation.
- How is the anisotropy of the damage/failure related to the microstructure of the material?



notch width of 0.75mm (0.03 inch)

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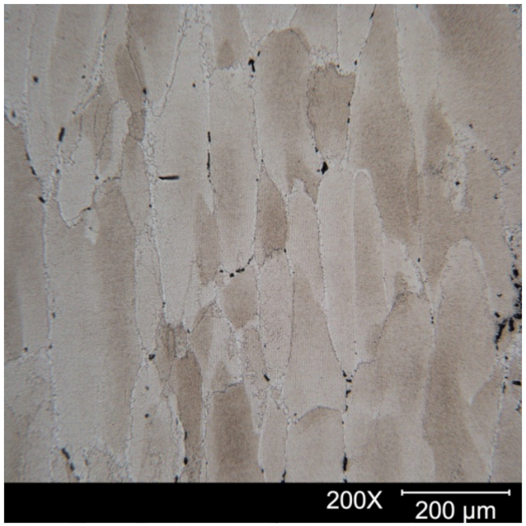
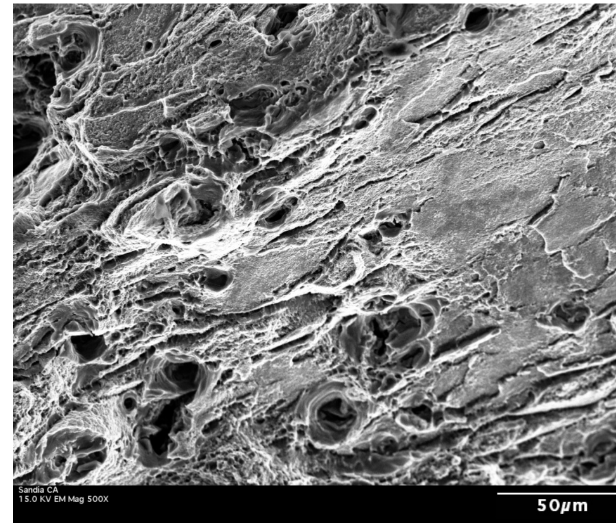
Conventional Techniques for Failure Study

Optical or SEM Imaging:



Optical @ 50x

SEM @ 75x



SEM @ 500x

- Sectioned surface of interrupted test or failure surface after material failure;
- Surface preparation may destroy the features;
- Surface only;

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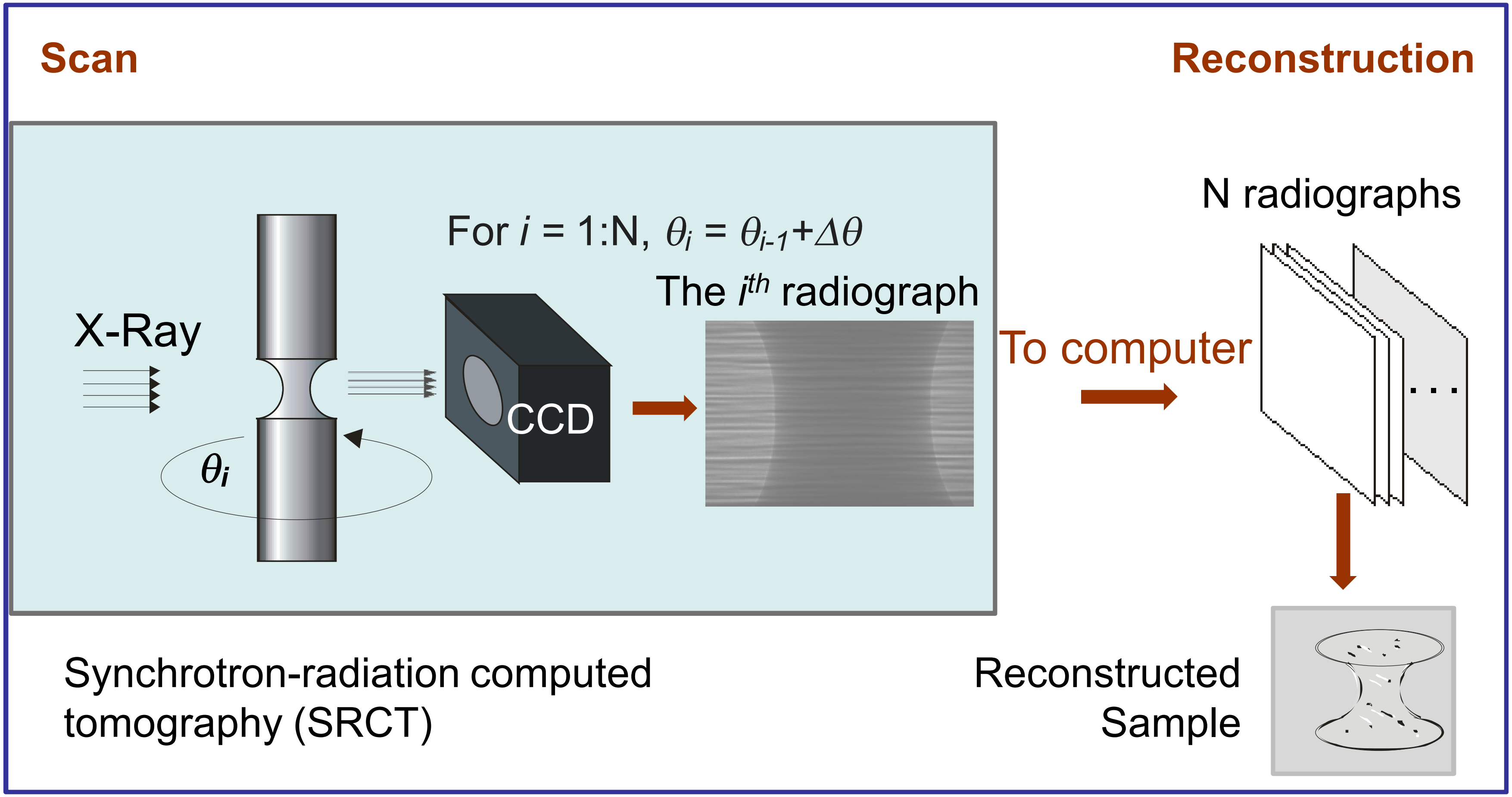
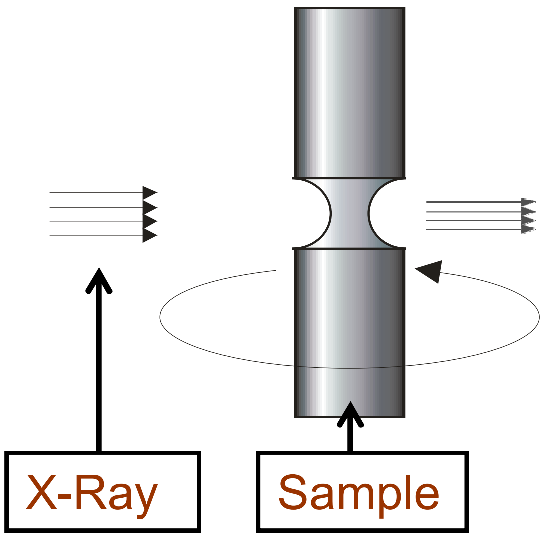
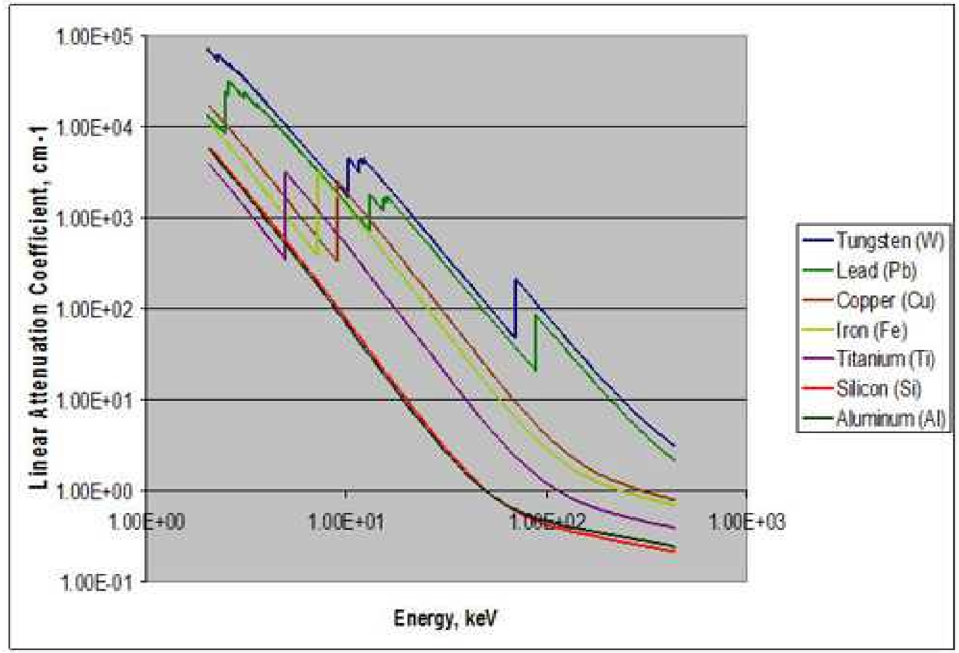
3D Imaging: X-Ray Computed Tomography (XCT)



- X-ray computed tomography (XCT) can reveal features inside the material body.

X-Ray Attenuation and Gray Scale of XCT Images





- X-ray attenuation reflects the proportion of X-rays scattered or absorbed as they pass through the material.
- It is a function of X-ray energy and material characteristics: density and atomic number.
- The gray levels in a CT slice correspond to X-ray attenuation: denser and heavier – lighter.

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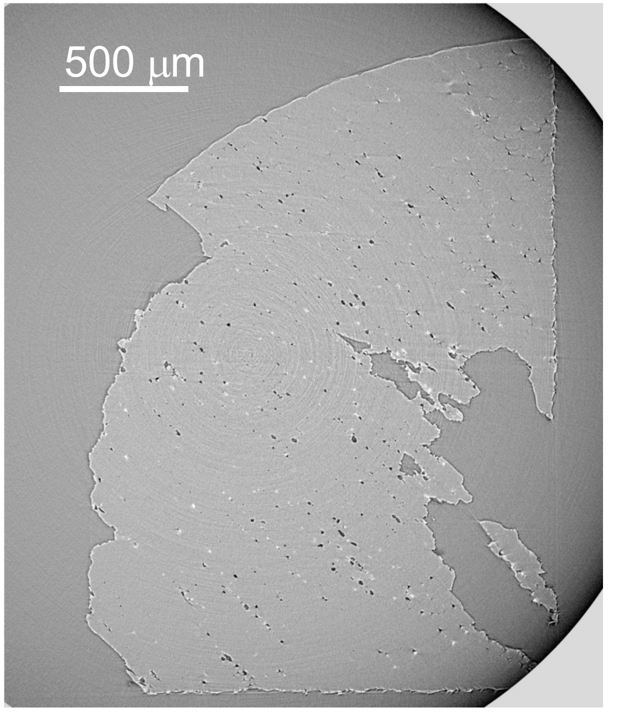
Aluminum Alloy 7075

Component	Al	Mg	Si	Cu	Zn	Fe	Cr	Mn
Wt.%	87-91	2.1-2.9	<0.4	1.2-2	5-6	< 0.5	0.18-0.28	<0.3

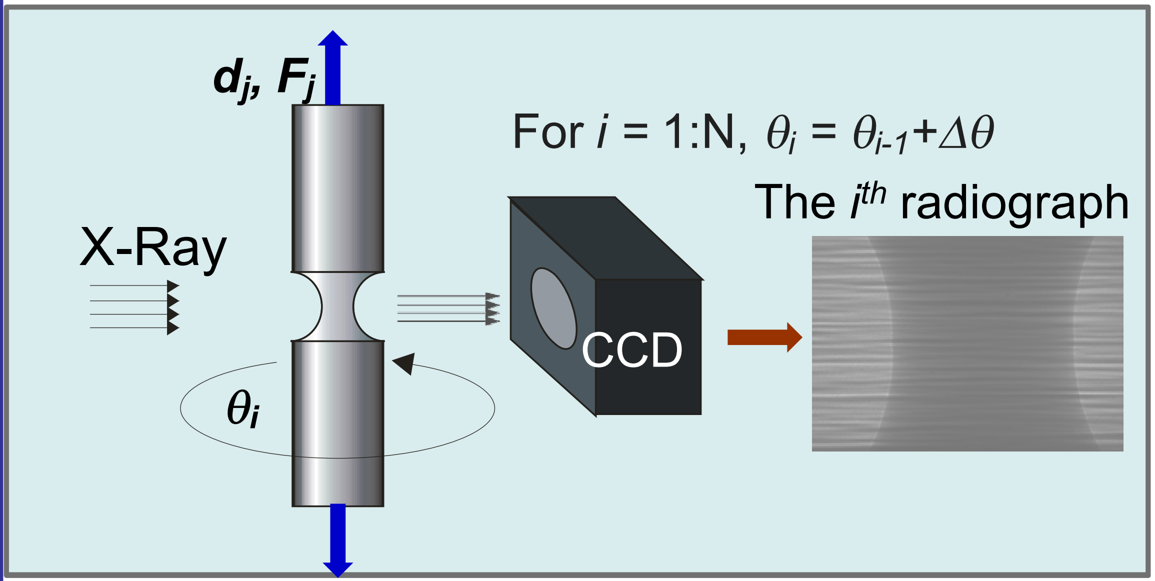
- There are other different chemical elements in Al alloy 7075.
- Intermetallic particles appear lighter than the aluminum matrix, and voids are the darker regions in the CT image.

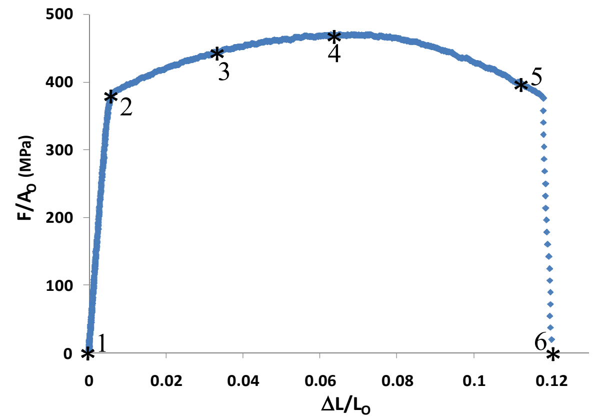


A CT slice showing the cross section of a failed specimen

4D Imaging: In-situ XCT Experiments

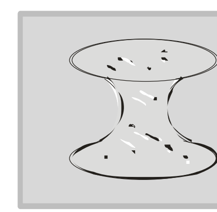
Scan For j = 1:M (> 4)





Synchrotron-radiation computed tomography (SRCT)

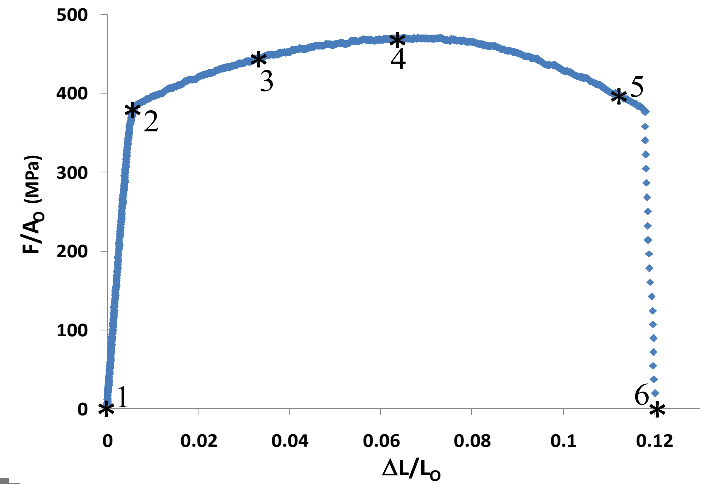
The j^{th} reconstructed sample



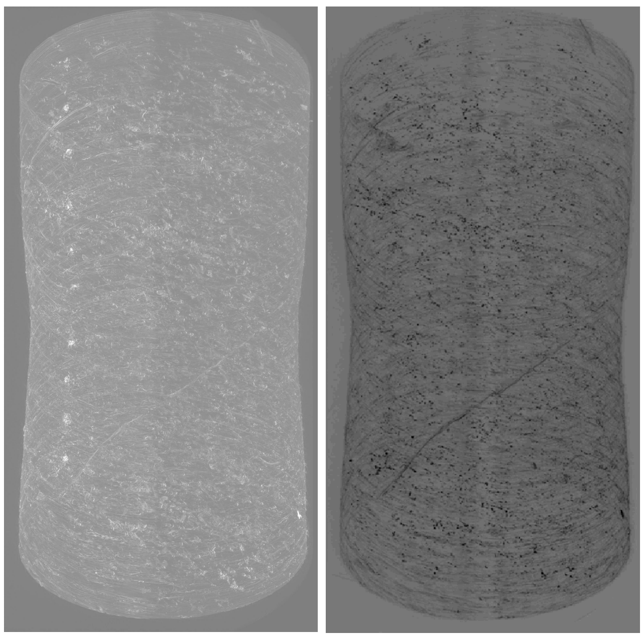
➡ Couple in-situ loading with XCT imaging to study the damage evolution as the specimen is subject to different loading levels.

Volume Visualization for In-Situ XCT

Smooth Tension Specimen



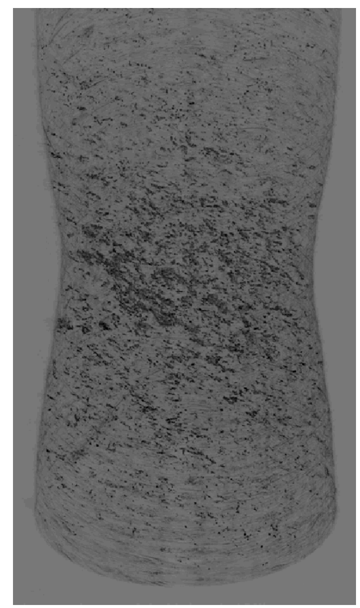
Scan1



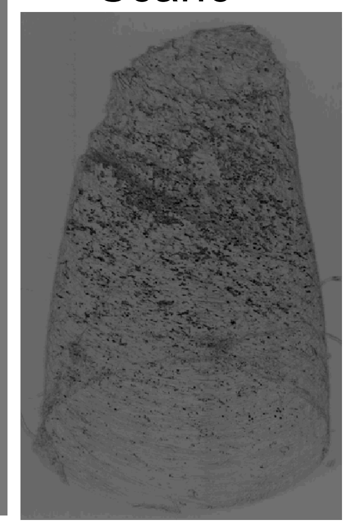
particles voids

Scan4

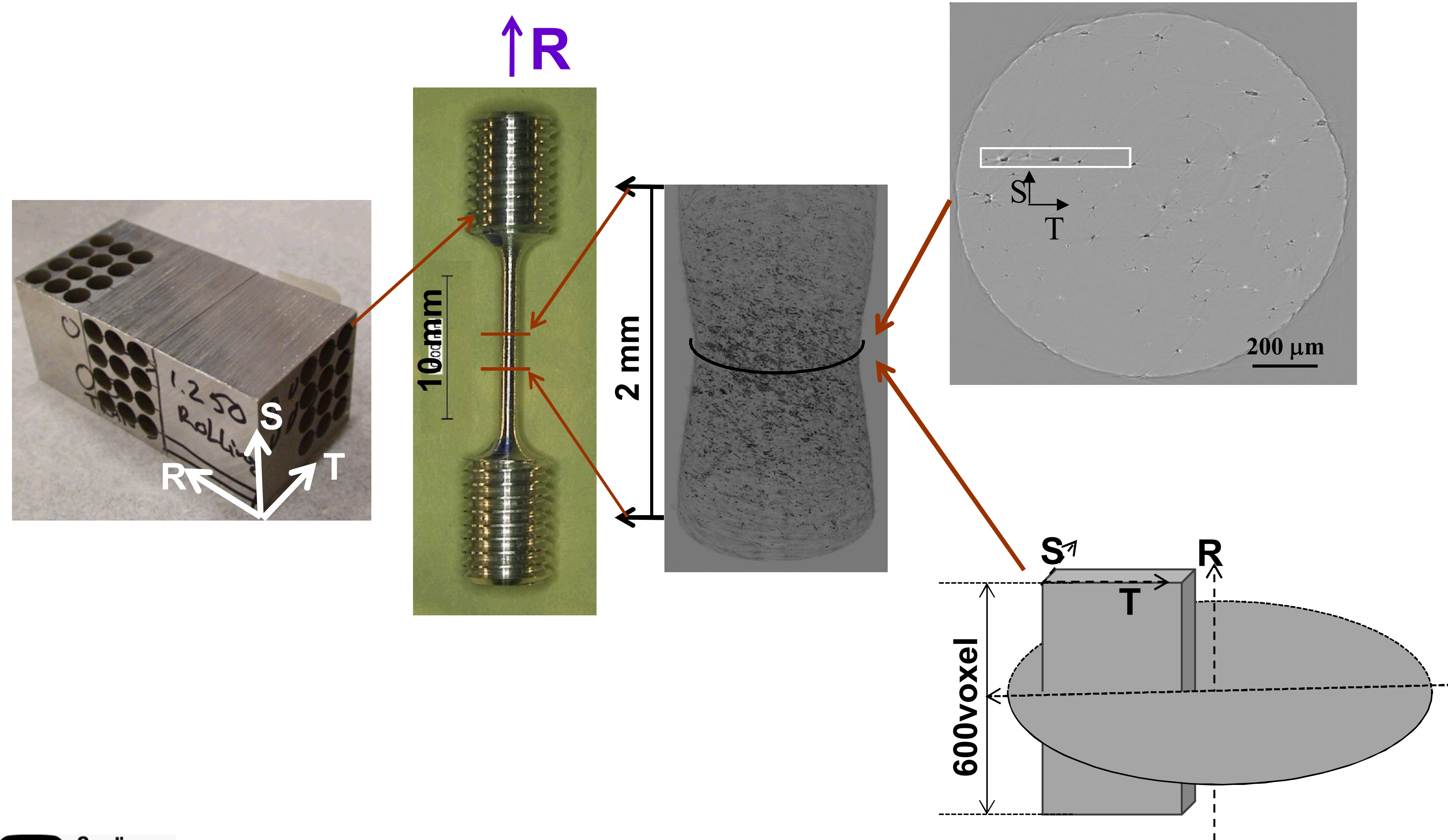
Scan5



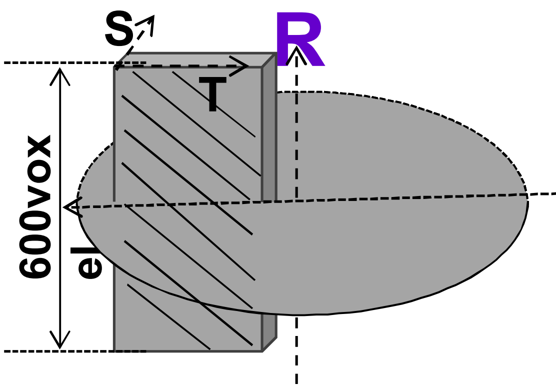
Scan6



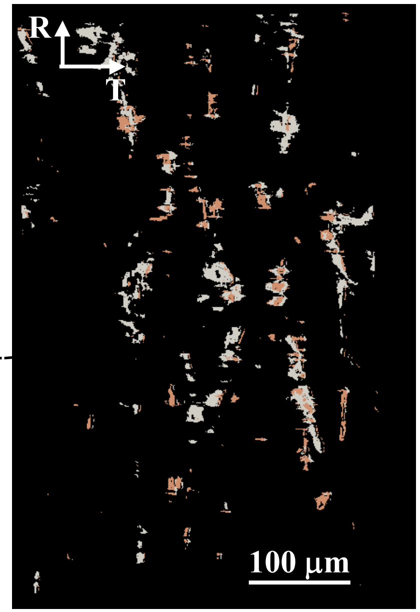
Void Evolution for the Specimen Loaded in the Rolling Direction (1)



Void Evolution for the Specimen Loaded in the Rolling Direction (2)



(a) volume used for projections in R-T plane

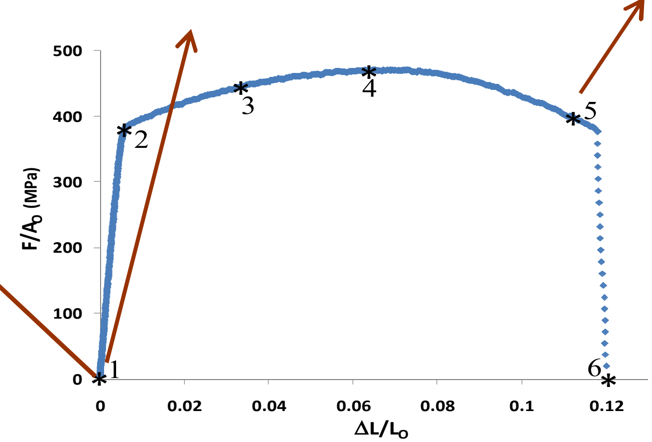


Initial voids and particles

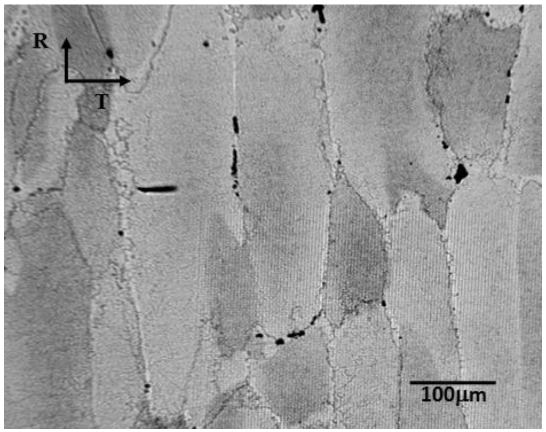
Initial Voids

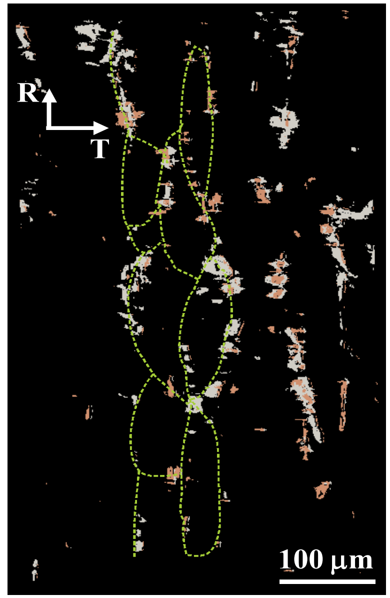
Voids near failure

Voids are mostly aligned with intermetallic particles.
No apparent local coalescence between adjacent voids.

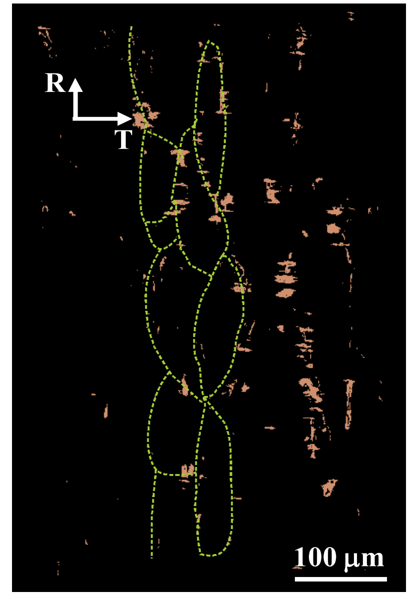


Void Evolution for the Specimen Loaded in the Rolling Direction (3)

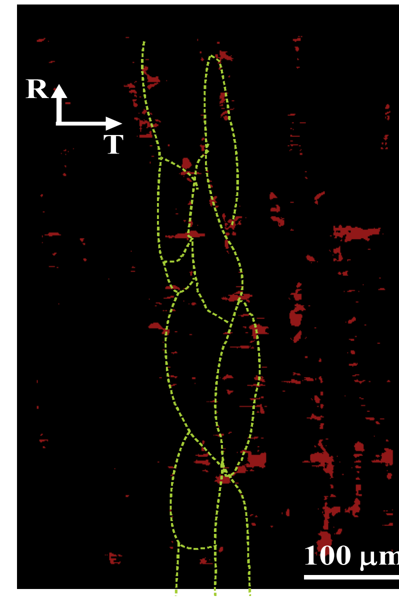




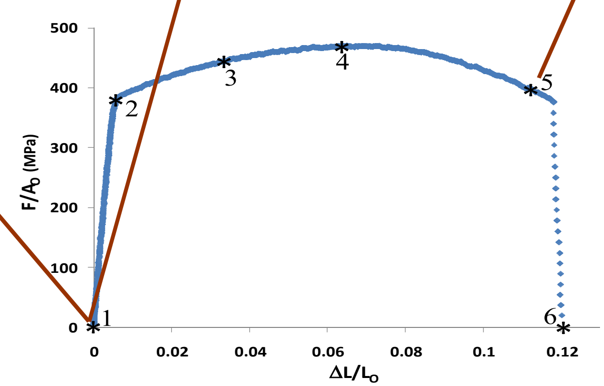
Initial voids and particles



Initial Voids



Voids near failure



Voids distribution seem to align with grain boundaries.

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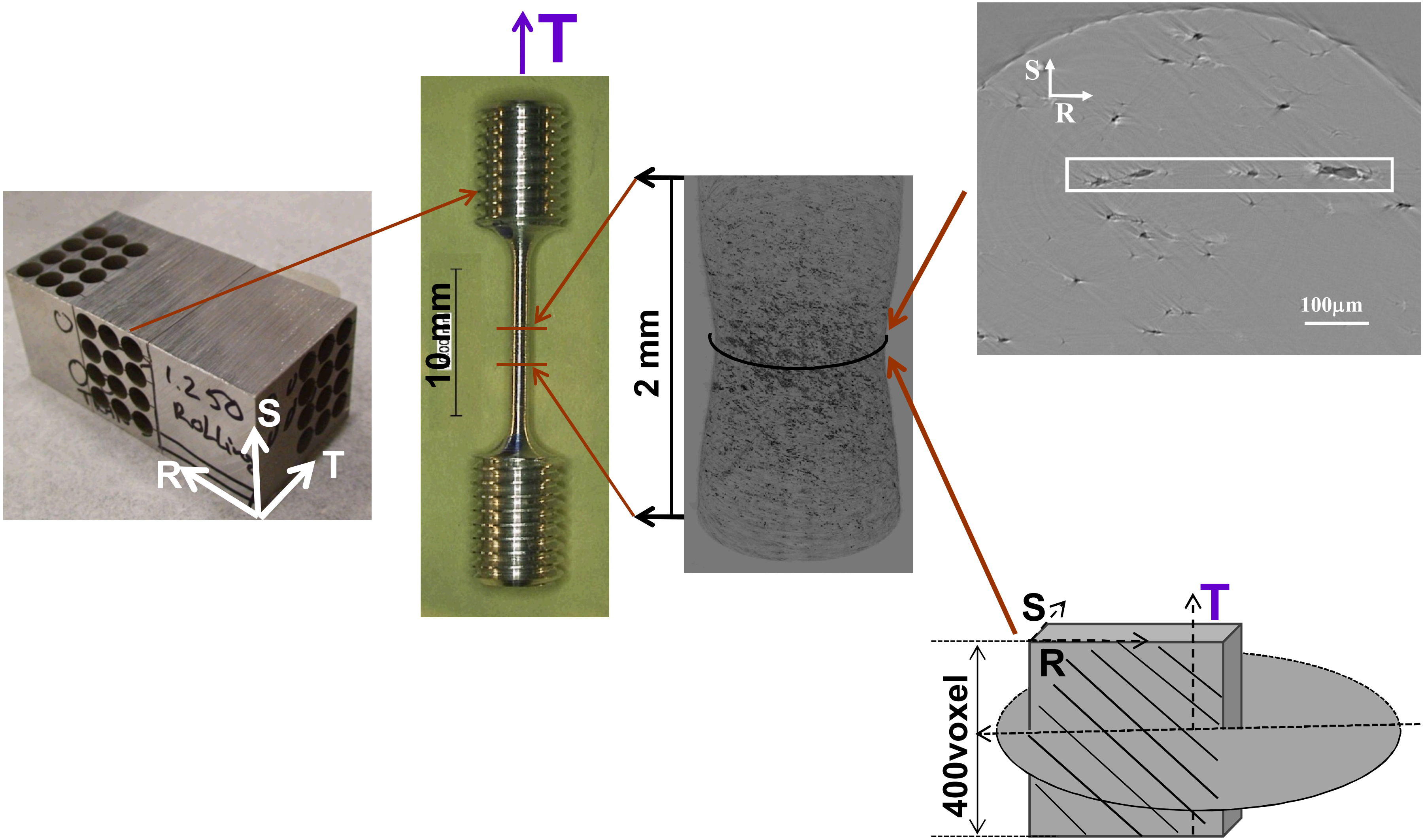
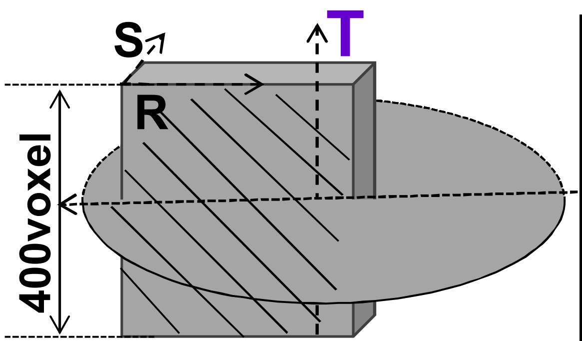
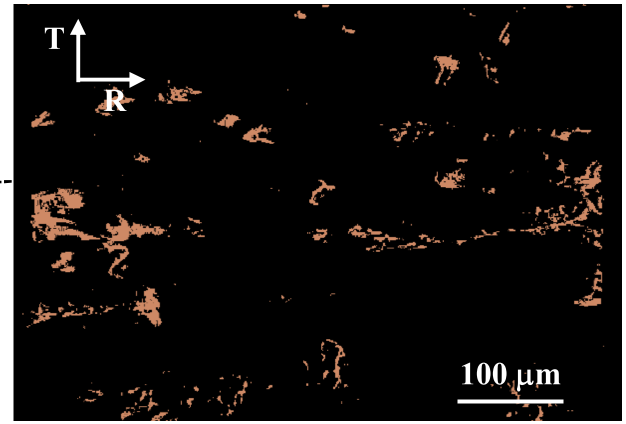
Void Evolution for the Specimen Loaded in the Transverse Direction (1)

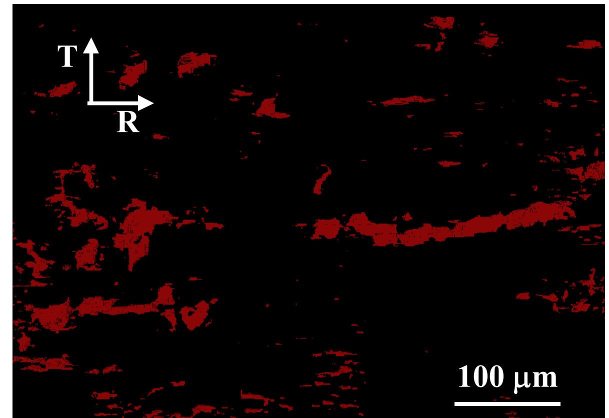


Void Evolution for the Specimen Loaded in the Transverse Direction (2)

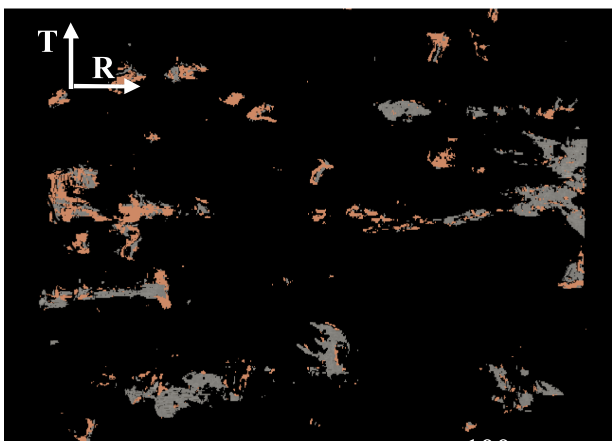




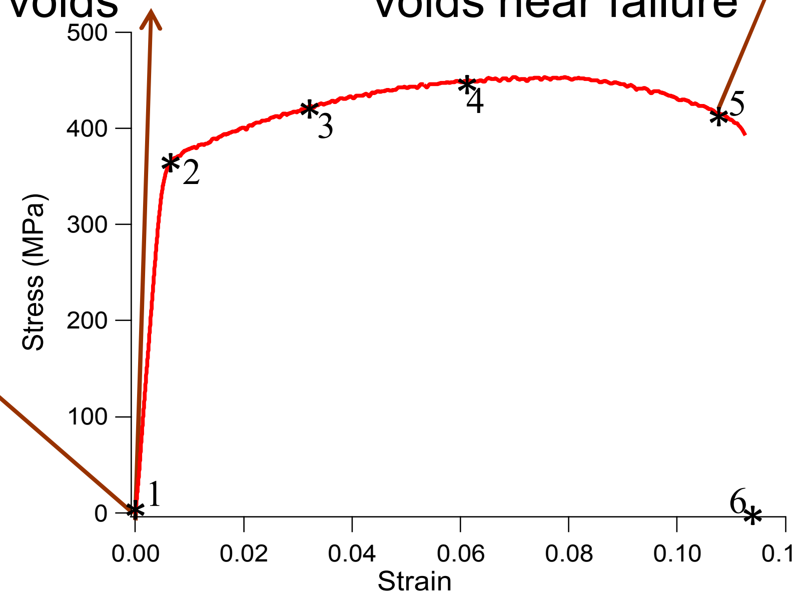
Initial voids



voids near failure



Initial voids and particles



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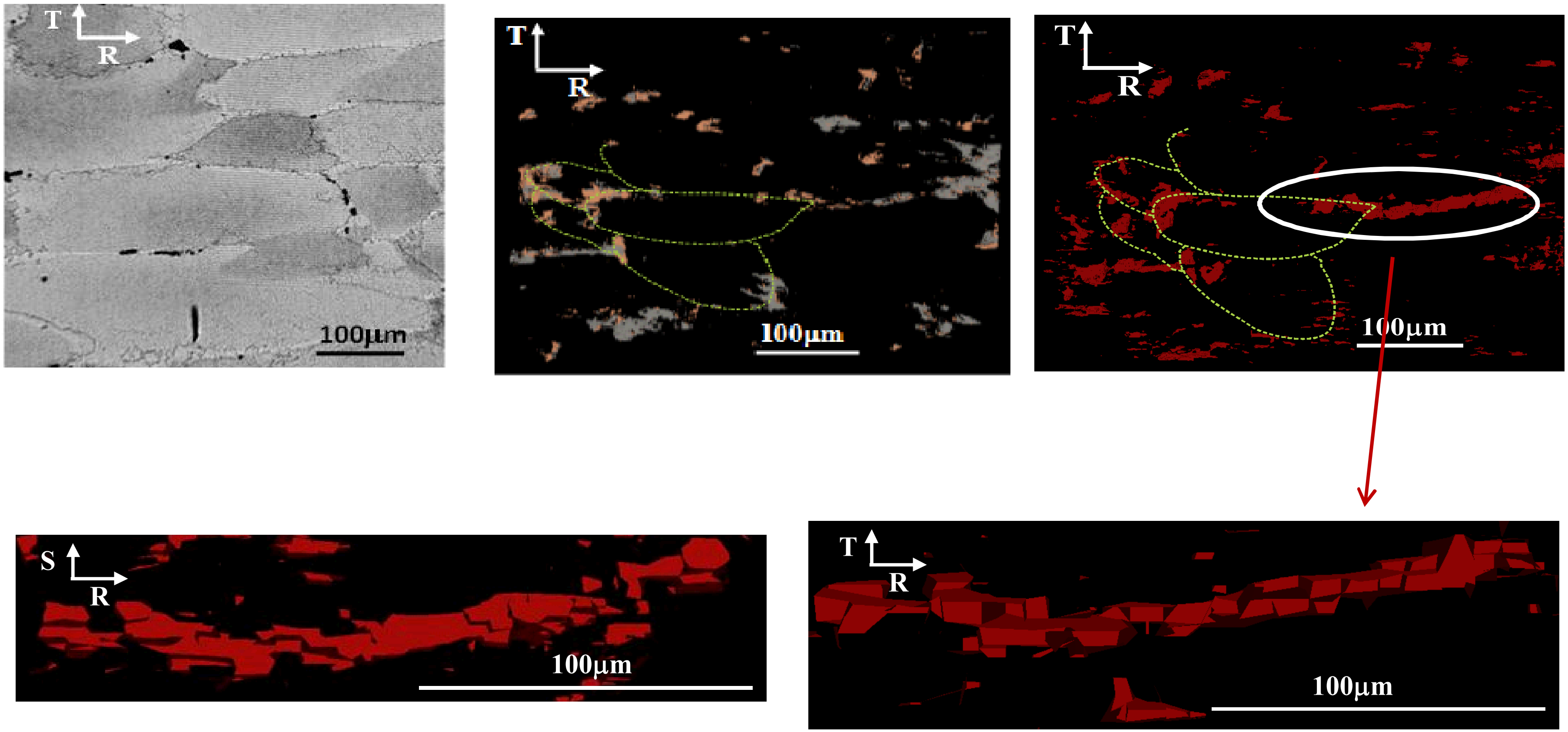
Voids distribution is also associated with intermetallic particles

Void Evolution for the Specimen Loaded in the Transverse Direction (4)



The voids distribution is aligned with particles along the grain boundaries.
Voids had significant local coalescence along the rolling direction.

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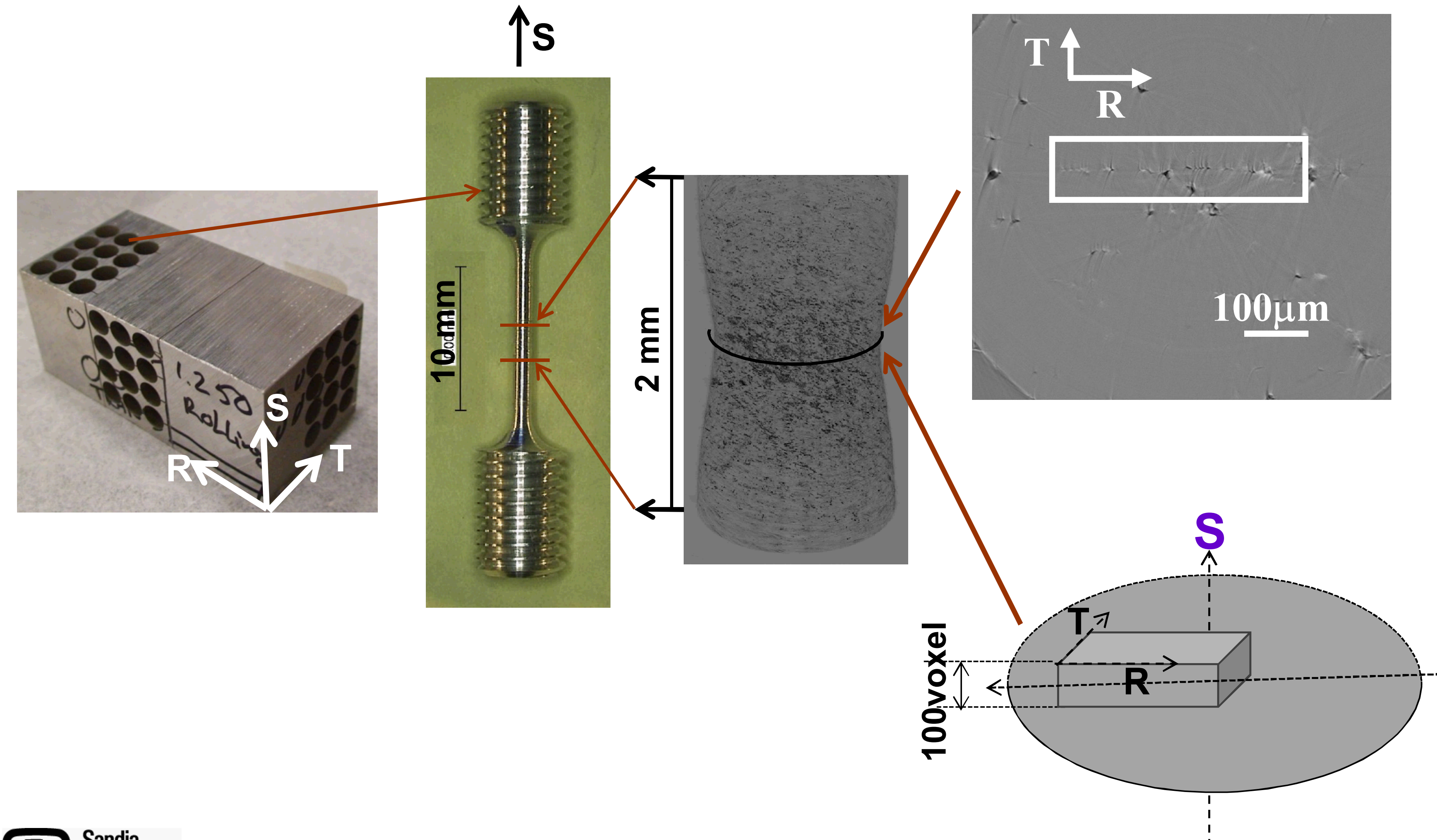
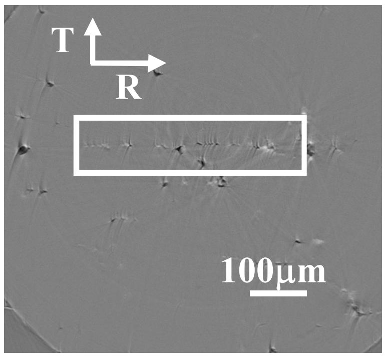
Void Evolution for the Specimen Loaded in the Short Transverse Direction (1)

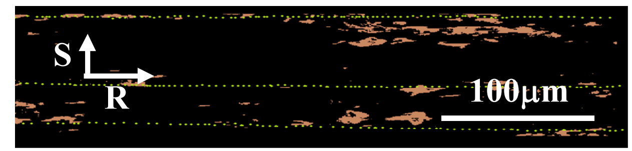


Void Evolution for the Specimen Loaded in the Short Transverse Direction (2)



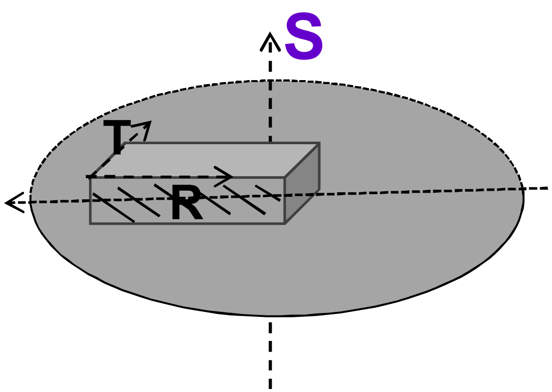
(a)

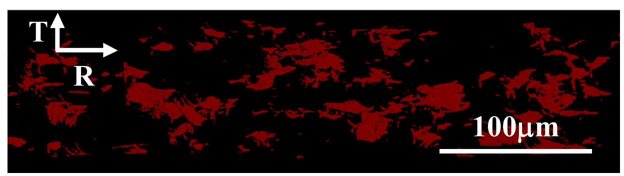
(b)



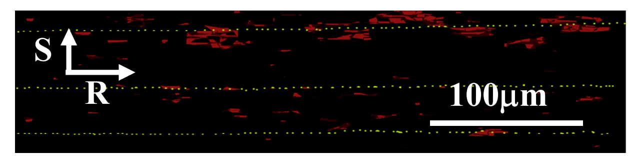
(c)

3D rendered image of voids at failure state





(d)



(e)

3D rendered image of voids at necking state

- Voids distribution form planar structures perpendicular to loading direction.
- Local void coalescence had planar preference in the R-T plane.
- Very limited local coalescence in short direction.

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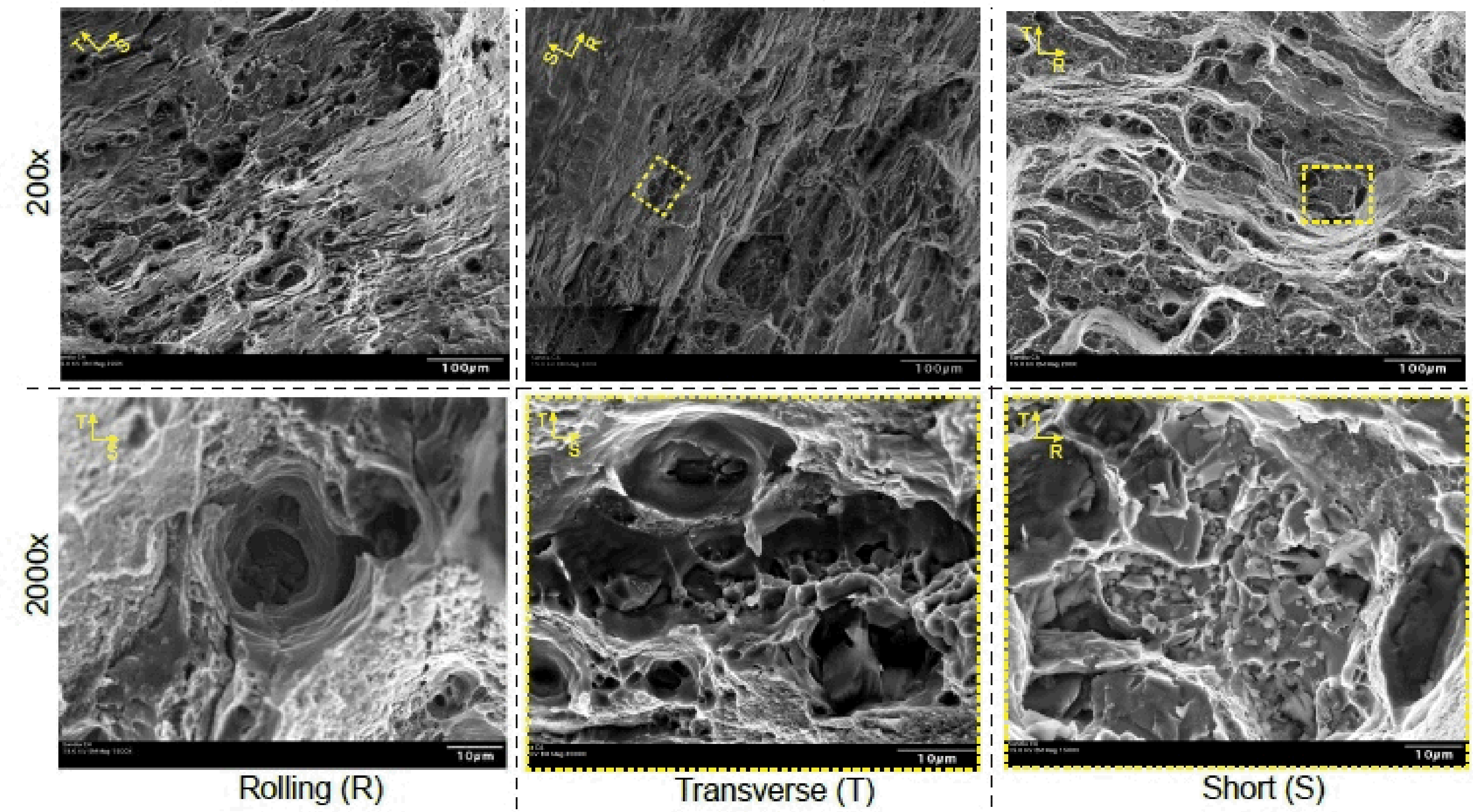
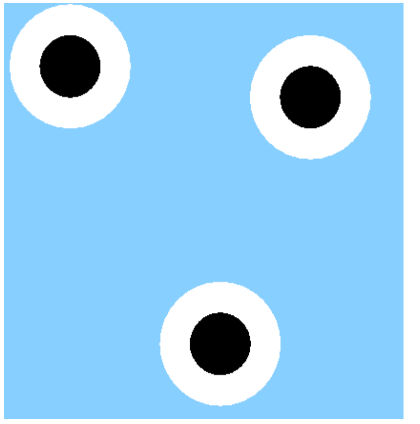
Fractographs of Tensile Specimens Loaded in Three Directions



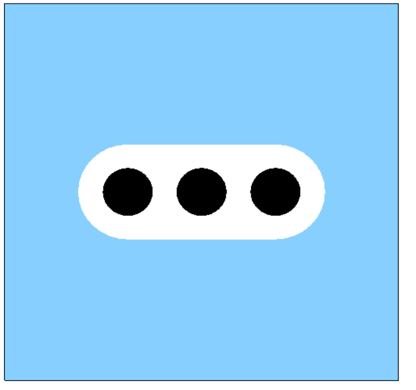
In-situ XCT observation of void evolution prior to global coalescence are confirmed from fractographs post material failure.

Different Void Evolution Mechanisms

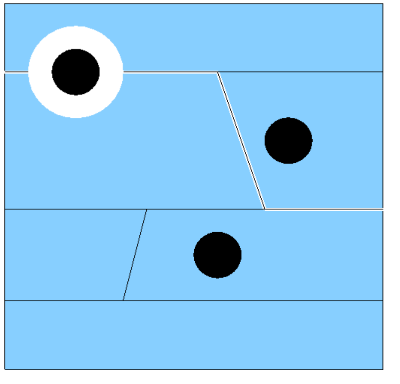
- For the specimens loaded in the rolling direction, local void growth via plastic deformation is dominant process prior to global coalescence. There is limited local coalescence.



- For the specimens loaded in the transverse direction, void local coalescence is dominant prior to global coalescence. They had one-dimensional preference along “stringers” in the rolling direction.



- For the specimens loaded in the short transverse direction, local coalescence is dominant prior to global coalescence. They have 2D planar preference in R-T plane.



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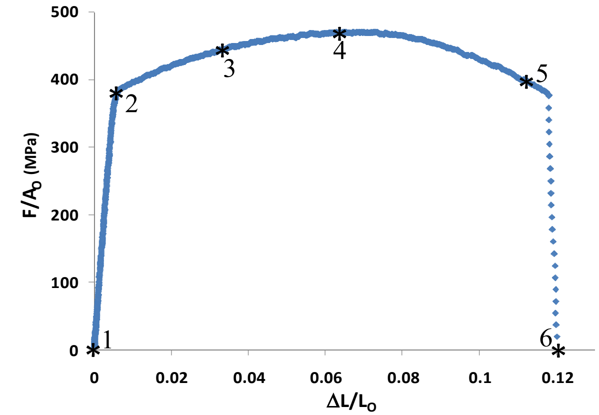
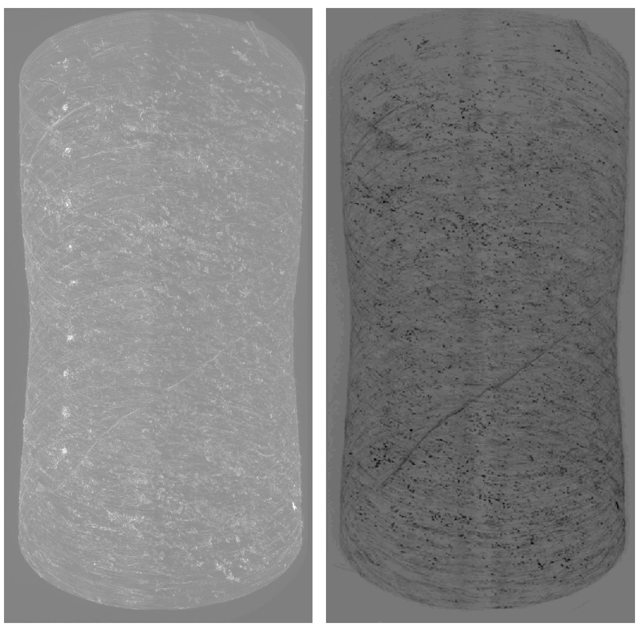
3D Tomographic Images from In-Situ XCT Test can Observe Damage Evolution

Smooth Tension Specimen



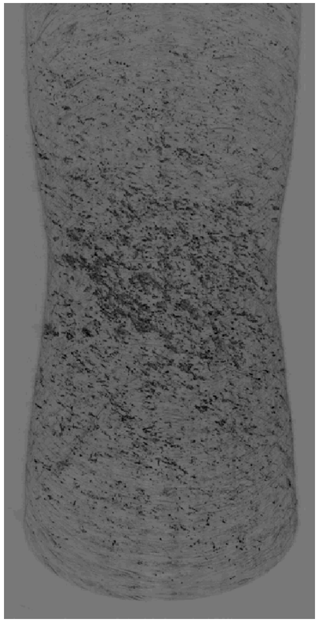
Scan1



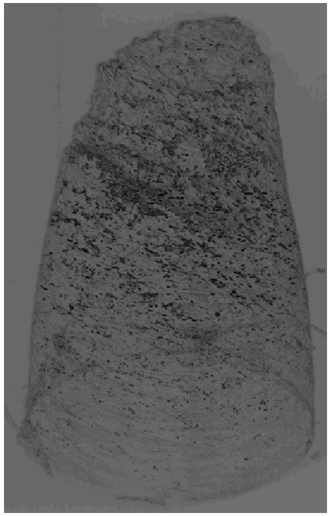
particle void

Scan4

Scan5



Scan6



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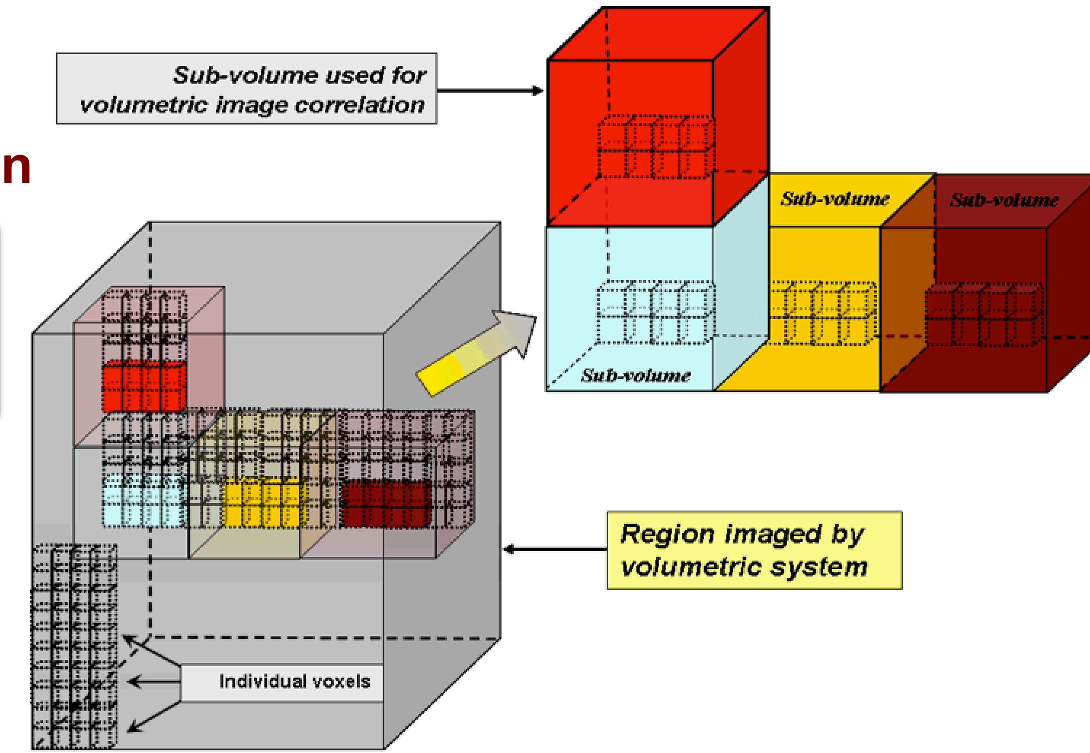
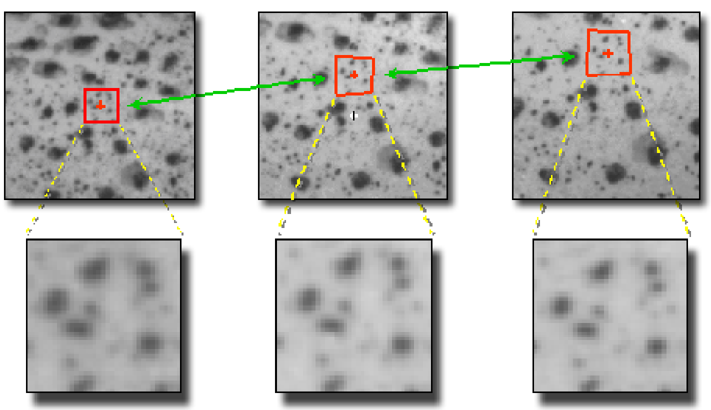
Digital Volume Correlation (DVC)

- Surface vs volume
- Pixels vs voxels
- Subsets vs sub-volumes
- Widely applied vs premature

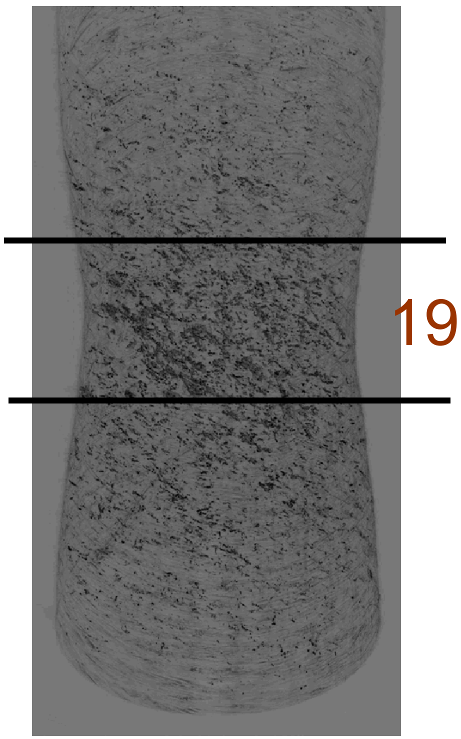
DVC- Digital Volume Correlation



DIC- Digital Image Correlation

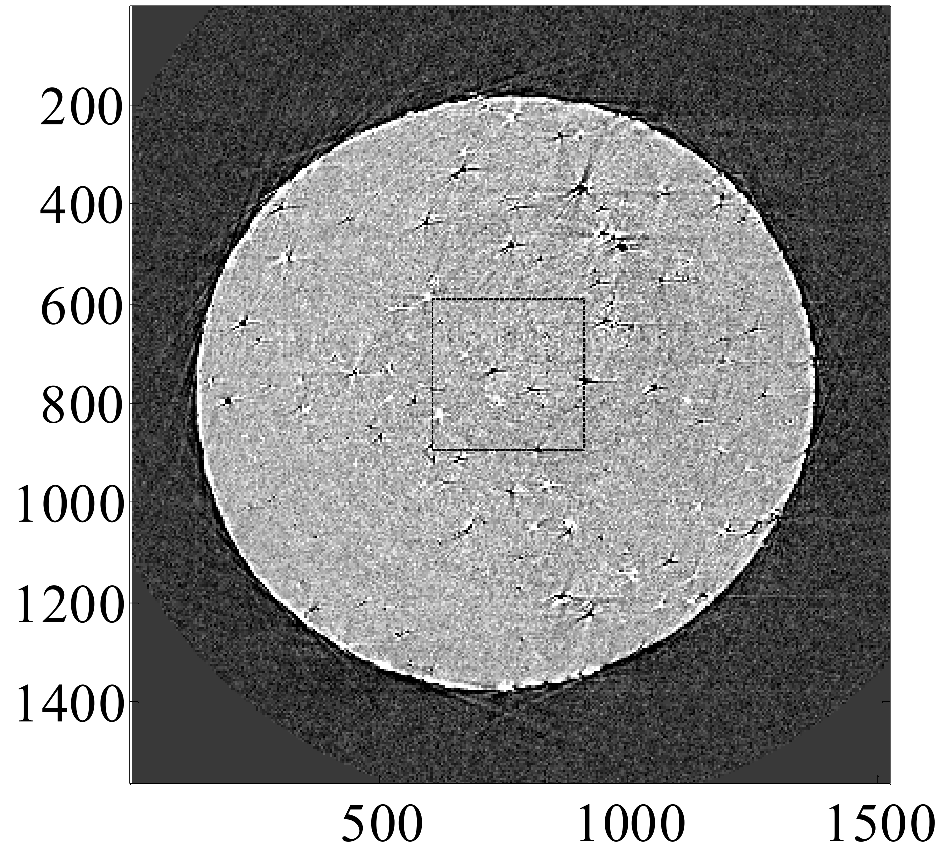


First Trial: Simple Translation of 3D Images



196 slices

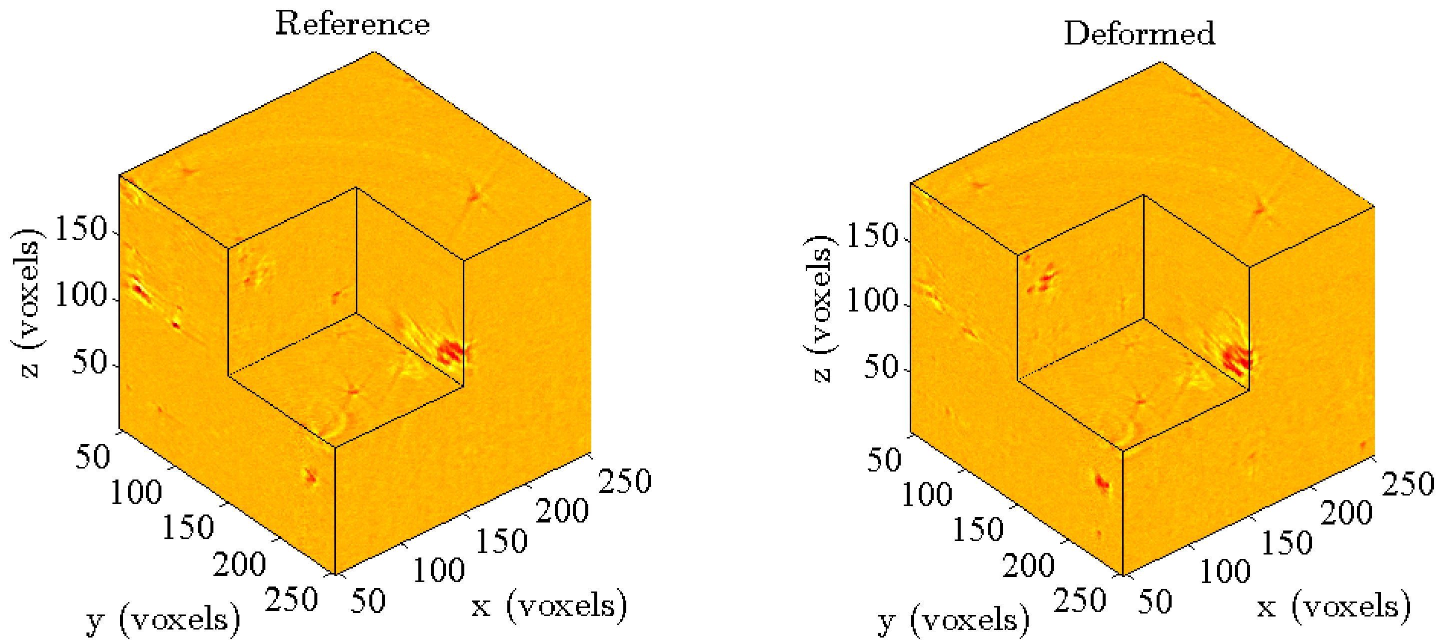
AOI selected through all the slices



Introduce displacement by shifting the images:
U=4, V= -5, W=0 (voxels)

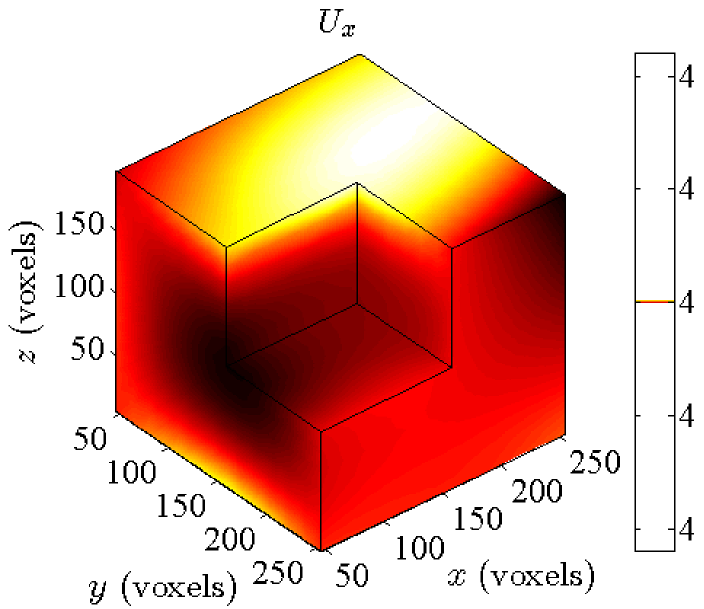
Reference and Deformed Volumes

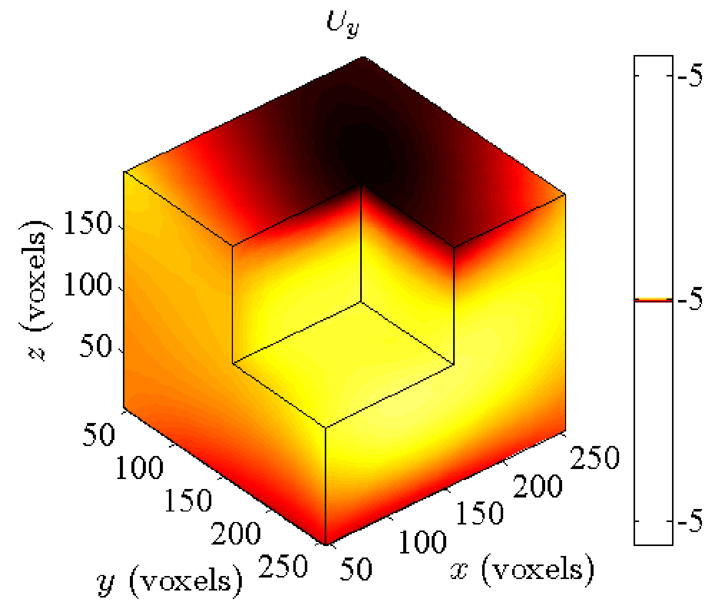
Centered cube of size 208x208x196

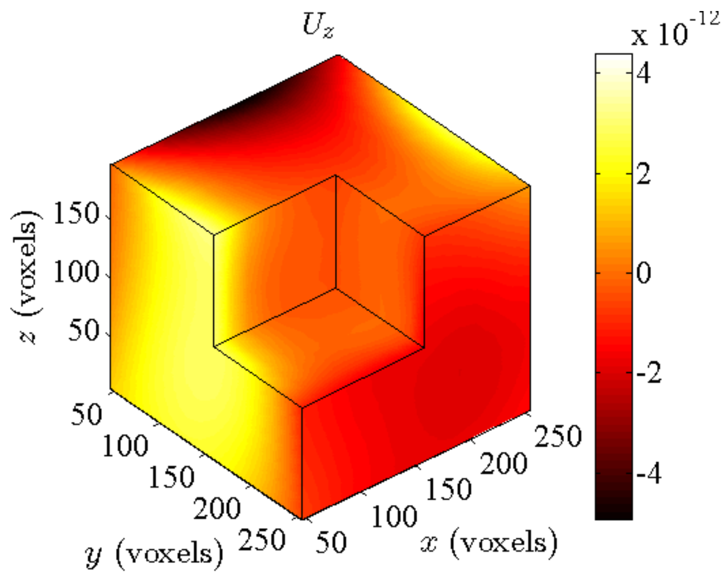


Artificially introduce displacement by shifting the images:
U=4, V= -5, W=0 (voxels)

Displacement Results from DVC

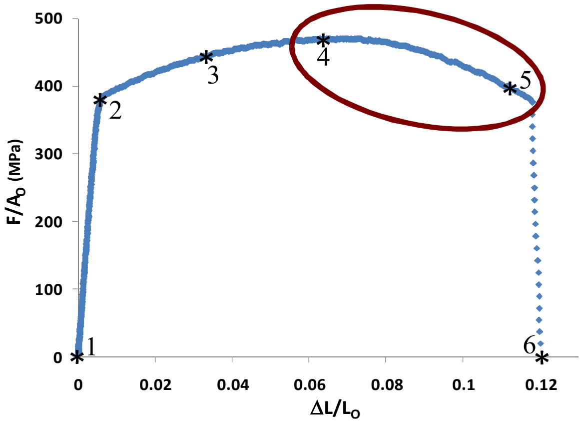




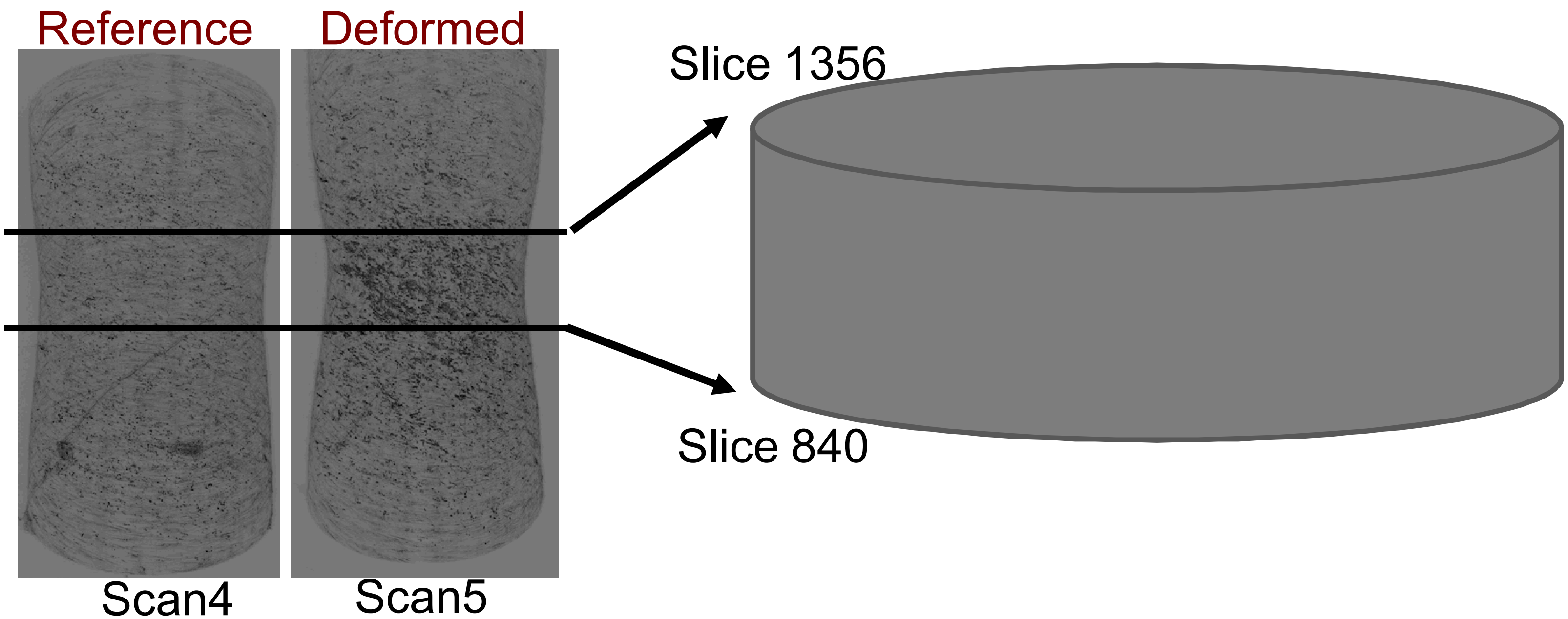


U=4
V=-5
W=0

Calculate Deformation Field from the Real Tomographic Image Set

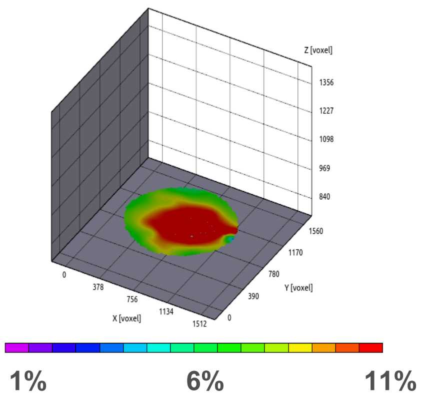


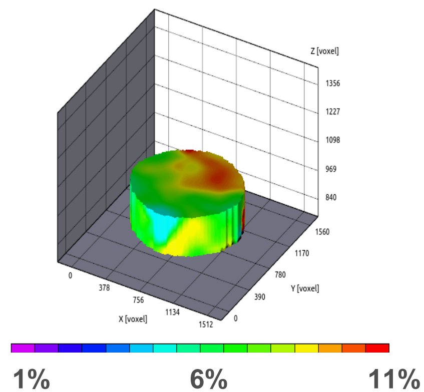
- One set of tomographic images from rolling direction: Reference-scan 4, Deformed – scan 5.
- Middle section of the scanned volume

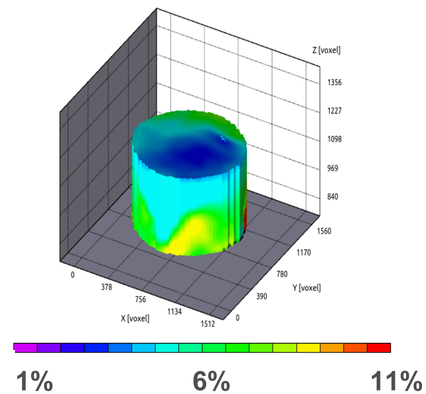


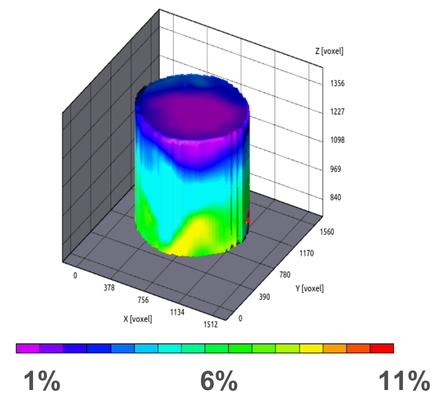
DVC Analysis Results for Axial Strain ε_{zz}

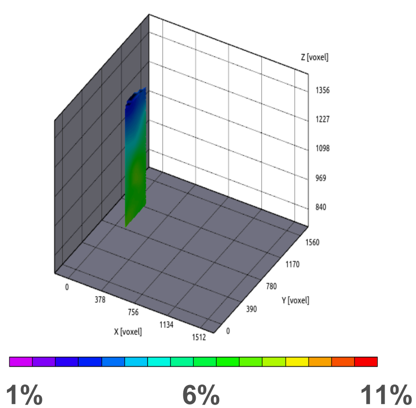
DVC can provide reasonable results for the low contrast, artifact-rich images.

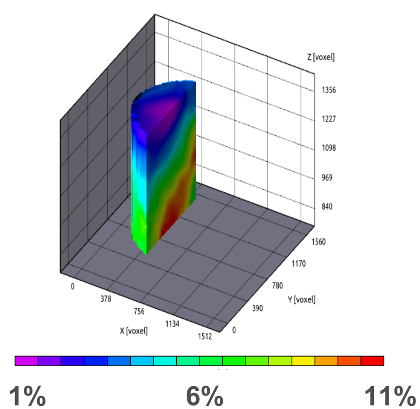


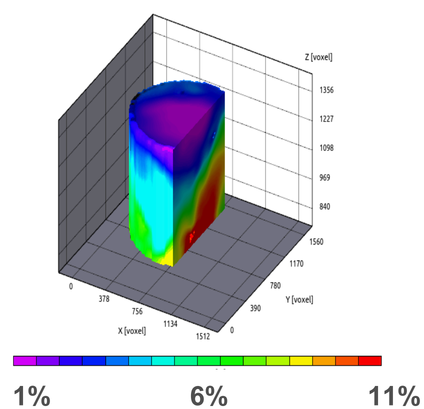


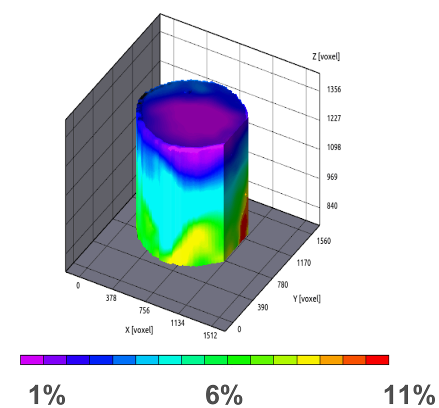












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