SAND2015-7620C

3D Deformation Field Throughout the Interior of Materials

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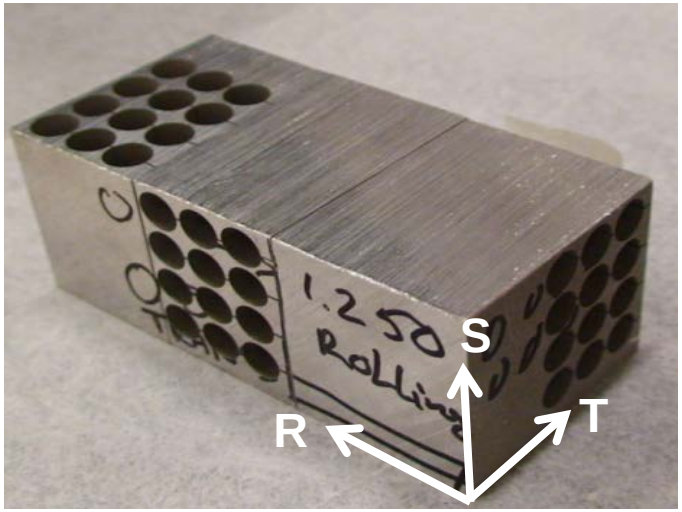
Background: Failure Modeling

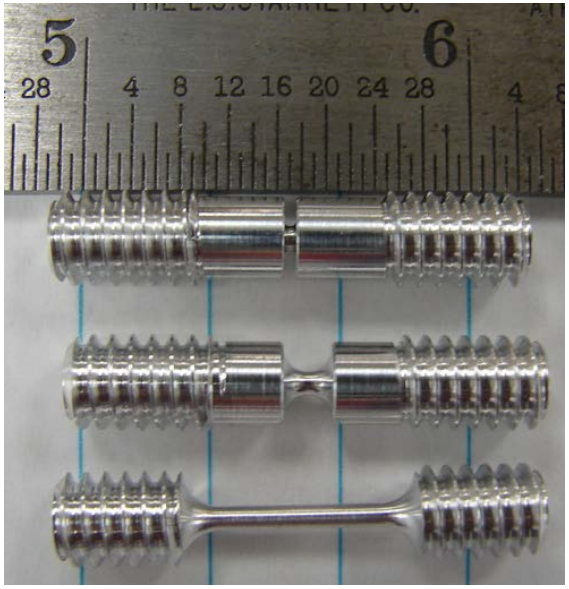
- Many micromechanics-based failure models were developed to predict the ductile failure of materials.
  - typically employ the isotropic void evolution model.
  - are inadequate to model the anisotropic damage in rolled material.
- These failure models are implemented into finite element analysis to predict the deformation inside the material body.
- However, current experimental deformation measurement is limited to the surface of the material.

Motivations

- Perform experiments to gain a fundamental temporal and spatial understanding of the failure process.
- Provide experimental data for developing the model of anisotropic of damage to accurately model the behavior of rolled materials.
- Develop an experimental technique that is able to measure the deformation inside a material body.

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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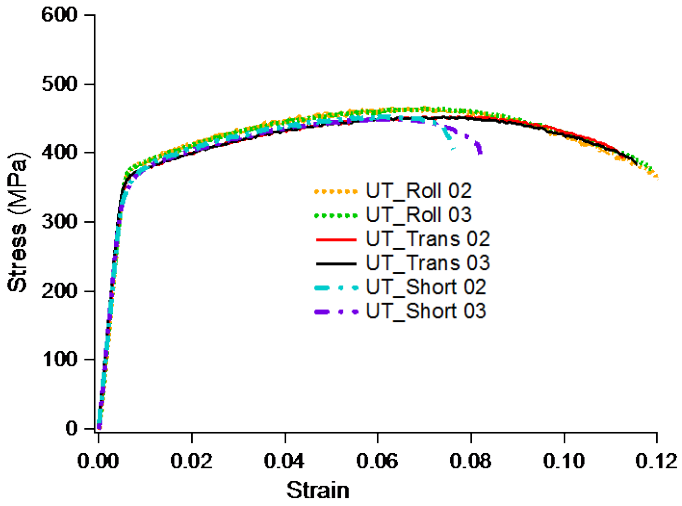
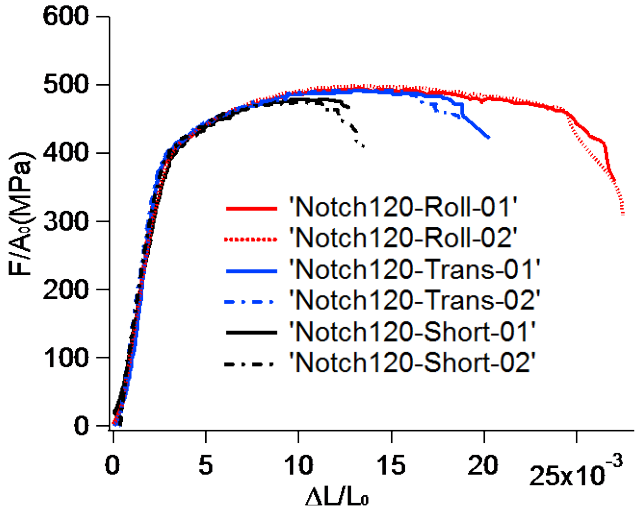
Anisotropy of Ductility in Rolled Material

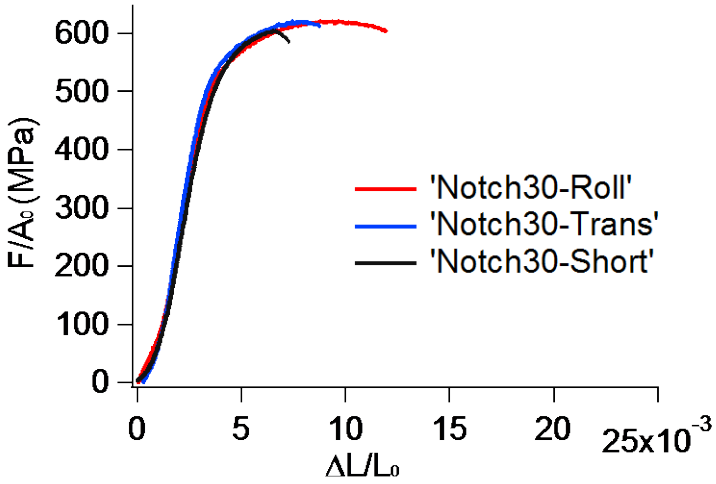


uniform tension



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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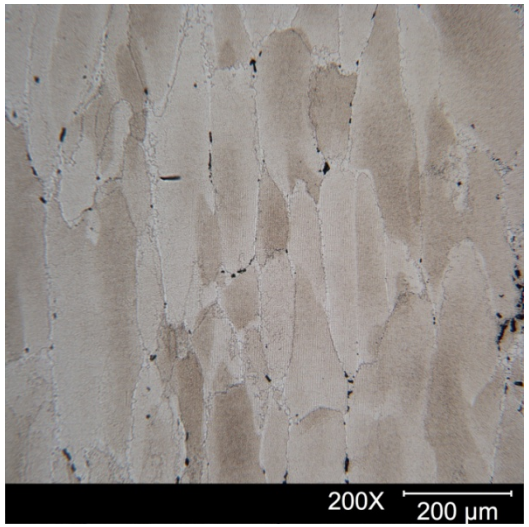
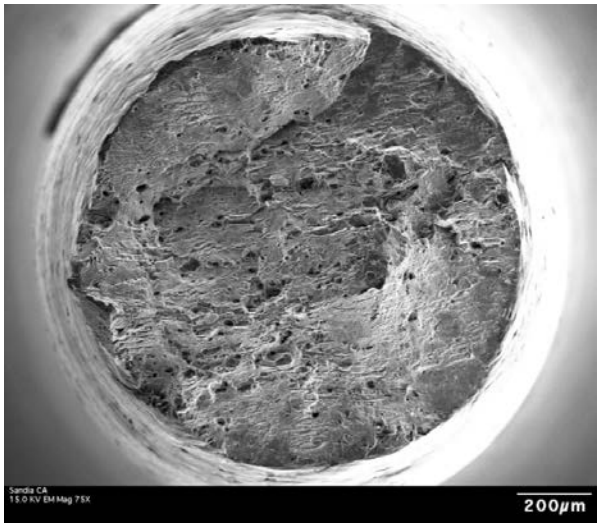
Conventional Techniques for Failure Study

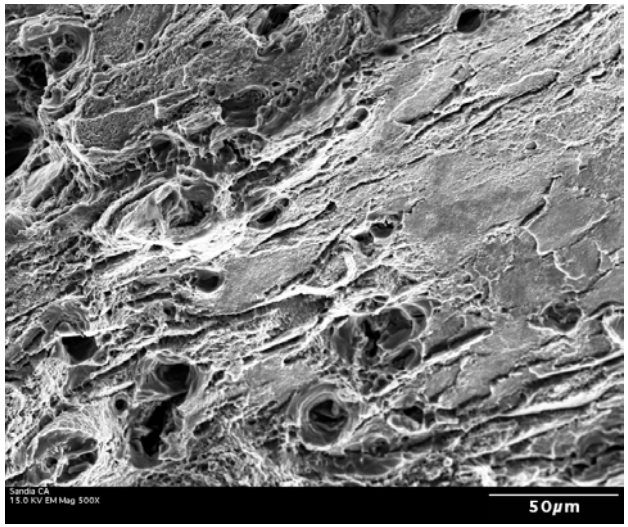
Optical or SEM Imaging:



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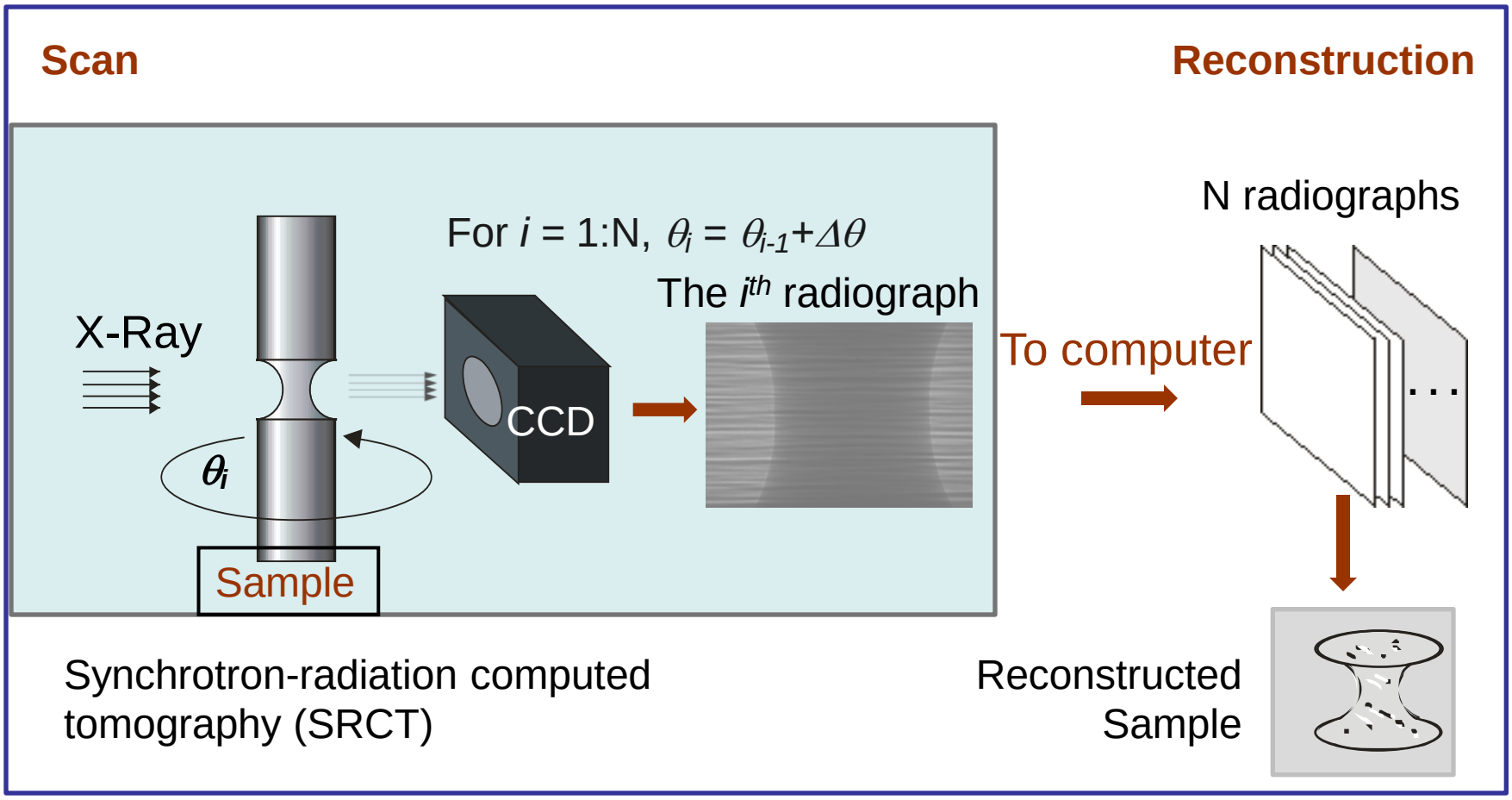
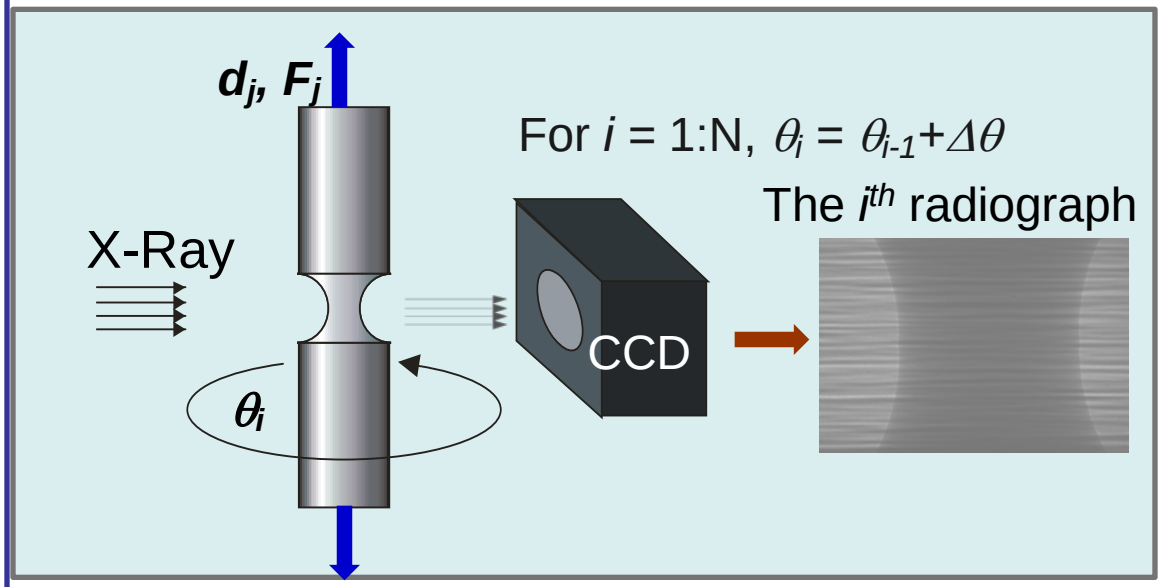
3D Imaging: X-Ray Computed Tomography (XCT)

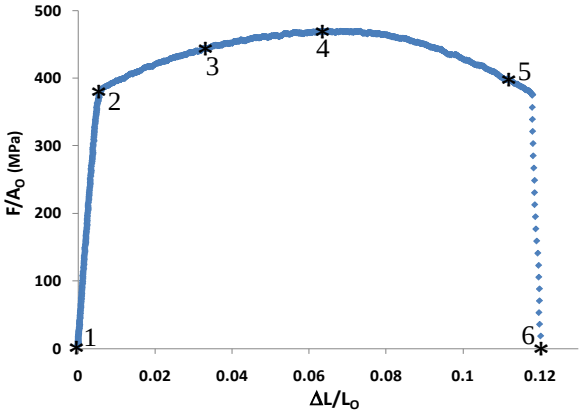


- X-ray computed tomography (XCT) can reveal features inside the material body.

4D Imaging: In-situ XCT Experiments

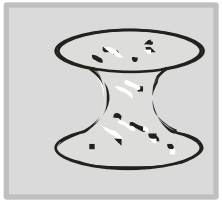
Scan For j = 1:M (> 4)





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.

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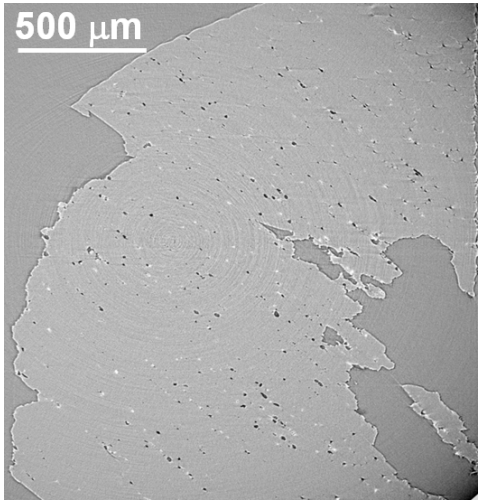
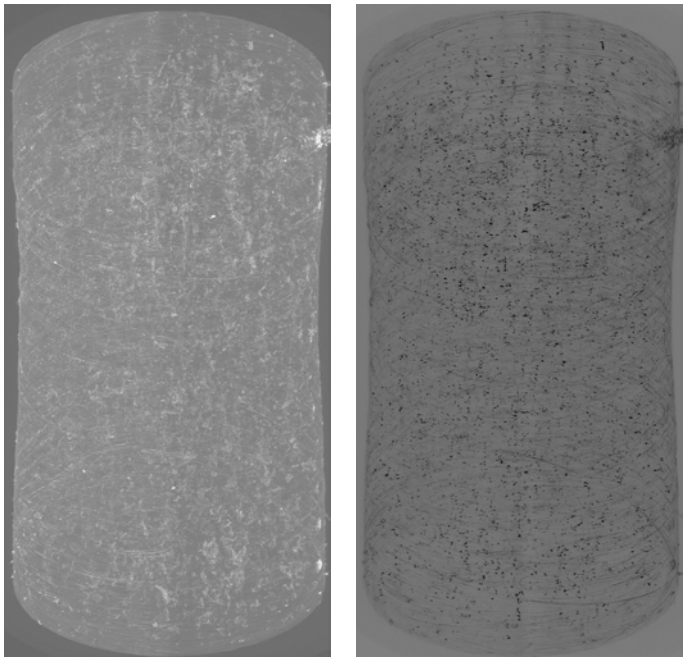
XCT Images of Aluminum Alloy 7075 - Voids and Particles

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 of failed specimen



(a) Particles (b) Voids

Reconstructed 3D images

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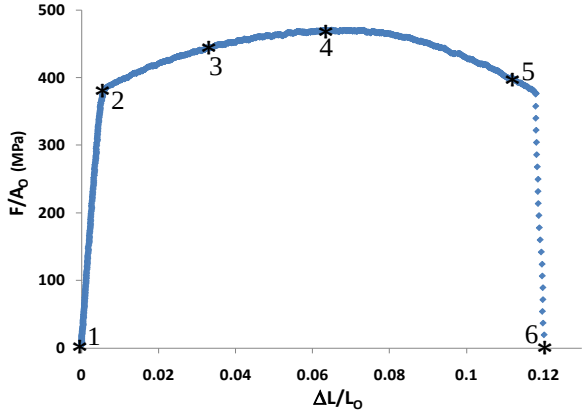
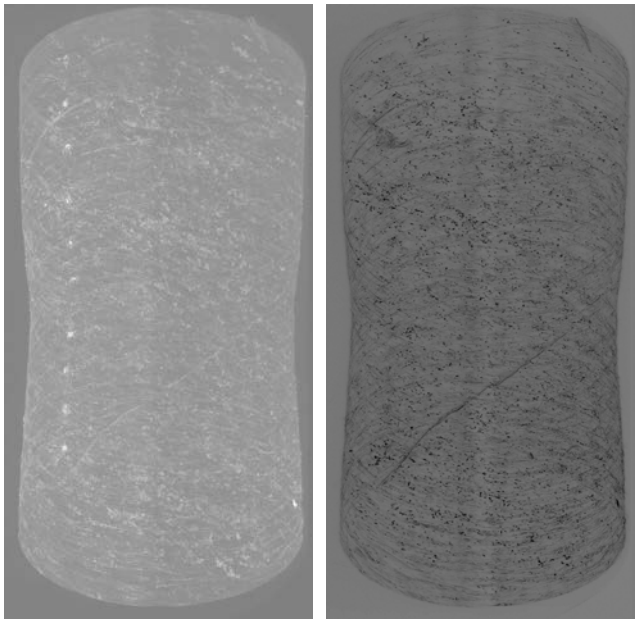
3D Tomographic Images from In-Situ XCT Experiments

Smooth Tension Specimen



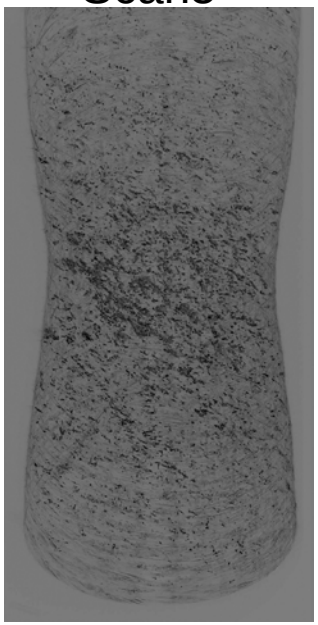
Scan1



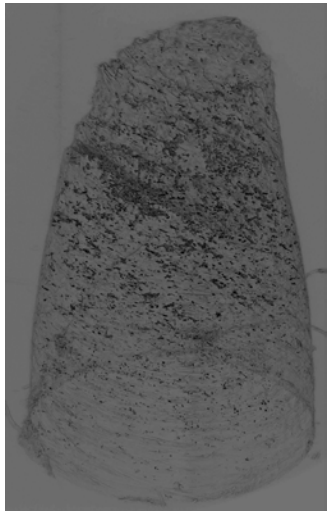
particle void

Scan4

Scan5



Scan6



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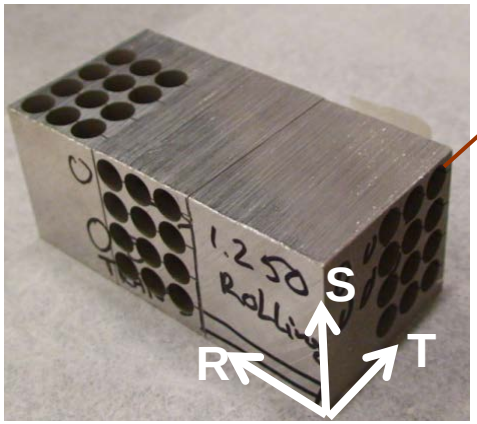
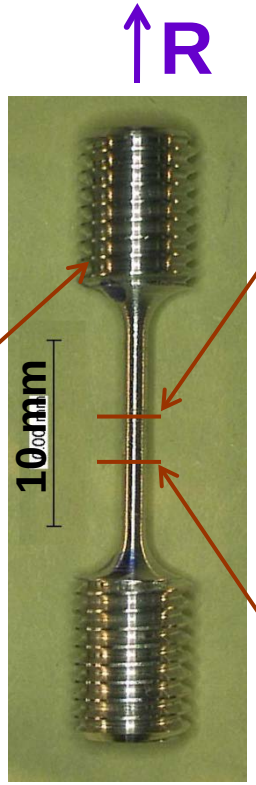
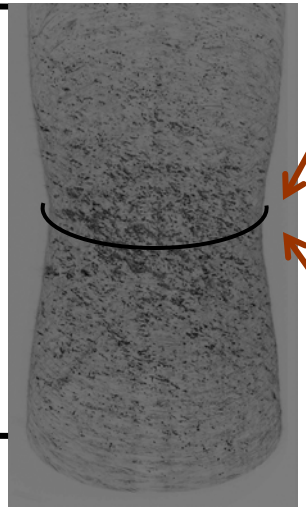
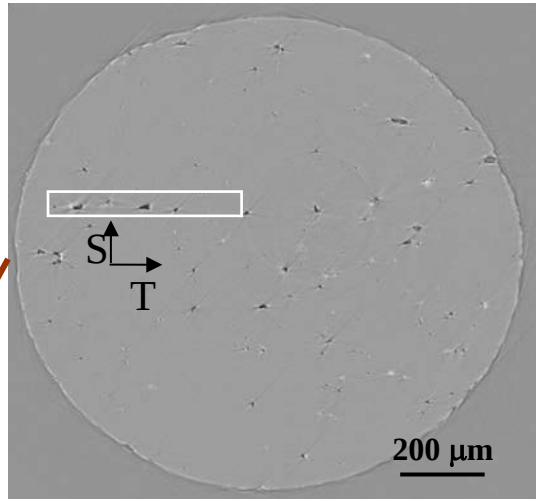
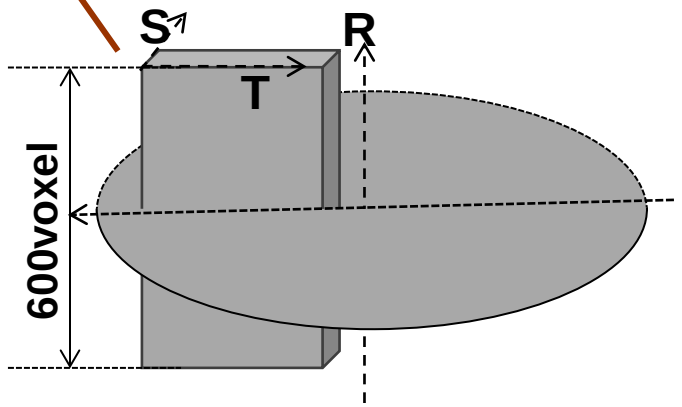
Void Evolution for the Specimen Loaded in the Rolling Direction (1)











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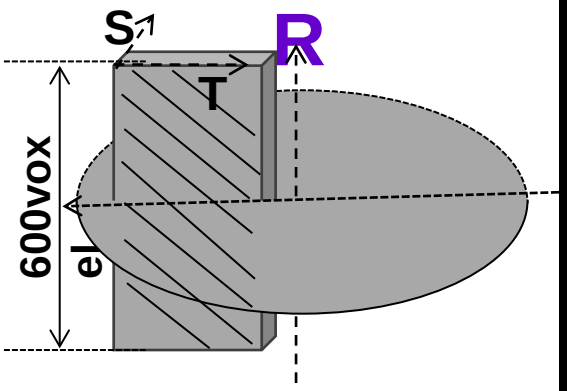
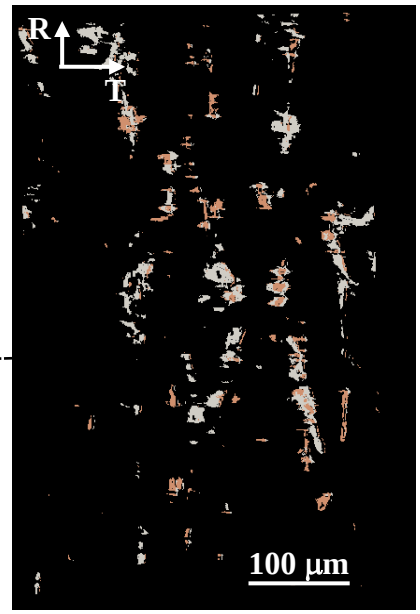
Void Evolution for the Specimen Loaded in the Rolling Direction (2)

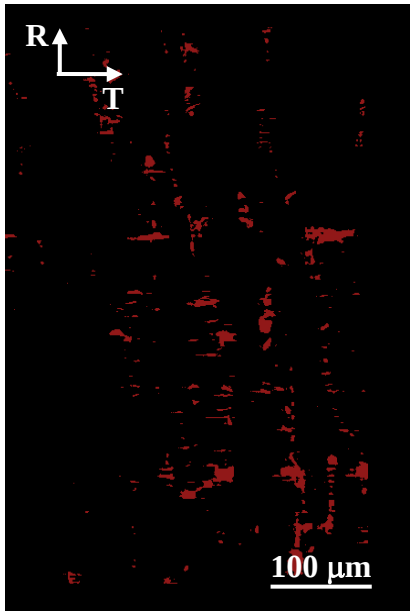


(a) volume used for projections in R-T plane



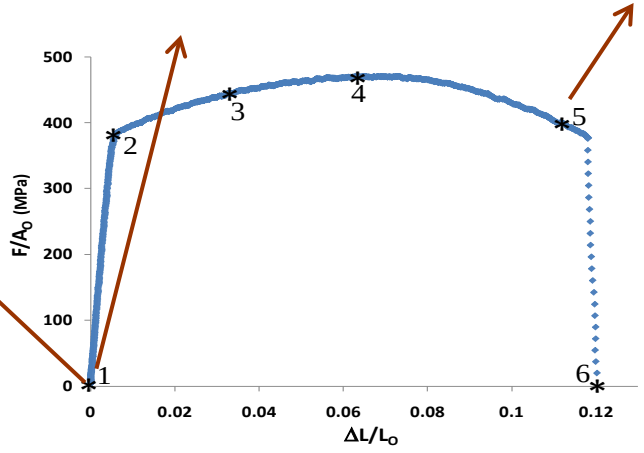
Initial voids and particles

Initial Voids



Voids near failure

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



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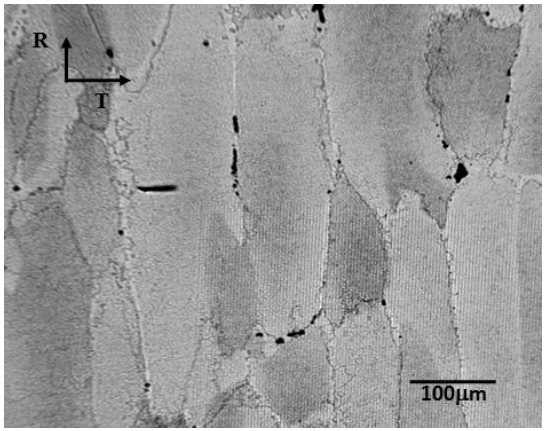
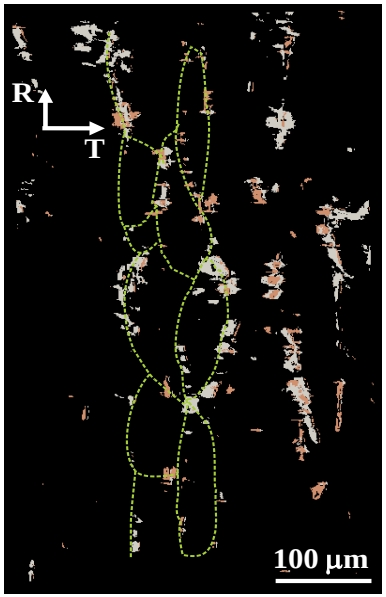
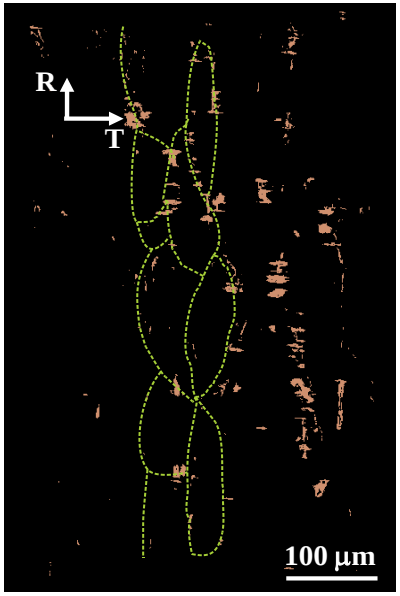
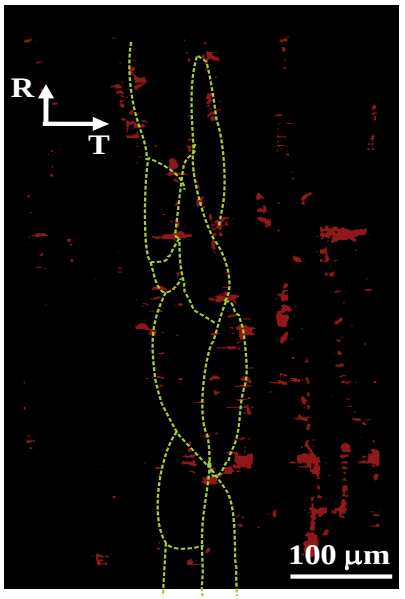
Void Evolution for the Specimen Loaded in the Rolling Direction (3)





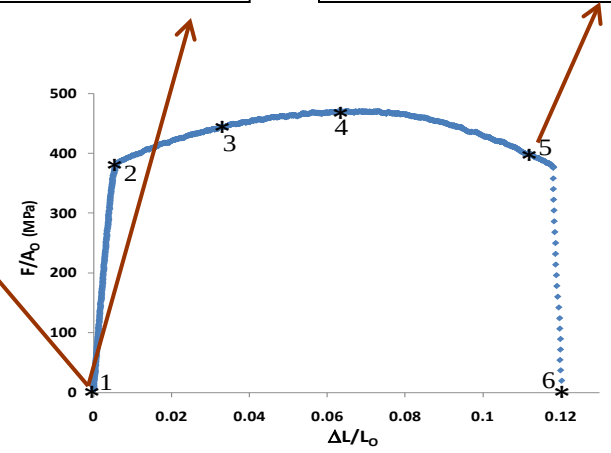




Initial voids and particles

Initial Voids

Voids near failure



Voids distribution seem to align with grain boundaries.

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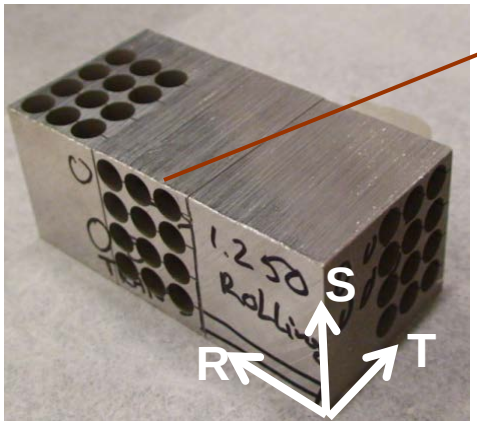
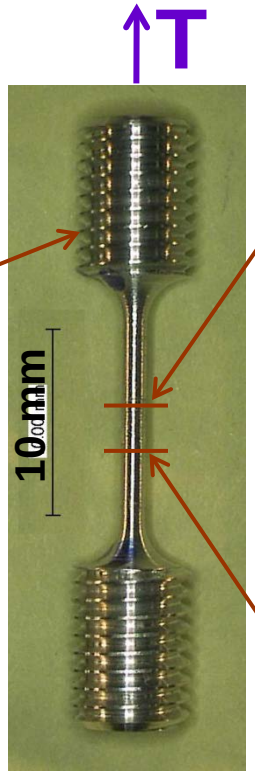
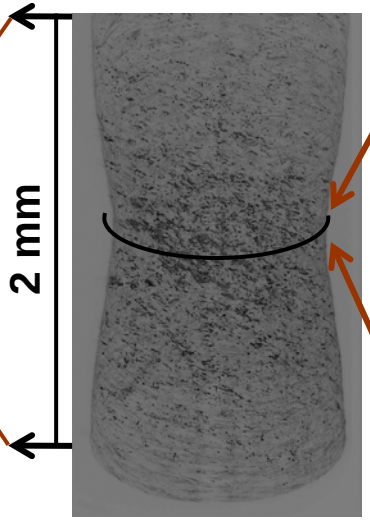
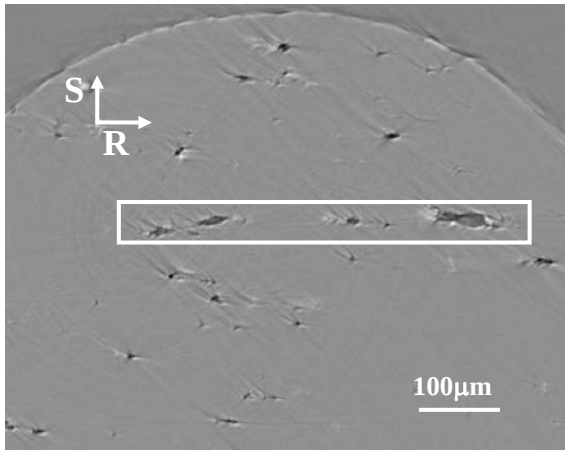
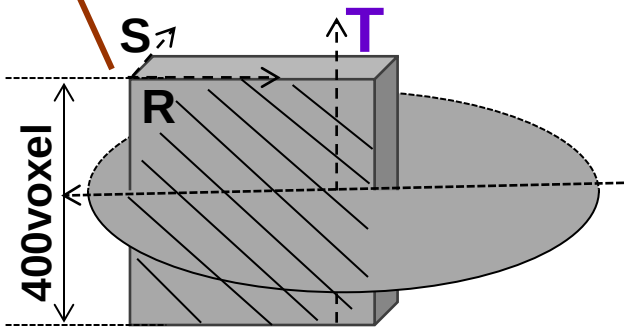
Void Evolution for the Specimen Loaded in the Transverse Direction (1)











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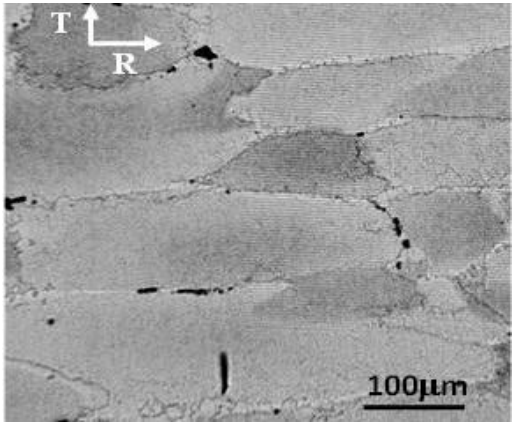
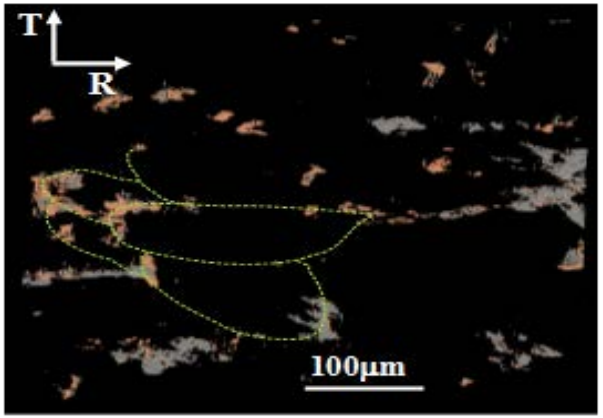
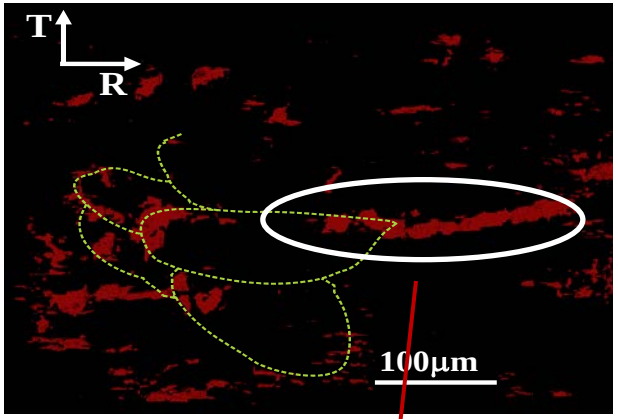
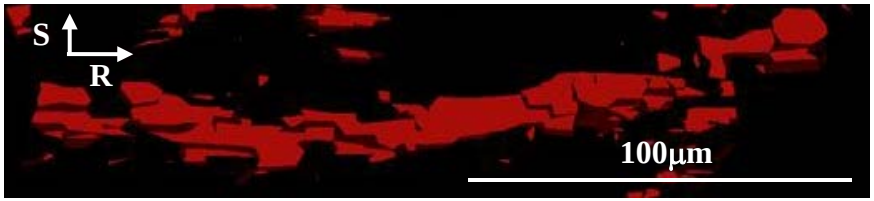
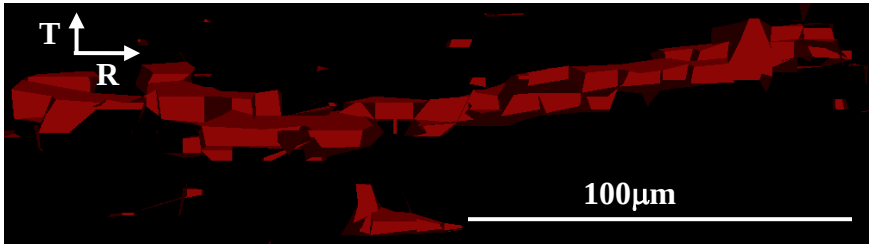
Void Evolution for the Specimen Loaded in the Transverse Direction (2)











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

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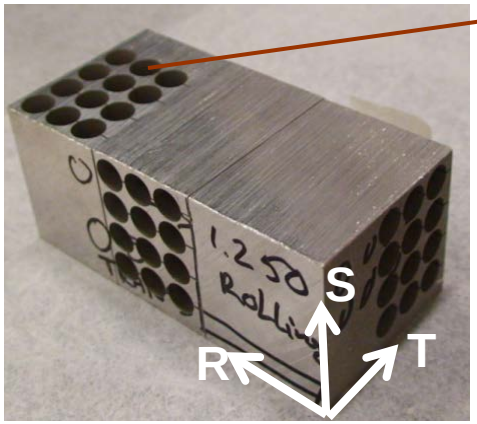
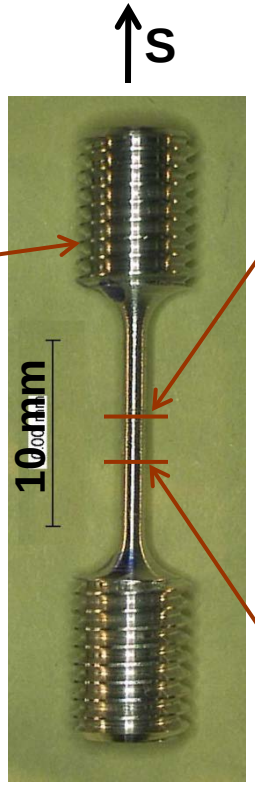
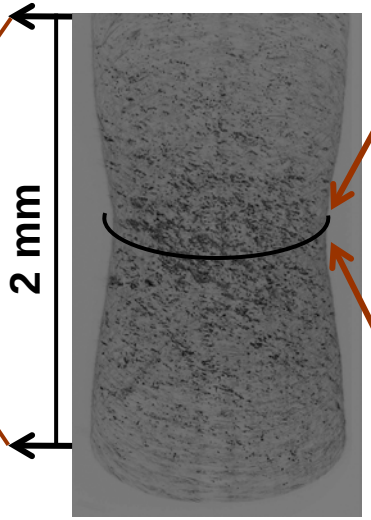
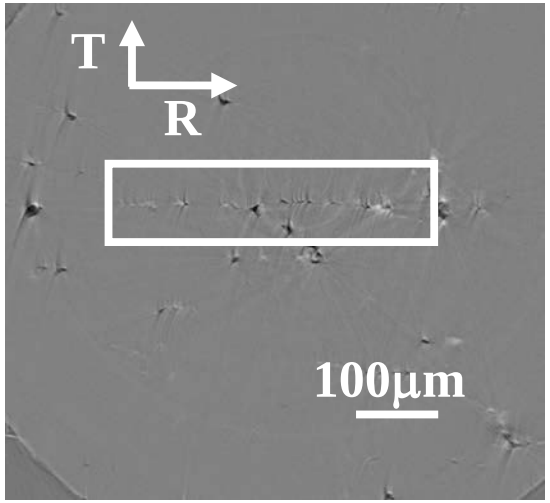
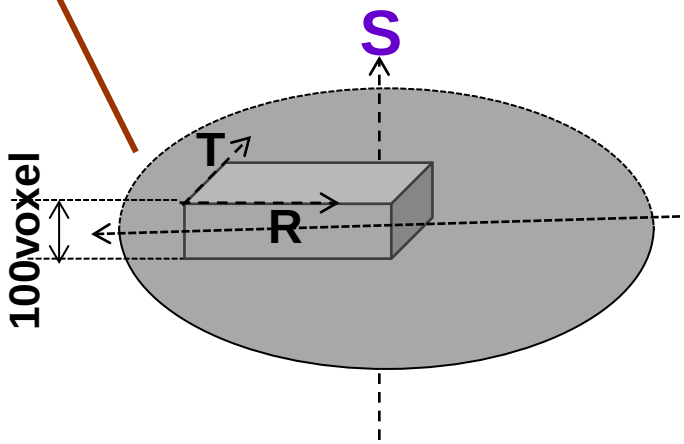
Void Evolution for the Specimen Loaded in the Short Transverse Direction (1)











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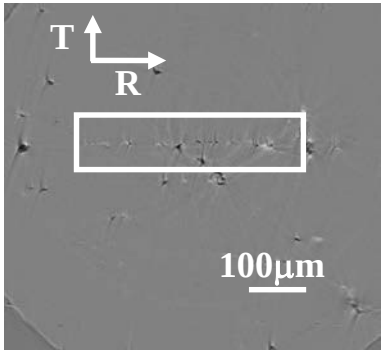
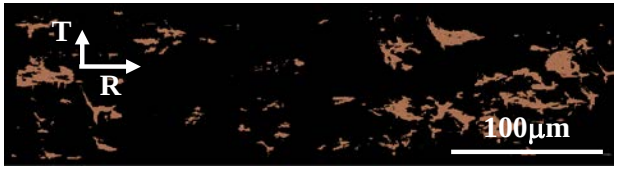
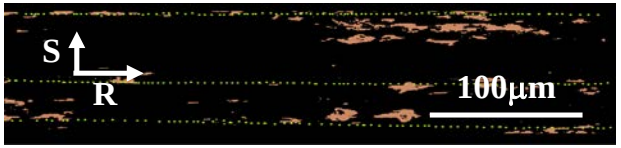
Void Evolution for the Specimen Loaded in the Short Transverse Direction (2)



(a)

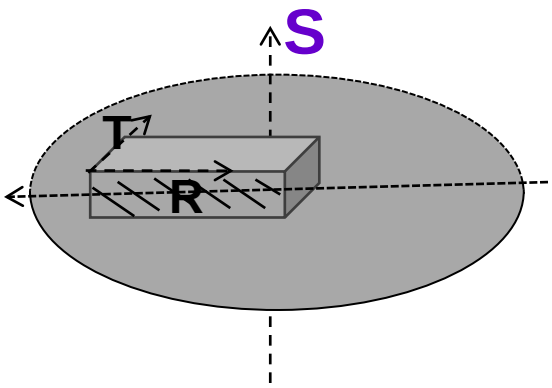


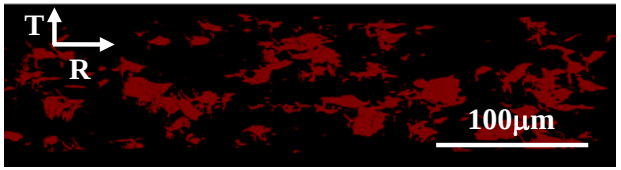
(b)



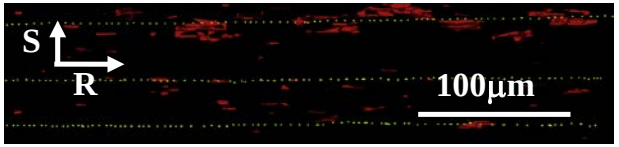
(c)

3D rendered image of voids at failure state





(d)

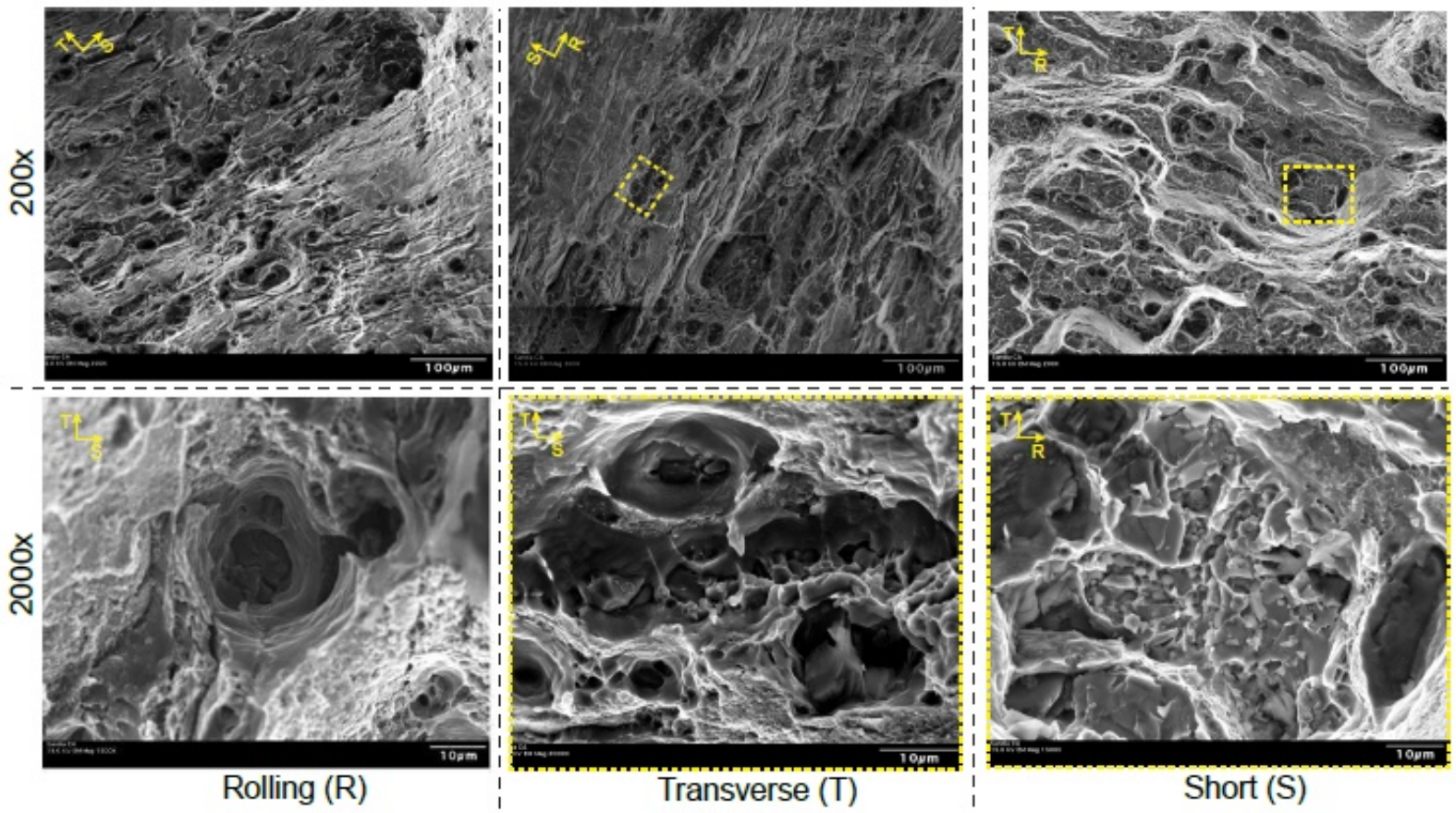


(e)

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.

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.

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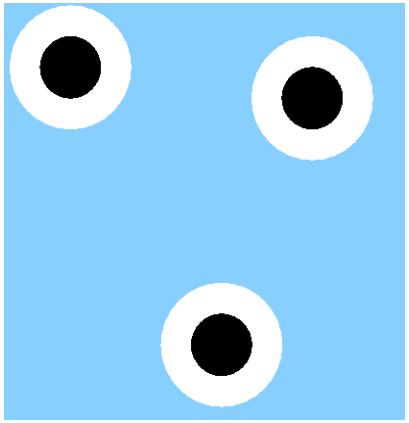
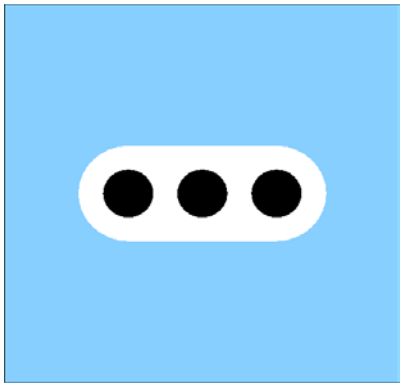
Different Void Evolution Mechanisms

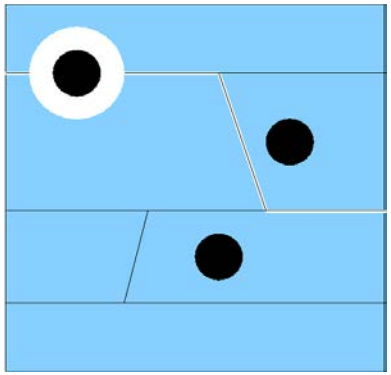
- For the specimens loaded in the rolling direction, local void growth via plastic deformation is dominant process prior to global coalescence. There is limited local coalescence.



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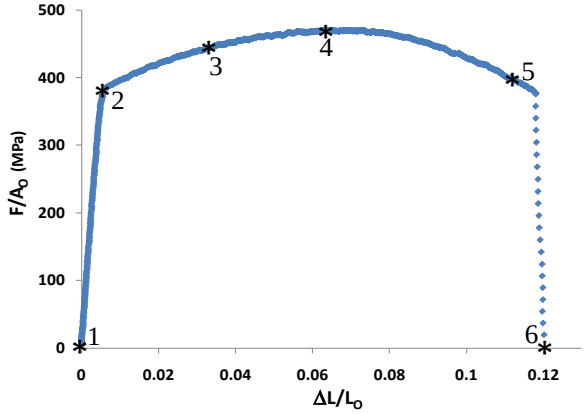
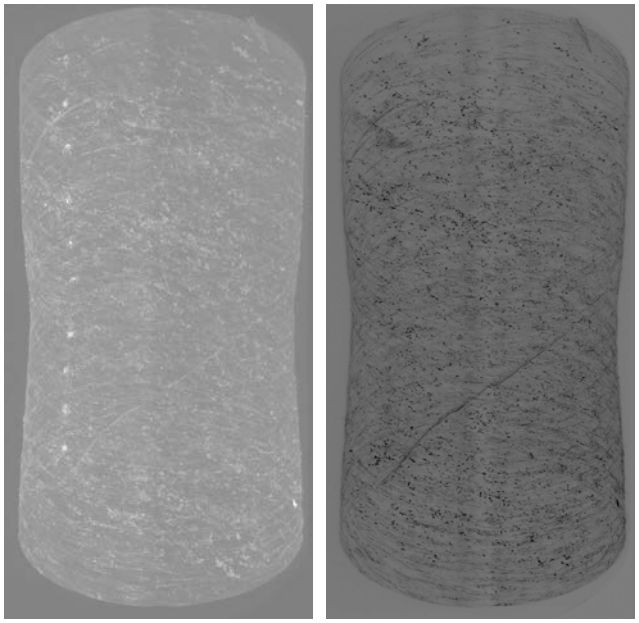
3D Tomographic Images from In-Situ XCT Test can Observe Damage Evolution

Smooth Tension Specimen



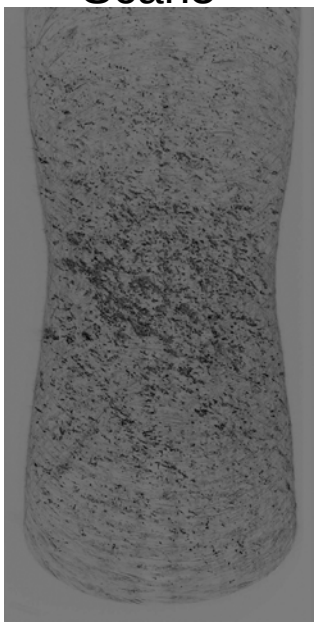
Scan1



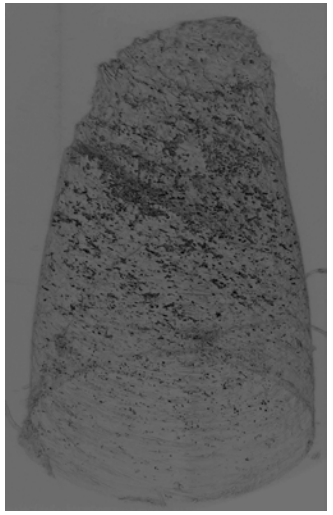
particle void

Scan4

Scan5



Scan6



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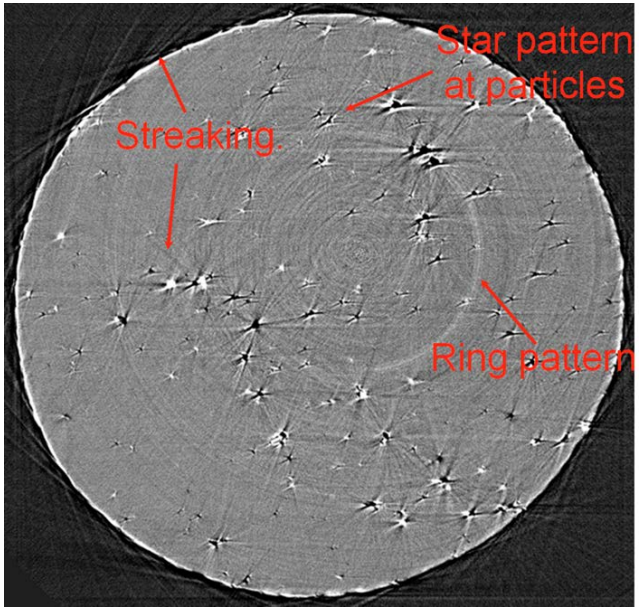
3D Volumetric Deformation Measurement using Existing XCT Images

- Internal features can not be physically modified
- Patterns from these features are not ideal

- Low contrast
- White streaks
- Ring patterns
- Some large areas without usable features



➡ *Feasibility Study:* Can we use these non-ideal patterns in the pre-existing tomographic images to calculate deformation field inside the material body???

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Analysis using Global DVC Correli-C8R

Hugo Leclerc, Jean-Noel Perie, Stephane Roux, Francois Hild. Voxel-Scale Digital Volume Correlation. Experimental Mechanics, Society for Experimental Mechanics (SEM), 2011, 51(4), pp.479-490.

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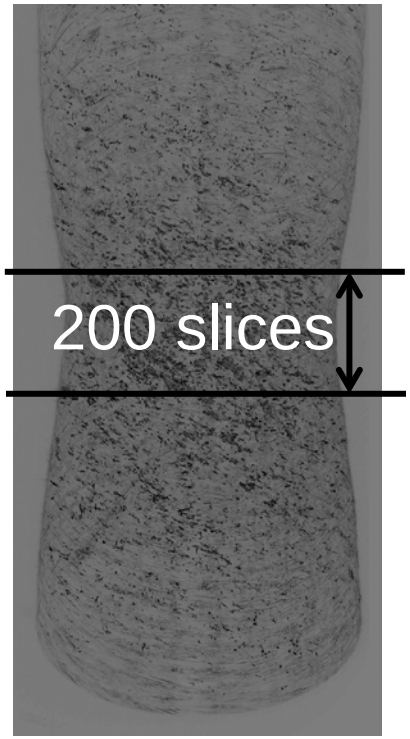
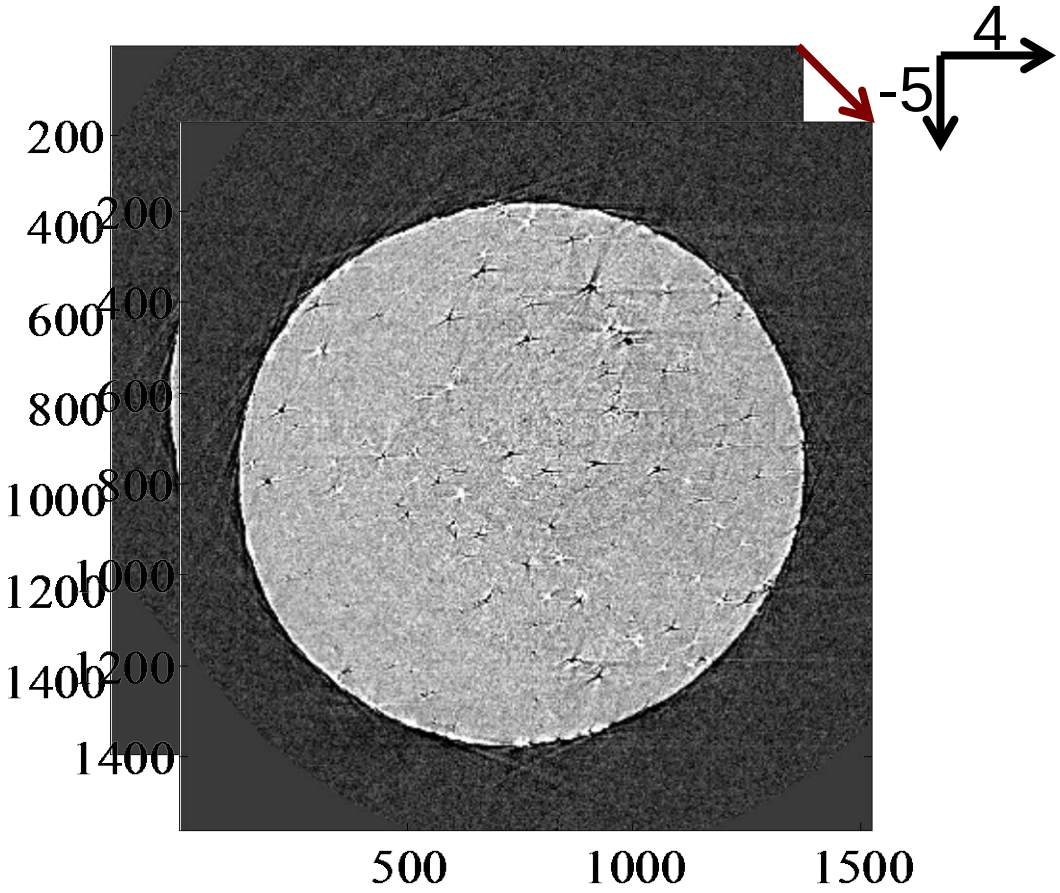
First Case: Simple Translation of XCT Slices in X-Y Plane



Scan 5

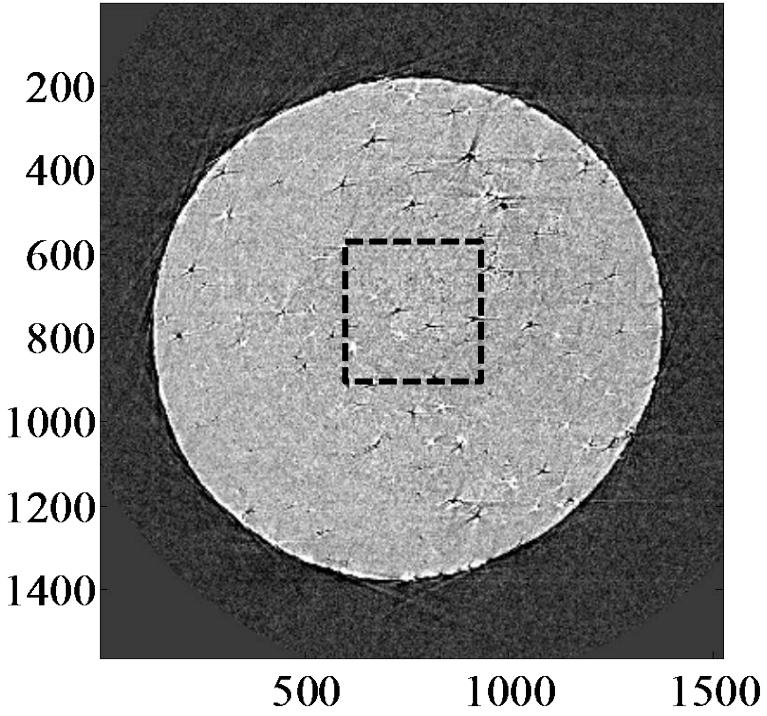


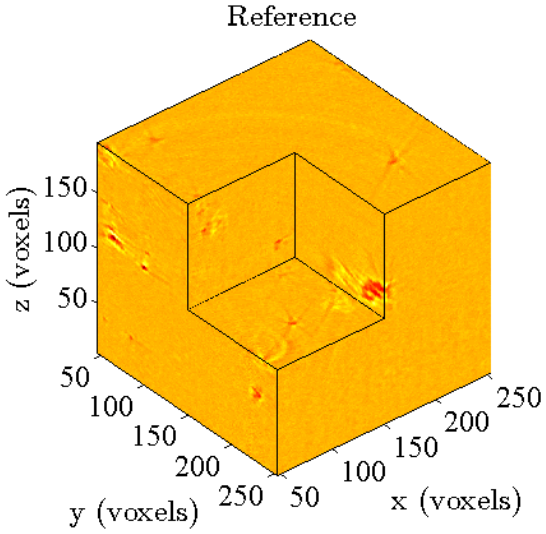
Introduce artificial displacements by shifting the images:

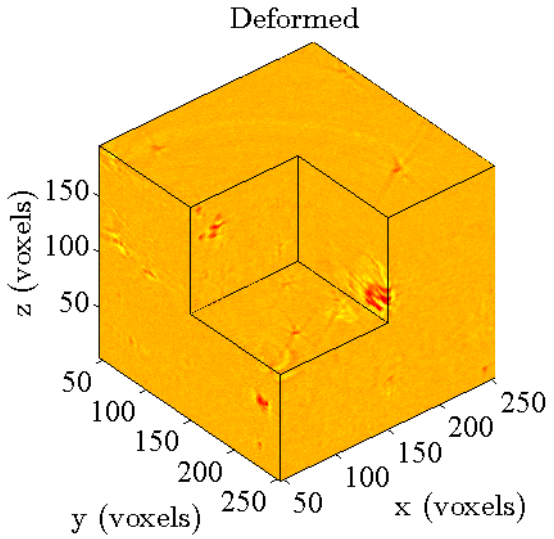
U=4, V= -5, W=0 (voxels)

Selected Reference and Deformed Volume for DVC Analysis

ROI (200x200X200) selected through 200 slices







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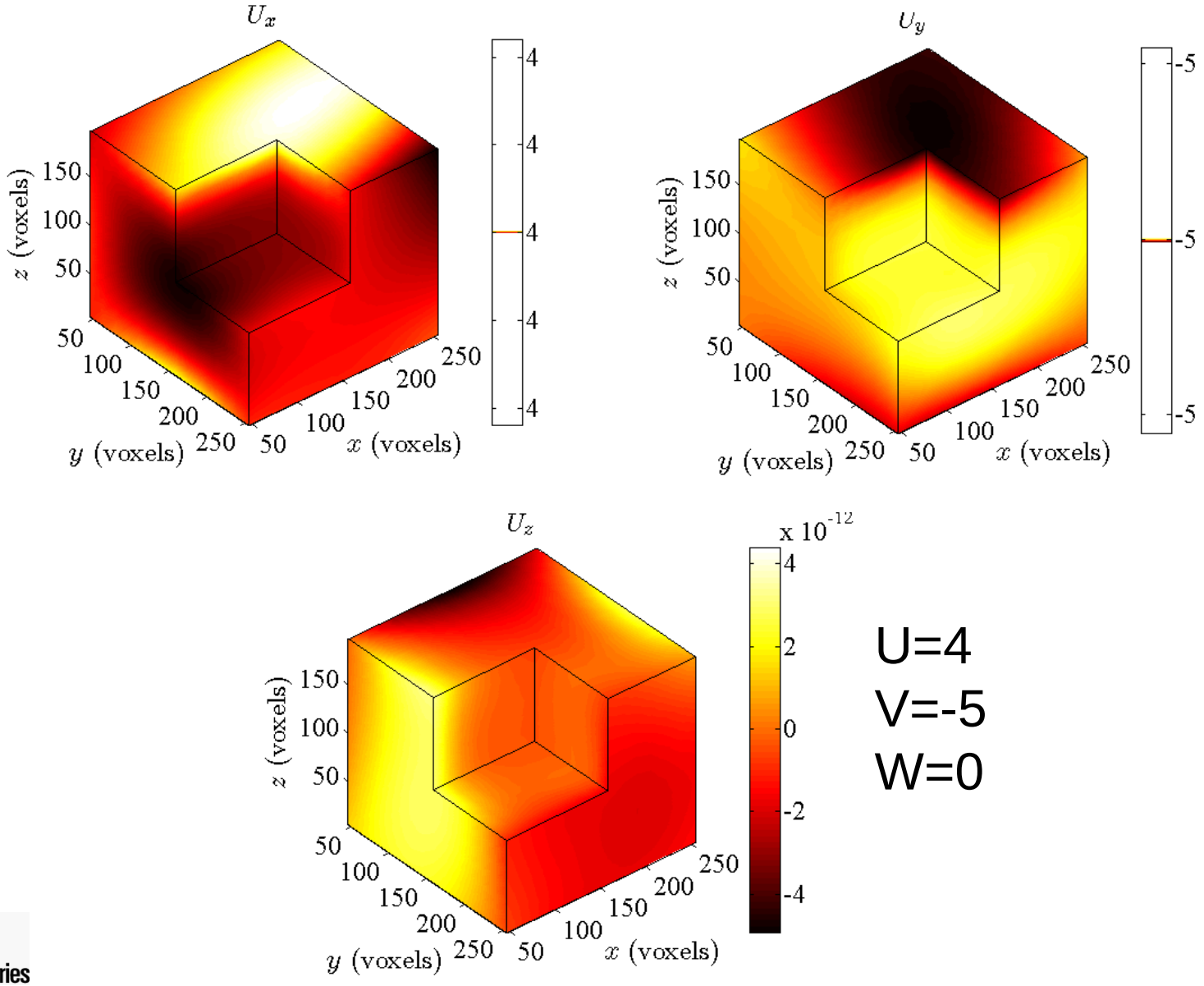
Deformation Analysis using Global DVC

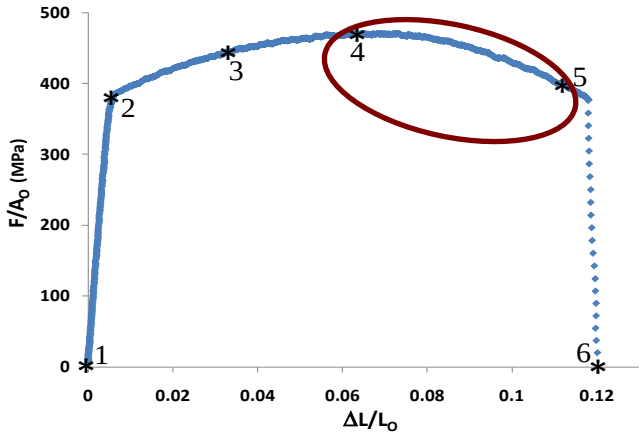
- Finite-element based Correli-C8R;
- A regular cubic mesh of size 16x16x16 vox^3 is chosen;
- Trilinear Q8 element is used;
- Mechanically regularized using equilibrium gap method;
- Regularization length is 50.

Displacement Results from DVC for the Trial Test

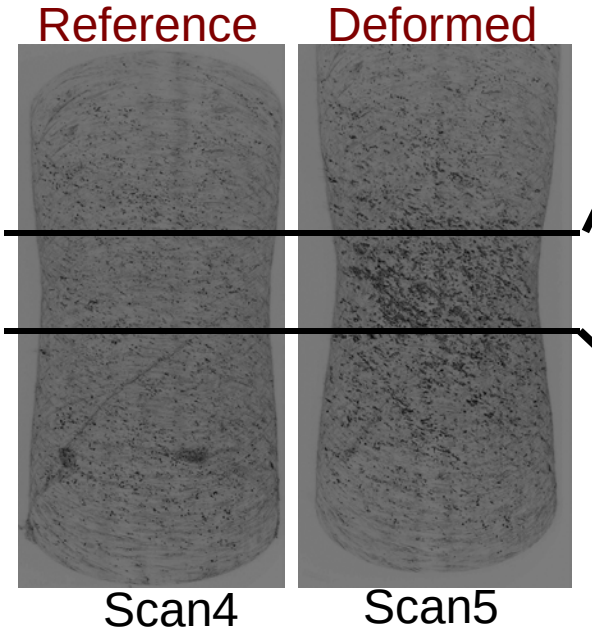


U=4
V=-5
W=0

Second Case: Subvolume Selected from Scan 4 and 5



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



- Scan 4: #996 - 1110
- Scan 5: #1057 -1171

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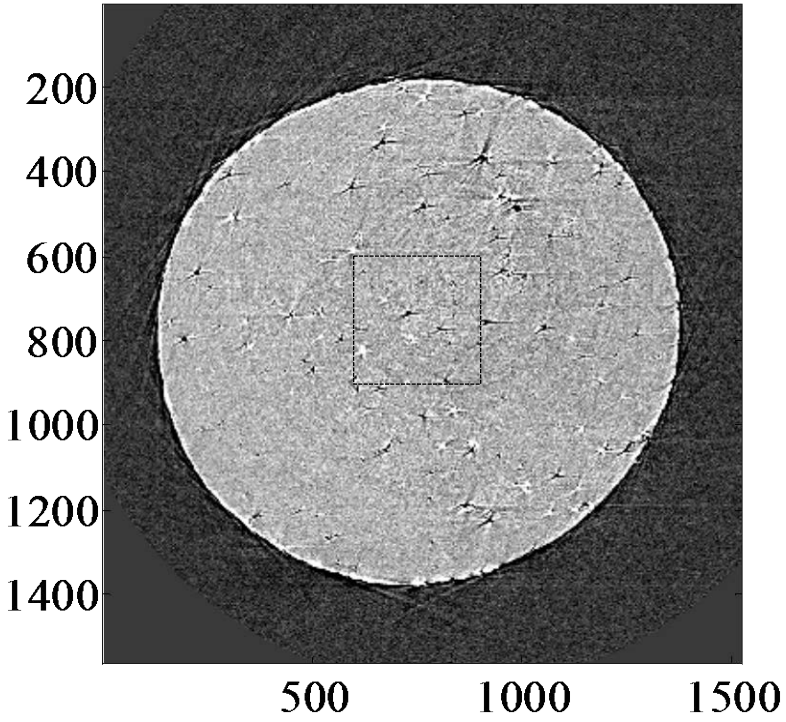
Region of Interest and DVC Parameters

UT-Roll01-0714-Scan5_994.tif



The square shows the size of the zone analyzed with Correli C8R

- ROI: [304 304 80] (centered in the 400×400×115 volume)
- Element size: 16
- Regularization length: 50

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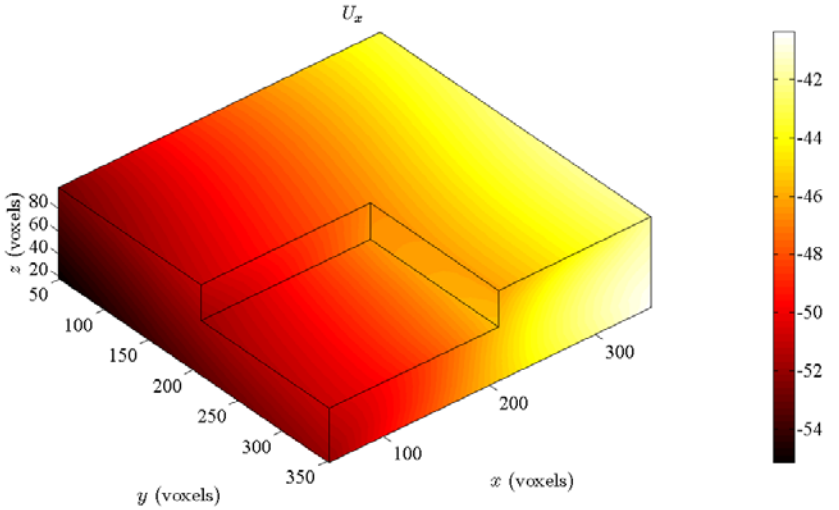
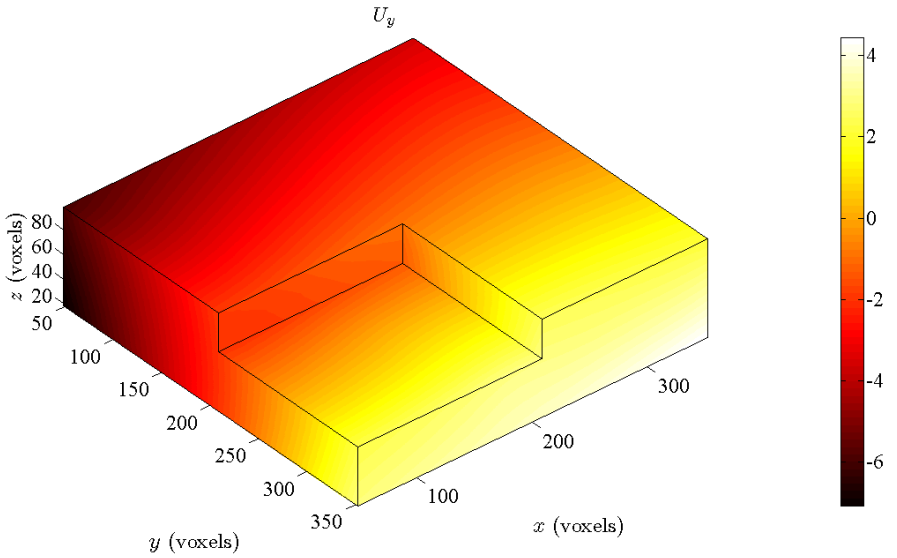
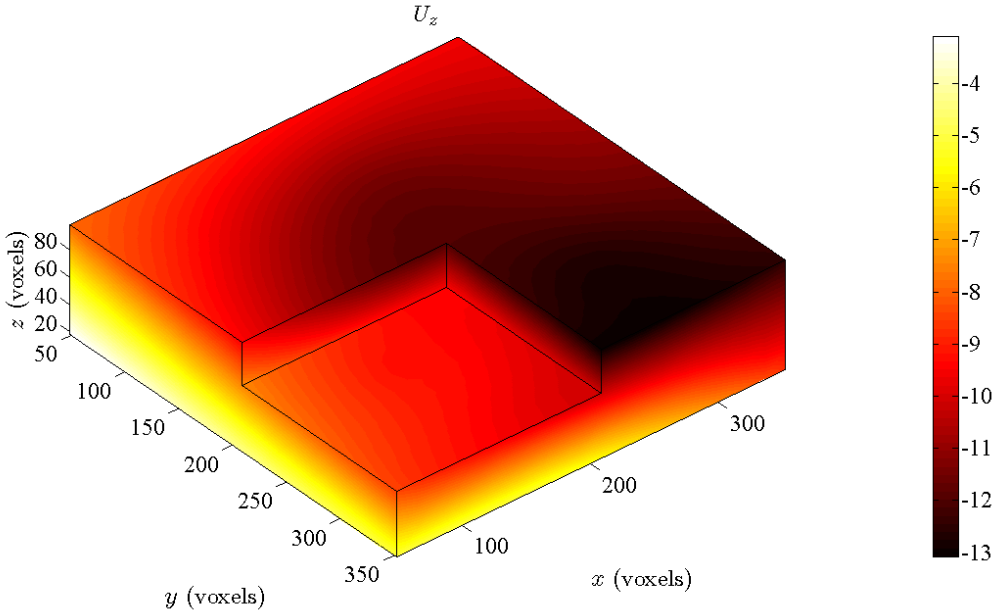
Displacement Fields







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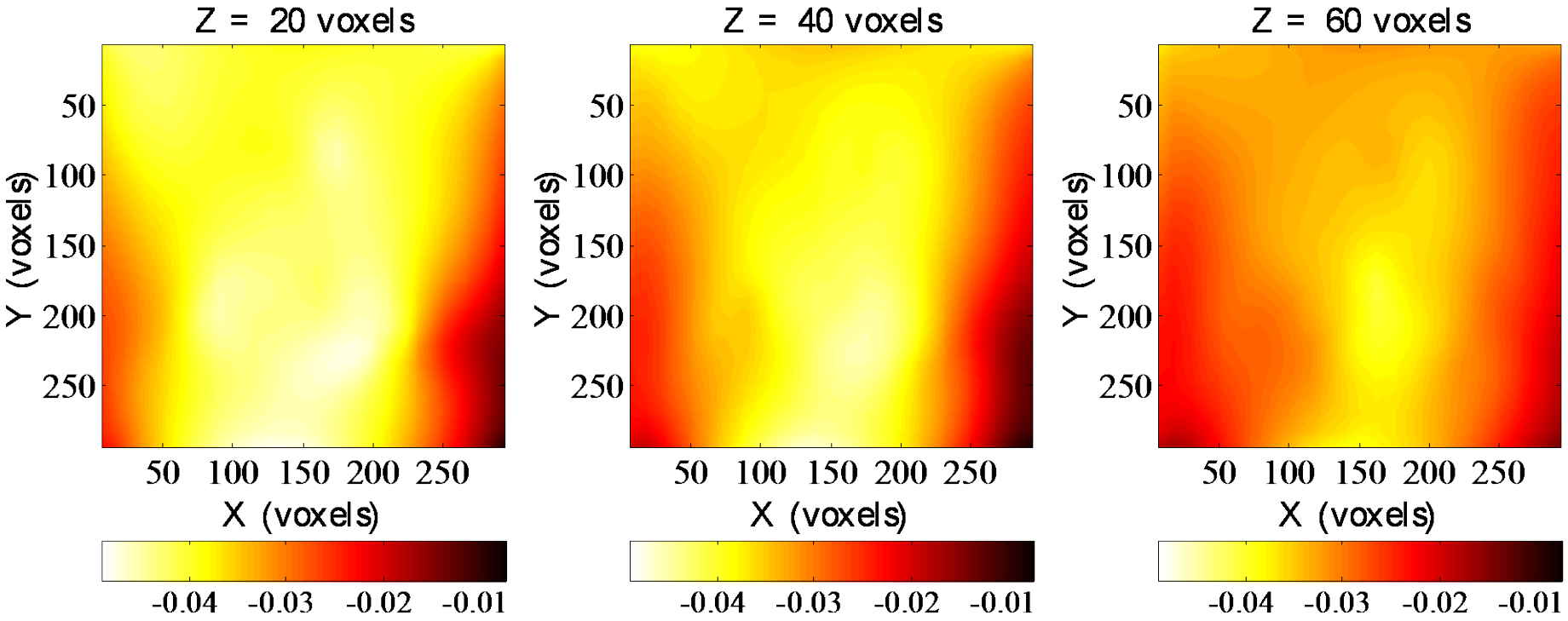
Strain Fields at Selected Cross Sections

ε_{xx}



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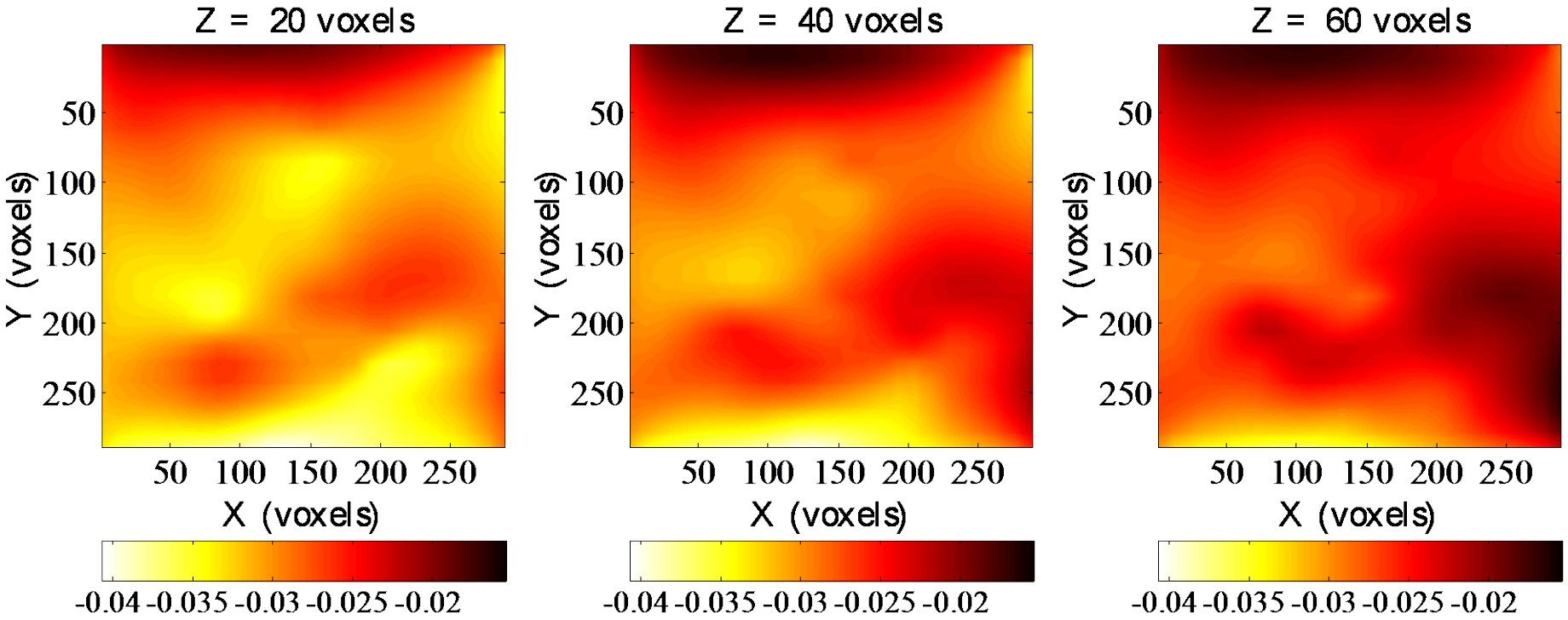
Strain Fields at Selected Cross Sections

ε_{yy}



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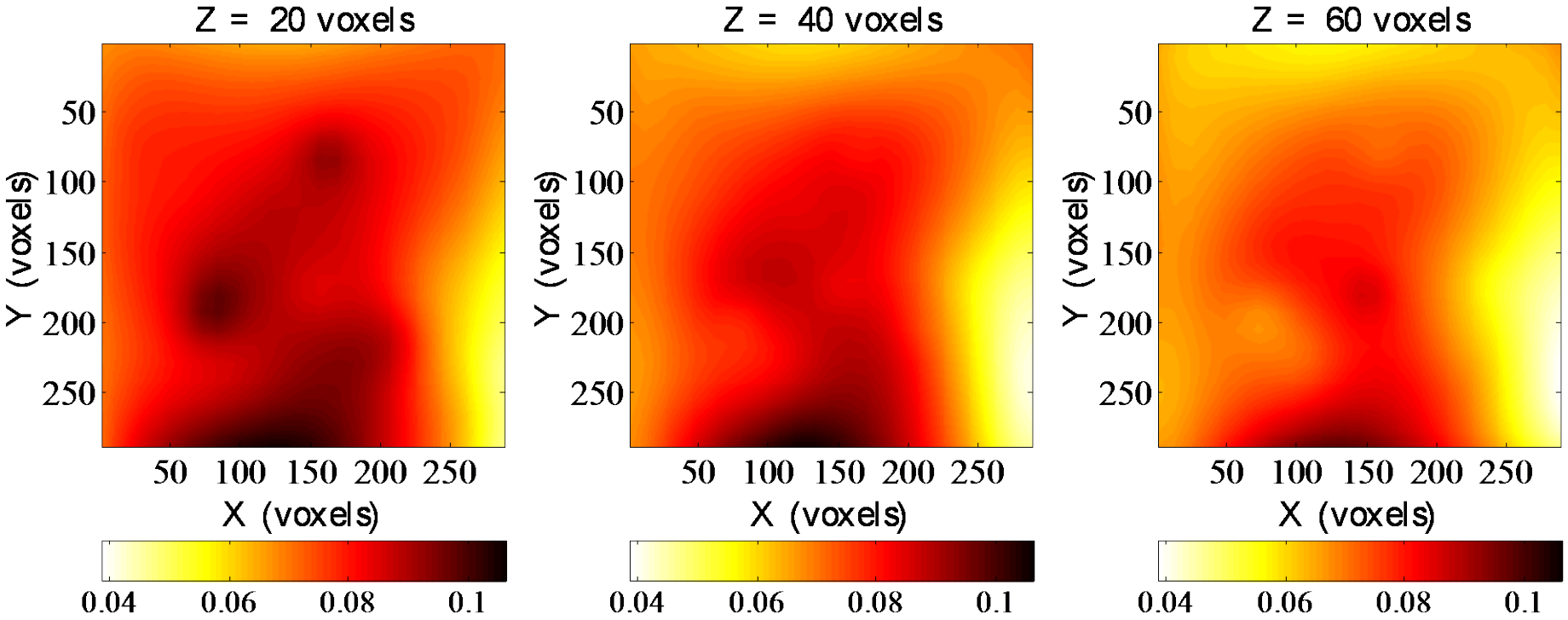
Strain Fields at Selected Cross Sections

ε_{zz}



This global DVC was quite successful without any special trick in spite of the large amplitude of displacements (50 pixels) and strain (up to 8% axially).

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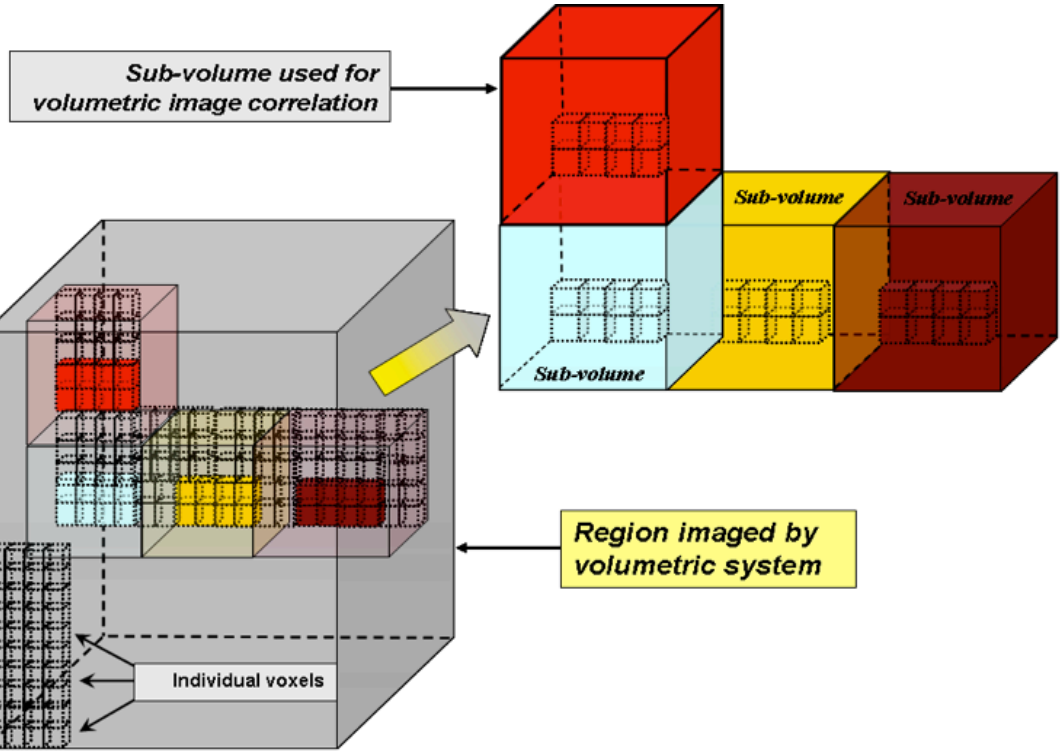
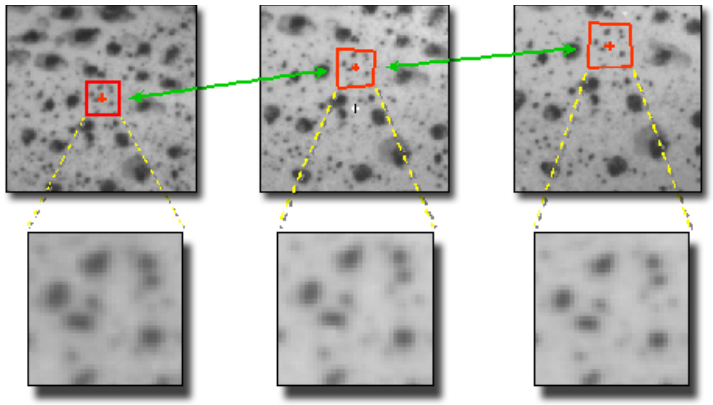
Local Digital Volume Correlation (DVC)

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

DVC- Digital Volume Correlation



DIC- Digital Image Correlation



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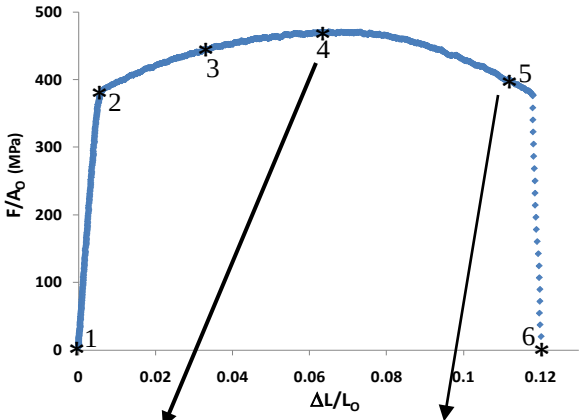
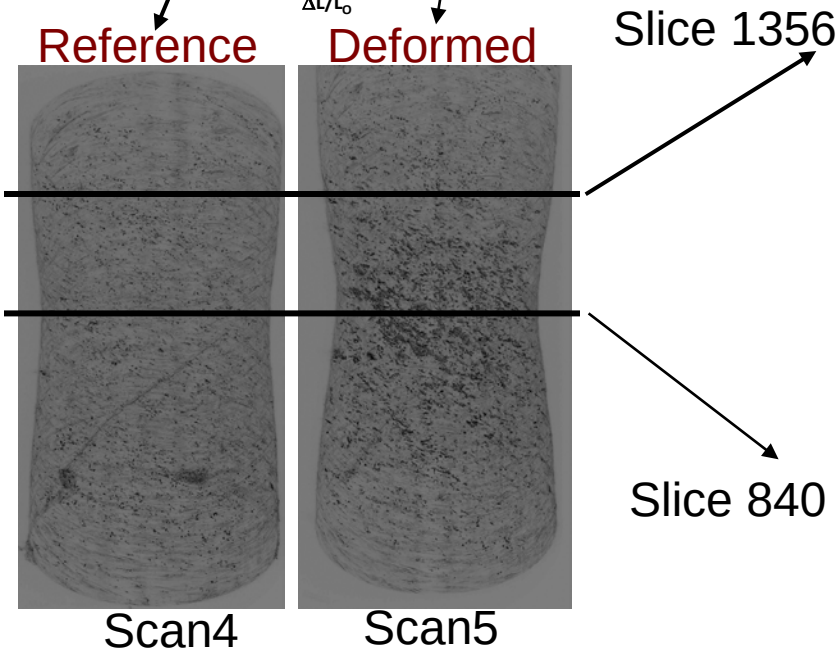
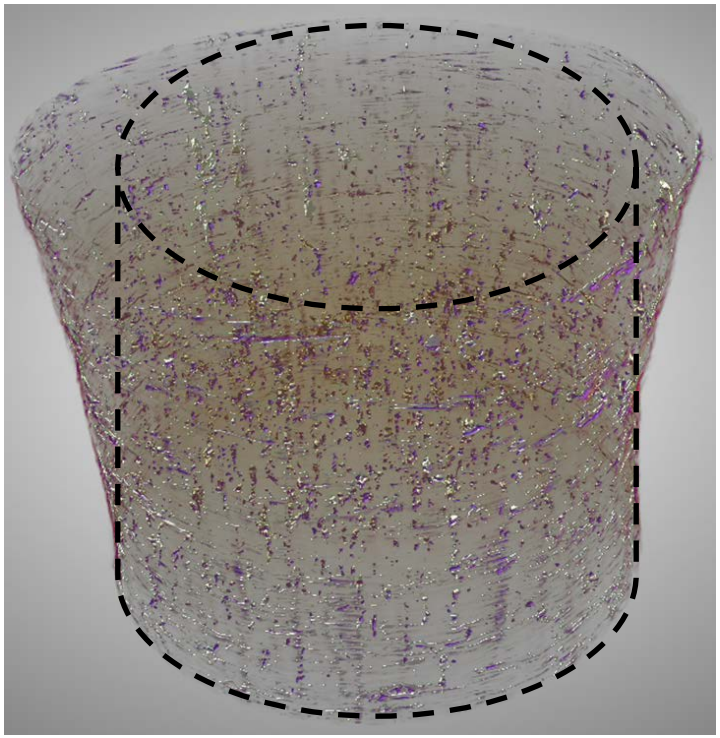
Third Case: Real Deformation Field from the Tomographic Image Sets using Local DVC



- One set of tomographic images from rolling direction
- Real deformation: Reference-scan 4, Deformed – scan 5
- 25x25x25 voxels of subvolume





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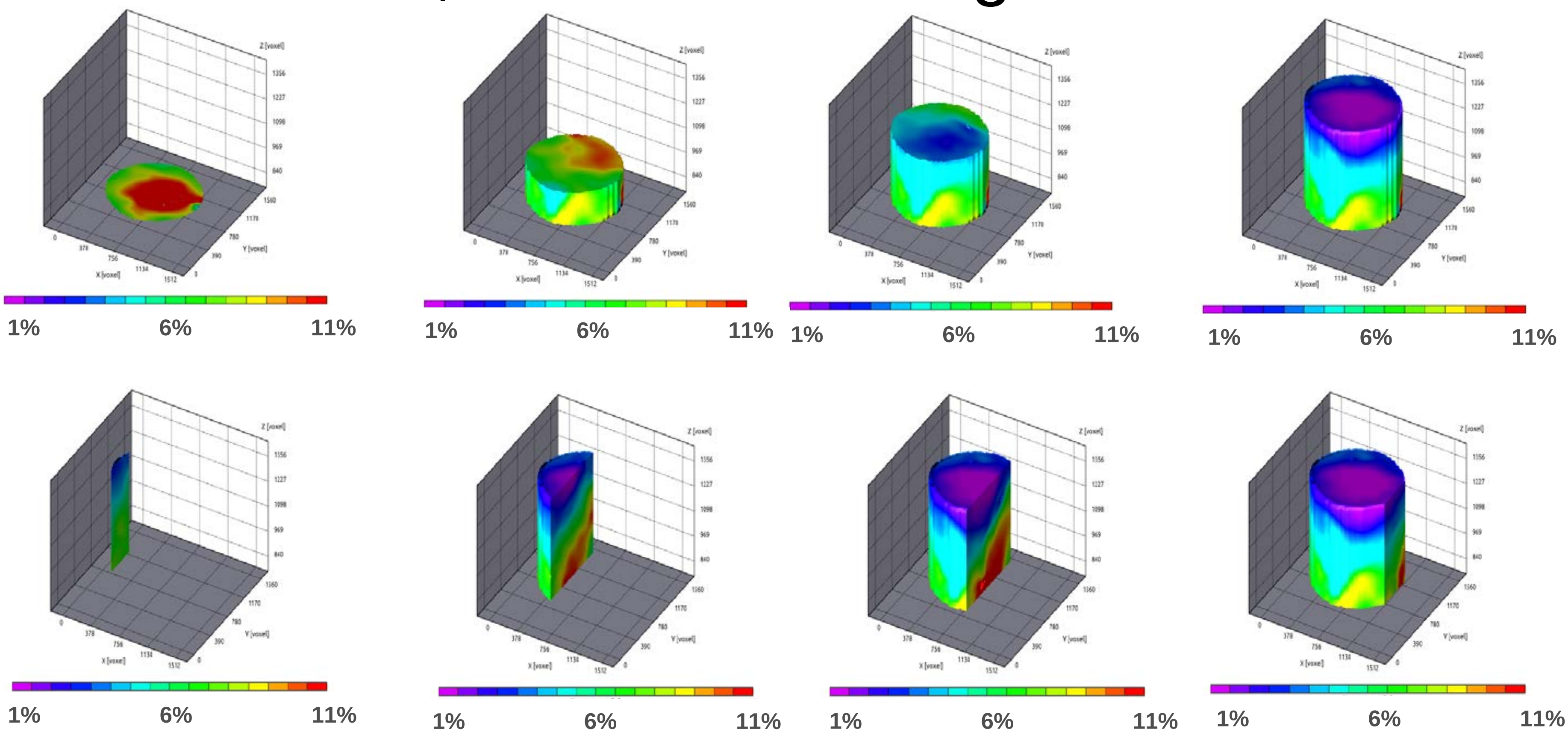
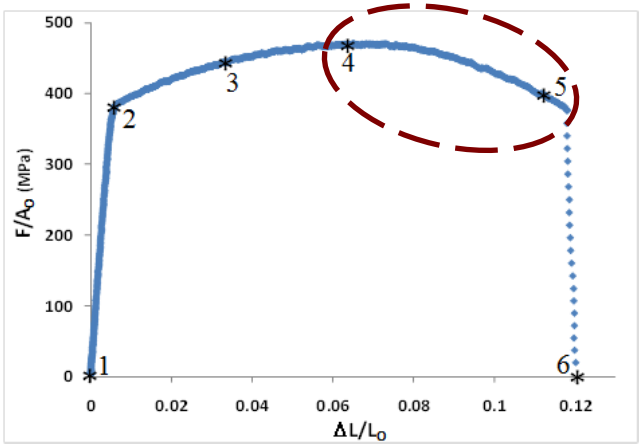
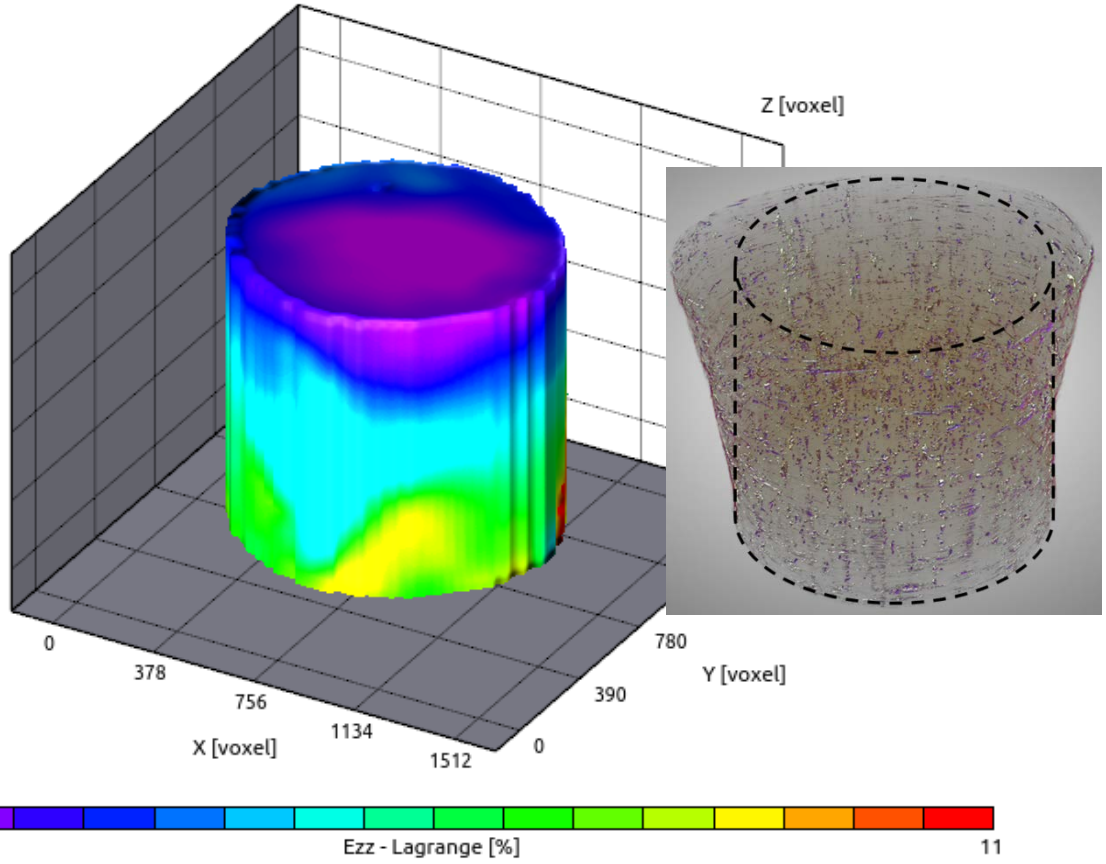
DVC Analysis Results for Axial Strain ε_{zz}

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



Reasonable DVC Results





We are able to use the non-ideal patterns in the pre-existing tomographic images to calculate 3D deformation field inside material body.

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Summary

- In-situ XCT experiment is able to study the different voids evolution mechanisms in the rolled material.
- DVC algorithms are able to calculate the deformation field inside the material body using the non-ideal patterns in the pre-existing tomographic images.
- However, there are data drop-outs due to the artifacts in the CT images.

Future Work

- How accurate are the DVC results?
  - Validate DVC results
  - DVC results uncertainty quantification
- How to improve the DVC results?
  - Improve 3D images
    - optimize imaging parameters
    - reduce artifacts
  - Develop/Improve DVC algorithm
- How to obtain DVC results faster?
  - Increase the efficiency of DVC

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Acknowledgement

Thanks the support of the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBL), and in particular Alastair MacDowell and Dula Parkinson at the 8.3.2 tomography beamline.

Thanks to Dr. Stephane Roux, LMT-Cahan, France for Global DVC and Dr. Hubert Schreier, Correlated Solutions Inc, SC for Local DVC Algorithms.

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