SAND2011-0013 C
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Voids Growth and Coalescence Study of Al 7075-T7351 using X-Ray Tomography

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Introduction

- Motivation
  - Develop models for reliable predictions of failure in structural alloys, e.g. high strength rolled aluminum alloys
- Current available models are inadequate to model the evolution of anisotropic damage in rolled aluminum alloys
  - Usually restricted to isotropic material behavior
  - Detailed descriptions of the ductile failure processes based on micro-mechanics are needed, i.e. void nucleation, growth and coalescence
- X-ray computed tomography (CT) could reveal the three-dimensional structure of inclusions and voids
  - Attenuation to X-rays is correlated to the density of the material
- *In-situ* X-ray CT may provide the detailed nature and evolution of the damage and its relationship to the material microstructure

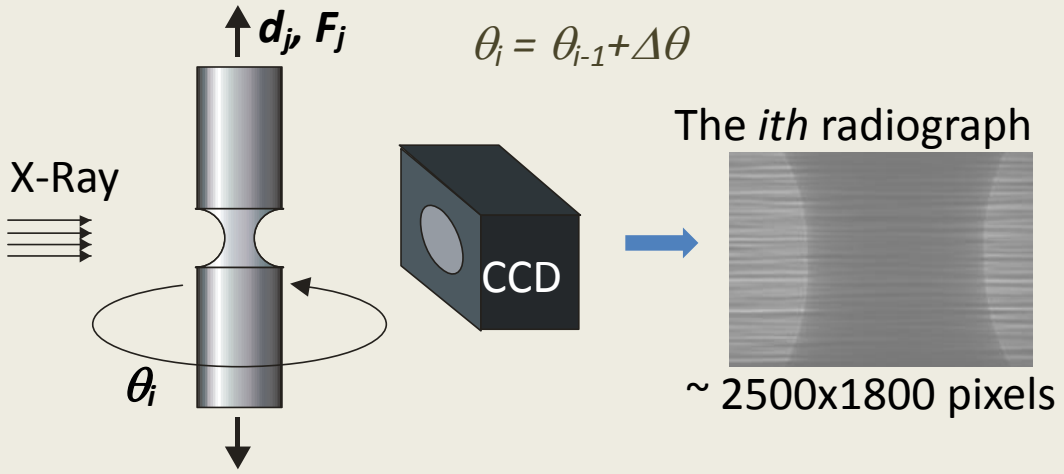
In-situ X-Ray CT Experiment

For j = 1:M (> 4)

Scan

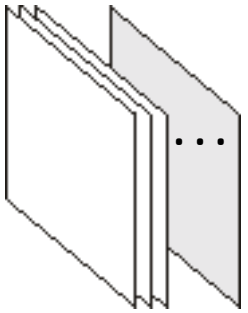
For i = 1:N (720 or 1440)

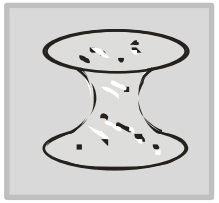
$\theta_i = \theta_{i-1} + \Delta\theta$



Reconstruction

N radiographs





Synchrotron-radiation computed tomography (SRCT)

The jth reconstructed Sample

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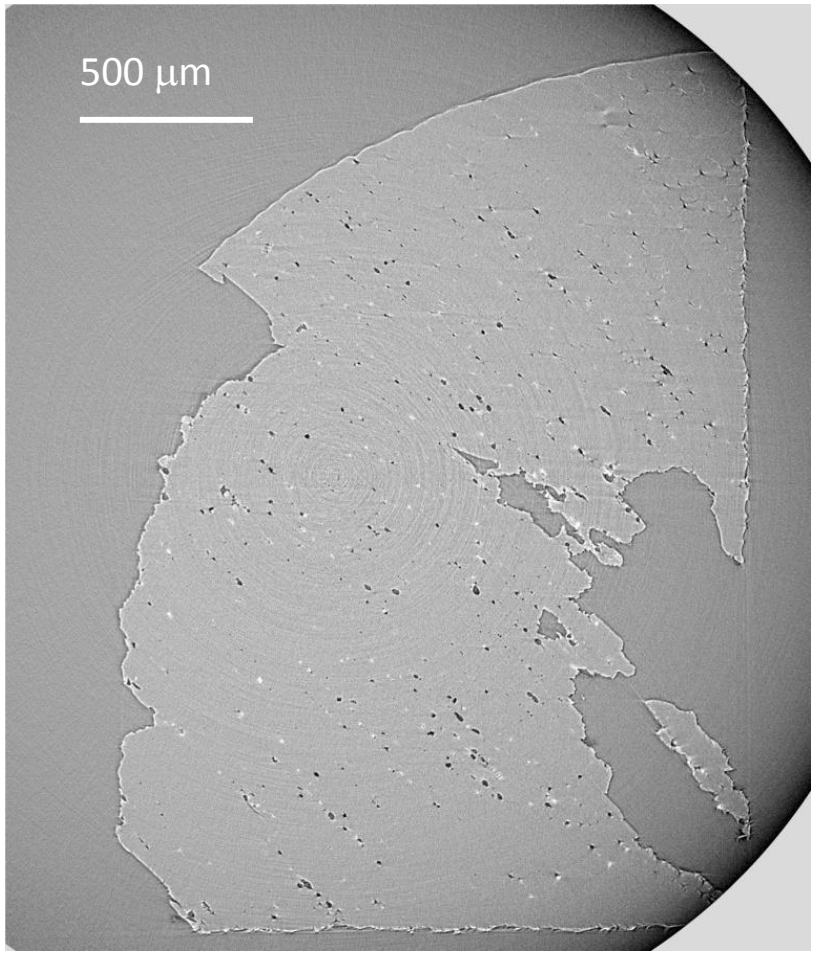
Initial Proof of Concept

- A previously failed Al 7075-7351 sample was examined on the micro-tomography beamline (8.3.2) at the Advanced Light Source at Lawrence Berkeley National Laboratory
- Specimen cross-section dimension less than 2 mm is adequate for X-ray tomography on the beamline
- Constituent particles appear lighter than the aluminum matrix, and voids are the dark regions
- Each scan takes more than an hour (or two hours)
- The resolution of SRCT is 900nm



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Experimental Plan

- 96 hours of beam time (in two 48-hour blocks) were granted for in-situ SRCT
- Planed to run at lest 6 specimens with at least 5 loading/damage states each
- Detail design/planning and determining experimental parameters before in-situ SRCT experiments were necessary to fully utilize the available beam time
  - The material
  - Specimens
  - Loading stage
  - Load-displacement curves
- SEM micro-structural analyses before/after in-situ SRCT experiment

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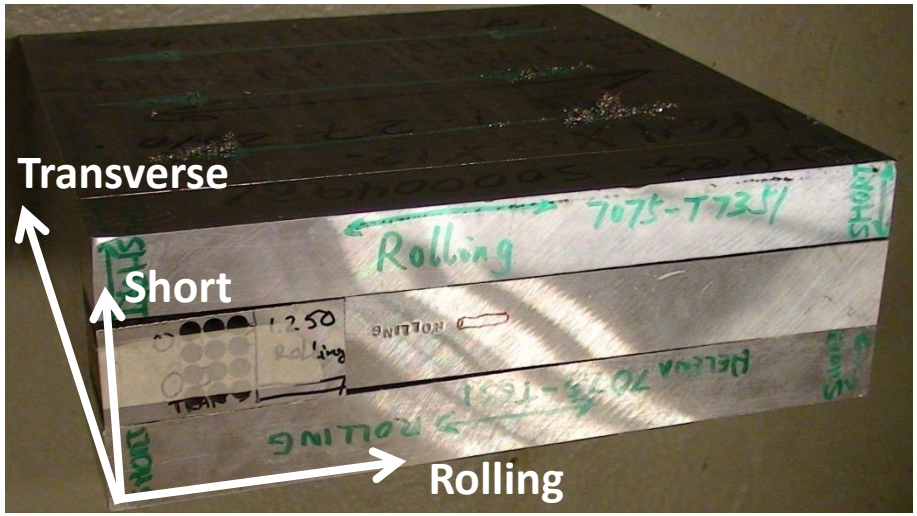
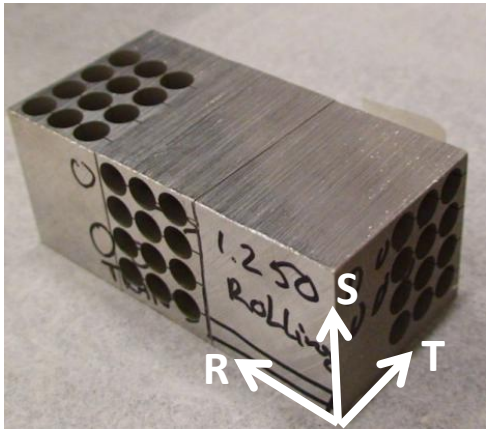
Material of Interest

- Specimens were machined from the center layer of a certified 4” rolled Al 7075-T7351 plate.





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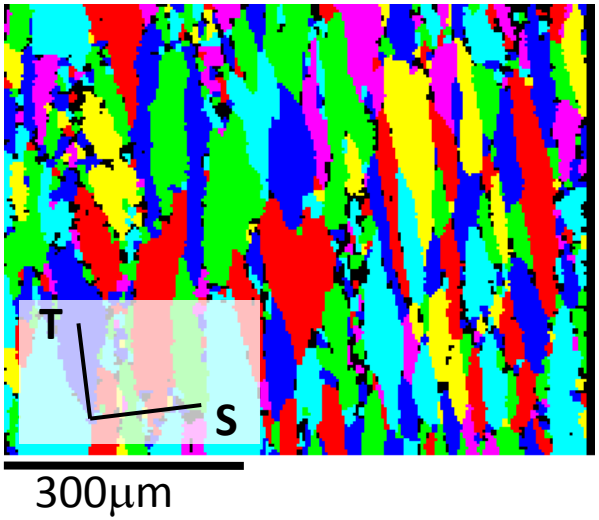
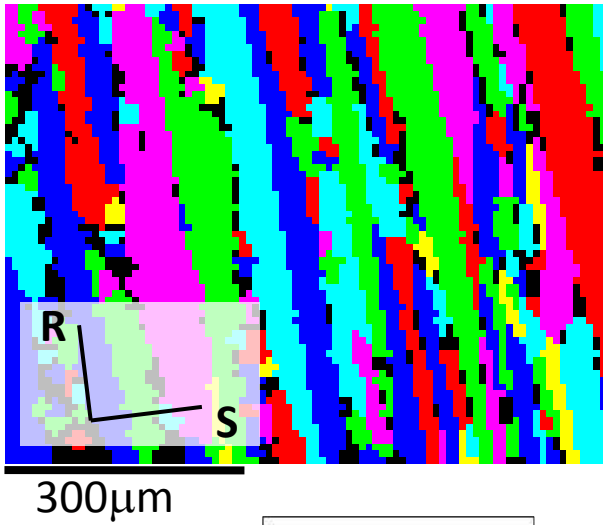
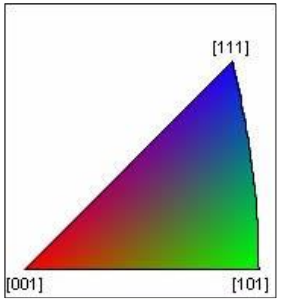
Grain Analysis Using EBSD







- The grain is about
  - 300 um long in R-direction,
  - 100 um in T- direction,
  - 50 um in S-direction
- Grain boundary is defined by 5^{o} angle difference in EBSD

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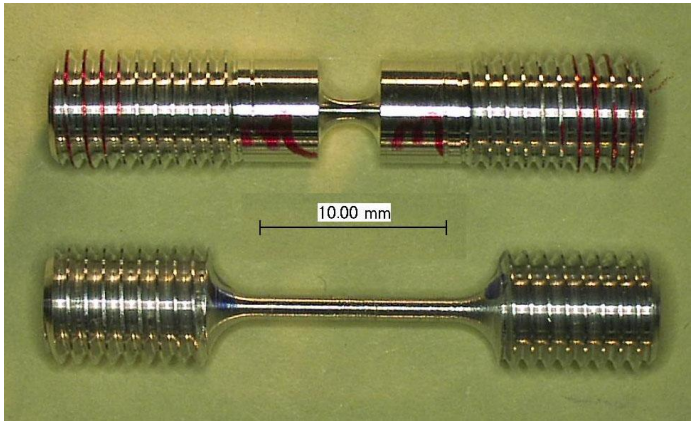
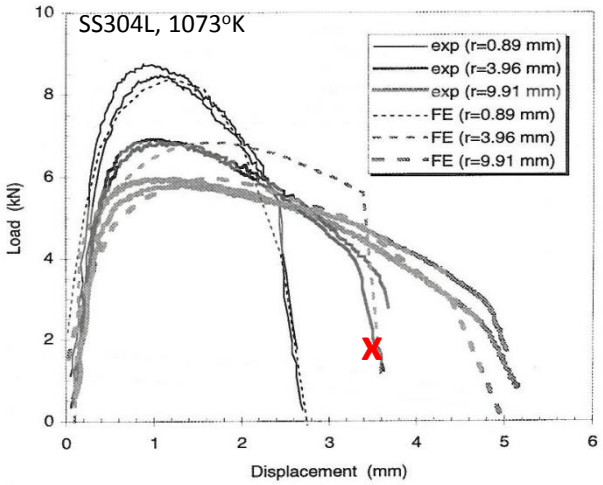
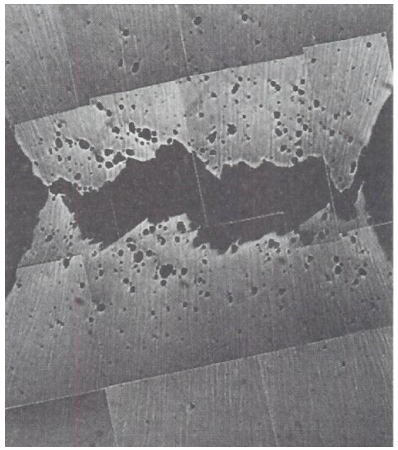
Specimens

- Uniform tension and notched tension with notch width of 3.05 mm (0.120 in)
- Same minimal diameter of 1.5 mm and same overall specimen length
- The geometry of the notch affects the stress triaxiality which is known to promote void growth







Specimen	Loading Orientation		
	R	T	S
Smooth	SR	ST	SS
Notch	NR	NT	NS

Lu WY, et. al., "High Temperature Sensitivity of Notched AISI 304L Stainless Steel Tests," Theoretical and Applied Fracture Mechanics 30 (1998) 139-152

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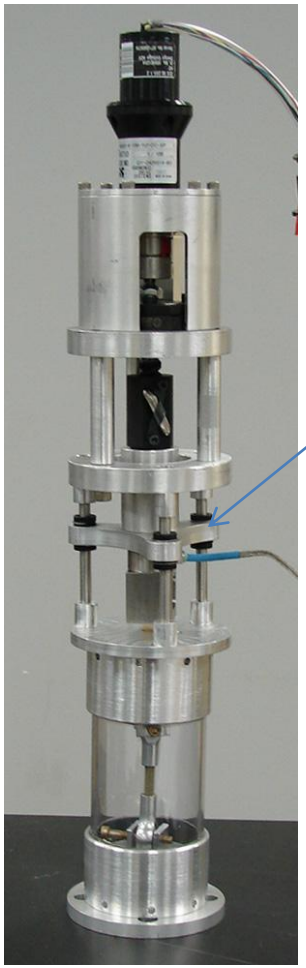
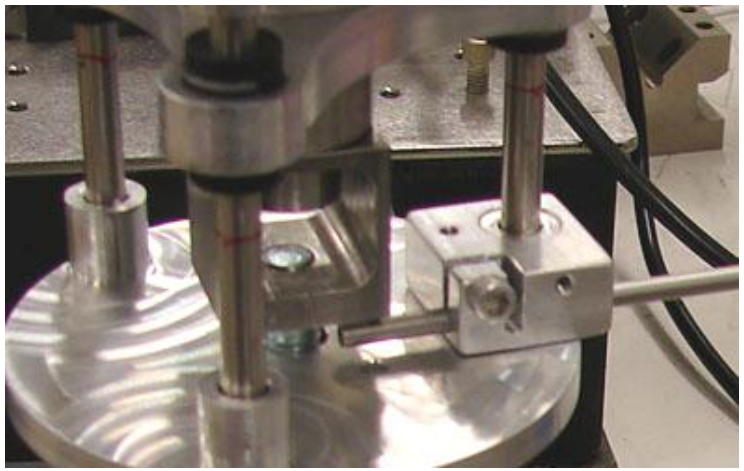
Loading Stage



- Modified beamline 8.3.2 loading stage for tensile loading
  - Step motor open-loop control
  - New fixture design for easy specimen mounting
  - New grips with ball joint for precision alignment
  - New confocal displacement sensor



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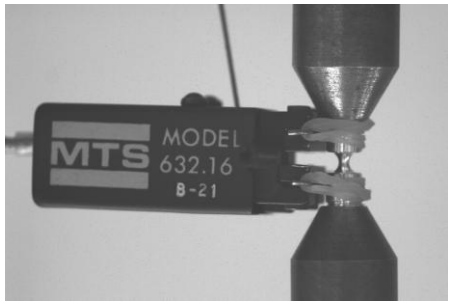
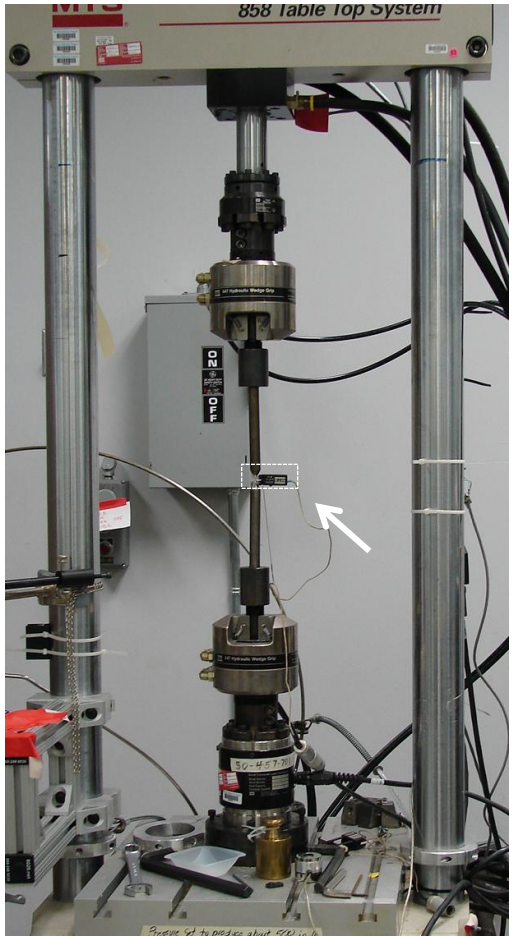
Tension Characterization

- The specimens were characterized offline by using both MTS 858 table top system and the beamline loading stage
  - Collecting CT data at desired strain/damage states during in-situ experiment
- MTS tension
  - Extensometer gage length is 0.3 inch
  - Displacement controlled test
  - Ball joint for precise alignment
- Loading Stage
  - Displacement sensor
  - Compliant frame





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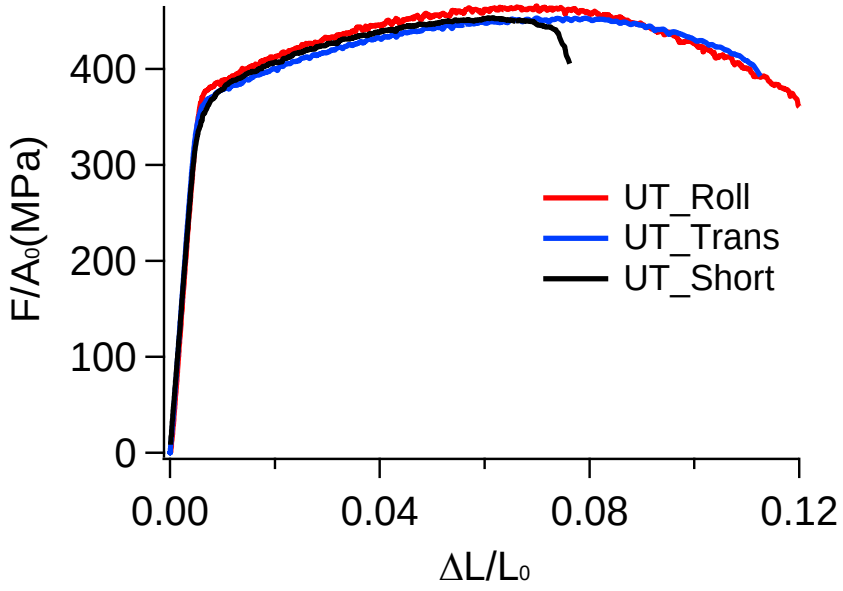
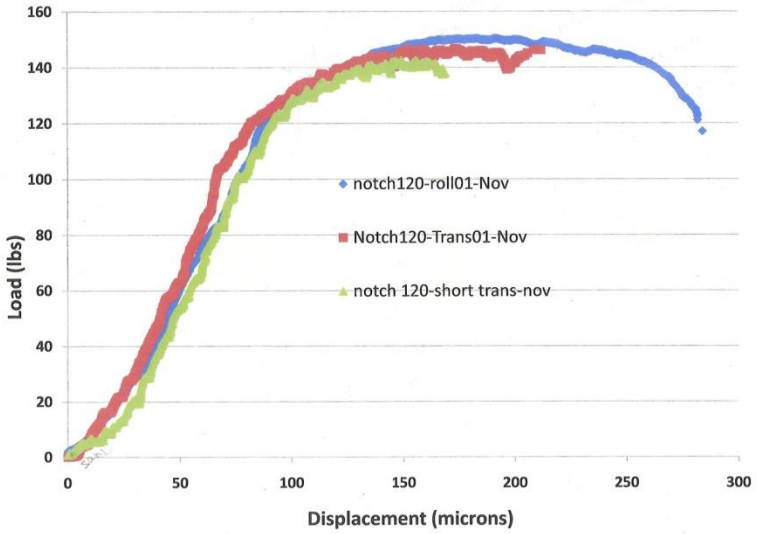
Anisotropy

- Load-displacement curves from MTS testing.
- The yield stress is about the same
- The failure disp./strain is the largest when loading in the rolling direction; the smallest is the short direction.

Uniform specimens



Notched specimens



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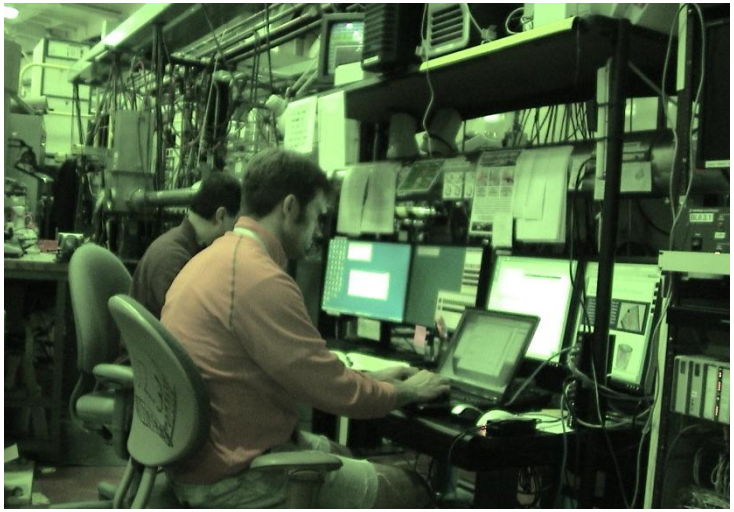
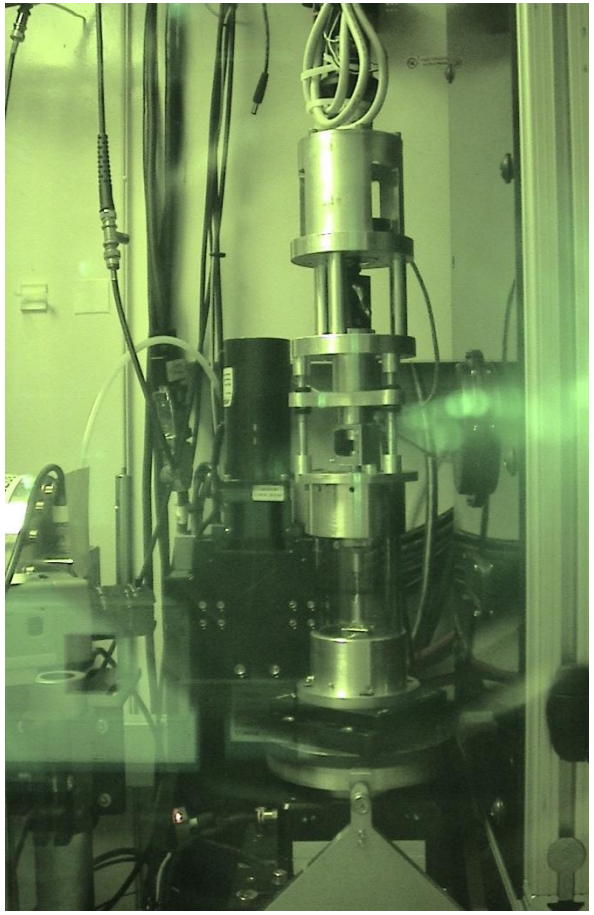
In-Situ SRCT Experiment





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Initial Results

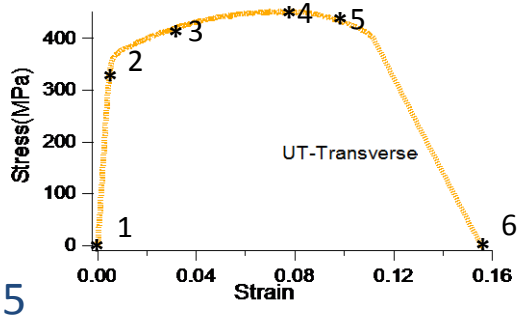
- A very large amount of tomography data
- Reconstruction was done using Octopus software

  (A Mota, H Jin, W-Y Lu, JW Foulk III, GC Johnson, "Quantifying the Debonding of Inclusions Through Tomography and Computational Homology," SAND2010-6446, September 2010)

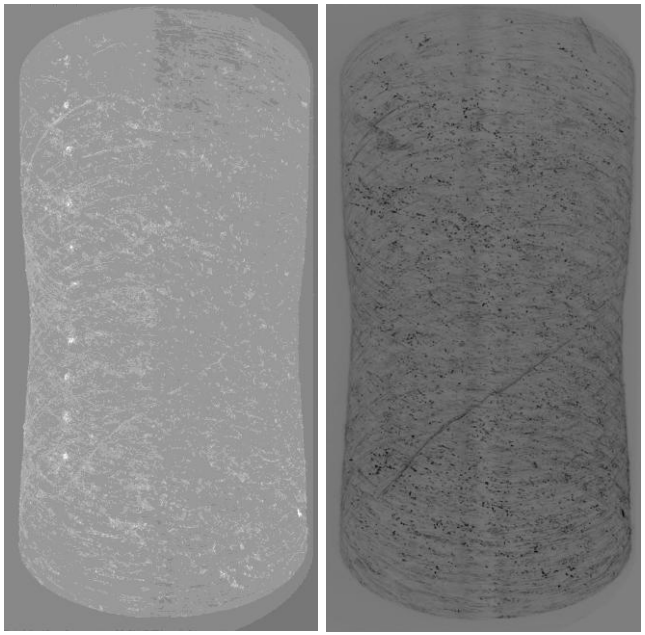
- Data visualization
  - Volume visualization of void/particle
  - Display data of a horizontal slice, perpendicular to the loading direction
  - Display data of a thin vertical section, parallel to the loading direction
- SEM micro-structural analyses

Volume Visualization

Smooth Transverse Specimen



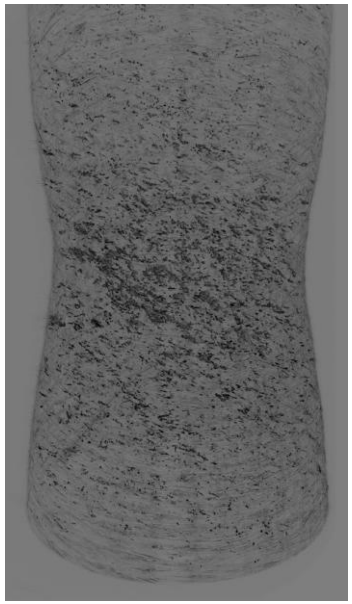
Scan1



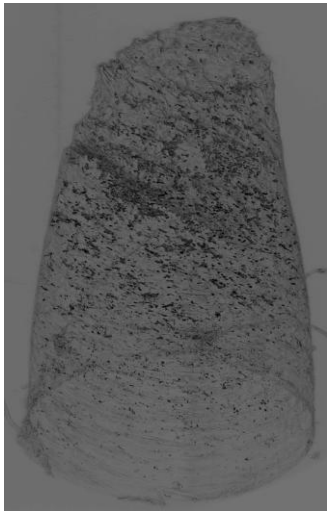
particle void

Scan4

Scan5



Scan6



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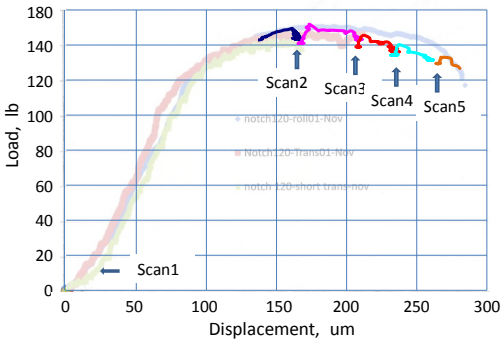
Volume Visualization

NR Specimen



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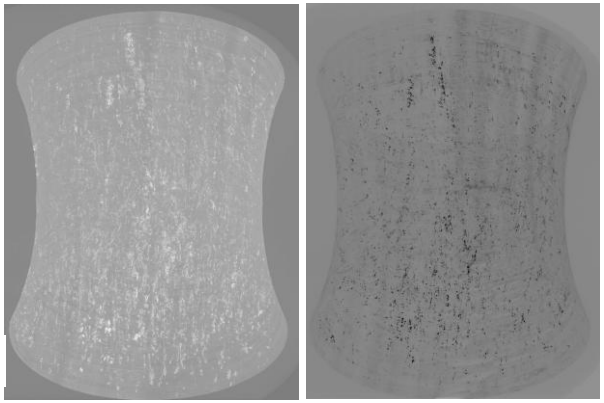

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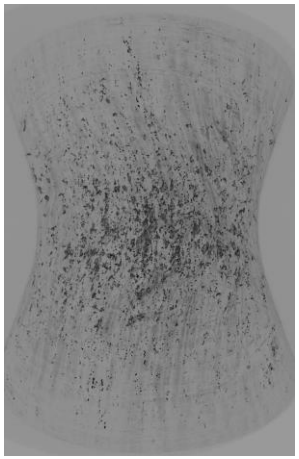

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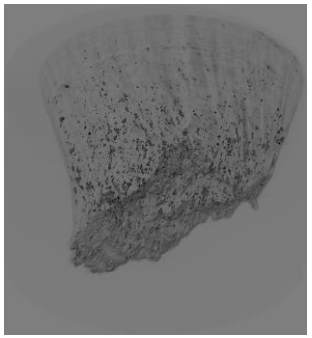
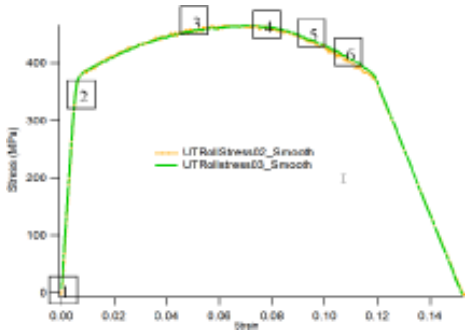


SR Specimen



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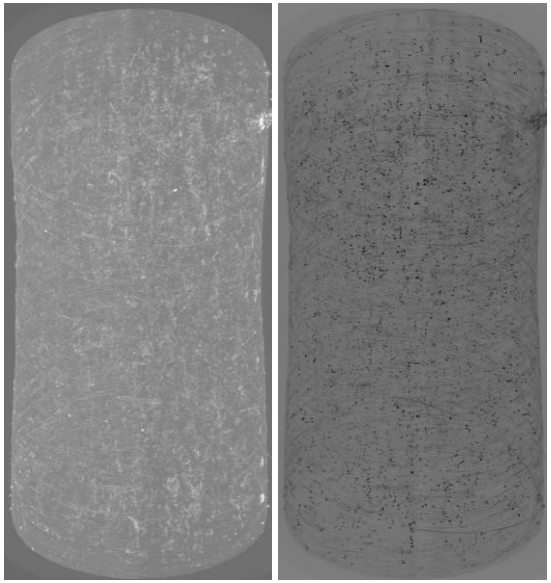

Scan6

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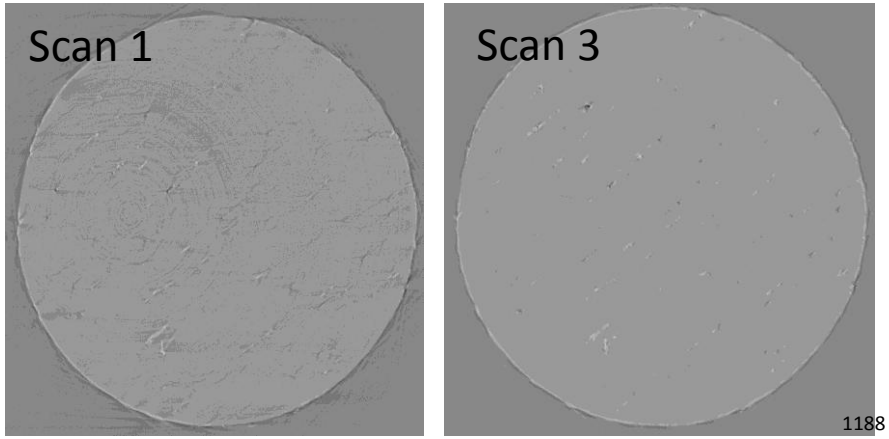
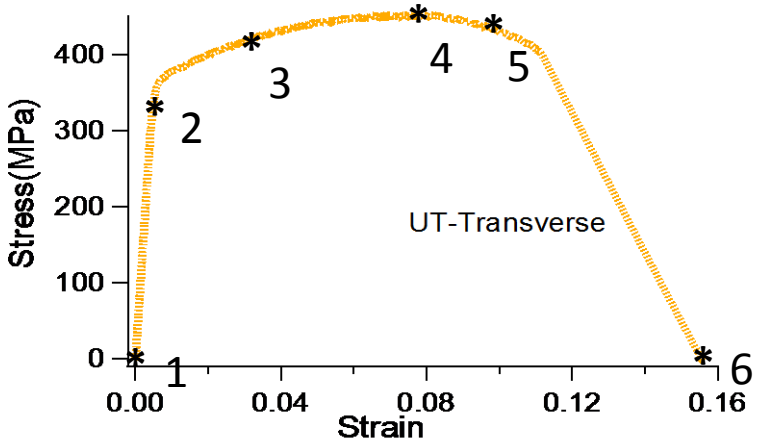
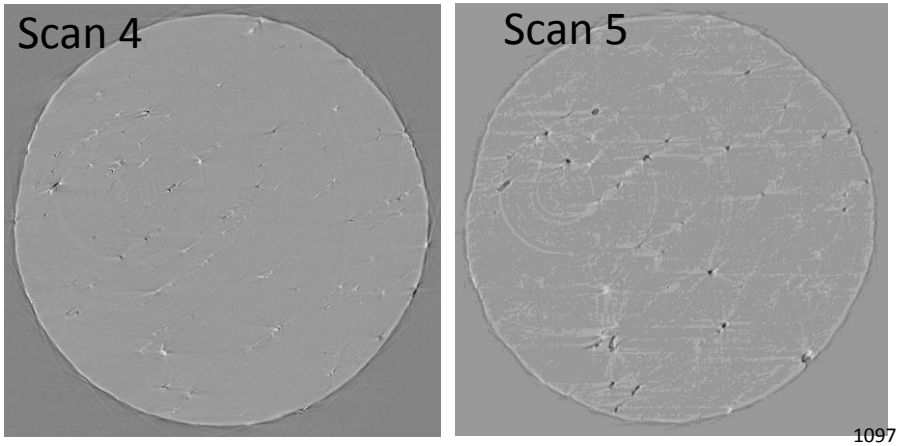
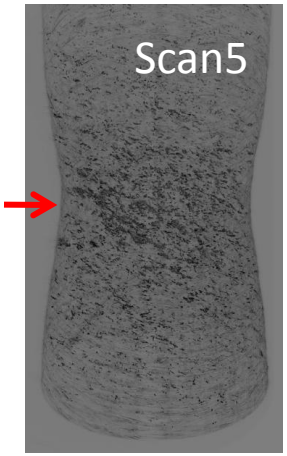
Data of a Horizontal Slice

ST Specimen

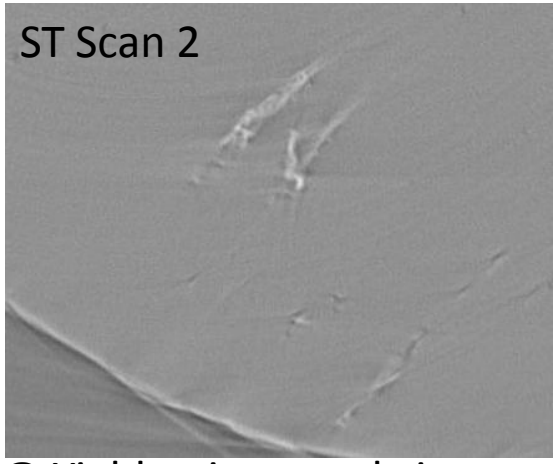




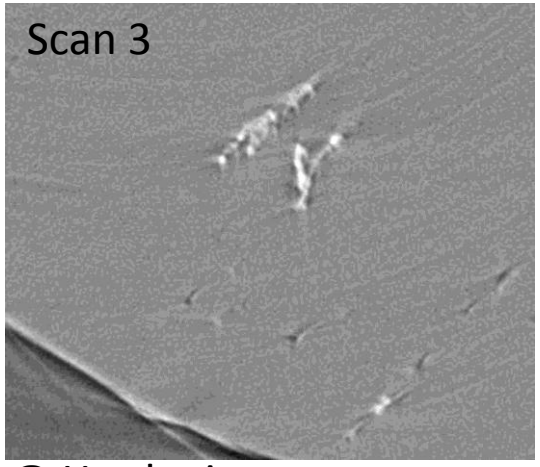




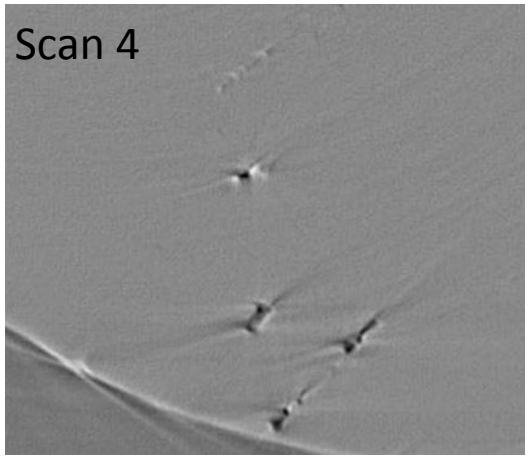
Voids Evolution



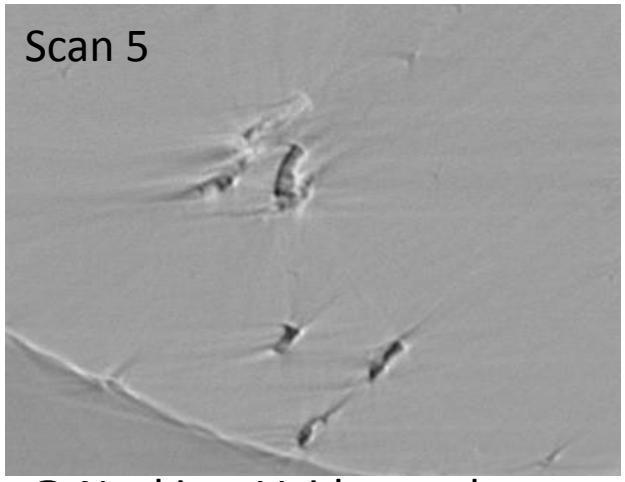
@ Yield point, nearly intact



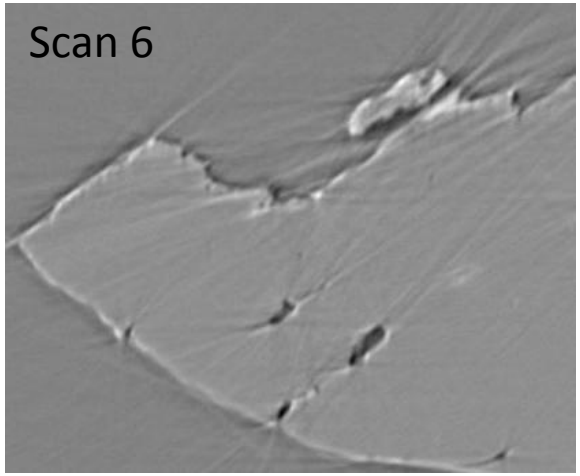
@ Hardening



@ maximum stress

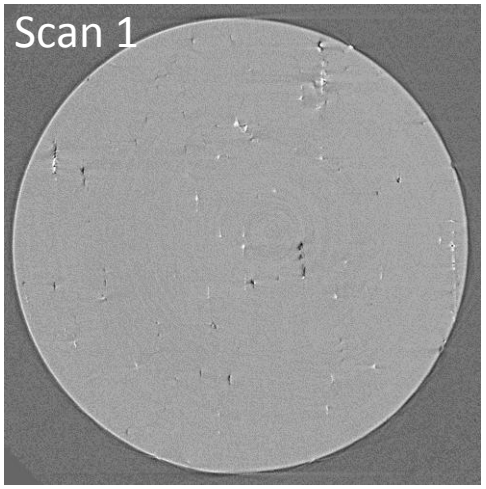


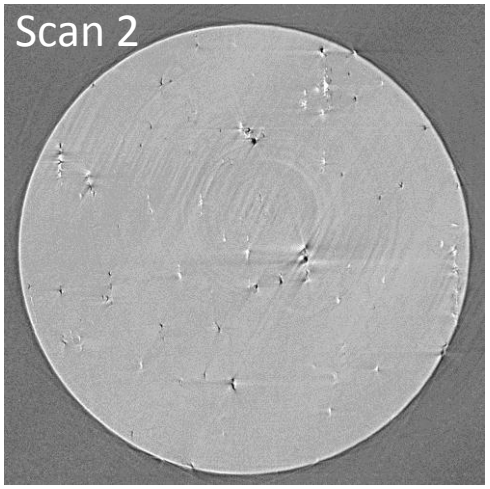
@ Necking, Void growth

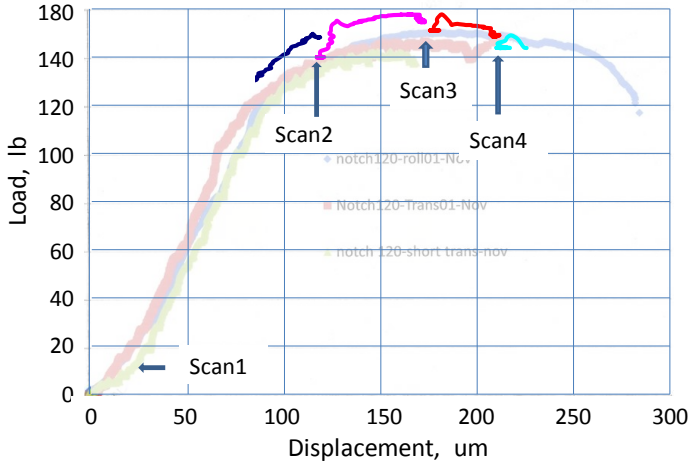


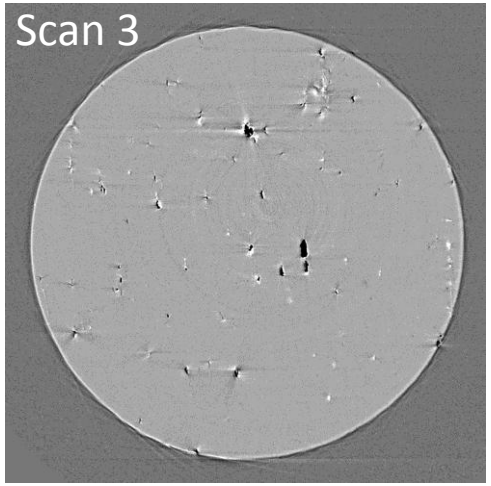
Coalescence and rupture

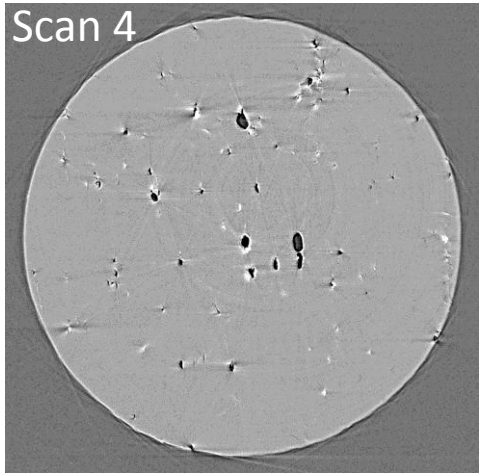
NT Specimen











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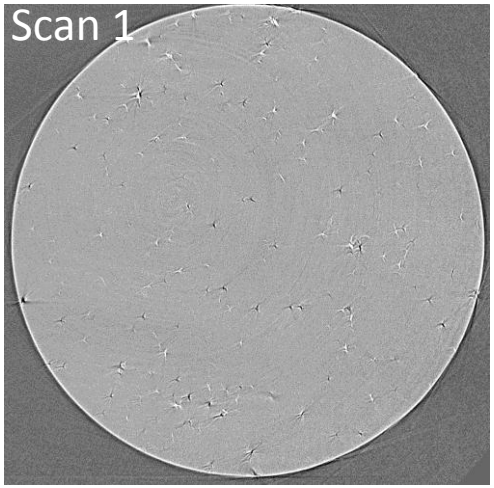
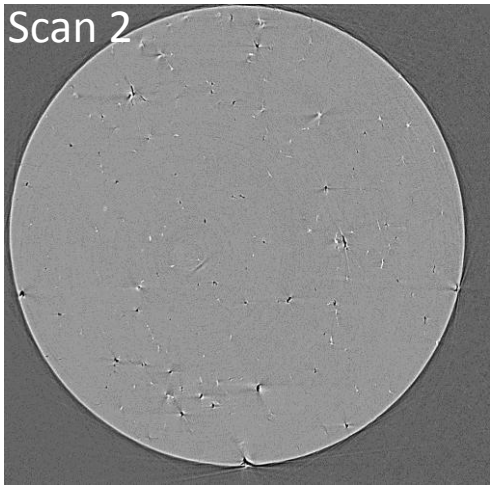
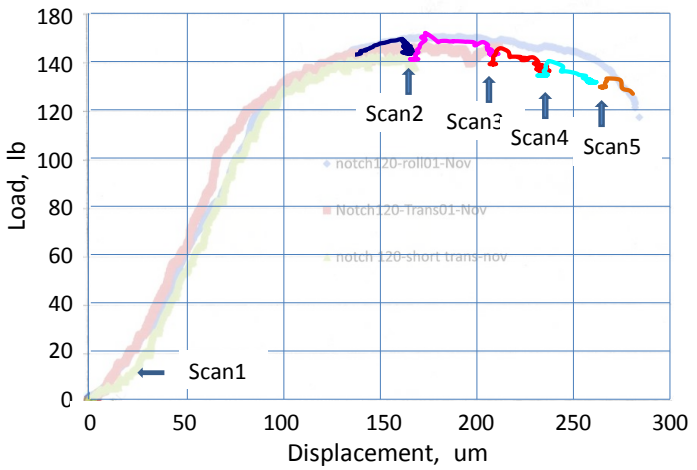
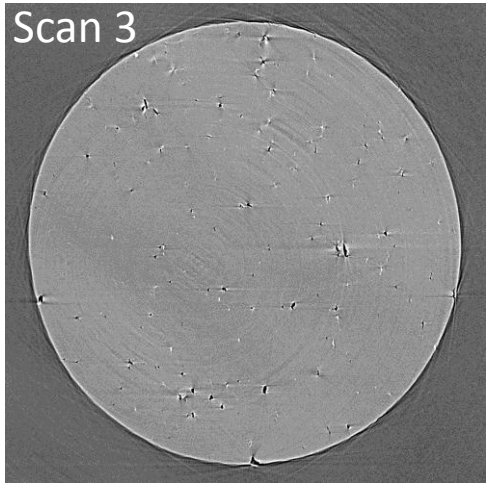
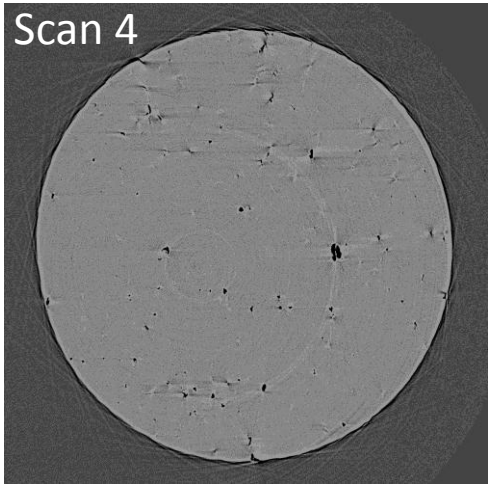
NR Specimen

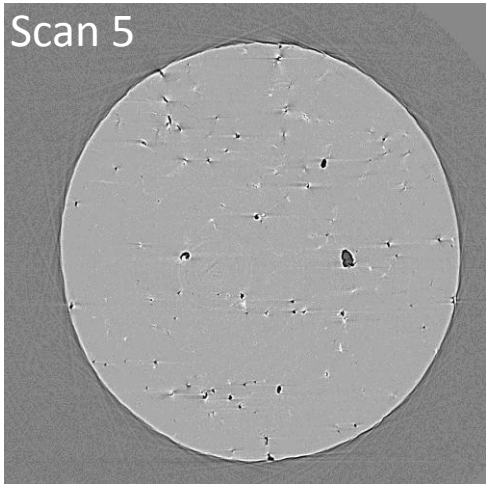












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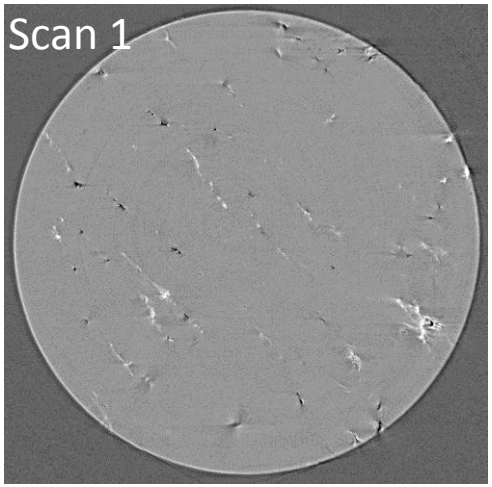
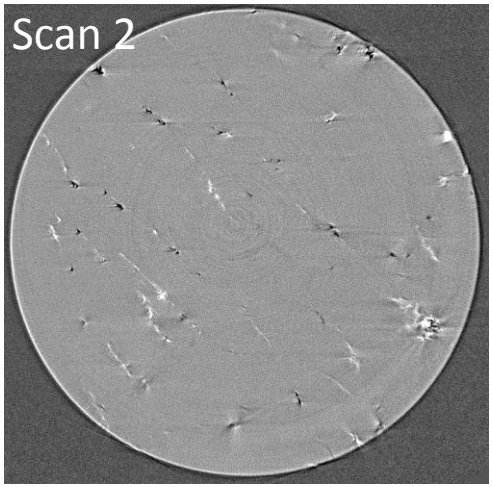
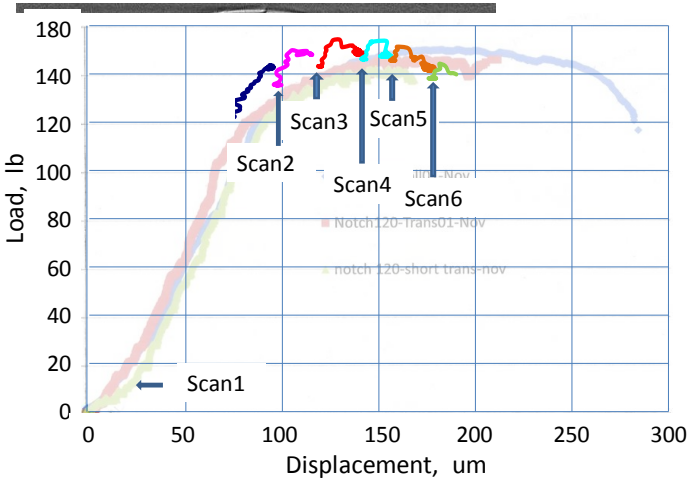
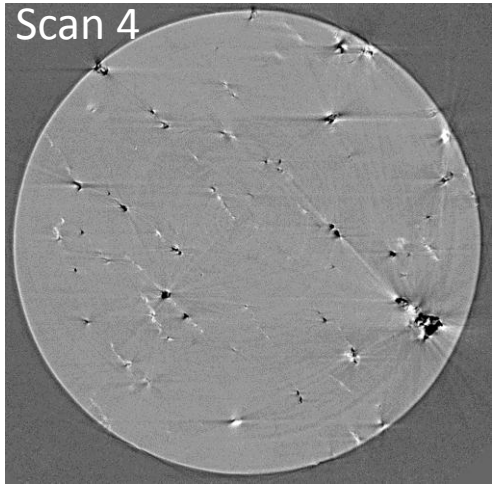
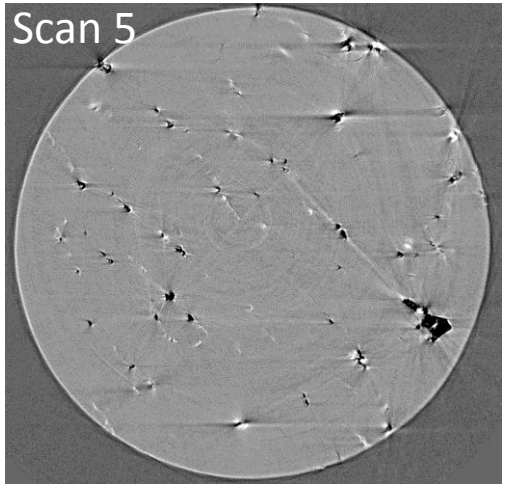
NS Specimen

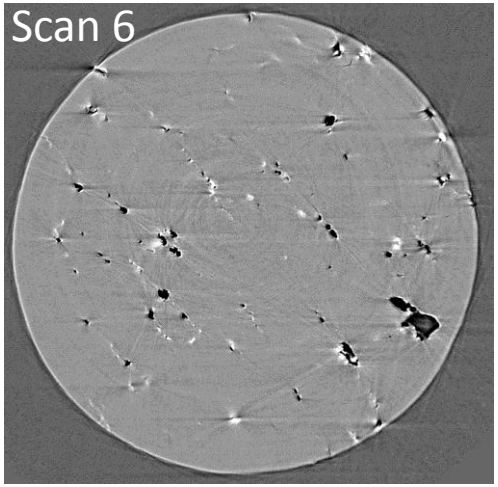












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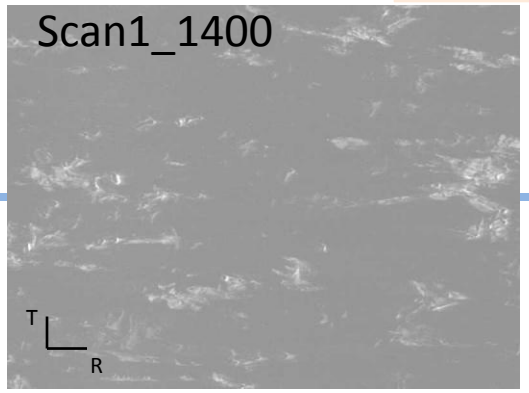
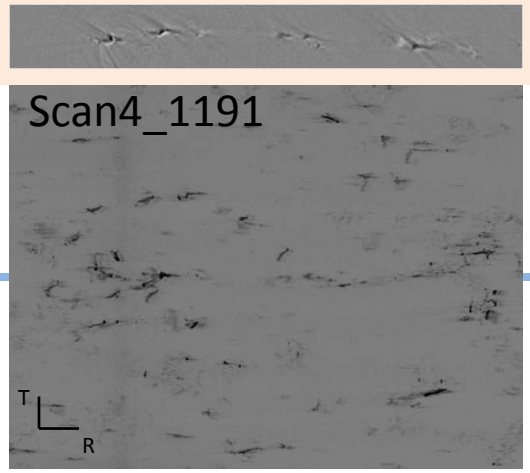
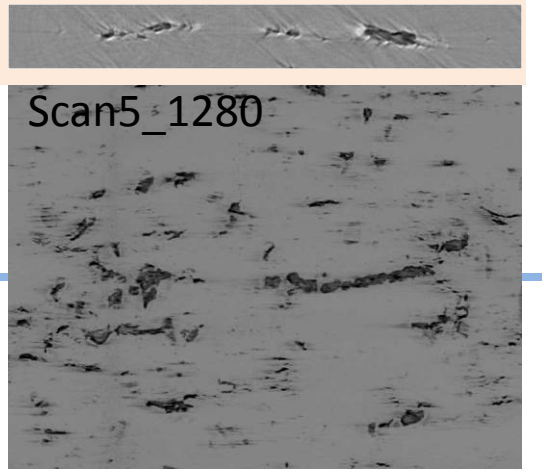
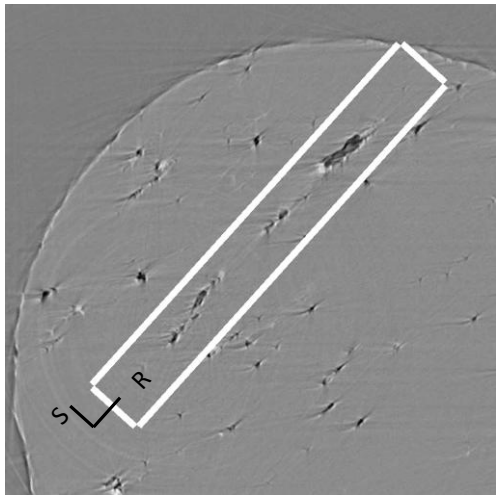
Data of a Thin Vertical Section

ST Specimen









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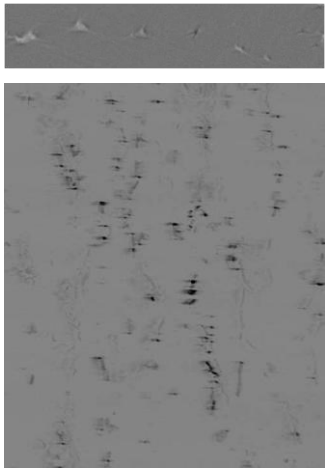
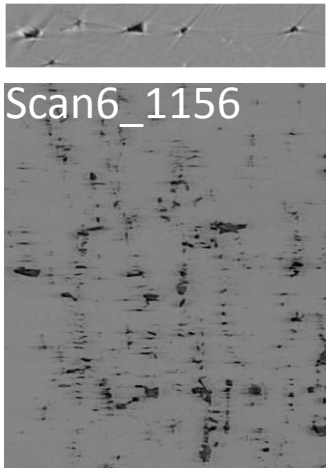
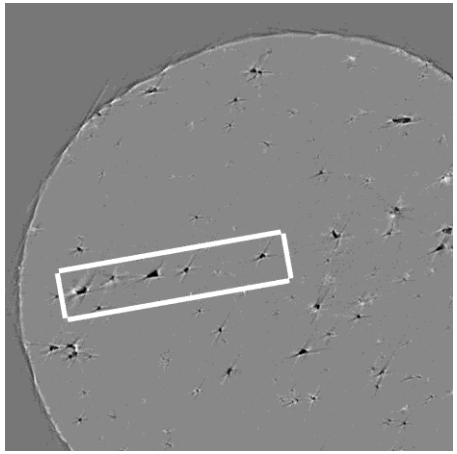
Voids Evolution

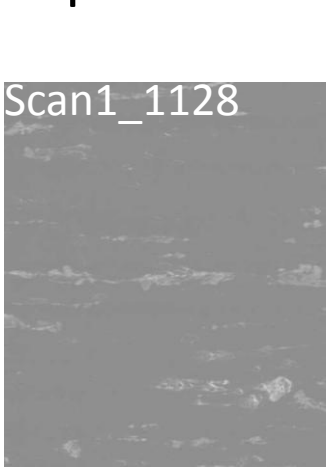
SR Specimen

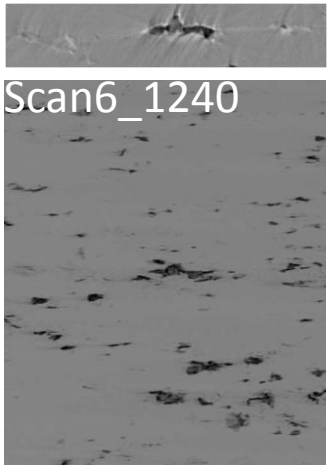


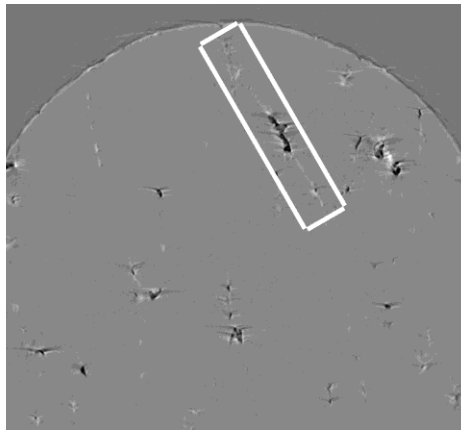




SS Specimen







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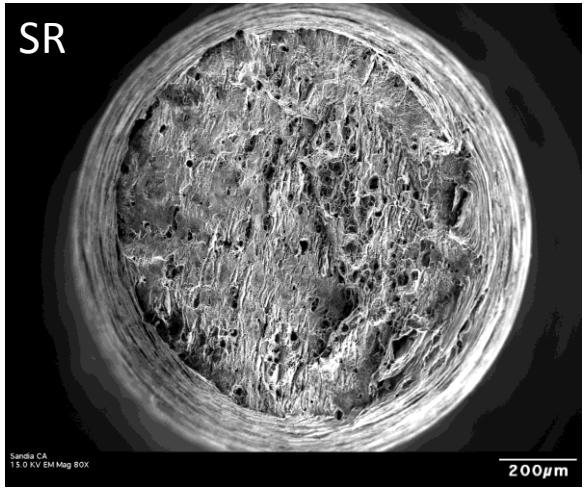
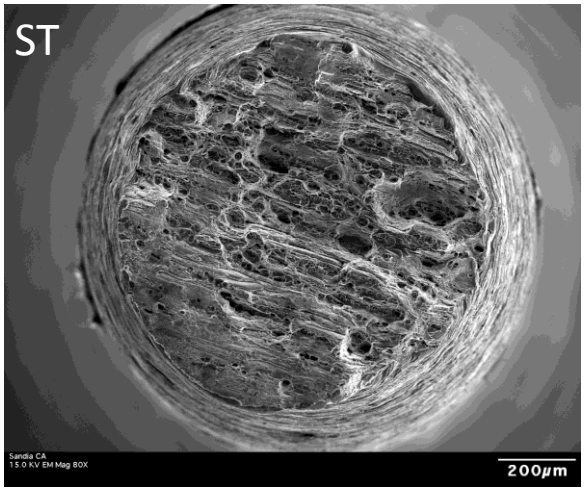
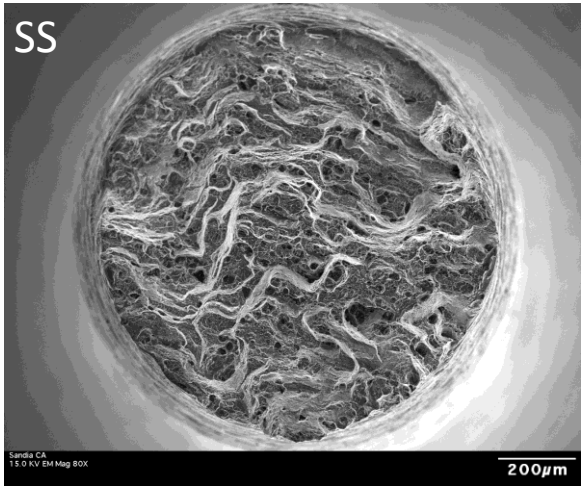
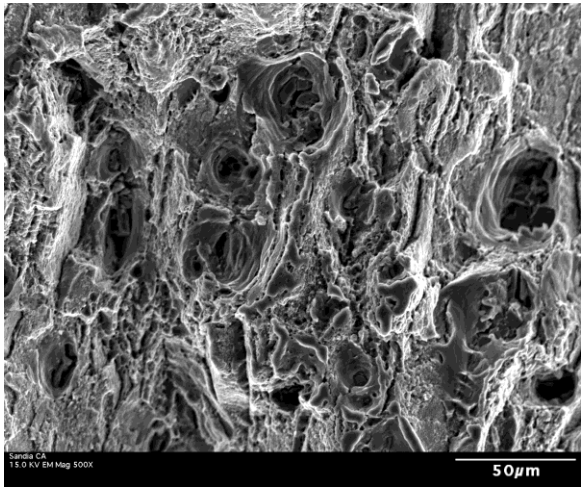
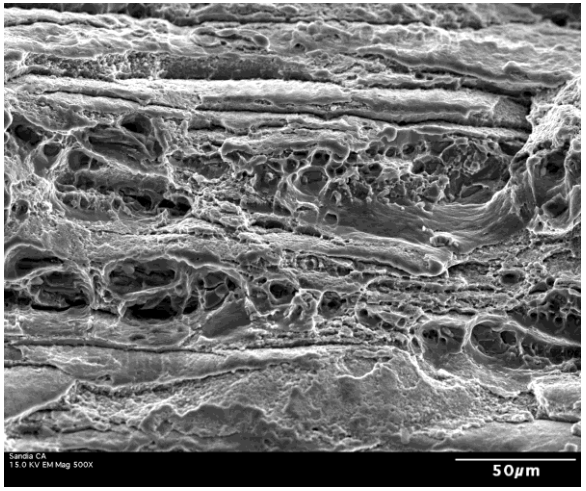
Failure Surfaces

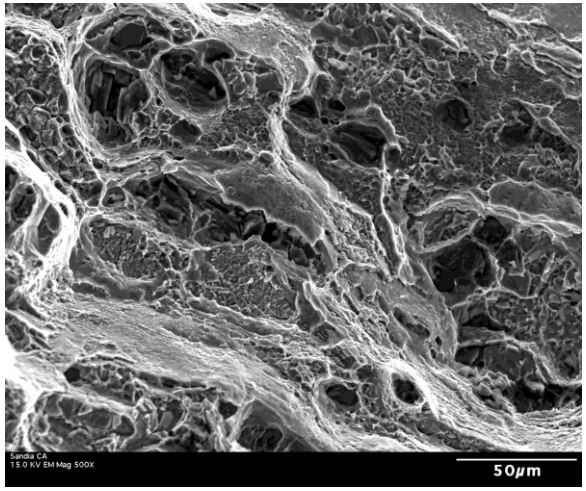












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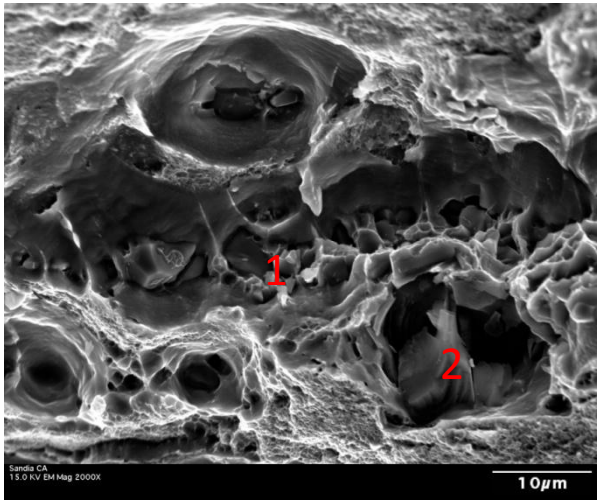
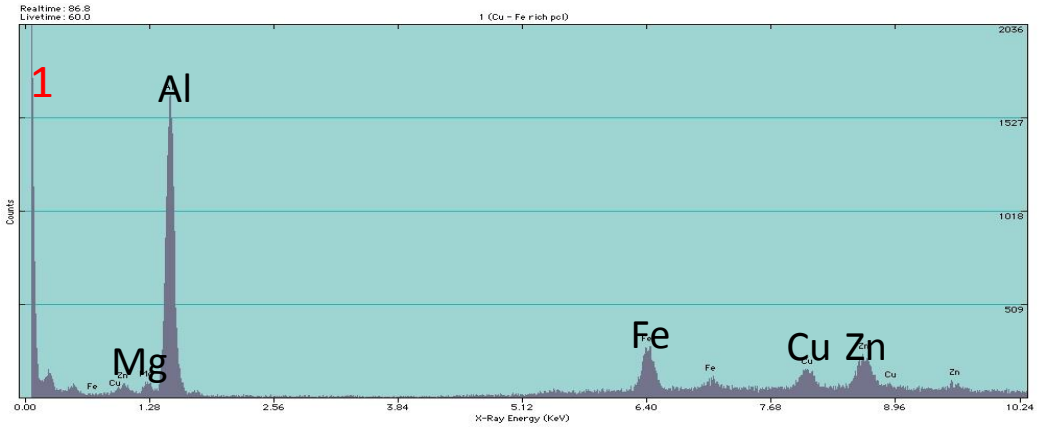
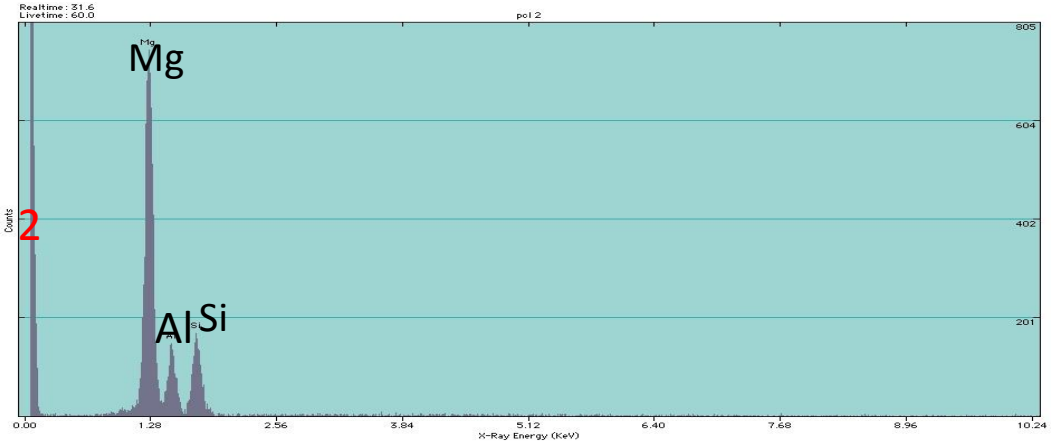
Second Phase Particles







- Both Iron-rich and Magnesium-rich second phase particle were identified
- Voids were initiated at the locations of the second phase particle

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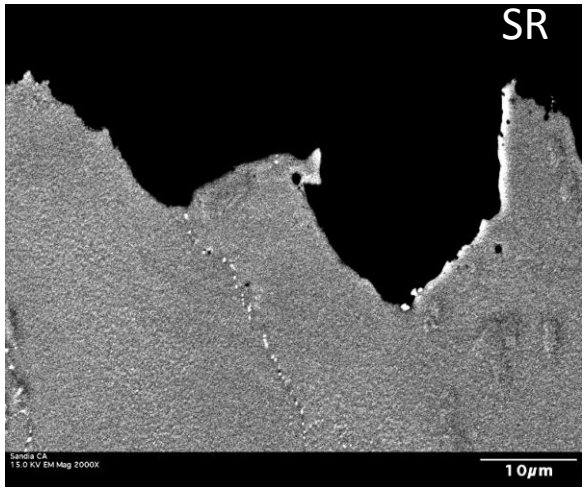
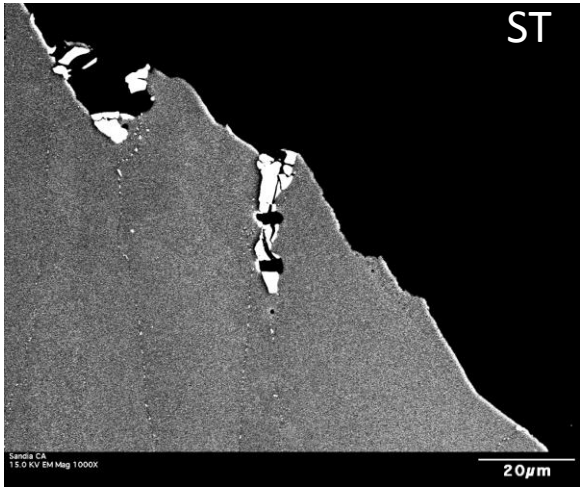
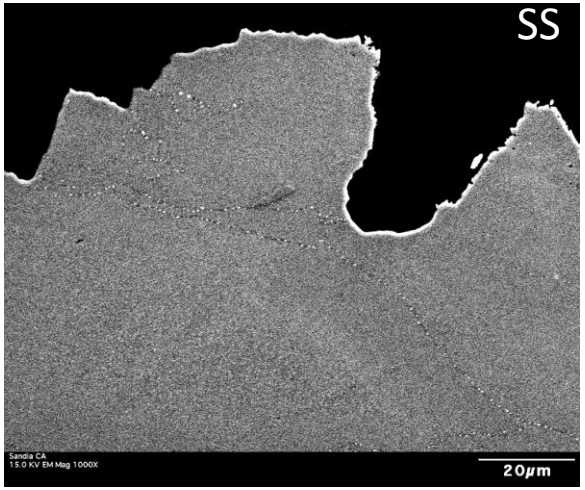
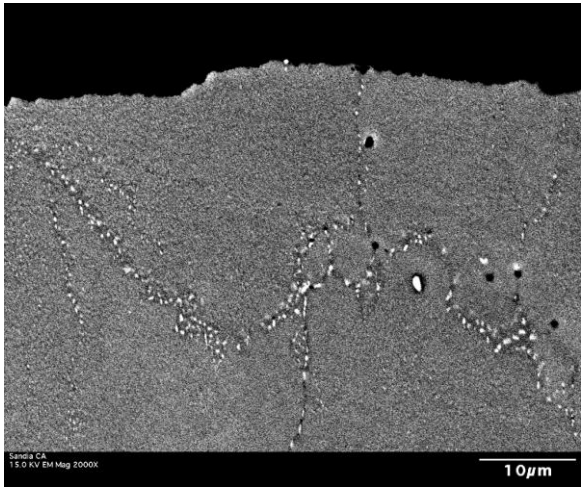
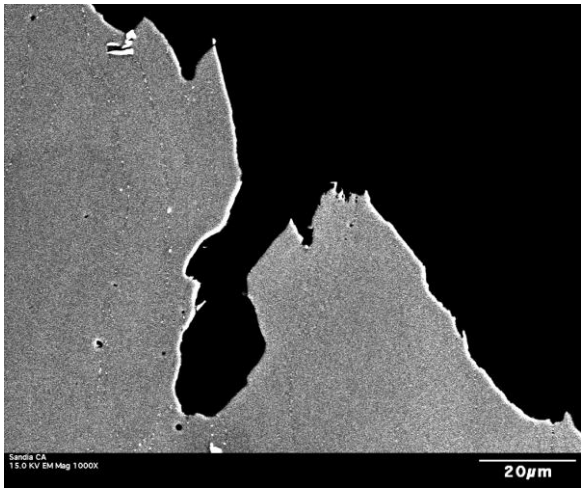
Failure Modes

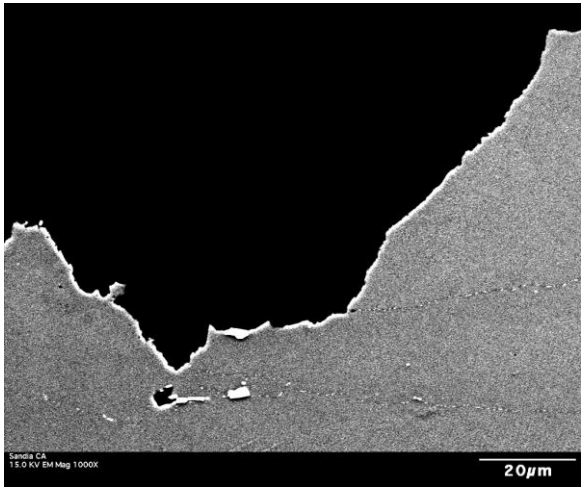












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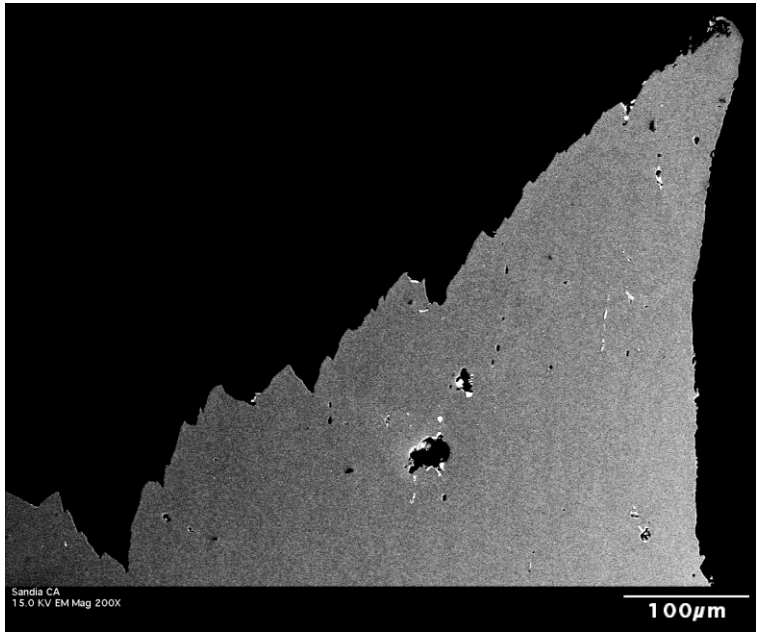
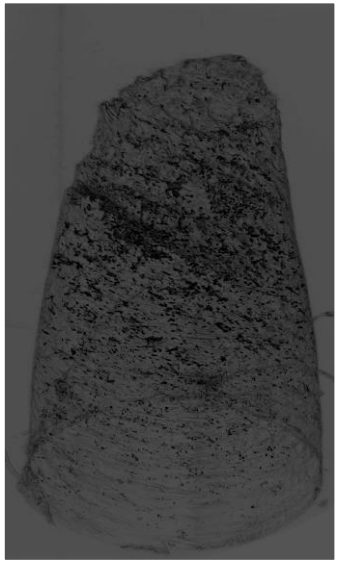
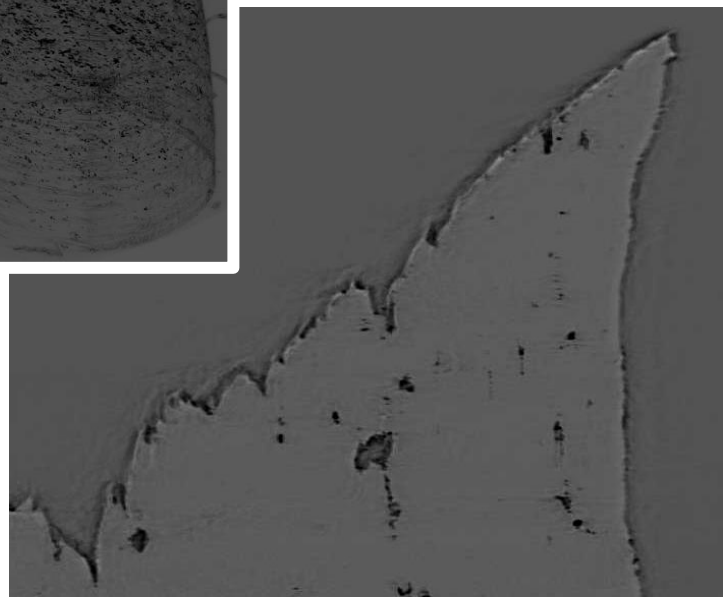
SEM vs SRCT







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Summary

- SRCT data were obtained for a few specimens of 7075-T7351 aluminum stretched to failure, loaded in principal material directions
- The resolution of SRCT data is 900nm, which allows elucidation of the mechanisms governing void growth and coalescence. The resolution may be not fine enough for nucleation.
- The constituent particles tend to align with the rolling direction in the form of stringers
- The voids and anisotropic failure are closely associated with these strings of particles
- Quantitative analyses in progress

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

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