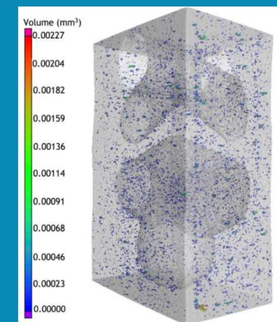
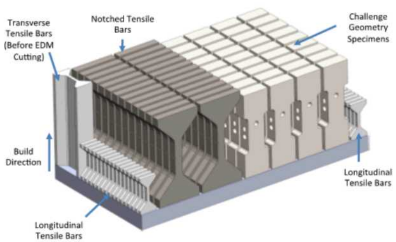
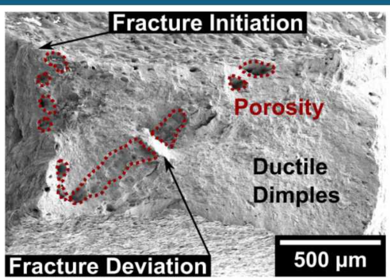
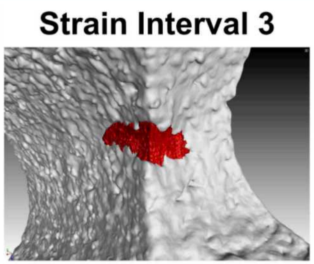
SAND2019-5980C

Experimental Reinvestigation of the Third Sandia Fracture Challenge: Evolution of Damage and Failure in an AM 316L SS Structure









Sharlotte Kramer, Thomas Ivanoff, Andrew Lentfer, and Jonathan Madison

Sandia National Laboratories

SEM Conference

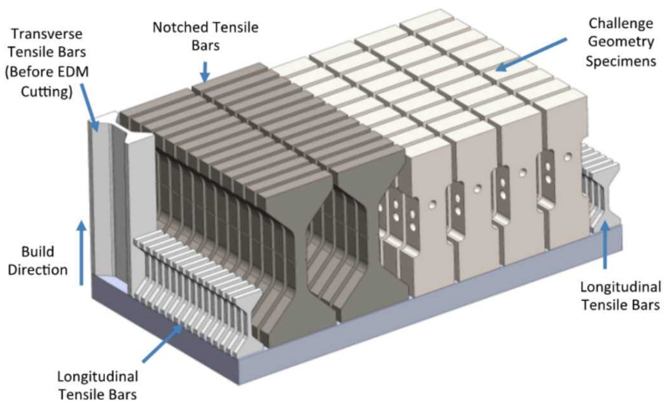
05 June 2019

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

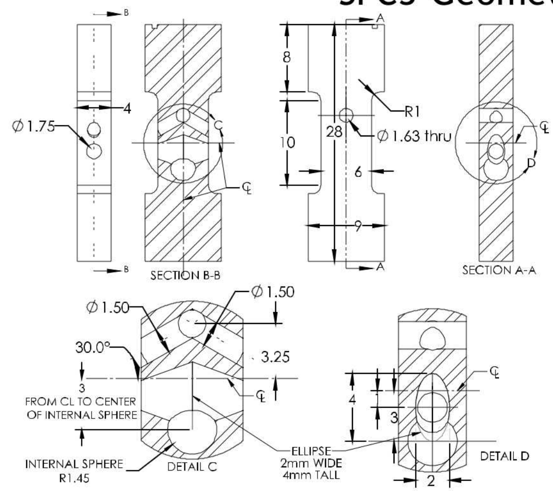
Motivation: Understanding Failure in AM Metal Structures and The Third Sandia Fracture Challenge

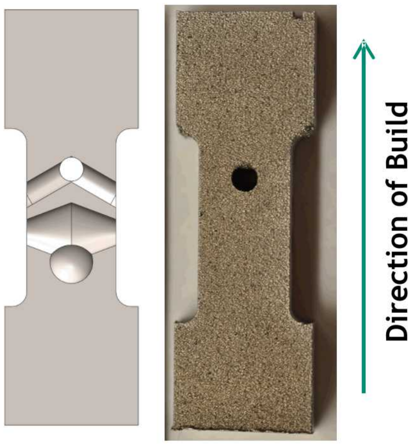
The Third Sandia Fracture Challenge explores the experiments and model methods required to predict ductile failure in AM metal parts.

AM 316L SS Build Plate:
Laser Powder Bed Fusion

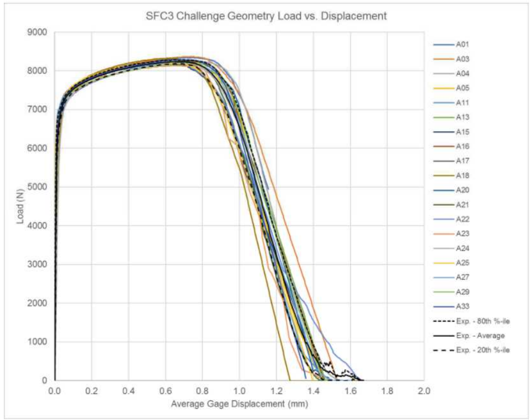


SFC3-Geometry Specimens

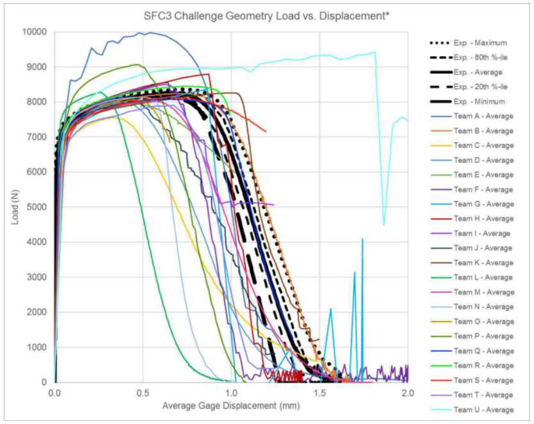




Load-Displacement Response of SFC3-Geometry Specimens



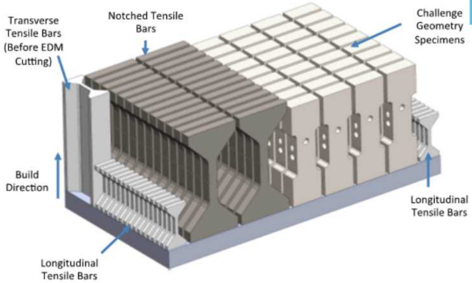
21 Nominal Predictions with Exp. Average and Bounds



Most predictions did not consider the AM porosity, but yet did reasonably well in predicting the global response. This implies that geometry, not porosity, dominates global behavior.

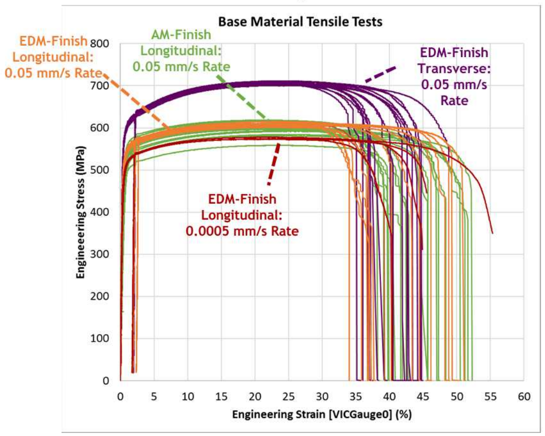
Motivation: Understanding Failure in AM Metal Structures and The Third Sandia Fracture Challenge

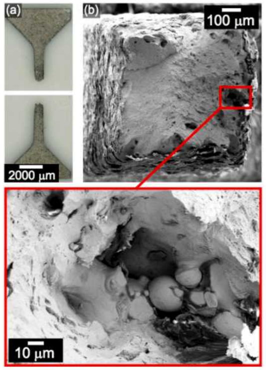
Question: What is the effect of pre-existing voids on deformation, damage, and failure in AM metallic structures like the SFC3-geometry specimens?



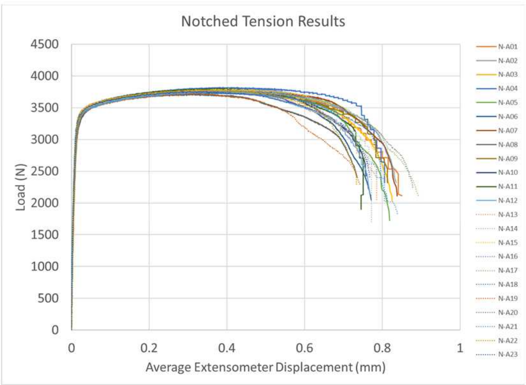
AM 316L SS Build Plate

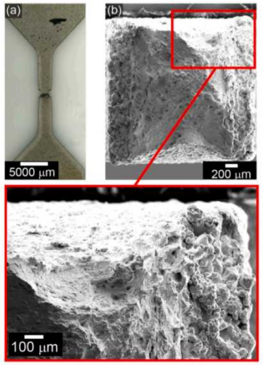
Tensile Specimens



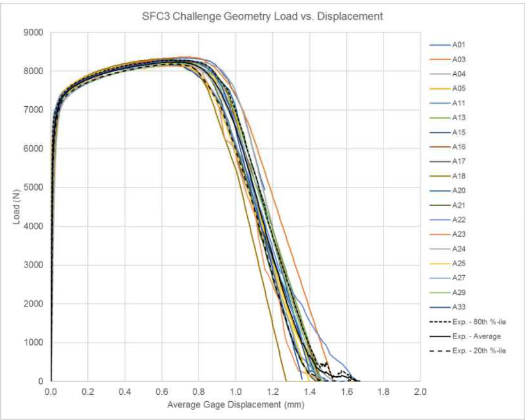


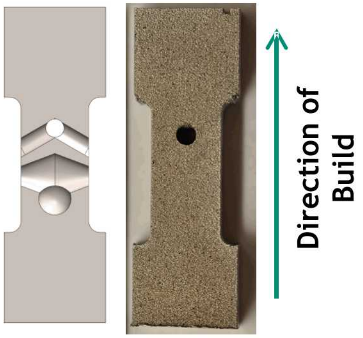
Notched Tensile Specimens





SFC3-Geometry Specimens



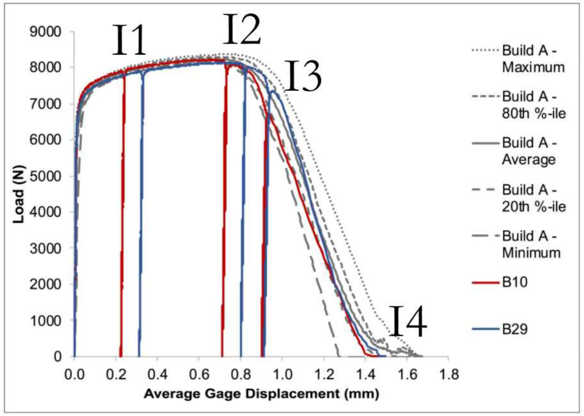


We will look at the global behavior and local crack initiation and growth relative to pre-test void population and the evolution of void growth and crack evolution.

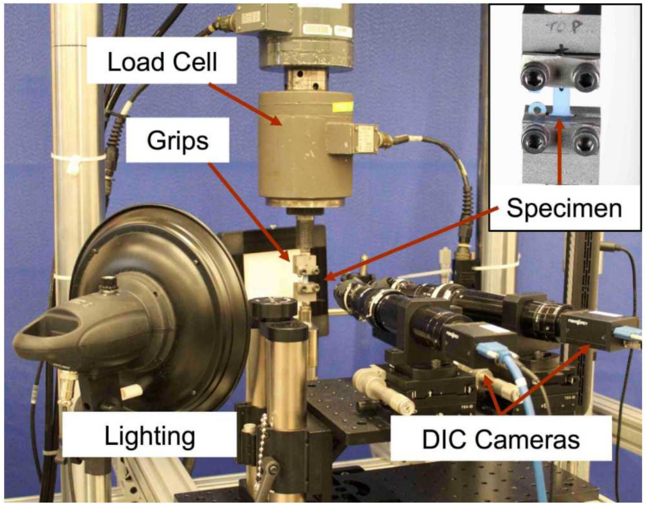
Experimental Approach: Interrupted Testing with Micro-CT

- Tested 6 “Build B” specimens to failure to see overlap with original “Build A” specimens
- Interrupted test intervals for six specimens:
  - I1 – To middle of hardening
  - I2 – Peak load
  - I3 – Visible crack
  - I4 - Failure
- All interrupted test specimens had the same failure mode as tests to complete failure

Interrupted Response

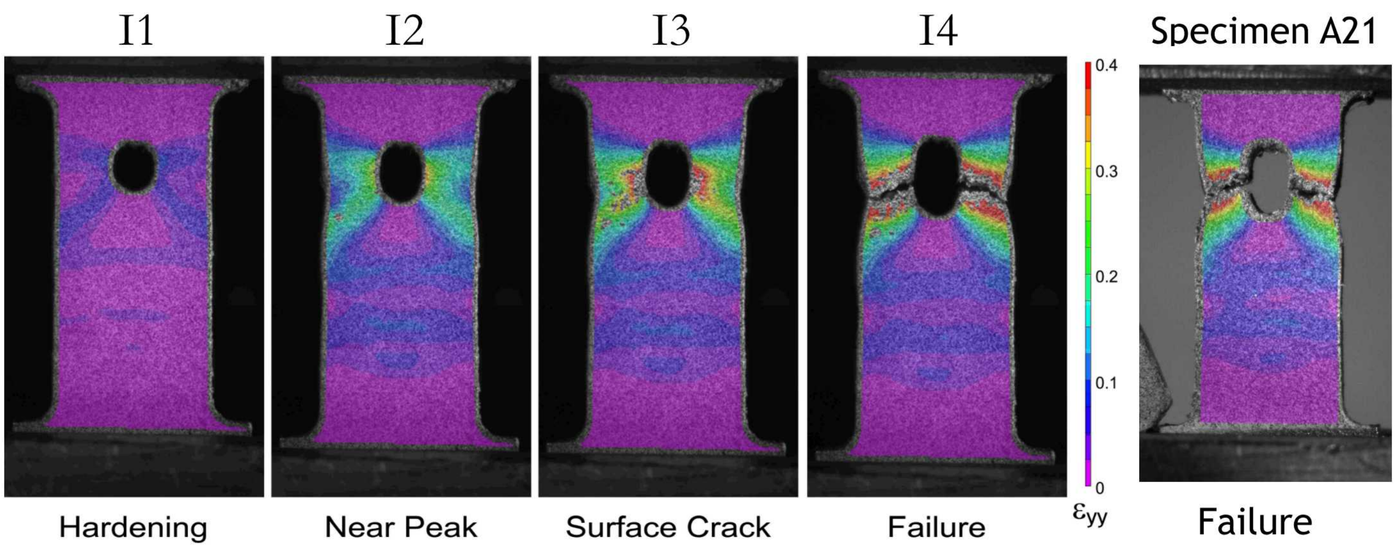


MTS 100-kN load frame with custom AM grips and Correlated Solutions Stereo DIC system (VIC3D)



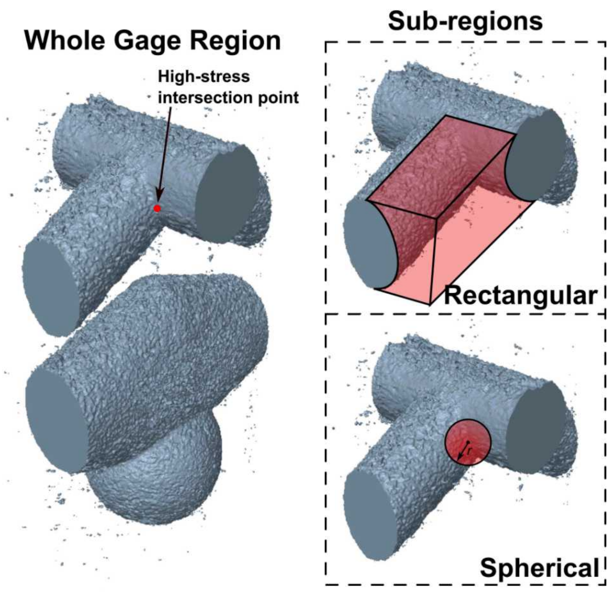
Hencky Tensile Strain Fields for B28

Subset Size (pix)	41
Step Size (pix)	8
Strain Window (pix)	9
Virtual Strain Gage (pix)	65
Virtual Strain Gage (mm)	0.517
Pixel to Length Ratio (pix/mm)	125.8



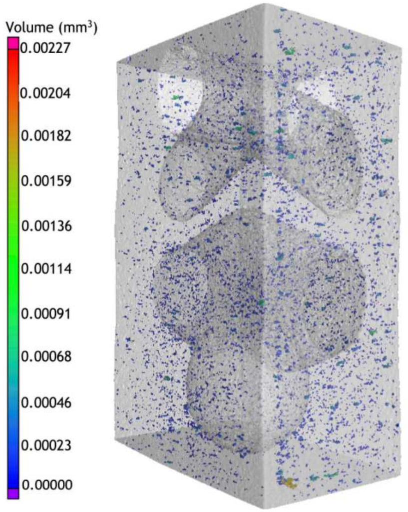
Micro-CT and Void Analysis Methods

- X-Ray Worx 225kV tubehead with a Varian cesium iodide 2520DX detector using North Star Imaging software
- **Voxel resolution of 6.2+/-0.6 µm**
- 16-bit tiff images reconstructed with Volume Graphics 3.2 Max software
- Image processing in FIJI and MATLAB
- Void analysis performed using IDL software with a requirement of **at least 8-connected voxels to count as a void with a minimum Equivalent Spherical Diameter (ESD) of 13-9-16.9 µm**

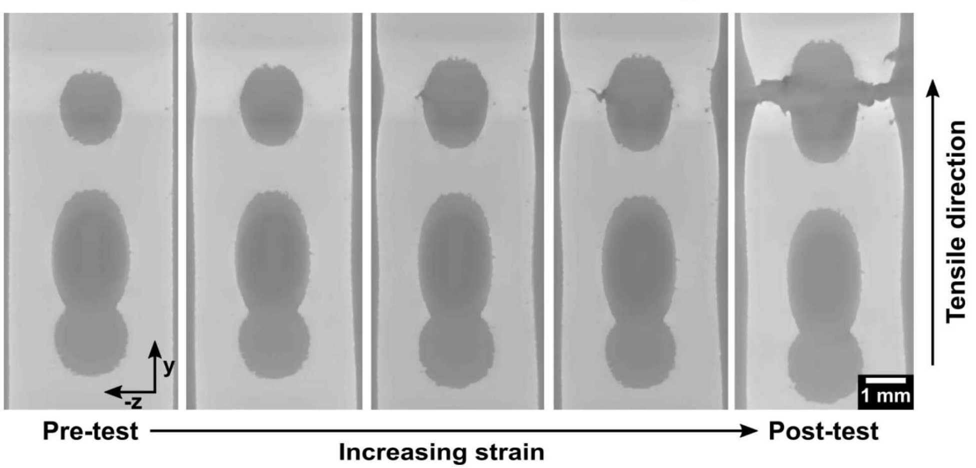


Isolation of voids with high-stress intersection point identified and different volumes for pre-test void analysis

Pre-test data showing voids



Ex situ micro-CT internal slices for Specimen B33



I0 I1 I2 I3 I4

Mechanical Response

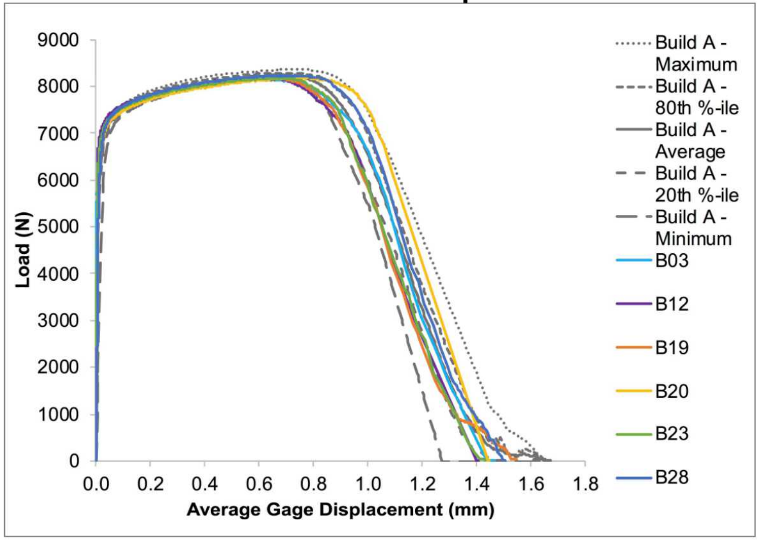
SFC3-Geometry specimens from "Build B" behaved similarly to those from "Build A", so analysis of "Build B" specimens is assumed represent that of all SFC3 specimens.

Global measures considered:

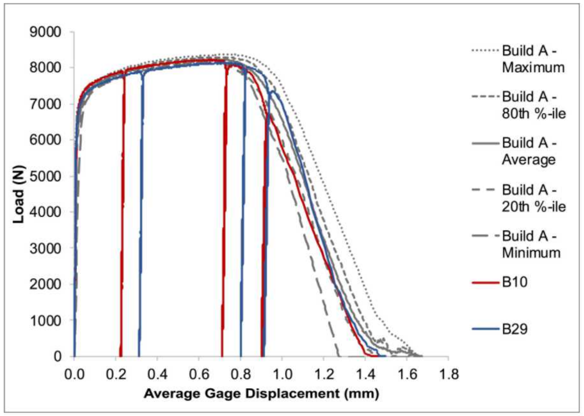
- Peak load
- Displacement at peak load
- Displacement at failure
- Maximum unloading rate

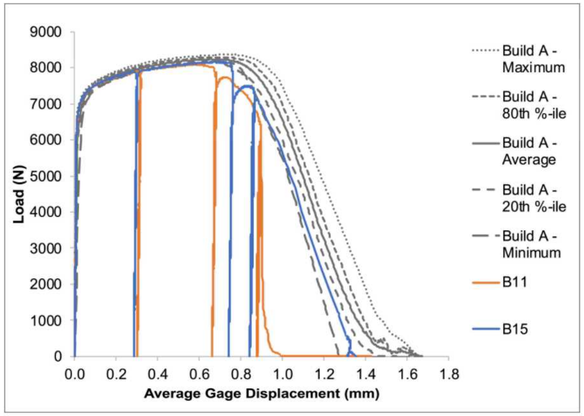
All measures for monotonic and interrupted "Build B" specimens were similar to that of the monotonic "Build A" specimens.

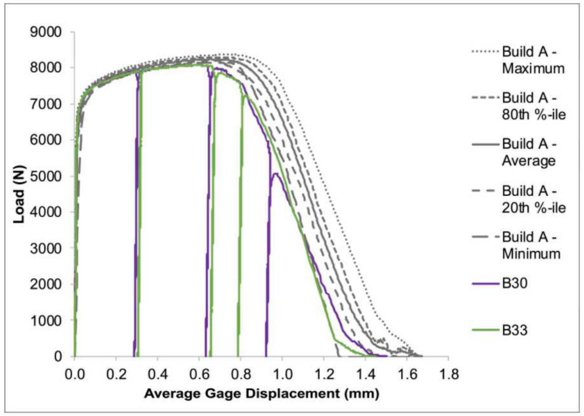
Monotonic Response



Interrupted Response







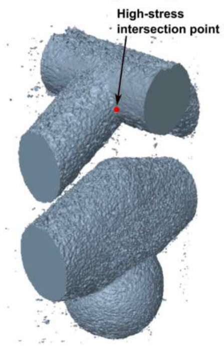
Influence of Aggregate Void Metrics on Mechanical Response

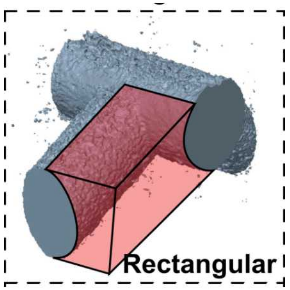
Original Hypothesis:
Metrics of aggregate pre-test void population will correspond to mechanical behavior

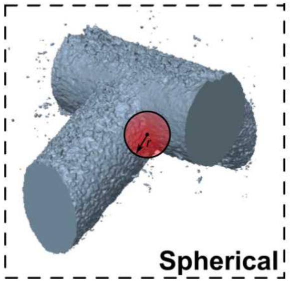
Finding:
Metrics of pre-test void population do not strongly correspond to variations seen in mechanical performance

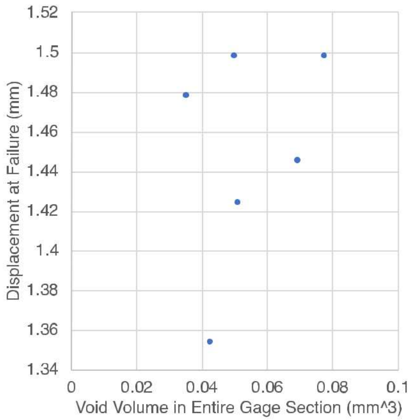
Example: Displacement to Failure Versus Void Volume Over Different Regions

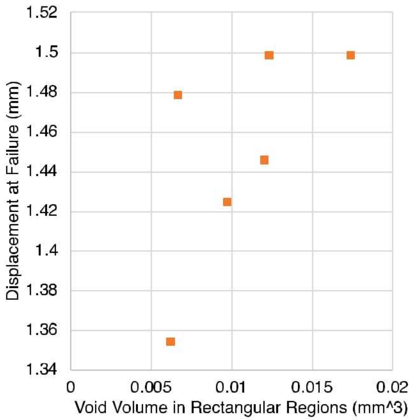
Whole Gage Region

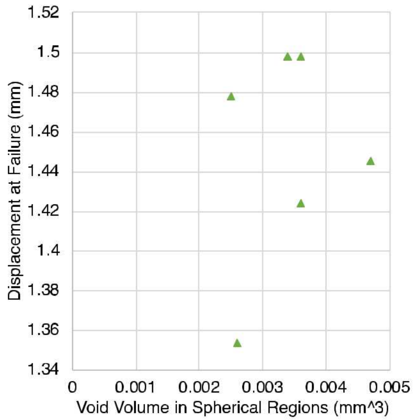






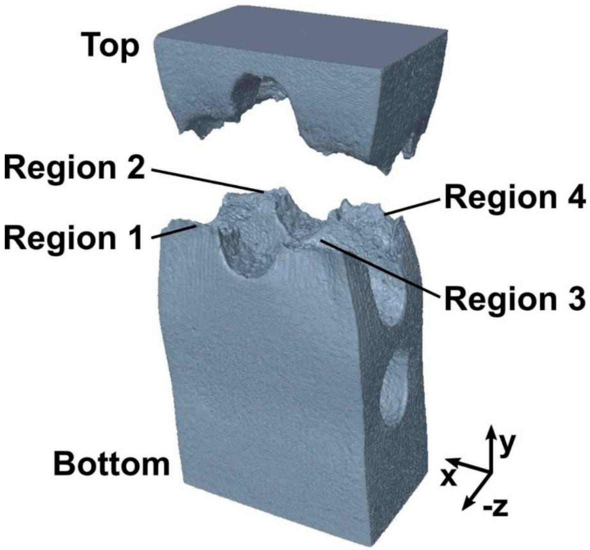


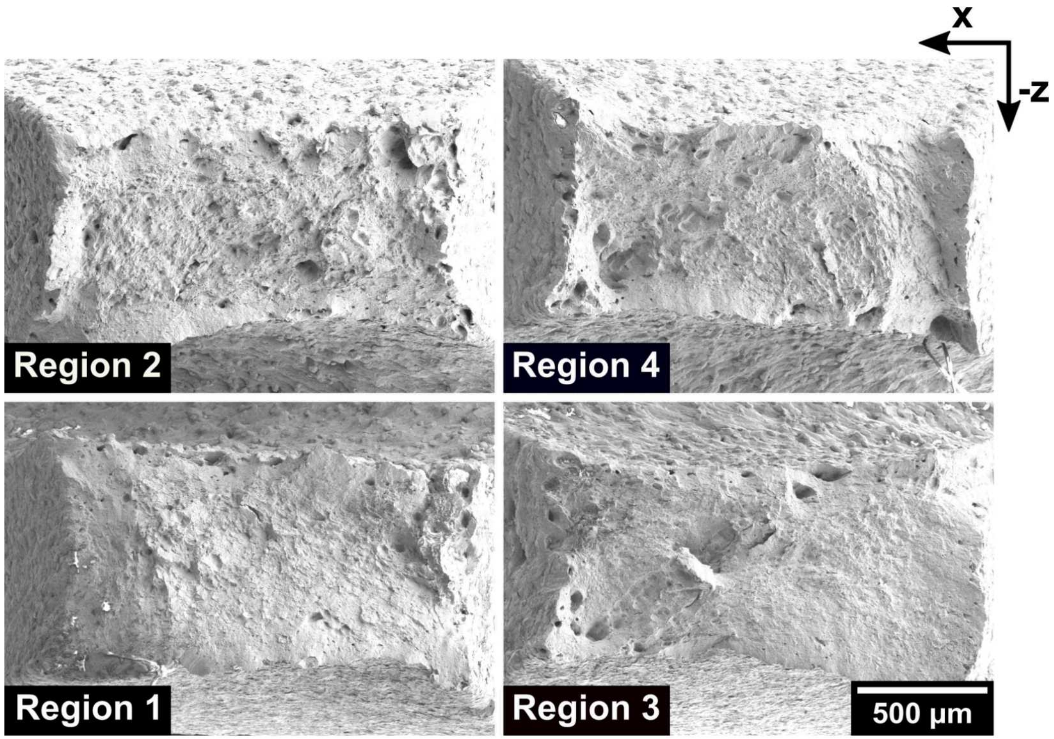




Influence of Void Presence on Fracture

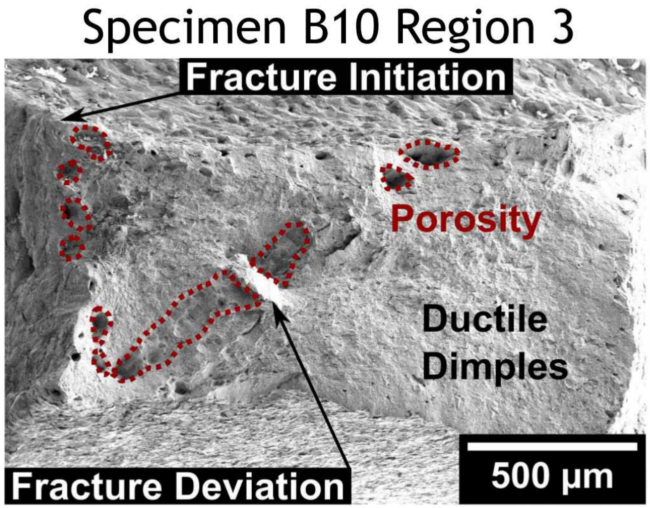
Specimen B10

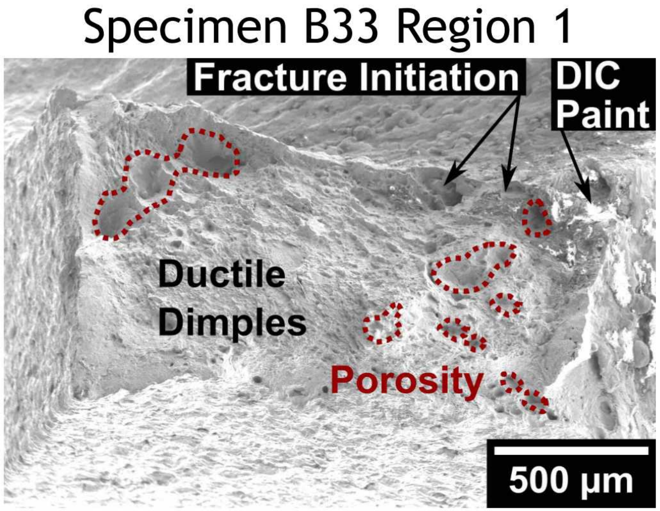




- Ductile dimples
- Intersected voids

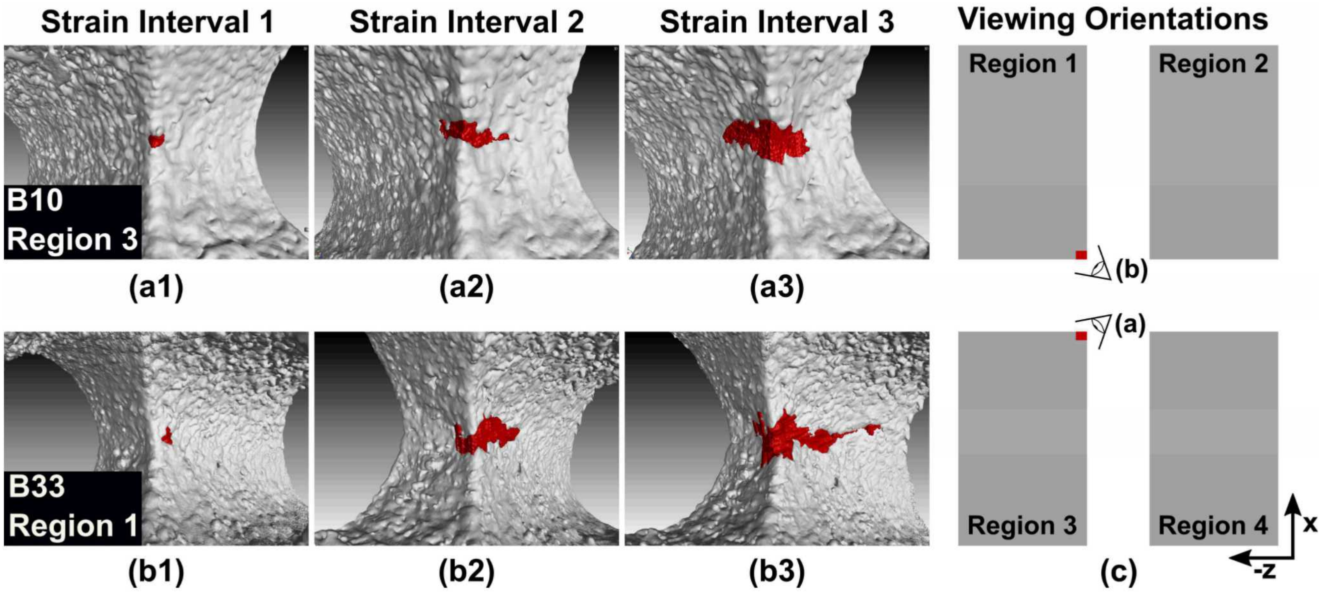
Influence of Void Presence on Fracture





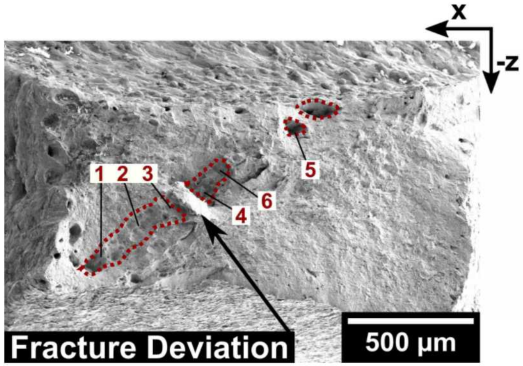
- Ductile dimples
- Intersected voids
- Fracture deviation
- Different crack initiation locations (Surface defect or geometric intersection point)

3D Reconstructions Highlighting Crack Volume

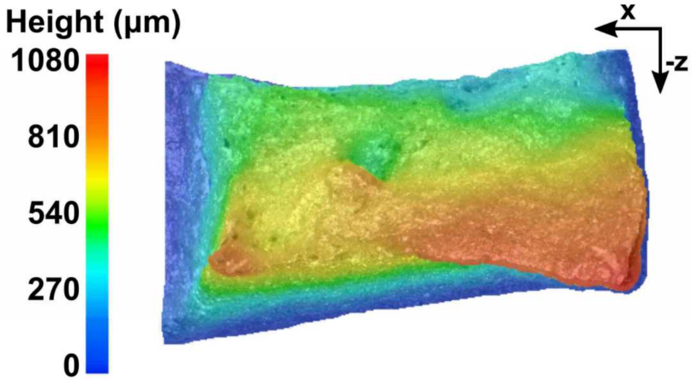


Void Evolution Under Increasing Plastic Strain

Specimen B10
Region 3

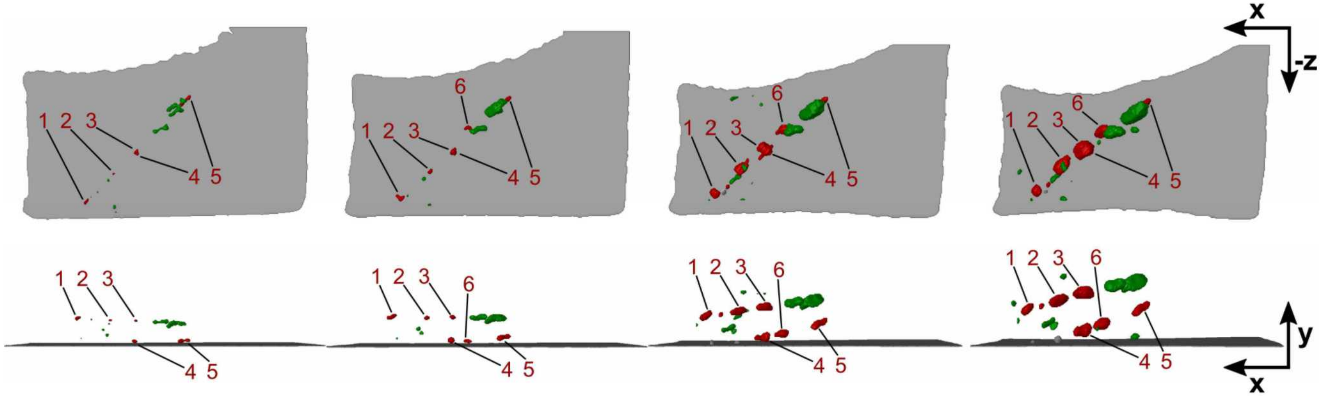


Fracture Surface with Voids Highlighted



Fracture Surface Height Map

Void Evolution: 3D Reconstruction of Voids Near the Fracture Surface (Red Voids Intersected Fracture Surface)



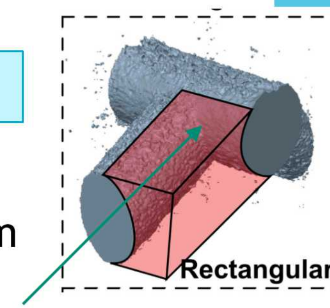
Pre-Test I1 I2 I3

- **All voids grew** regardless of their involvement with the fracture surface.
- **New voids** (or voids too small to be resolved in pre-test scan) such as void 6 **appeared due to deformation** and grew larger than many voids observed in pre-test.
- **The fracture surface did not intersect some of the largest pre-test voids** in this region (see green).
- During I4, **the crack deviated** from the plane of voids 1-3 down to voids 4-6 (or from void 4-6 up to voids 1-3), avoiding the large green voids nearby.

Influence of Local Porosity on Fracture Initiation

Local porosity can change the fracture initiation location and timing.

- **Surface Defect:** Depressions with depths >50 μm
- **Surface Roughness:** Smooth depressions with depths between 11-33 μm



High-Stress Intersection Point

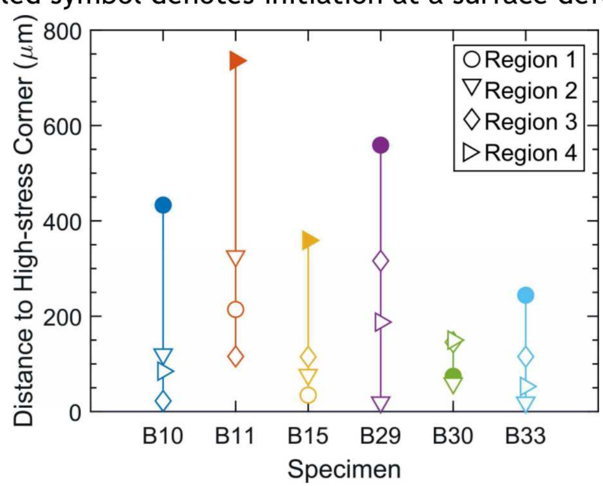
Loading Interval of Fracture Initiation

Specimen	Region 1	Region 2	Region 3	Region 4
B10	1*	2	1	2
B11	2	2	1	1*
B15	2	3	2	1*
B29	1*	1	3	2
B30	1*	2	3	3
B33	1*	1	2	2

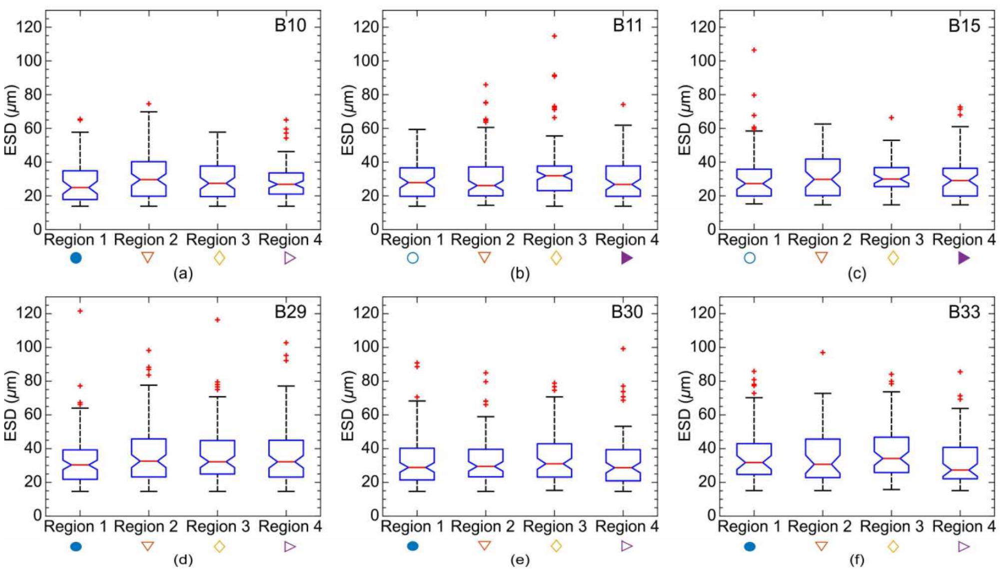
* denotes fracture initiation at a surface defect

Distance of Fracture Initiation Site to High-Stress Intersection Point

(Filled symbol denotes initiation at a surface defect)



Box and Whisker Plots of Equivalent Spherical Diameter (ESD) of Pre-Test Void Population in Rectangular Sub Regions and Table of Pre-test Size of Surface Defects Initiating Fracture



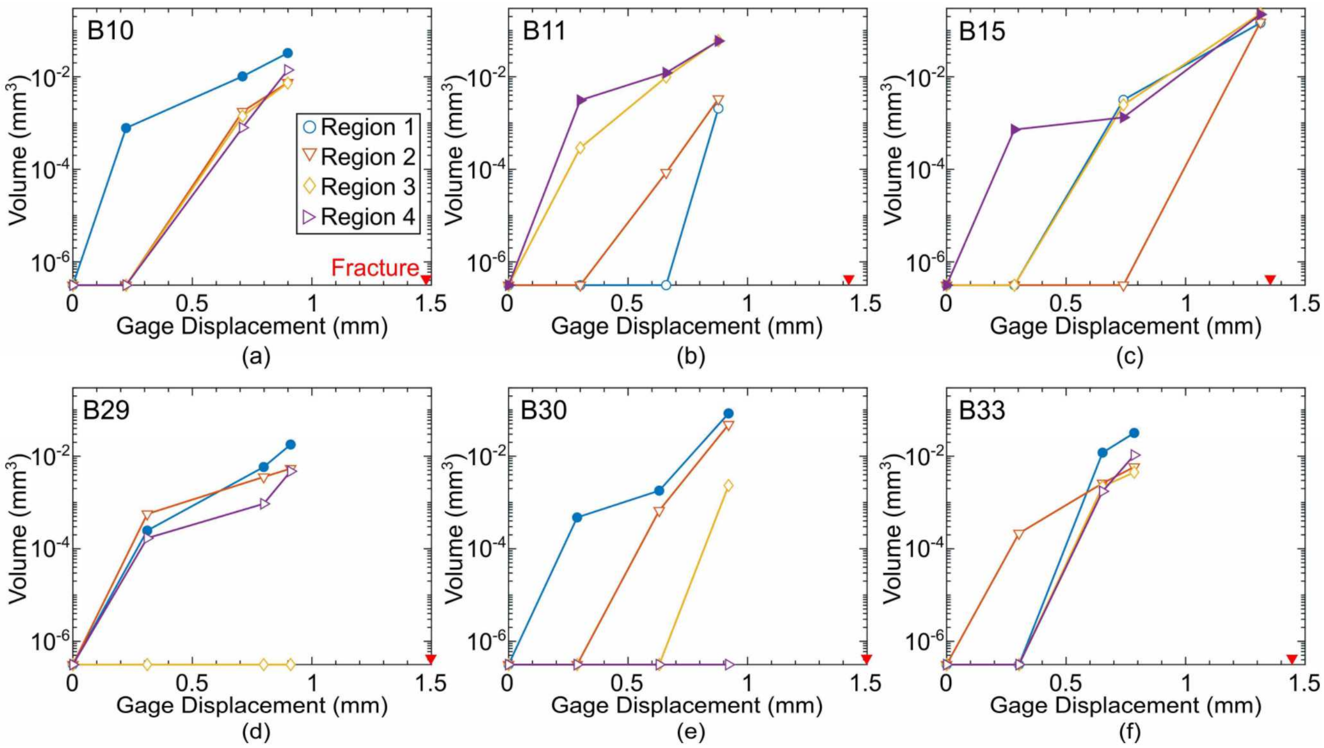
Specimen	B10	B11	B15	B29	B30	B33
Surface Defect ESD (μm)	102	169	80	57	73	113
Region	1	4	4	1	1	1

Influence of Local Porosity on Fracture Growth

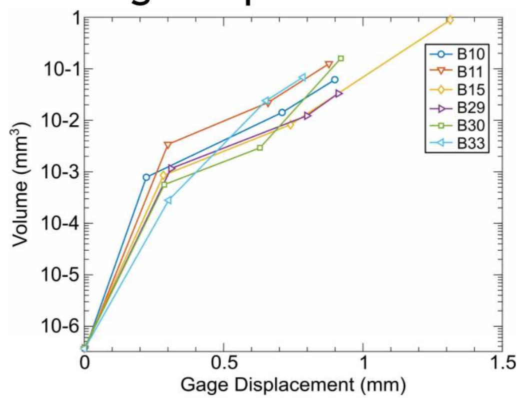
Cracks that initiated at a surface defect tend to grow faster than those that initiated at the high-stress intersection point.

Unloaded Crack Volume After Each Interval for Each Region Versus Unloaded Gage Displacement

(Filled symbol denotes initiation at a surface defect)



Total Unloaded Crack Volume Versus Unloaded Gage Displacement



Despite variation in crack volume evolution between regions, agglomerate volume evolution does not greatly vary between specimens, much like mechanical response.

Future Work

Goal:

Deconvolve influence of several variables including void size, void location, void population, surface roughness, and geometric features on overall part performance.

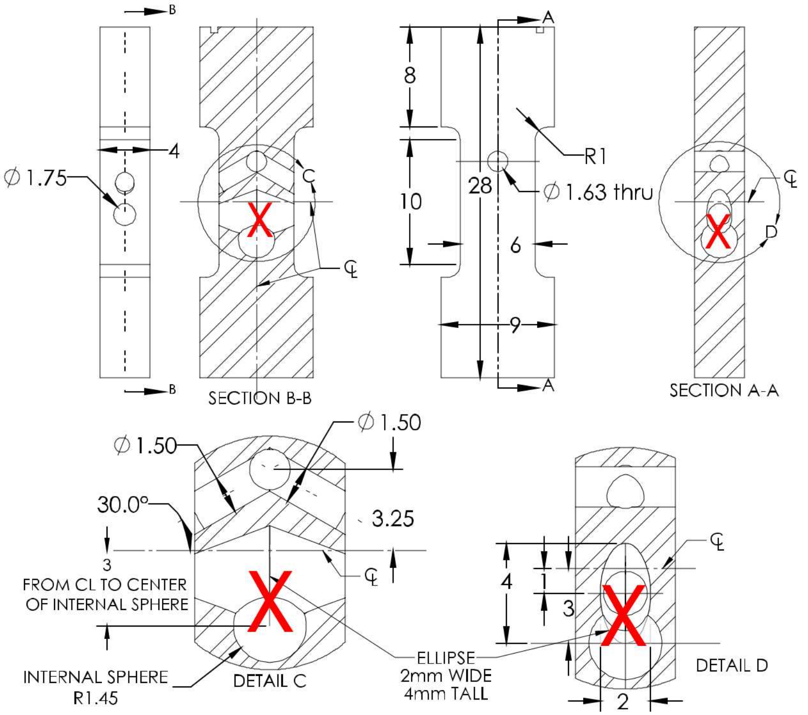
Various SFC3 Cases to Experimentally Study:

- Case 1: AM-built structure with only the through-hole and angled channel features;
- Case 2: AM-built tensile bar with surface roughness removed and the through-hole and angled channel features machined into the part;
- Case 3: a wrought-metal tensile bar with the through-hole and angled channel features machined into the part;
- Case 4: Case 1 that has undergone Hot Isostatic Pressing (HIP); and
- Case 5: Case 2 that has undergone HIP.

Additional Cases:

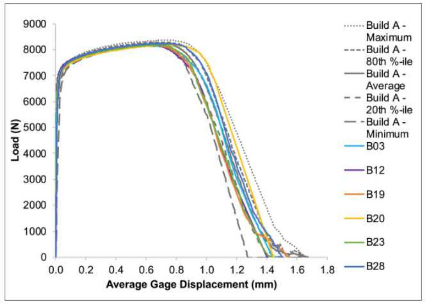
- Different geometric feature sizes relative to void sizes;
- Geometries with only one or two feature; and
- Many more!

SFC3 Geometry Denoted Features To Be Removed

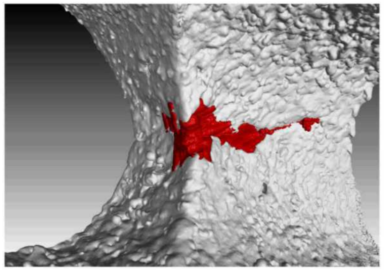


Conclusions

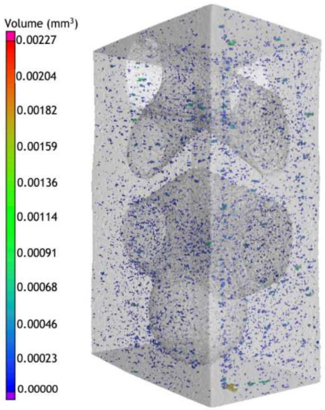
Geometry Dominates Global Behavior in SFC3 Specimens:
Metrics of the pre-existing void population do not correlate with the global mechanical behavior of the SFC3 specimens, but rather the large stress concentrations from the geometry overwhelmingly dominate the global behavior.



Voids Influence Local Crack Initiation and Growth:
Voids and surface defects influence local crack initiation and growth by introducing variation in crack initiation site in some cases and deviation from initial crack path to intersect voids.



Open Question: When Do Voids or Geometry Dominate?
Future work is required to deconvolve influence of several variables including void size, void location, void population, surface roughness, and geometric features on overall part performance.



Questions

More details will be available in the summer in a special volume of the *International Journal of Fracture.*

S.L.B. Kramer, et.al., "The third Sandia Fracture Challenge: predictions of ductile fracture in additively manufactured metal" (DOI: 10.1007/s10704-019-00361-1), (in press).

S.L.B. Kramer, et.al., "Evolution of Damage and Failure in an Additively Manufactured 316L SS Structure: Experimental Reinvestigation of the Third Sandia Fracture Challenge" (DOI: 10.1007/s10704-019-00357-x), Published Online March 2019.

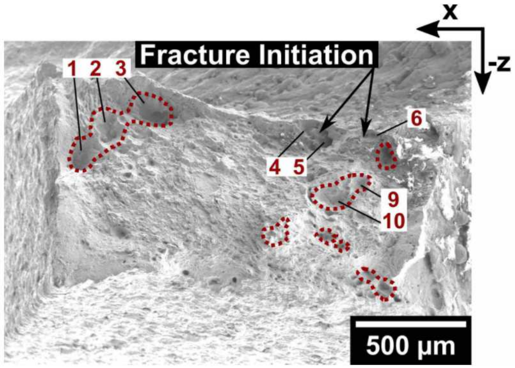
Backups

Global Measure of Mechanical Response

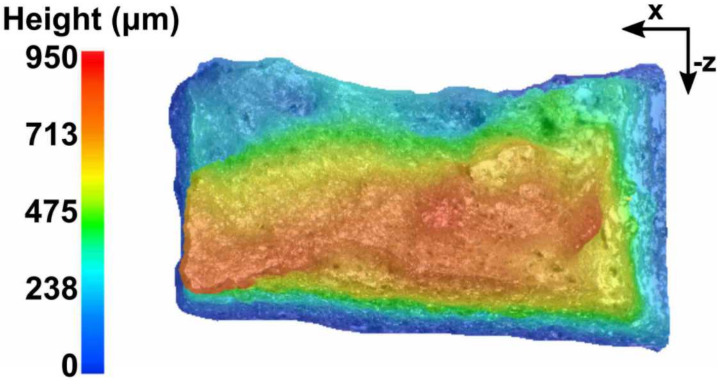
Specimen	Test Type	Peak Load (kN)	Disp. At Peak Load (mm)	Disp. At Failure (mm)	Maximum Instantaneous Unload Rate			
					Max. Unload Rate (kN/s)	Unload Slope (kN/mm)	Disp. (mm)	Load (kN)
B03	Monotonic	8.201	0.647	1.441	−6.0	−21.5	1.064	5.641
B12	Monotonic	8.186	0.597	1.402	−13.1	−13.1	1.155	3.222
B19	Monotonic	8.195	0.590	1.574	−3.3	−20.0	1.048	5.061
B20	Monotonic	8.184	0.782	1.446	−24.5	−17.5	1.086	6.211
B23	Monotonic	8.190	0.653	1.486	−2.8	−20.4	1.209	2.574
B28	Monotonic	8.240	0.683	1.505	−7.3	−20.2	1.072	5.930
B10	Interrupted	8.213	0.621	1.478	−1.1	−17.1	1.100	4.251
B11	Interrupted	8.090	0.575	1.424	−7.8	−2133.2	0.901	4.201
B15	Interrupted	8.156	0.684	1.354	−5.7	−5.6	1.092	4.011
B29	Interrupted	8.140	0.705	1.498	−3.8	−18.3	1.141	4.172
B30	Interrupted	8.078	0.591	1.498	−0.7	−18.5	1.281	0.890
B33	Interrupted	8.077	0.581	1.445	−4.4	−17.9	1.191	1.581

Void Evolution Under Increasing Plastic Strain

Specimen B33
Region 1

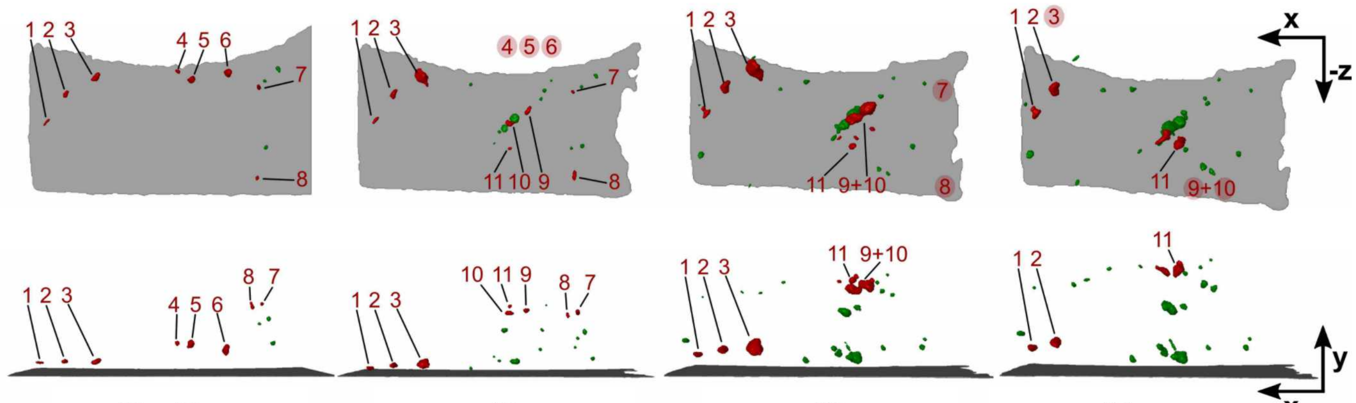


Fracture Surface with Voids Highlighted



Fracture Surface Height Map

Void Evolution: 3D Reconstruction of Voids Near the Fracture Surface (Red Voids Intersected Fracture Surface)



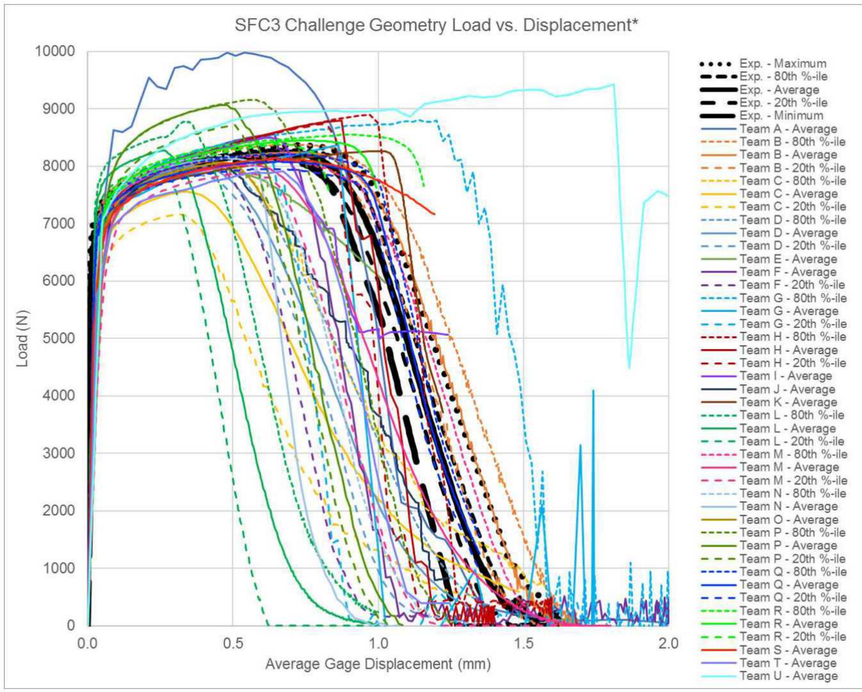
Pre-Test
I1
I2
I3

- Voids grew regardless of their involvement with the fracture surface.
- New voids appeared and grew larger than many voids observed in pre-test.
- Cracks initiated at surface defects.
- Some voids are consumed during the fracture that occurs on multiple fronts, not just from one general area.
- The crack does not greatly deviate from the nominal crack path, even though it initiated away from the high-stress intersection point.

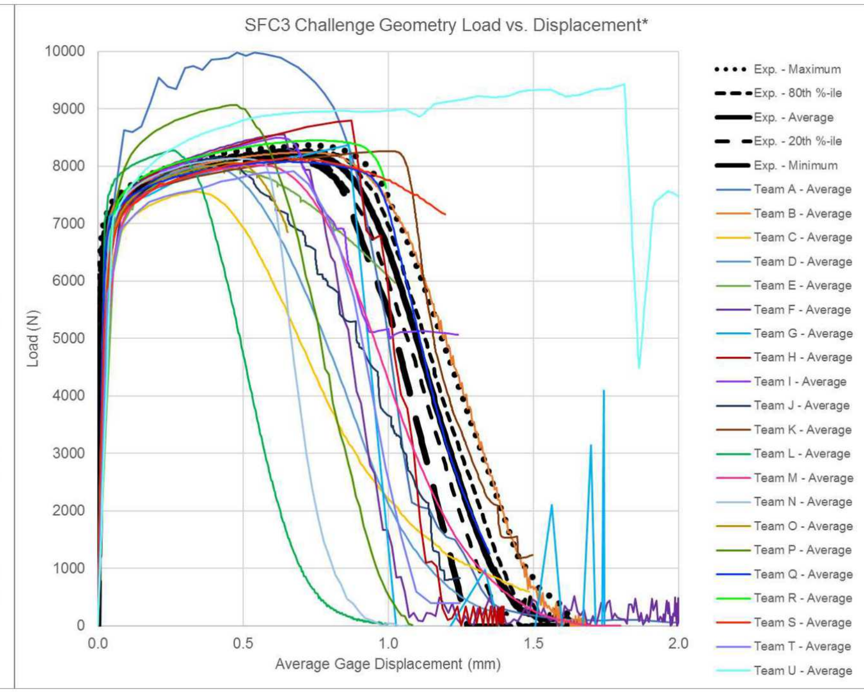
Predictions: Question 3

Report the force vs. gage displacement D for the test.

21 Predictions and Bounds with Exp. Average and Bounds

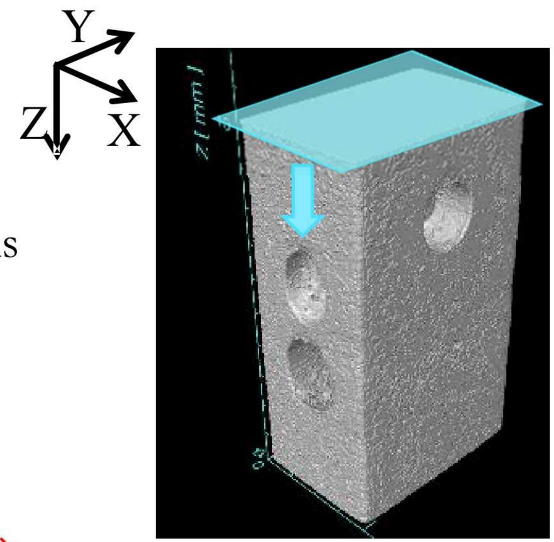


21 Nominal Predictions with Exp. Average and Bounds

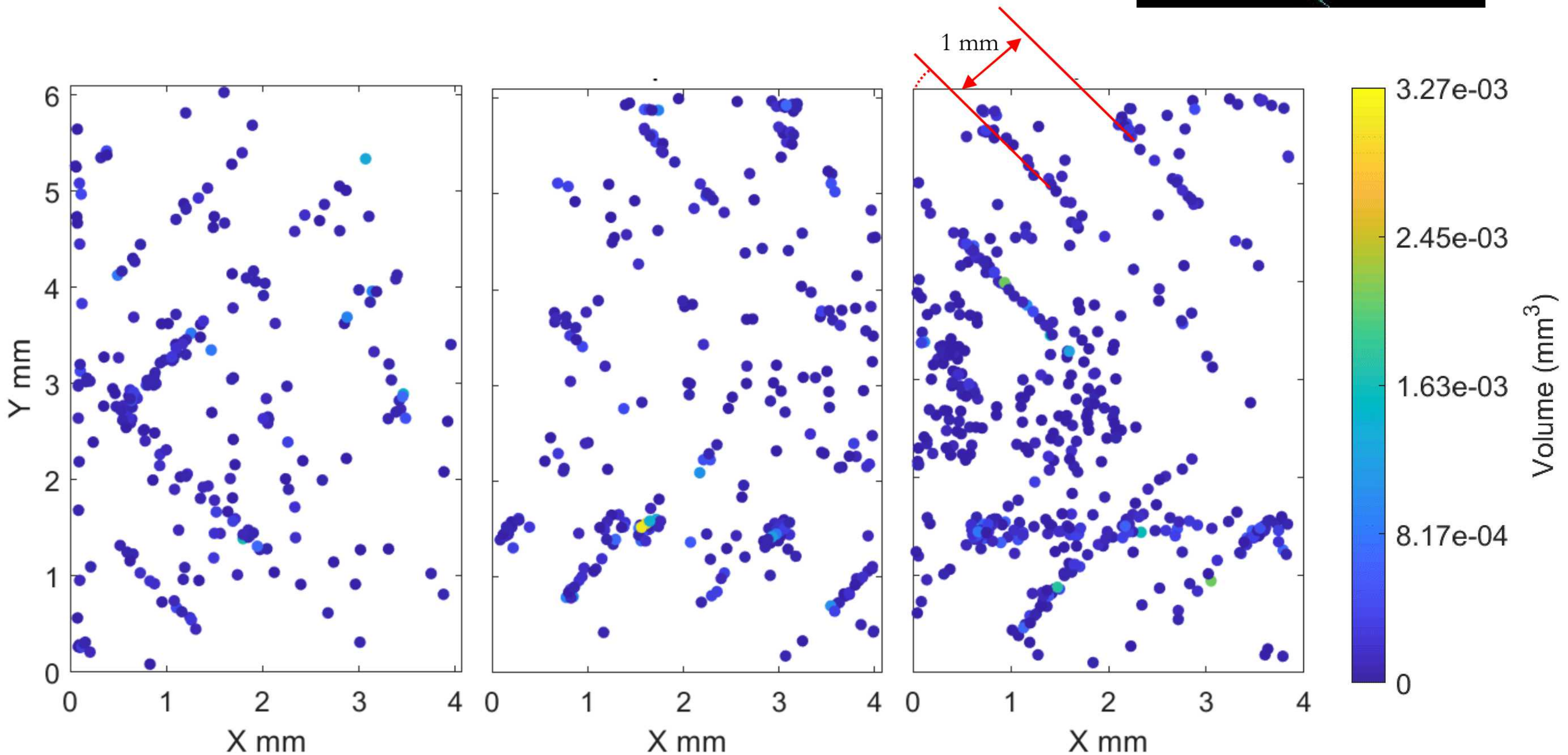


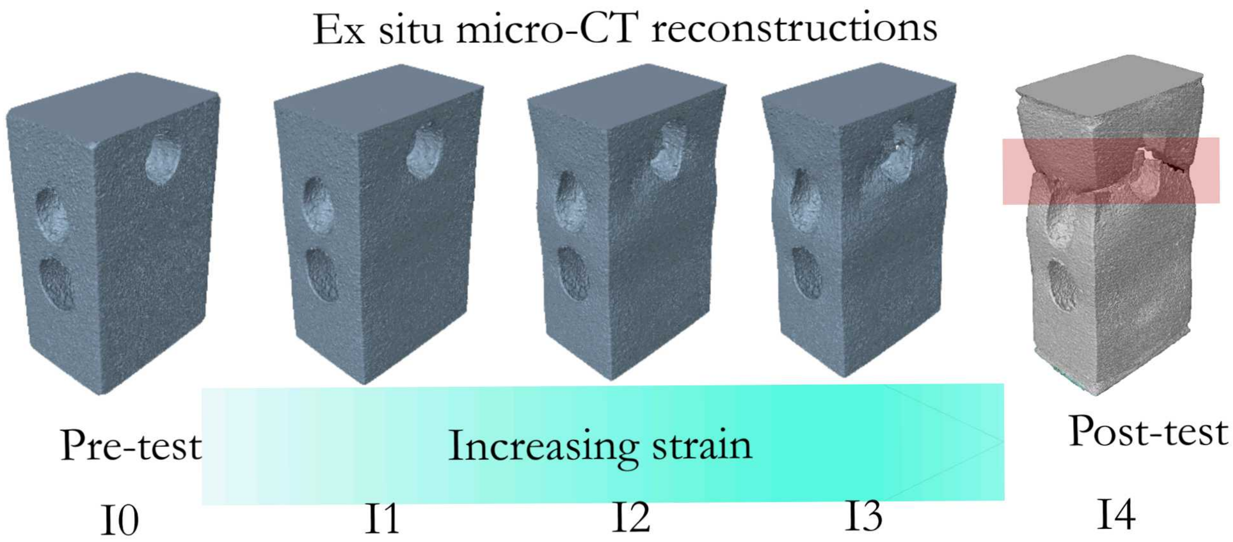
- More teams under-predicted the failure displacement than over-predicted.
- There were only two teams whose nominal prediction fell within the bounds of the experimental data (Teams B and Q).
- The uncertainty bounds on predictions ranged from too small to too large, with most unlike the experiments where there was little initial variability with moderate variability after peak load.

SFC3: Porosity Distribution



Diagonal hatch pattern strongly visible in XY-projections
- 45° orientation of defects with respect to sample surface
- 90° orientation of defect trails to one another
- Approximately 1 mm spacing between parallel defect trails




Ex situ micro-CT reconstructions
Pre-test
Increasing strain
Post-test
I0
I1
I2
I3
I4