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Mechanical Property Variation in Metal Lattice Struts

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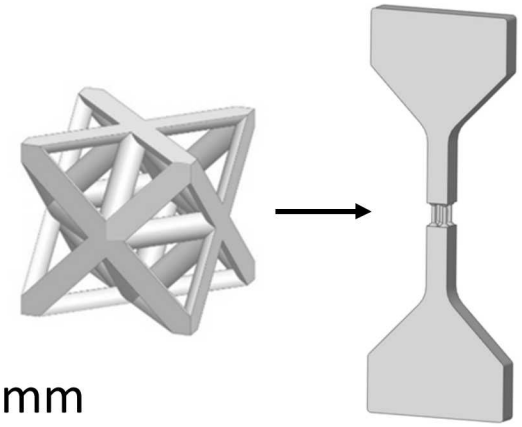
GOAL

Improve the understanding of how defects impact mechanical properties to enhance designers' ability to manufacture metal lattice structures reliably.

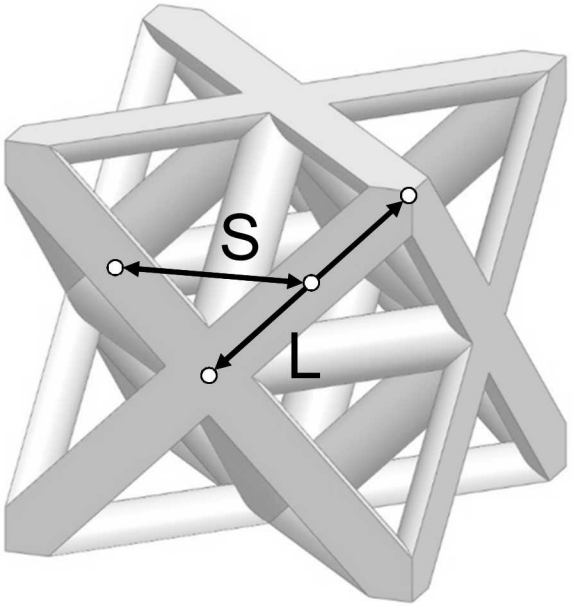
Overview

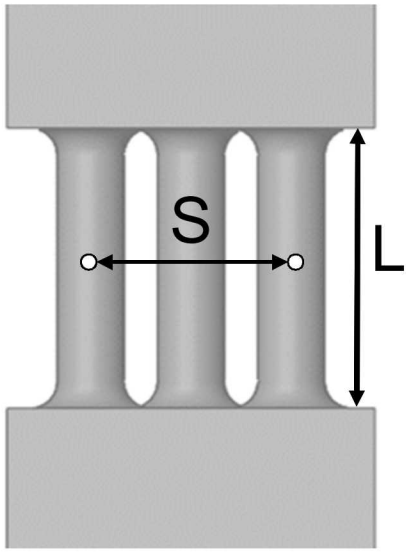
- Evaluate properties of lattice struts
  - EOS M270
  - Stainless steel 17-4 PH powder
- Vary size and orientation
  - Strut diameters: 0.5 mm, 0.65 mm, and 0.82 mm
  - Vertical and horizontal build orientations
- CT evaluation of parts
- Tensile Tests
- Failure Analysis

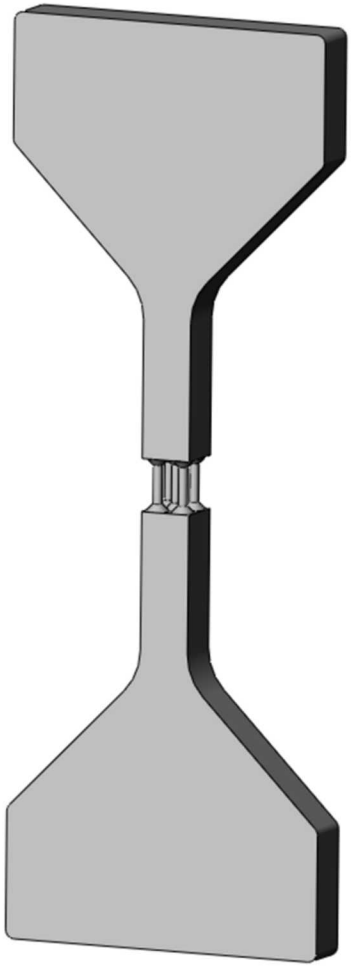


Vertical Strut Builds

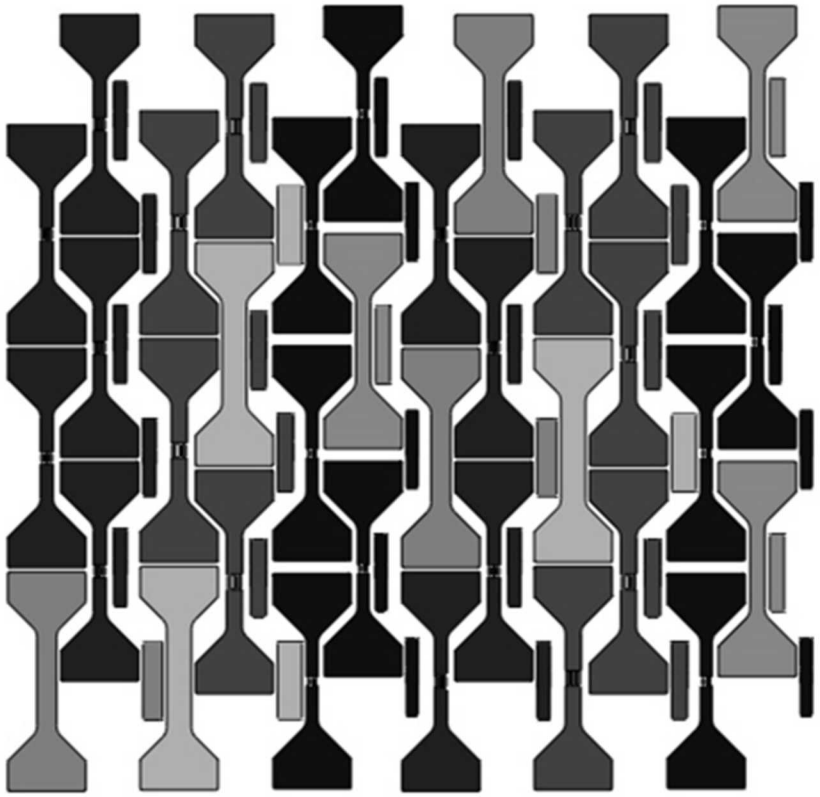
- Spacing based on the octet truss design
- Horizontal and vertical copies
- Three different sizes (representing 3, 4, and 5 mm unit cells)

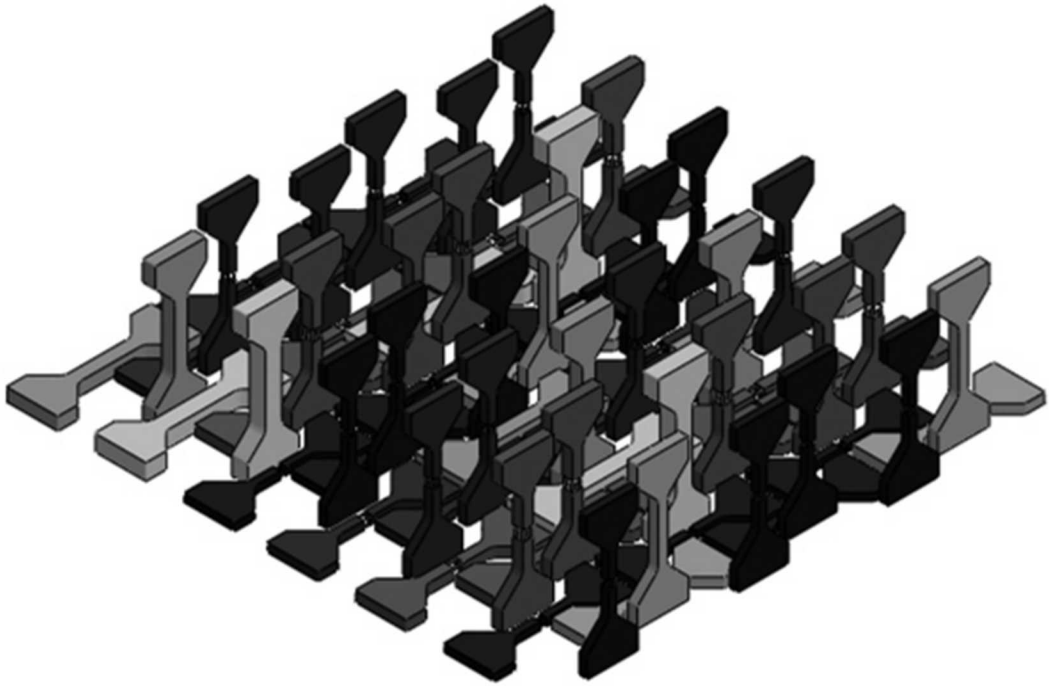




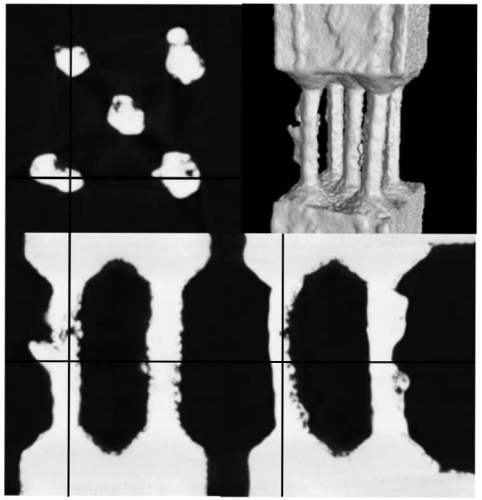
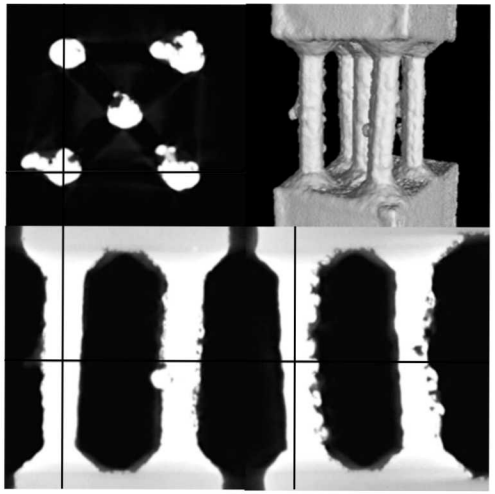
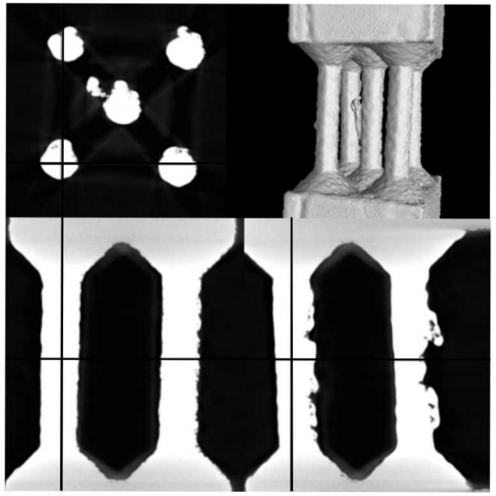
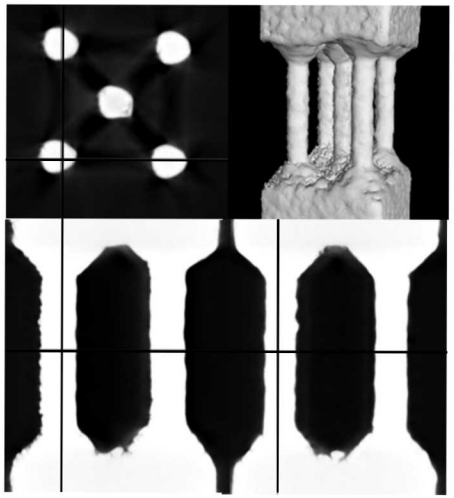
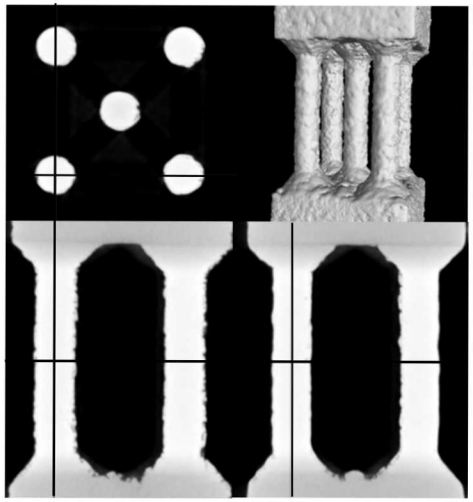
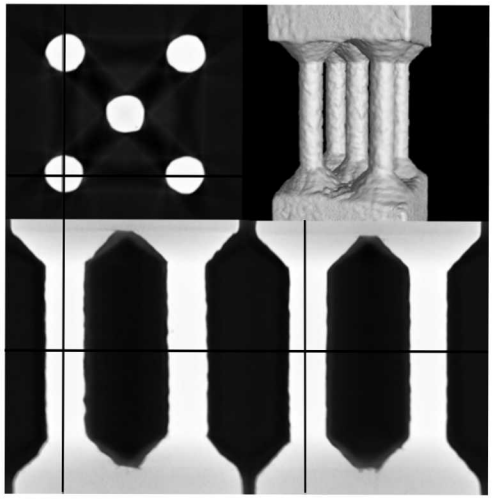


Build Layout

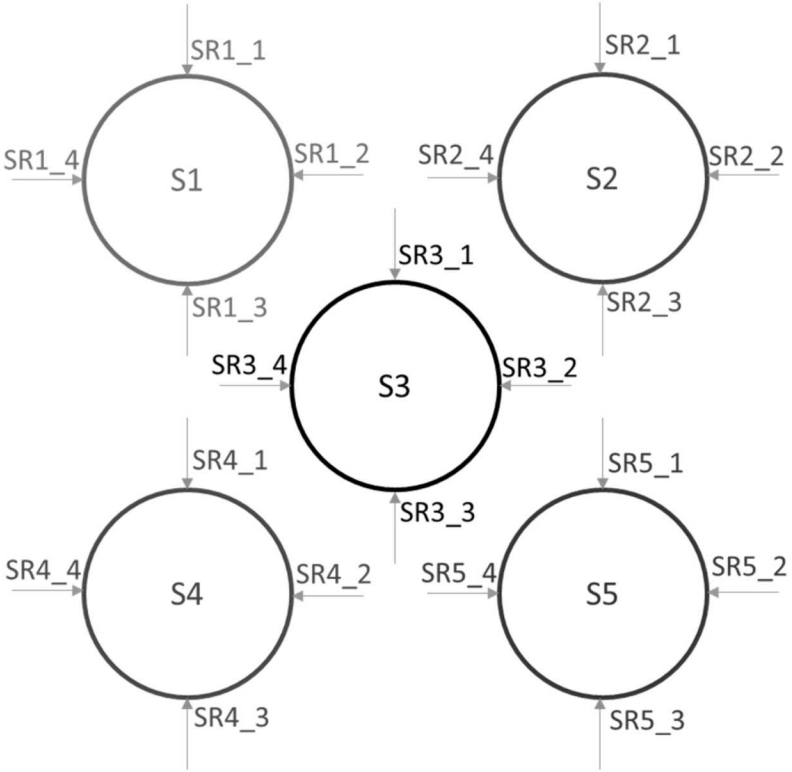


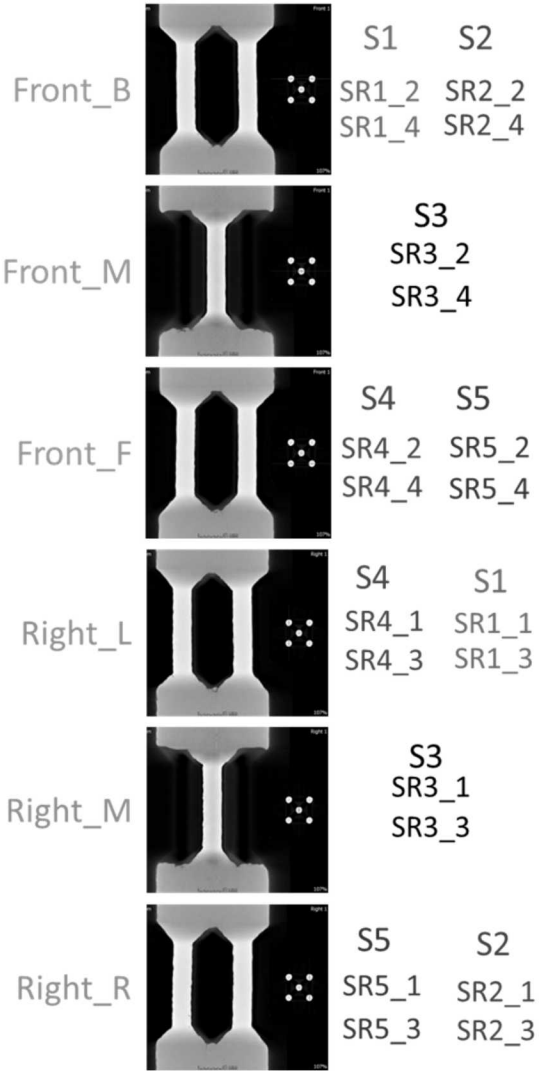


CT Results-Configuration Comparison

	0.50 mm Strut	0.65 mm Strut	0.82 mm Strut
Horizontal			
Vertical			

Roughness Measurements

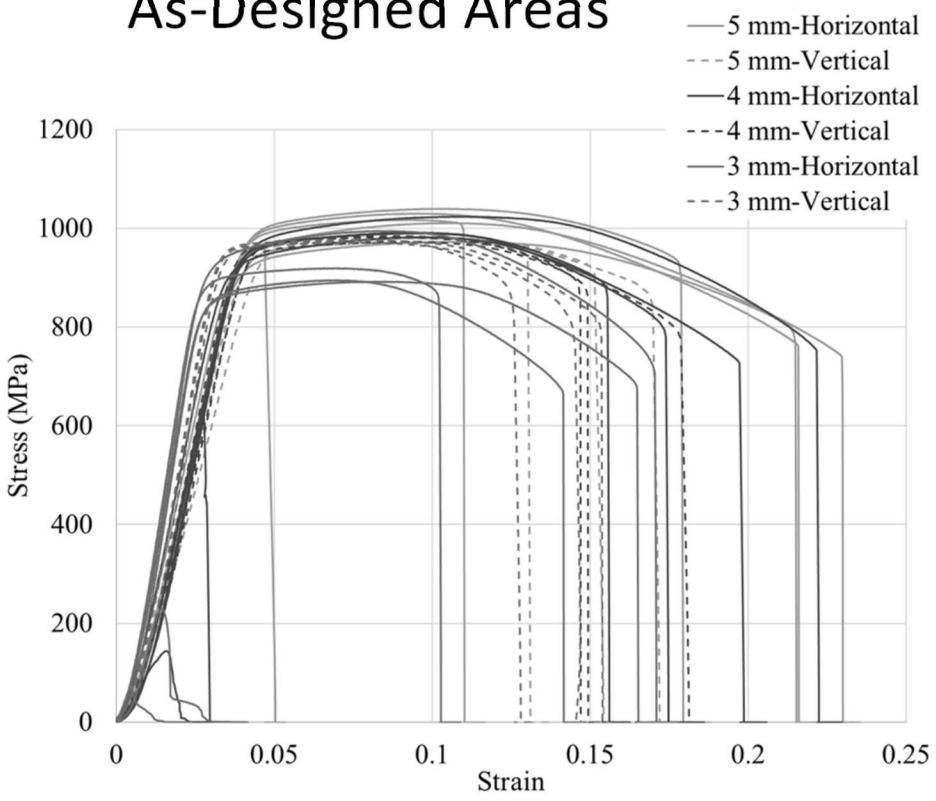




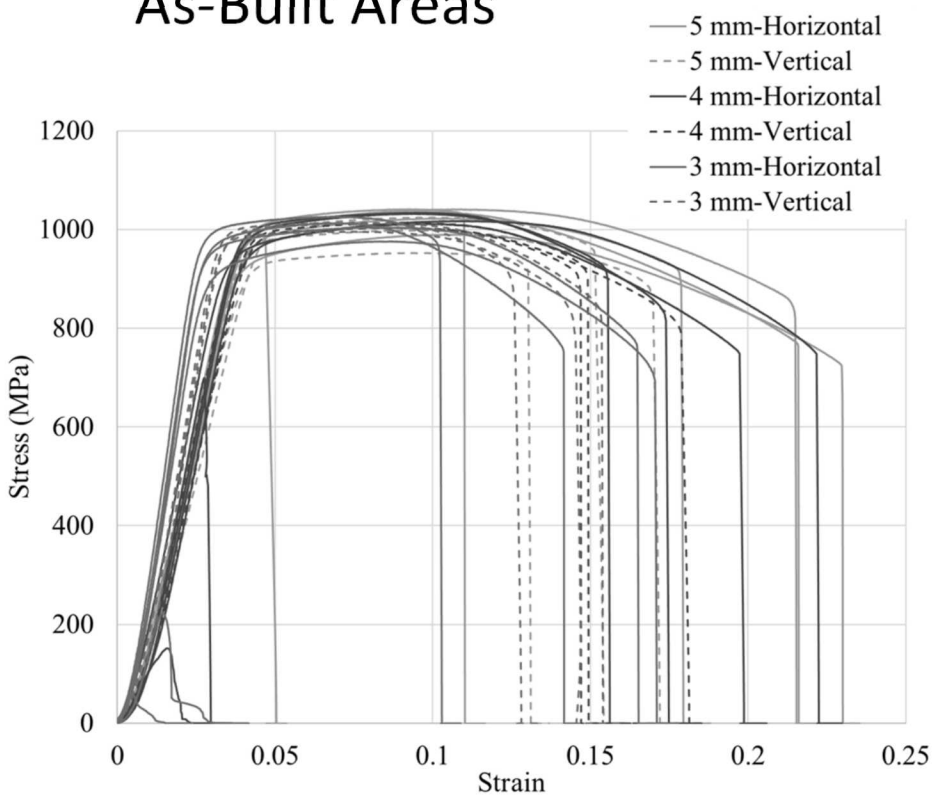
DESTRUCTIVE EVALUATION
SOLID BARS

Stress-Strain

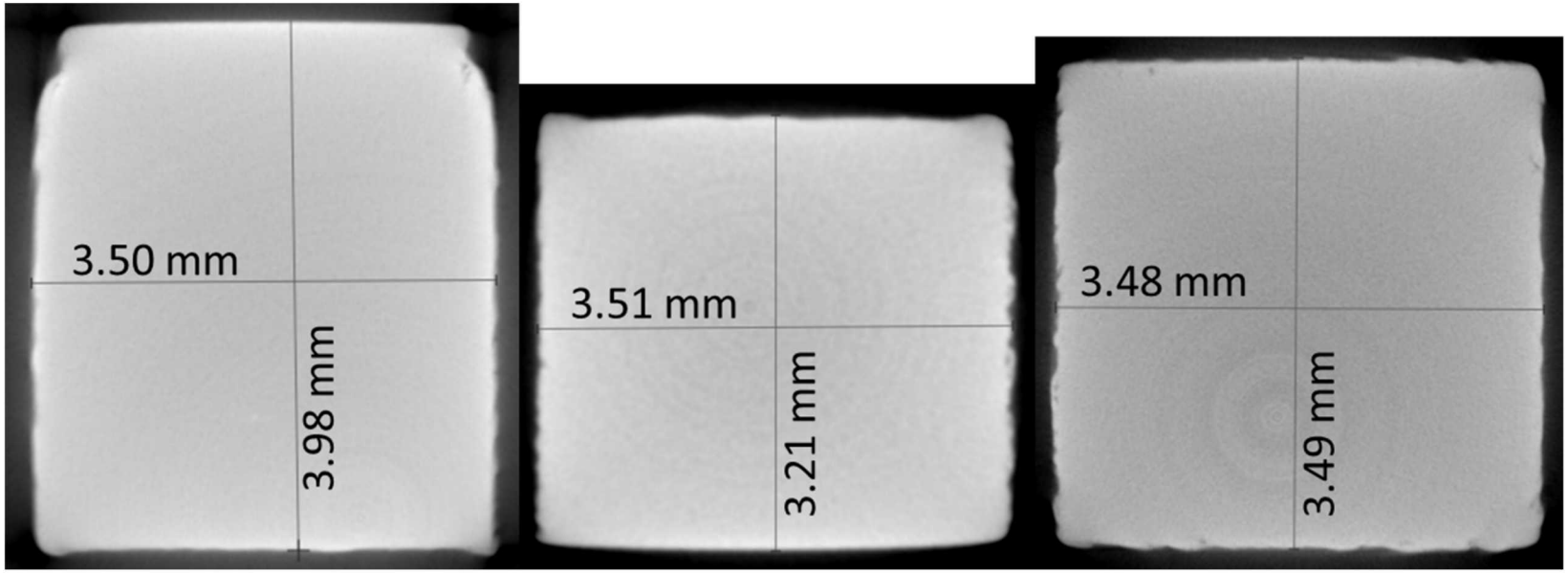
As-Designed Areas



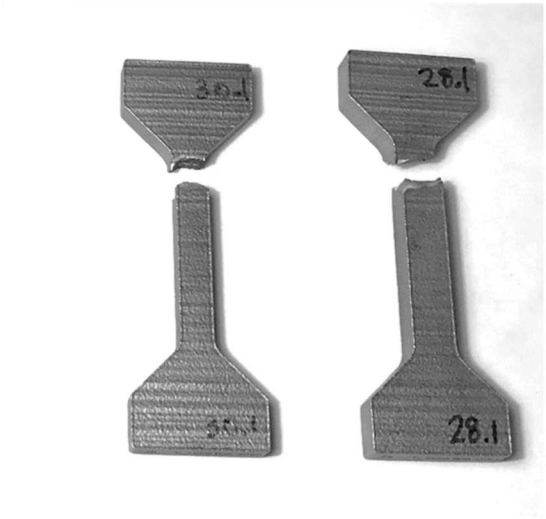
As-Built Areas

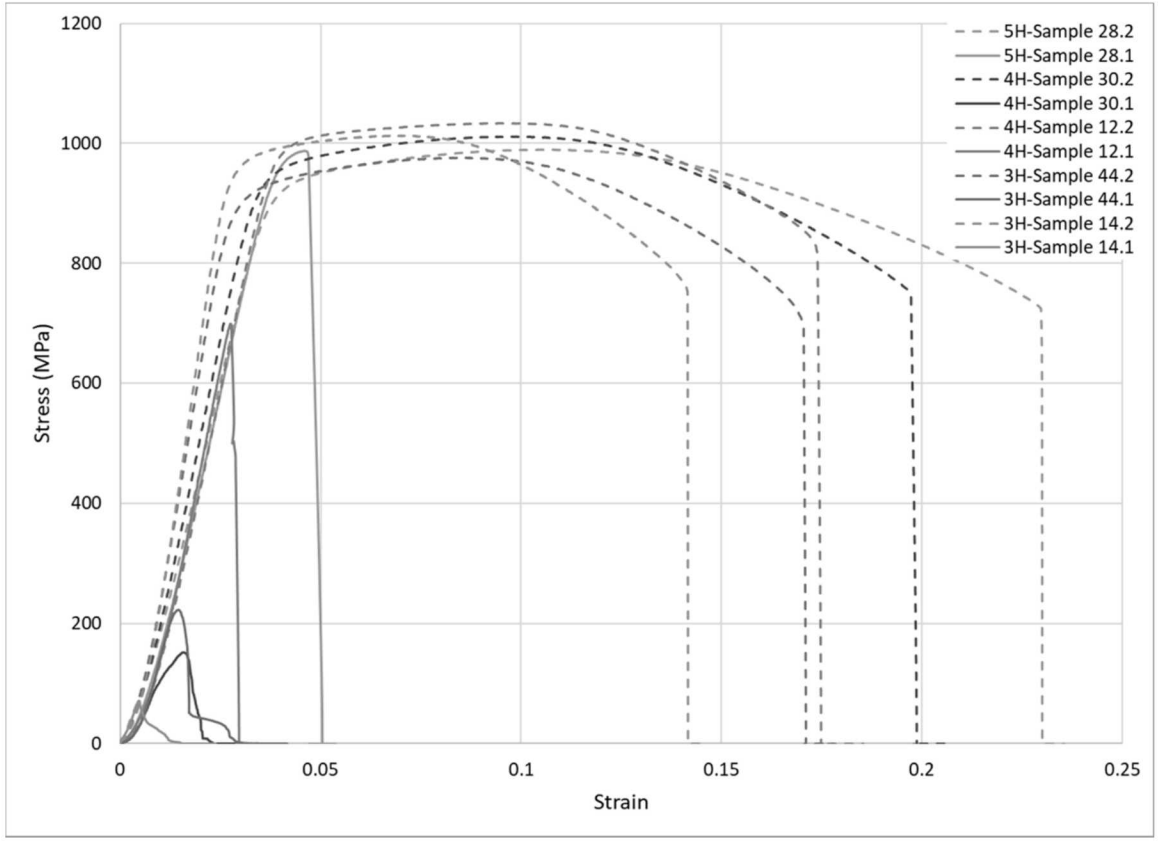


Why Designed Area Adds Variation

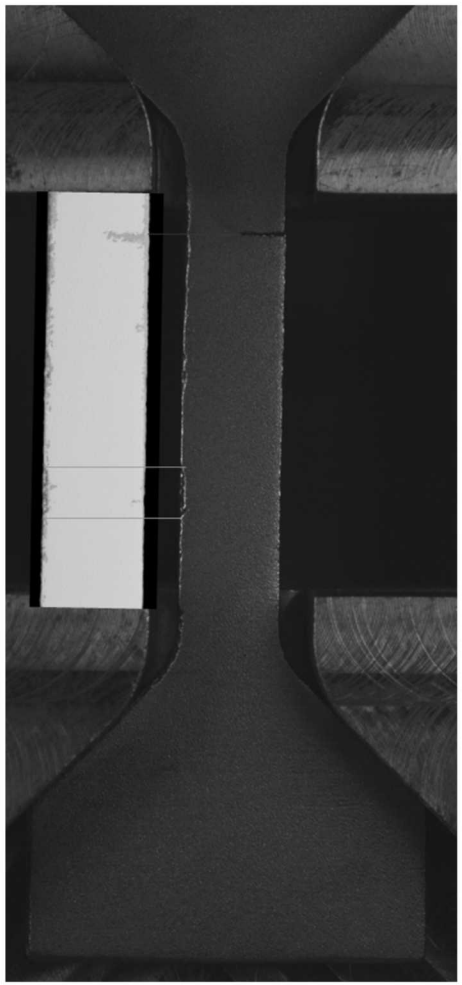


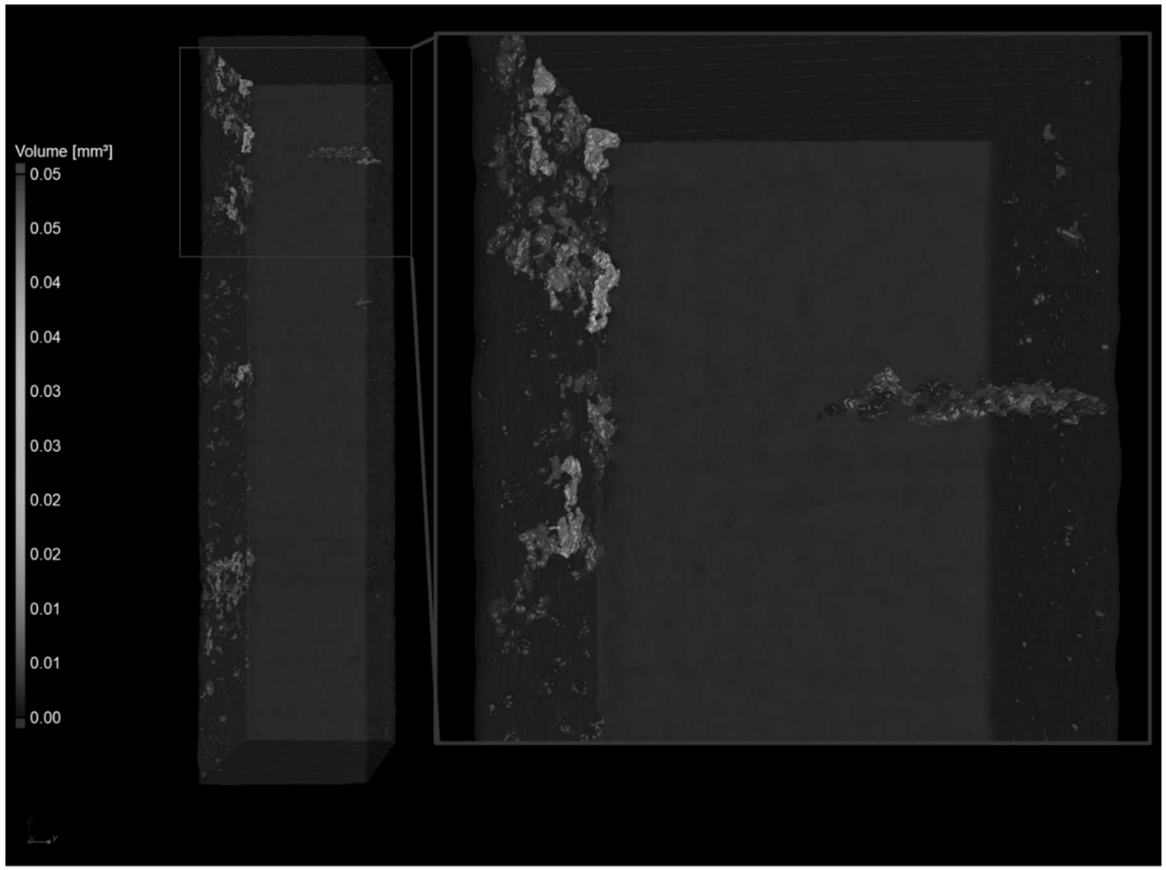
Brittle/Low-Ductility Samples



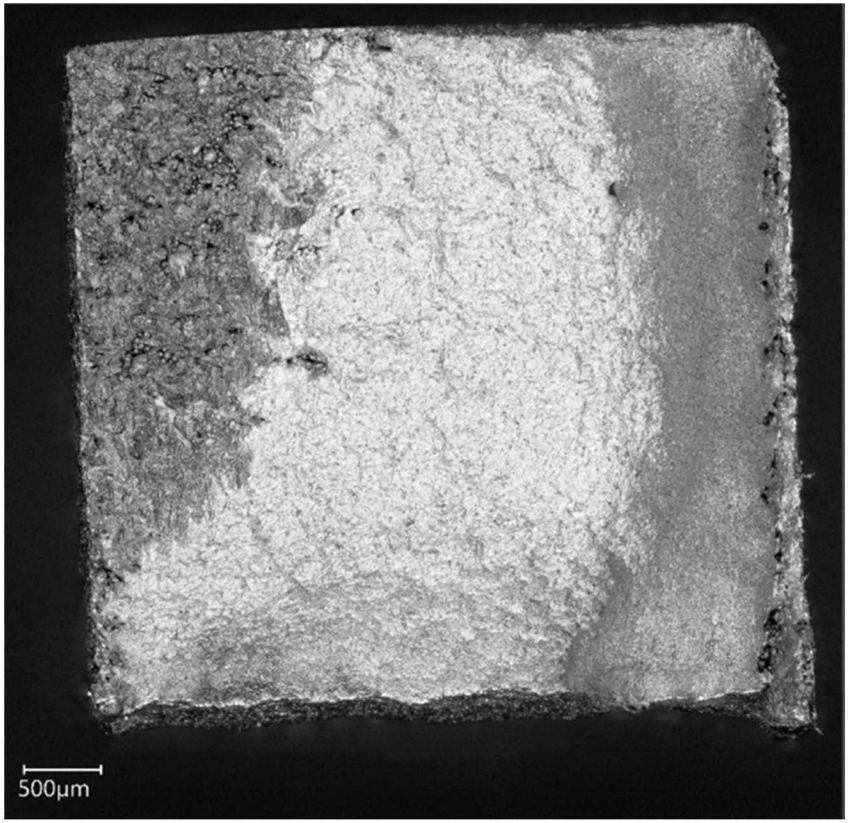


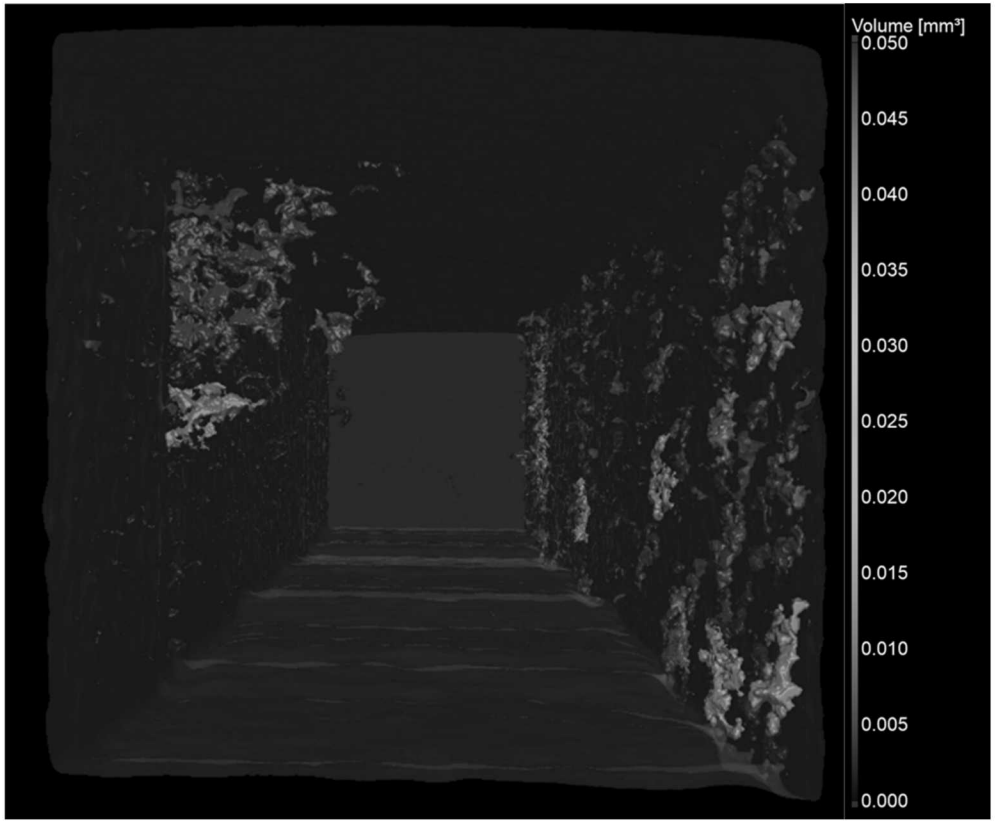
Porosity in Sample 12.1 (4 mm, Horizontal)





Porosity Impact

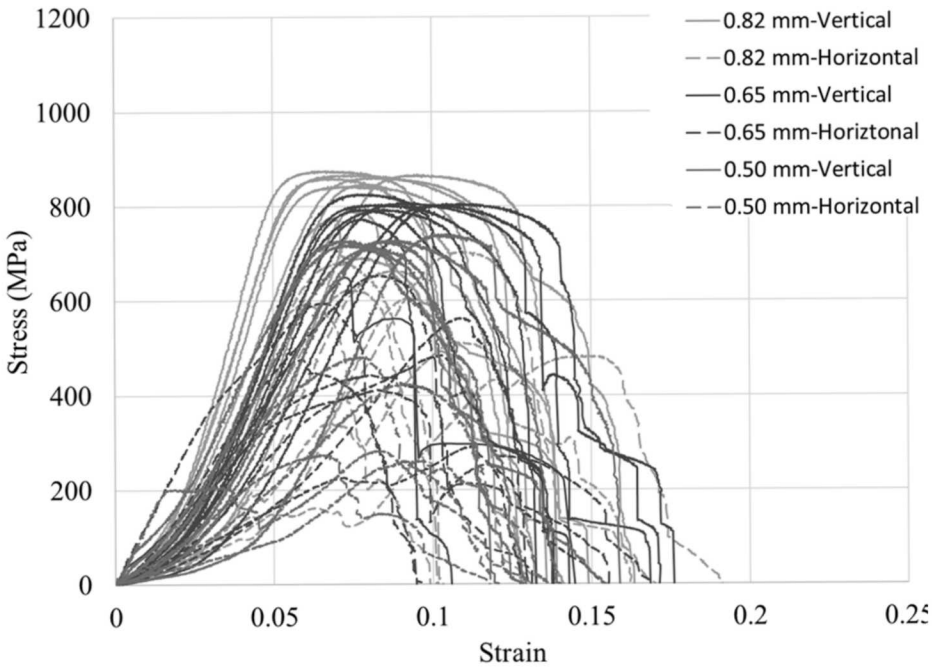




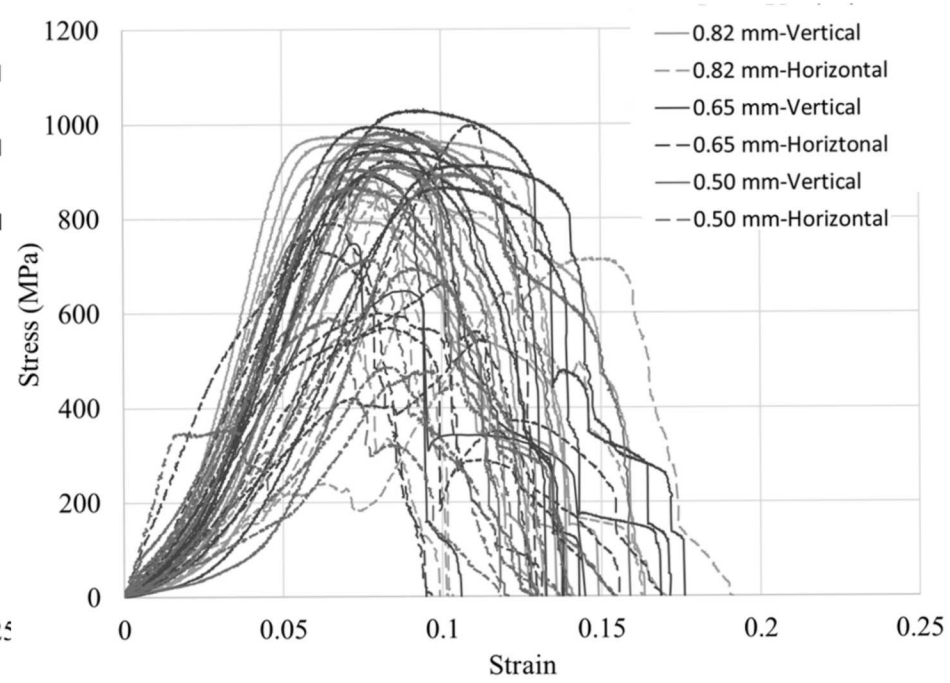
DESTRUCTIVE EVALUATION
STRUT BARS

Stress-Strain

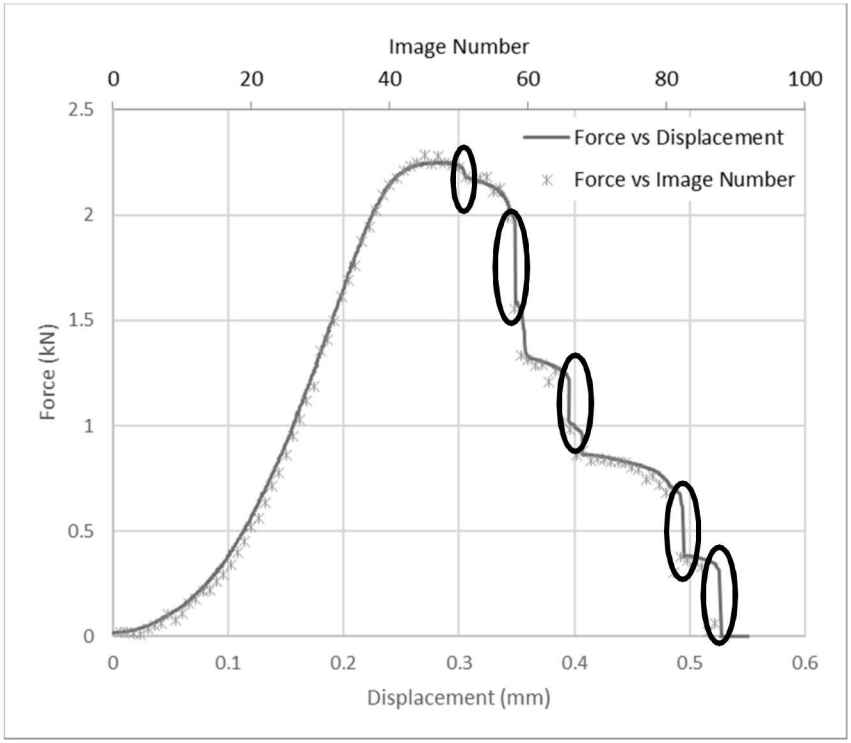
As-Designed Areas

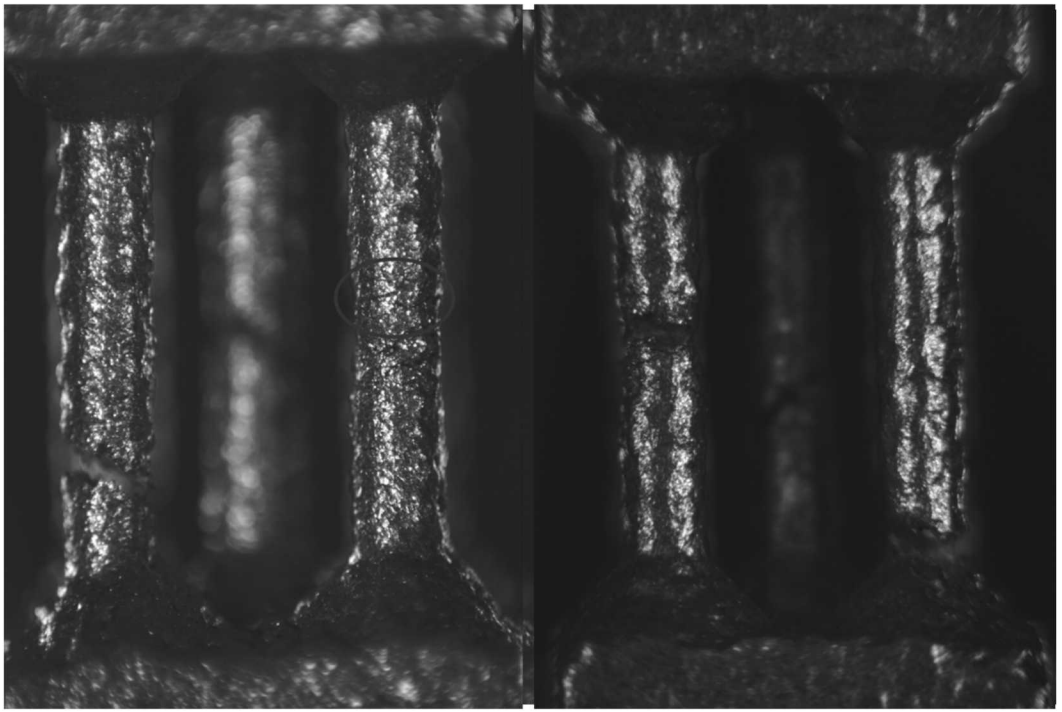


As-Built Areas

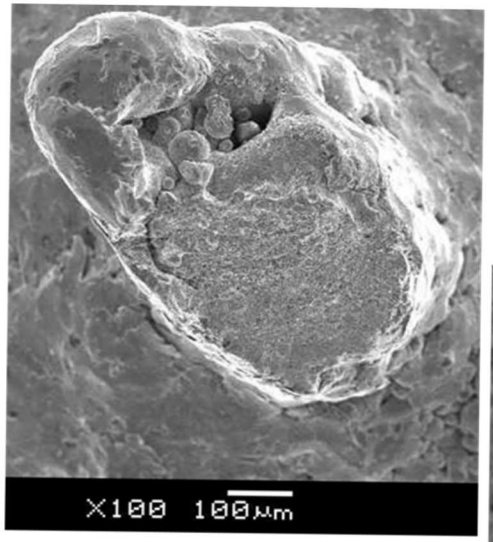


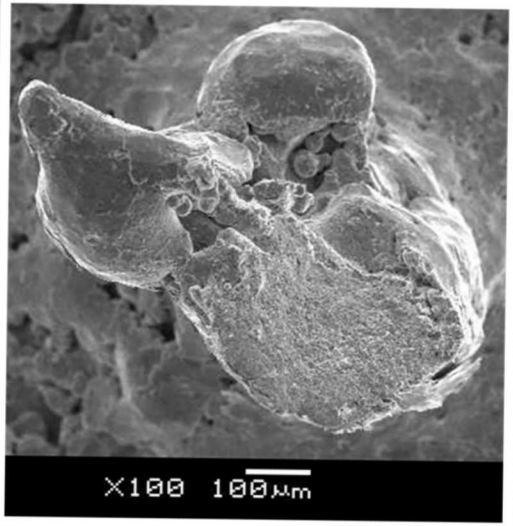
Crack Propagation Through Sample

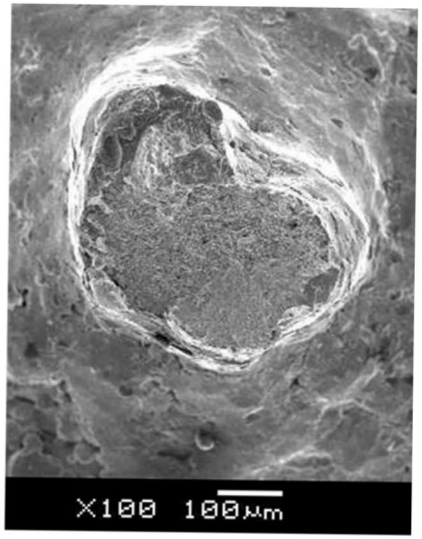


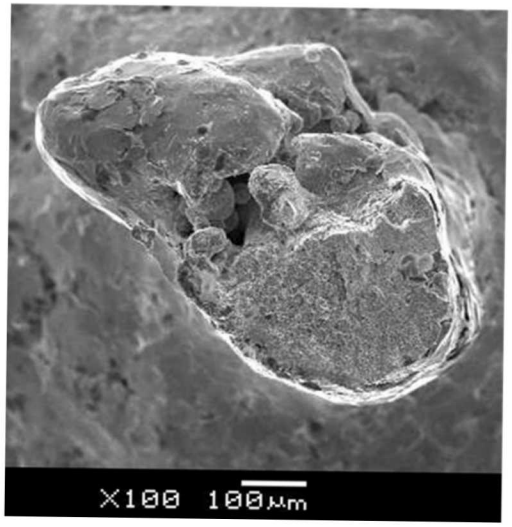


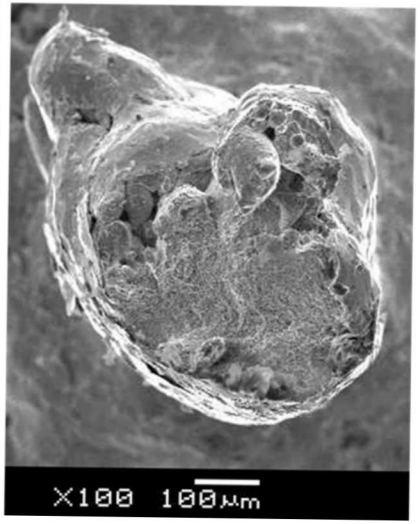
Fractography-Sample 68 (0.50 mm, Horizontal)



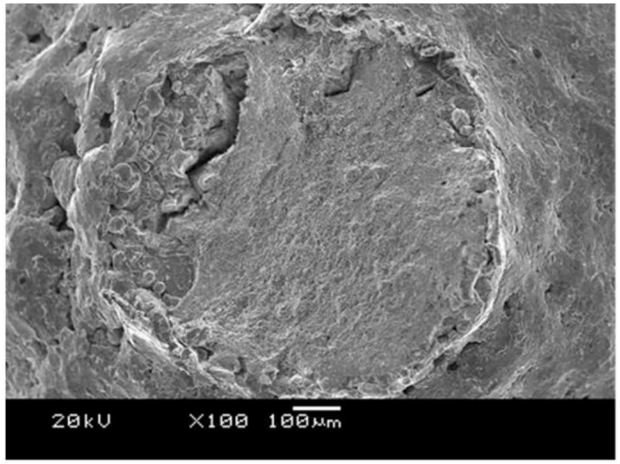


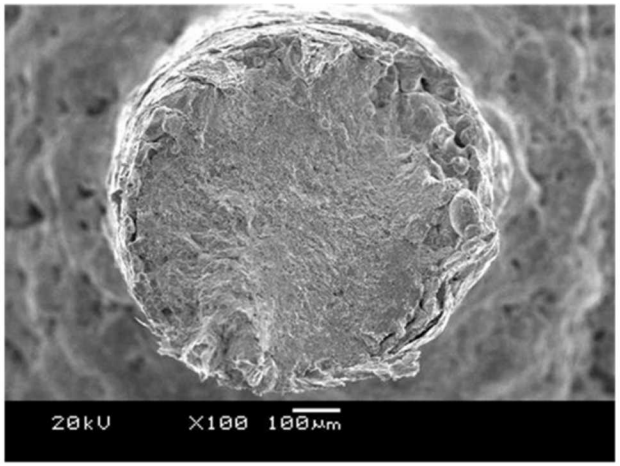


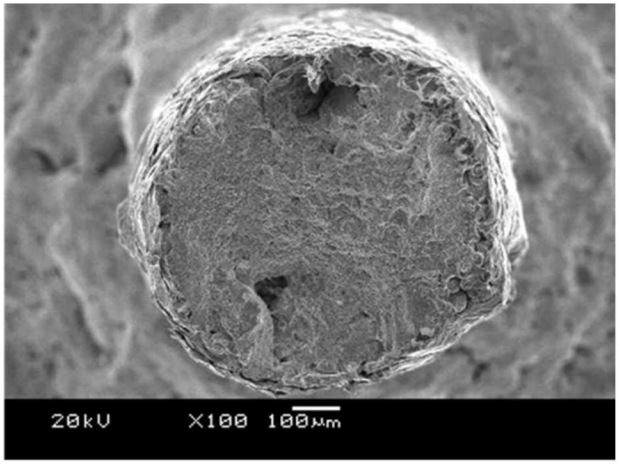


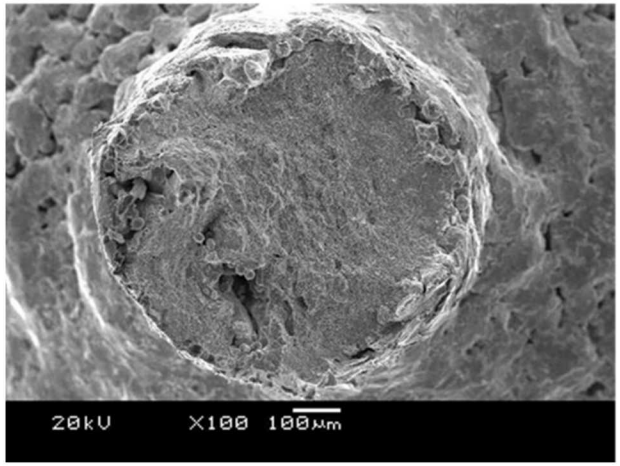


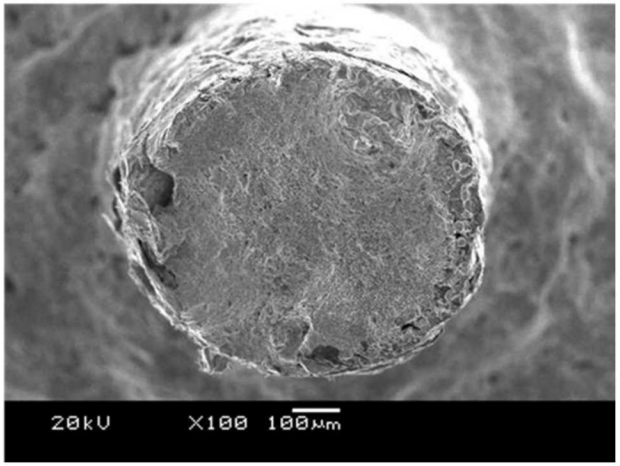
Fractography-Sample 51 (0.82 mm, Vertical)





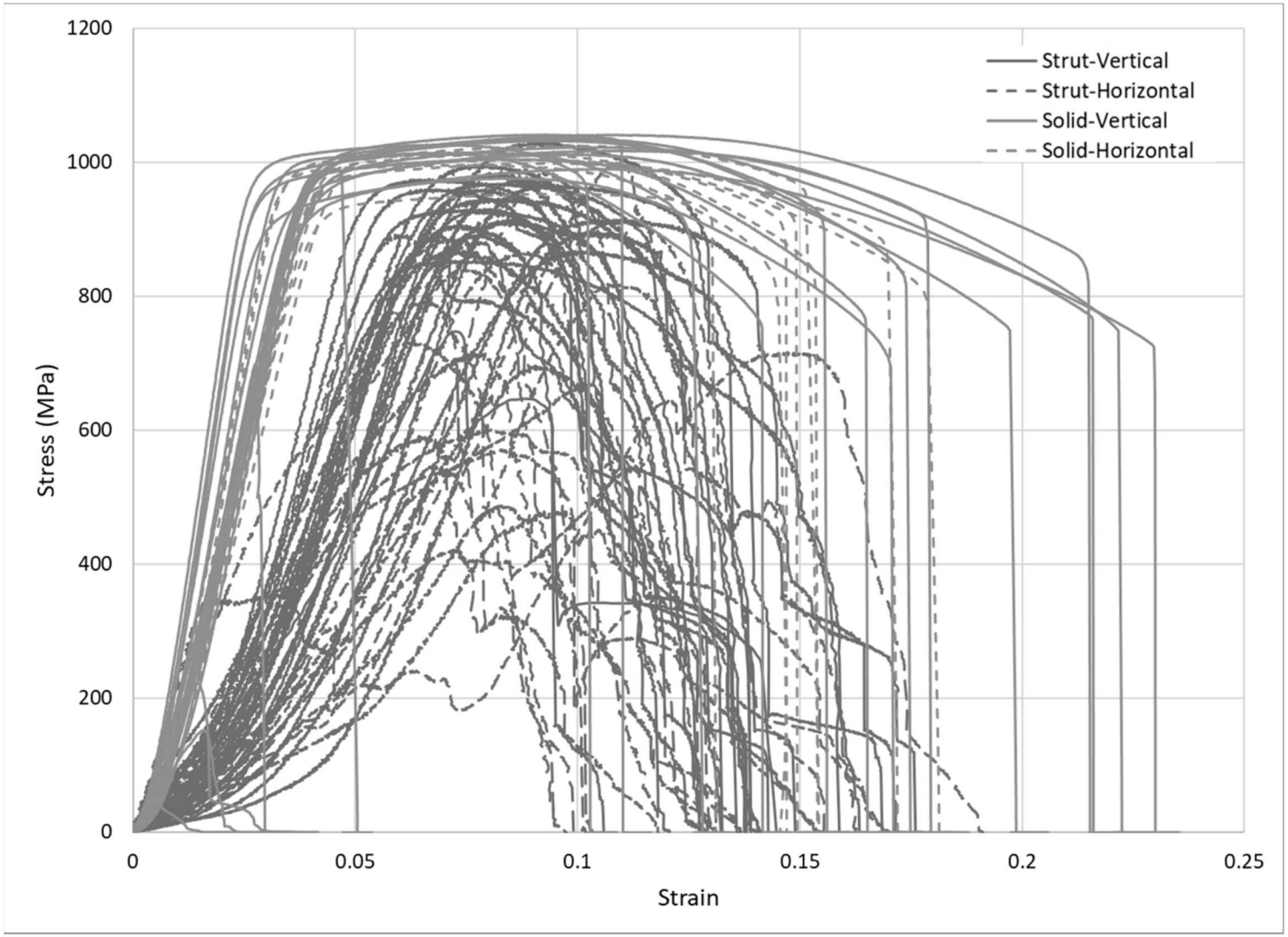




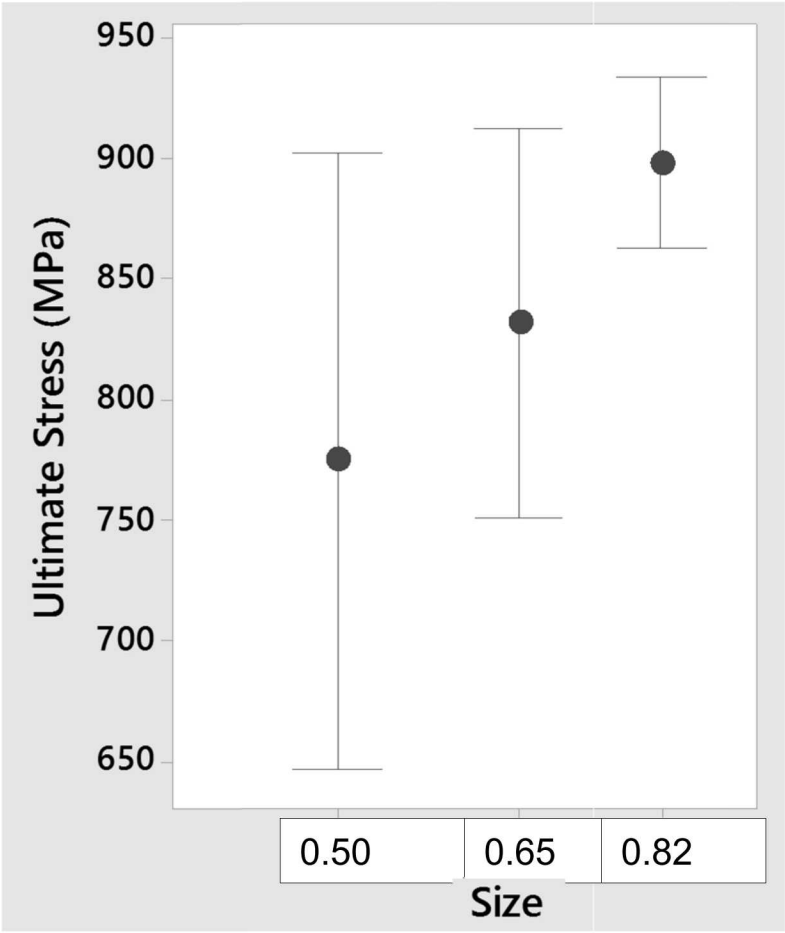


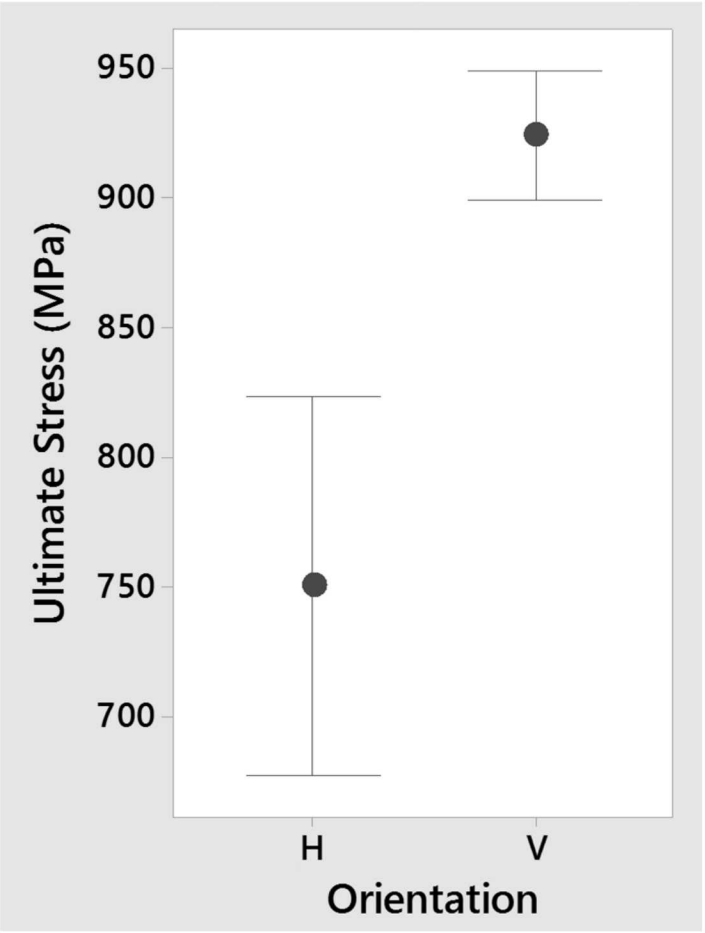
DATA ANALYSIS

Comparison of All Samples



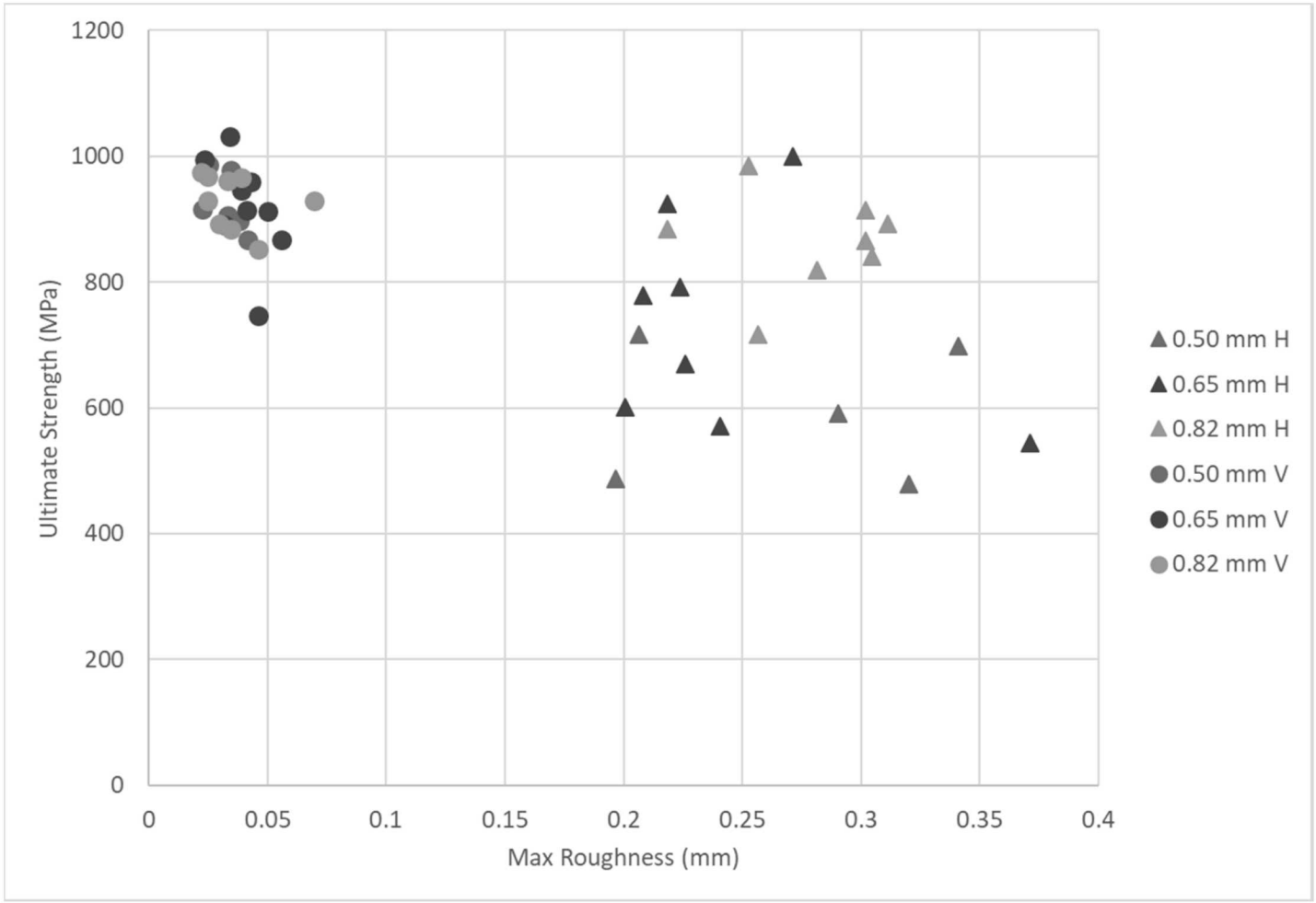
Ultimate Stress of Strut Samples





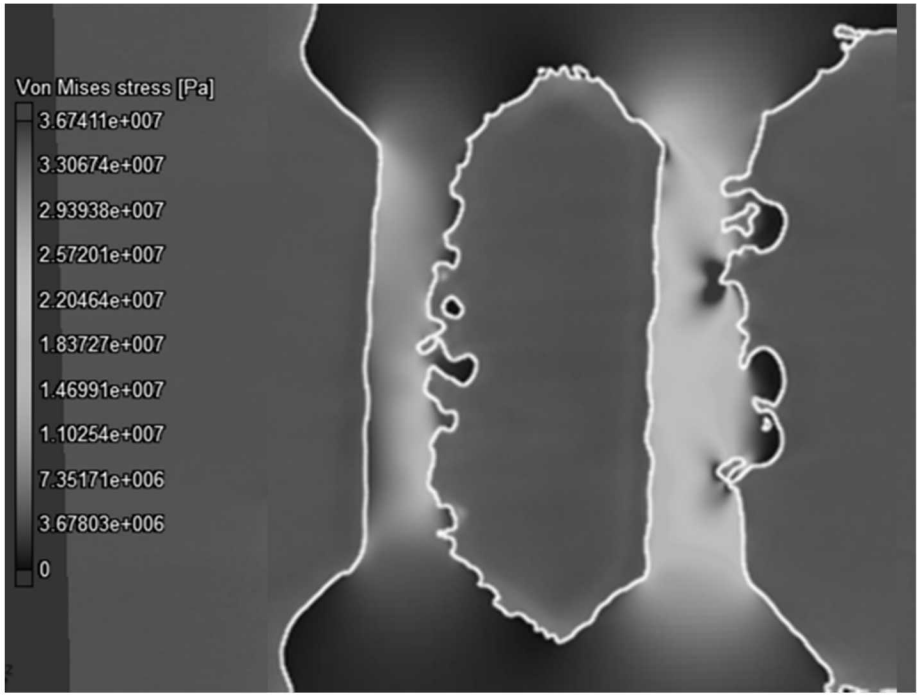
95% Confidence Interval for the Mean

Strut Roughness Compared to Strength

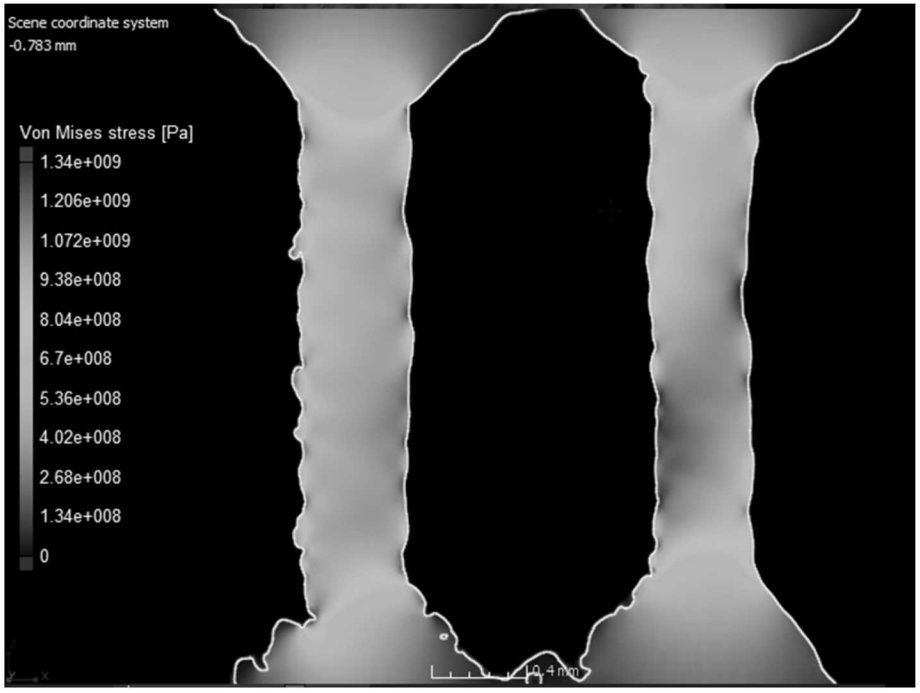


Stress Analysis of CT Data

Sample 32- 0.50 mm, Horizontal



Sample 7- 0.50 mm, Horizontal



Conclusions

- The heterogeneity of struts can dominate performance
- Unsupported features have large variation in part geometry and performance
- Surface roughness impacts part performance
- Impacts depend on feature size
- Porosity can have a large impact on part performance
- Parts are generally smaller than designed
- Still much to learn about performance of additive parts

Acknowledgements

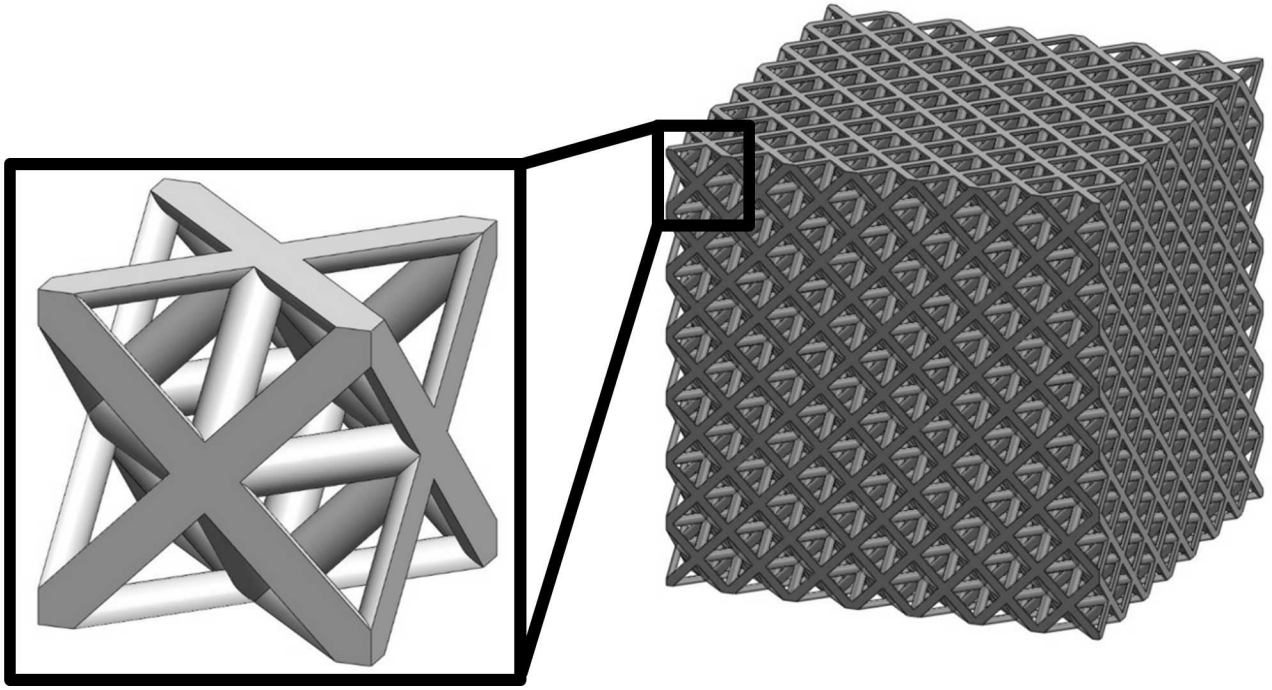
- Sandia National Labs
  - Allen Roach
  - Brad Boyce
  - Tommy Woodall
  - David Moore
  - Andrew Lentfer
  - Laura Swiler
  - Elliott Jost
  - John Miers
- Stratasys Direct Manufacturing
  - Ryan Ramon
  - Ashley Chipman
- Dr. Taleff

THANK YOU!

QUESTIONS?

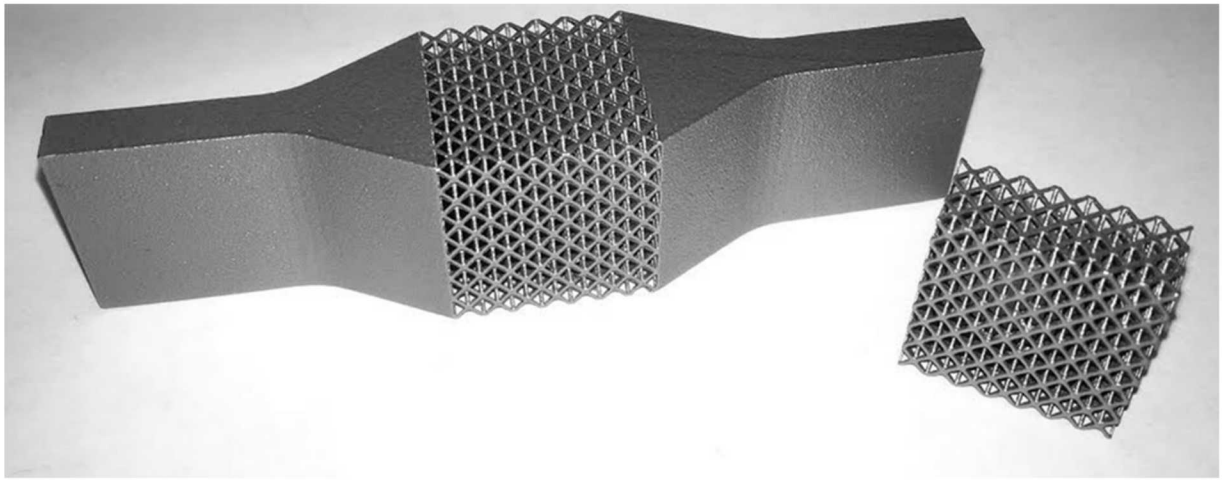
BACKUP SLIDES

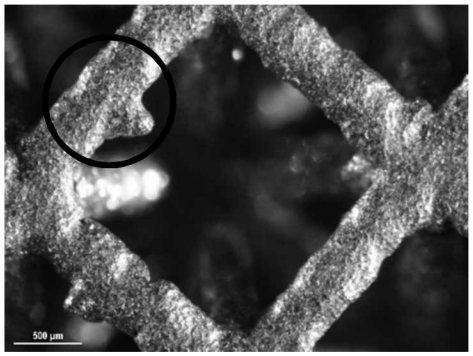
Octet Truss Lattice

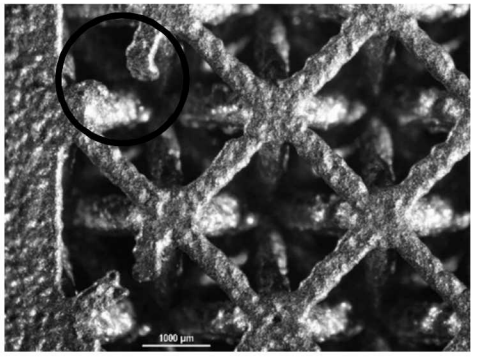


- Lattice structures offer favorable tradeoffs between strength and weight
- Structurally efficient due to nodal connectivity

Initial Test Parts



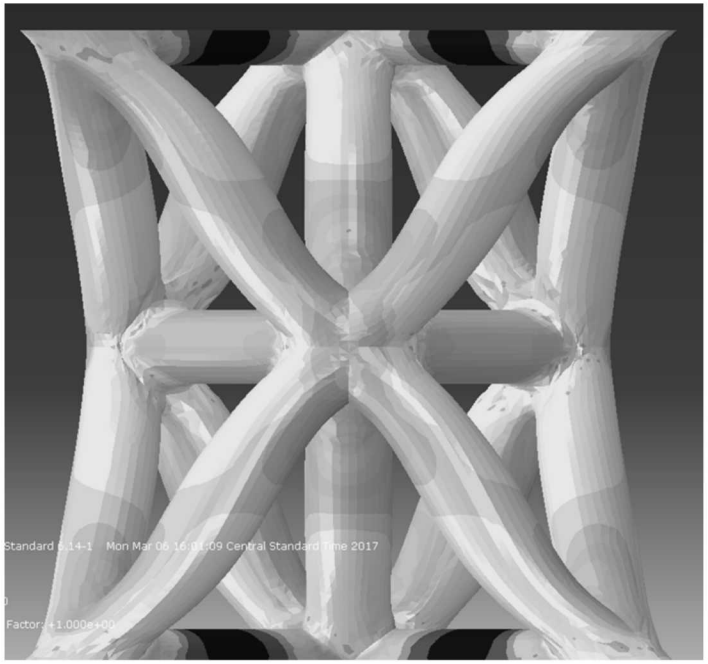




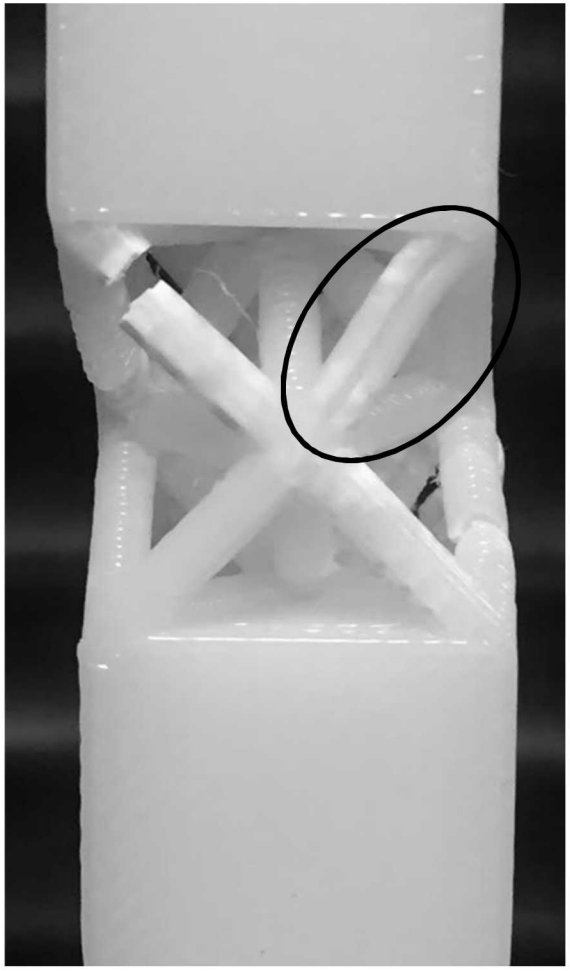
- Small amount of powder remained in the bar
  - Removed with a needle
- Struts were not completely round
- A few struts were missing

Deformation Studies

Abaqus Simulation



Plastic Test



Build Process

1. Direct Metal Laser Sinter the parts

   17-4 PH stainless steel powder on an EOS M270 with 20 micron layers

2. Heat Treatment

   Austenitizing by heating (solutionizing) to 1900°F for an hour, then air/oil cool

3. Part Removal

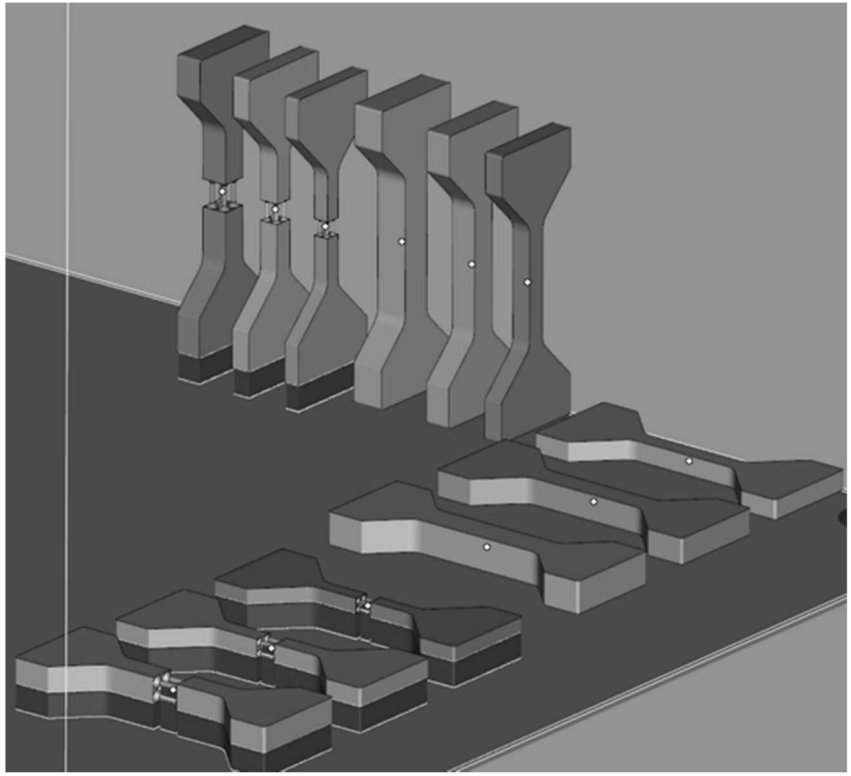
4. Hot Isostatic Pressing

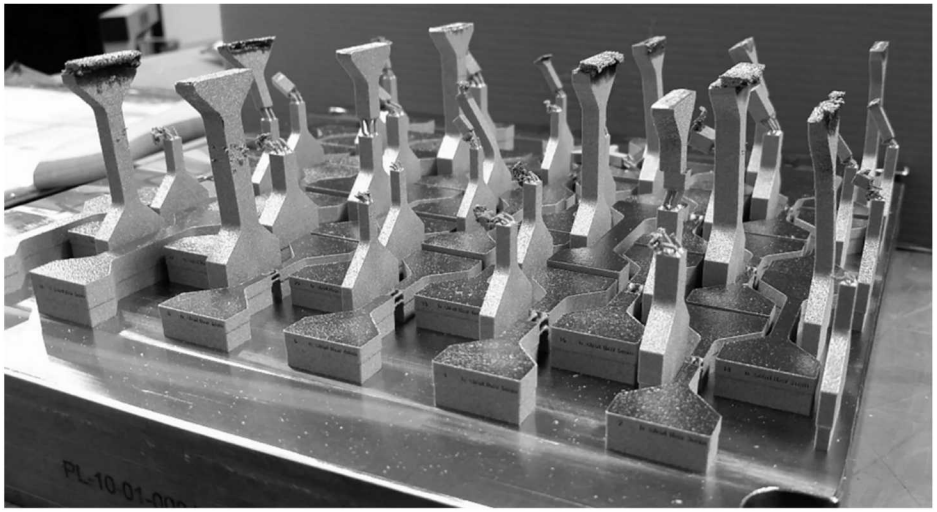
   2125±25 °F x 240±60 min x 14.75±0.25 ksi

5. Heat Treatment

   Austenitizing by heating (solutionizing) to 1900°F for an hour, then air/oil cool, and then complete the H1150 heat treatment.

Learning About Manufacturability

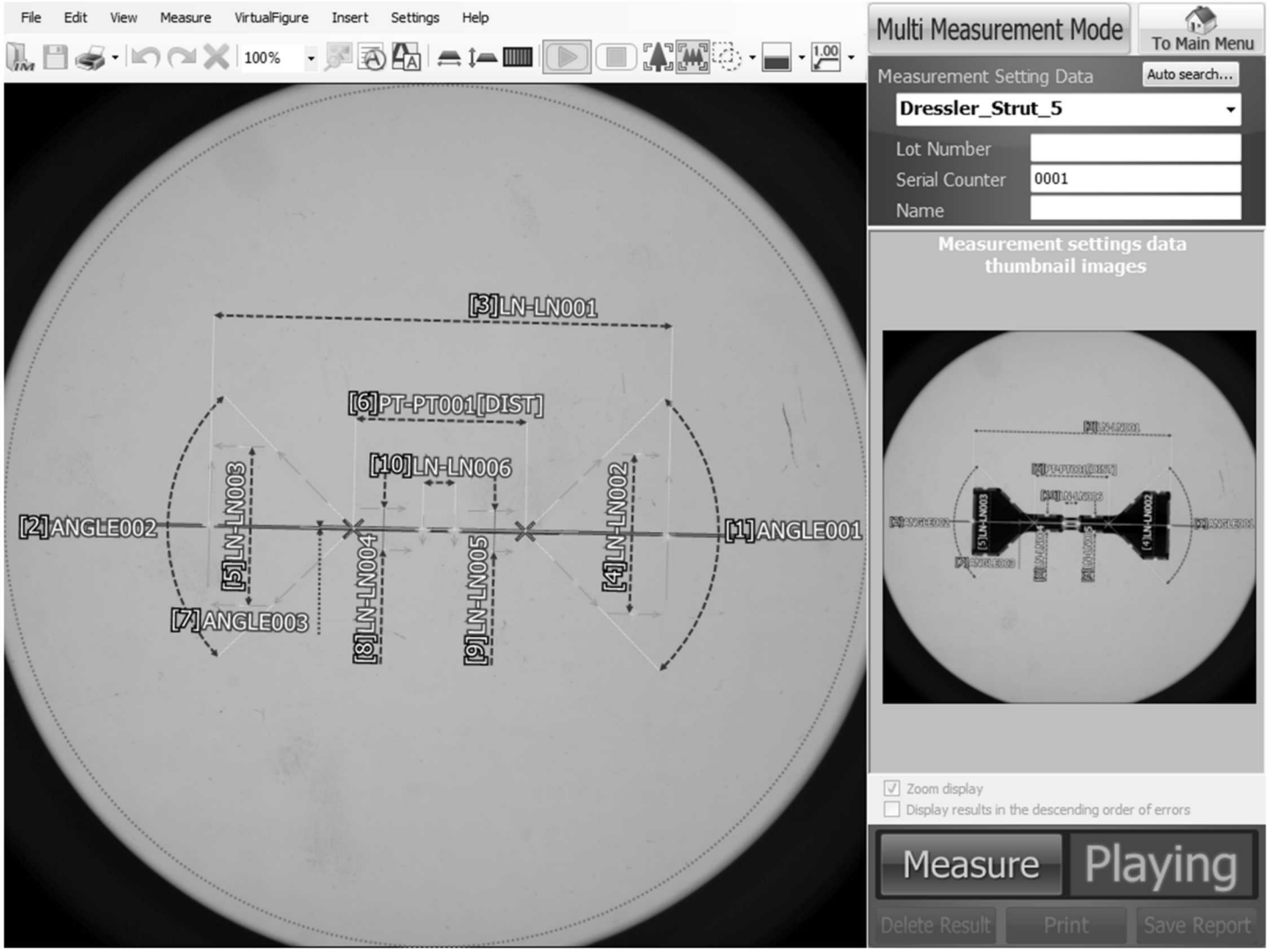




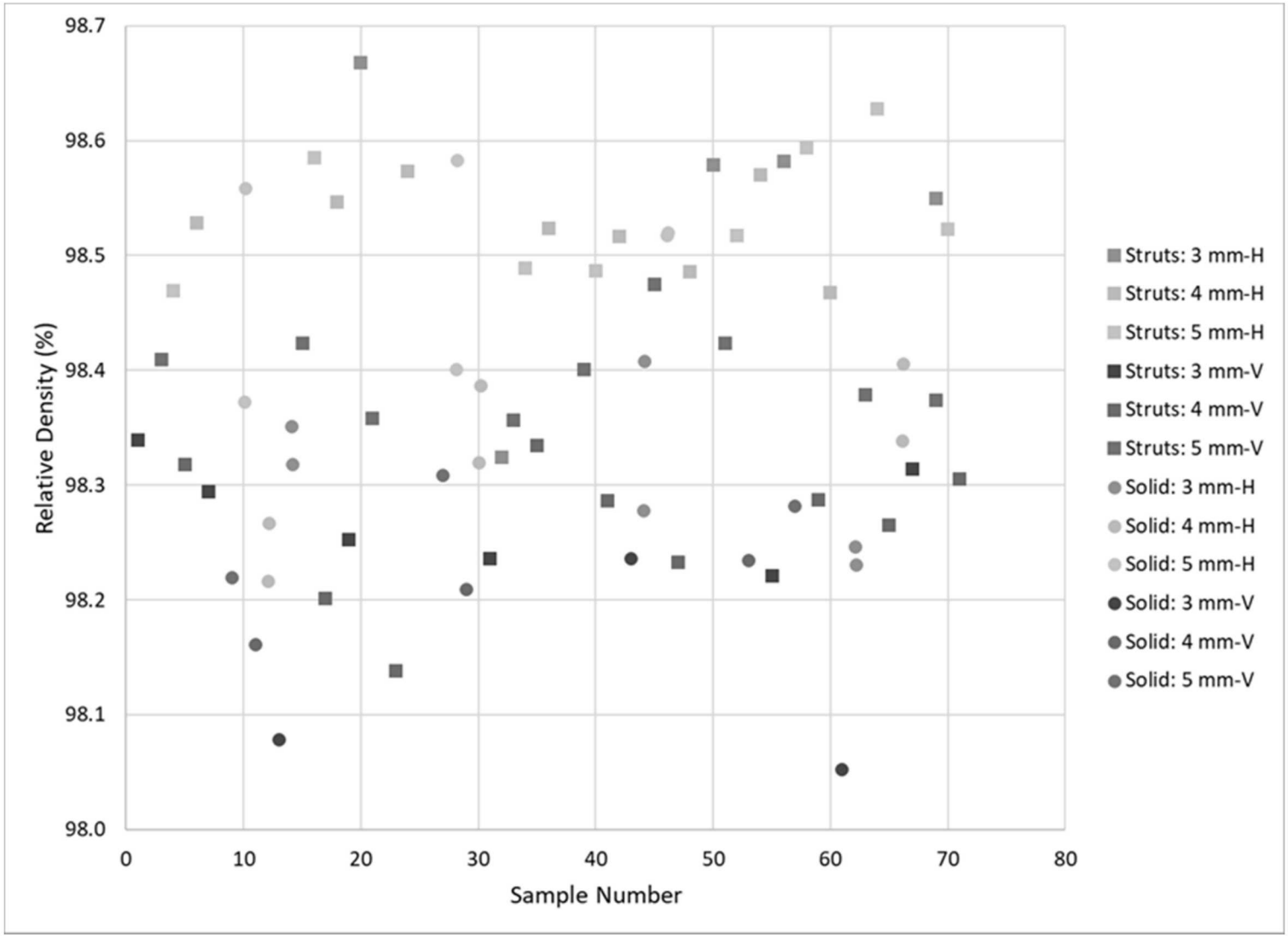
Rebuild Results

Unfortunately, horizontal bars were broken during removal from the build platform.

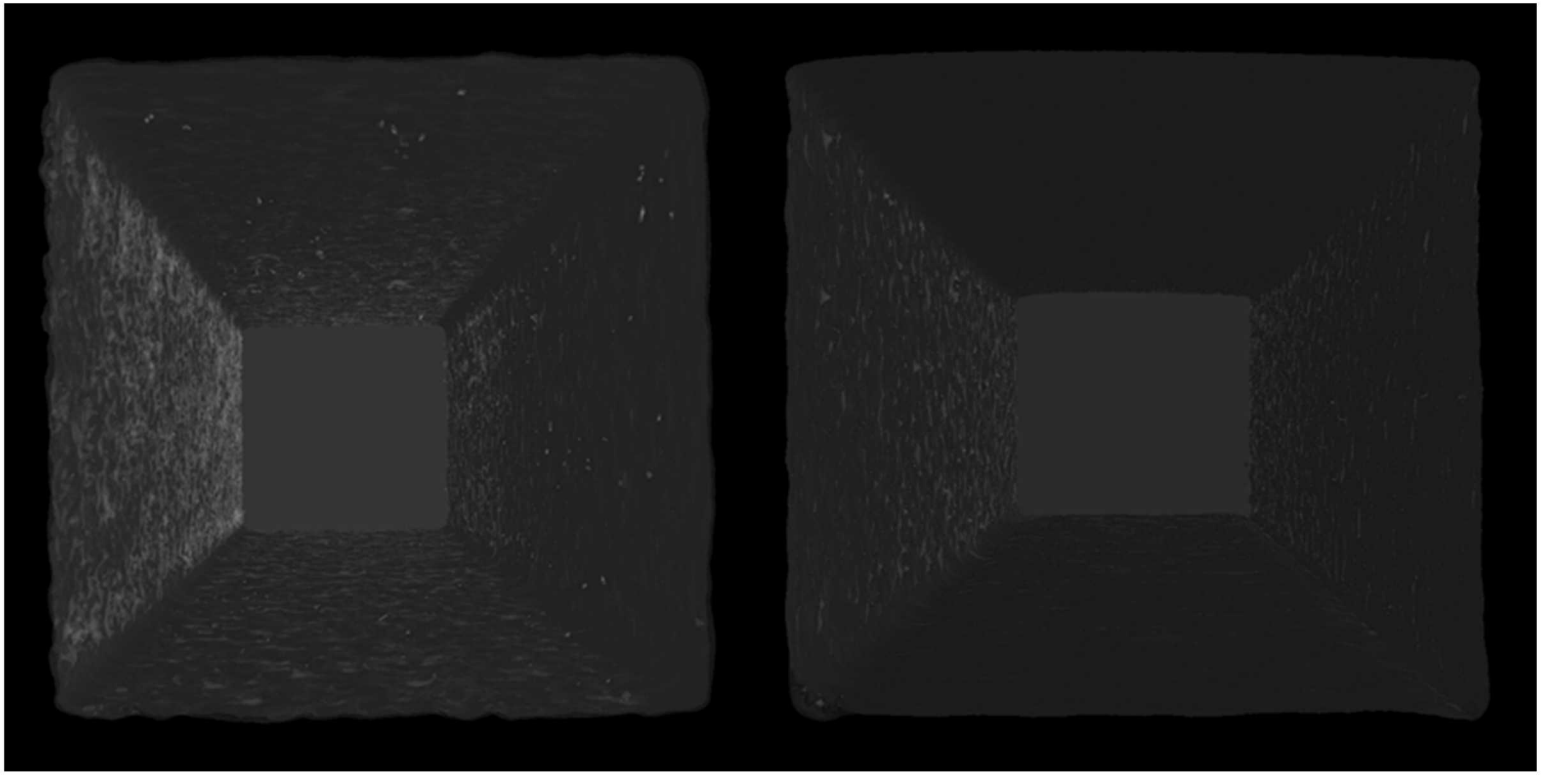
Geometric Characterization



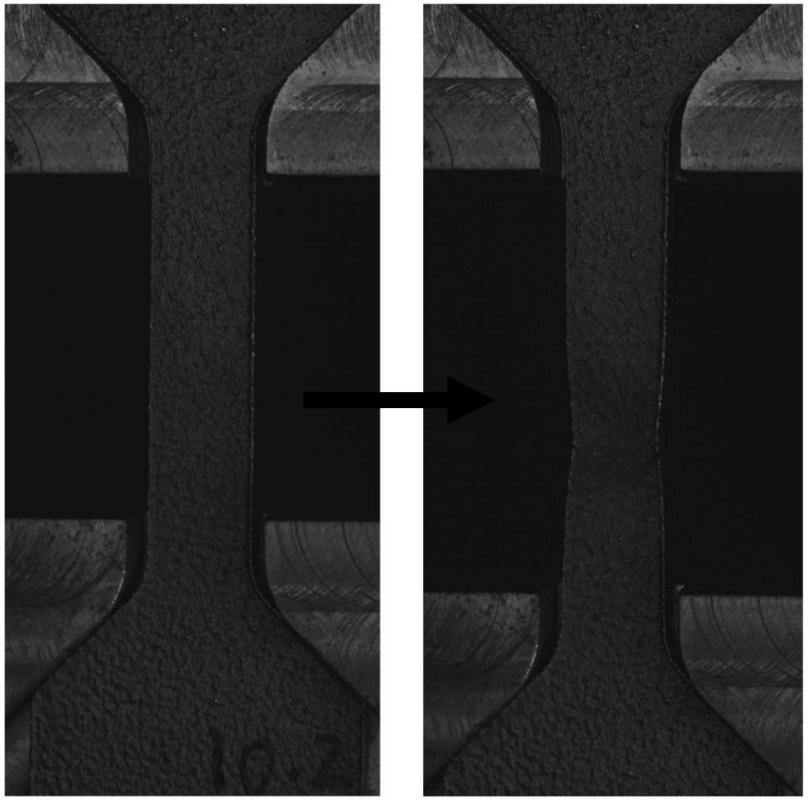
Density Measurements

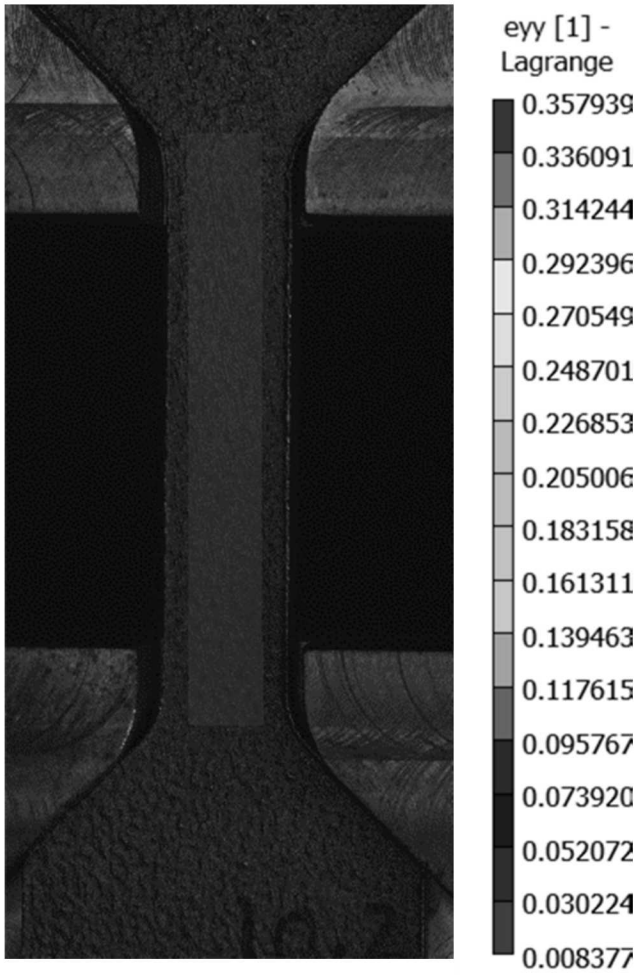


Porosity Analysis



Strain through Digital Image Correlation





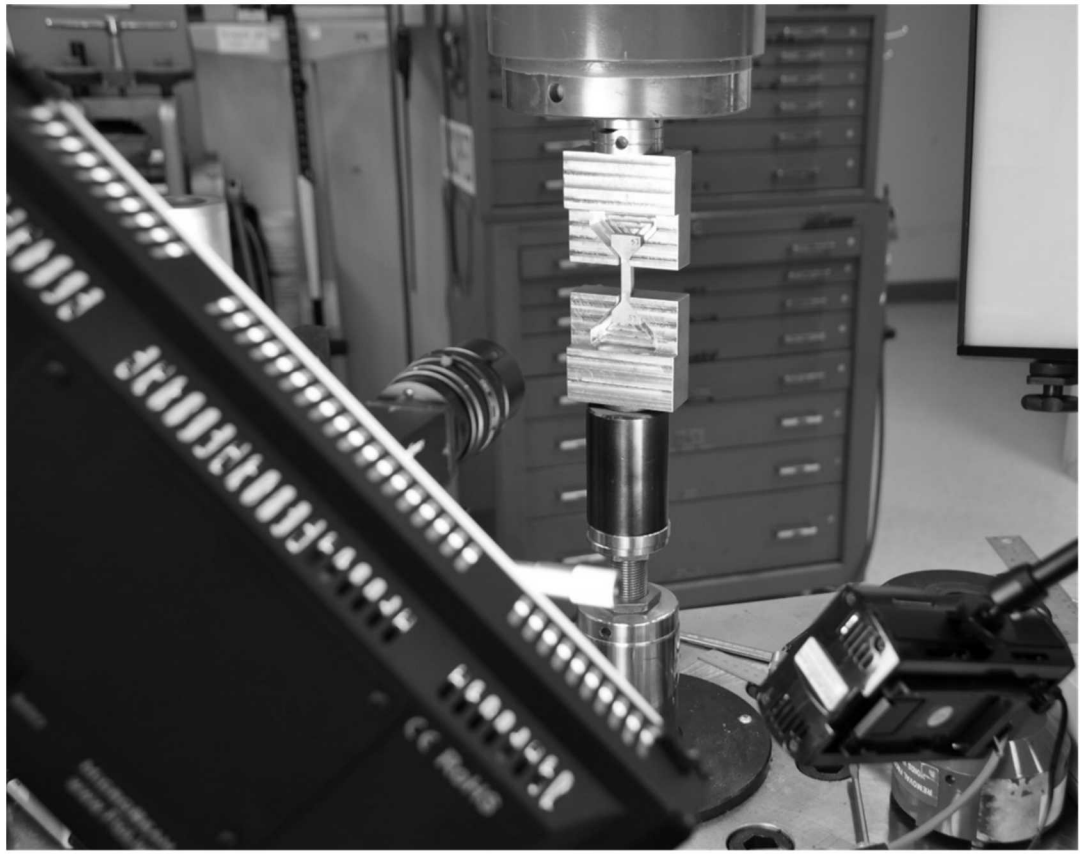
Test Setup

Data Acquisition: 15 Hz

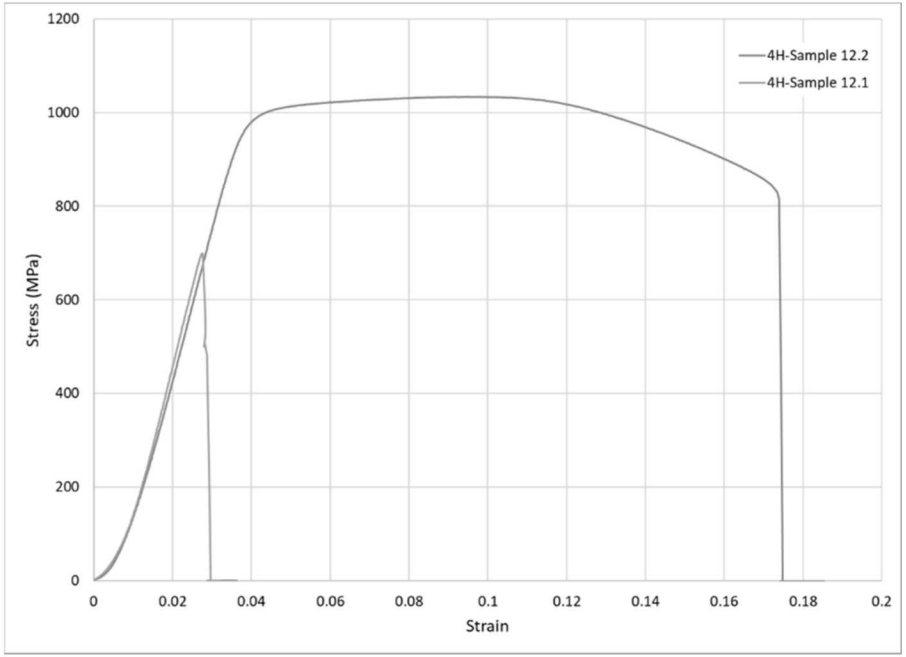
Image Acquisition: Varied

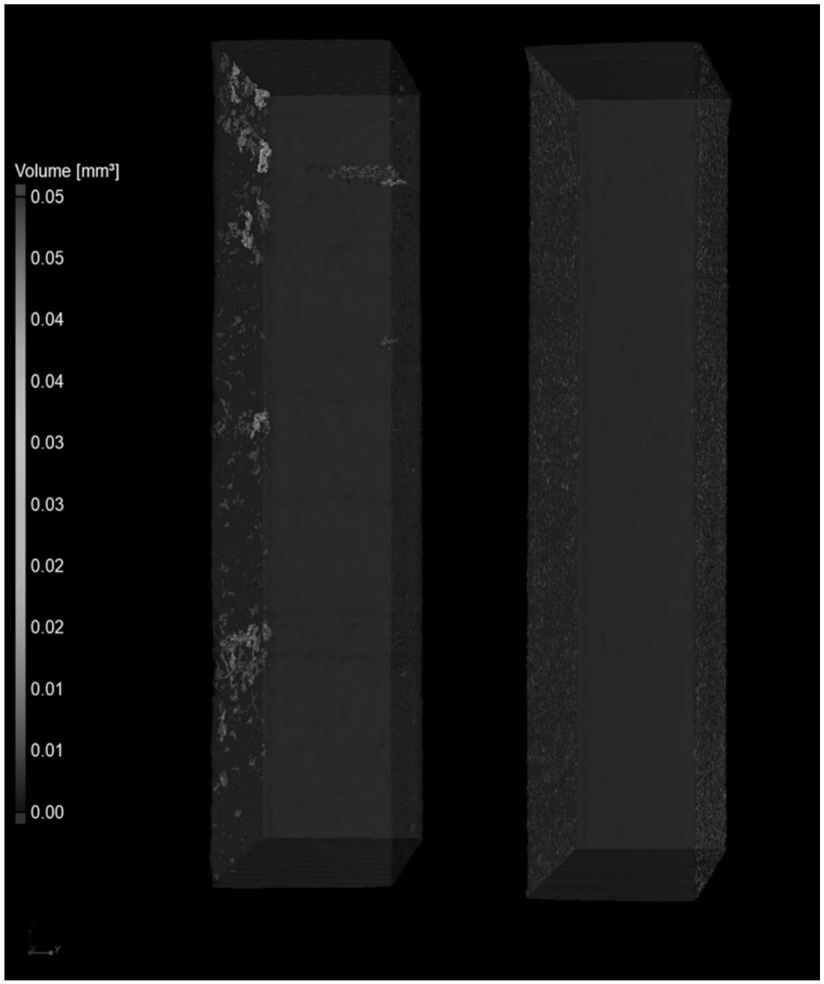
Actuator Rate:

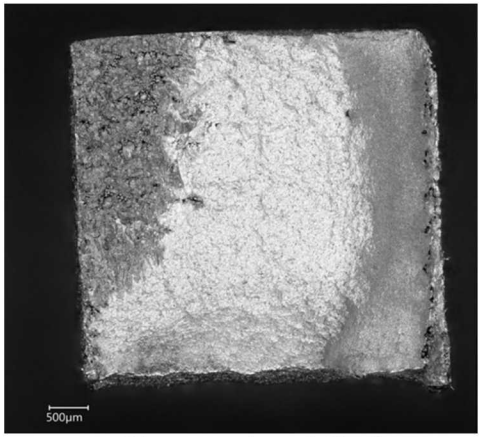
- 3 mm- 1.9 mm/min
- 4 mm- 2 mm/min
- 5 mm- 2.1 mm/min



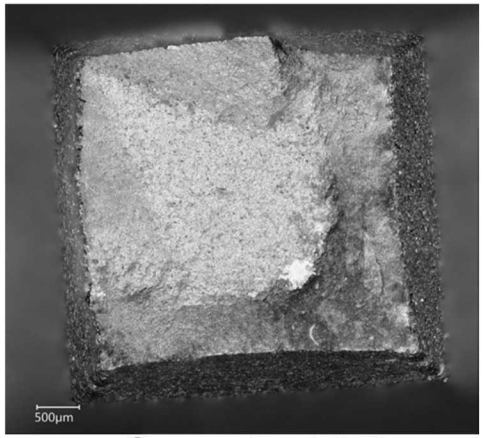
Sample 12.1 Versus 12.2 (4 mm)







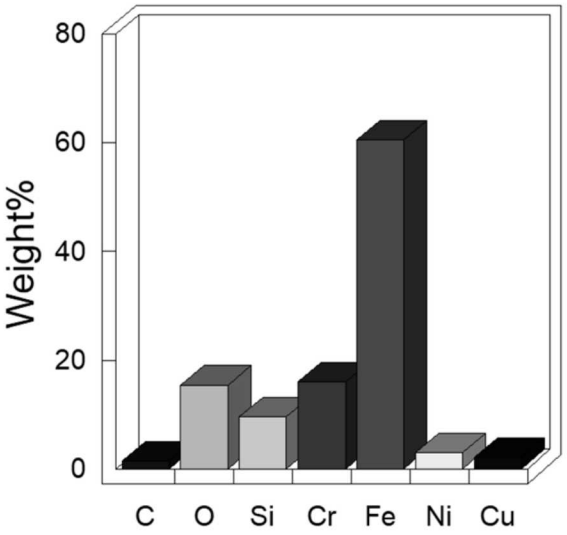
Sample 12.1

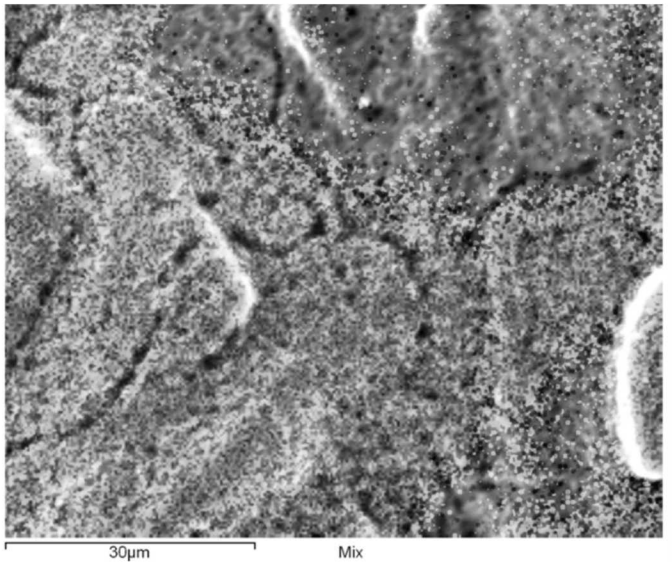


Sample 12.2

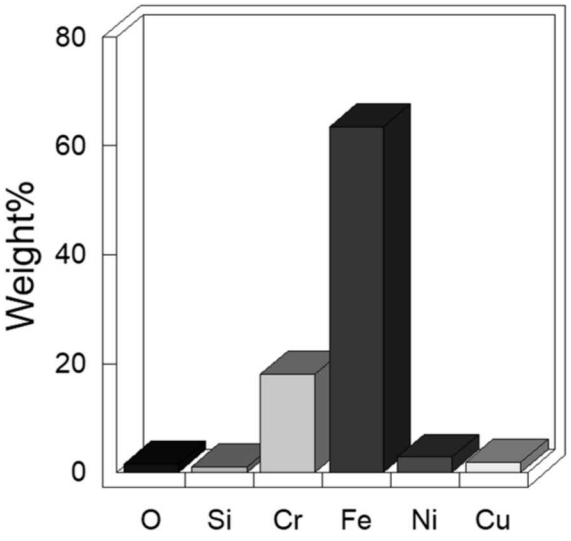
Sample 14.1 Versus 14.2 (3 mm)

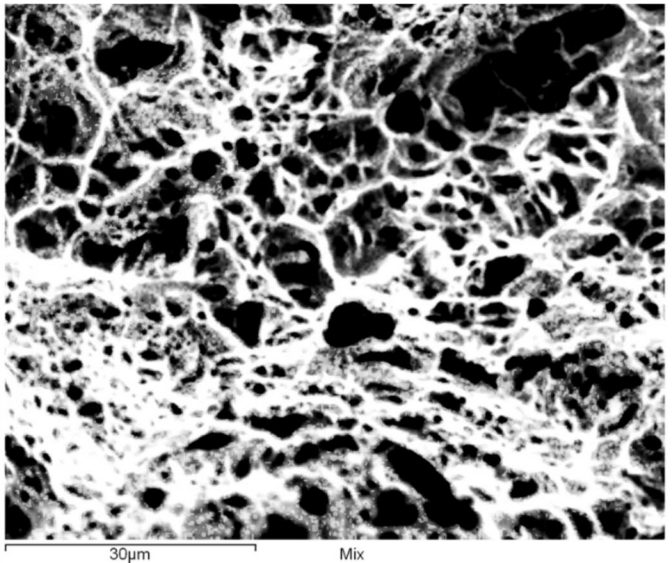
Sample 14.1



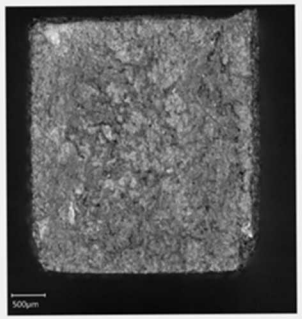
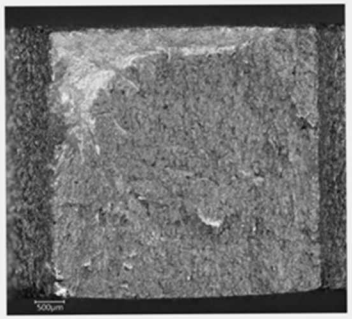
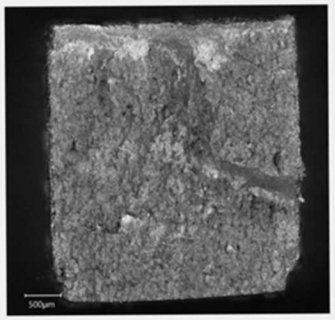
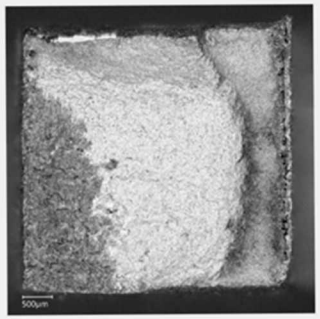
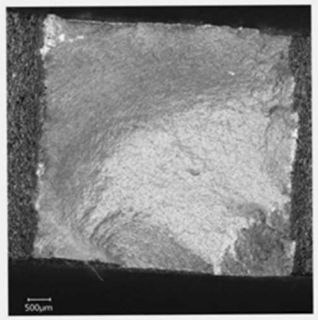
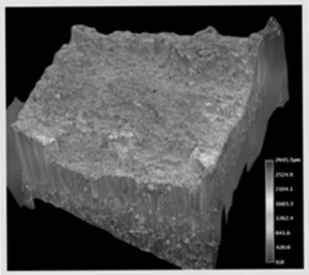
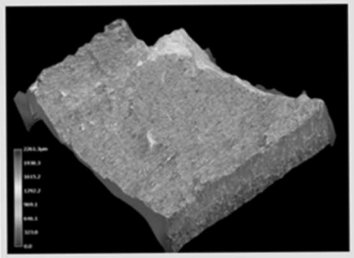
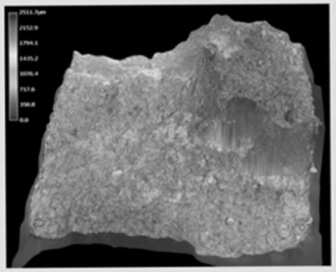
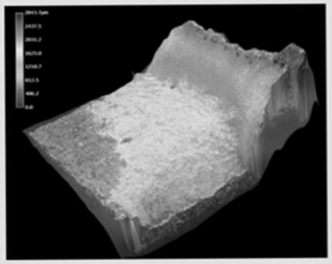
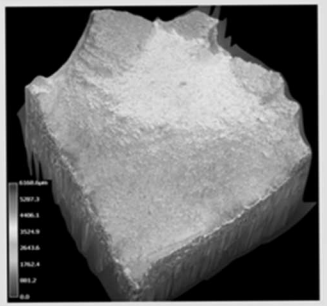


Sample 14.2





Impact on Performance

	Sample 14.1 (3 mm)	Sample 30.1 (4 mm)	Sample 44.1 (3 mm)	Sample 12.1 (4 mm)	Sample 28.1 (5 mm)
Ultimate Strength	71 MPa	152 MPa	223 MPa	699 MPa	988 MPa
Discoloring					
Height Map (Height Range)	 (0-2945.7 µm)	 (0-2261.3 µm)	 (0-2511.7 µm)	 (0-2843.7 µm)	 (0-6168.6 µm)

Test Setup

Data Acquisition: 15 Hz

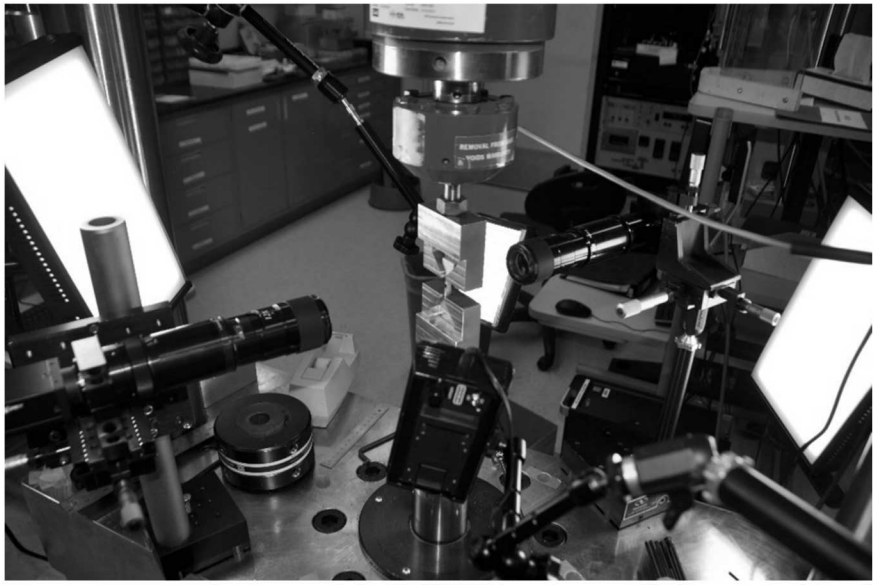
Image Acquisition: 1 Hz

Actuator Rate:

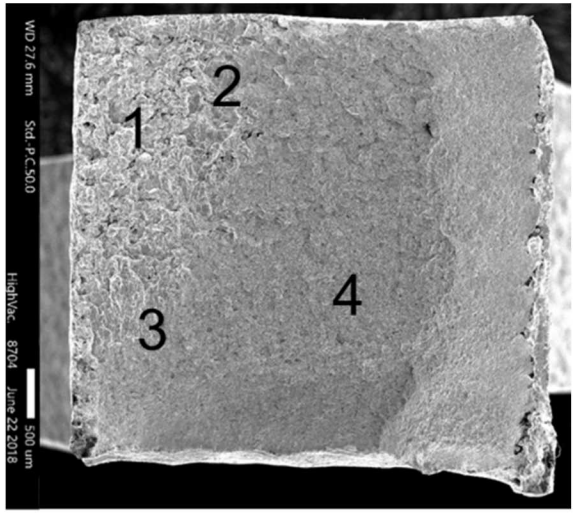
0.50 mm- 0.225 mm/min

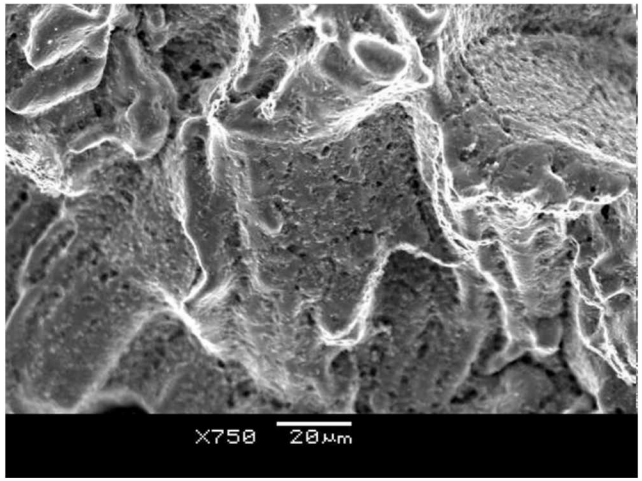
0.65 mm- 0.3 mm/min

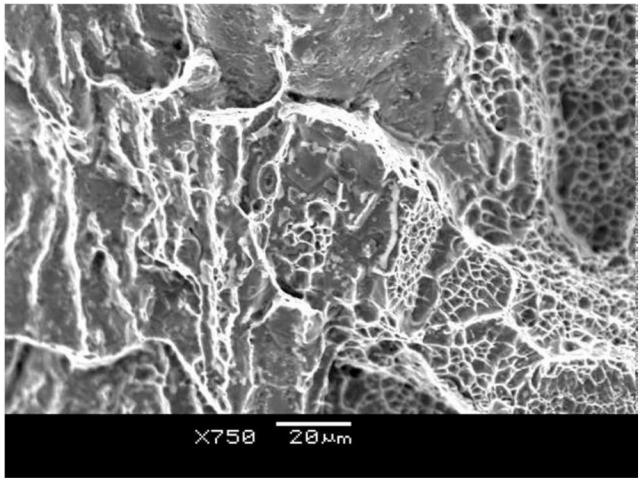
0.82 mm- 0.375 mm/min

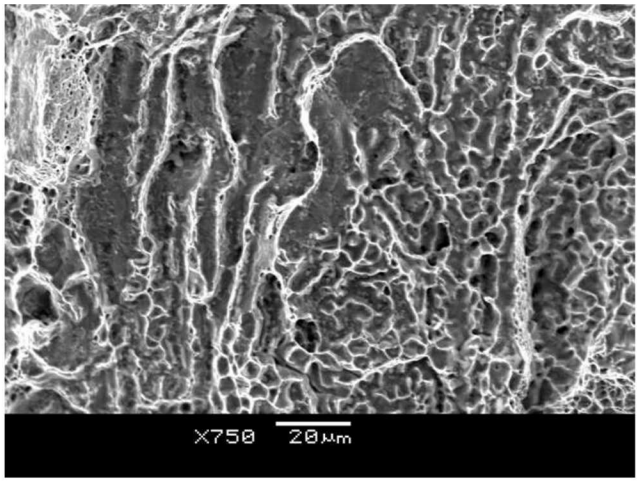


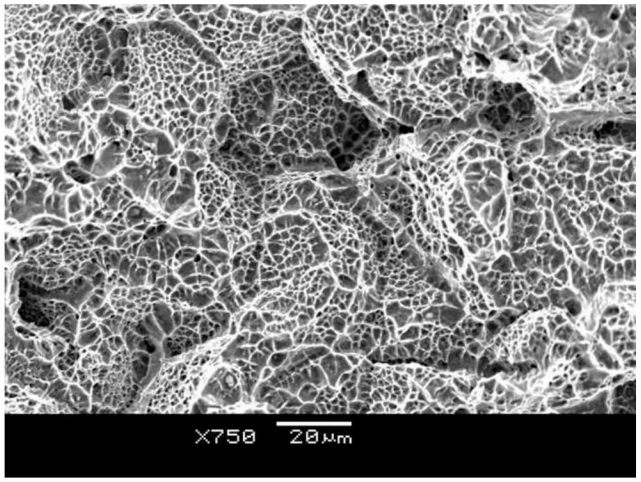
Regions of Interest in Sample 12.1





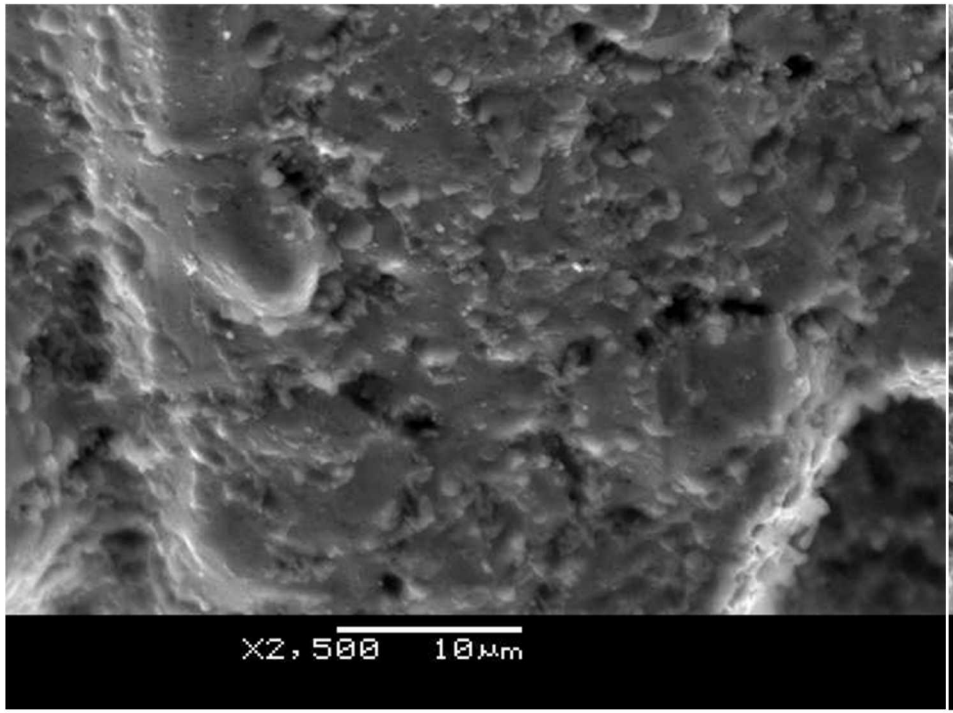




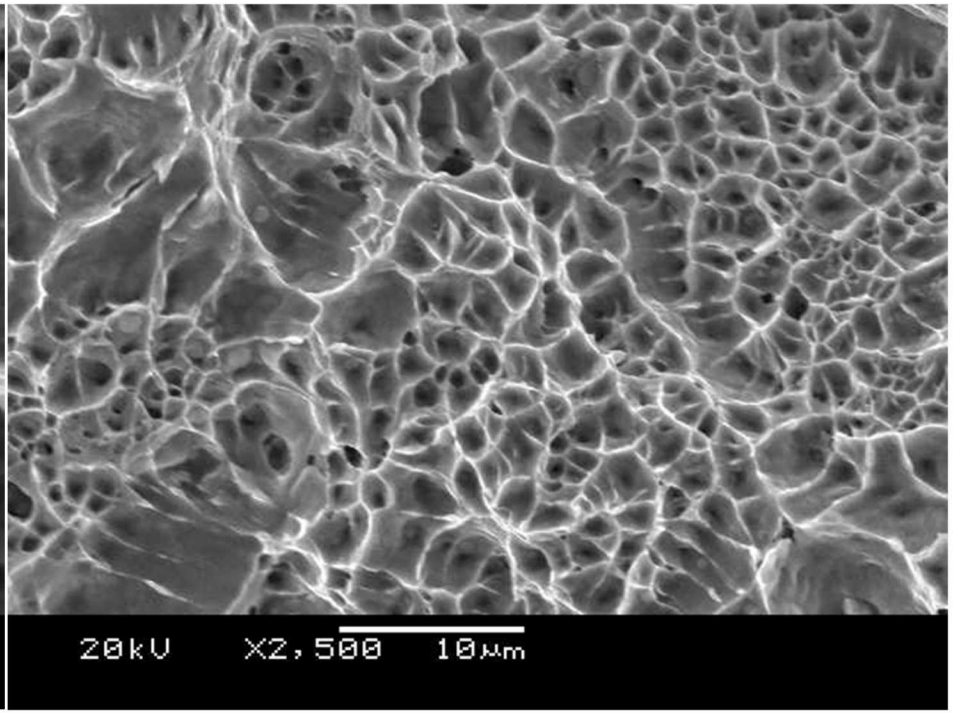


Fractography

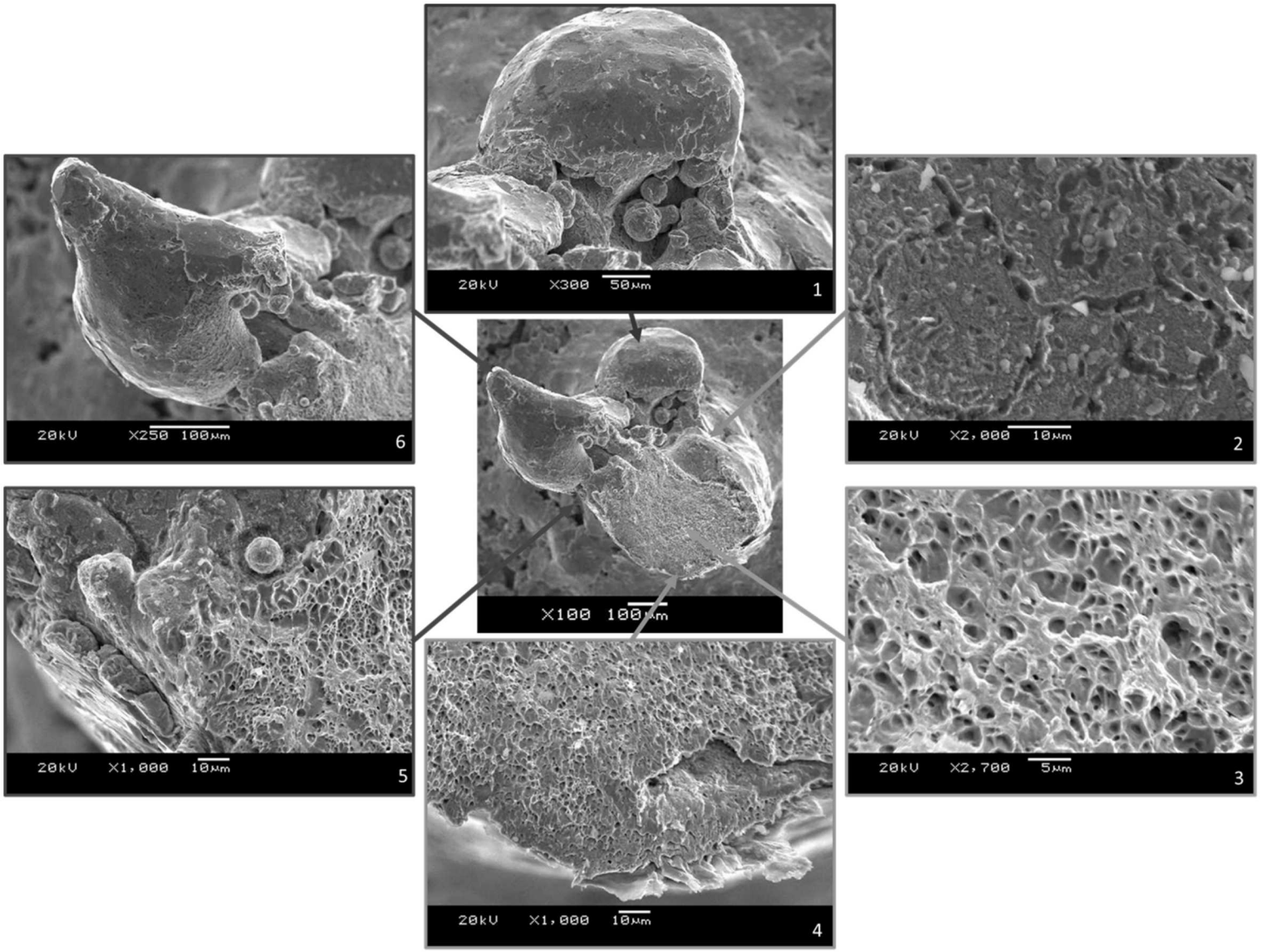
Sample 12.1



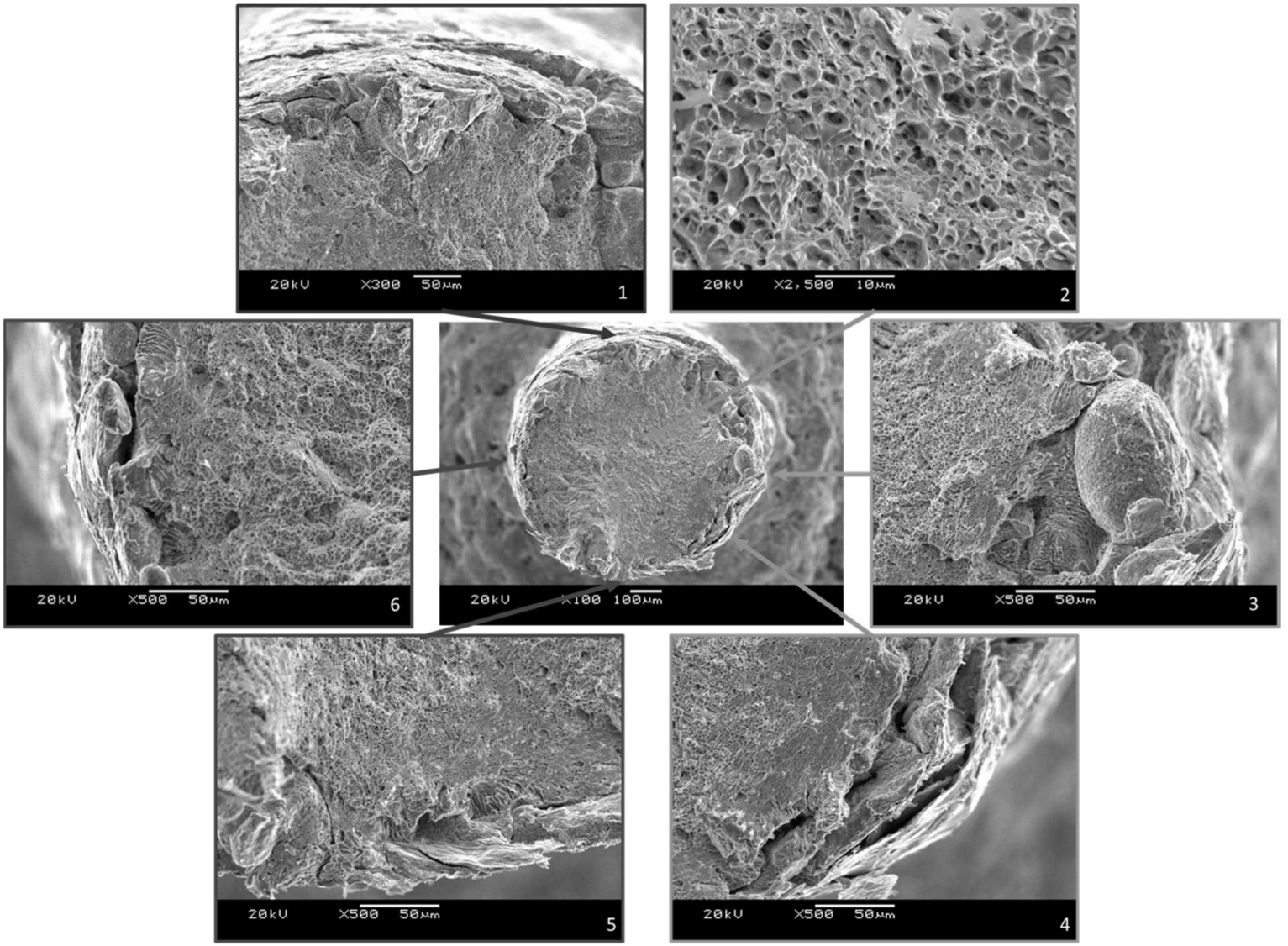
Sample 12.2



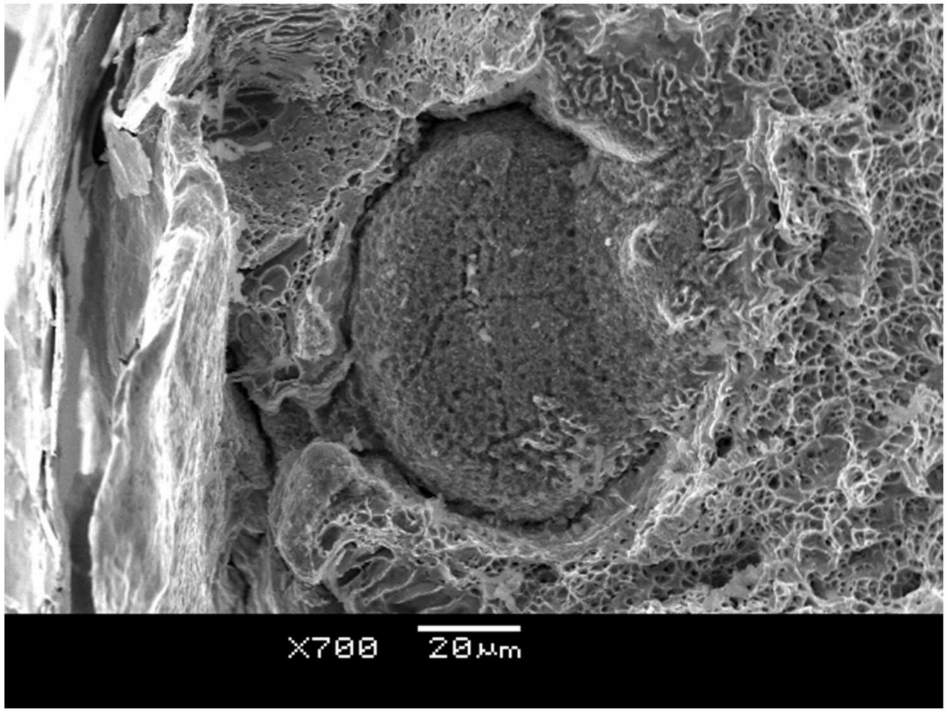
Sample 68-Center Strut

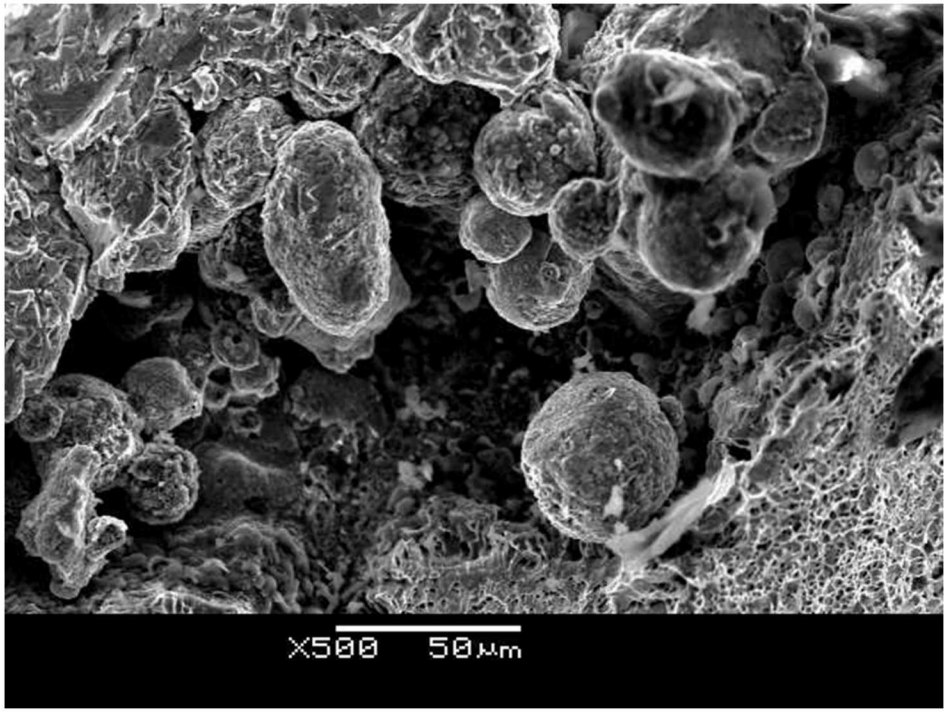


Sample 51-Center Strut

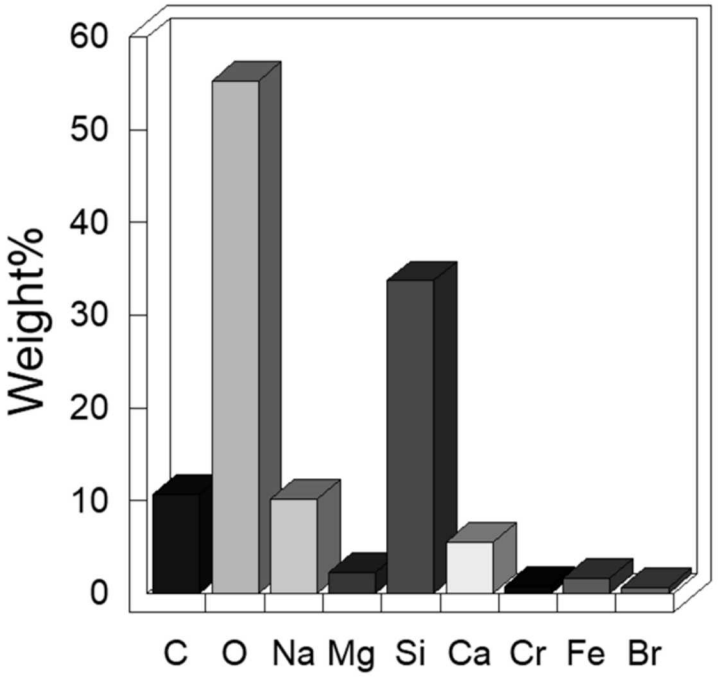


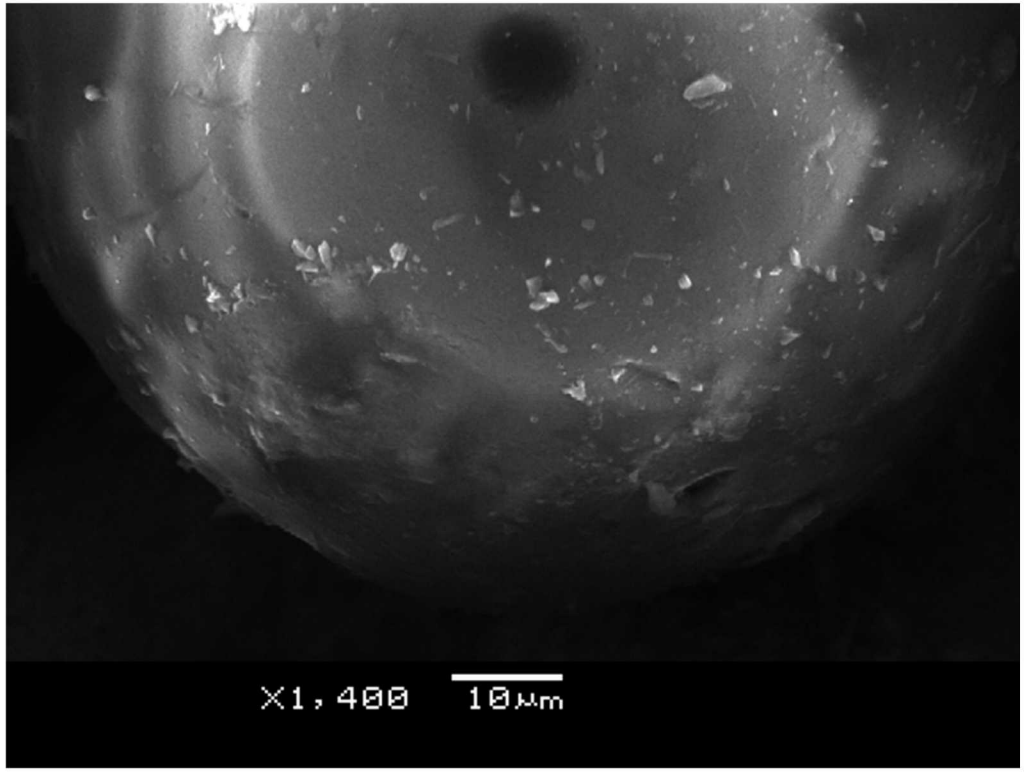
Variation in Unsintered Particles



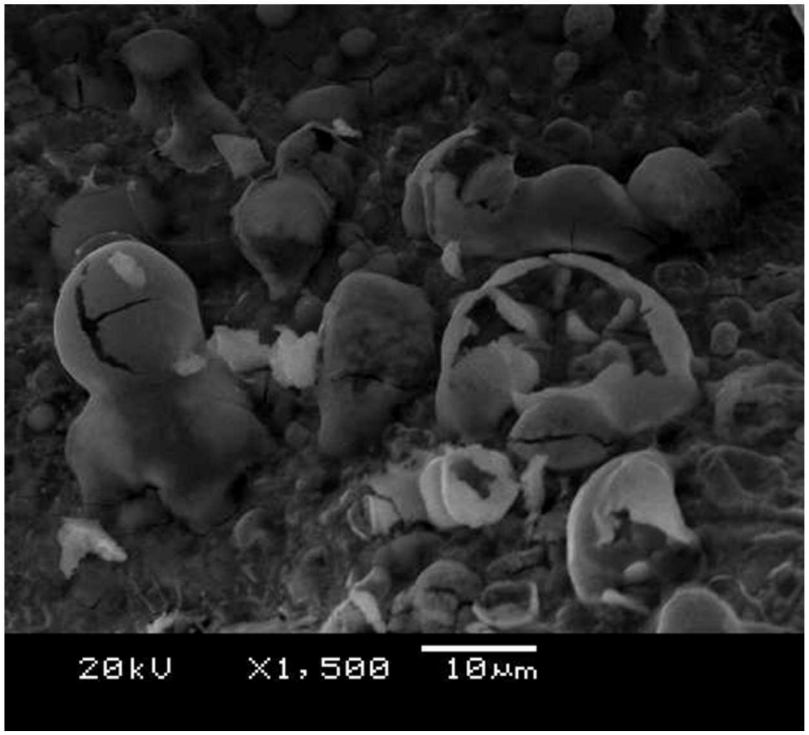


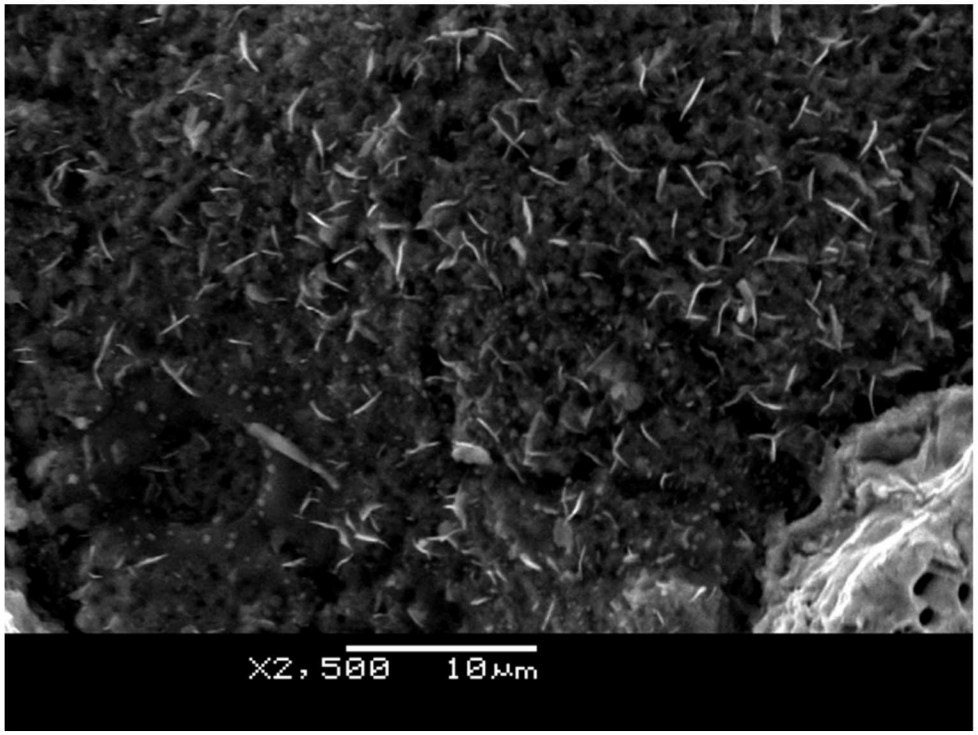
Impurity in Sample 6



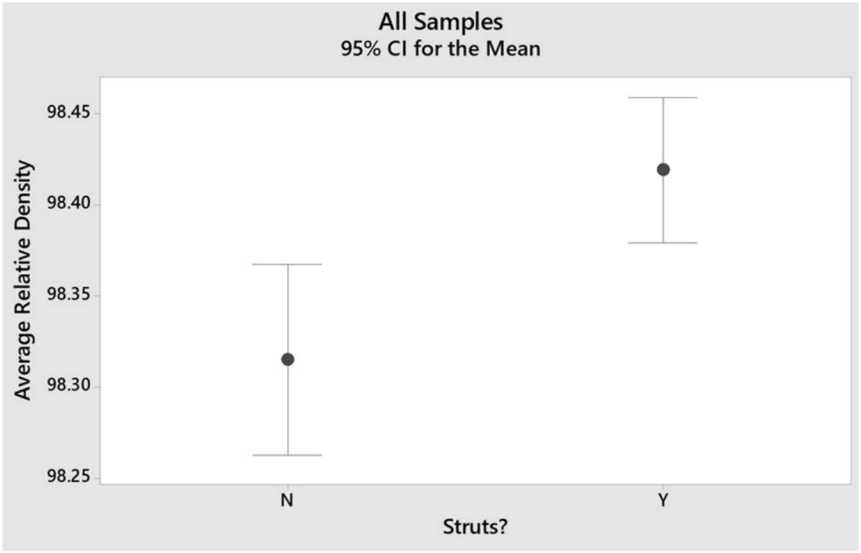


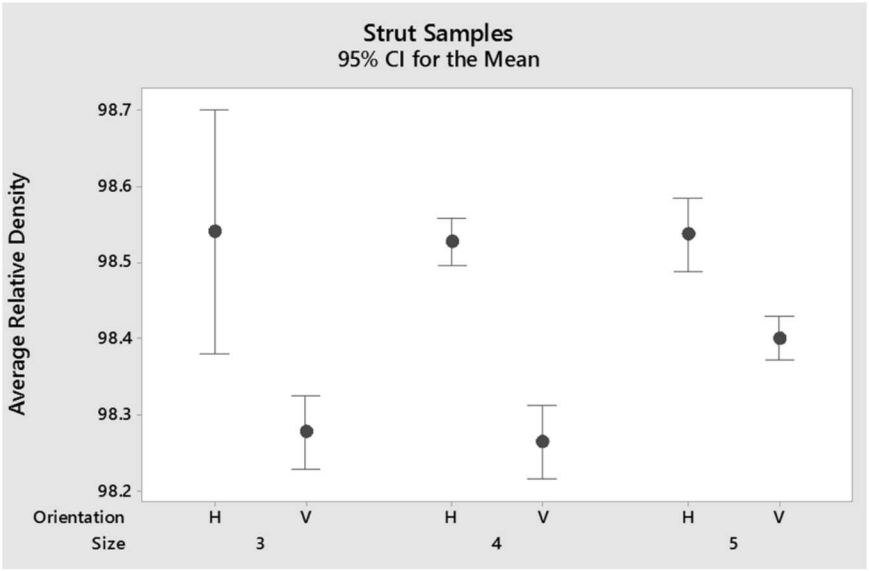
Unidentified Fracture Objects

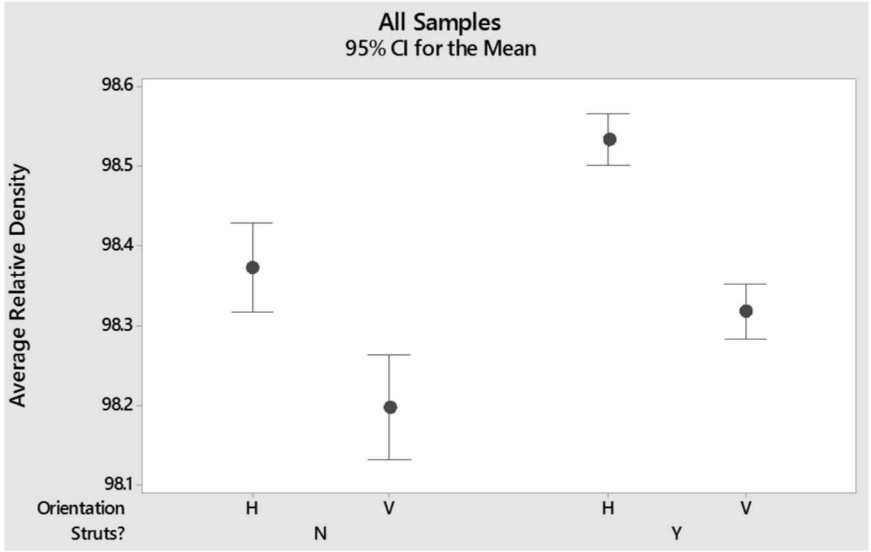




Density

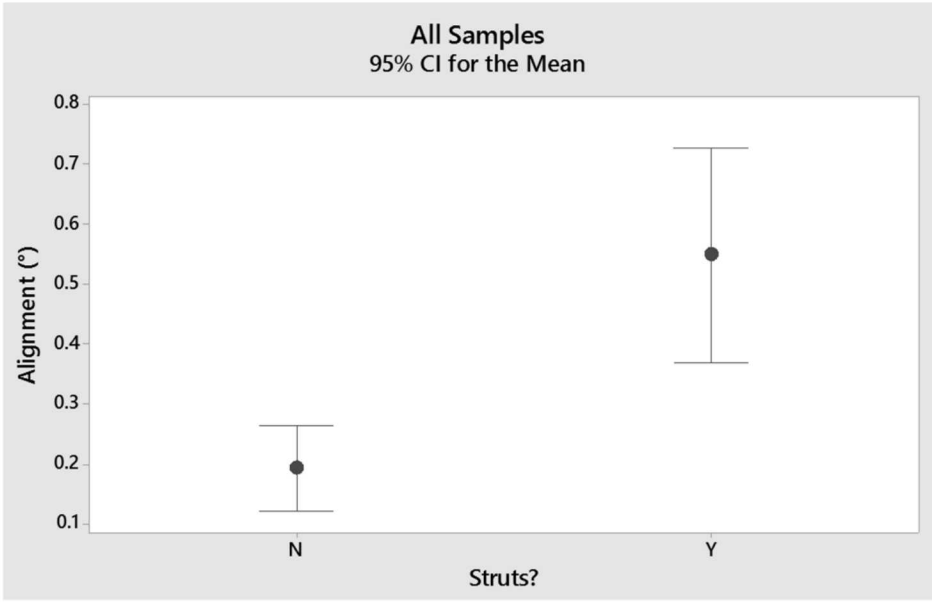


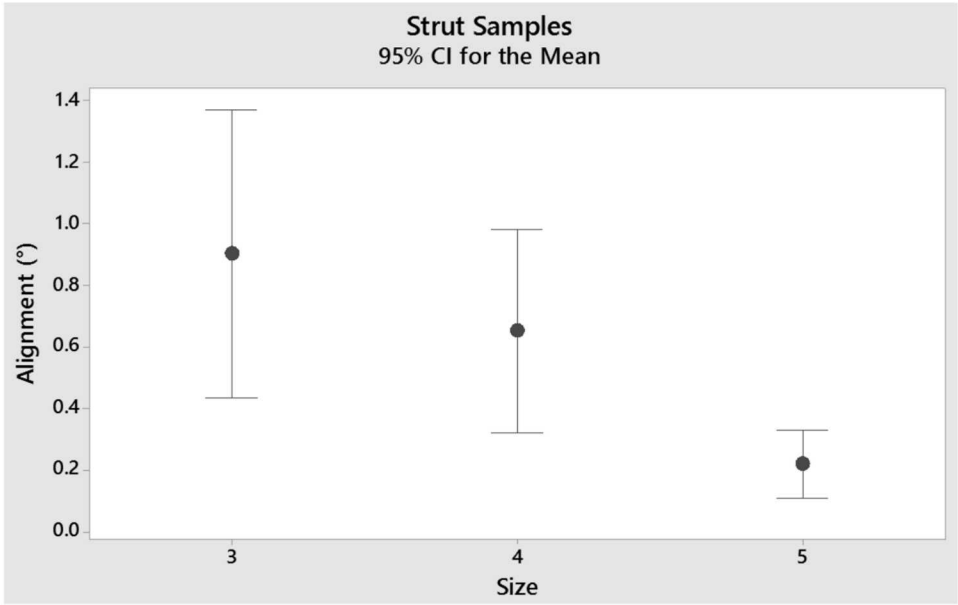




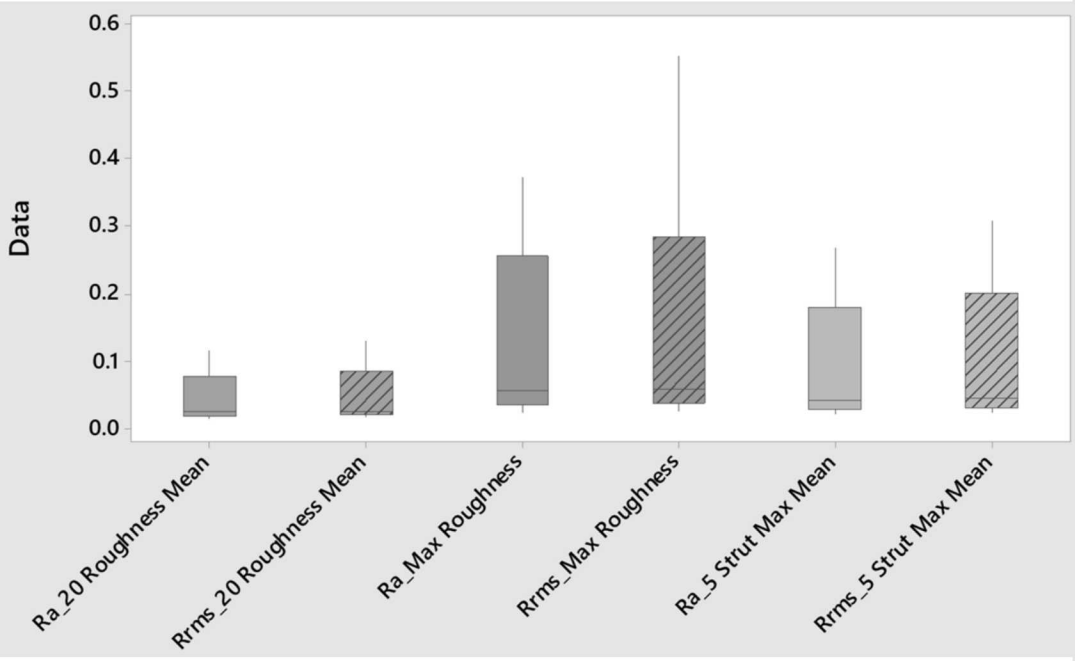
Gage R&R attributes 40% of variation to measurement replications

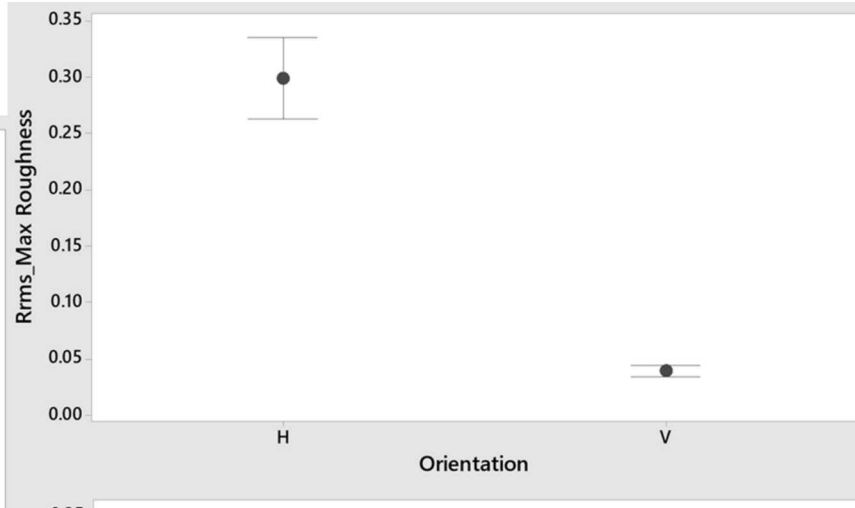
Grip Alignment

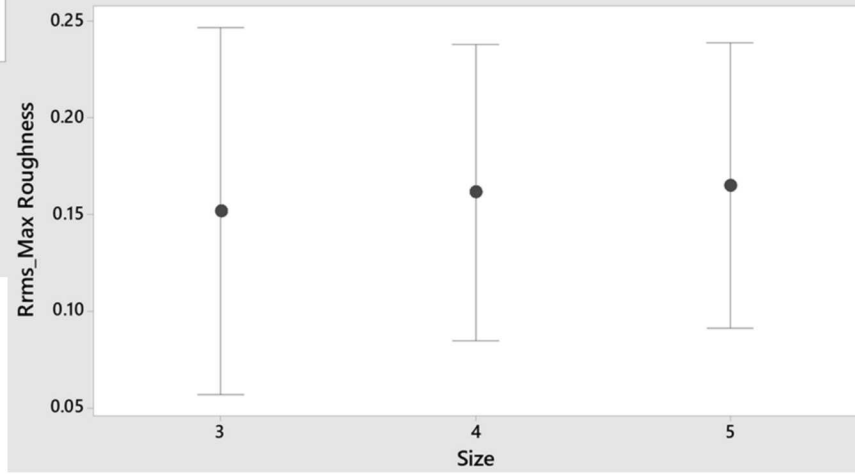




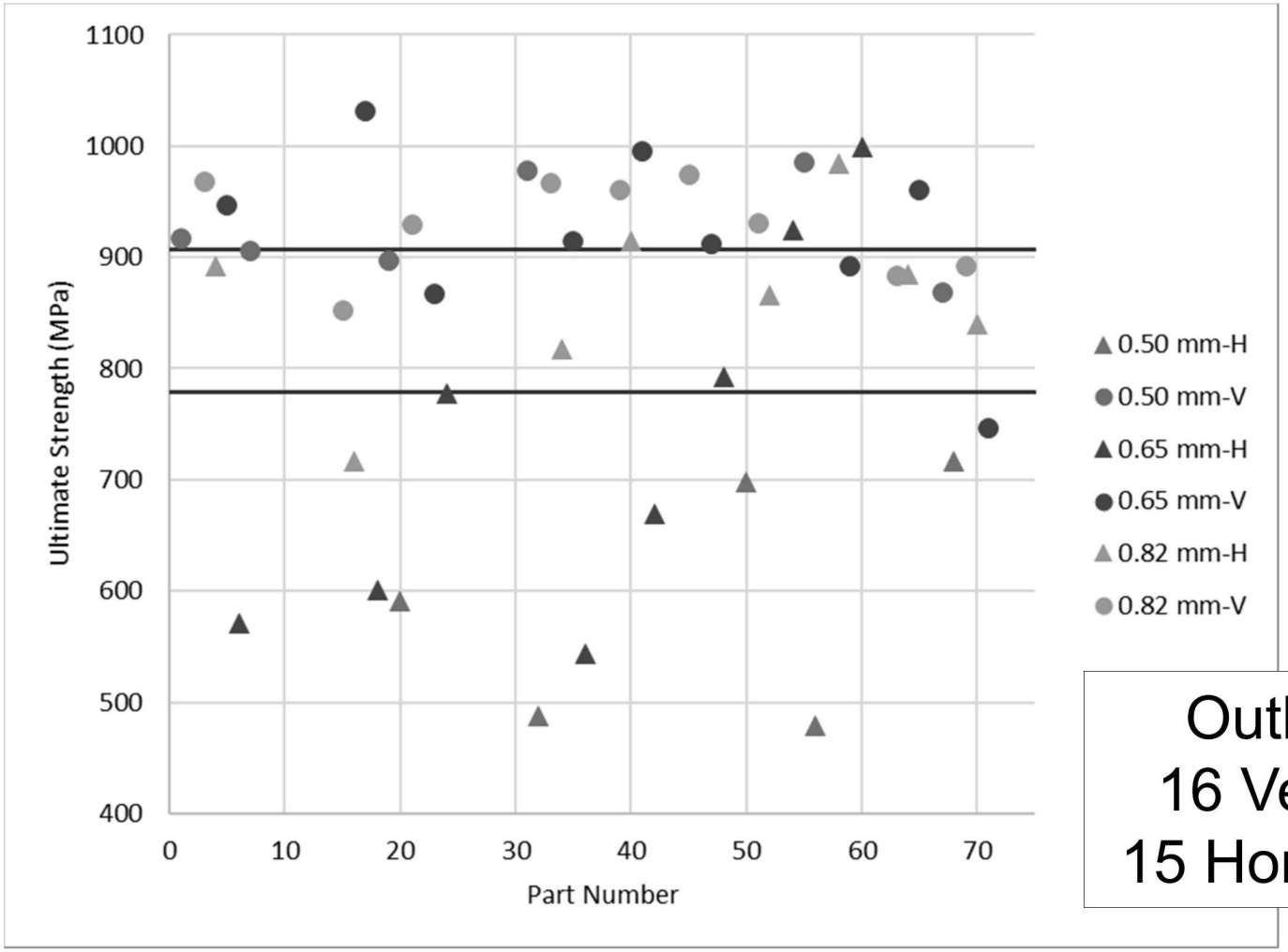
Strut Roughness





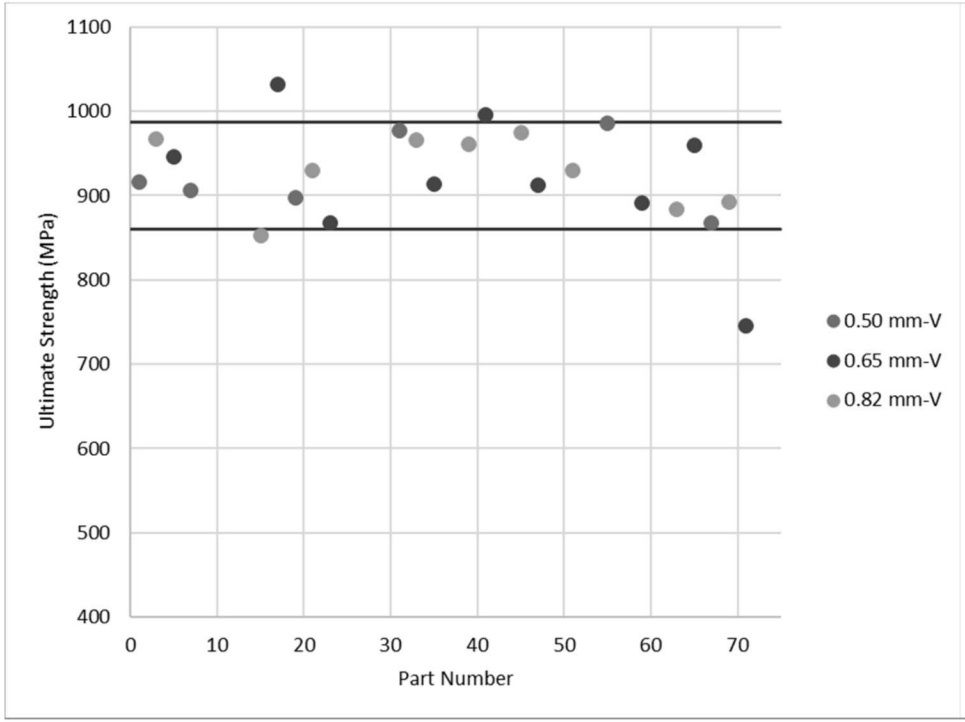


Struts: Ultimate Strength Outliers

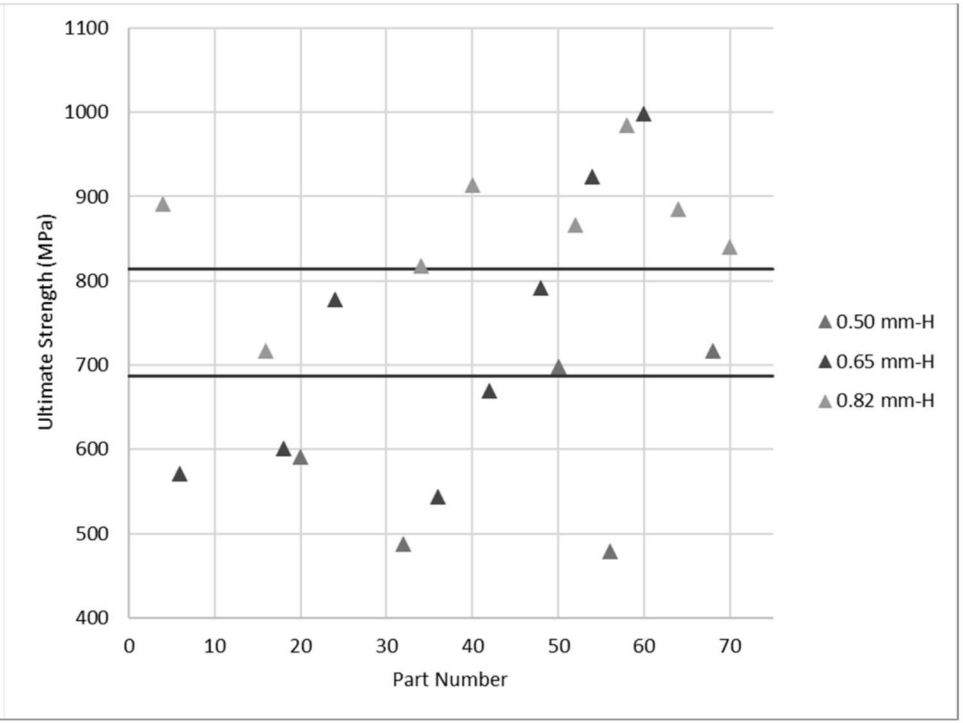


Outliers:
16 Vertical
15 Horizontal

Struts: Ultimate Strength Outliers

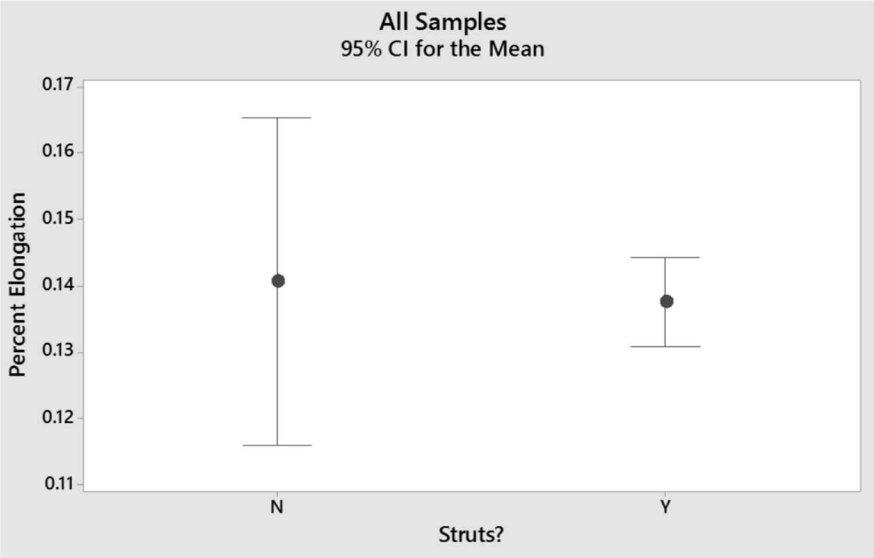


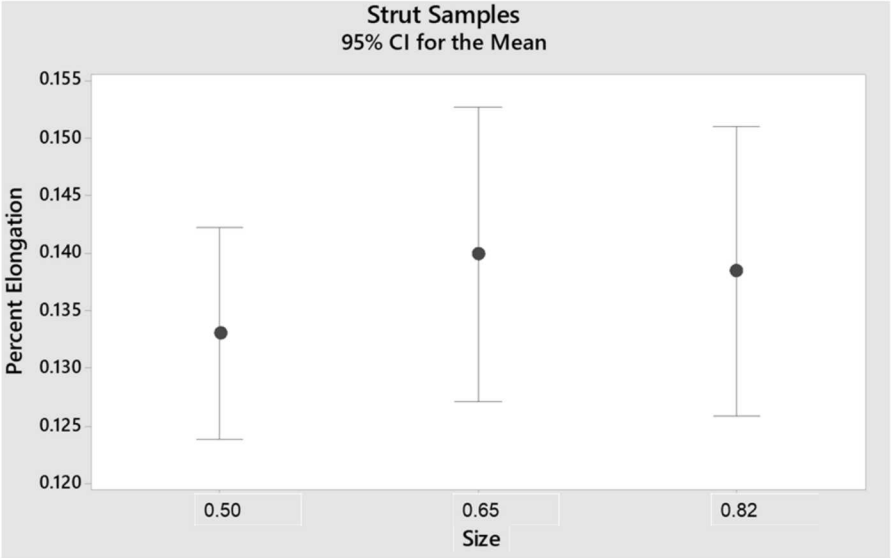
4 Outliers



16 Outliers

Percent Elongation





Stress Analysis of CT Data

Sample 32- 0.50 mm, Horizontal