

Mechanical Property Variation in Metal Lattice Structures

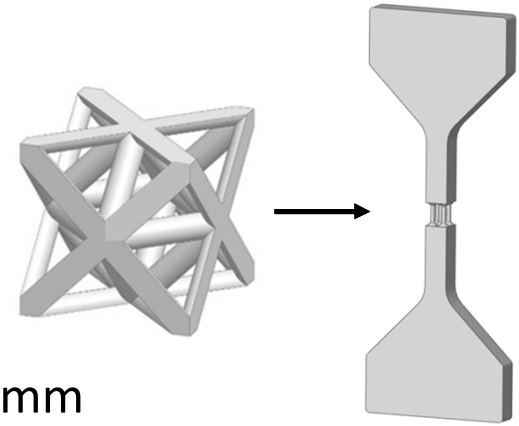
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The University of Texas at Austin

GOAL

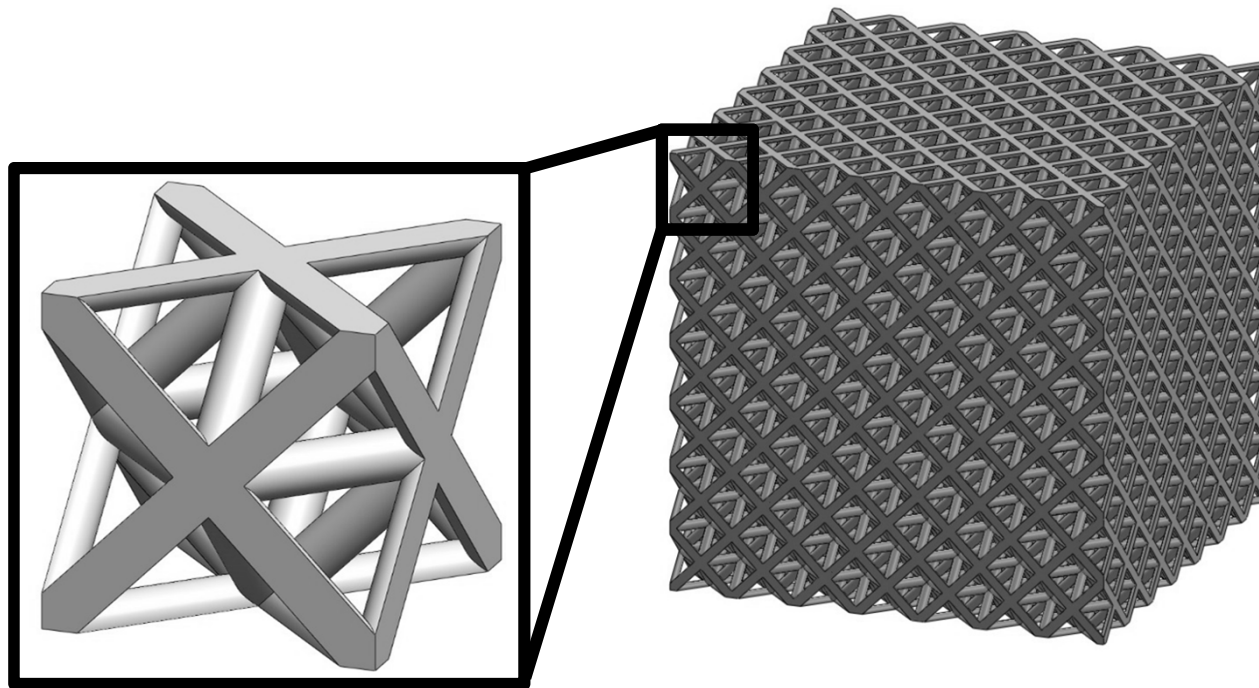
Improve the understanding of how defects impact mechanical properties to enhance designers' ability to manufacture metal lattice structures reliably.

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
- Non-destructive evaluation of parts
 - Geometry characterization
 - Density measurements
 - CT scans
- Destructive evaluation
 - Tensile tests
 - Failure analysis

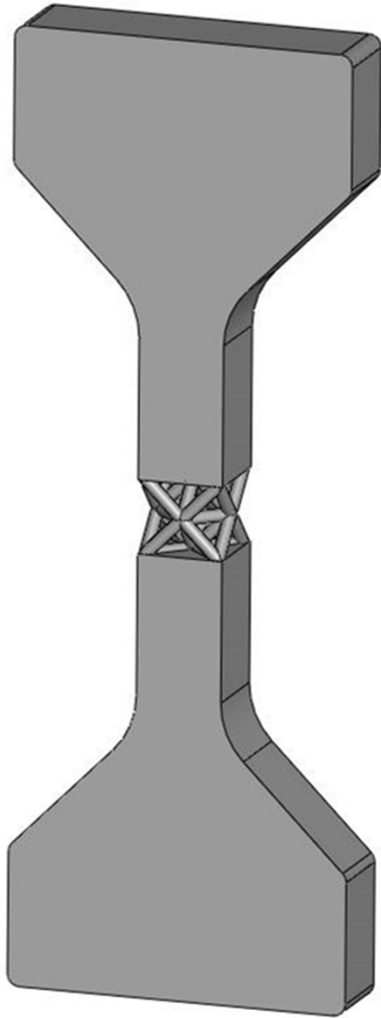


Octet Truss Lattice



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

Single Unit Cell Builds

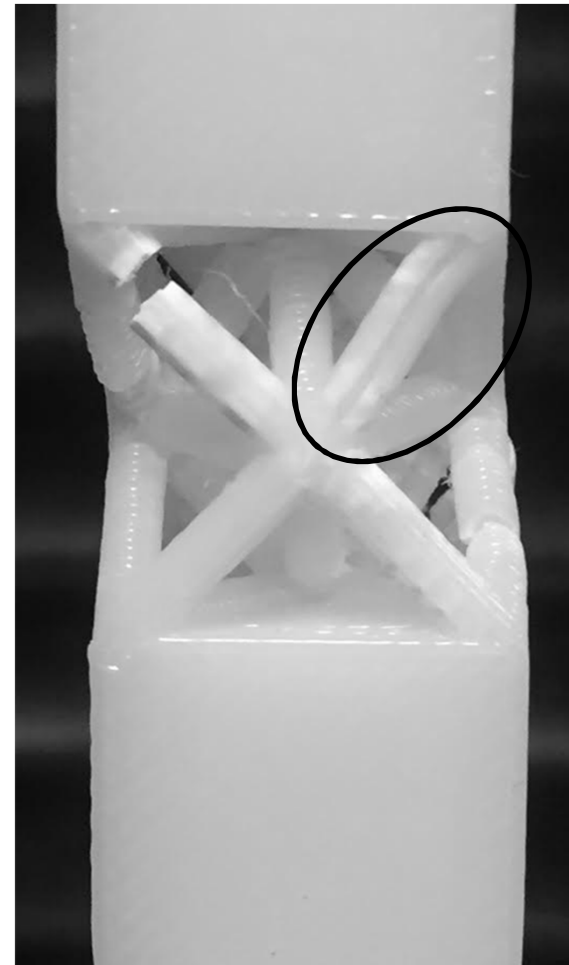
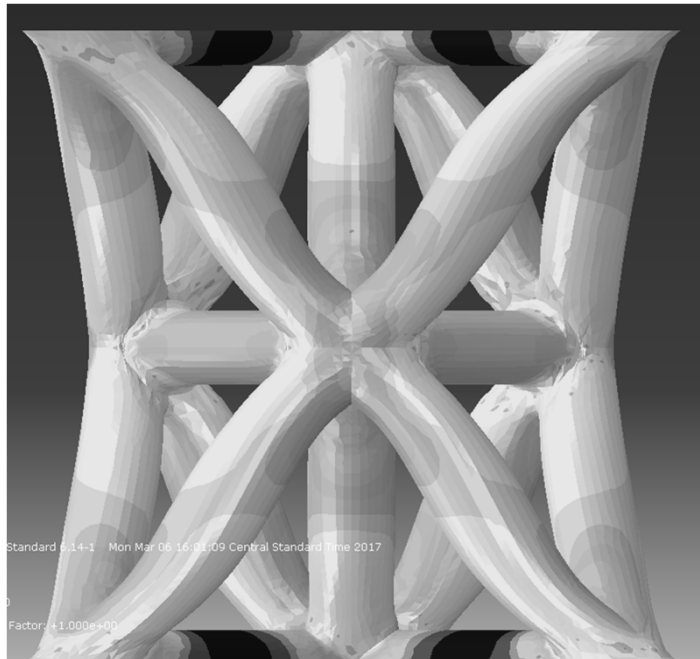


- Individual strut behavior is difficult to analyze in the full lattice structure
- Data depicting how defects impact these small features is important in understanding lattice behavior
- Concerned about struts bending due to limited boundary conditions

Deformation Studies

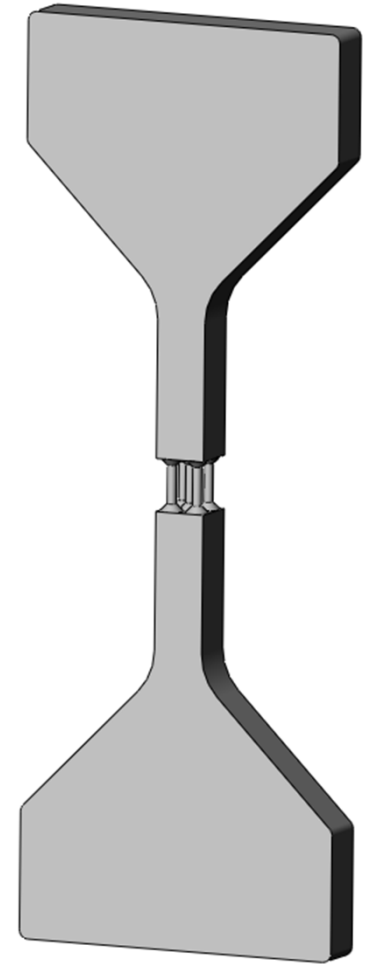
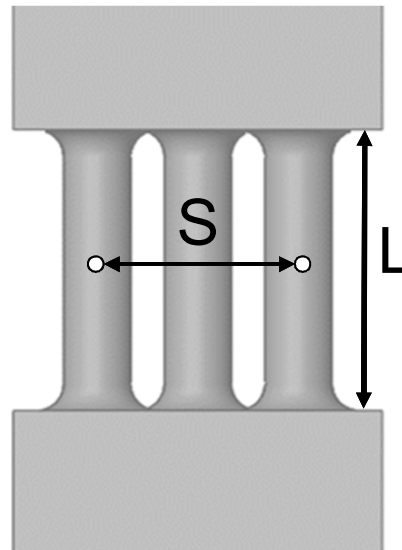
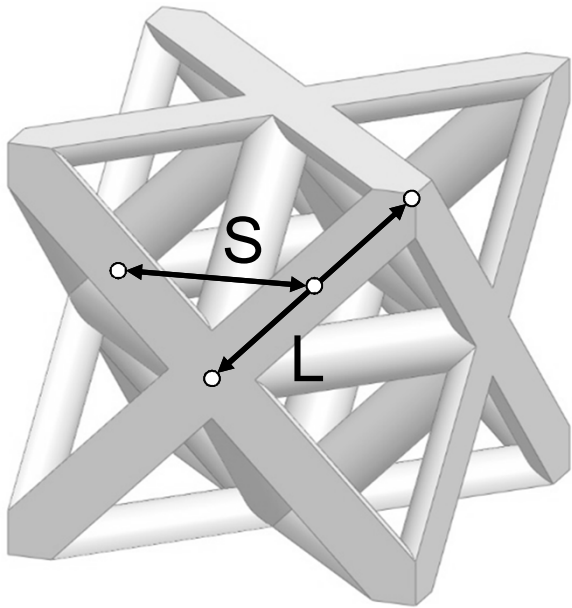
Plastic Test

Abaqus Simulation

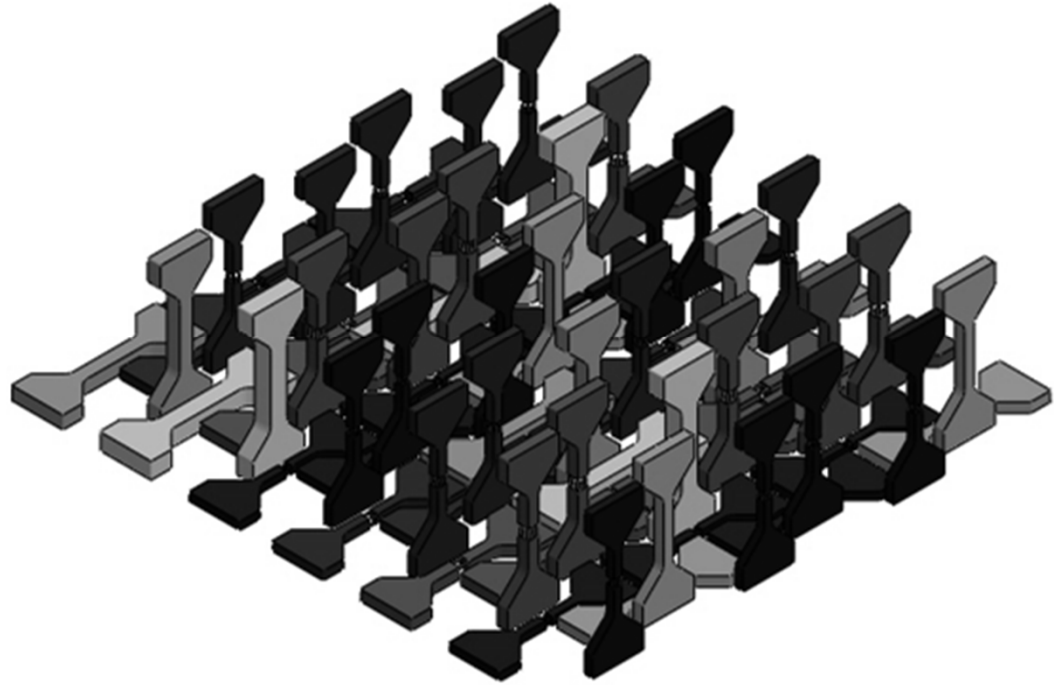
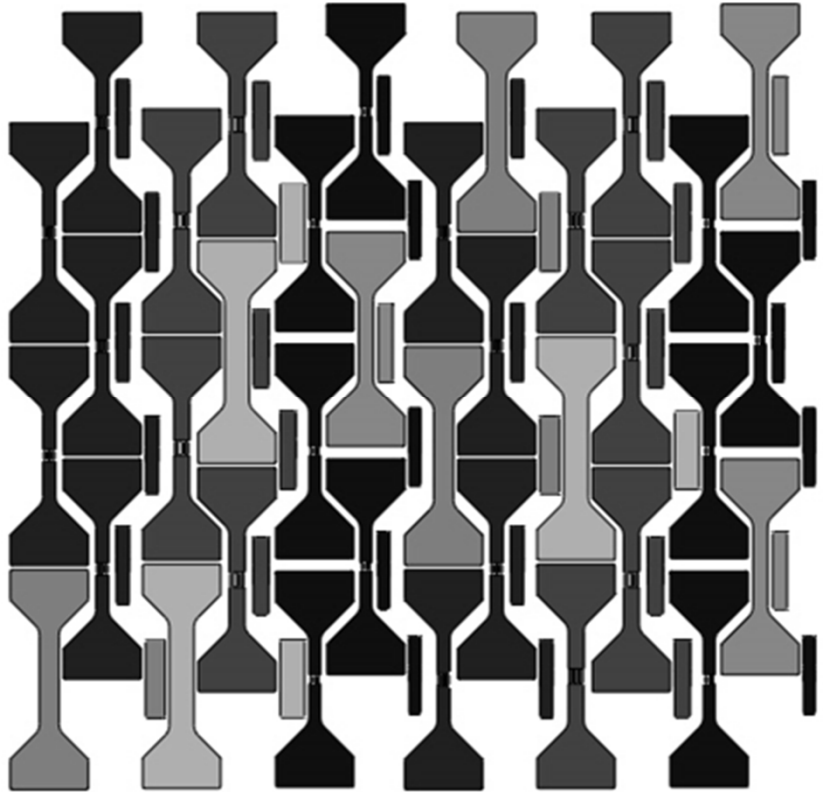


Vertical Strut Builds

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



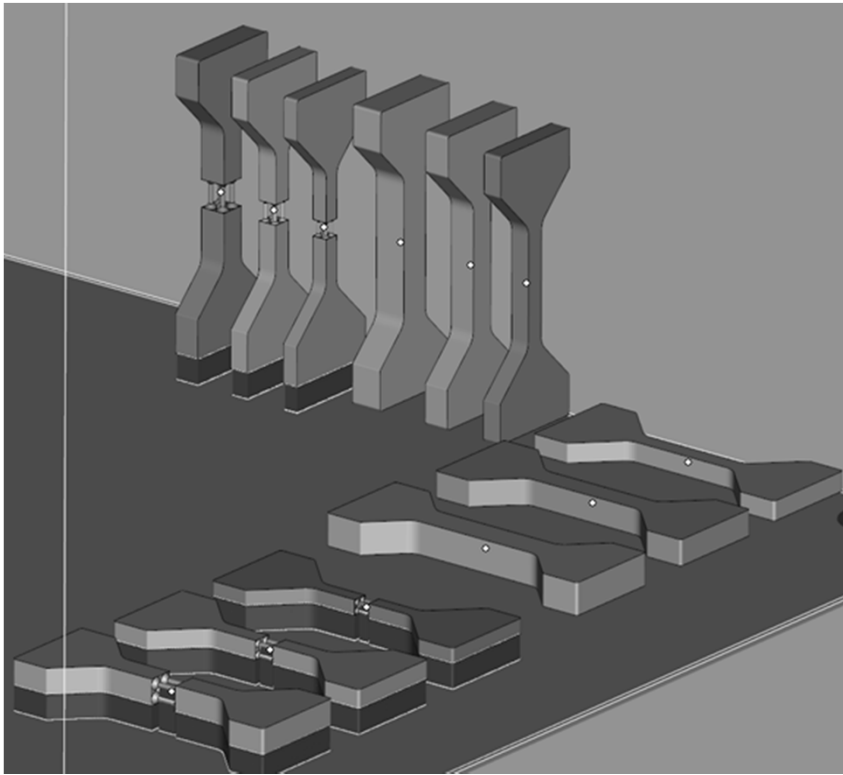
Build Layout



Build Process

1. DMLS the 17-4PH steel parts on an EOS M270
2. Heat treat while on build platform: Austenitizing by heating (solutionizing) to 1900°F for an hour, then air/oil cool
3. Remove from build platform
4. HIP with the following parameters: 2125±25 °F x 240±60 min x 14.75±0.25 ksi
5. Heat treat again: Austenitizing by heating (solutionizing) to 1900°F for an hour, then air/oil cool, and then complete the H1150 heat treatment.

Learning About Manufacturability



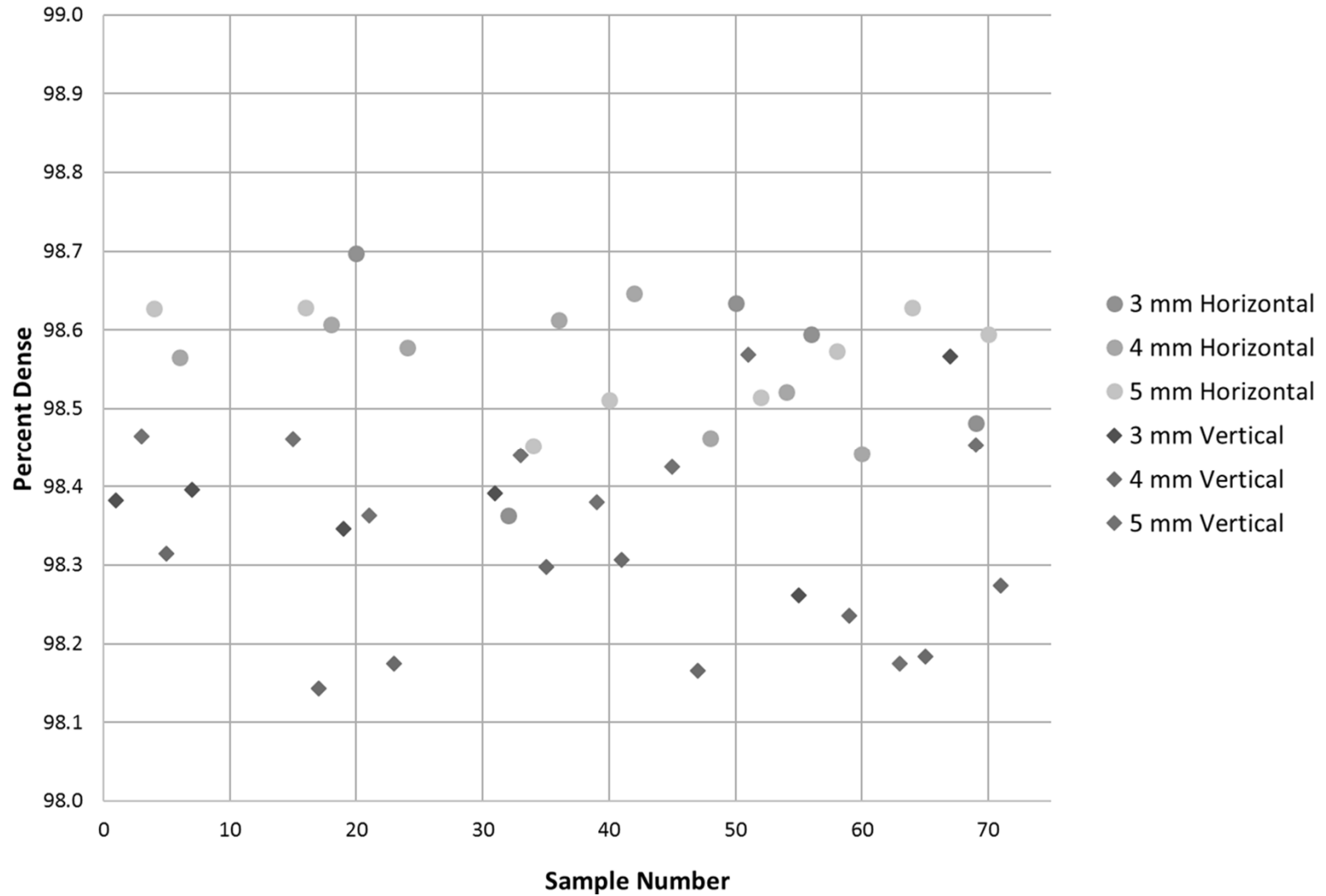
Rebuild Results



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

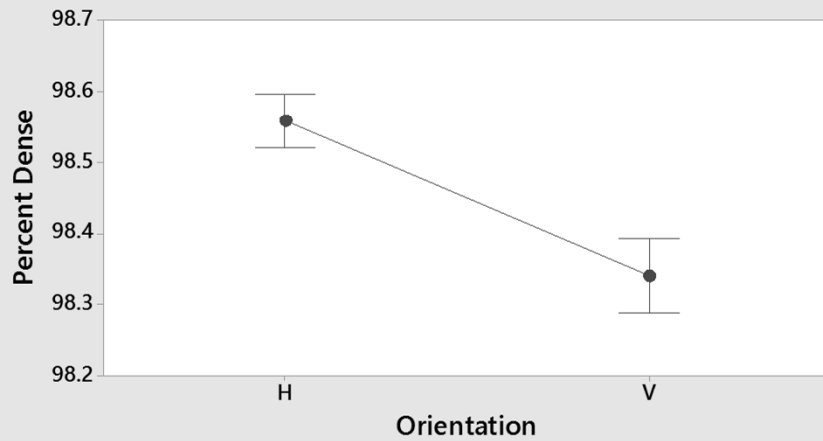
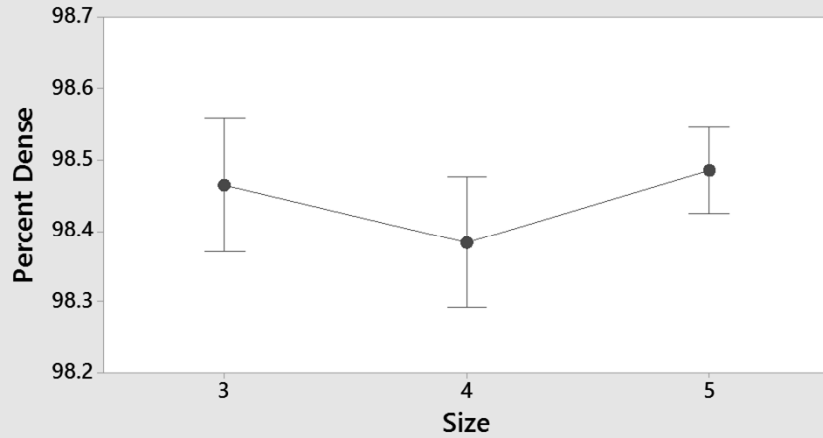
NON-DESTRUCTIVE EVALUATION

Density Measurements

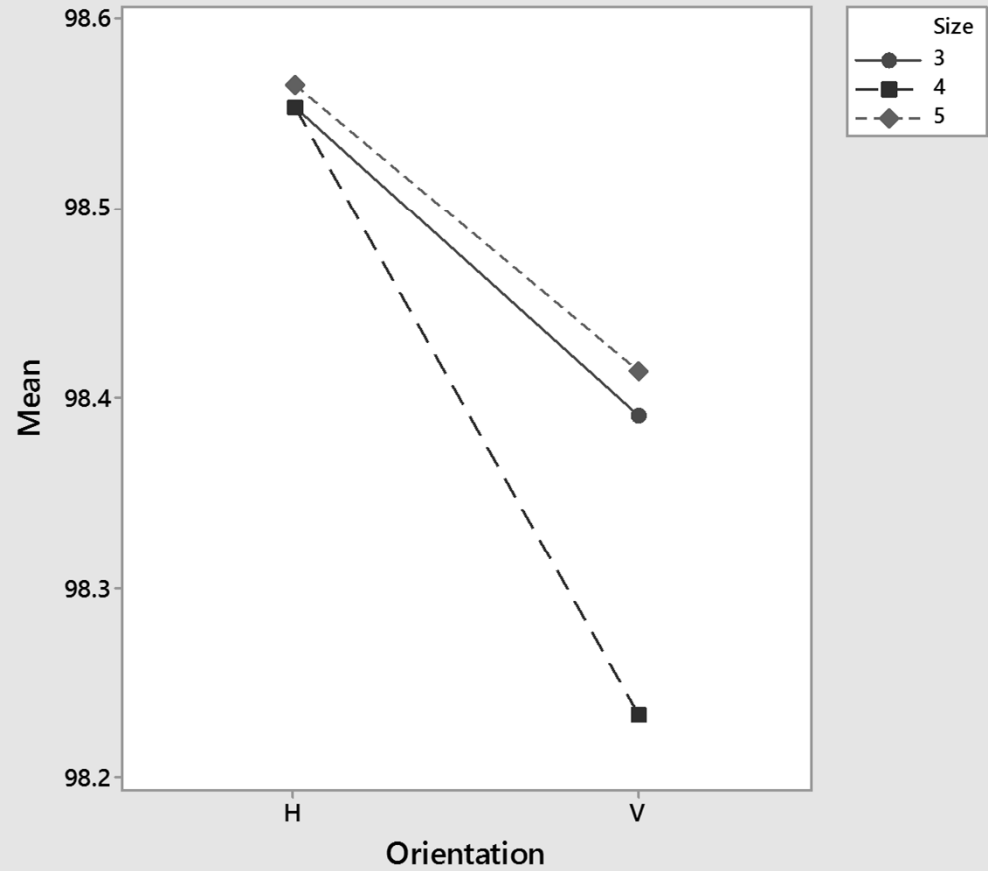


Density Effects-Strut Bars

Interval Plot of Percent Dense
95% CI for the Mean



Interaction Plot for Percent Dense
Data Means

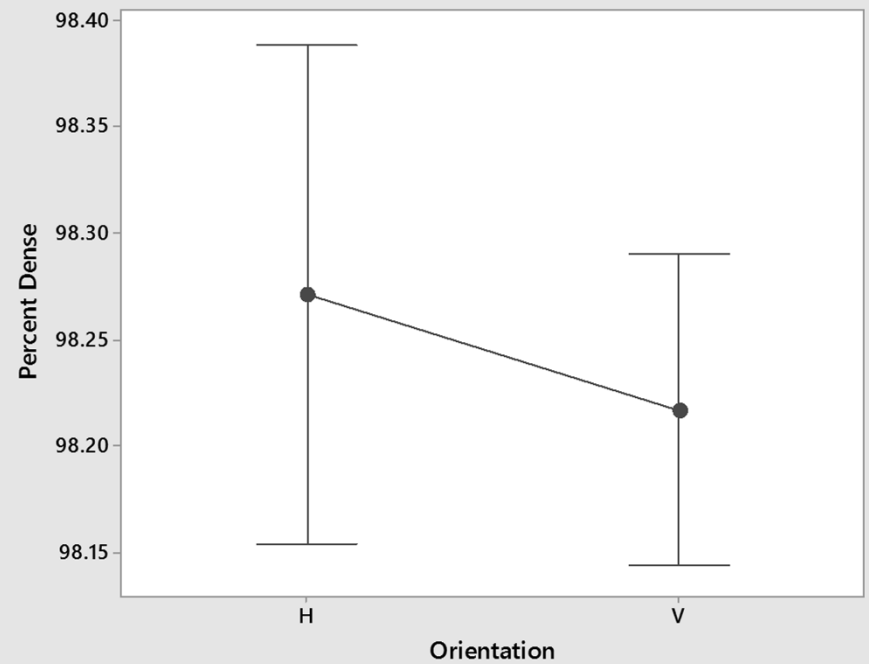


Density Effect-Solid Bars

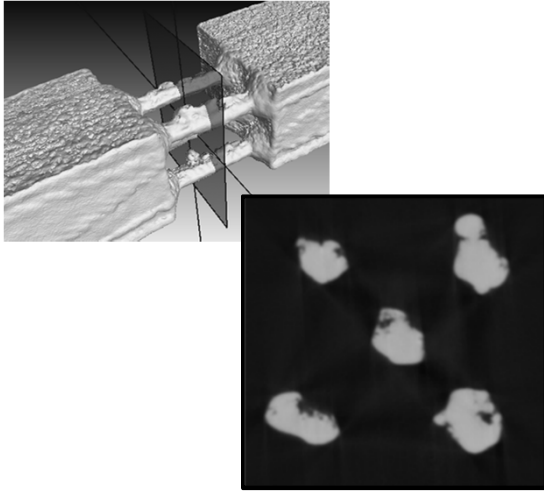
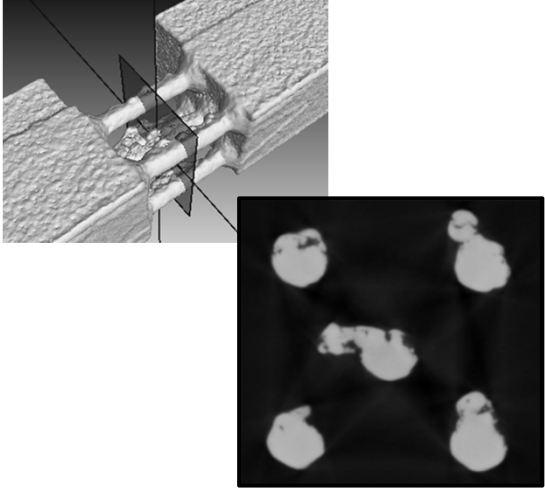
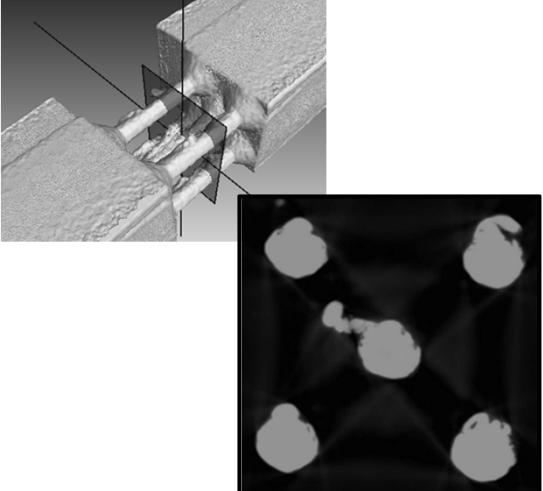
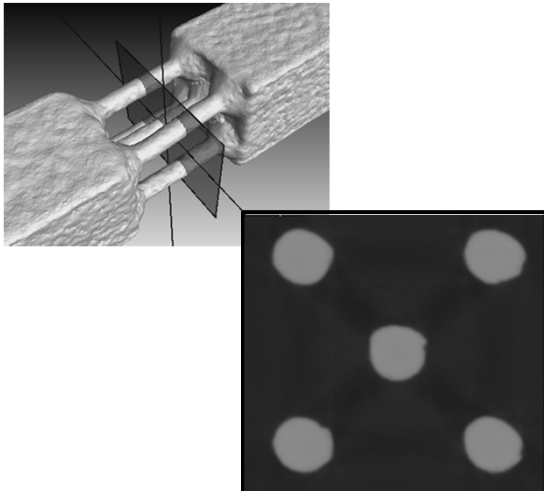
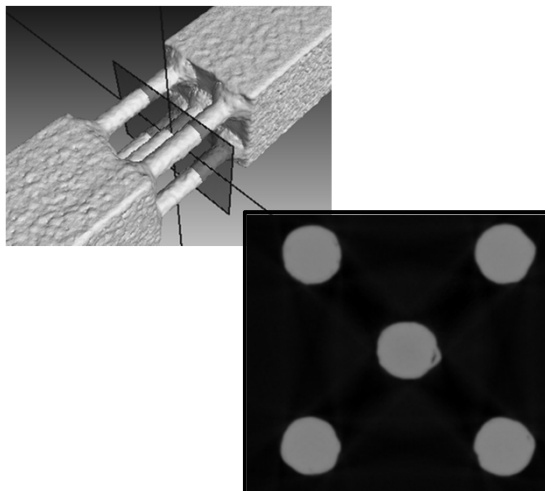
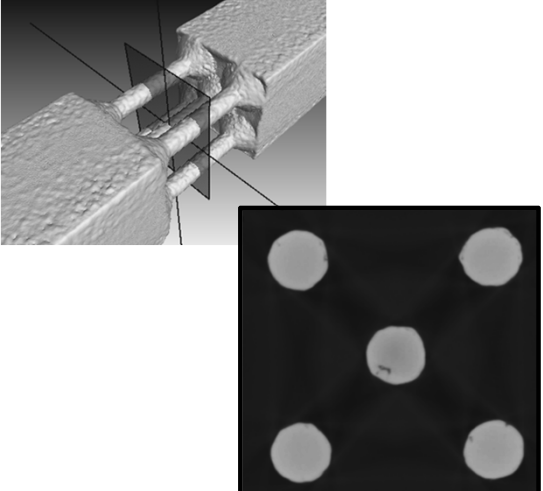
Interval Plot of Percent Dense_1
95% CI for the Mean



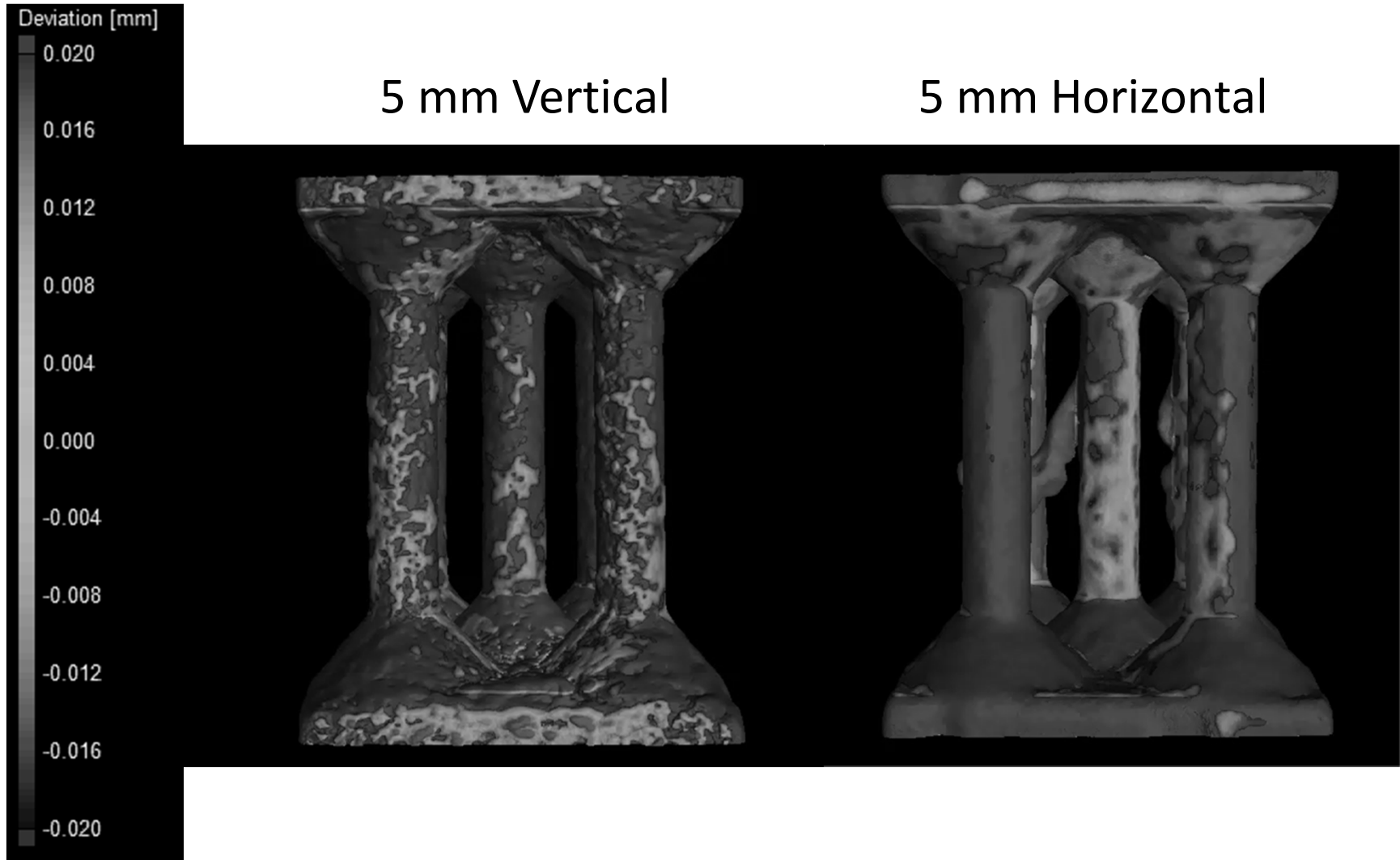
Interval Plot of Percent Dense_1
95% CI for the Mean



CT Results-Configuration Comparison

	'3 mm Bar'	'4 mm Bar'	'5 mm Bar'
Horizontal Bar	 <p>This panel shows a 3D CT reconstruction of a horizontal bar with three 3 mm diameter bars. The 3D view includes a vertical plane and a horizontal plane. The corresponding 2D slice shows four bright spots arranged in a diamond pattern, representing the cross-sections of the three bars.</p>	 <p>This panel shows a 3D CT reconstruction of a horizontal bar with three 4 mm diameter bars. The 3D view includes a vertical plane and a horizontal plane. The corresponding 2D slice shows four bright spots arranged in a diamond pattern, representing the cross-sections of the three bars.</p>	 <p>This panel shows a 3D CT reconstruction of a horizontal bar with three 5 mm diameter bars. The 3D view includes a vertical plane and a horizontal plane. The corresponding 2D slice shows four bright spots arranged in a diamond pattern, representing the cross-sections of the three bars.</p>
Vertical Bar	 <p>This panel shows a 3D CT reconstruction of a vertical bar with three 3 mm diameter bars. The 3D view includes a vertical plane and a horizontal plane. The corresponding 2D slice shows four bright spots arranged in a diamond pattern, representing the cross-sections of the three bars.</p>	 <p>This panel shows a 3D CT reconstruction of a vertical bar with three 4 mm diameter bars. The 3D view includes a vertical plane and a horizontal plane. The corresponding 2D slice shows four bright spots arranged in a diamond pattern, representing the cross-sections of the three bars.</p>	 <p>This panel shows a 3D CT reconstruction of a vertical bar with three 5 mm diameter bars. The 3D view includes a vertical plane and a horizontal plane. The corresponding 2D slice shows four bright spots arranged in a diamond pattern, representing the cross-sections of the three bars.</p>

CT Results-Comparison to Nominal



Geometric Characterization

The screenshot displays a software interface for geometric characterization. The main window shows a circular image of a part with various measurement annotations. The annotations include:

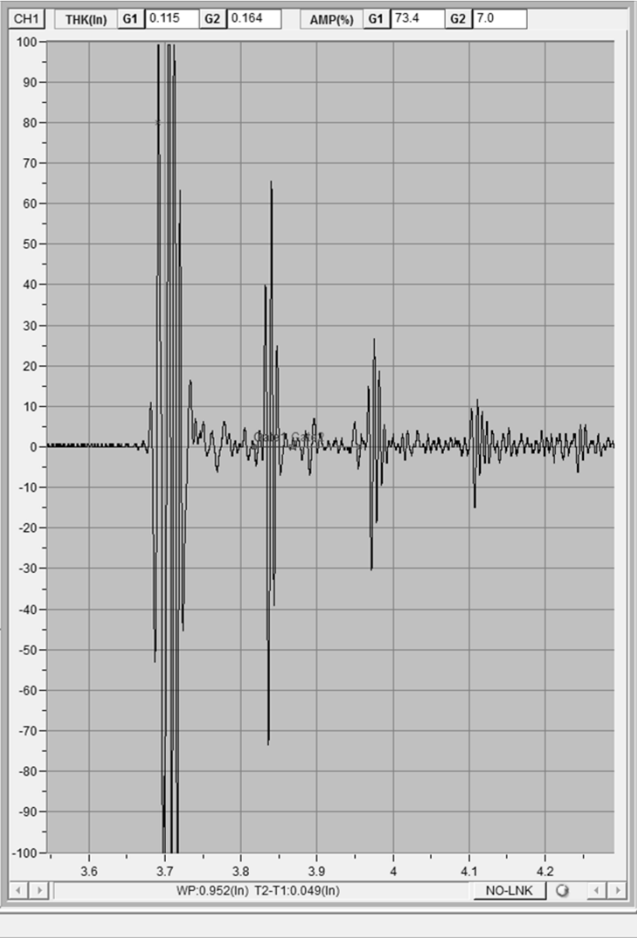
- [1] ANGLE001
- [2] ANGLE002
- [3] LN-LN001
- [4] LN-LN002
- [5] LN-LN003
- [6] PT-PT001 [DIST]
- [7] ANGLE003
- [8] LN-LN004
- [9] LN-LN005
- [10] LN-LN006

The right-hand panel is titled "Multi Measurement Mode" and contains the following sections:

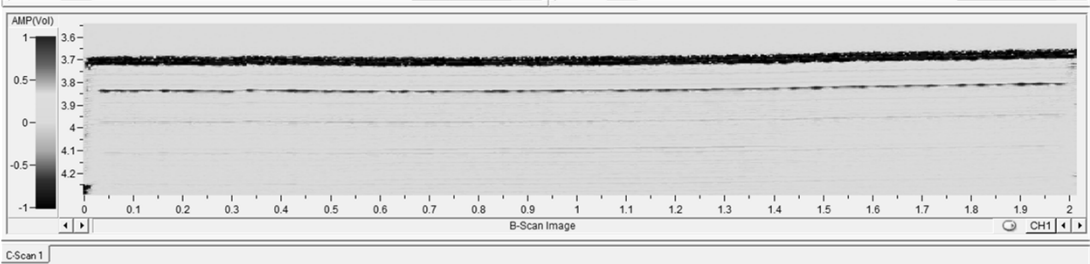
- Measurement Setting Data:** A dropdown menu set to "Dressler_Strut_5", and input fields for "Lot Number", "Serial Counter" (0001), and "Name".
- Measurement settings data thumbnail images:** A smaller version of the main image with the same measurement annotations.
- Options:** Two checkboxes: "Zoom display" (checked) and "Display results in the descending order of errors" (unchecked).
- Buttons:** "Measure" (disabled), "Playing" (active), "Delete Result", "Print", and "Save Report".

Ultrasonic Testing

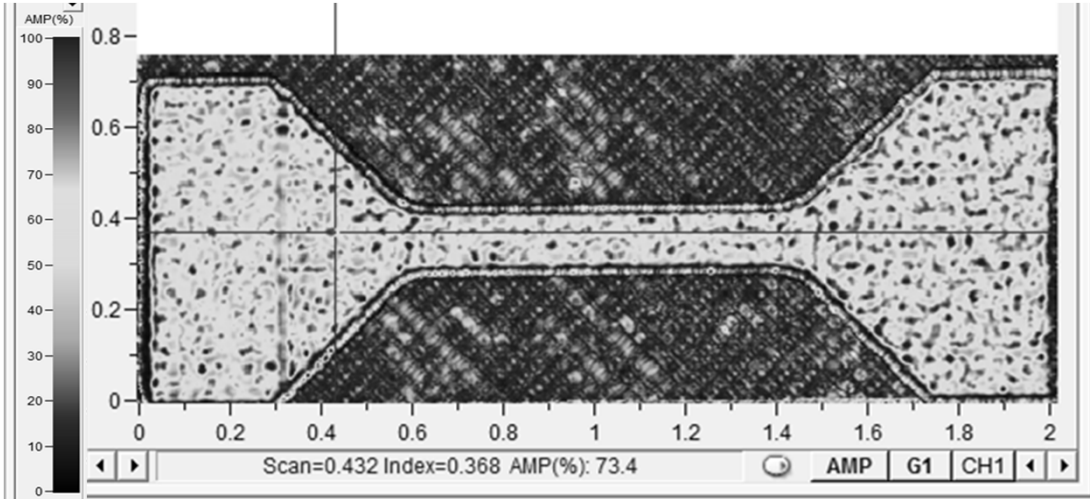
A-Scan



B-Scan



C-Scan



DESTRUCTIVE EVALUATION STRUT BARS

Test Setup



Data Acquisition: 15 Hz

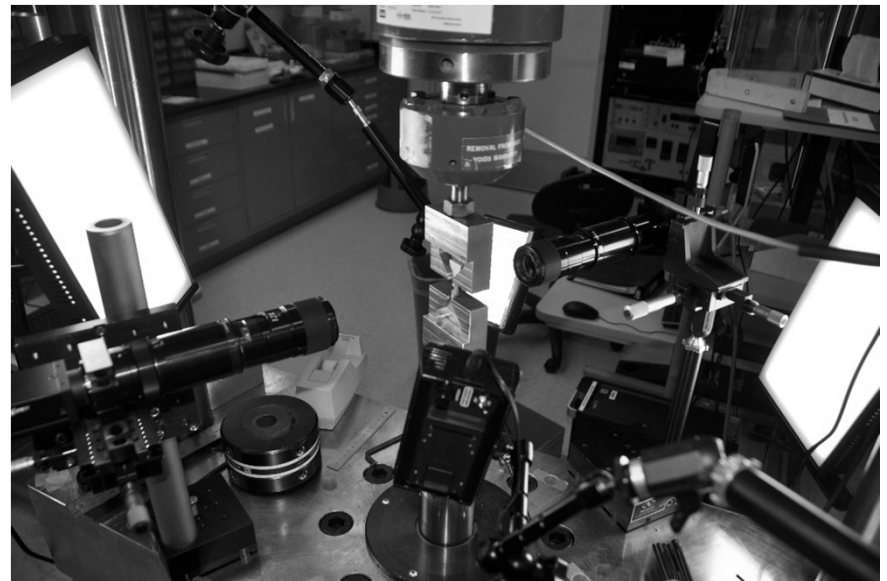
Image Acquisition: 1 Hz

Actuator Rate:

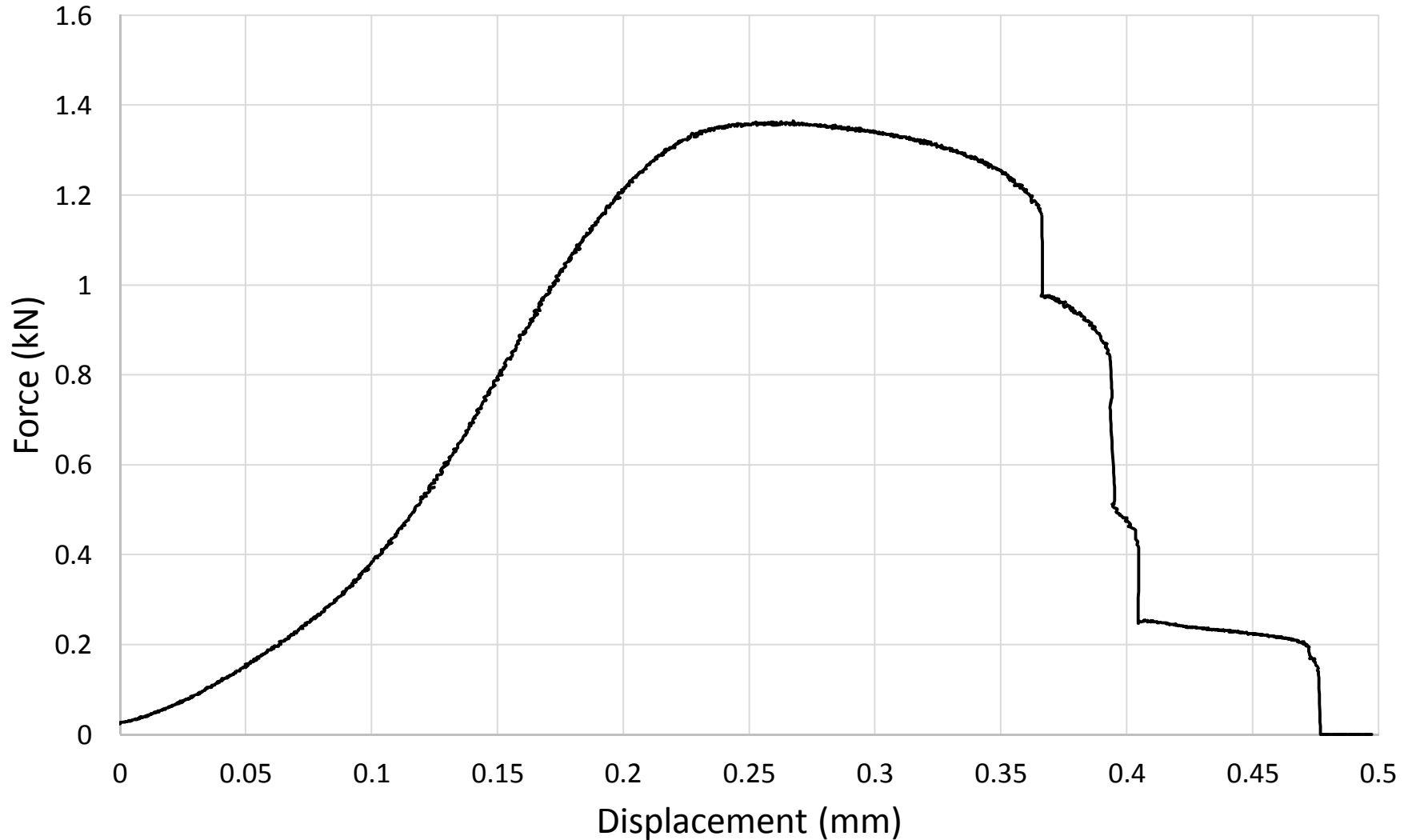
3 mm- 0.225 mm/min

4 mm- 0.3 mm/min

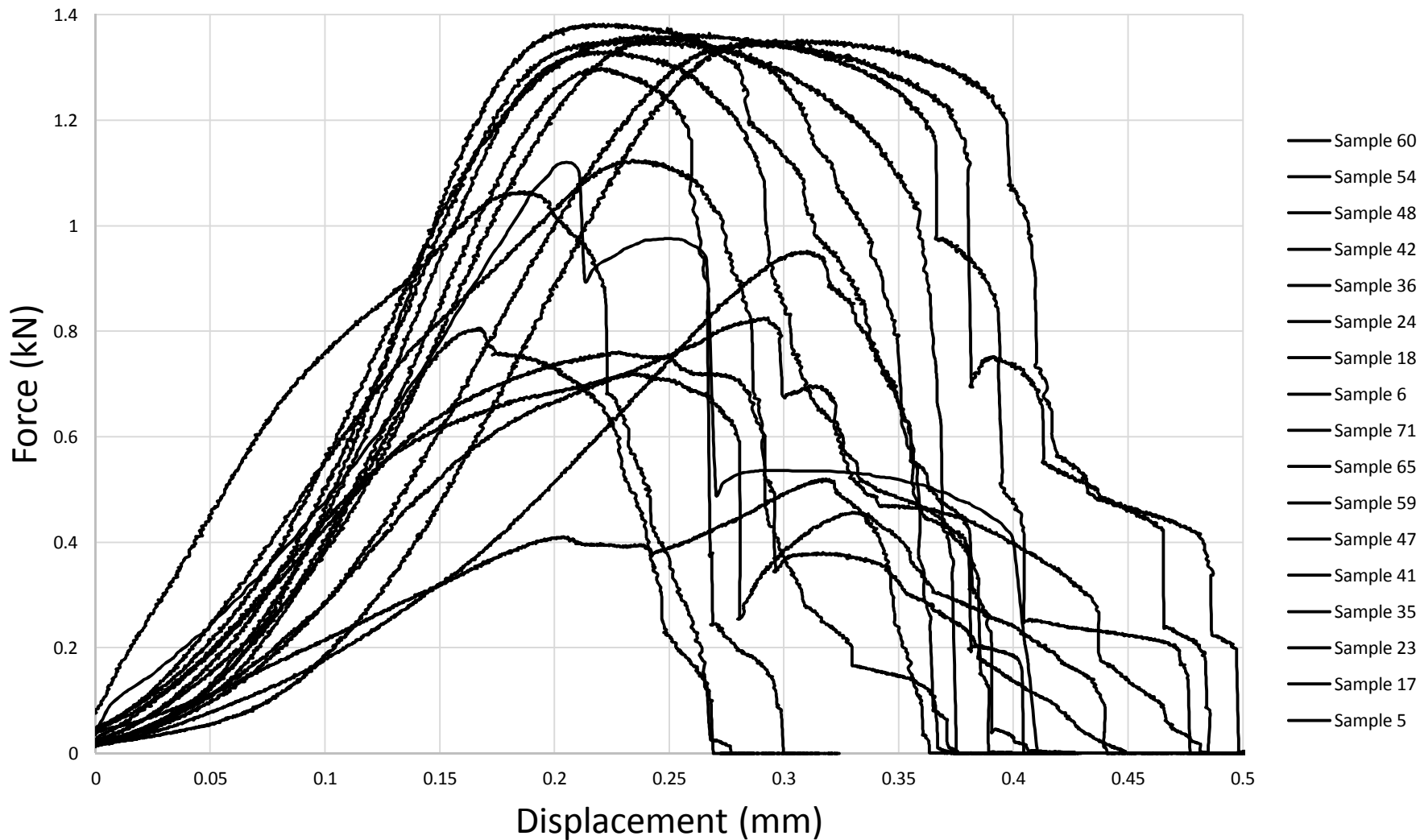
5 mm- 0.375 mm/min



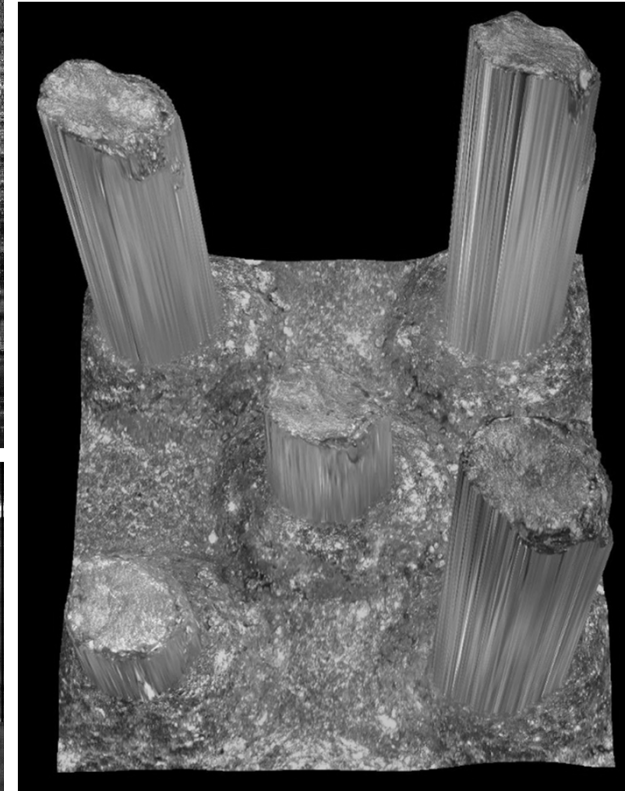
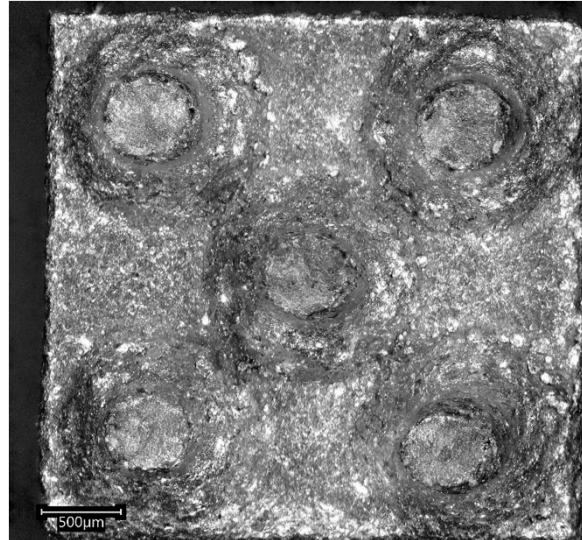
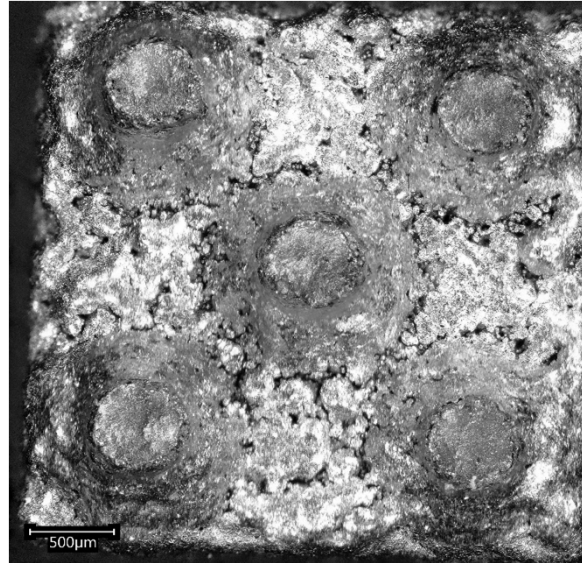
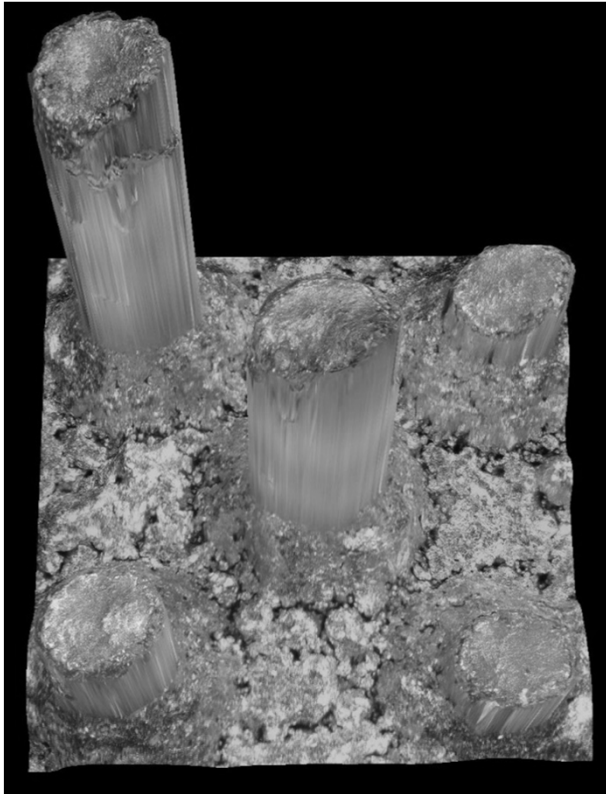
Force-Displacement: Sample 17 (4 mm)



Force-Displacement: 4 mm Variation



Fractography: Sample 17





DESTRUCTIVE EVALUATION SOLID BARS

Test Setup

Data Acquisition: 15 Hz

Image Acquisition: Varied

Actuator Rate:

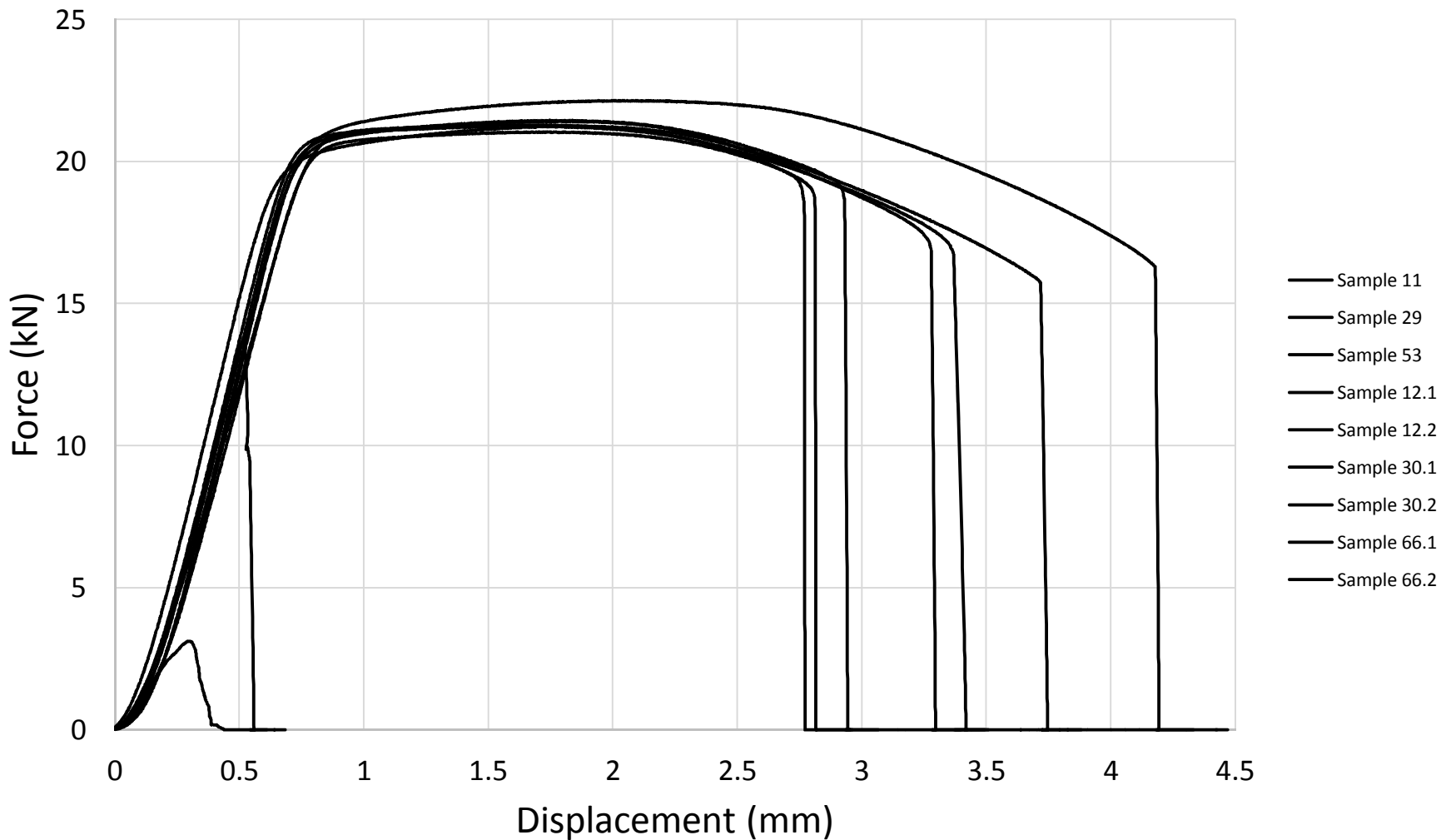
3 mm- 1.9 mm/min

4 mm- 2 mm/min

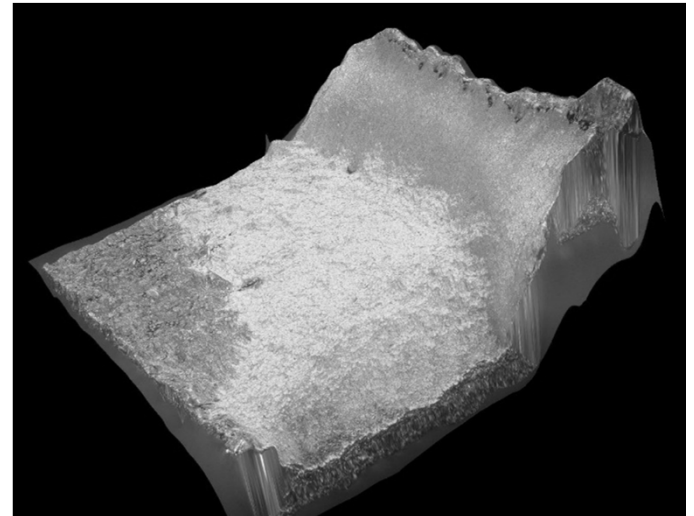
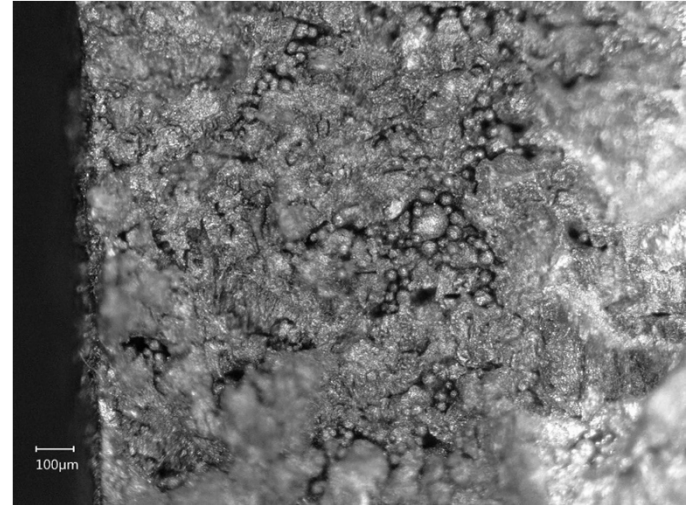
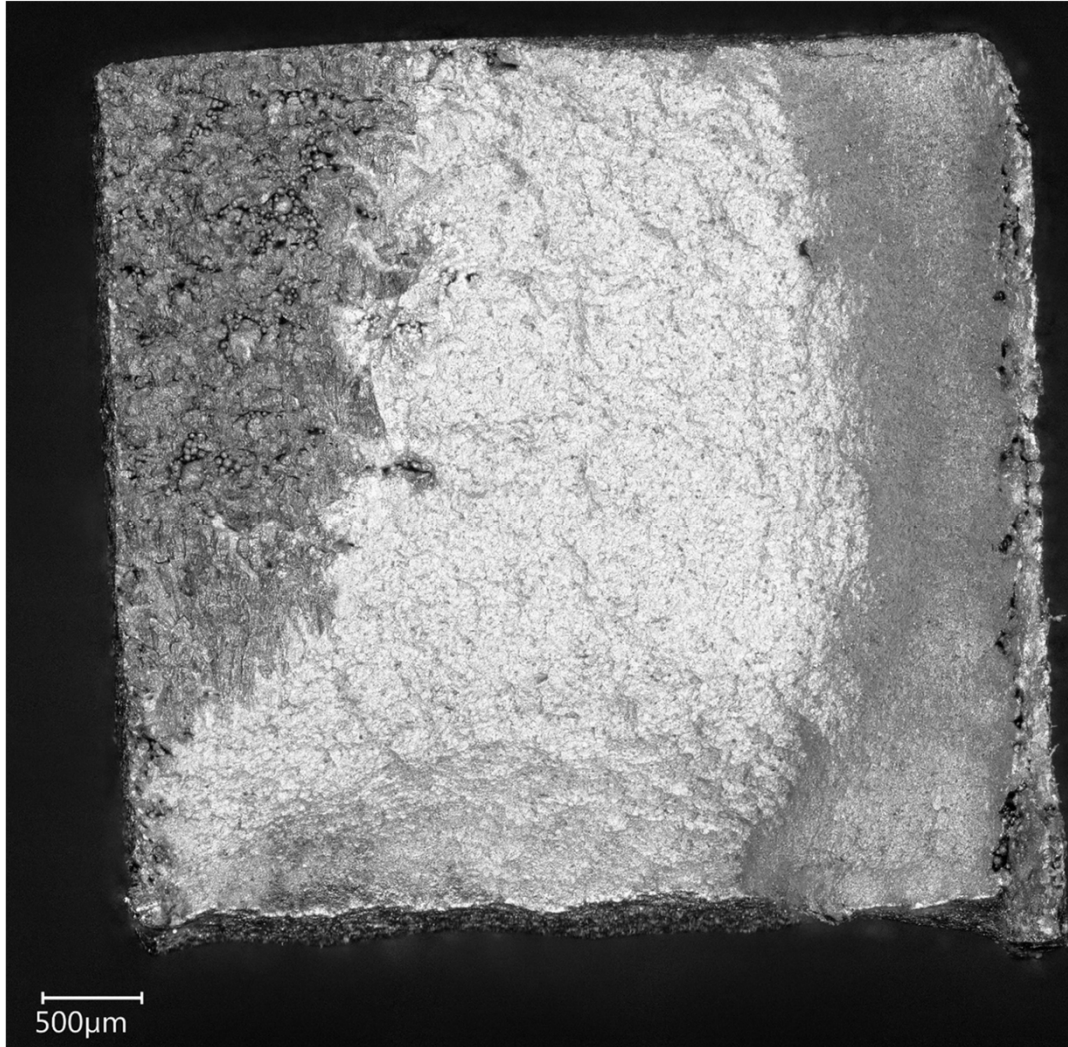
5 mm- 2.1 mm/min



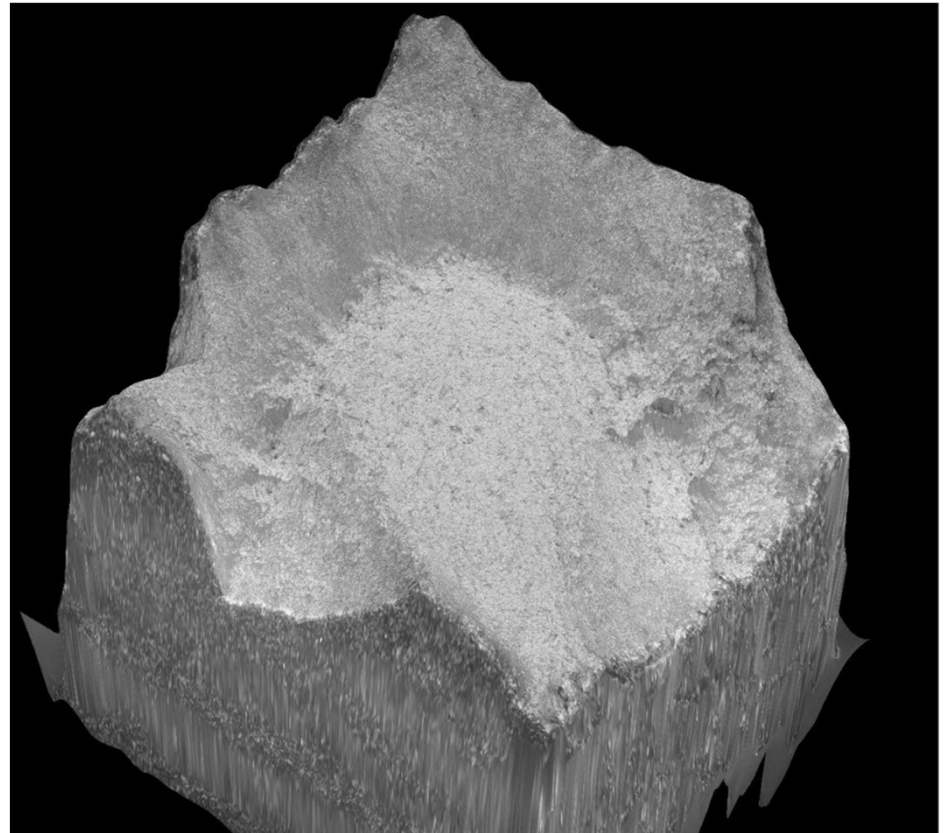
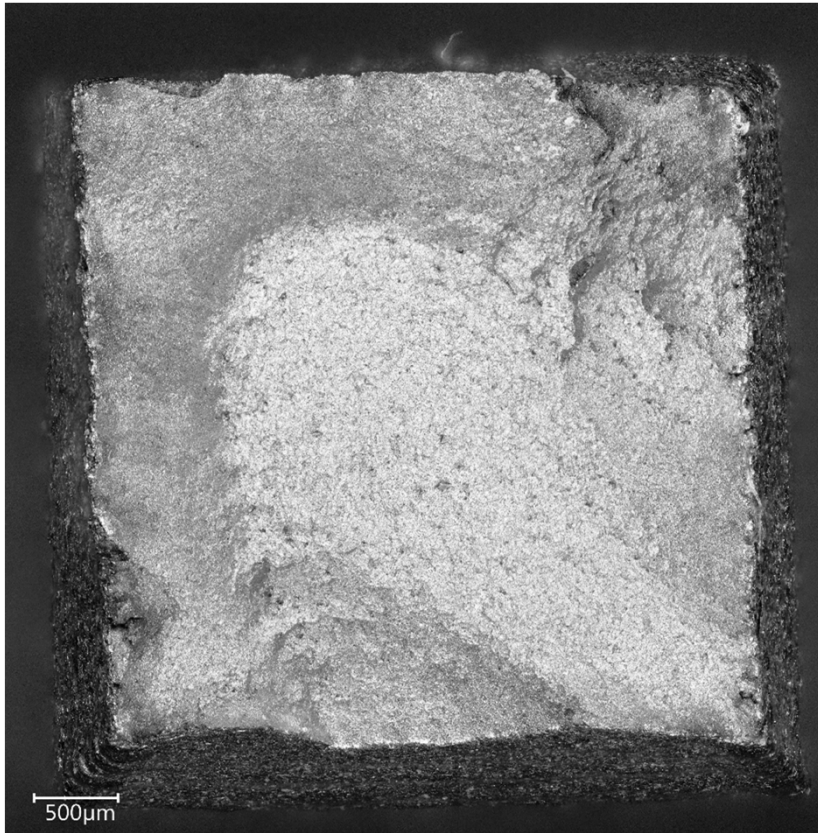
Force-Displacement: 4 mm Variation



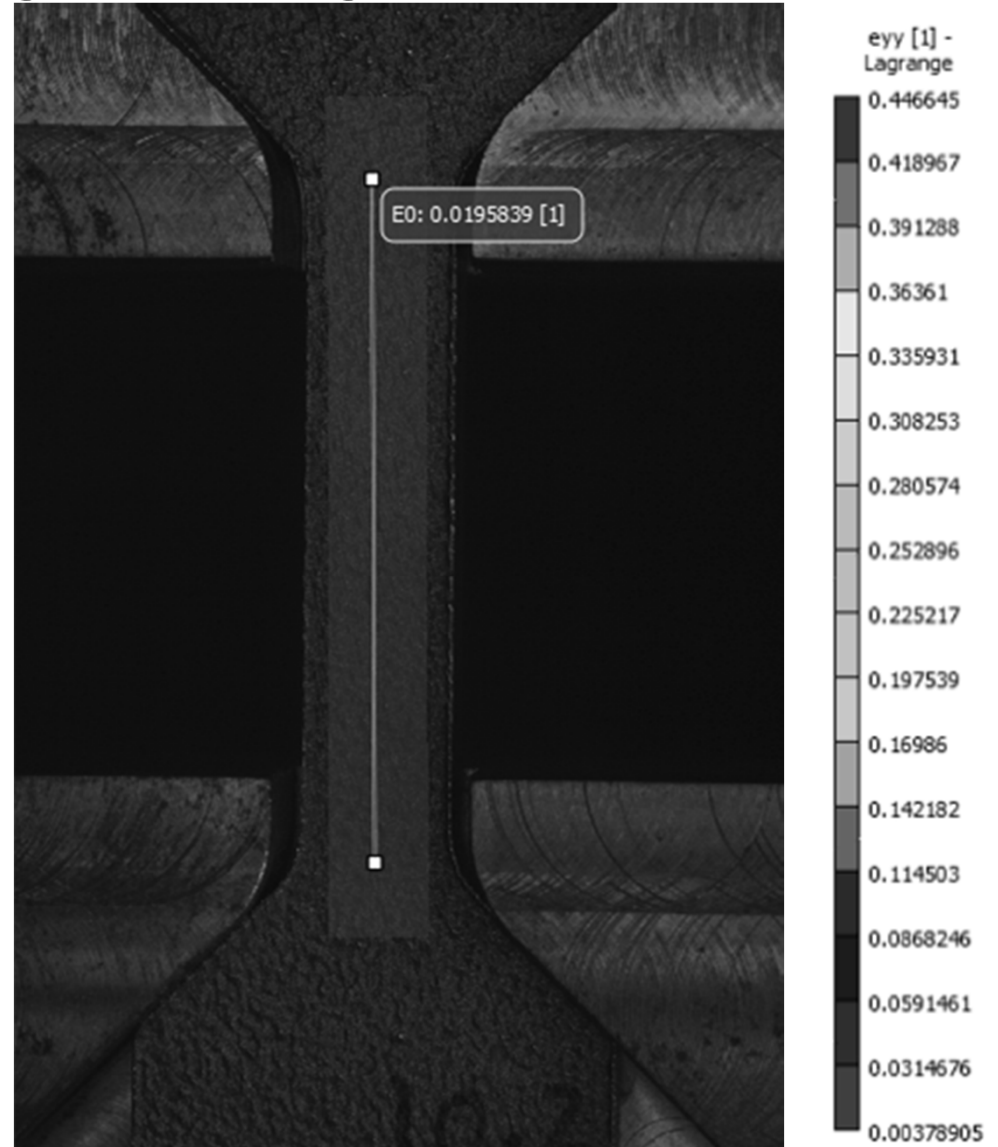
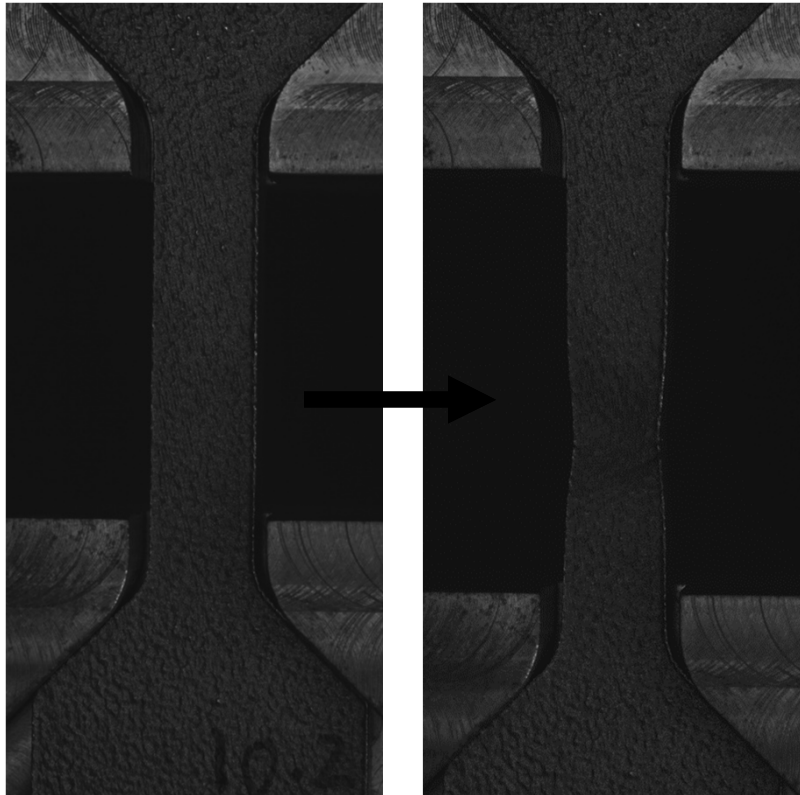
Fractography Sample 12.1



Fractography: Sample 66.1



Strain through Digital Image Correlation





Future Work

- Data Analysis
- Look for correlations between NDE and part performance



Acknowledgements

- Sandia National Labs
 - Allen Roach
 - Brad Boyce
 - Tommy Woodall
 - David Moore
 - Andrew Lentfer
 - Laura Swiler
- Stratasys Direct Manufacturing
 - Ryan Ramon
 - Ashley Chipman

THANK YOU!

QUESTIONS?

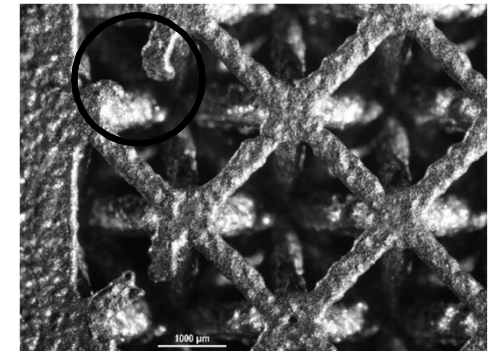
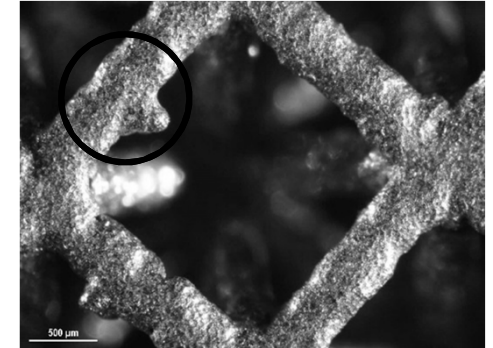
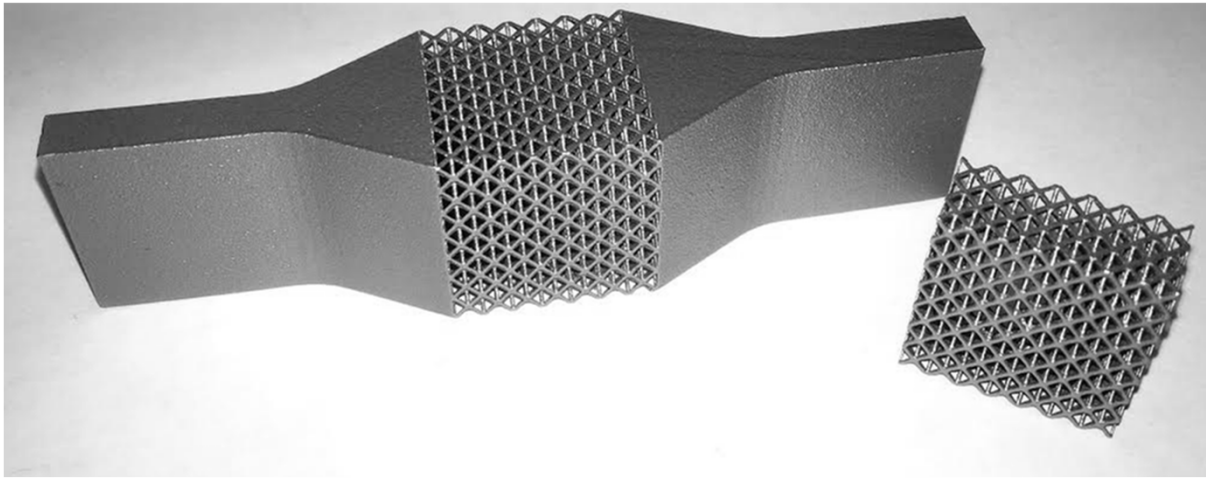
Sources

- Kalsi M, Hacker K, Lewis K. (1999). A Comprehensive Robust Design Approach for Decision Trade-Offs in Complex Systems Design. ASME. *J. Mech. Des.*
- Jared B, Boyce B, Madison J, Ostien J, Rodelas J, Salzbrenner B, Swiler L, Underwood O. (2016). Quantifying Material Performance & Defect Signatures in Laser Powder Bed Fusion.
- ACF Group, Inc. (n.d.). Laser Sintering. Retrieved from http://lasersint.com/wordpress/?page_id=195



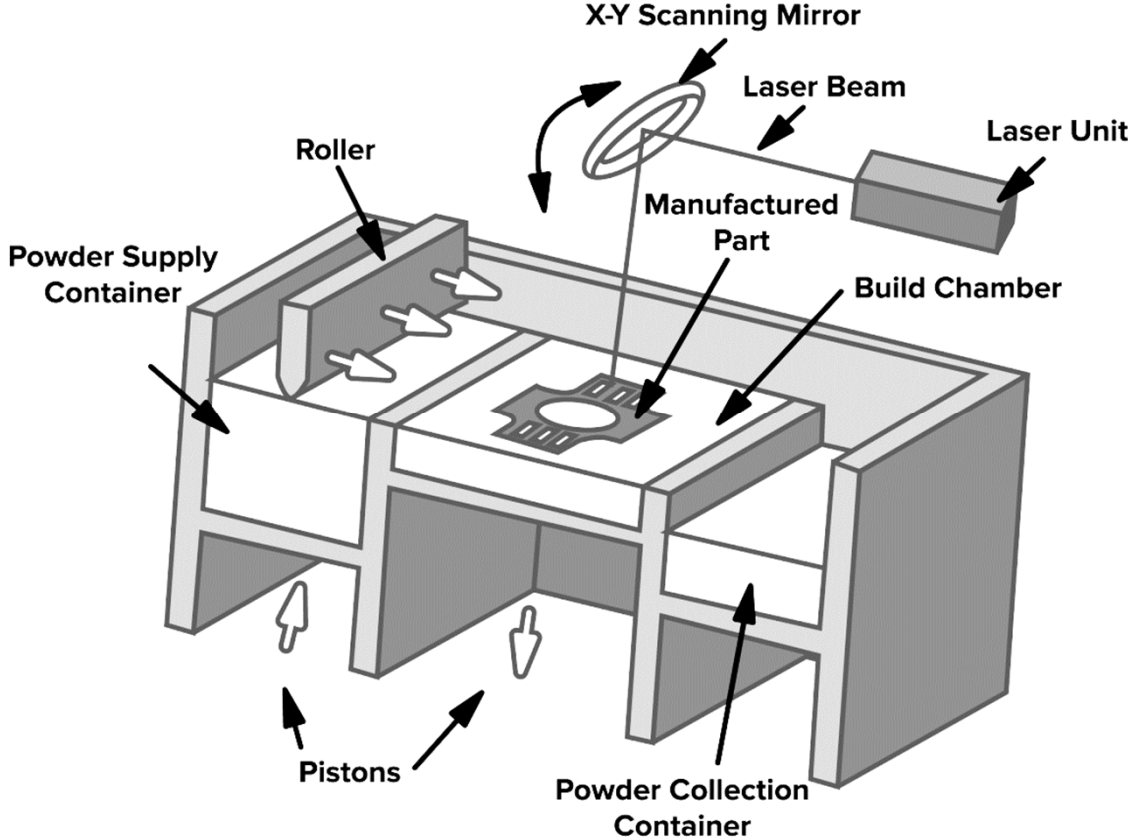
BACKUP SLIDES

Initial Test Parts



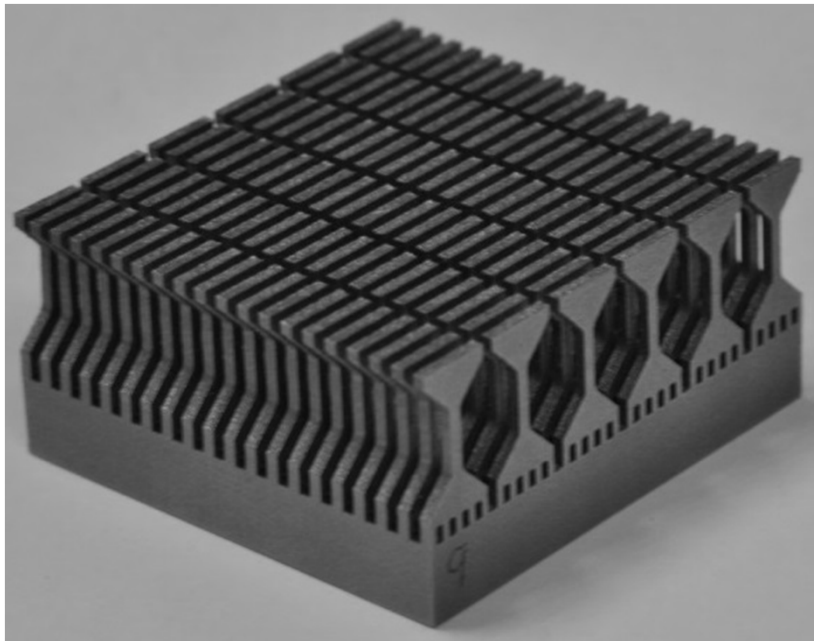
- Small amount of powder remained in the bar
 - Removed with a needle
- Struts were not completely round
- A few struts were missing

Direct Metal Laser Sintering (DMLS)

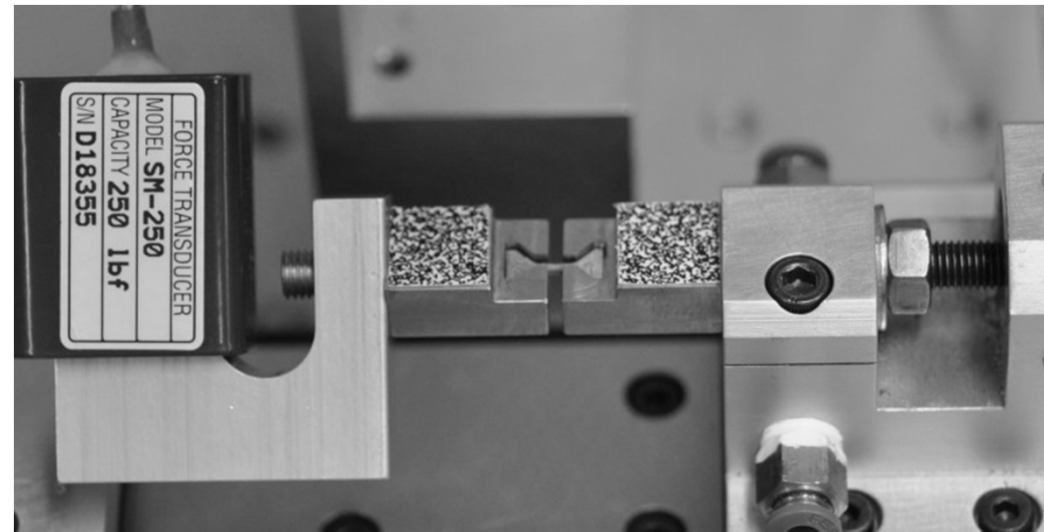


(ACF Group, Inc., n.d.)

High Throughput Testing

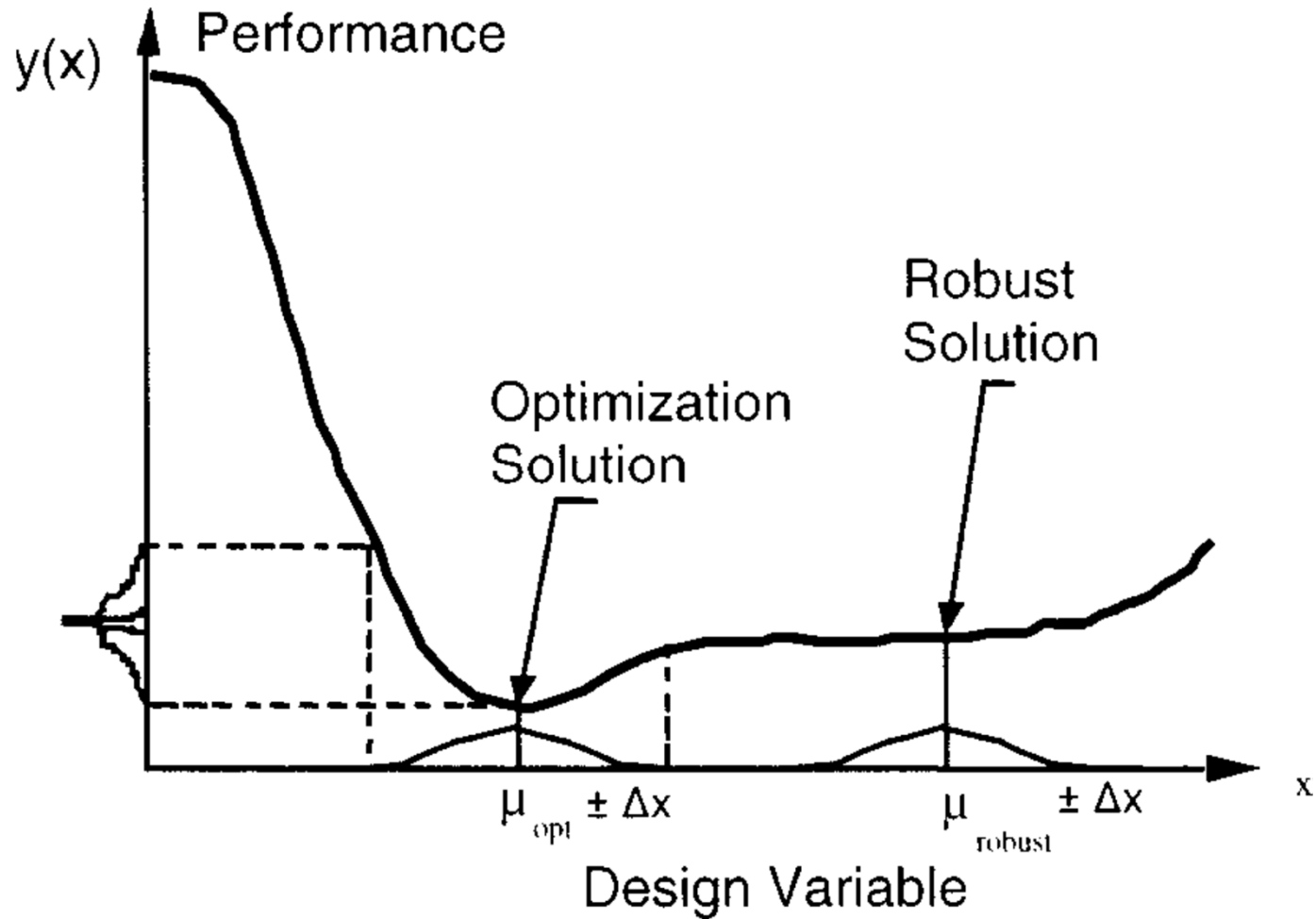


(Jared et al, 2016)



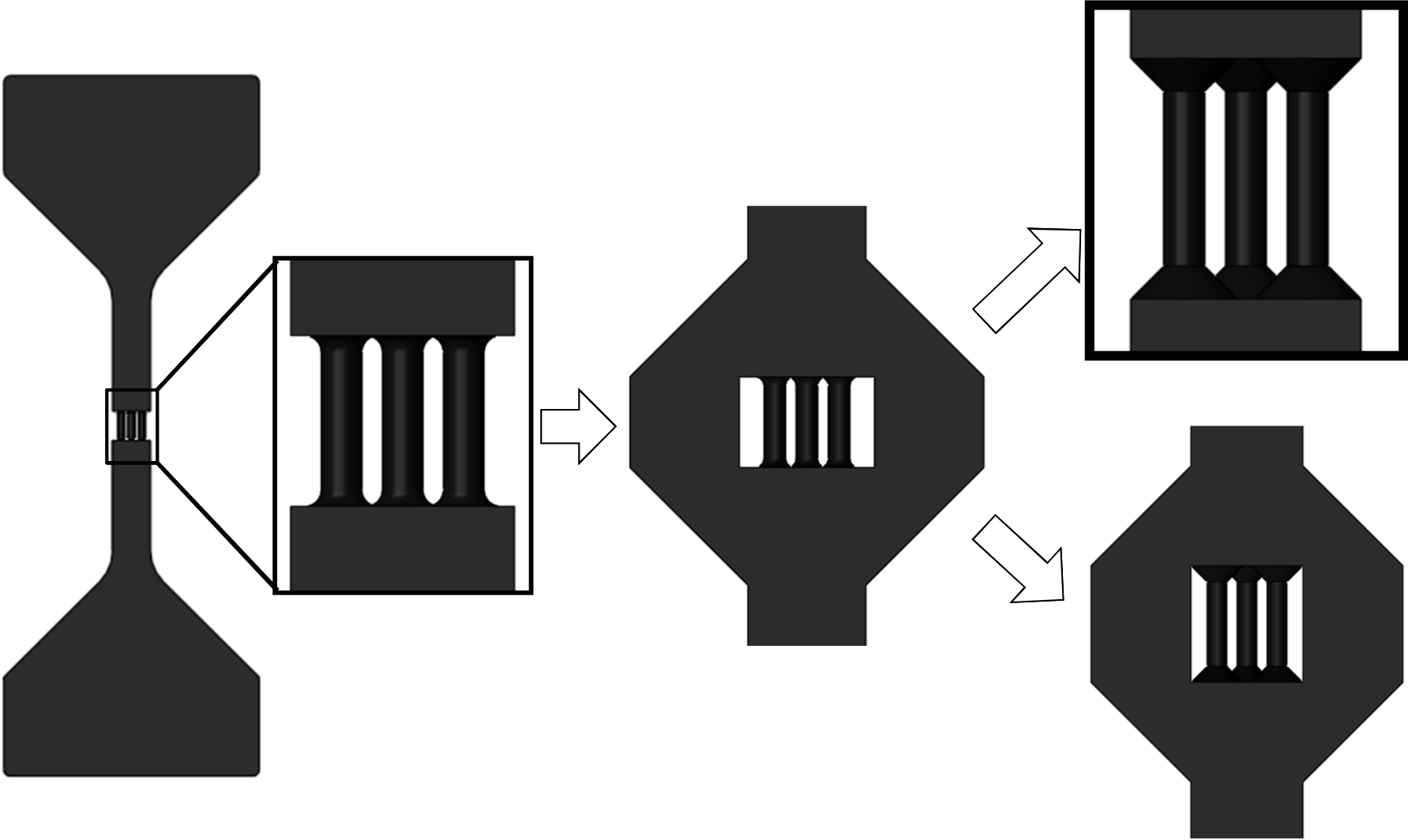
(Jared et al, 2016)

Robust Design

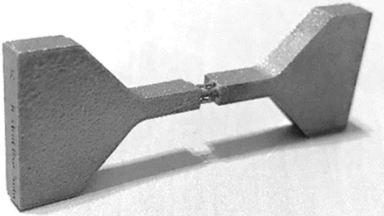
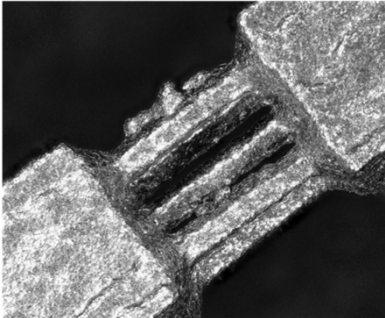
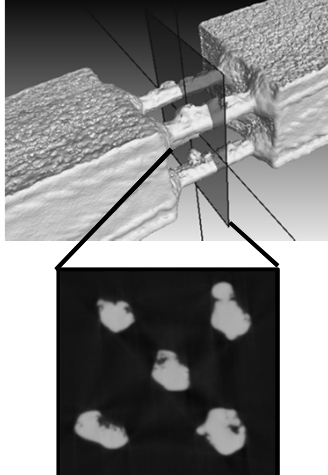
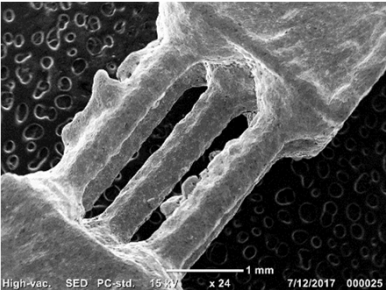
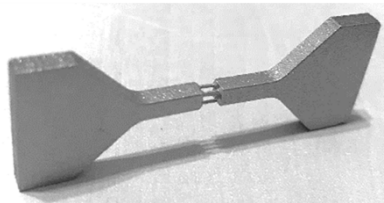
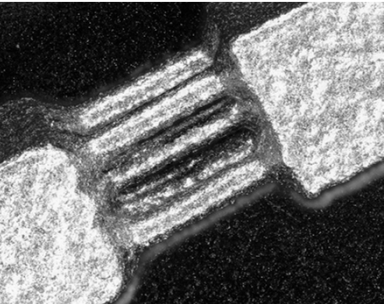
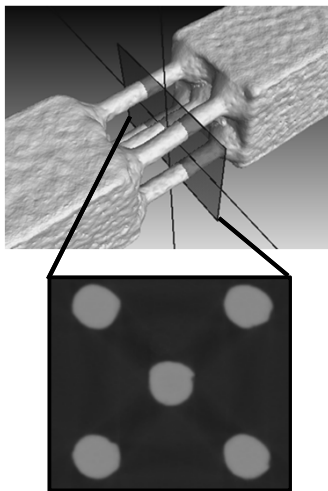
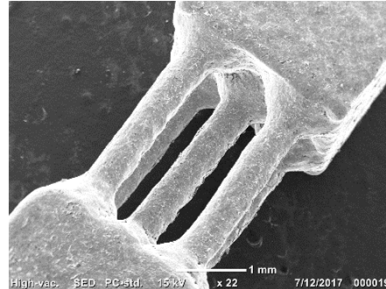


(Kalsi, Hacker, & Lewis, 1999)

Design for Manufacturability



Strut Inspection-Orientation Comparison

	Visual Inspection	Microscope	CT Scan	SEM
3 mm Horizontal Bar				
3 mm Vertical Bar				

Full Lattice Builds

