Characterization of AM Samples with Mechanical and Nondestructive Testing – Lessoned Learned

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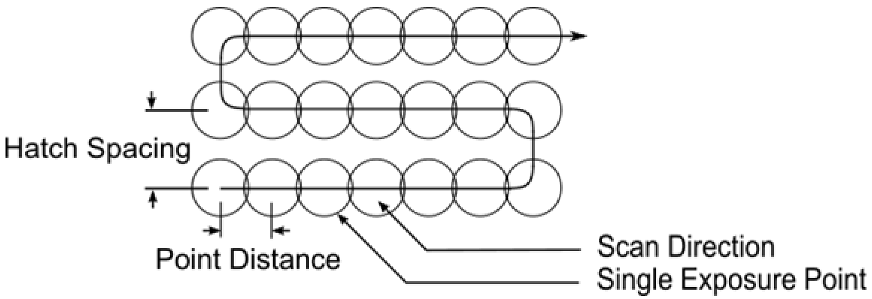
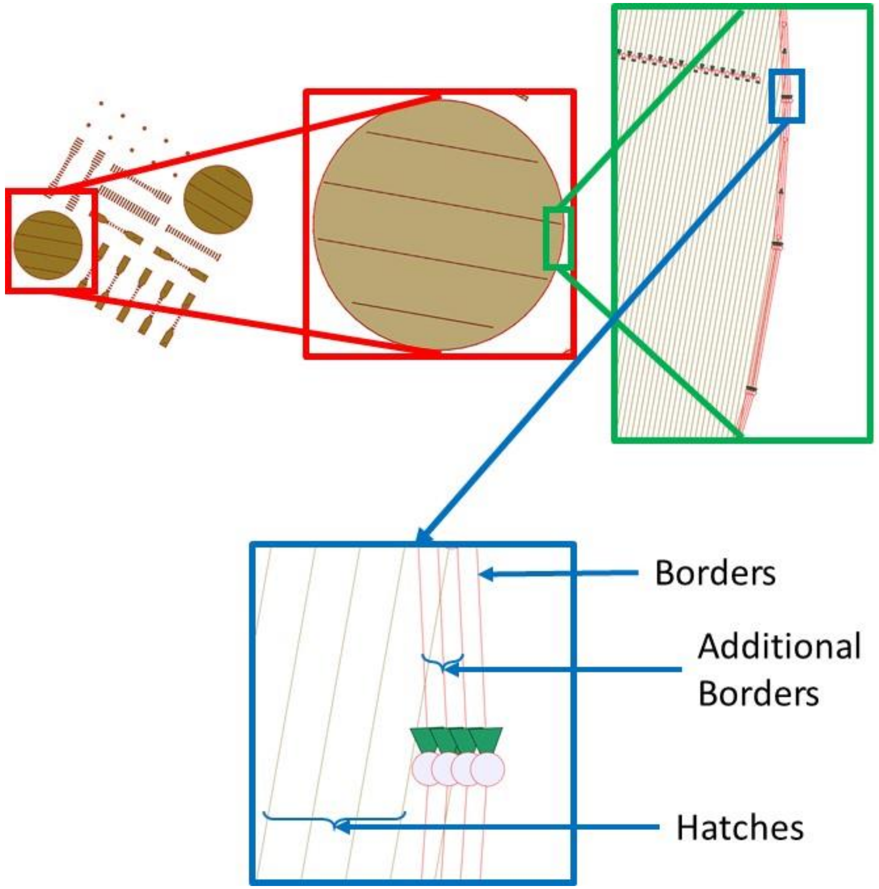
Additive Manufacturing Build Information - Metal Parts

A Renishaw AM250 LPBF machine was used to create the uniaxial tensile samples. The operational settings: 200 W 1070 nm wavelength Yb - fiber laser that operates in a power modulated pulsed wave (PW) mode. The powder layer thickness is (60 um). The PW mode allows for laser power, point distance, exposure time, and hatch spacing to be controlled for each layer within the build volume.

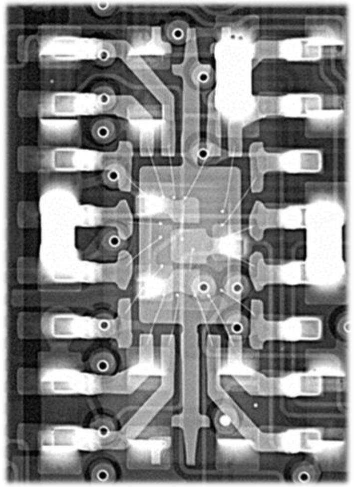


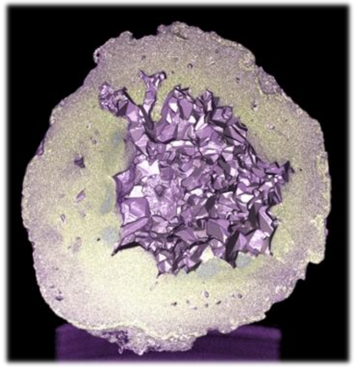


Slice Thickness 60µm
Spot Size: 70µm
Layer to Layer Rotation: 67°
Invokes:
- Borders
- Hatching
- Down-skins

Commands:
- Borders
- Additional Borders
- Hatches
- Down-skin hatch
- Down-skins border
- Down-skins additional borders

Radiography Inspection Capabilities





- Locate Minute/Hidden Cracks
- Locate Poor Electrical Connections
- Measure Internal Dimensions
- Locate/Quantify Density Variations
- Pre-Test & Post-Test Comparisons
- CAD to CT Data Comparison
- Porosity/Inclusion Analysis

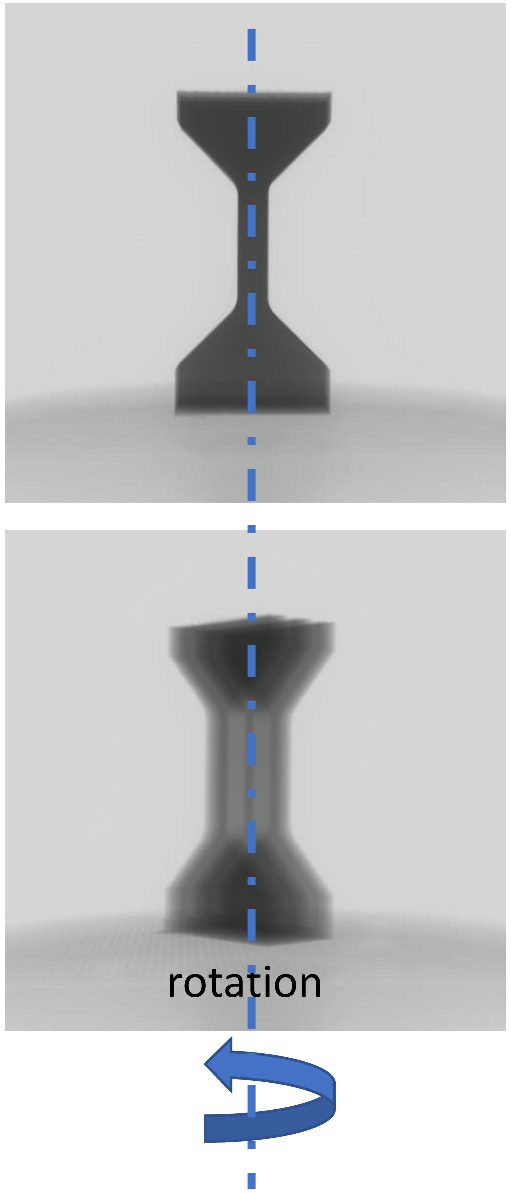
- Mini Focus Radiography (< 450 KV)
- Computed Tomography [CT]
- Detector FOV: 16" x 16" & 8" x 10"
- Helical Scan Technique
- Curved-Linear-Detector Array
- Image Processing

- Materials Research and Development
- Quality Control and Production Inspection
- Reverse Engineering
- Verification of Internal Components
- Failure Analysis
- Testing Diagnostics
- Non-Visual Dynamic Event Monitoring

- Film Radiography (~ 25 micron spatial resolution, various film sizes
- Computed Radiography [CR] (~ 50-100 micron spatial resolution, 16-bit)
- Digital Radiography [DR] (~5.8 micron spatial resolution, 16-bit)

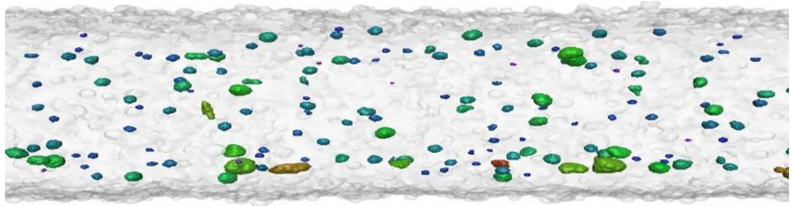
Devices	X-ray System	Energy Level	Part Thickness	Nominal Feature Size	Deliverables
4	Micro Focus	10-220 kV	<1" Steel	10um	Film, CR, CT, DR
3	Mini Focus	10-450 kV	~2" Steel	100-200um	Film, CR, CT, DR
1	Micro Focus (Nikon)	10-450 kV	~2" Steel	10-25um	Film, CR, CT, DR
2	High Energy	6-9 MeV	~12" Steel	85-200um	Film, CR, CT, DR
1	Flash X-ray	450 or 1 MeV	~6" Steel	500um	Film, Screens
1	Nano Focus	160 kV	<.25" Steel	500nm	CT
3	Portable Pulsed	270kV-370kV	~1" Steel	100-200um	Film, CR, DR

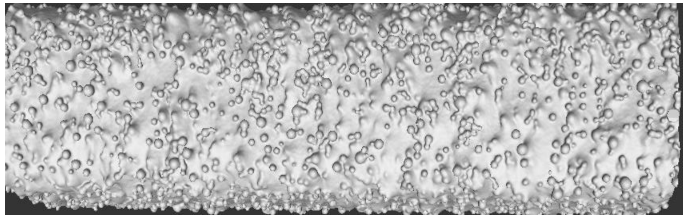
Typical Computed Tomography Set-up



The Computed Tomography (CT) technique collects penetrating radiation measurements from the object’s x-ray opacity using a flat amorphous silicon digital detector. This technique generates a 3-D image from each thin slice of an object’s volume.

These projections are collected and mapped together to create a volumetric data set. The fraction of the x-ray beam that is attenuated will directly relate to the density and thickness of the material through which the photon (x-ray) has traveled.

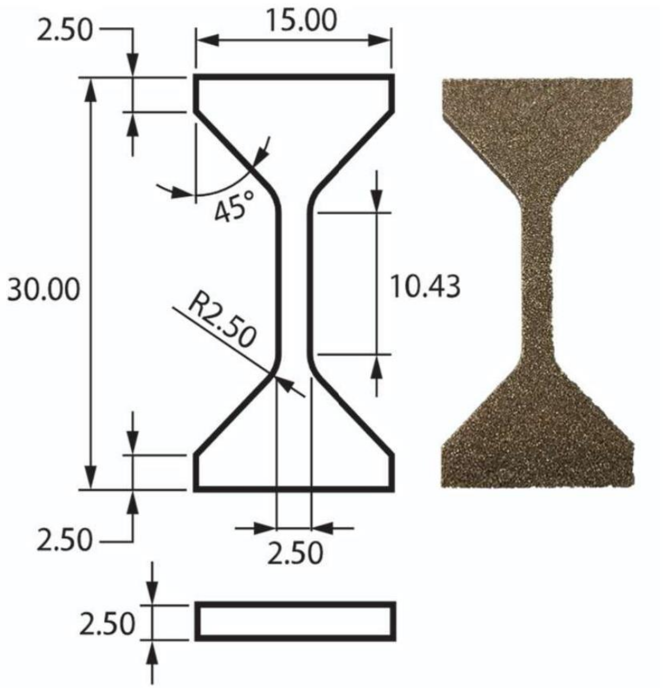




Mechanical Load Testing

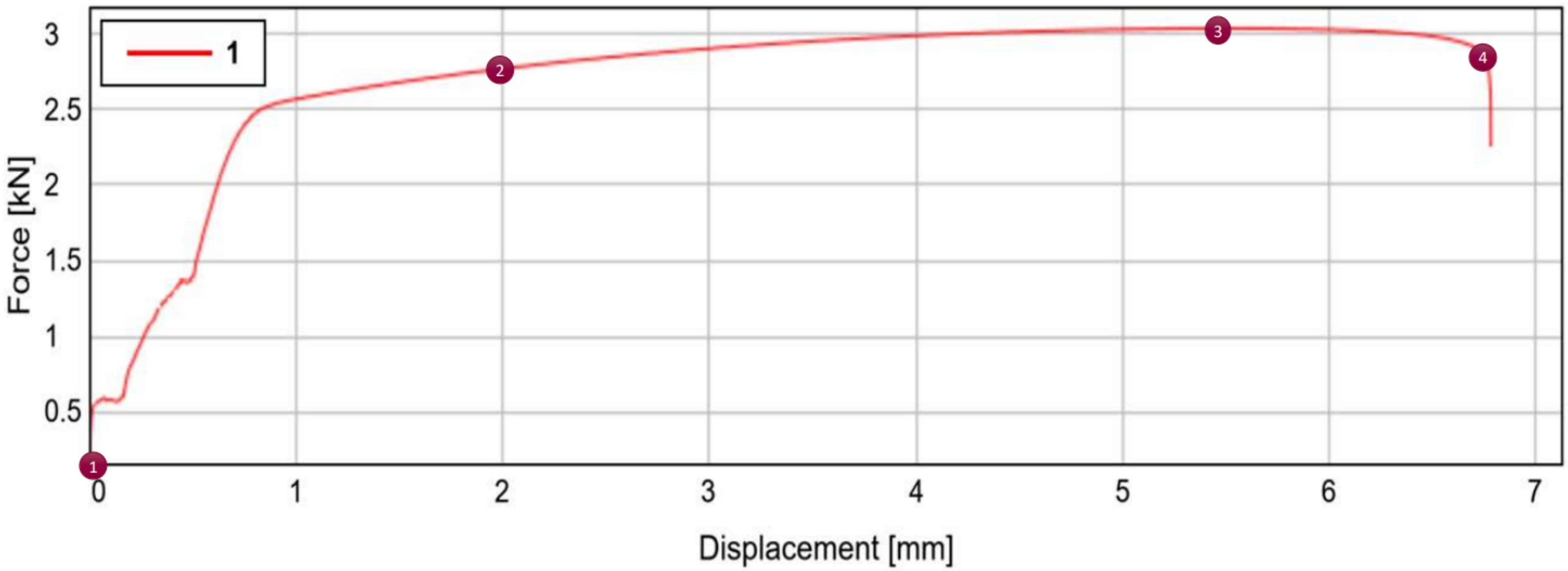
An Instron 6800 floor series universal test machine was used for mechanical testing. The machine was set for a displacement rate of 1 mm/minute. Each specimen was subjected to three different loading conditions to observe the evolution of pores and cracks up to ultimate failure. A 2 mm displacement is approximately 20% strain. Once the peak force drops by 0.5% from the maximum value the testing stops. Specimen failure is defined as a 10% drop from the current value.

The specimens were pulled one more time to separate them apart for fractography (SEM).



Engineering drawing (units are in mm)

Mechanical Load Testing Results - Sample 1



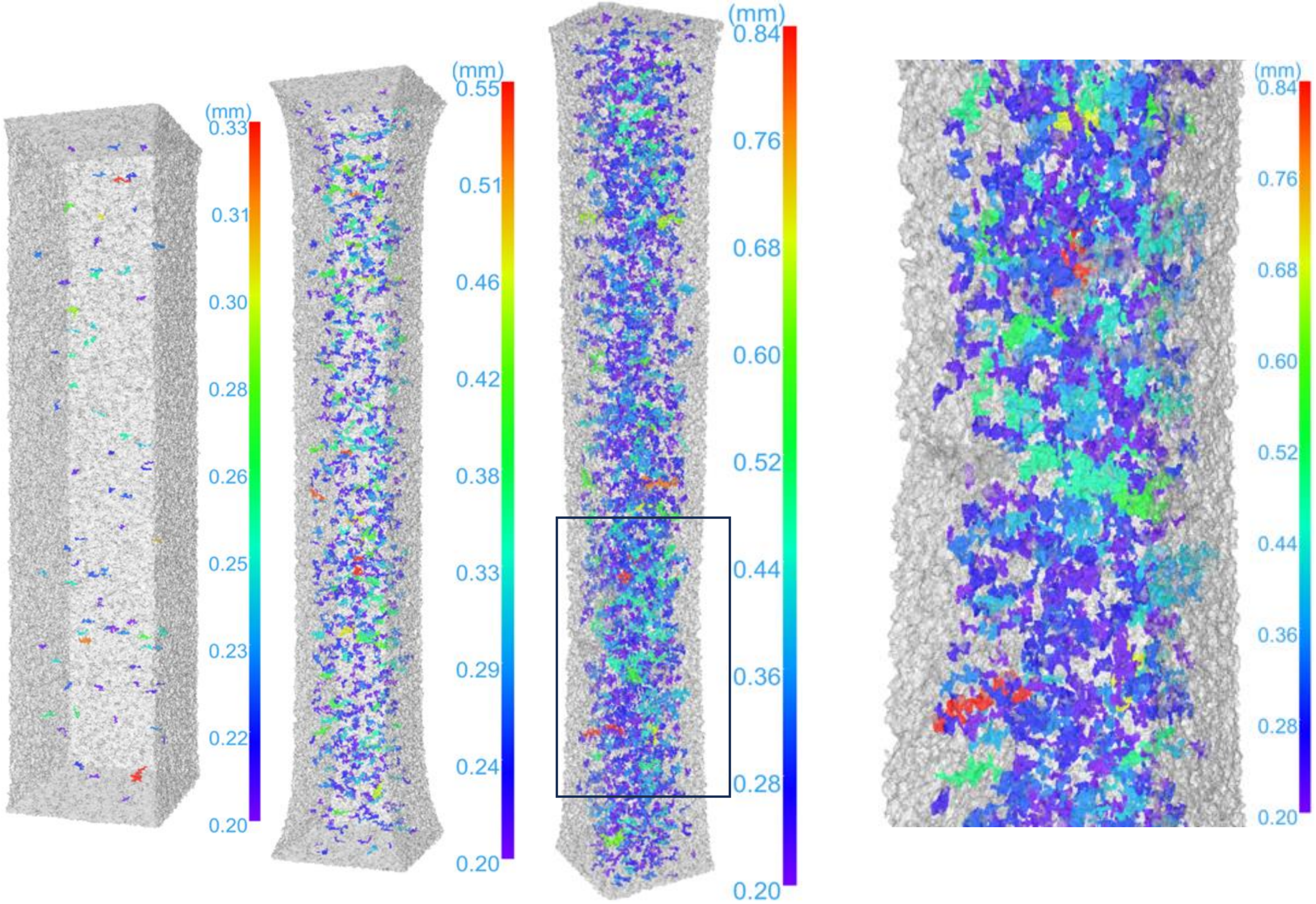
1 no deformation

2 Small plastic deformation (2 mm displacement)

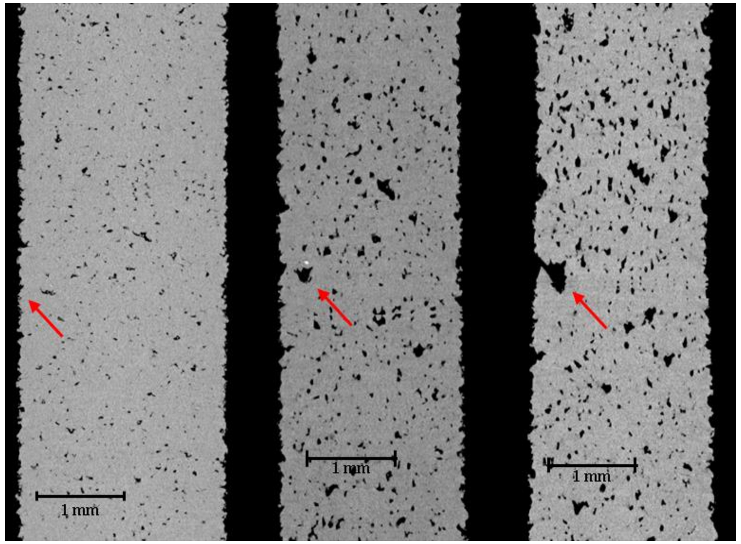
3 Maximum load before necking starts (0.15 % force drop from the peak)

4 Maximum displacement before sample breaks (0.5% force drop from the peak)

Observed Failure Mechanisms 1 of 2

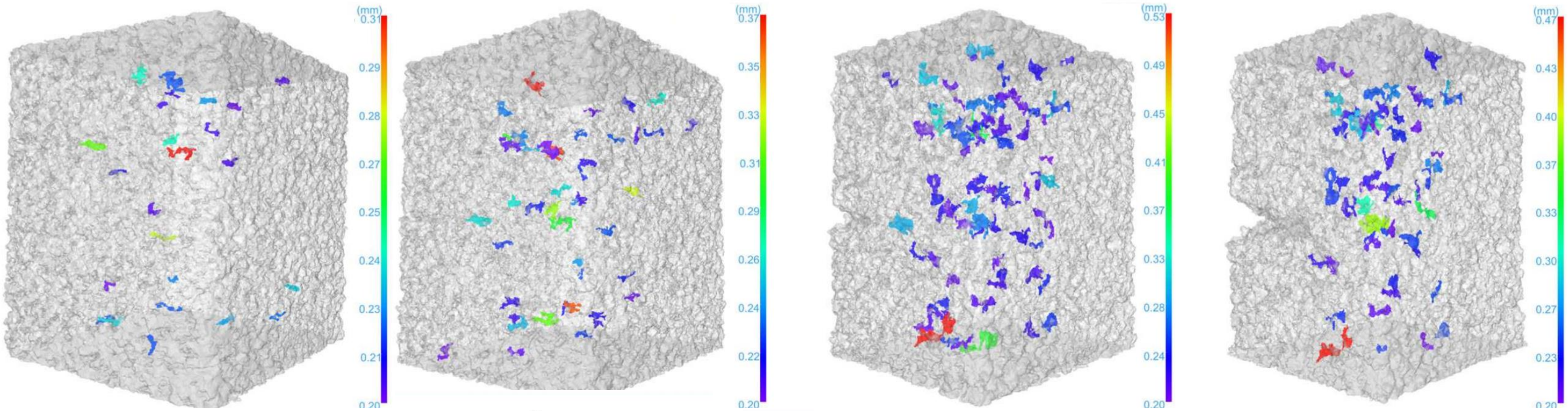


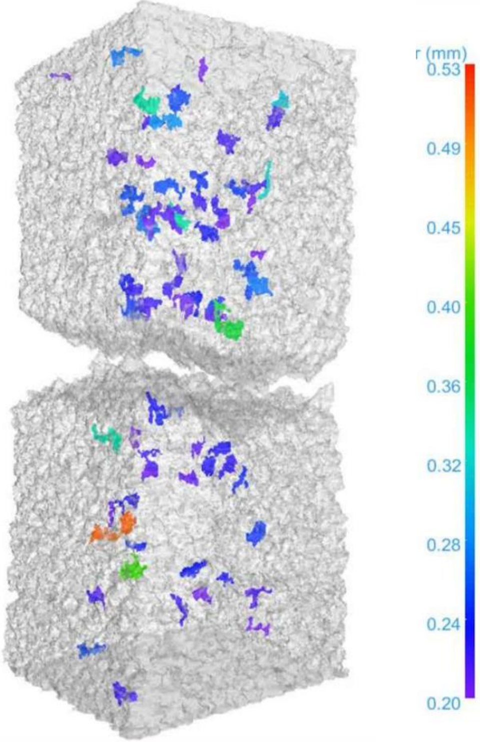
Non deformed, peak stress, yield

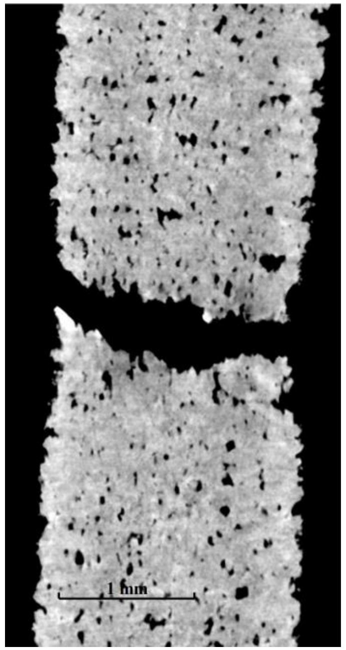


Non deformed, peak stress, yield

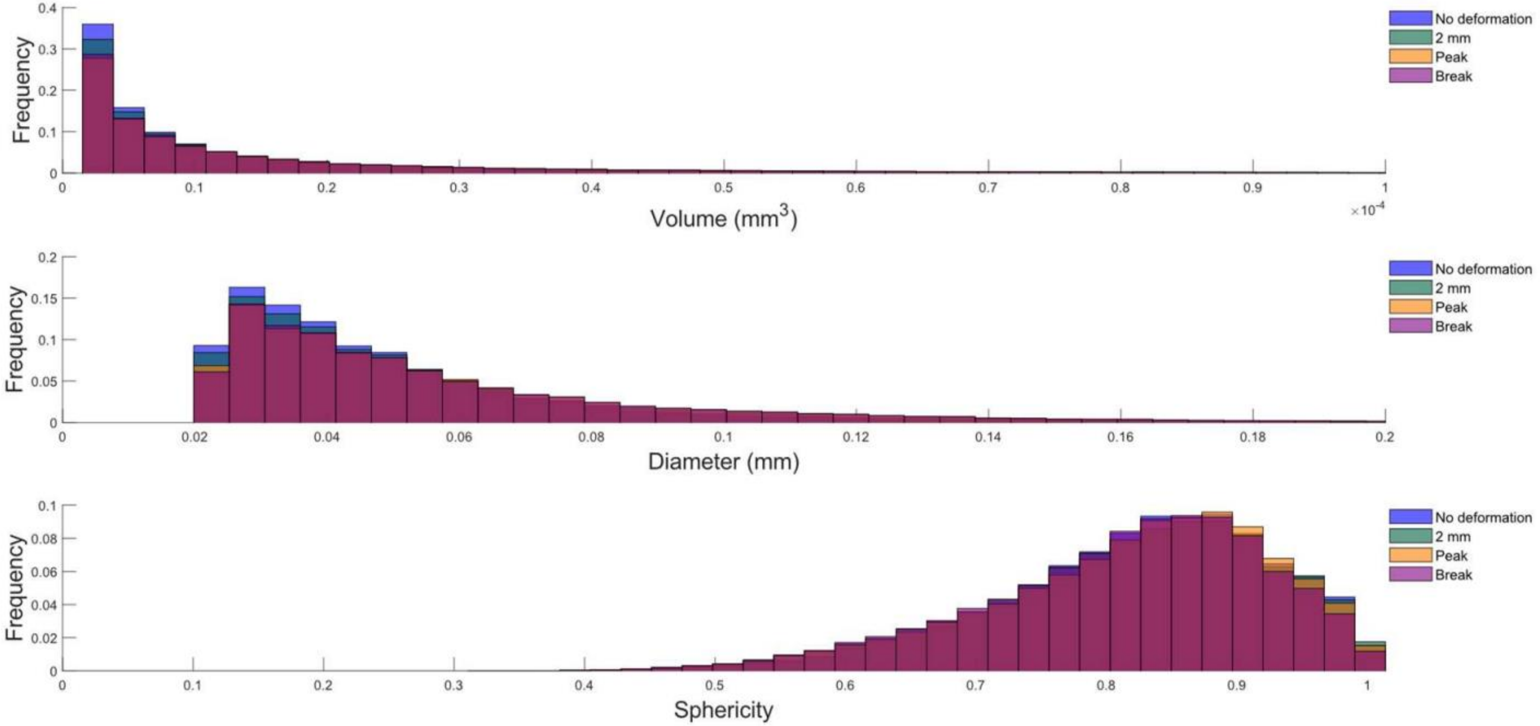
Observed Failure Mechanisms 2 of 2







Void Characterization using Software



Pore volume, diameter, and sphericity distributions

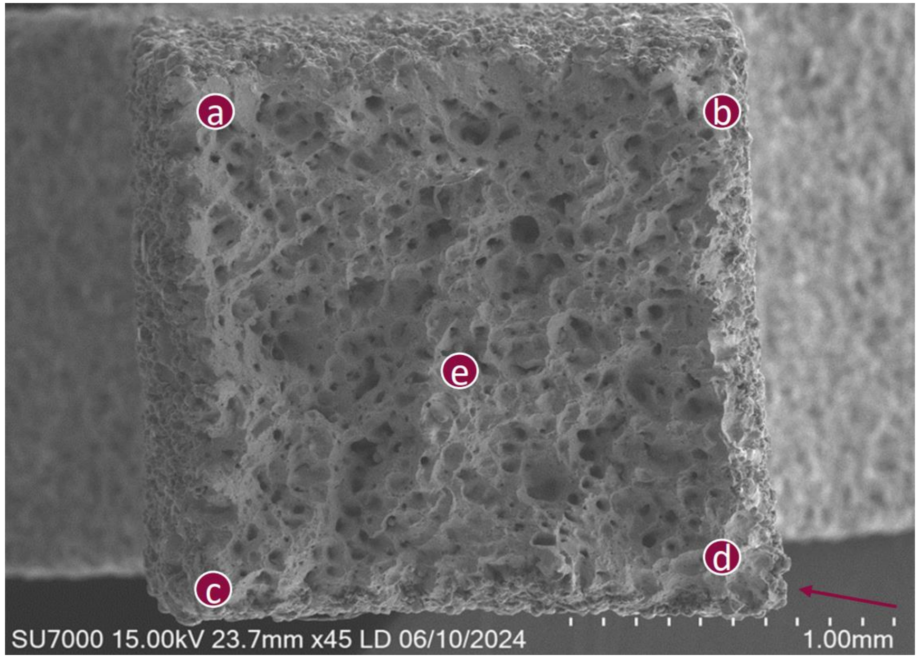
Sphericity Characterization

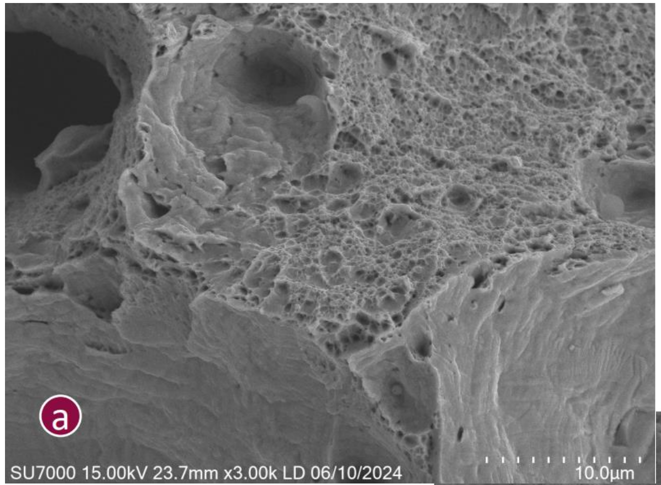
Minimum 0.32

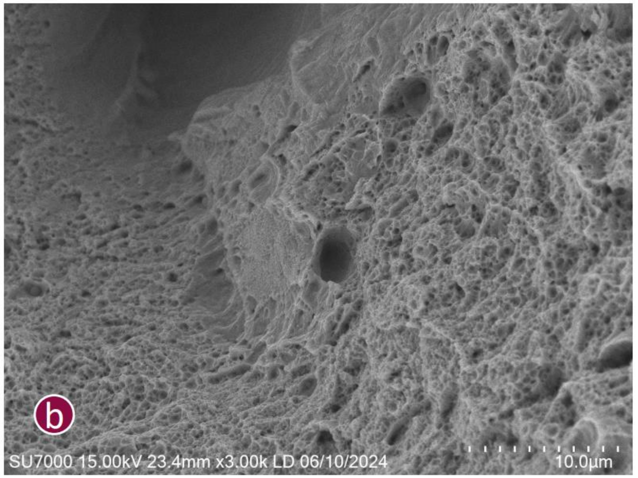
Mean 0.81

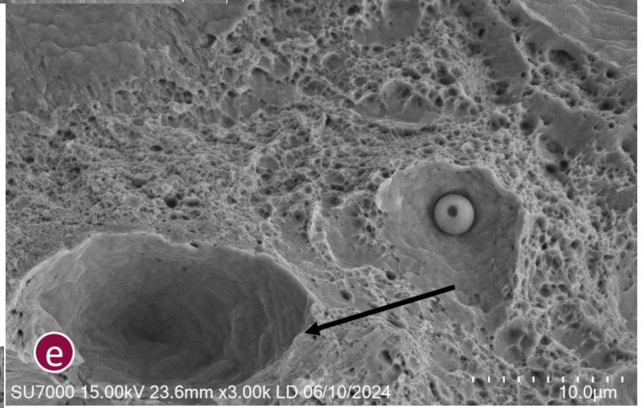
Standard deviation +/- 0.11

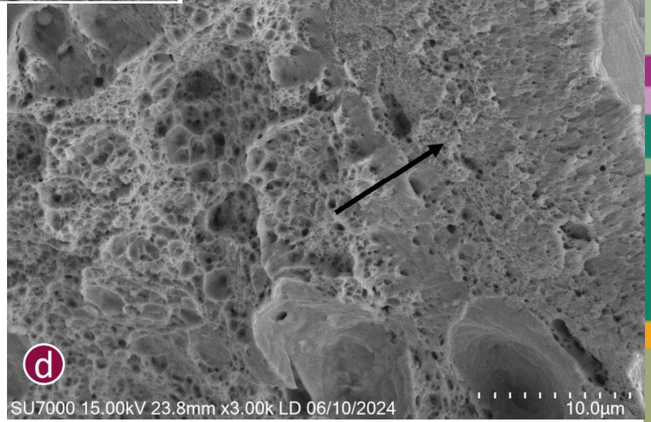
Fractography Example











Images were created with a HITACHI Schottky Field Emission Scanning Electron Microscope - Model SU7000.

Porosity Analysis Summary Questions to Ask

- Are the porosity distributions consistent in size and shape?
- Does the data show a location and pattern of pores that are generally consistent across samples of the same size?
    - Do the samples have more larger porosity on one outside of volume?
    - Is lack of fusion porosity present at the edges of each sample? Is this consistent across all samples, regardless of size)
    - Generally where is the higher porosity located?
- Is porosity variance indicative of printer laser power, powder distribution changes or gas flow variations over the build plate?
- Where do the pores tended to cluster? Around the edges of the sample of in the gage section?

Summary of Results (CT Software Porosity Analysis)

VGDefX™ detects pores (gas porosity), key-hole porosity and lack-of-fusion defects but the program is more difficult to use. This analysis should find all the smallest pores/voids that are present. It might miss voids that are near or open to the surface.

The porosity comparison can be documented throughout the build volume and in our case it increases along the build *z-axis.* Each sample thickness has a unique porosity signature and distribution. VGDefX is a more defined detection algorithm that is more useful.

The general probability criterion finds the required “critical” defects. Care must be taken within the selected ranges so the algorithm does not compute false positive identification of pores from scanning artifacts. Surface breaking defects might be missed if the volume does not close at the surface.

Conclusions

Void diameter and volume is calculated based on an assigned gray scale value. All detected gray scale values must be larger than the defined background voxels. This value is specified in the baseline materials definition menu within the software detection program. The local contrast threshold is specified within the program establishes the part's local contrast. If the voxel search area is brighter than the local contrast voxel level, a higher probability of detection is assigned to the voxel. A voxel-by-voxel grouping algorithm connects the voxel into a maximum likelihood for detection.

Additive Manufacturing process performance is spatial energy dependent and not a point property value. The manufacturability trade space is not apparent. The size, scale, feature and geometry will change the mechanical properties and the porosity distribution within the specimen. The processing engineer must document microstructure changes with respect to AM process settings. **Dog bone tensile samples may be a quick experimental approach for process mapping and help determine the optimum setting of laser power and velocity**.

When porosity forms a trail within several layers, the laser power is too high and does not allow proper evaporation of the gas from the liquid before the metal solidifies. Computed tomography has the ability to analyze spatial distribution of key-holing, gas porosity and lack of fusion within uniaxial tensile samples.

Other Inspection Methods

Sandia Ultrasonic Inspection Capabilities

- Locate defects, flaws and inclusions
- Quality assurance

- Material characterization
- Porosity evaluation

Devices	Ultrasonic Systems	Services Provided
1	Mistras UltraPAC^{TM} UPK-T10	Immersion ultrasound scan; A-scan images, B-scan images, and C-scan images
1	Mistras UltraPAC^{TM} UPK-T36	Immersion ultrasound scan; A-scan images, B-scan images, and C-scan images
1	Mistras UT Tablet	Contact ultrasound; A-, B-, and C- scan images
1 ea.	TD PS45 Pocket-Scan 8 channel, 32 channel	Contact ultrasound; A-scan images; capable of monitoring multiple probes in through transmission and pulse echo; portable
1	NDT Solutions MAUS	Contact ultrasound; A- and C-scan images; portable
2	Olympus 5077PR Square Wave Pulser/Receiver	Contact ultrasound; A-scan images; material property measurments
3	Olympus OmniScan	Contact ultrasound and phased array; A-, B- and C-scans for both methods; portable
1	Olympus 1000i	Contact ultrasound; A- and B-scans; portable

Infrared (IR) Inspection Capabilities

- Temperature Measurements
- Measuring fast thermal events
- Surface Crack Detection
- Subsurface corrosion detection
- Variations in coatings
- Electrical Maintenance
- Heat loss from buildings
- Search and Rescue
- Material Sorting and Identification

Devices	IR Equipment	Resolution	Services Provided
1	VoyageIR	Microbolometer IR camera - 30 Hz @ 320 X 256 14 bit USB	Heat gun with trigger control. Handheld color touchscreen (live or saved images available). Disbonds and internal fracture of composites.
2	EchoTherm	FLIR 6106; 60 Hz 14 bit, 640 x 512 Pixels InSb detector.	Corrosion Detection thin metal structures and polymer printed parts
1	FLIR E-60 Handheld	Focal plane array IR Camera 320 X 240	Temperature Measurements -20 to 650 °C
1	FLIR	FLIR 8501sc, 1280 x 1024 Pixels InSb detector.	Camera controlled by ethernet cable to a laptop. High speed data recording available, microscope lens for high zoom applications.

Eddy Current Inspection Capabilities

- Surface Crack Detection
- Subsurface Crack Detection up to ¼” in depth
- Non-Conductive Coating Thickness
- Thin Plate Thickness Measurement
- Material Loss (Corrosion) Inspections
- Conductivity Testing in IACS%
- Metal Sorting and Identification
- Bolt Hole Inspection
- Phased Array Inspections

Devices	Eddy Current Systems	Frequency Range	Services Provided
1	Nortec 500	10 Hz-12 MHz	Bolt Hole, Crack Detection, Thickness Measurements, Corrosion Detection, Metal Sorting
1	Olympus 600	10 Hz-12 MHz	Bolt Hole, Crack Detection, Thickness Measurements, Corrosion Detection, Metal Sorting
1	Omni-Scan Eddy Current Array Scanner	20 Hz-6 MHz	Bolt Hole, Crack Detection, Thickness Measurements, Corrosion Detection, Metal Sorting, Phase Array, Automated Inspections

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Magnetic Particle Testing

- Surface Crack Detection
- Subsurface crack detection
- Weld inspection

Devices	MT Equipment	Type	Services Provided
1	PL-10 AC Magnetizing Coil	AC Inspection	Surface and subsurface crack detection on ferrous materials
1	DA-200 Yoke	AC and DC inspection.	Surface and subsurface crack detection on ferrous materials

When to Use Penetrant Testing

- Capabilities
  - Detection of VERY small defects on the surface (≈ 5 - 10 µm)
  - Crack, Pore, Leak Detection
  - Ability to inspect complex shapes

- Limitations
  - Defects MUST be open to the surface and the surface must be free of anything that could interfere with penetrant materials
  - Excess surface roughness/porosity can hide relevant defects
  - Very high temperatures (> 160 ℉) can vaporize dye and reduce visibility of indications
  - Visual acuity of inspector

Penetrant Testing Compared to Other NDE Methods

- Advantages
  - Portable
  - Low Cost
  - Quick
  - Can be used on (almost) any material

- Disadvantages
  - Nature of part surface determines effectiveness of testing
  - Multiple steps must be controlled and performed accurately to maintain reliability
  - Post-cleaning is required after inspection. Some penetrant residue may remain even after cleaning.
  - Chemical handling

Acknowledgements

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