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# Computed Tomography Inspection of Additive Manufactured Components at Sandia National Laboratories



PRESENTED BY

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# Contributors

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# Roadmap

- What is Additive Manufacturing (AM) and why use it?
- What is Computed Tomography (CT) and why use it?
- Test Setup
- How is CT Improving AM

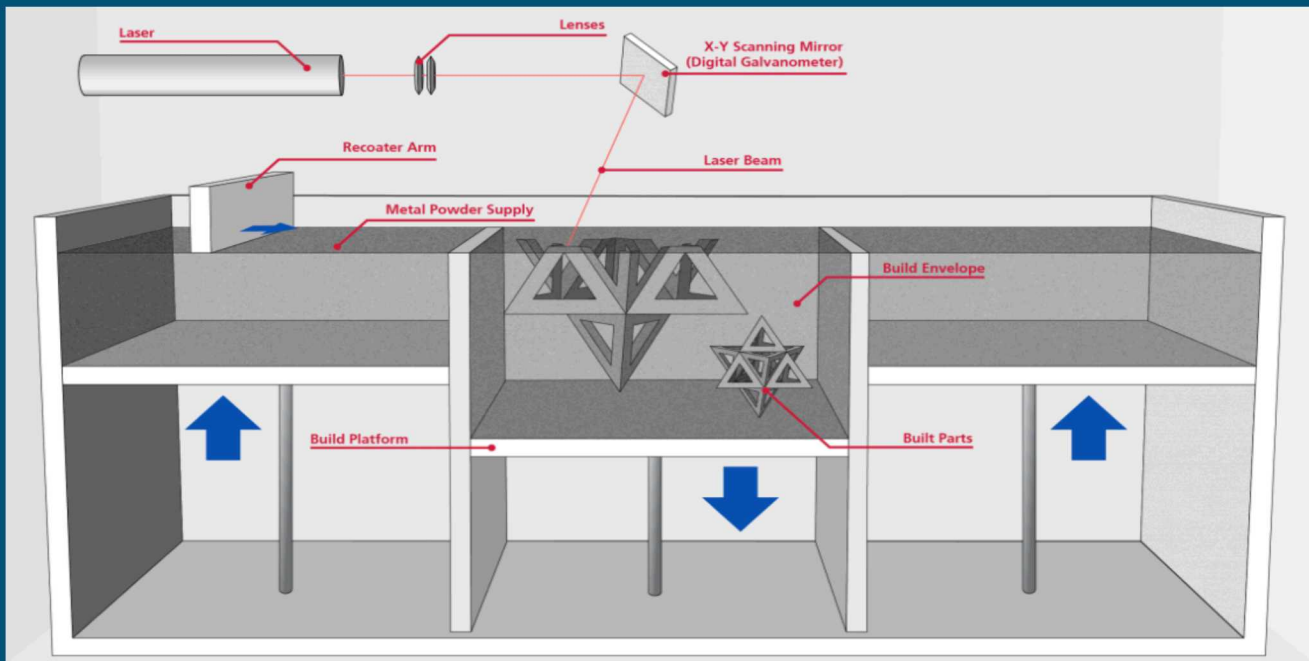
# What is Additive Manufacturing (AM)???

**ASTM F2792:** A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.

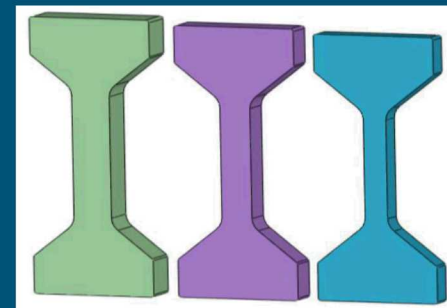
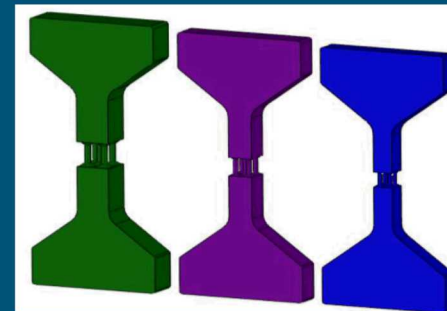
- 3D model (CAD)
- Metal Powder
- Direct Metal Laser Sintering (DMLS)



3D Systems  
ProX 200



Direct Metal Laser Sintering (DMLS) Process Description



Tensile Specimen CAD Models



DMLS-Printed Tensile Specimens

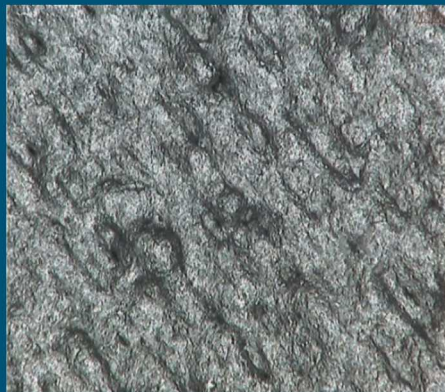
# Why Use AM?

## Quick Production



*fixture generated in 1 day*

*surface finish ~ 5µm Ra*



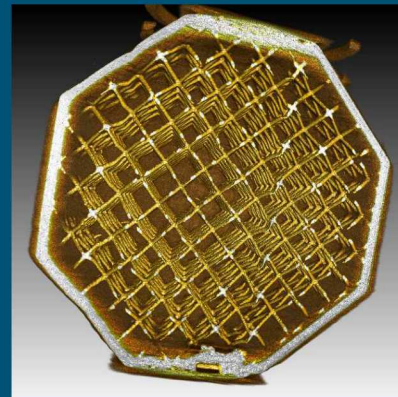
Control of Material Properties



*AM Polyhedron*

## Internal Structures

### *Internal Lattice*



## Cost Reductions



*Bomb Disablement Hand: \$10k vs \$250k*

### *Titanium bracket*

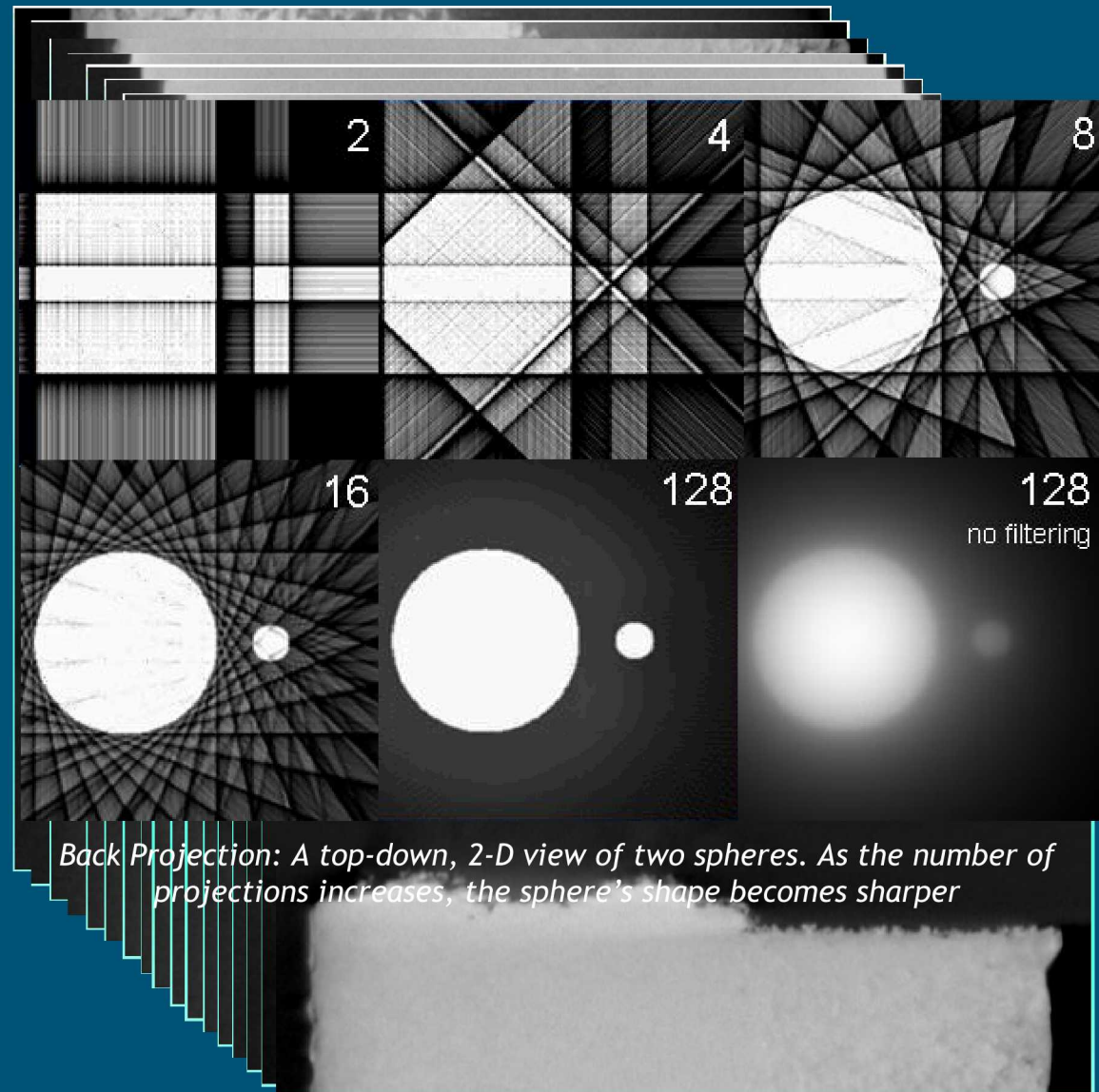


Design Limited by Imagination, not Manufacturing Processes

# What is Computed Tomography (CT)???

## Definition of 'Tomography'

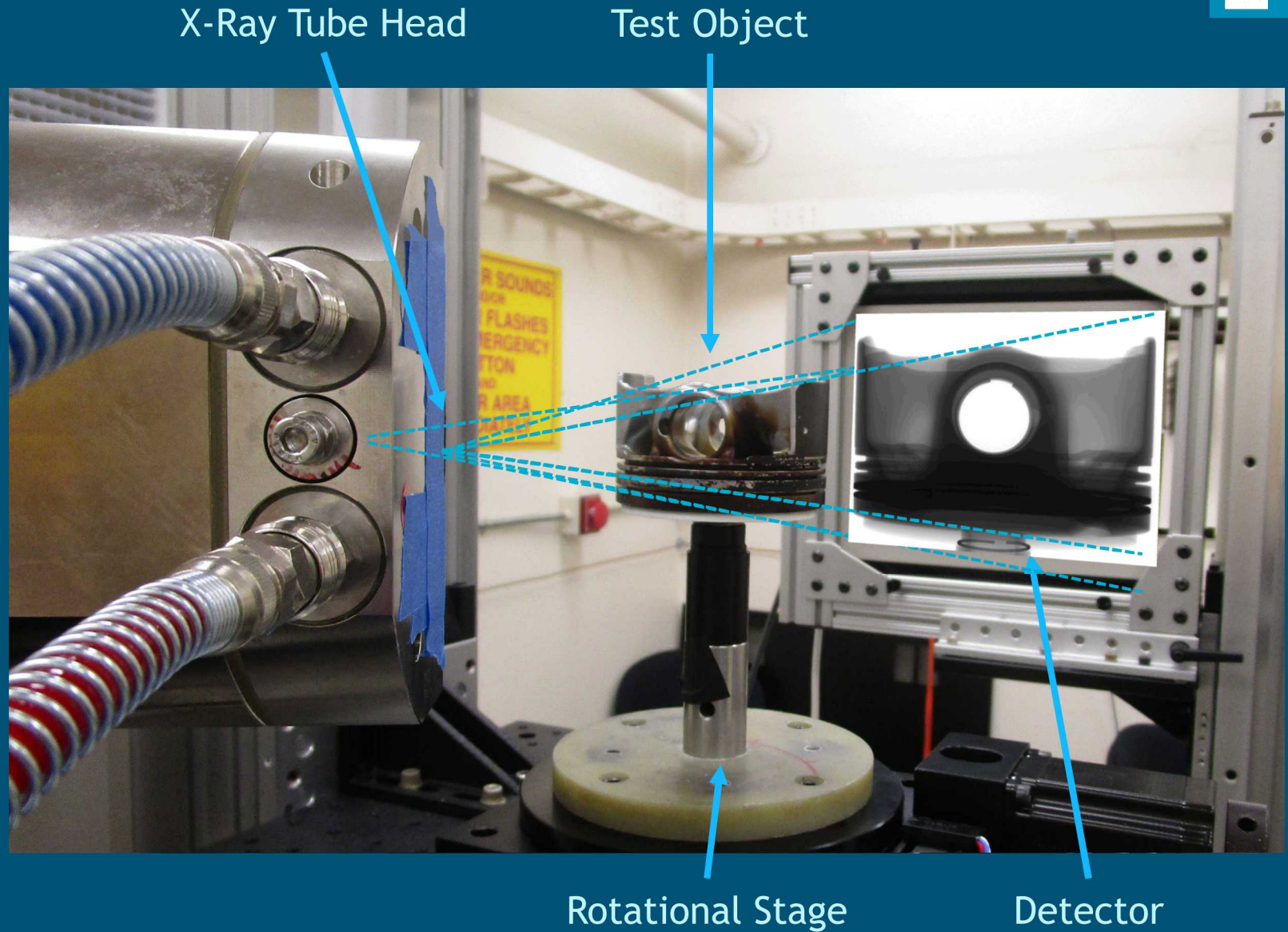
- 'Tomo' (Greek): A cut, section
- '-graphy' (Greek): A form of representation
- Method
  - X-Rays attenuate as they penetrate an object
  - **Many** radiographs of an object are taken
  - The amount of attenuation is a function of an object's density and the energy of the x-ray
  - A computer uses a filtered back-projection algorithm to reconstruct an object



*Back Projection: A top-down, 2-D view of two spheres. As the number of projections increases, the sphere's shape becomes sharper*

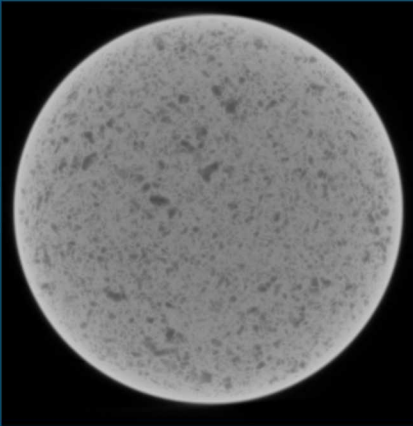
# CT Test Setup

- X-Ray Tube Head
  - 130 kV Nano-Focus
  - 450/225 kV Micro-Focus
  - 6 MeV (1 mm Focal Spot)
- Rotational Stage
  - Angle Increments  $\approx 0.02^\circ$
- Cesium Iodide Detector
  - 0.127 mm Pixel Pitch
  - 9.6" x 7.5" Active Area



# Why Use CT?

## Porosity

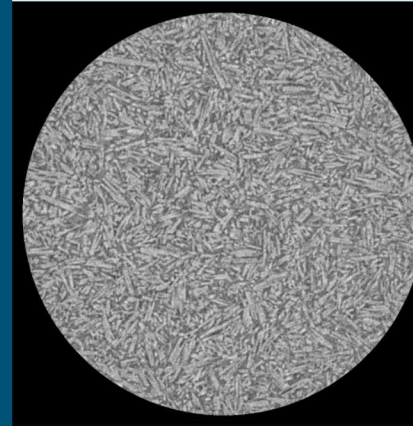


Minimum 20 mm Thickslab

AM Tensile Bar

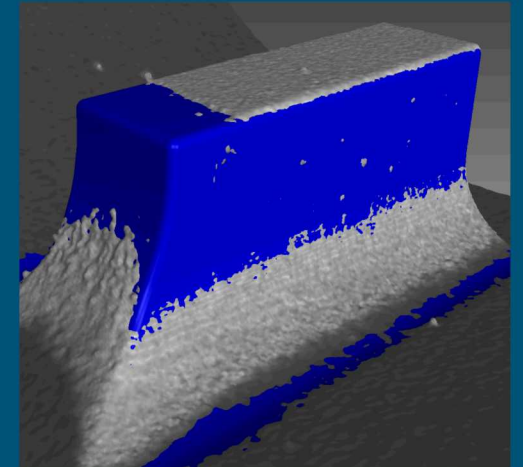


## High Resolution



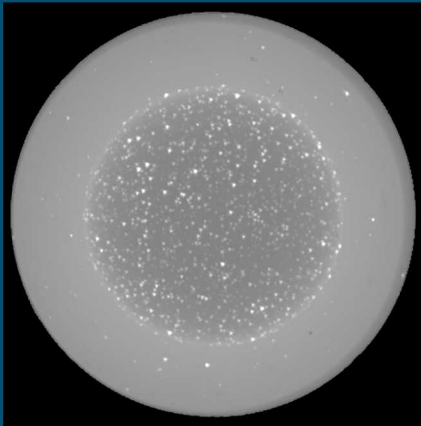
Nano-CT (880 nm pixel resolution)

Actual/Nominal Comparison



## View Internal Structures

Maximum 20 mm Thickslab



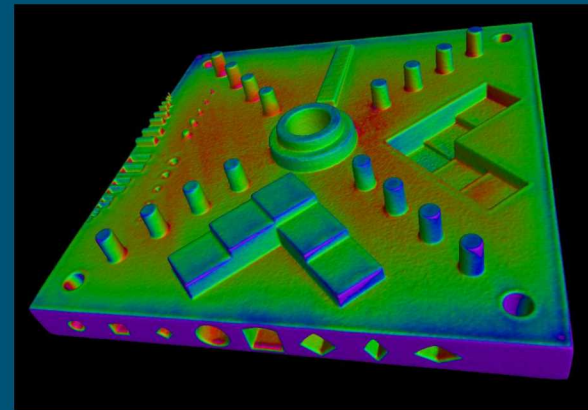
## Inclusions



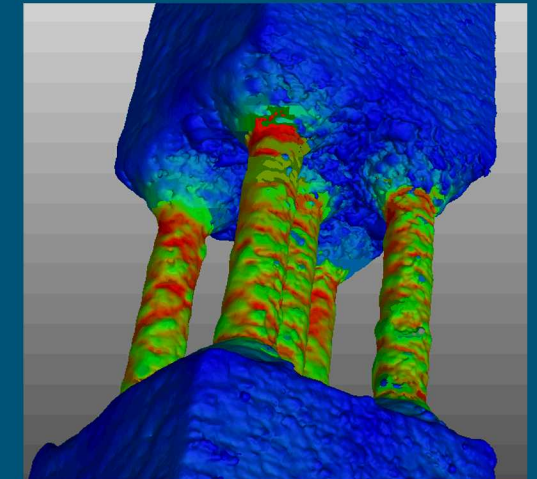
Artificial Pores

## Model Creation & Comparison

AM NIST Standard

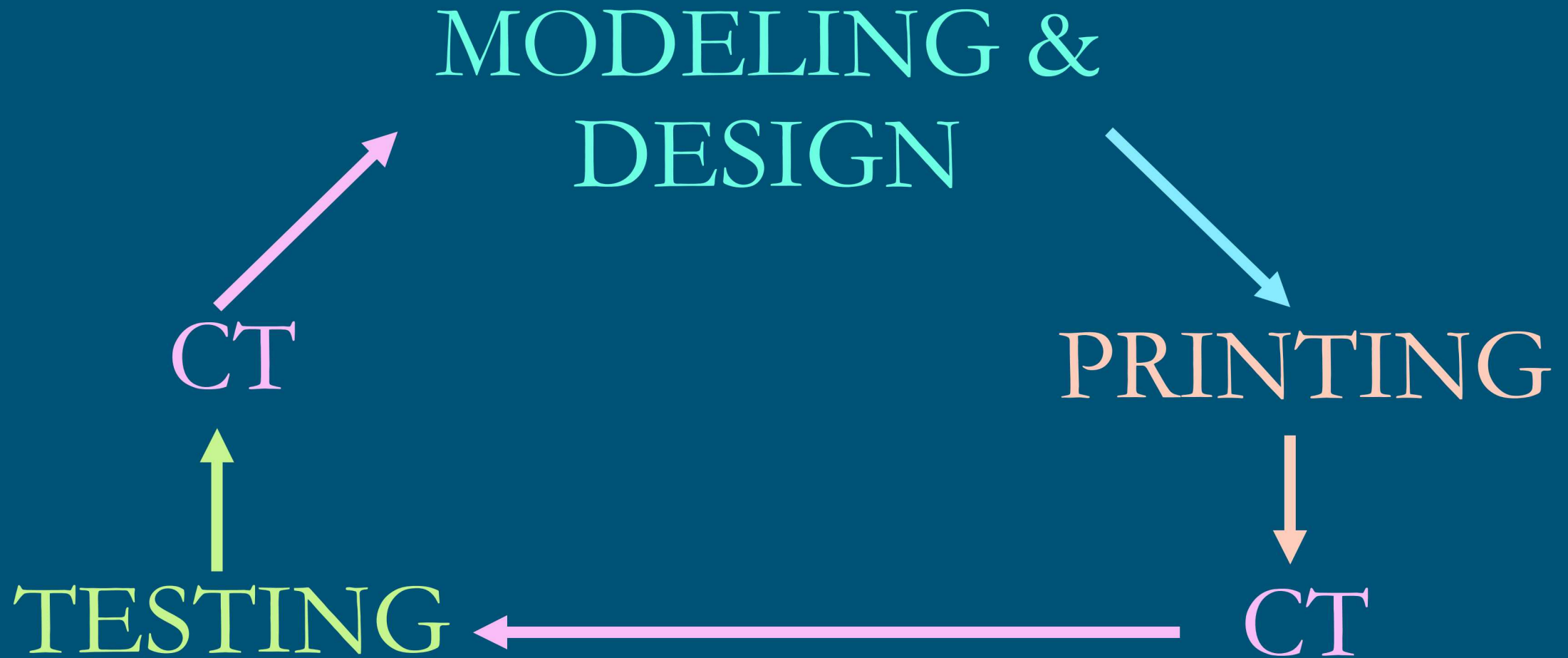


## Metrology



Structural Mechanics Simulation

# How Sandia is Using CT to Improve the AM Process

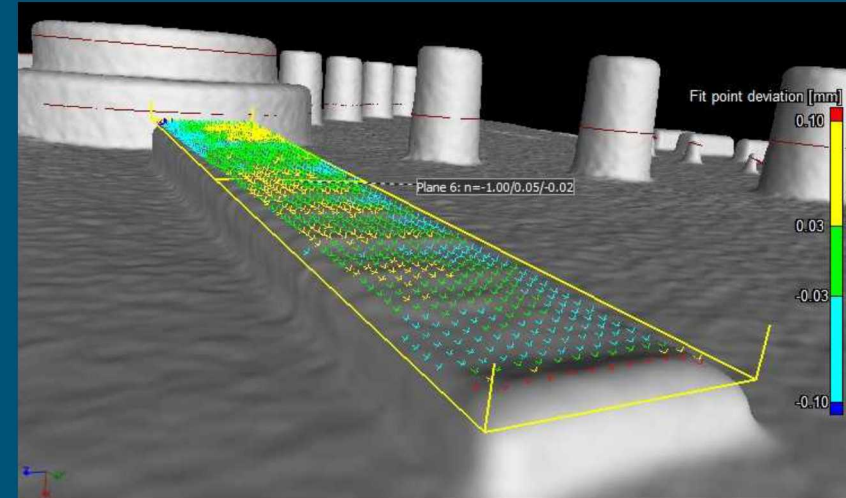


## Example of AM Specimen Production

1. DMLS 17-4PH Steel on EOS M270 with 20 micron layers
2. Heat Treatment: Austenitizing to 1900° F for one hour, then air/oil cool
3. Removed from build platform
4. Hot Isostatic Pressing (HIP): 2125° F for 240 min @ 14.75 ksi
5. Heat Treat: Austenitizing to 1900° F for one hour, then air/oil cool, then H1150 heat treatment

# How CT is Improving AM Process

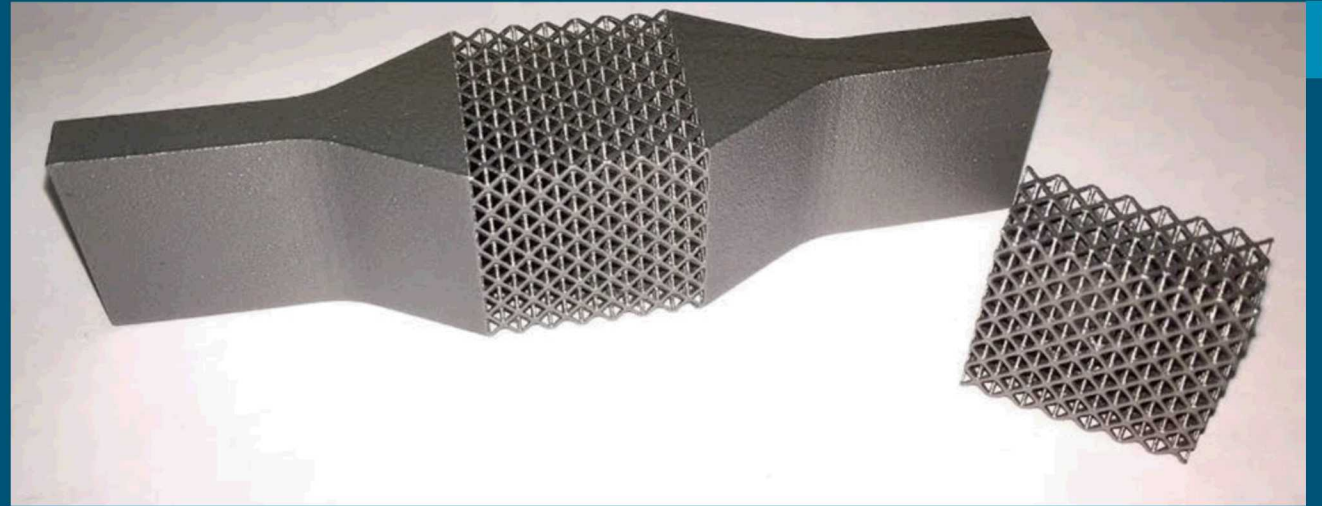
- Metrology
  - Helpful, but CT is not a qualified measuring method yet
- Material Characterization
  - Relative Density
  - Porosity
  - Lack of Fusion
  - Inclusions
- Model Building & Confirmation
  - CT Scan → Model
  - As-Printed vs. As-Designed



*Colored 'Fit Points' show the deviation between the plane and the part's surface*

# Lattice Struts

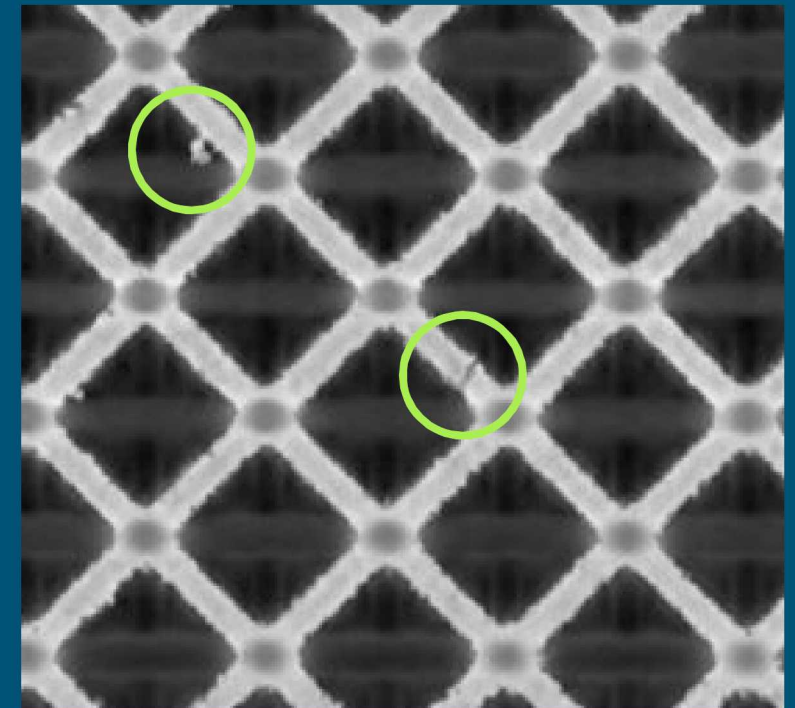
Defective internal struts are impractical to detect with any other detection method, besides CT.



*Extra and missing material*

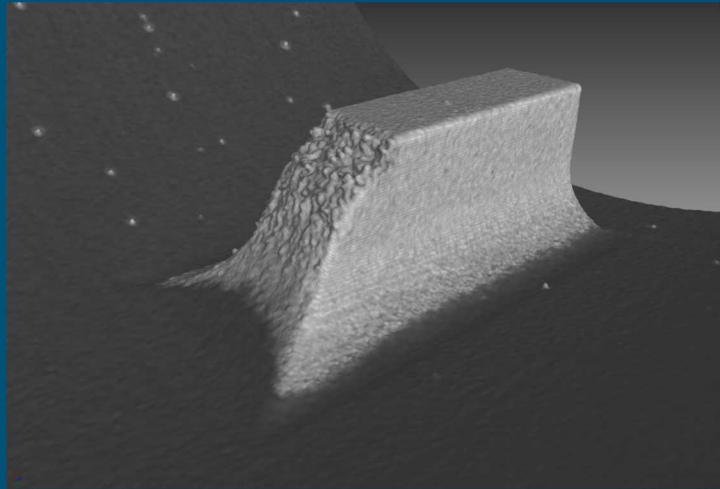


*Unsintered strut*

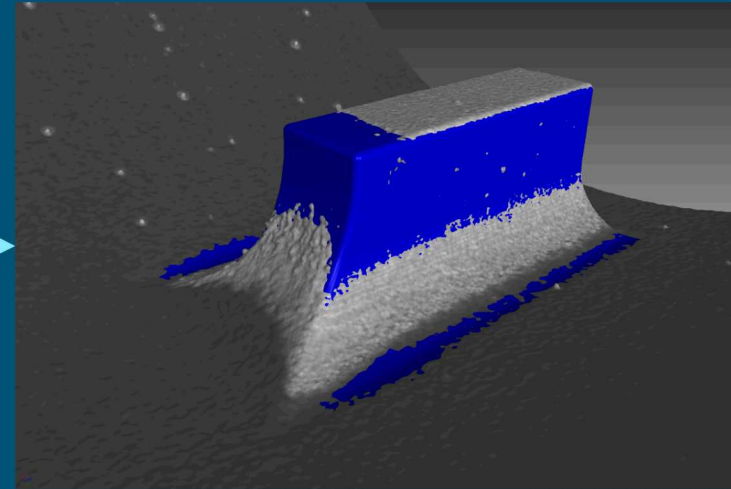


*CT slice view of missing and extra material of internal struts*

# Actual Nominal Comparison

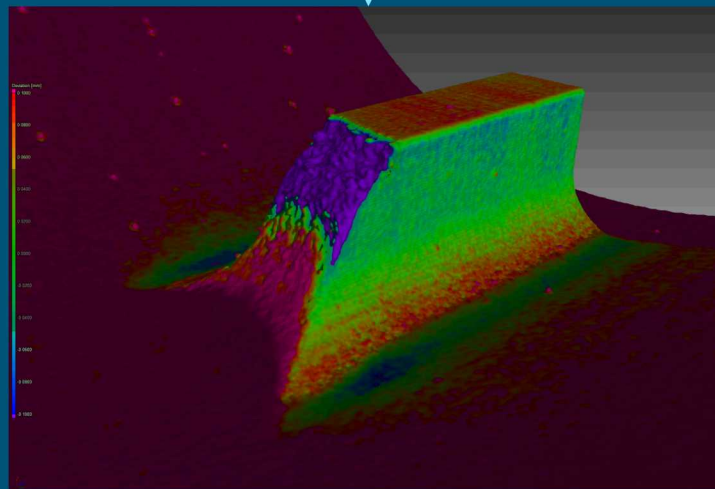


*Actual Reconstruction*



*CAD Model with Reconstruction*

A “clean” CT scan (relatively free from visual artifacts) is necessary to obtain an accurate surface



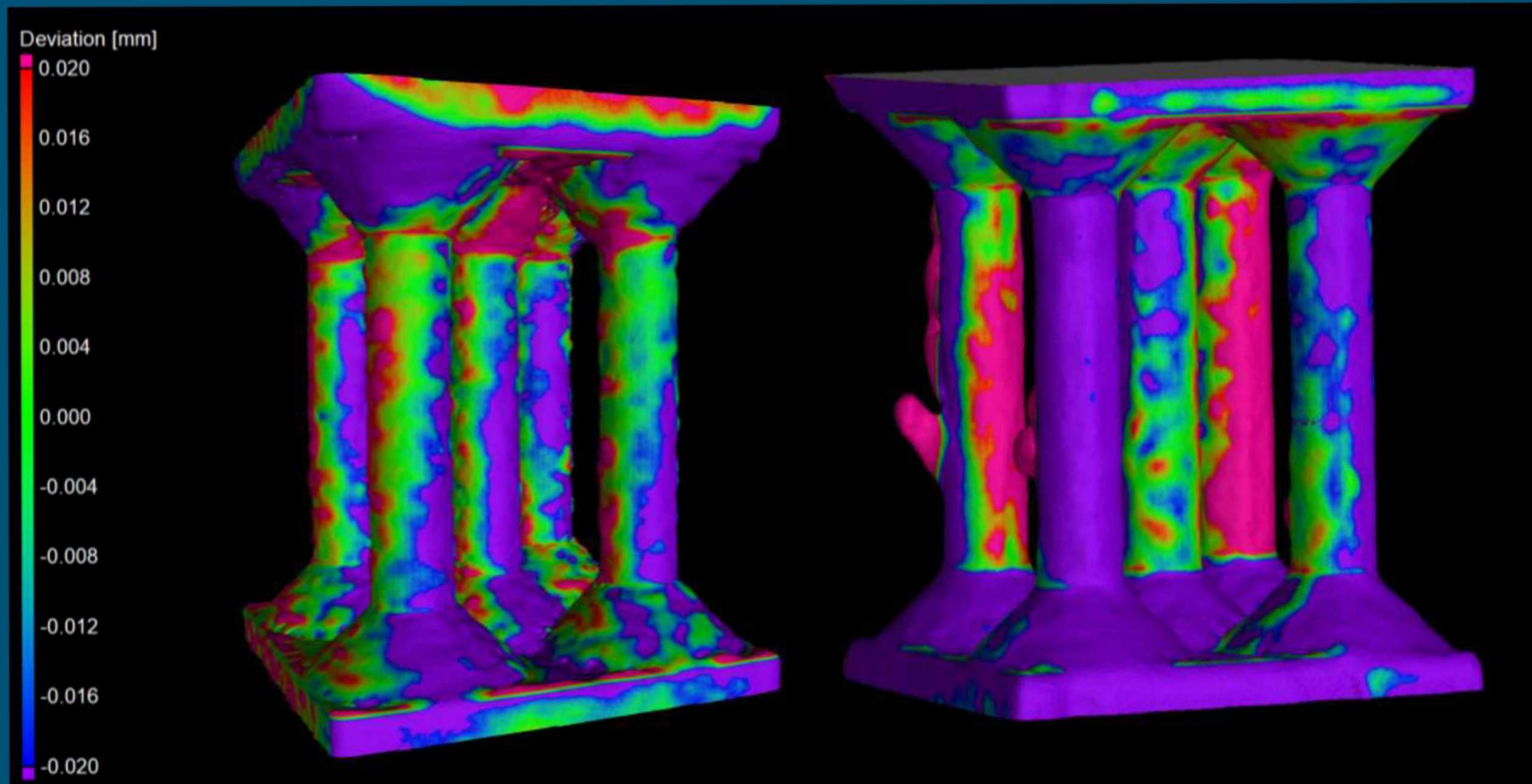
*Actual/Nominal Comparison*

The surface is used by the software to mate the actual design with the printed part

# CT Findings on AM Samples

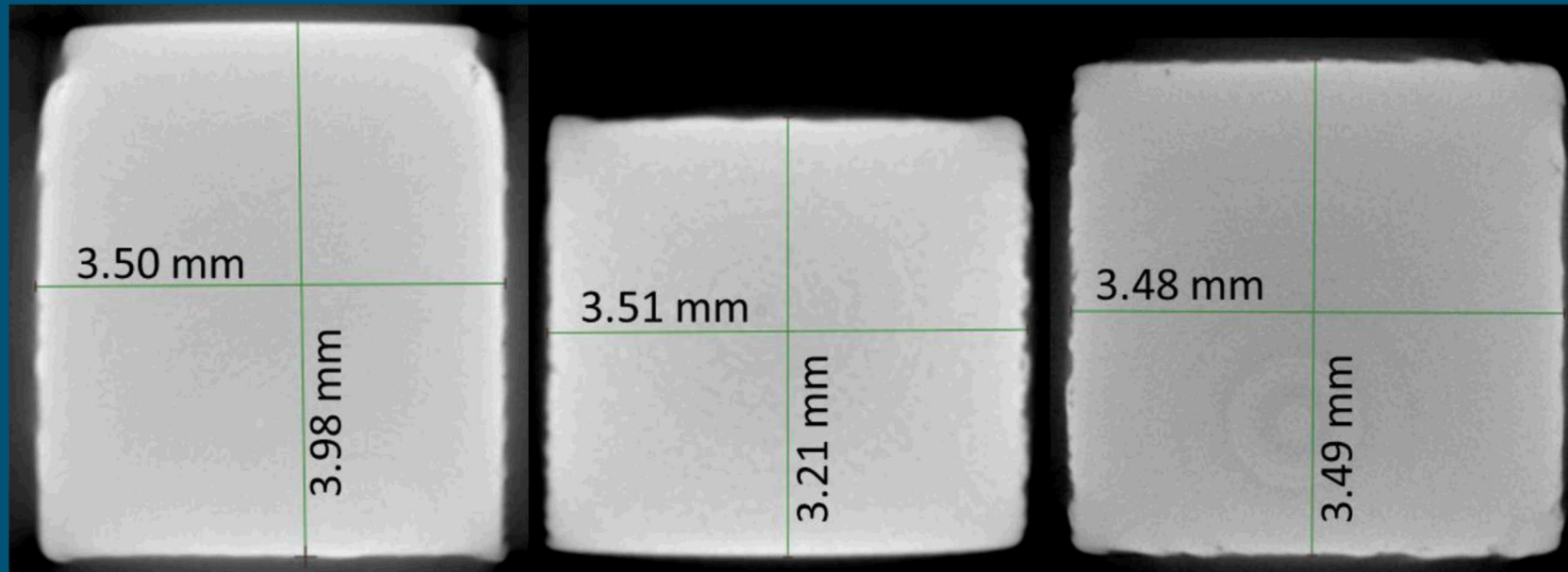
## Actual Nominal Comparison

- What can an actual/nominal comparison teach us about a build technique?
- Led to Cross-Sectional Surface Area Investigation



# CT Findings on AM Samples

CT scans of samples were used to determine cross-sectional surface areas.



Horizontal Build

Support structure (top)  
attached to sample

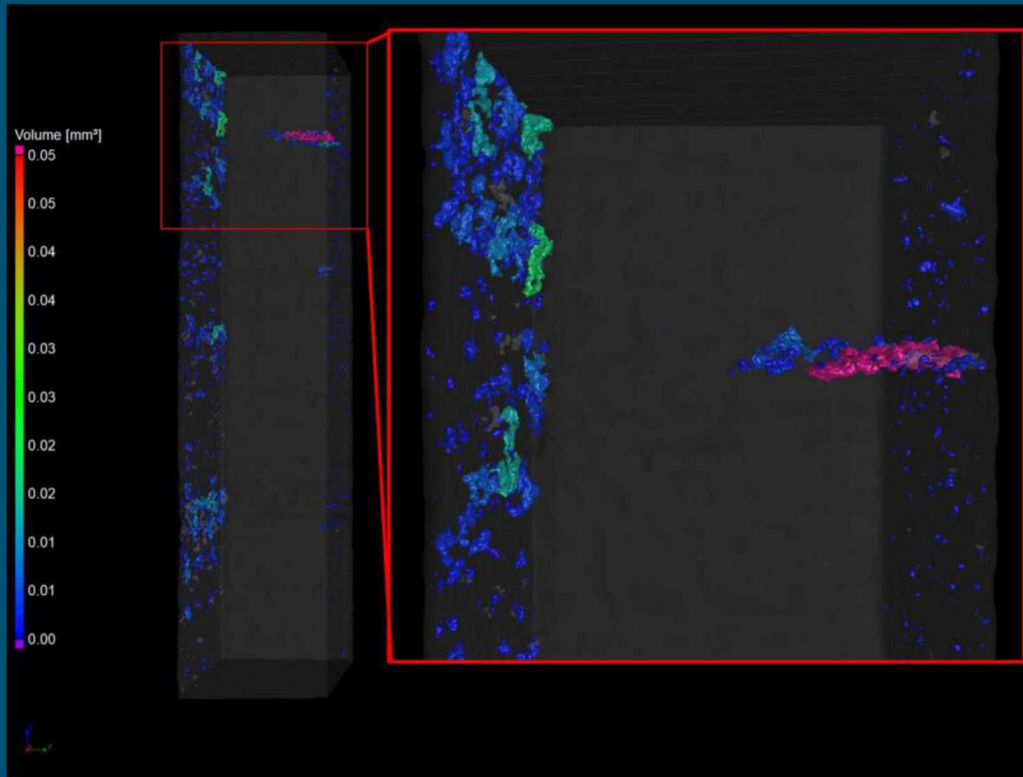
Horizontal Build

Support structure and  
part of sample  
removed (top)

Vertical Build

No material added or  
removed

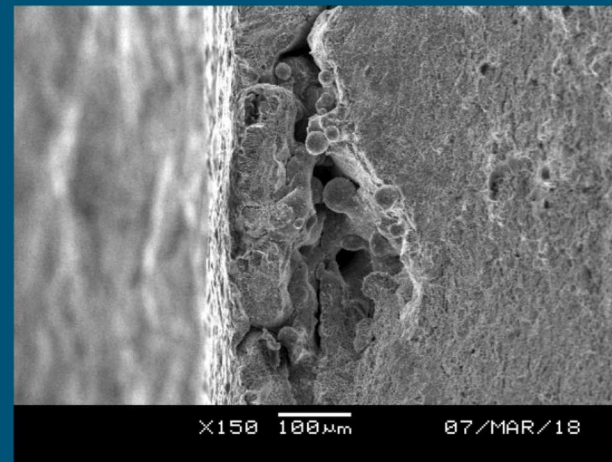
# Porosity Analysis



*Porosity analysis revealed porosity connected to the surface*



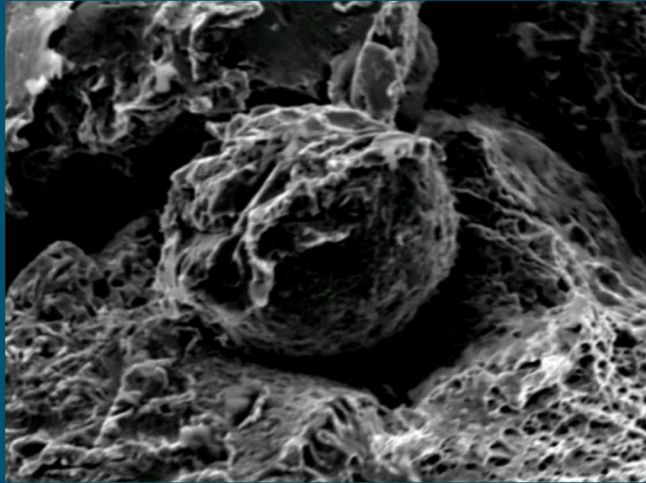
*Surface of fracture site*



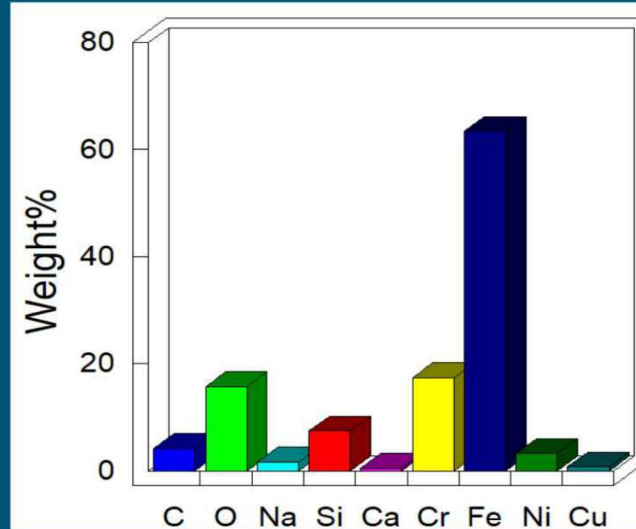
*Unsintered particles causing oxidation at the site of the fracture*



# Material Contamination

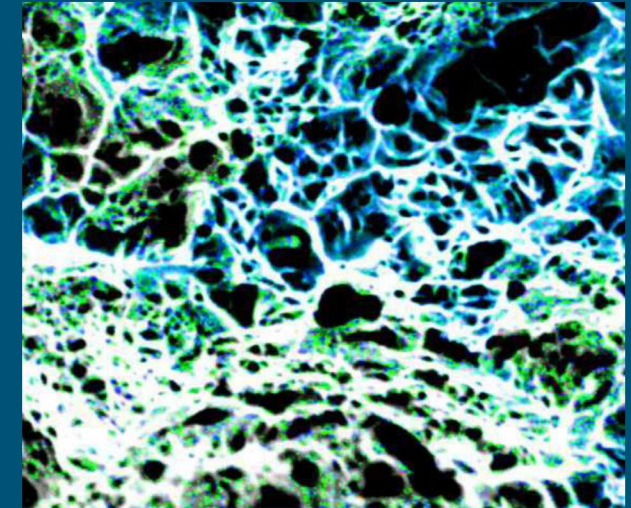


SEM view of unsintered particle

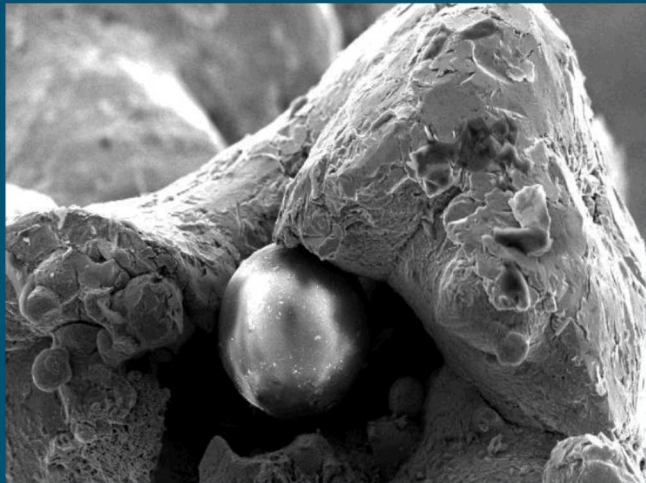


Chemical content of normal particle

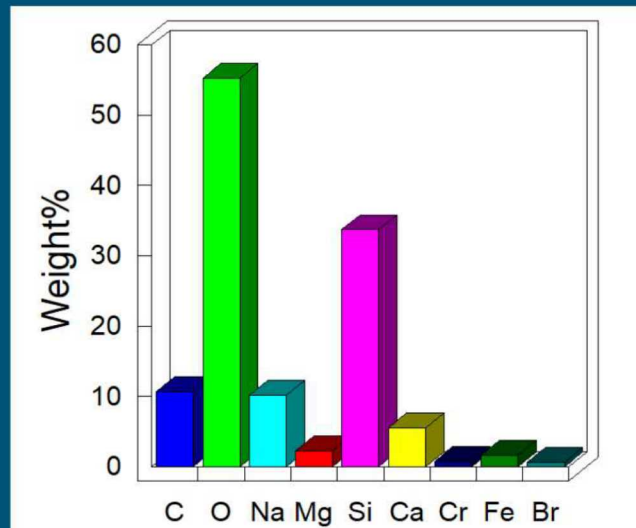
Normal powder of 17-4PH Steel contains high amounts of Iron.



Composition mapping, showing Si in red, Cr in blue, and Fe in green

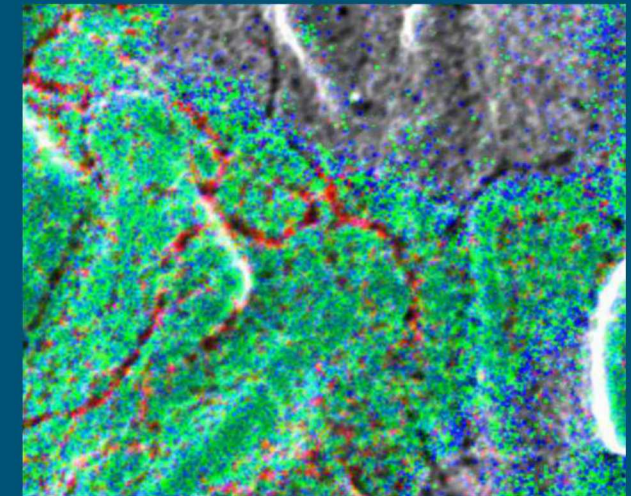


SEM view of impurity



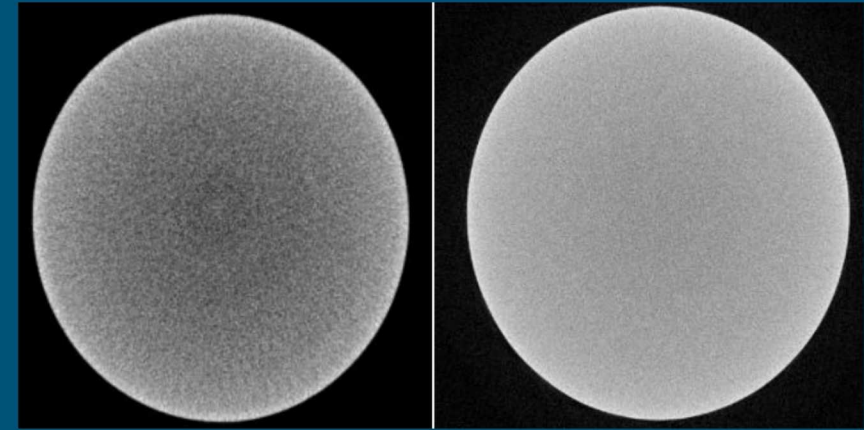
Chemical content of impurity

Powder contamination from unknown particle contained high amounts of Oxygen and Silicon.

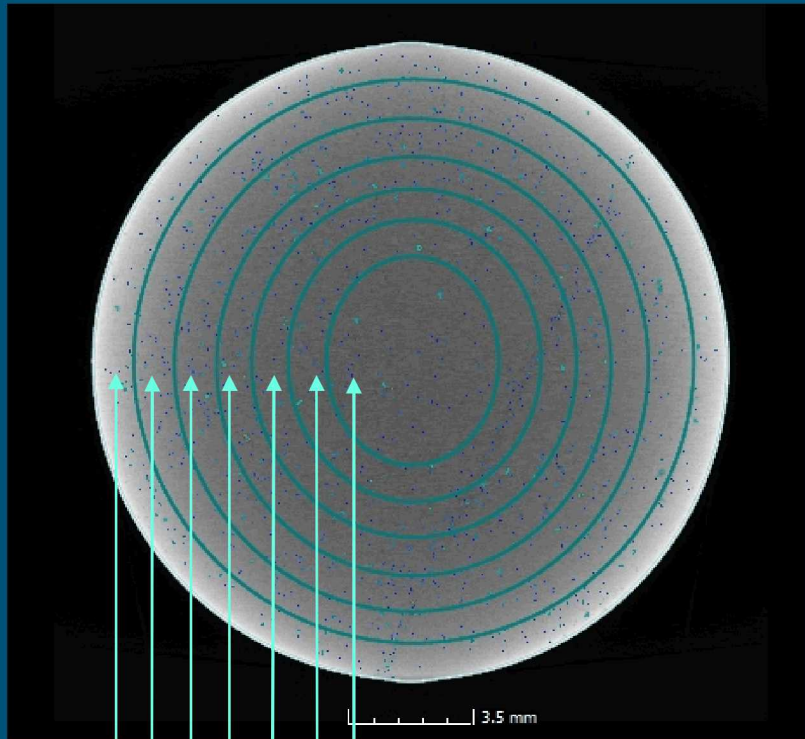


# Data Segmentation

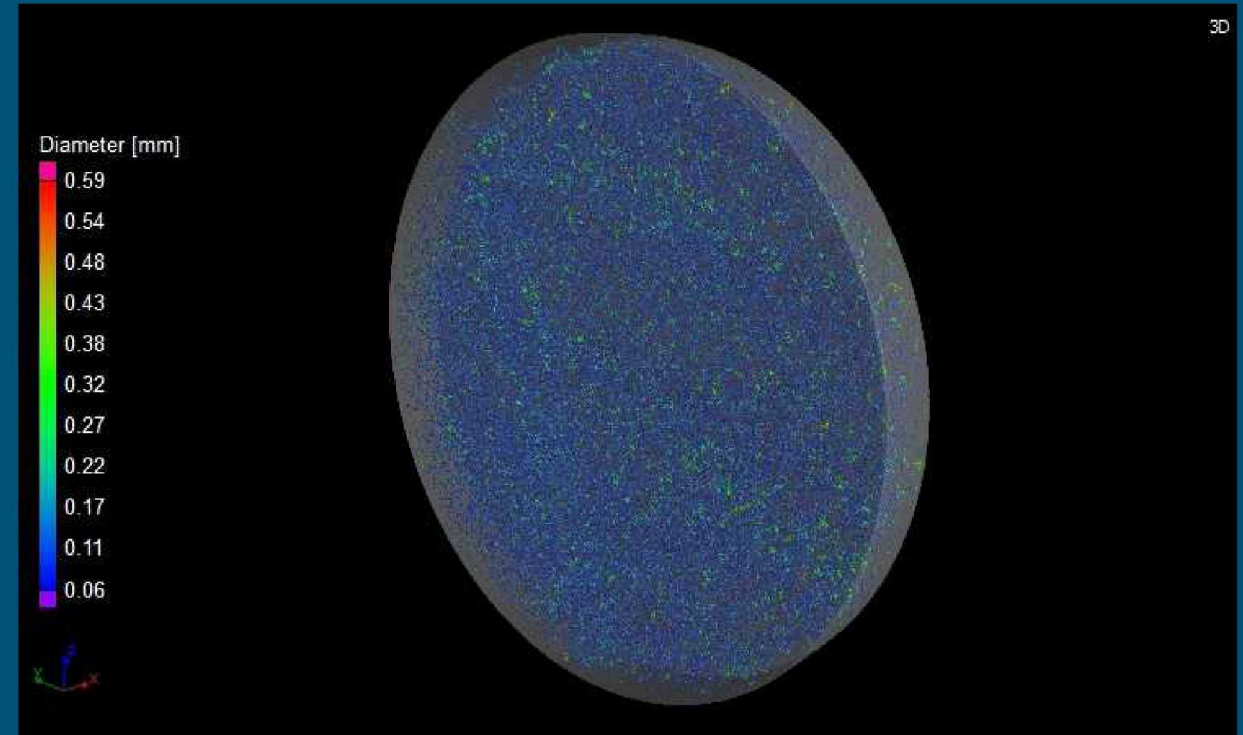
Beam Hardening: Artifact caused by high energy photons passing straight through an object, and low energy photons scattering or stopping completely.



*Non-linear x-ray attenuation (left), complete x-ray penetration (right)*

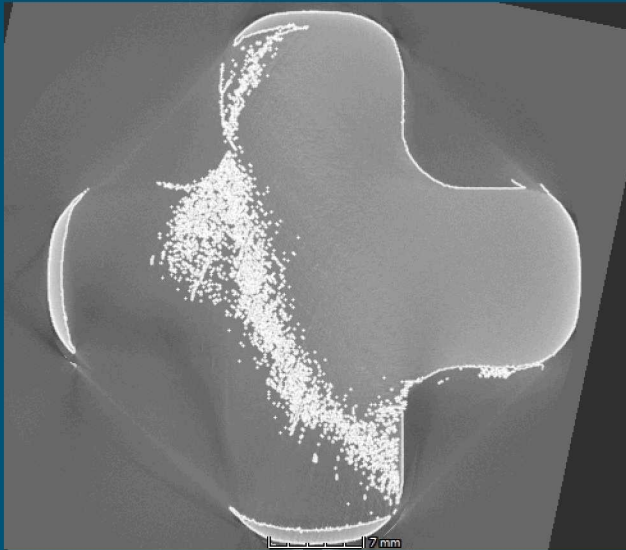


*Seven separate, yet similar, segmentations of the object*

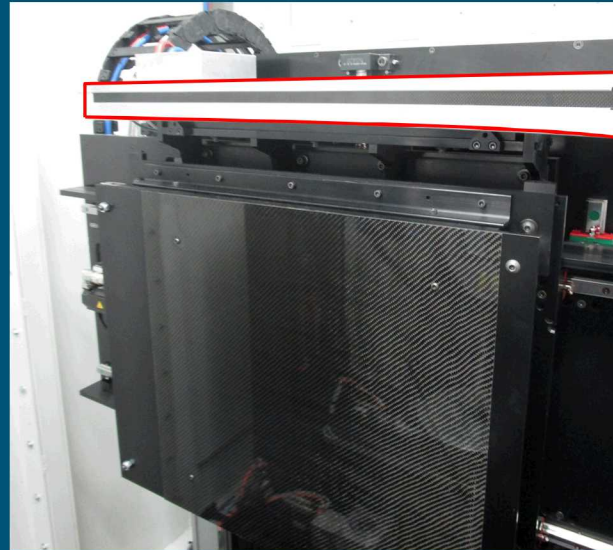


*Final result of all seven segments' porosity analysis*

# As-Printed Model Creation



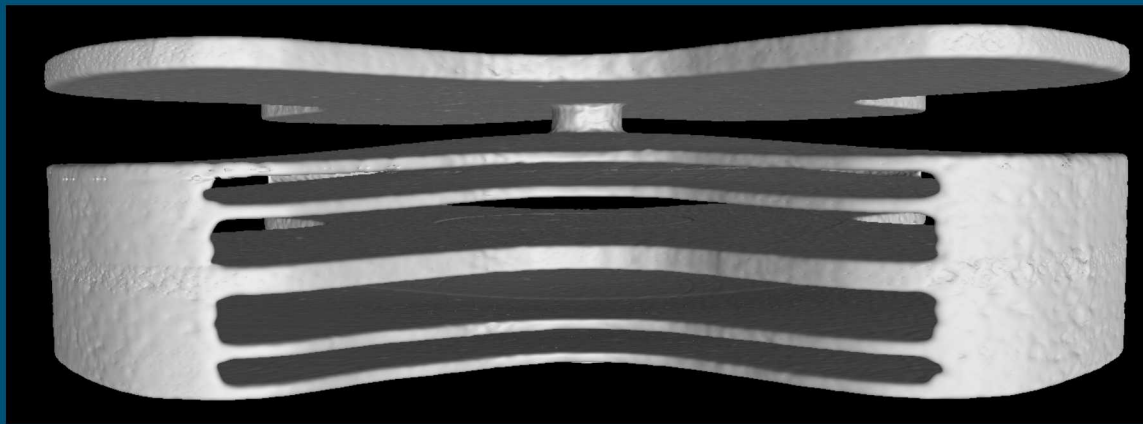
*Beam hardening causing failed surface determination*



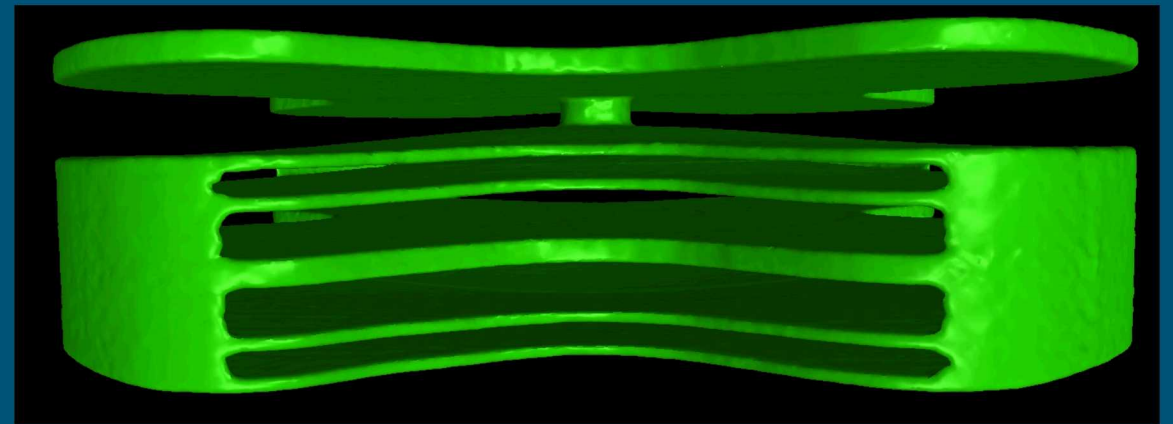
*Curved Linear Detector Array (CLDA) located above flat-panel detector*



*CLDA contains a single row of pixels, reducing scatter and improving signal to noise ratio*

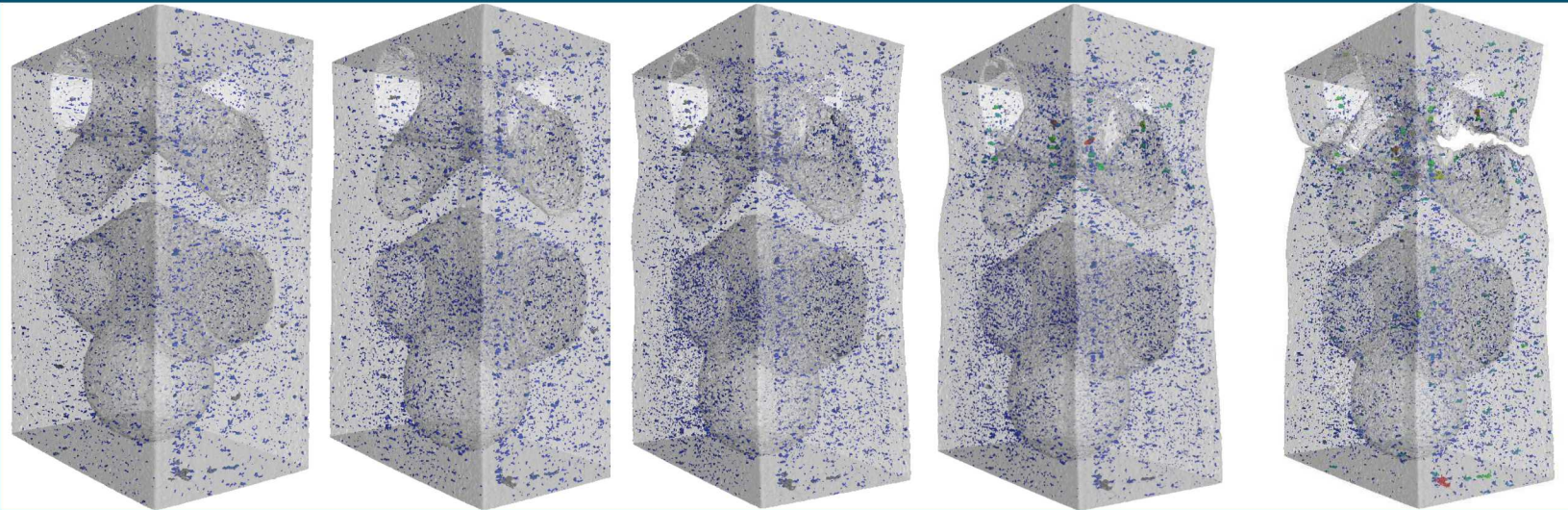


*CT reconstruction*



*Mesh model created from CT reconstruction*

# Sandia Fracture Challenge



Pre-pulled

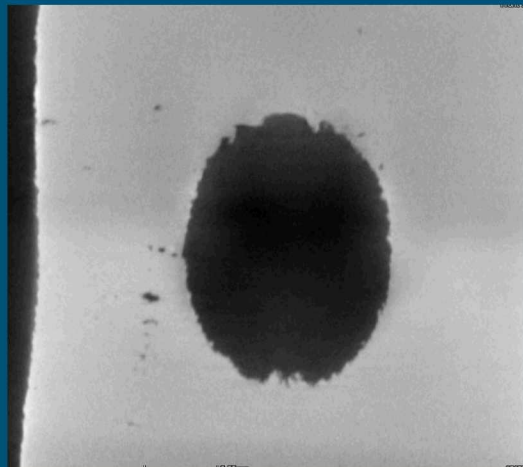
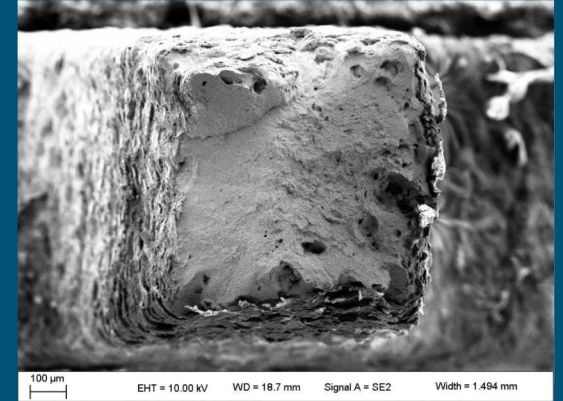
Iteration 1

Iteration 2

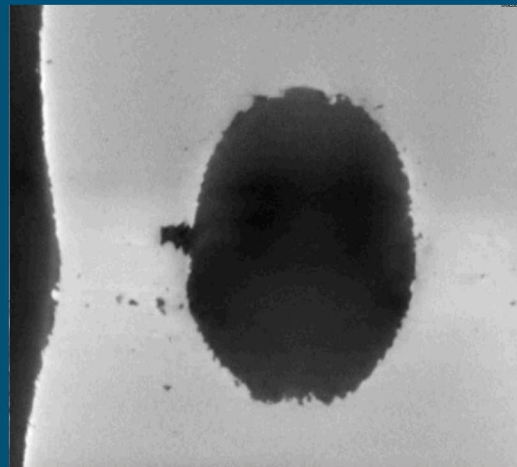
Iteration 3

Separation

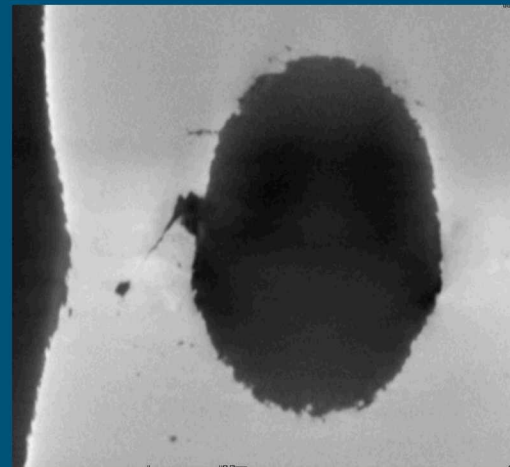
*Porosity was tracked for every stage of the test*



Iteration 1

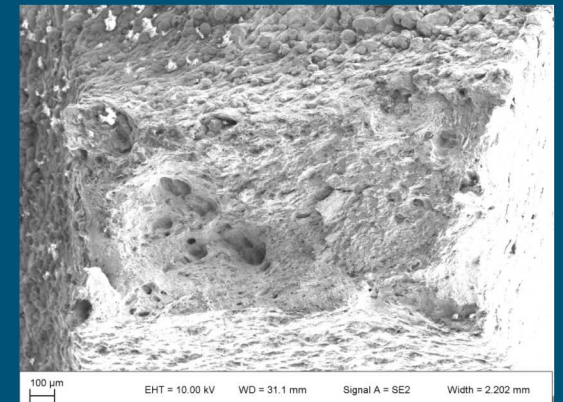


Iteration 2

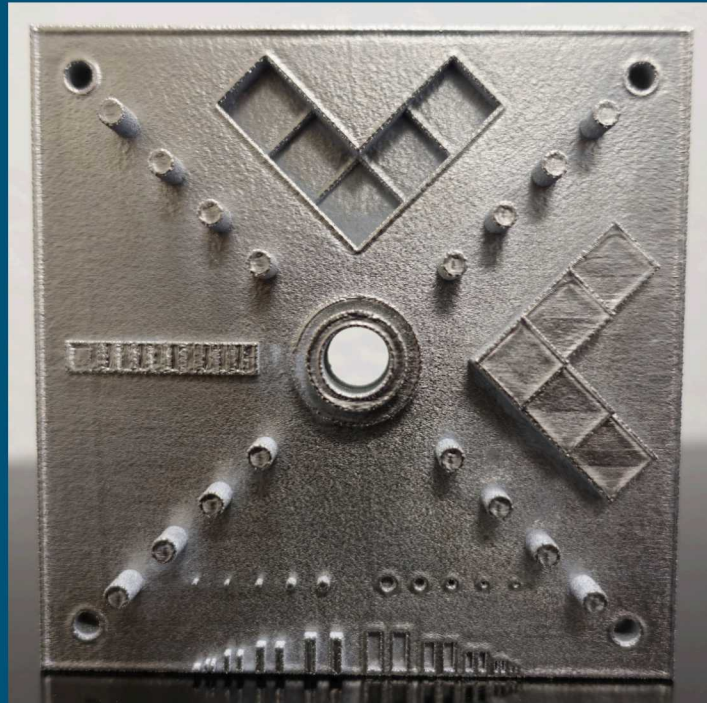


Iteration 3

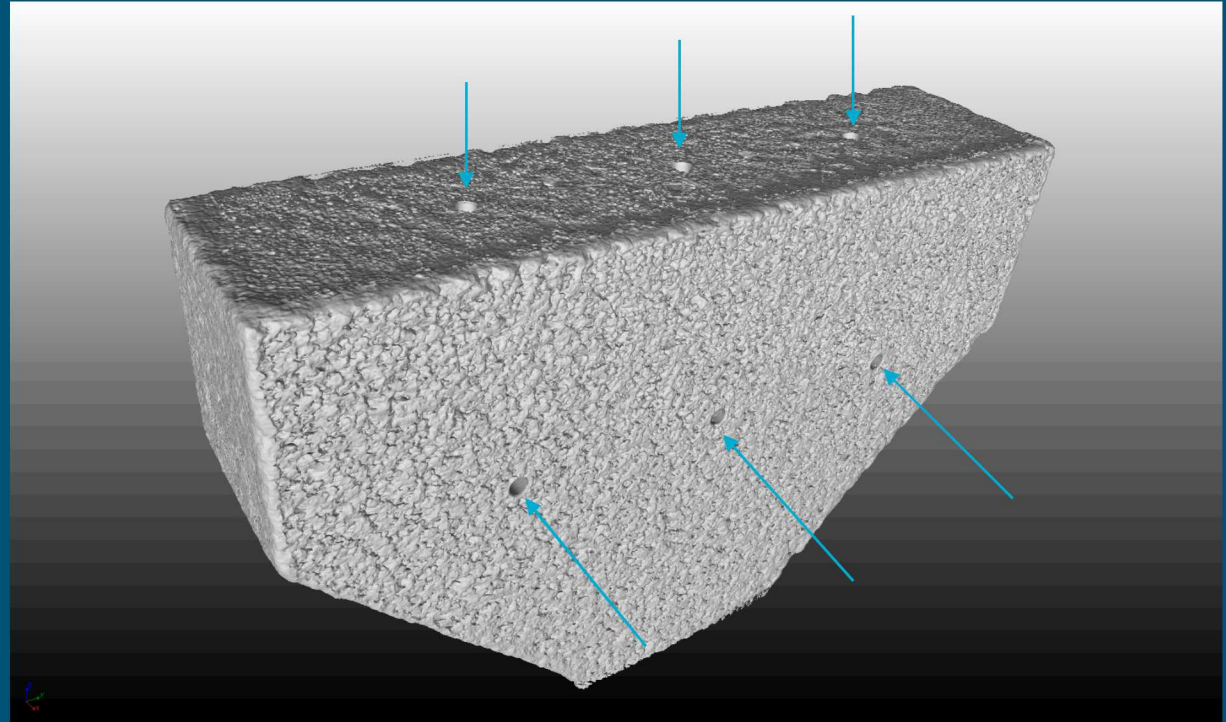
*Surface-crack growth sequence*



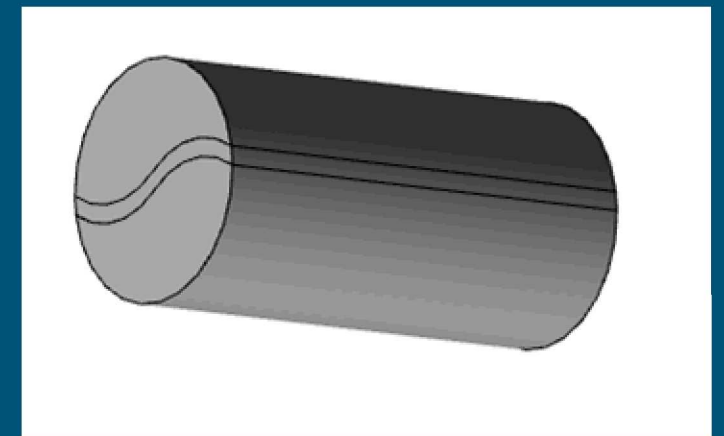
# Qualifying CT



AM NIST standard (Titanium) used for CT and AM verifications. Cannot be used for porosity

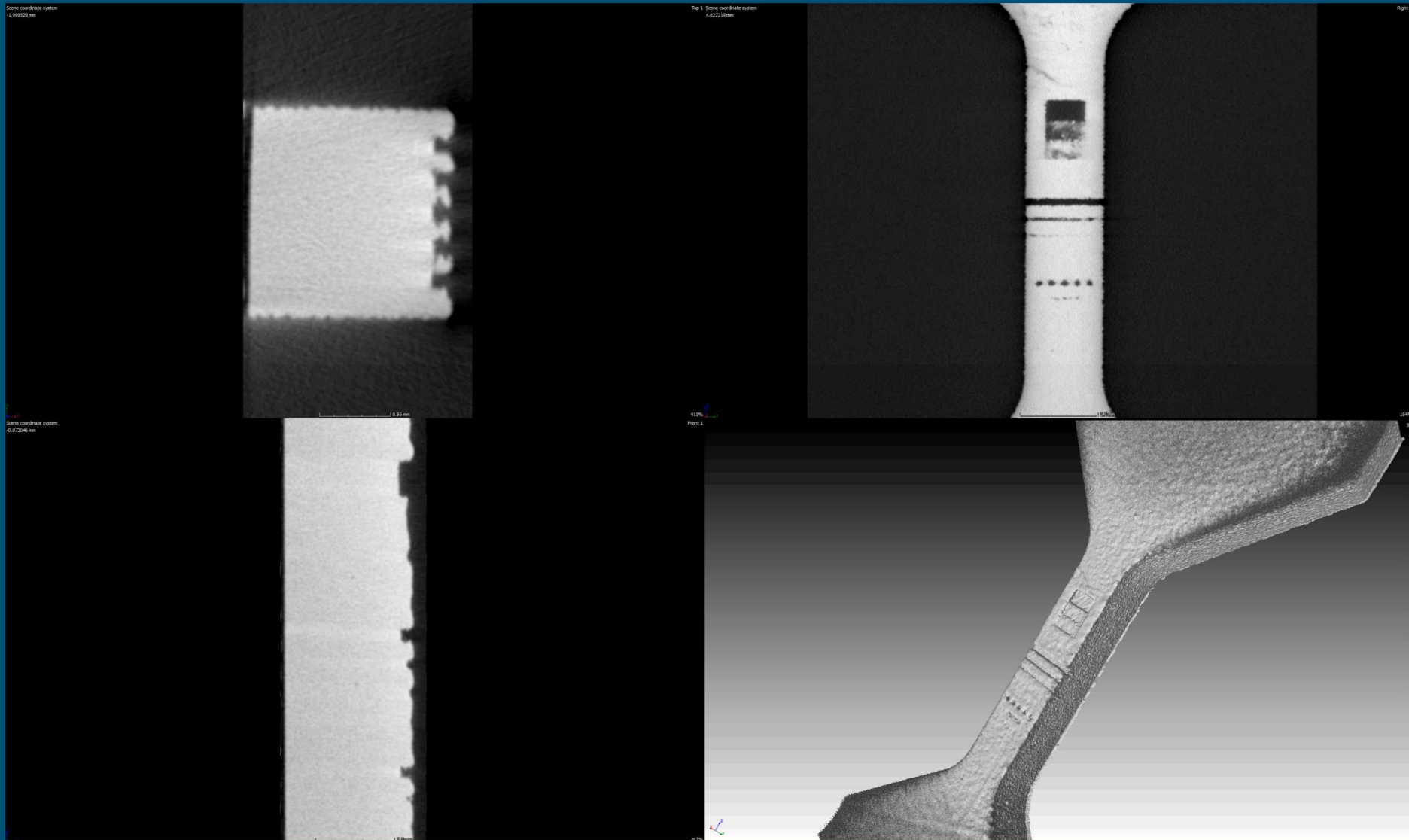


Side-Drilled-Holes can be used to measure CT accuracy



Pringle, with simulated porosity

# Multi-Functional Printing



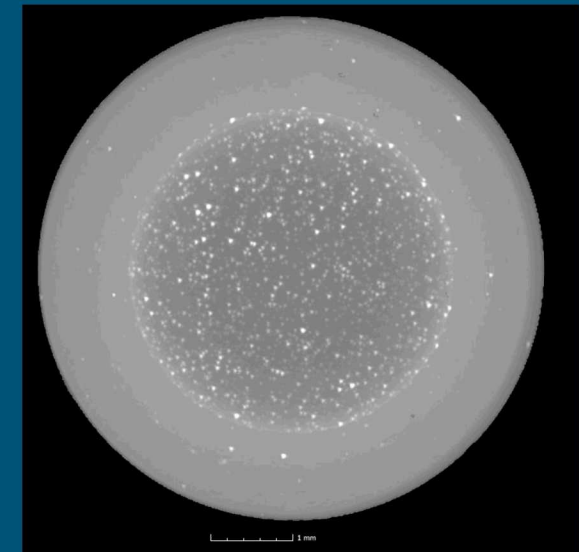
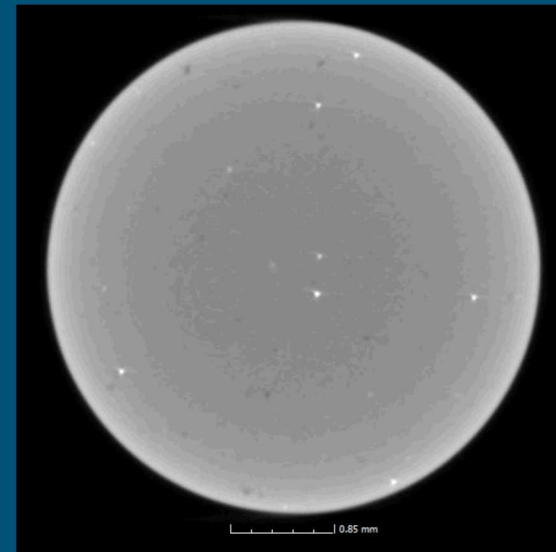
*Negative steps, insets, and cylinders printed on the surface of the tensile specimen*

# Lessons Learned

- Never mix different materials in a printer
- Ensure printer material is contaminant-free before printing
- Caution must be used when reusing printed material
- Design should include over-building where loss of material is expected
- CT metrology requires more study and validation
- Accuracy of CT data depends on many factors



*Different types of metal powders*



*Highly dense contaminant discovered in pull-specimen after CT*

# Questions



# BACKUP SLIDES



# Factors Affecting CT Data

## Method

- Sampling
- Averaging
- Pixel Binning
- Exposure Time
- Filter
- Artifact Reduction
- Geometry
- Positioning
- Energy
- Flux

## Material

- Physical Properties
- Size
- Density
- Geometry

## Hardware

- Detector Type
- System Alignment
- Rotational Stage
- X-Ray Source

## People

- Stress
- Fatigue
- Expertise

## Software

- Detector Calibration
- Motion Calibration
- Reconstruction Algorithms
- Segmentation
- Filters
- Artifact Reduction

## Environment

- Vibration
- Scatter
- Temperature

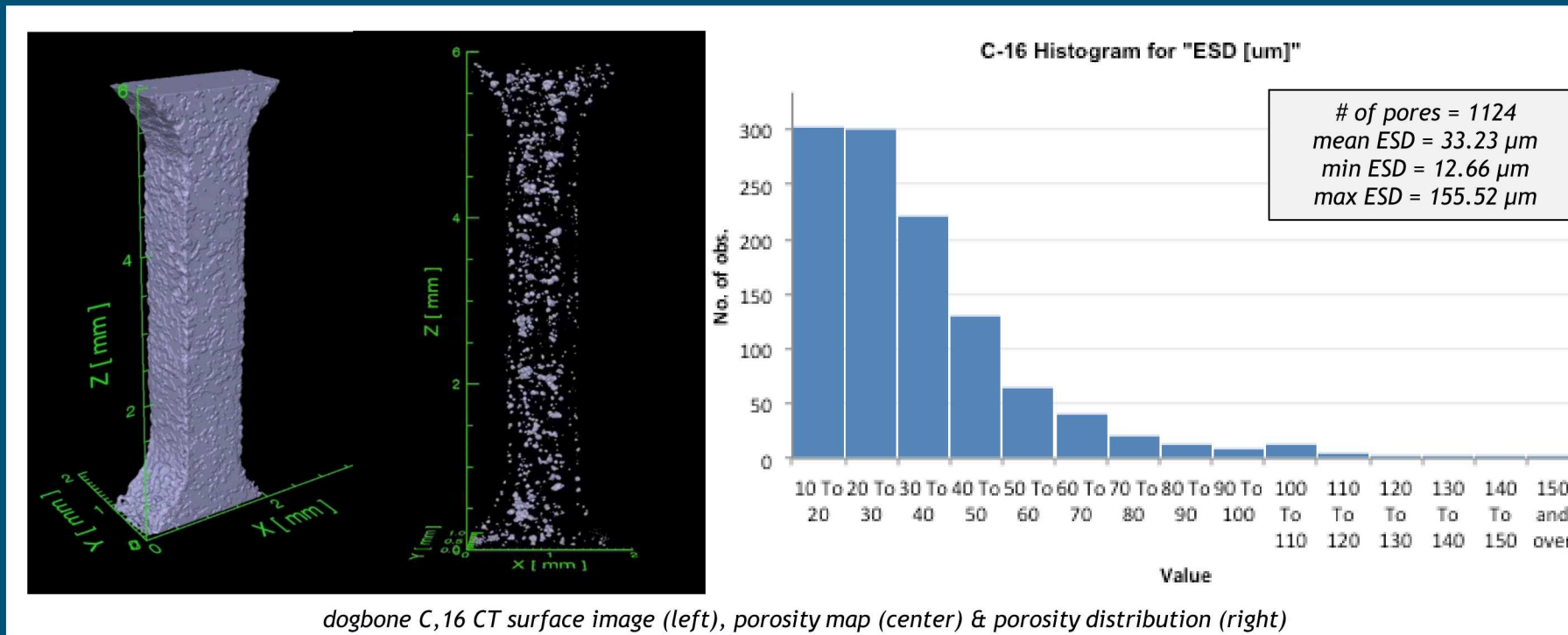
# Computed Tomography

## Quantifying defect distributions

- what can we see? does it inform material behavior predictions?
- porosity exists in L-PBF parts, is CT reliable to ID critical defects?
- preliminary analyses indicate part differences

## What is a valid reference or corollary?

- comparing w/serial sectioning, density (via Archimedes)



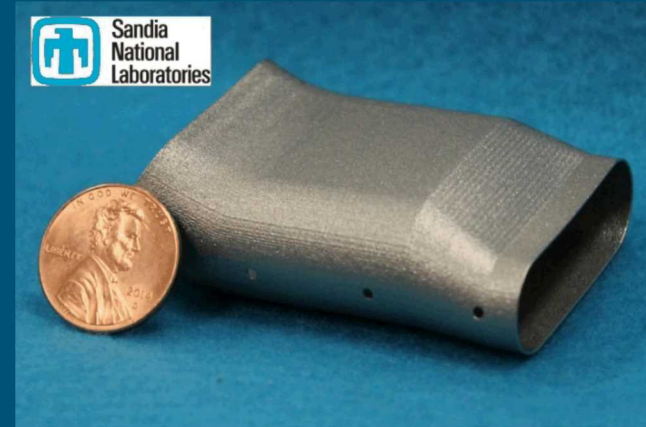
# Computed Tomography

## Industry shift

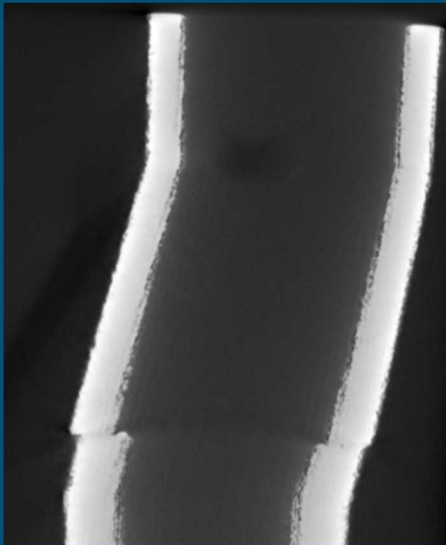
- 5 years ago – inspection, not metrology
- now – necessary for AM complexity

## Interests

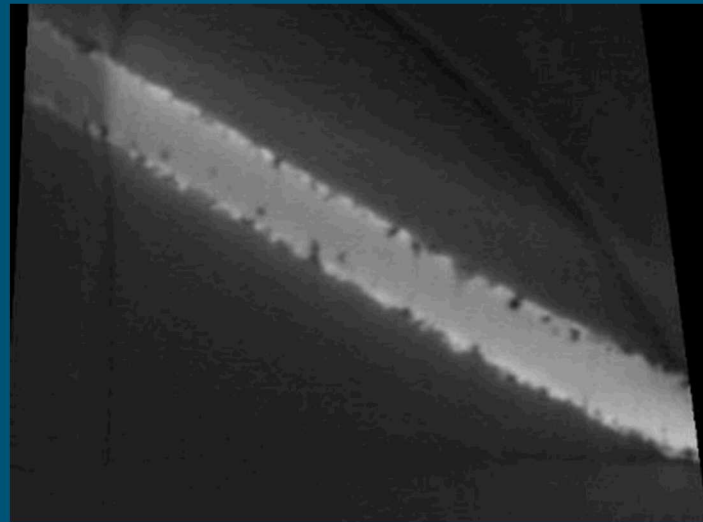
- standards & verification
- material characterization
- dimensional metrology
- big data (throughput, handling)
- SNL capabilities in CT systems, data, metrology



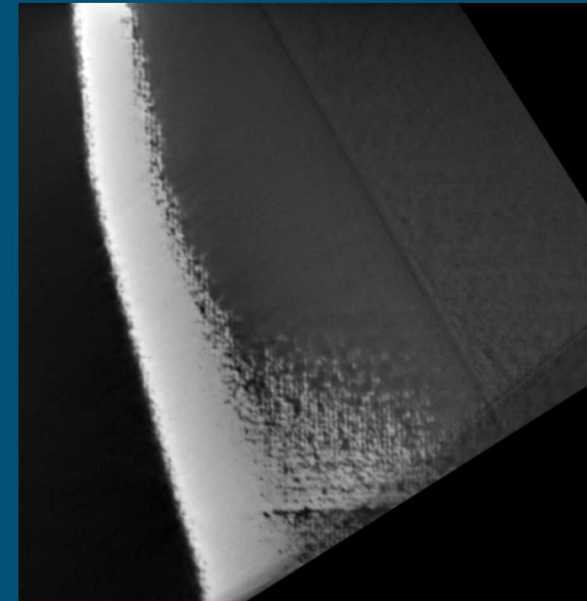
AM housing prototyped in 17-4PH stainless steel



defects - material or measurement?

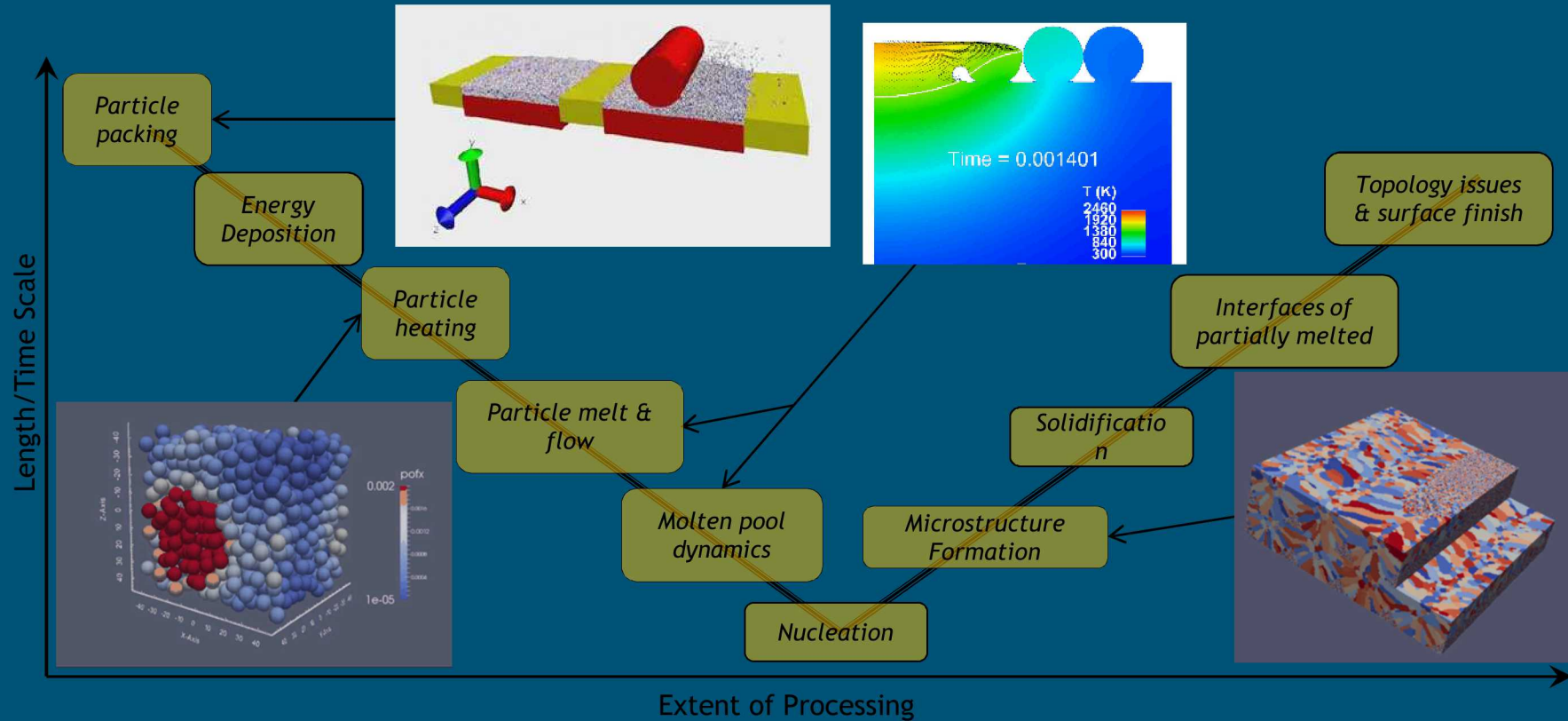


detecting material voids & defects



able to see build layers

# Process Simulations



## Process

- reduce experimentation
- laser-material interaction
- discrete particle physics
- process -> structure relationships
- process limits

## Defect impact

- understand formation mechanisms
- explore uncertainty quantifications
- predict response from stochastic process knowledge

# Problem Statement

Models of parts are generated with topology optimization methods. Geometries are non-standard and difficult to measure with conventional tools.

Measurement of porosity is critical in determining the quality of additively manufactured parts.

Porosity is ill-defined, most definitions are application specific.

Computed tomography is advantageous because of its ability to measure non-standard geometries and internal features.

**Computed tomography is not qualified as a measurement technique.**

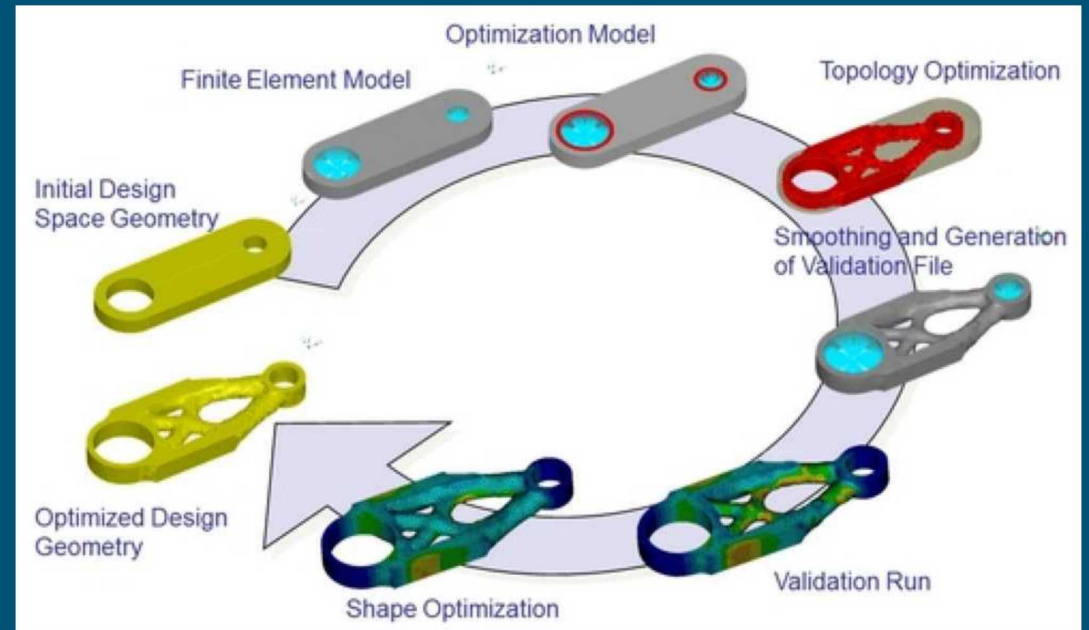
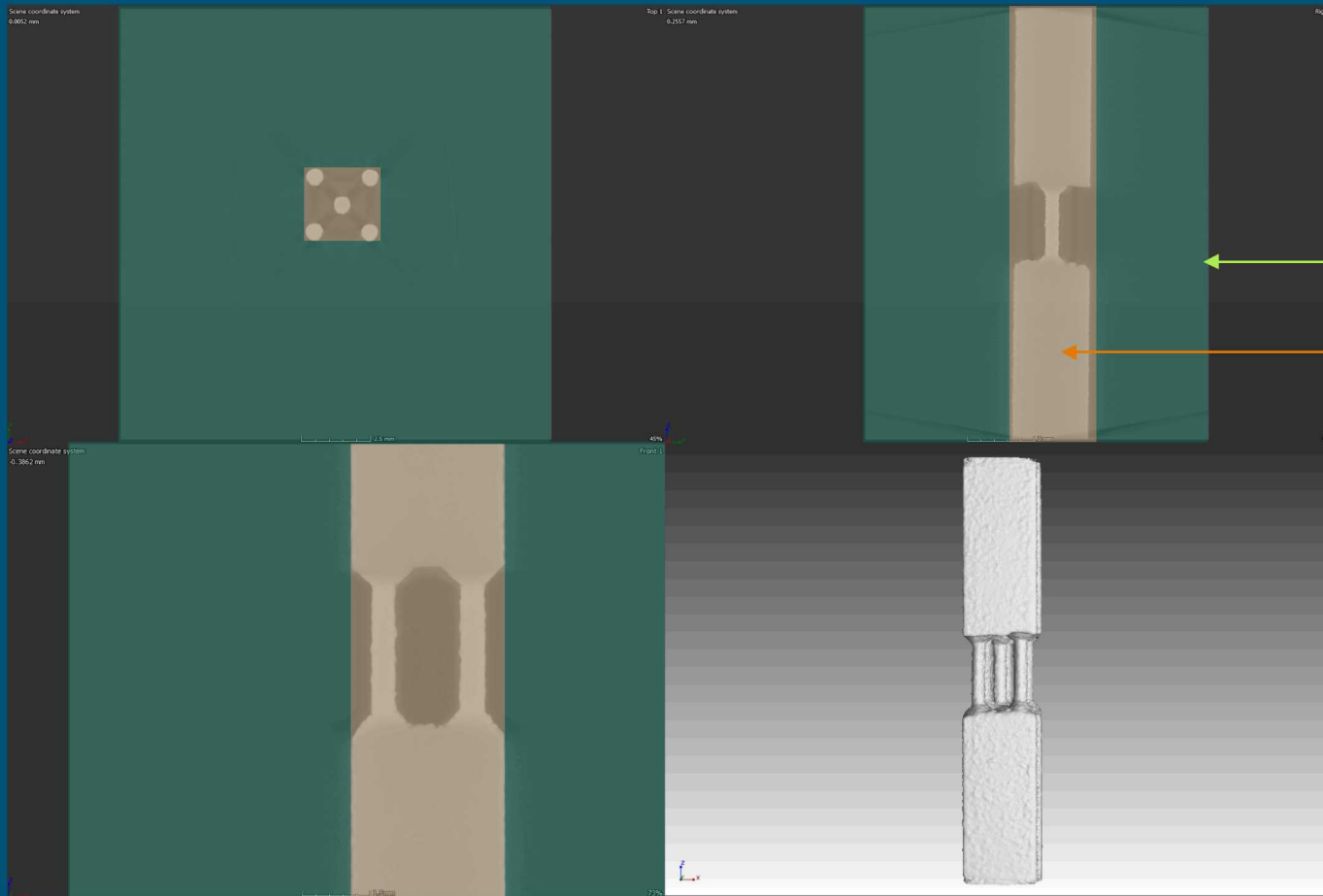


Figure 1: A cartoon showing the design process for additively manufactured parts. The initial design is processed via a topology optimization program. The optimized designs are generally organic in shape.

# CT Volume Size



4,028,428,800 voxels

116,583,720 voxels

Computer Hardware:  
2 Intel Xeon CPUs E5-2630 v4  
128 GB RAM  
2 NVIDIA 1080 Ti GPUs