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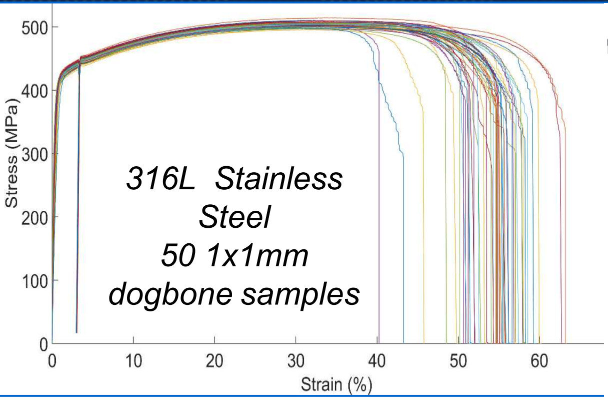

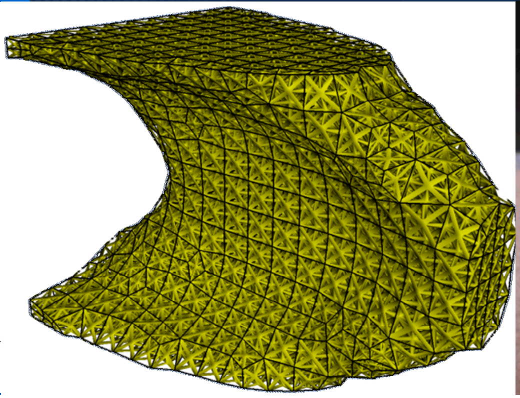

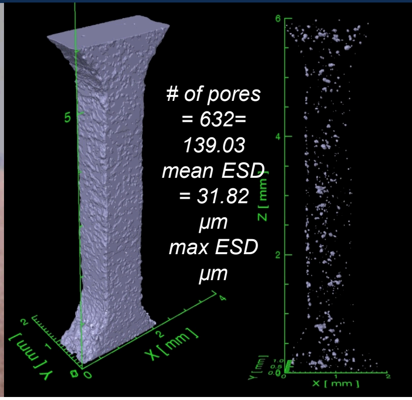

Additive Manufacturing – A New World of Opportunities and Challenges

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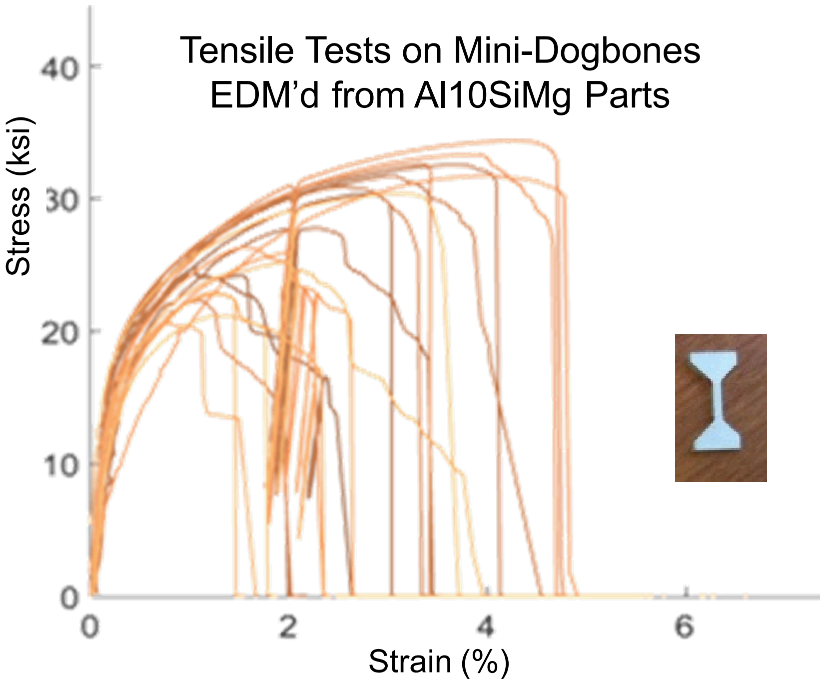
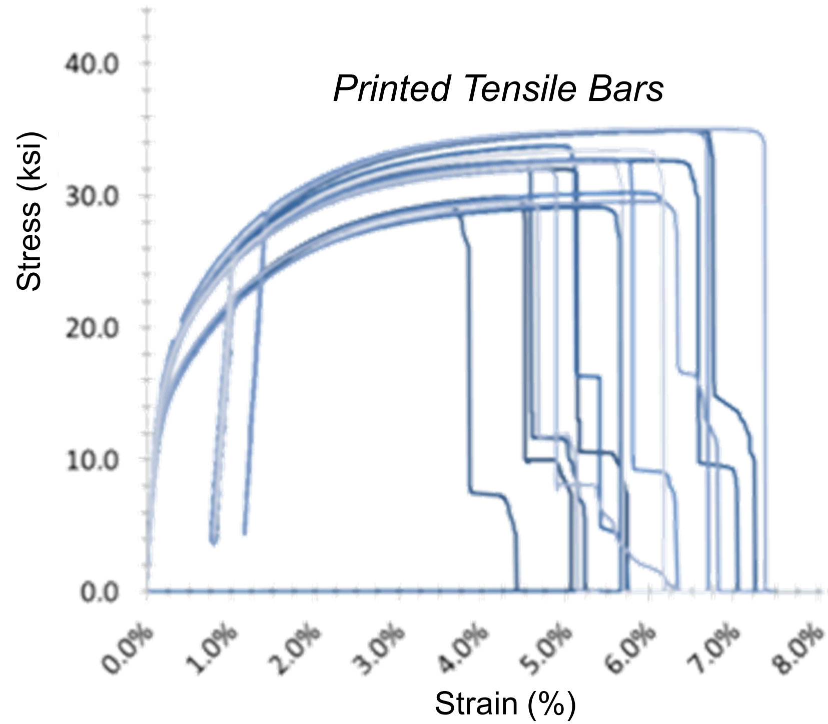
Graded Implementation Slide

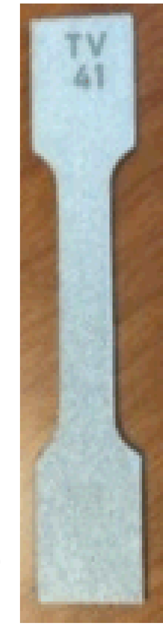
Impact Tests

AM vs. Traditional Designs

But, Variability of AM Properties and Inability to Assure Properties Prevented Insertion



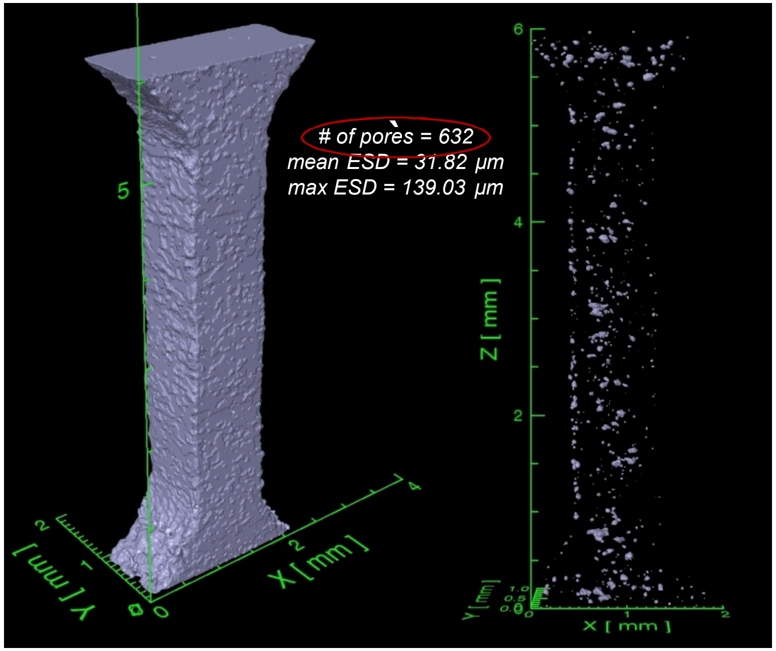




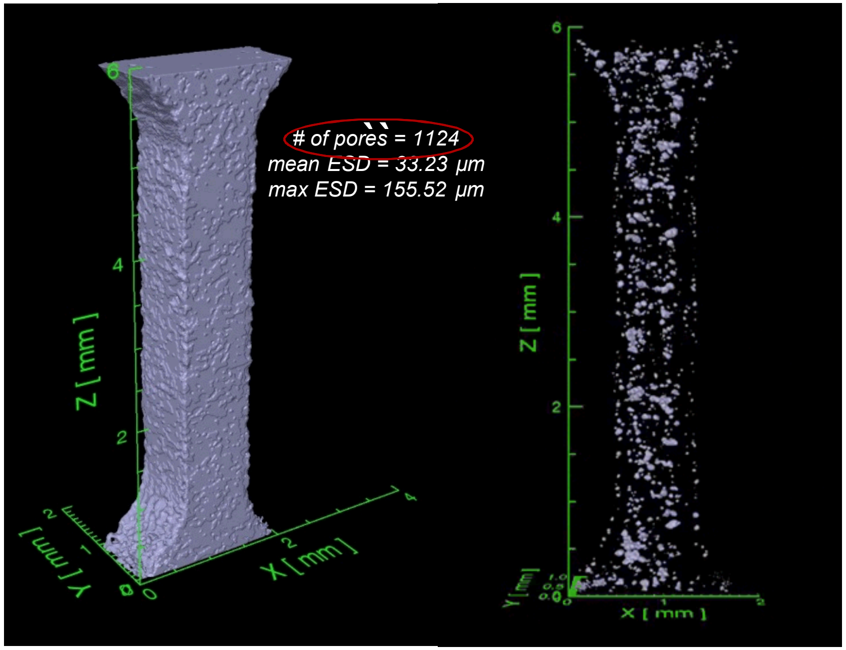
- Test results appear to vary with sample size ⇒ defect sensitivity
- Porosity in is higher in areas where mini-dogbones were EDM'd

Still Working to Understand Defect Sensitivities and Failure Modes

- AlSi10Mg dogbones
  - Gage sections imaged with resolution of 7 or 10 µm voxel edge length
- Quantifying defect distributions
  - What can we see? Does it inform material behavior predictions?
- 632 pores vs. 1124 similar size pores below; Very similar tensile test results; Why ???



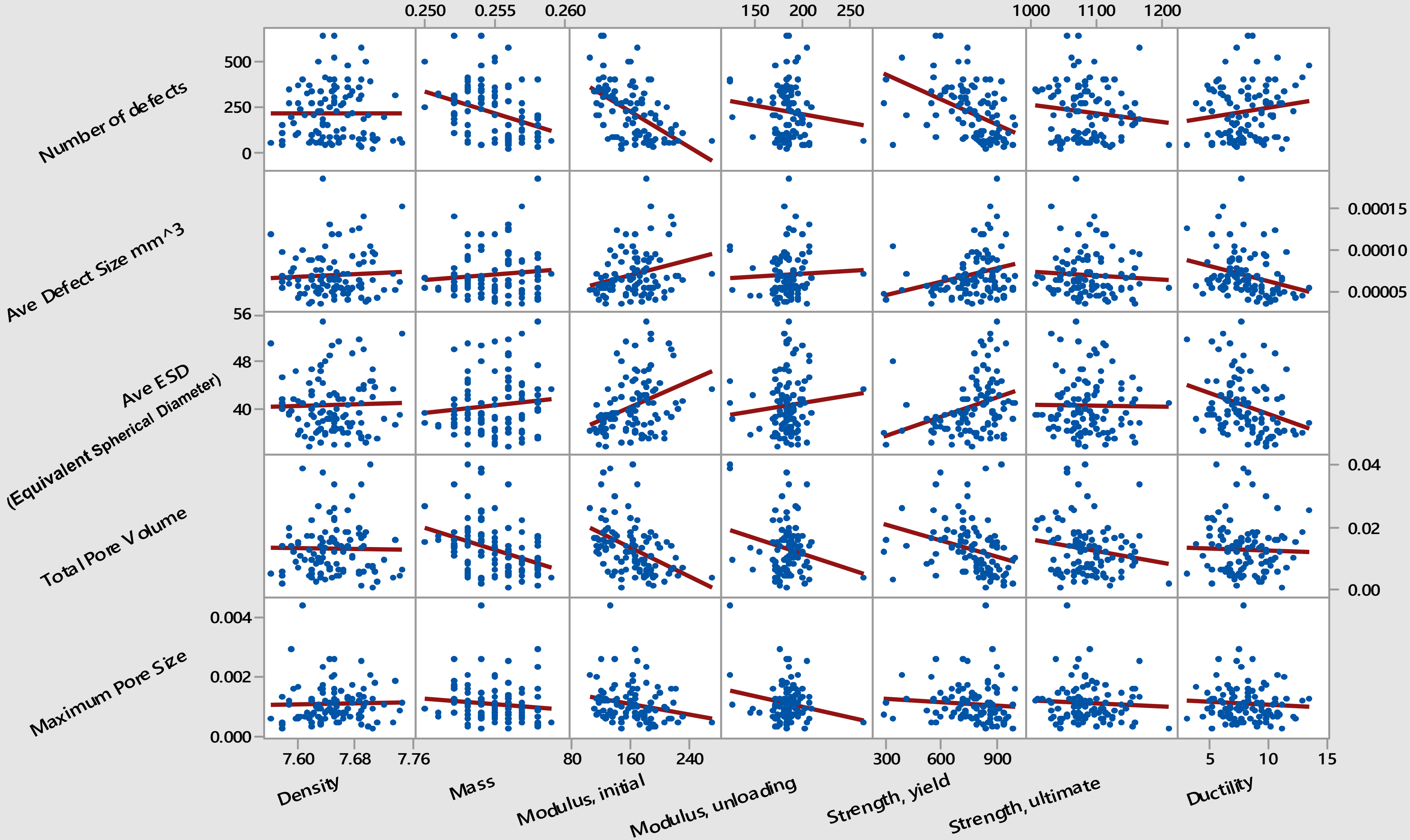
dogbone B,16 CT surface image (left), porosity map (right)



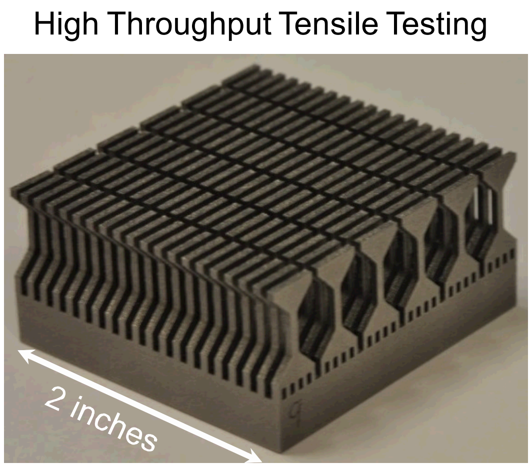
dogbone C,16 CT surface image (left), porosity map (right)

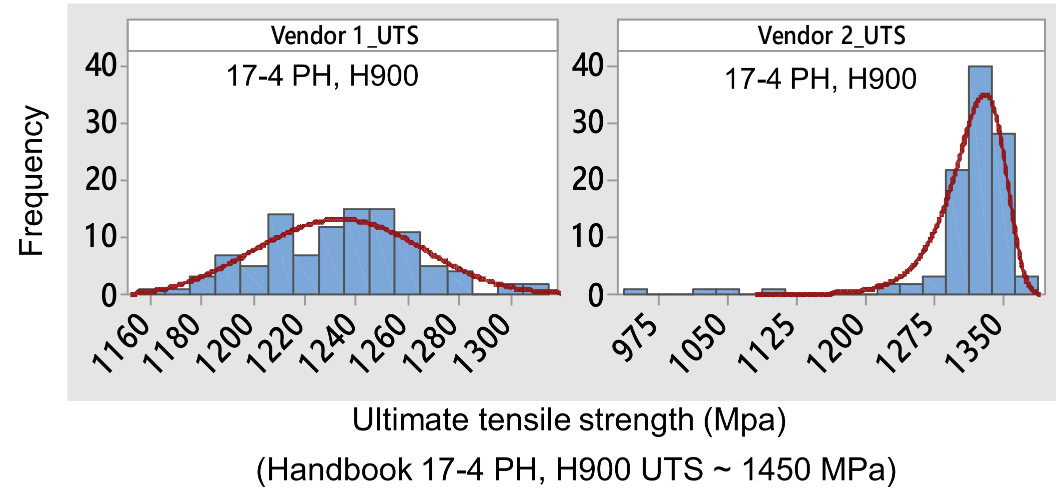
ESD = equivalent spherical diameter

On-going Data Analytics Studies To Investigate Potential Relationships



How Can We Assure That a Specific AM Component is Reliable?



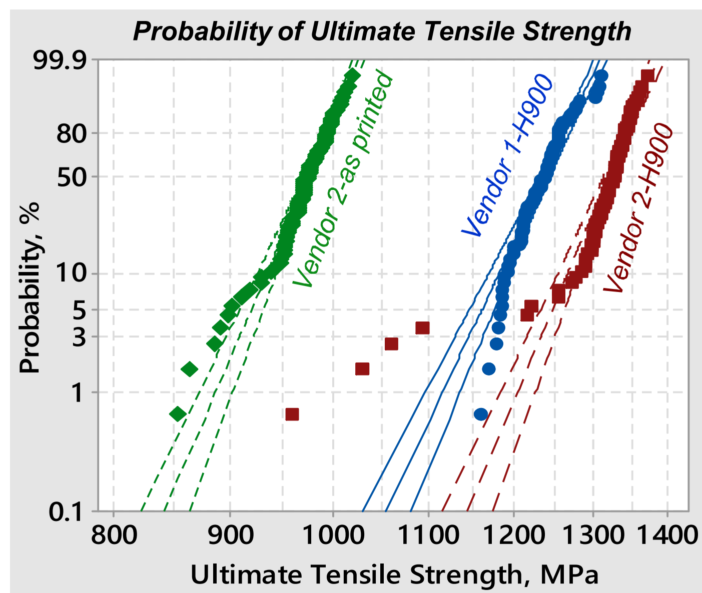


- 17-4 behavior similar to ceramics & castings
- Weibull distributions prove appropriate

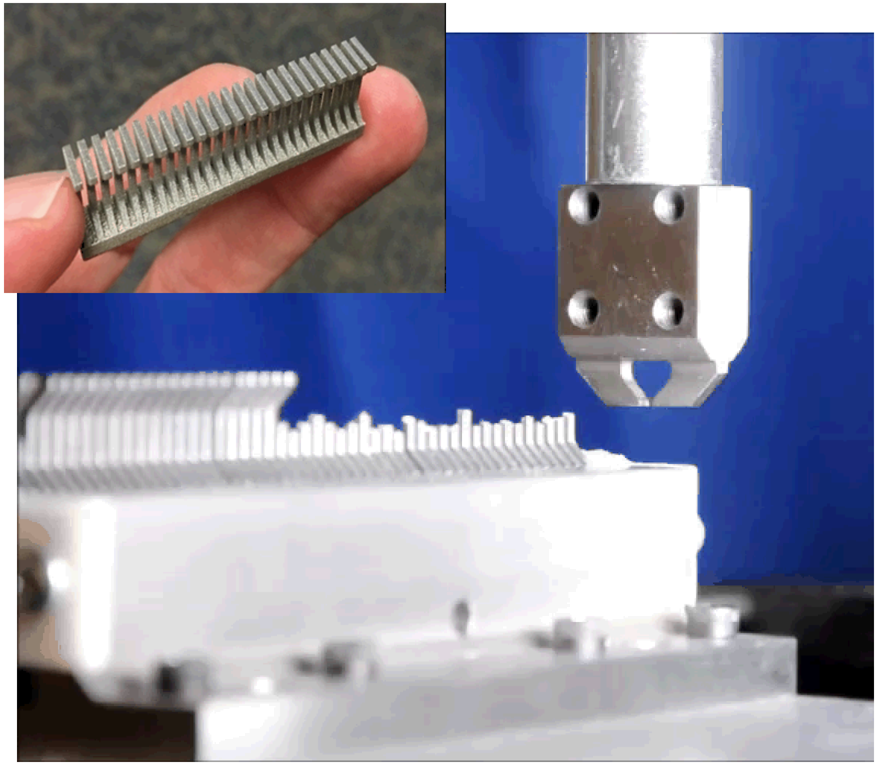
$$\log\left(\log\left(\frac{1}{1-P}\right)\right) = m \cdot \log(\sigma) + \log\left(\frac{V \cdot \log(e)}{\sigma_o{}^m}\right)$$

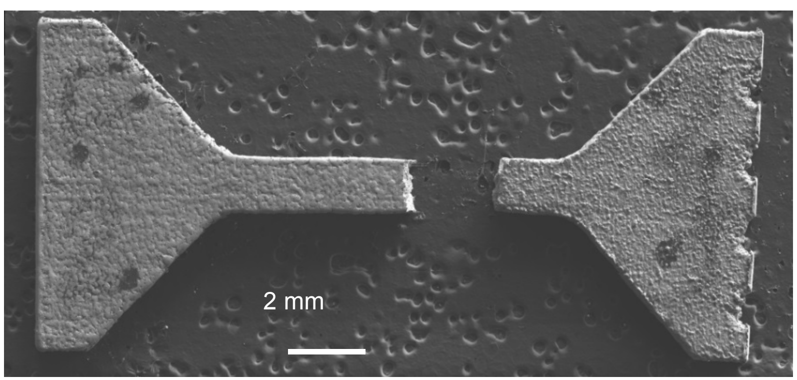
where

- P = probability of failure at stress, σ
- m = Weibull modulus, i.e. scatter
- V = material volume
- σ_o = strength for which P = 0

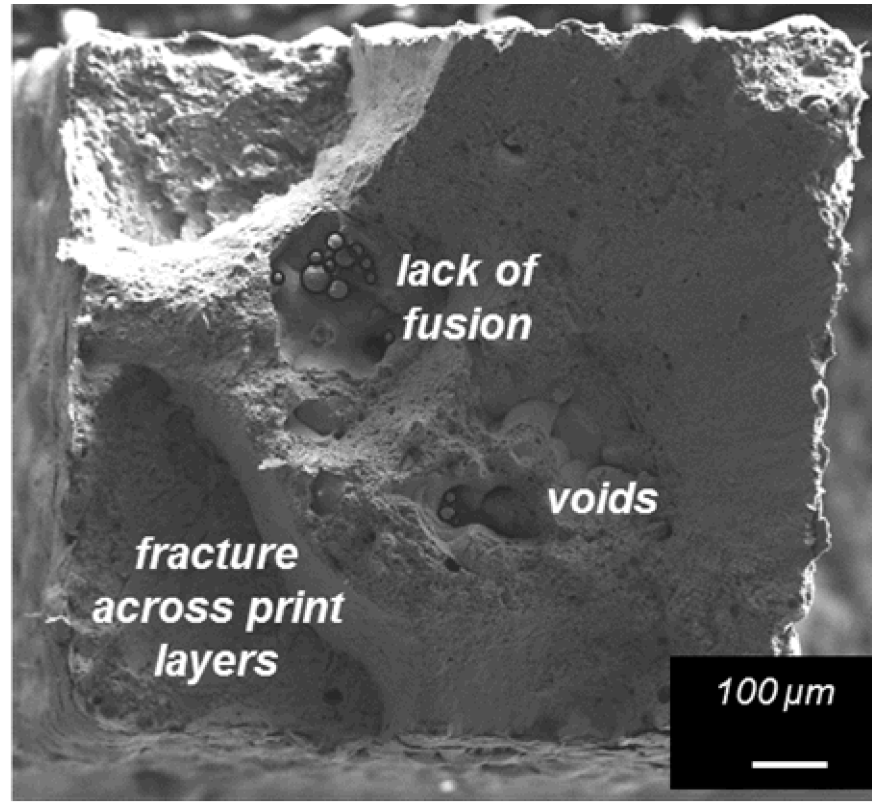


High Throughput Tensile Testing





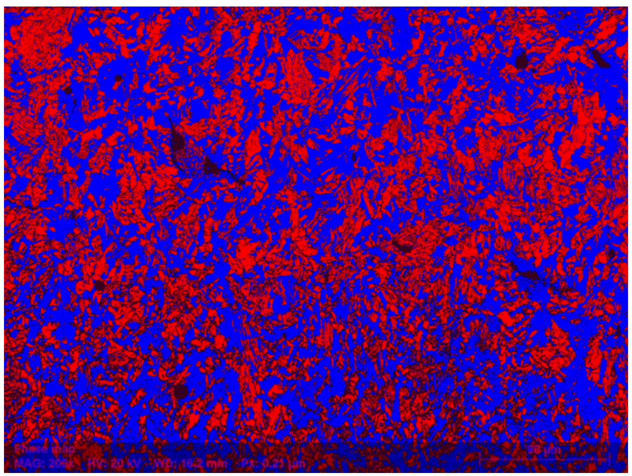
17-4 PH SS, H900 “brittle” fracture



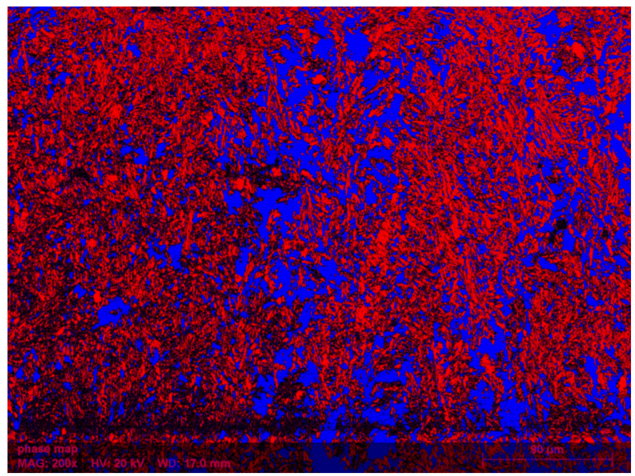
Failure at 2% elongation

High % Retained Austenite in AM 17-4 PH SS

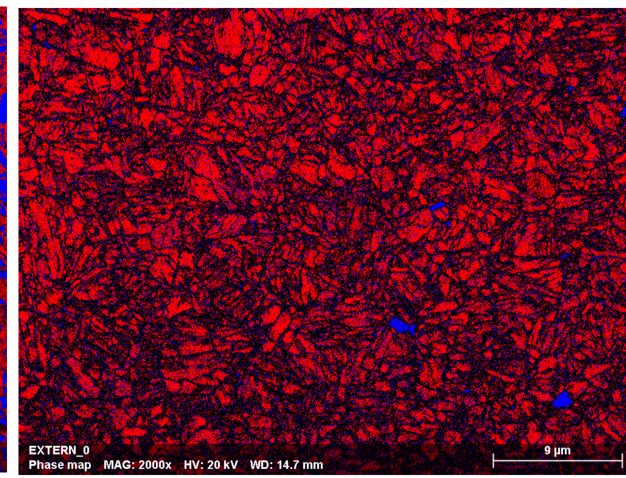
- Anomalous phase composition in AM vs. wrought 17-4 PH Stainless
  - Large fraction of retained austenite after solution heat treatment + H900 age
  - Cryo treatment to -196°C for 5 min still does not transform austenite



As-printed, 47% Austenite



SHT + H900 Age, 43% Austenite

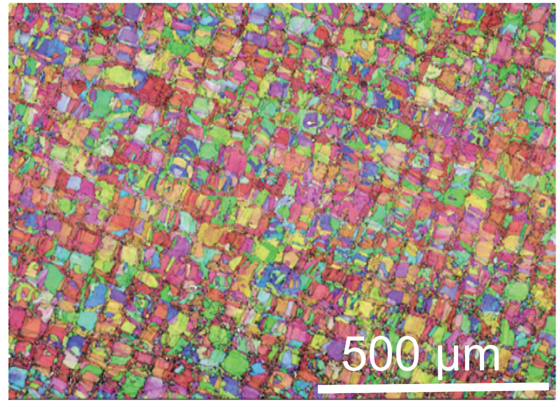


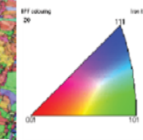
Wrought Sheet Shows Fine-grained Martensite

Blue *= austenite (FCC),* ***Red*** *= martensite / ferrite (BCC),* ***Black*** *= not indexed*

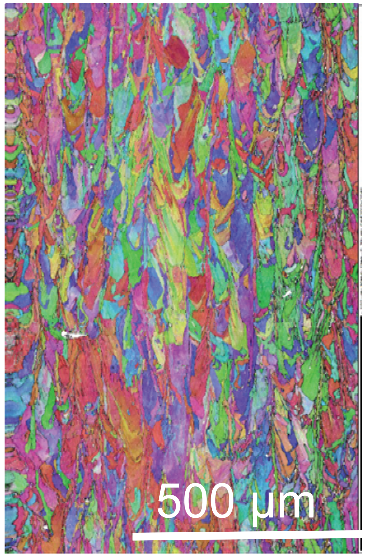
AM 316L Has Unique Microstructure with Reasonable, But Still Variable, Strain-to-Failure

Top View
(Normal to Build Direction)



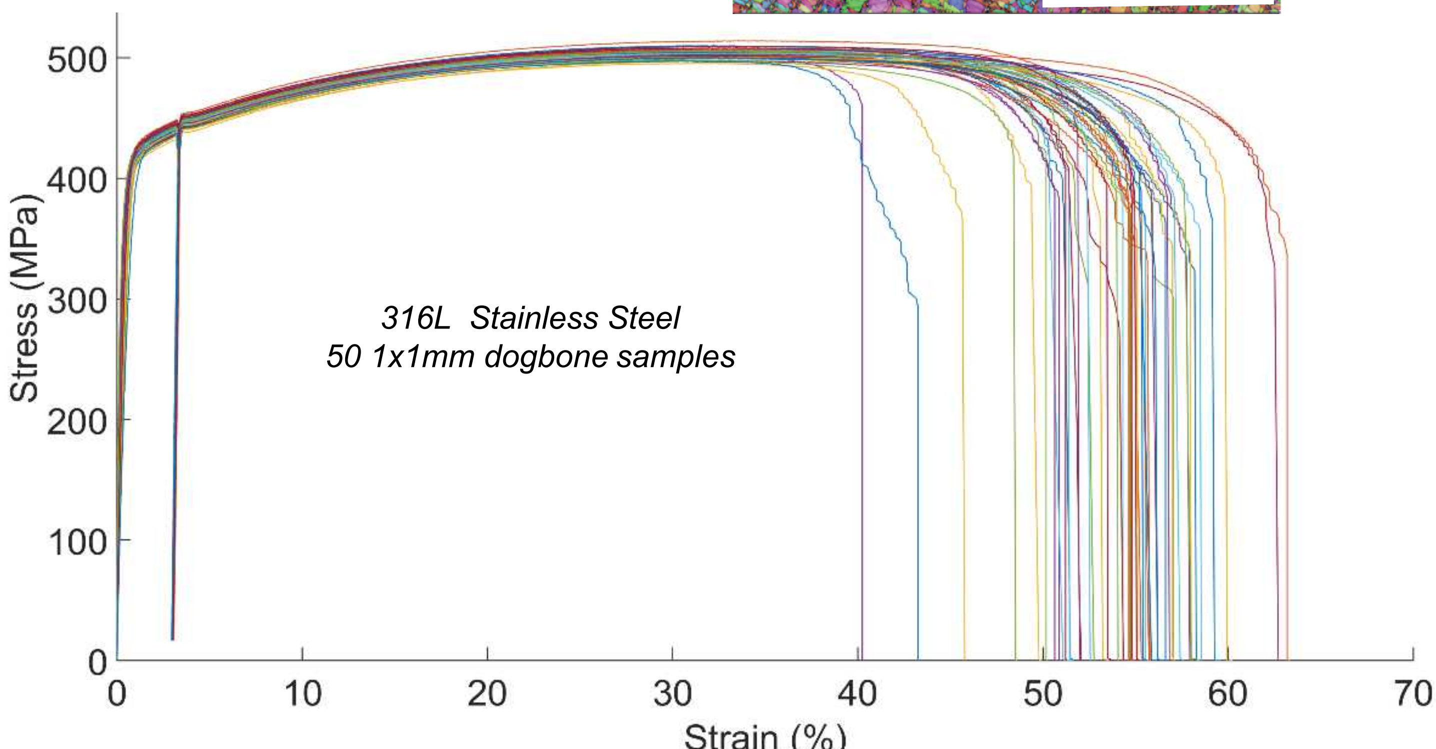


ProX 200 EBSD maps for 316L SS



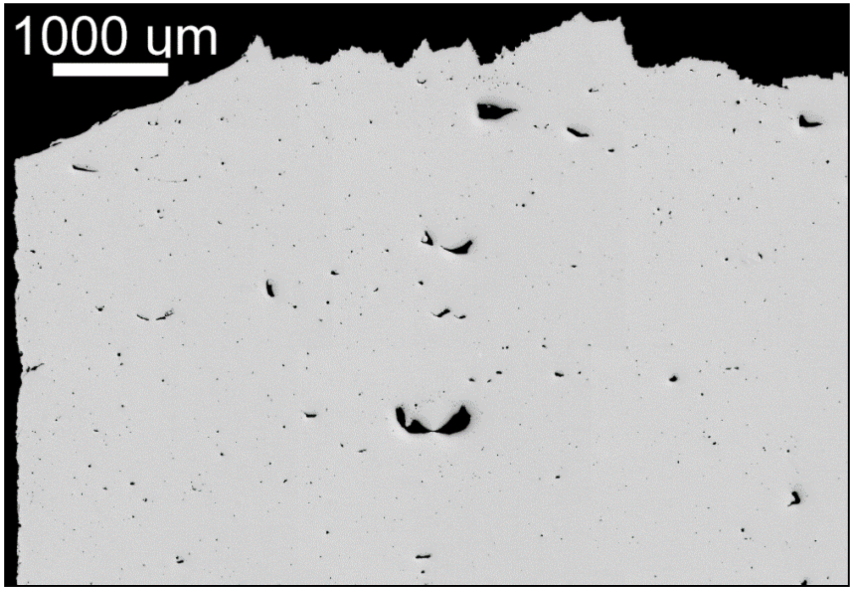
Cross Section
(Parallel to Build Direction)

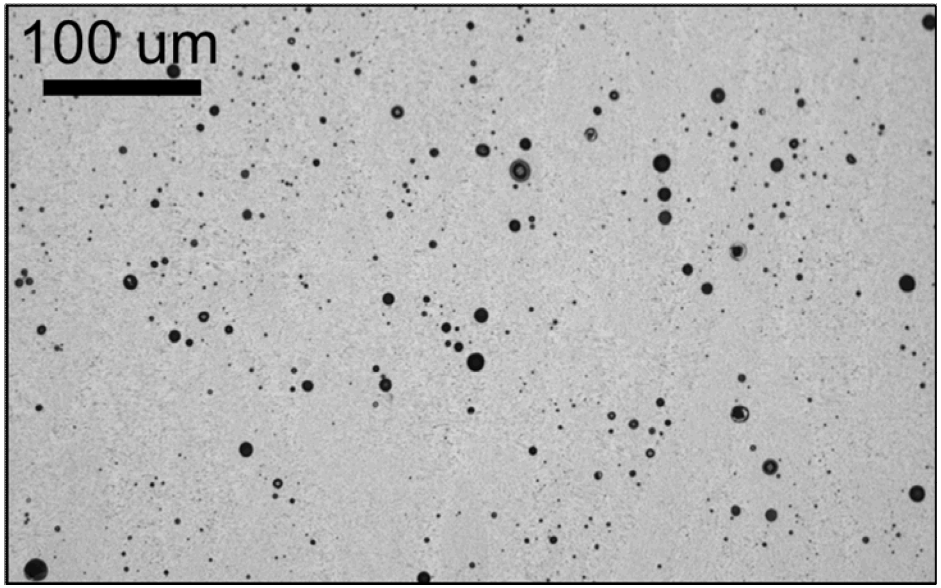
Typical Handbook Values for 316L SS
UTS ~ 515 MPa
YS ~ 205 MPa
Strain-to-Failure ~ 60%



Metallographic Porosity (*RoboMET*.3D™)

- Technique characteristics
  - Destructive - automated serial sectioning/imaging
  - Image analysis to measure porosity
- We find two basic types of porosity in AM AlSi10Mg
  - Lack of fusion (from the process) irregular, ~ 10+ to 500+ microns
  - Gas porosity (from the powder) spherical, < ~10 microns

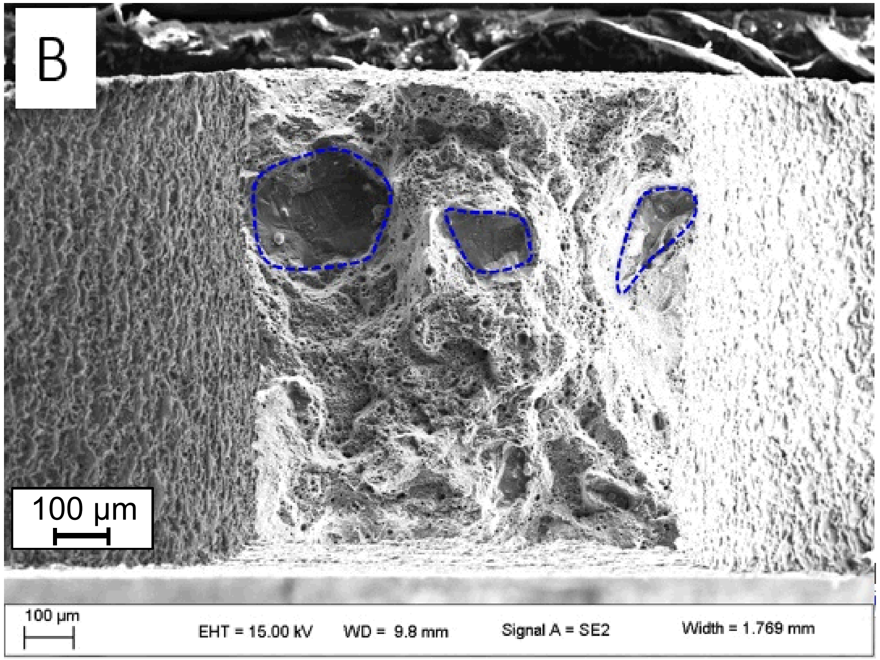


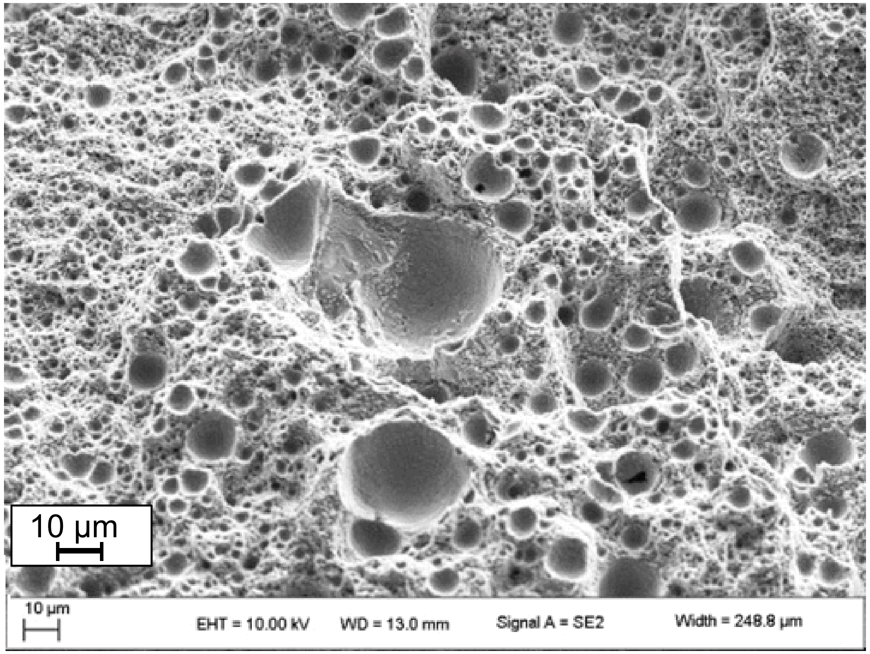


(note 10X difference in magnification between these two images)

Fracture Surface Porosity

- Technique characteristics
  - Fractured sample (destructive)
  - Biased sampling, may not be representative of bulk
  - Human/manual, subjective selection of porosity
  - Magnification effect on data

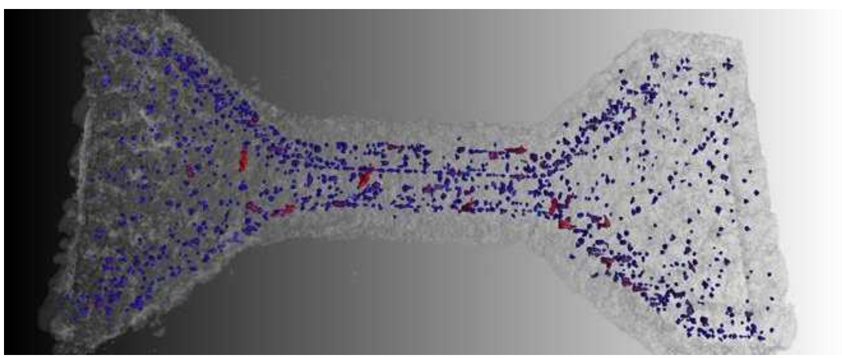


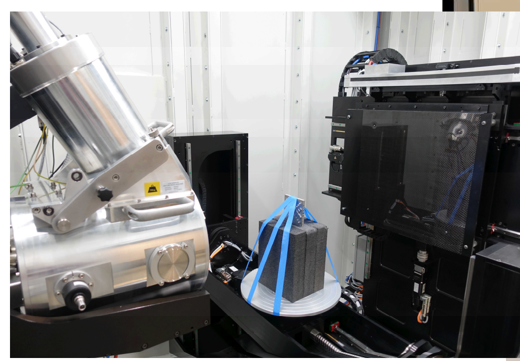


D.F. Susan, T.B. Crenshaw, and J.S. Gearhart, *Journal of Materials Engineering and Performance* 24(8), pp. 2917-2924, June 2016.

Computed Tomography Porosity

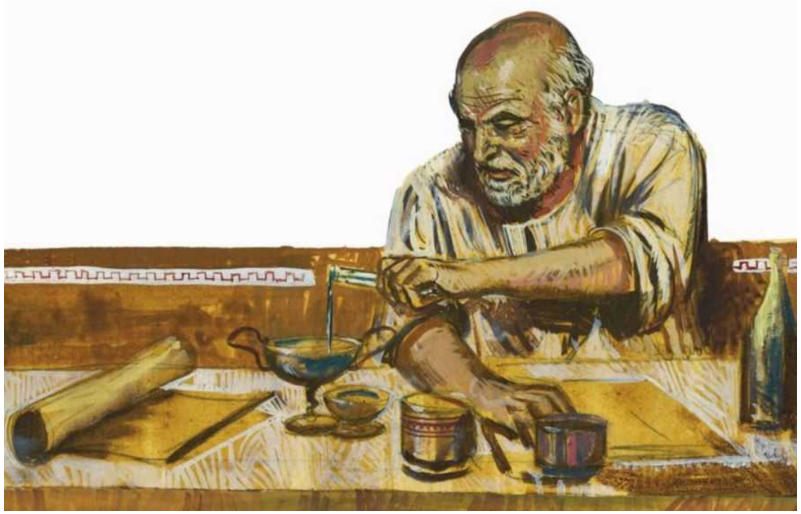
- Technique characteristics
  - Nondestructive
  - Amenable sample – X-rays have to be able to penetrate
  - Resolution/time can be issues; i.e., resolution/speed tradeoff
  - May not detect very small (gas) porosity or pores filled with unmelted powder

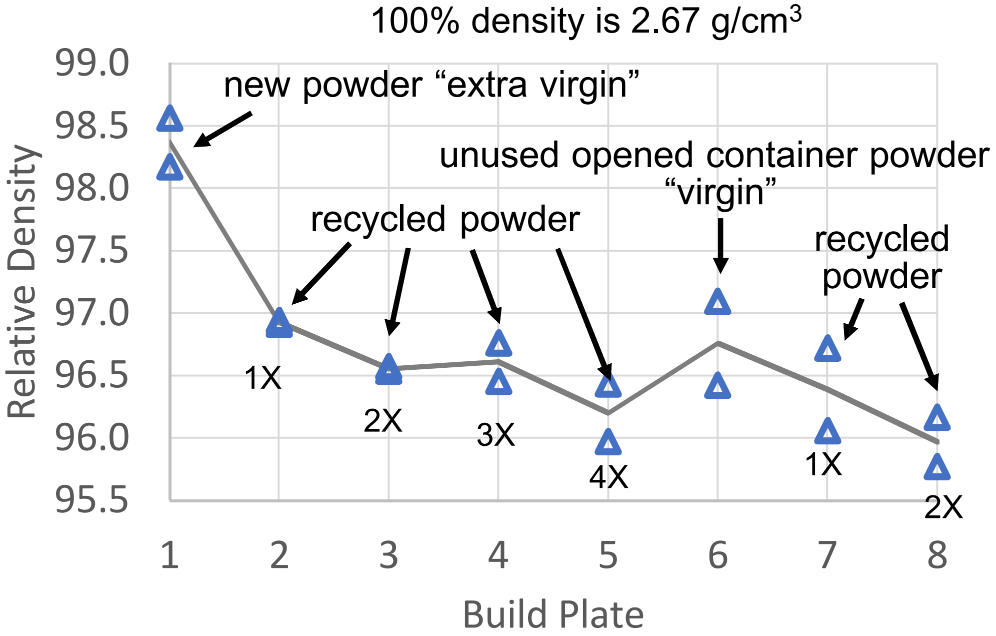




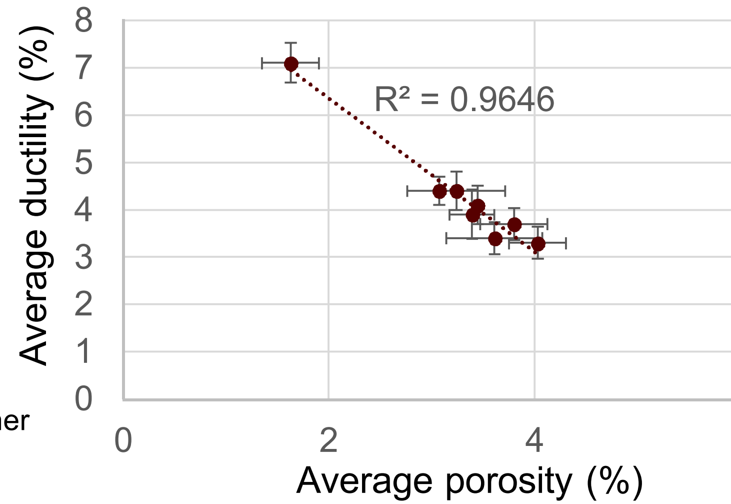
Density – Archimedes Porosity

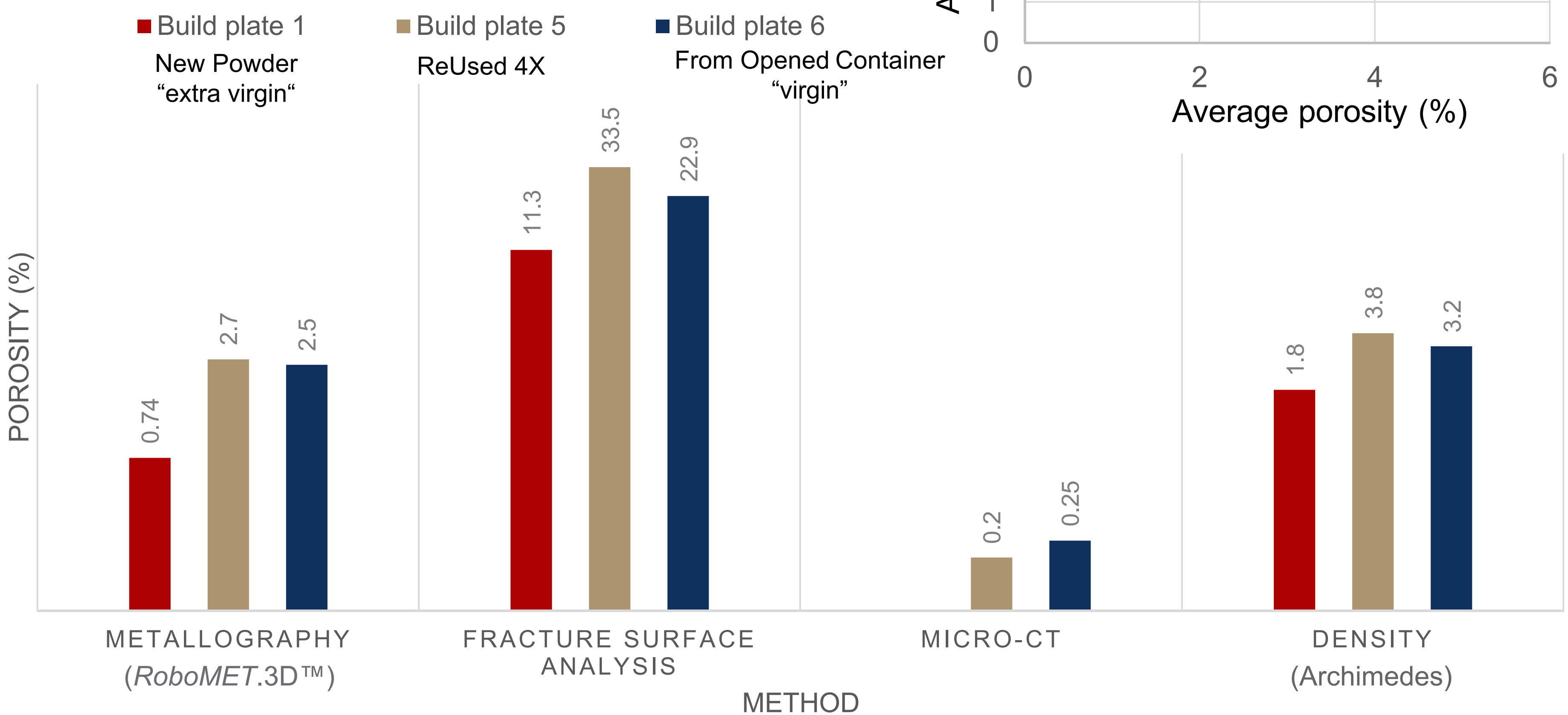
- Technique characteristics
  - Nondestructive
  - Relatively quick and inexpensive
  - Immersion of part
  - Surface voids and wetting can be convoluting factor
  - Won't account for pores filled with unmelted powder





Results Vary With Measurement Method





CT Missed Very Small Pores – Does That Matter?

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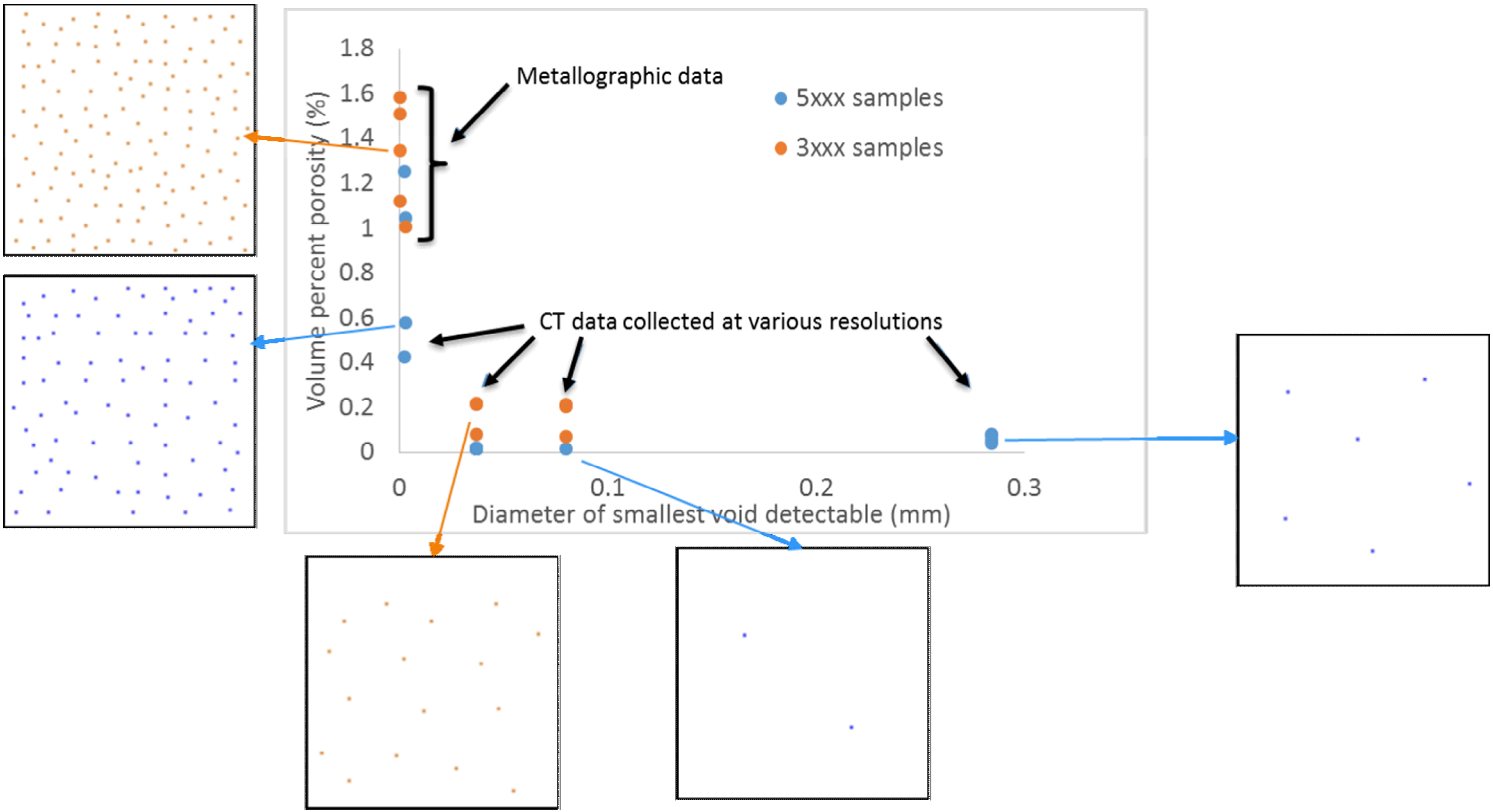
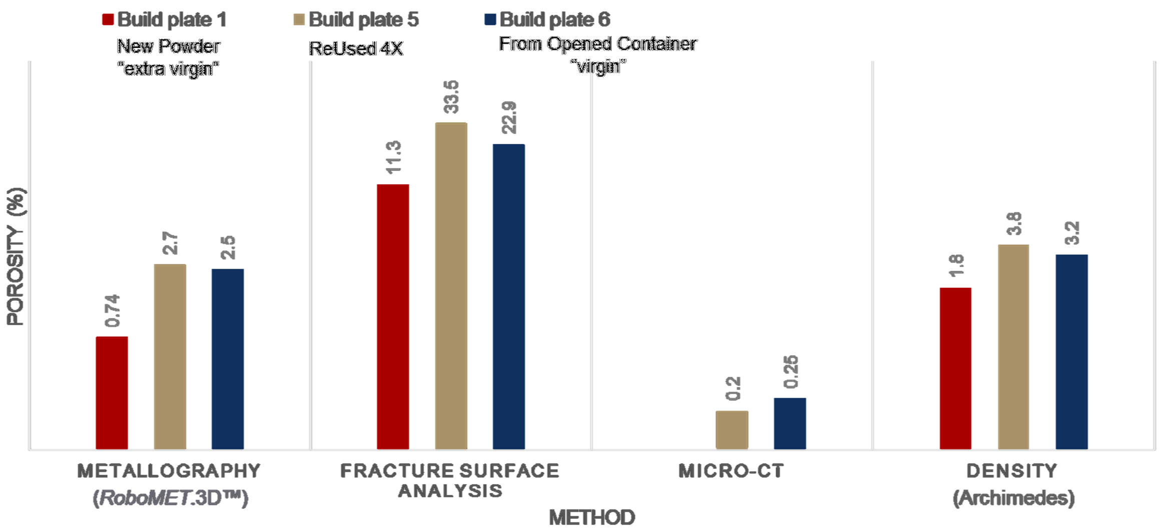
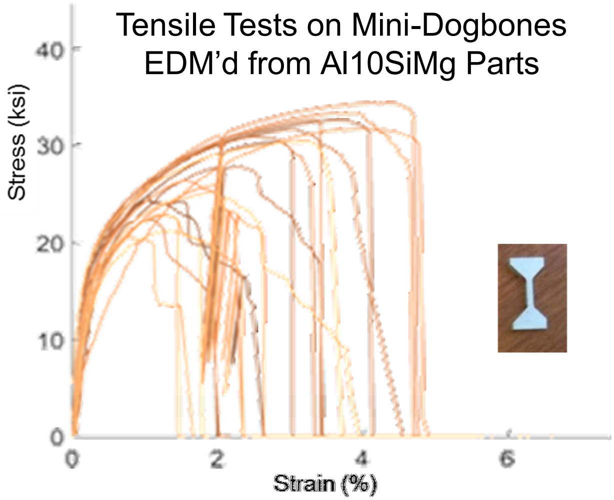
Images show examples of the measured % porosity in two different AlSi10Mg builds



Key Take Aways

- Porosity results vary with method; Archimedes seemed to correlate better with Metallography than CT, but more work is needed
- To select the best NDE method for a given application, we will need to know what defects are of concern (i.e., what is a "critical" defect?)





Three Primary Areas of Emphasis in Ongoing Sandia AM R&D

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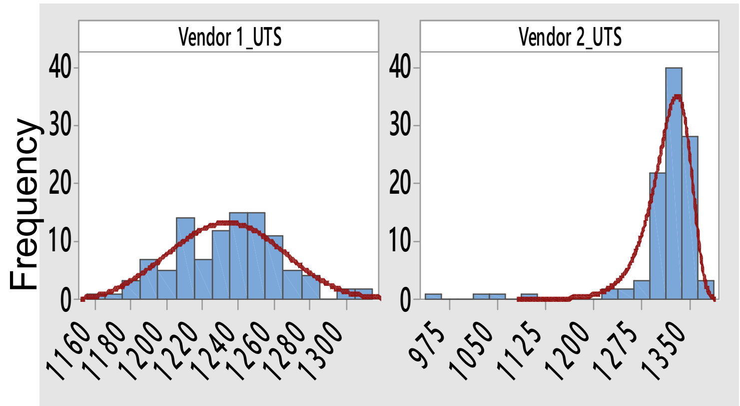


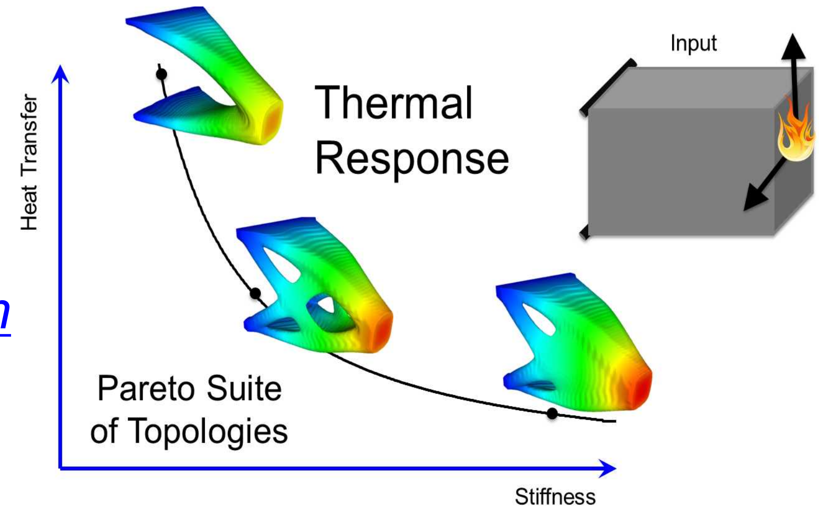
Ultimate Tensile Strength 17-4 PH (MPa)
(Typical wrought H900 ~ 1450 MPa)

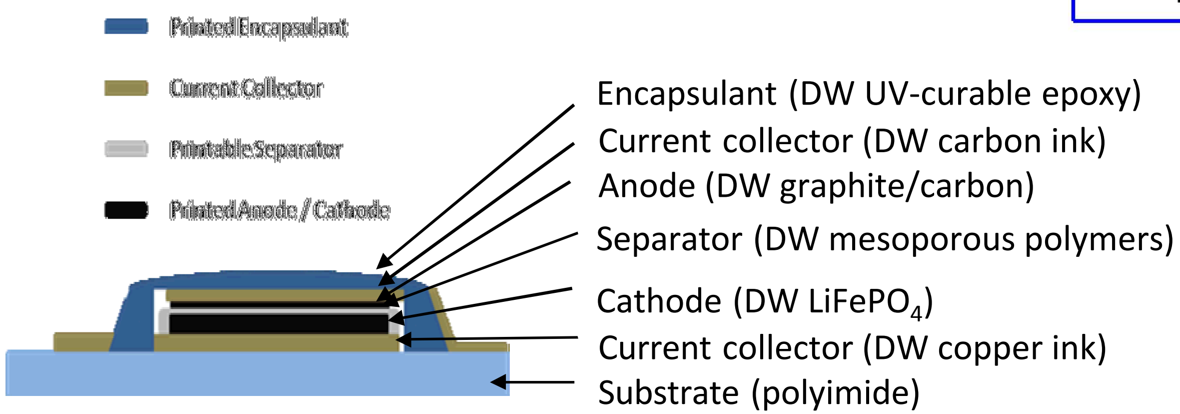
Materials Assurance

(Process & Materials Experiments & Modeling)

Engineering Analysis Driven Design

(PLATO v 1.1)





Multi-Material Additive Manufacturing

(Printed electronics, packaging, ceramics,…)

Analysis-Driven AM Design Optimization

We combined Topological Optimization (TO) with eXtended Finite Element Modeling (X-FEM) & LENS® to optimize selected properties, e.g., strength/weight ratio.

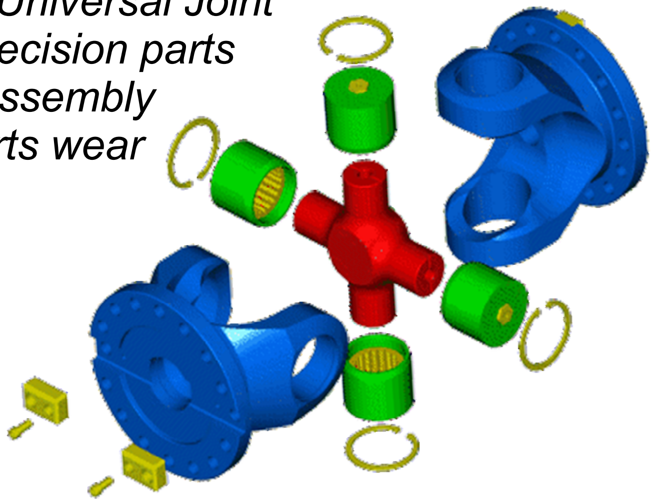
"Titanium Cholla" -- Minimum Weight, Maximum Strength, Rapidly Manufactured!

With AM it is faster and cheaper to build this optimized shaft than a solid shaft!

Dead Cholla cactus. TO designs often resemble natural structures (bio-mimicry).

Conventional Universal Joint

- *Many hi-precision parts*
- *Complex assembly*
- *Moving parts wear*



"Loxosphere"

- *1 piece*
- *No assembly*
- *No moving parts*

AM Design Via Functional Prioritization

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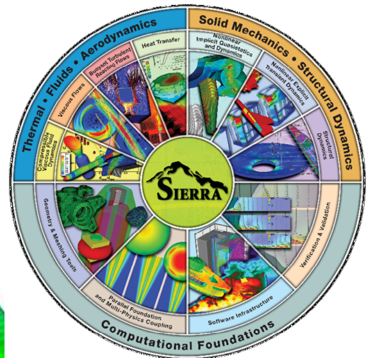
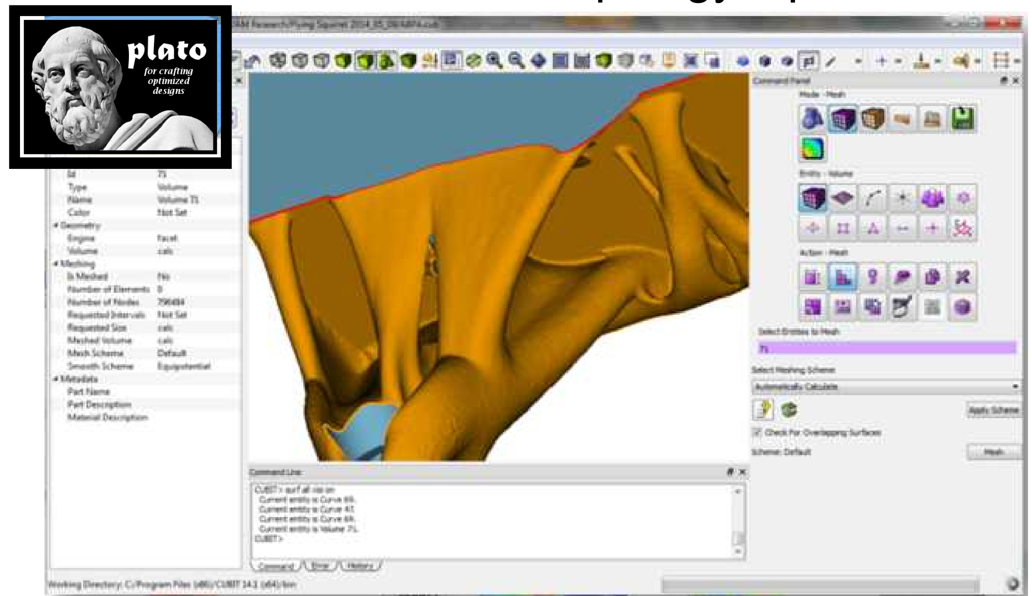
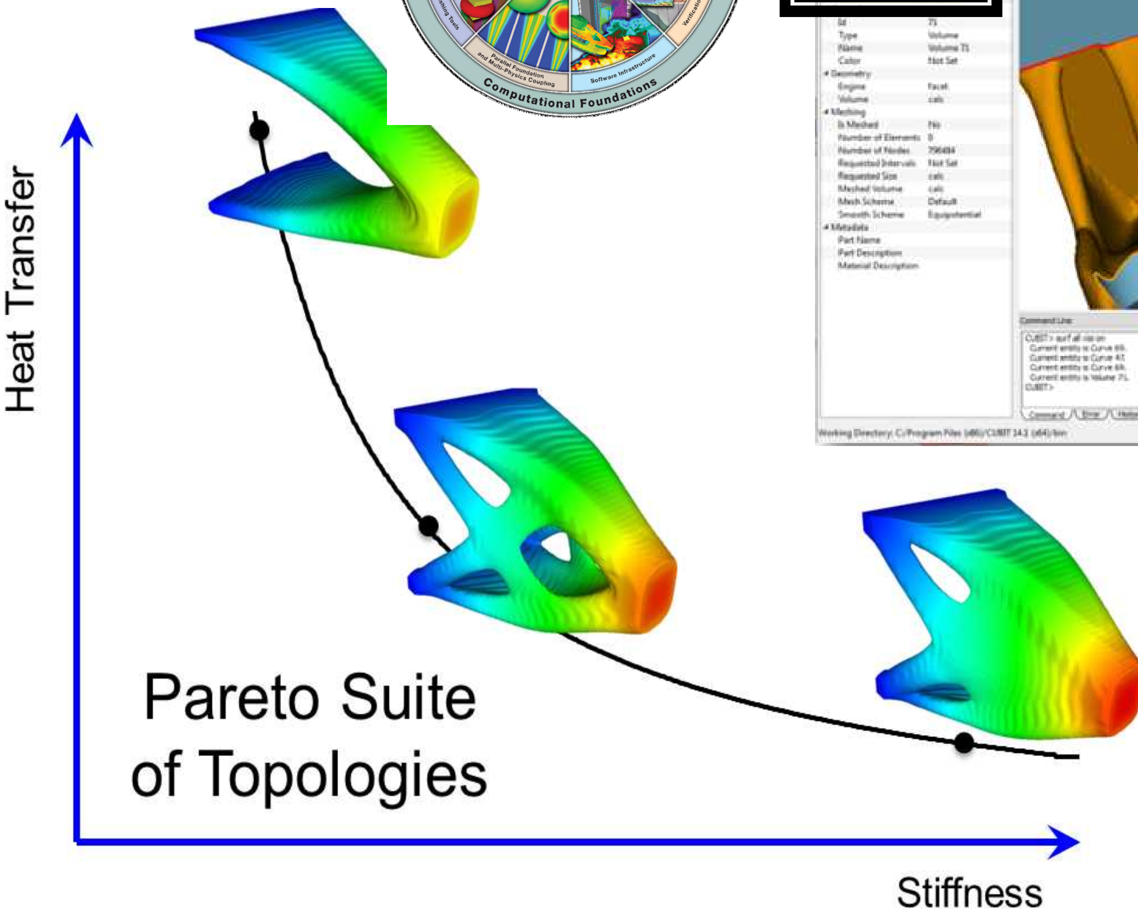
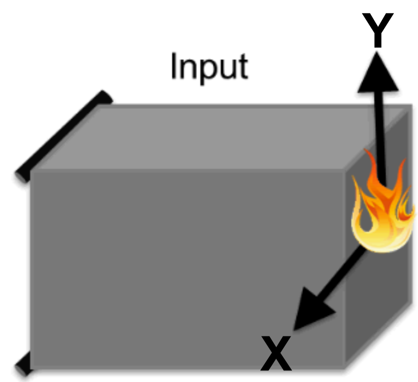


User-Friendly GUI Interface

PLATO - PLAtform for Topology Optimization







Optimizing Stiffness at Fixed Mass, How Do We Inspect?

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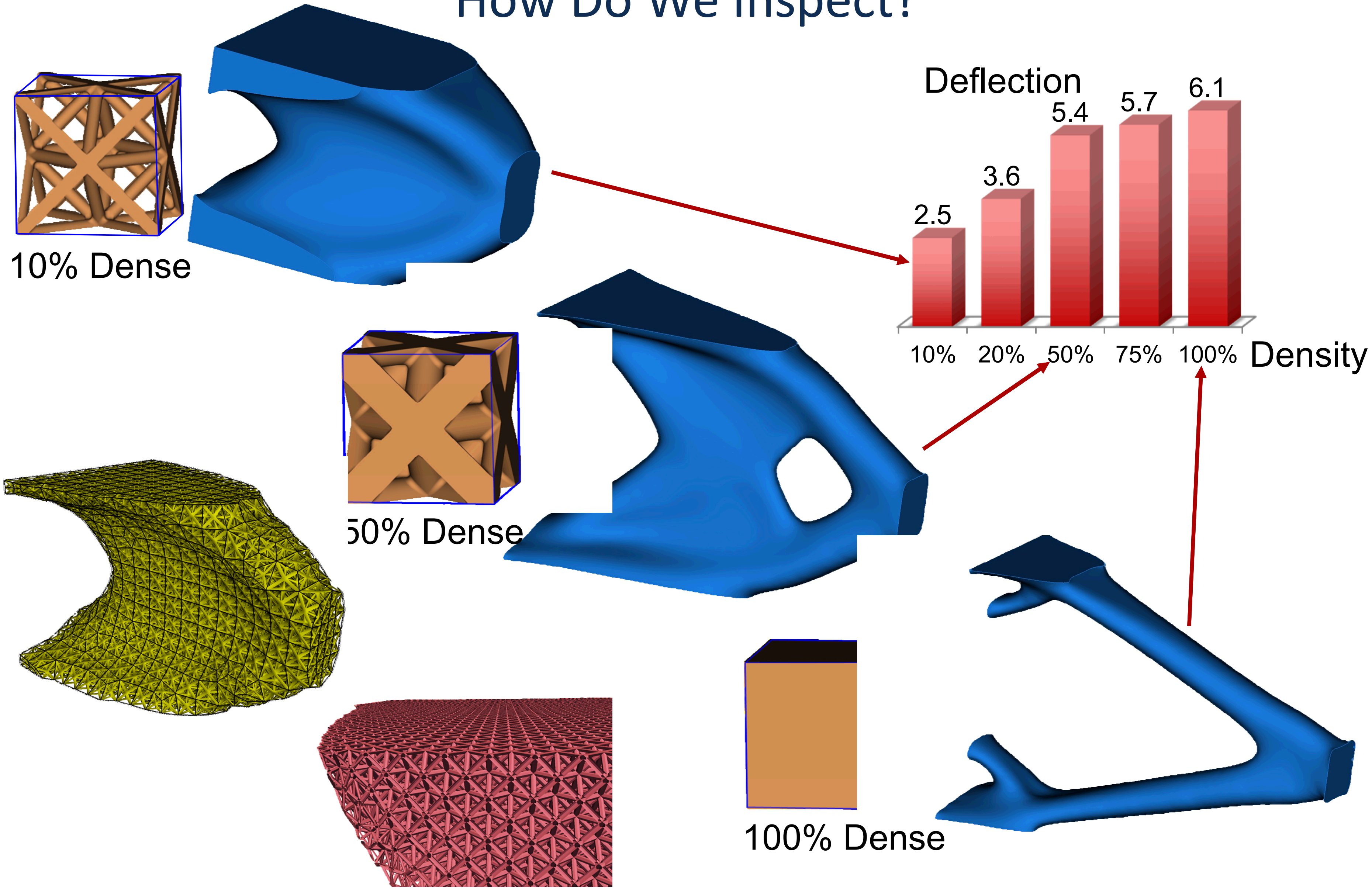

Direct Write Covers a Wide Range of Materials & Size Scales, Posing More Potential NDE Challenges

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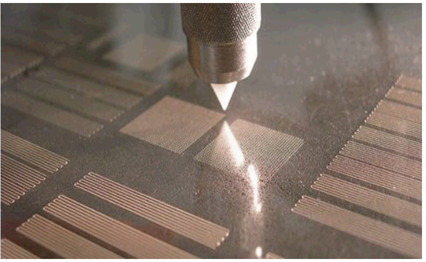
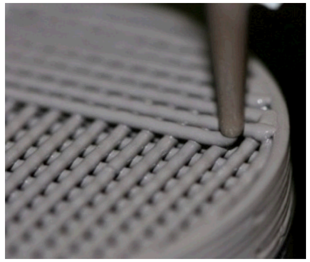
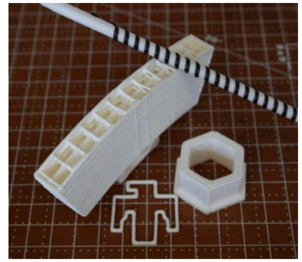
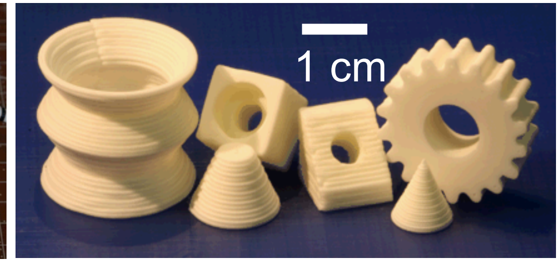
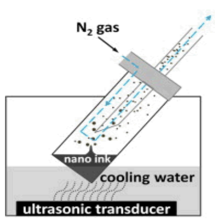
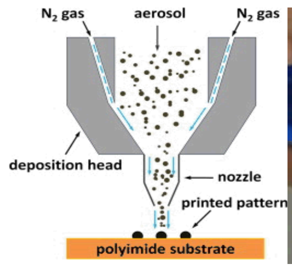
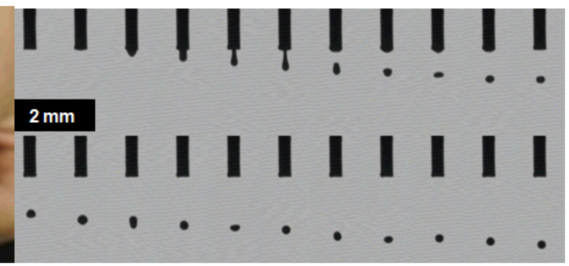
Direct Write by Extrusion Casting (Robocasting)

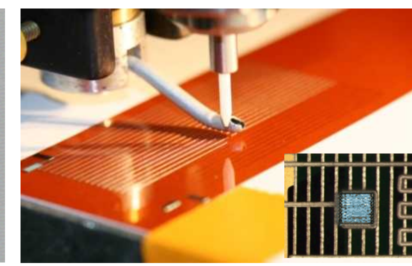





Direct Write by Aerosol & Ink Jet Deposition

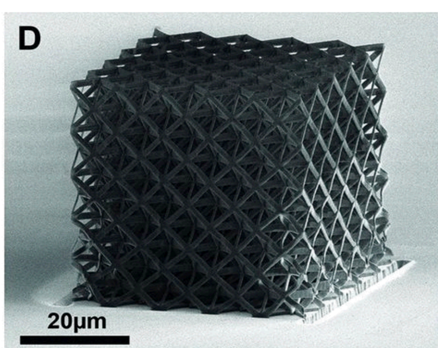


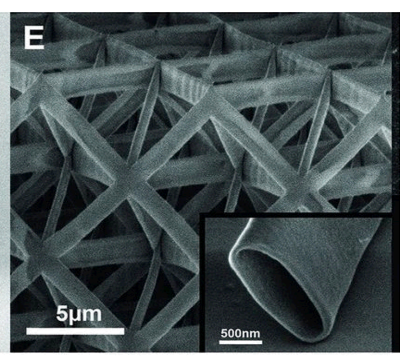


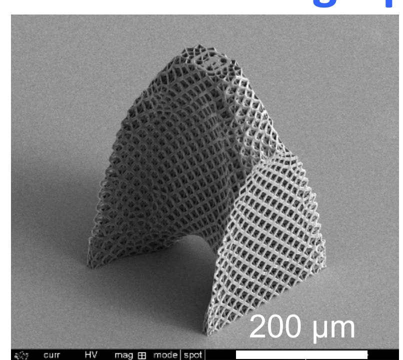



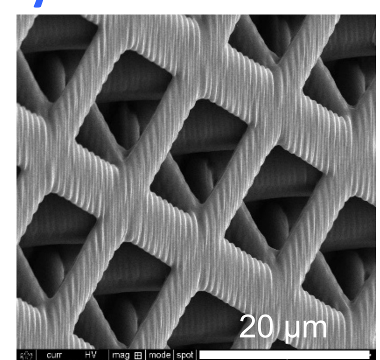


Direct Write by Laser Photo-Lithography









Summary

- AM offers great new opportunities, but it is still immature and presents significant challenges
- Materials variability and assurance represent major barriers to stockpile insertion
- To achieve effective NDE, we need a better fundamental understanding of “critical” defects
- New design possibilities and multi-material structures present additional NDE challenges
- Sandia looks to team with AWE and the other NNSA sites to improve NDE for AM