

# *Additive Manufacturing at Sandia -- New Opportunities & Technical Challenges*

**Dr. Mark F. Smith**

Deputy Director For Additive Manufacturing  
Material, Physical, & Chemical Sciences Center

Ph: 505-845-3256 [mfsmith@sandia.gov](mailto:mfsmith@sandia.gov)

# Sandia Materials & Process Science

Activities Range from Basic R&D to Specialized Production

~300 Staff, ~\$125M FY18

- *Fundamental Materials & Process Science*
  - Develop/integrate theoretical insights, computational simulation tools, and experiments to provide foundational, predictive understanding
  - Develop innovative new materials and process technologies
  - Create advanced materials analysis & process diagnostics tools
- *Materials & Process Advanced Development*
  - Advanced & exploratory materials & process development
  - Production process development & technology transfer
- *Materials Engineering/Production Support*
  - Materials & process selection/optimization
  - Problem solving, production support
  - Understanding & quantifying the margins



## Multiple Large Materials R&D Facilities

Center for Integrated Nano Technologies



Advanced Materials & Processes Laboratory



Integrated Materials Research Laboratory



Advanced Materials Laboratory



Processing & Environmental Technology Laboratory



Ion Beam Laboratory



Thermal Spray Research Laboratory



Sandia National Laboratories

# 30+ Years of Sandia AM Technology Development & Commercialization

## FastCast \*

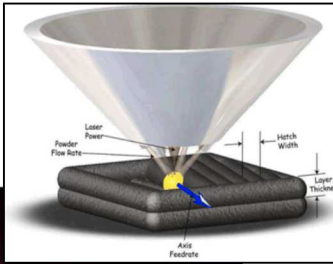
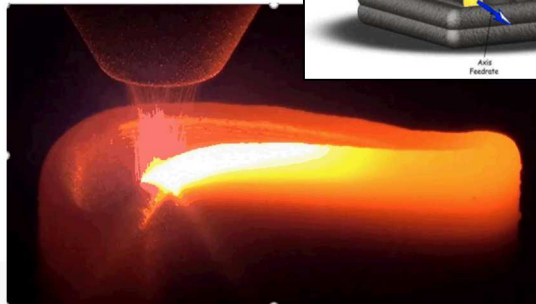
Development Housing



## Laser Engineered Net Shaping \*

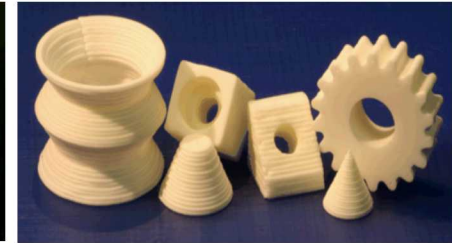
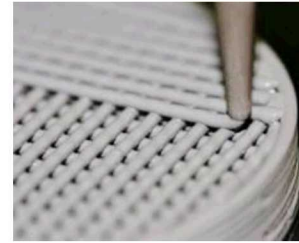
LENS®

LENS Blade



## RoboCast \*

Ceramic Parts

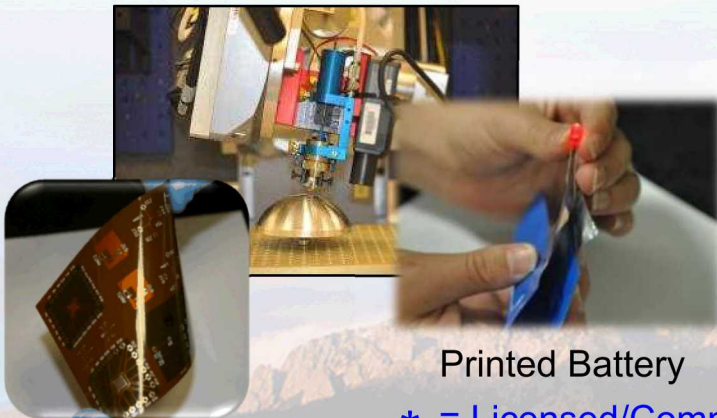


Energetic Materials



## Direct Write

Conformal Printing

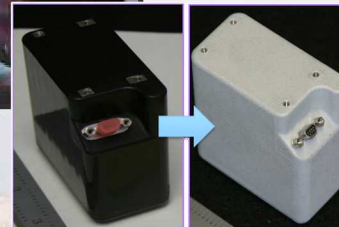


Printed Battery

## Thermal Spray



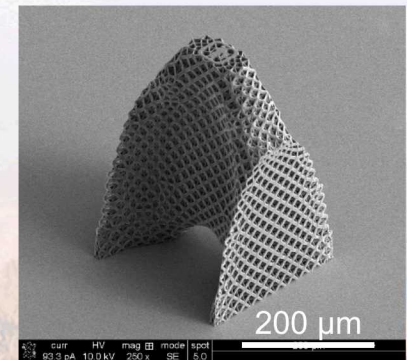
Spray-formed Rocket Nozzle



Metal on Plastic

## Micro-Nano Scale AM

Lattice Structure

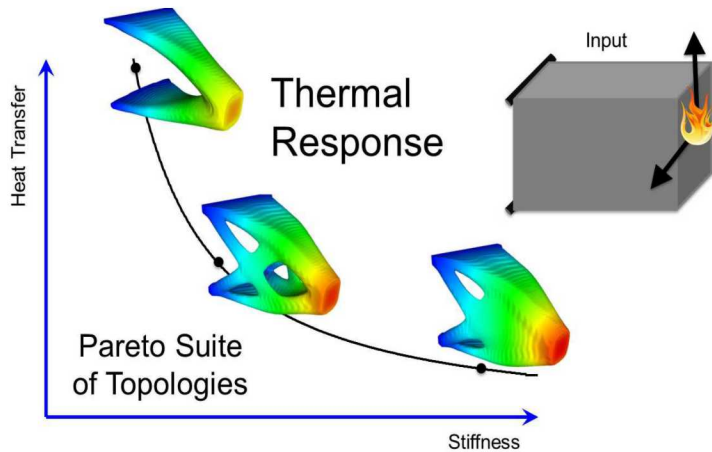


Flexible Electronics

\* = Licensed/Commercialized Sandia AM technologies  
Underline = Current Capability/Activity

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

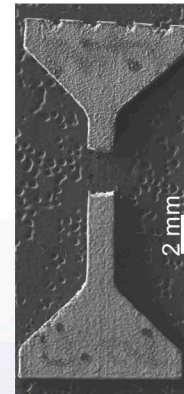
FY18 Sandia AM: >30 Projects, ~\$17M Total Investment, ~50/50 R&D vs. Applications



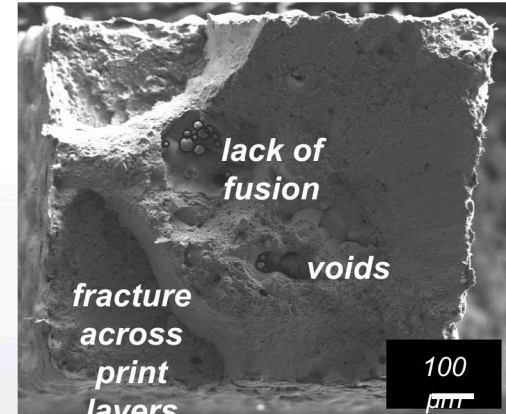
## Engineering Analysis Driven Design (Computer created/optimized AM design - PLATO)



## Materials Reliability (Assure/quantify reliability of AM materials)



17-8 PH SS,  
H900, "brittle"  
fracture



Failure at 2% elongation



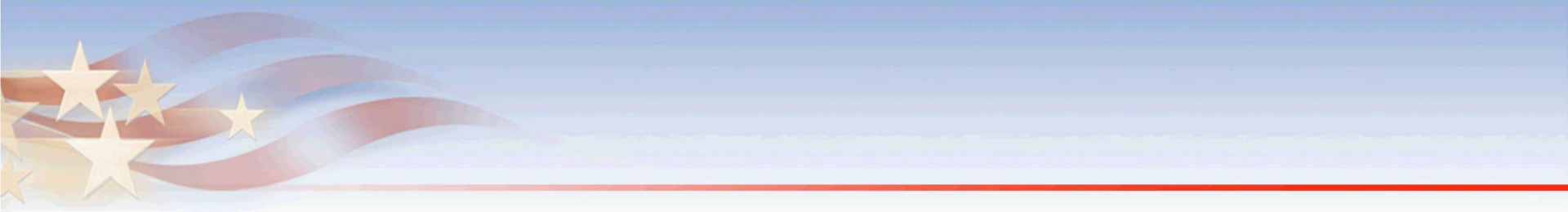
- Printed Encapsulant
- Current Collector
- Printable Separator
- Printed Anode/Cathode

- Encapsulant (DW UV-curable epoxy)
- Current collector (DW carbon ink)
- Anode (DW graphite/carbon)
- Separator (DW mesoporous polymers)
- Cathode (DW  $\text{LiFePO}_4$ )
- Current collector (DW copper ink)
- Substrate (polyimide)

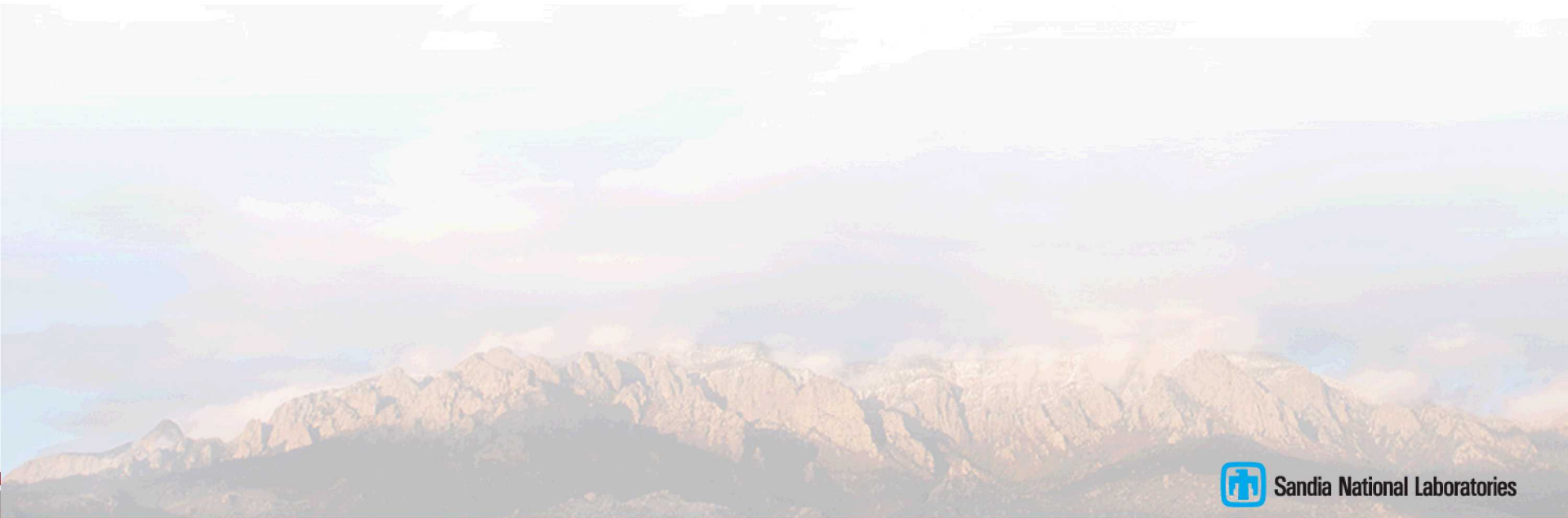
Printed  $\text{LiFePO}_4$  Battery

## Multi-Material Additive Manufacturing

(Printed electronics, packaging, ceramics, ...)



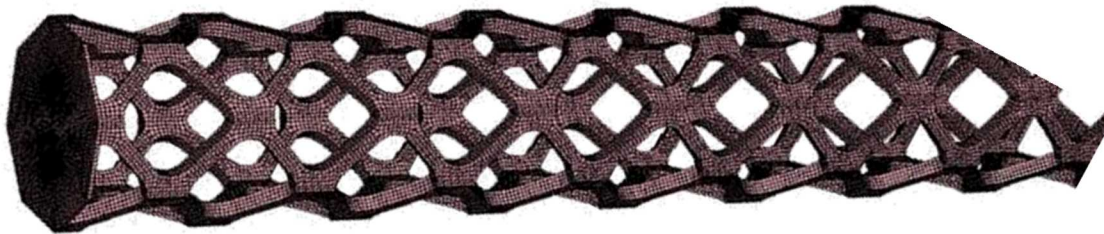
# Design/Analysis Tools



# Analysis-Driven Design Optimization

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

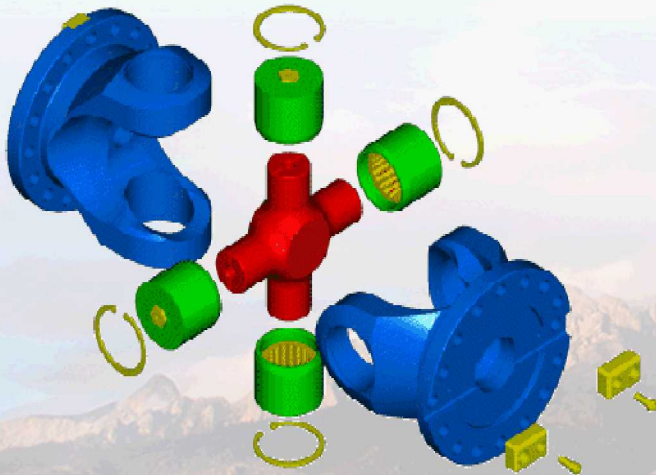
*“Titanium Cholla” LDRD -- Minimum Weight, Maximum Strength, Rapidly Manufactured!*



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



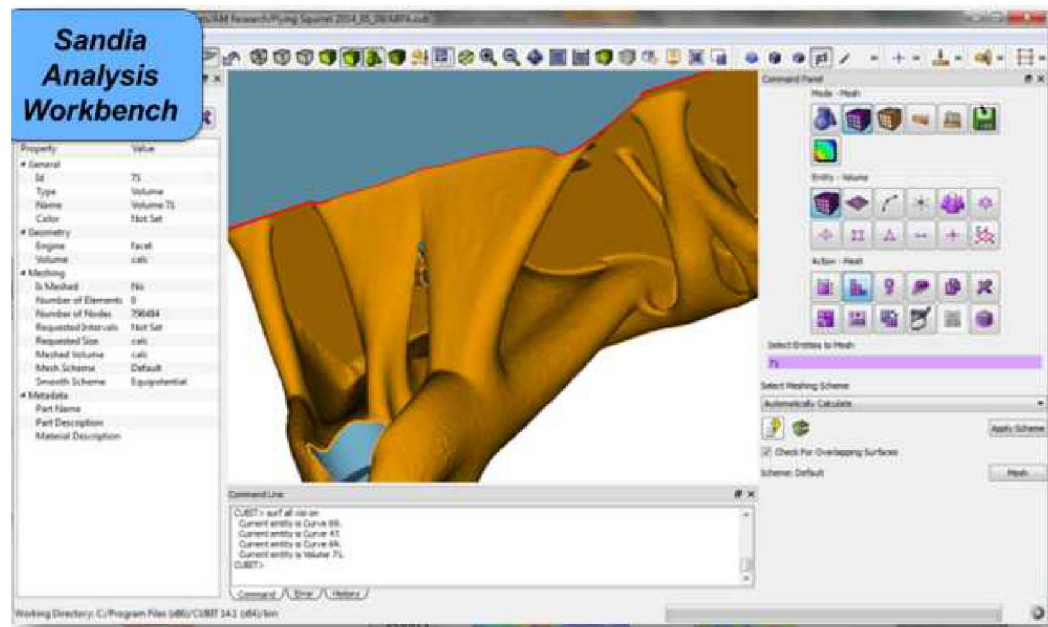
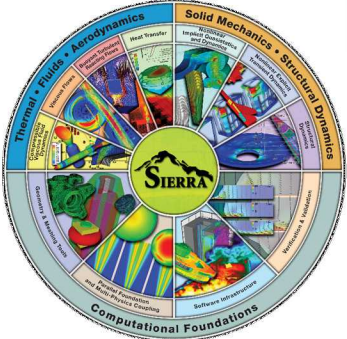
*Core of a dead Cholla cactus (optimized designs often resemble natural structures -- bio-mimicry)*



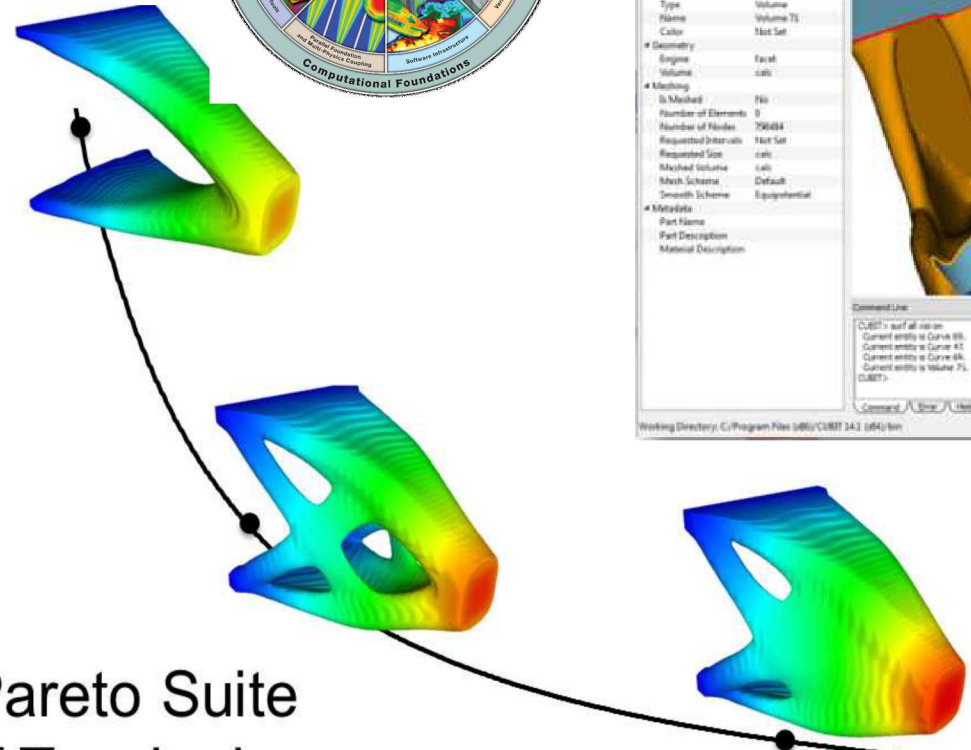
*“Loxosphere” Universal Joint printed as a single integrated assembly – fewer parts, no assembly, no frictional wear!*

# AM Design Via Functional Prioritization

User Friendly Interface

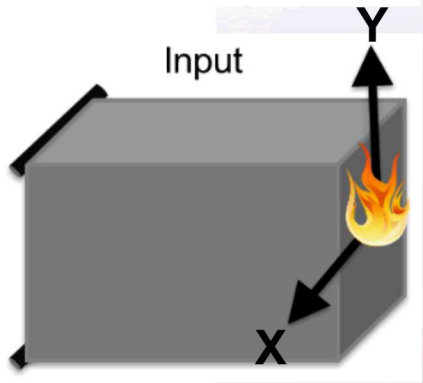


Heat Transfer

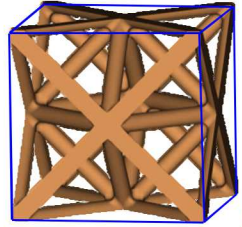


Pareto Suite of Topologies

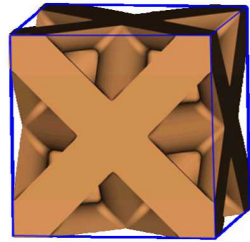
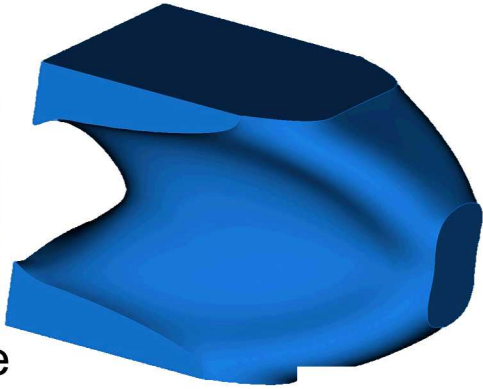
Stiffness



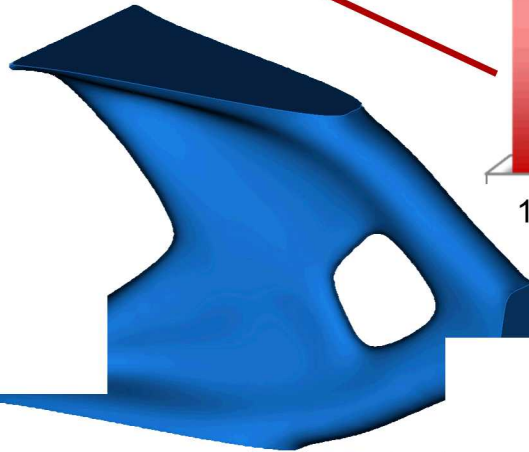
# Optimizing Stiffness at Fixed Mass



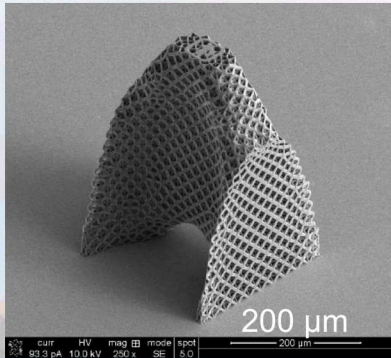
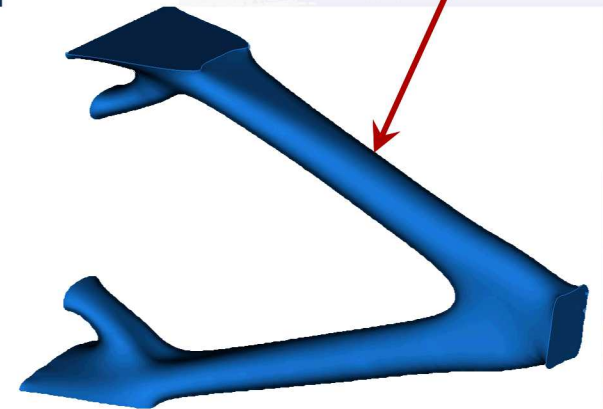
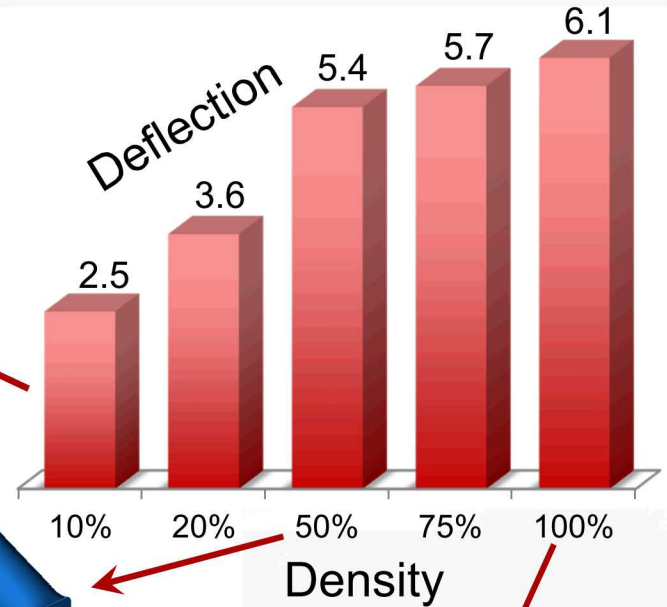
10% Dense



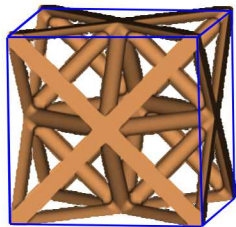
50% Dense



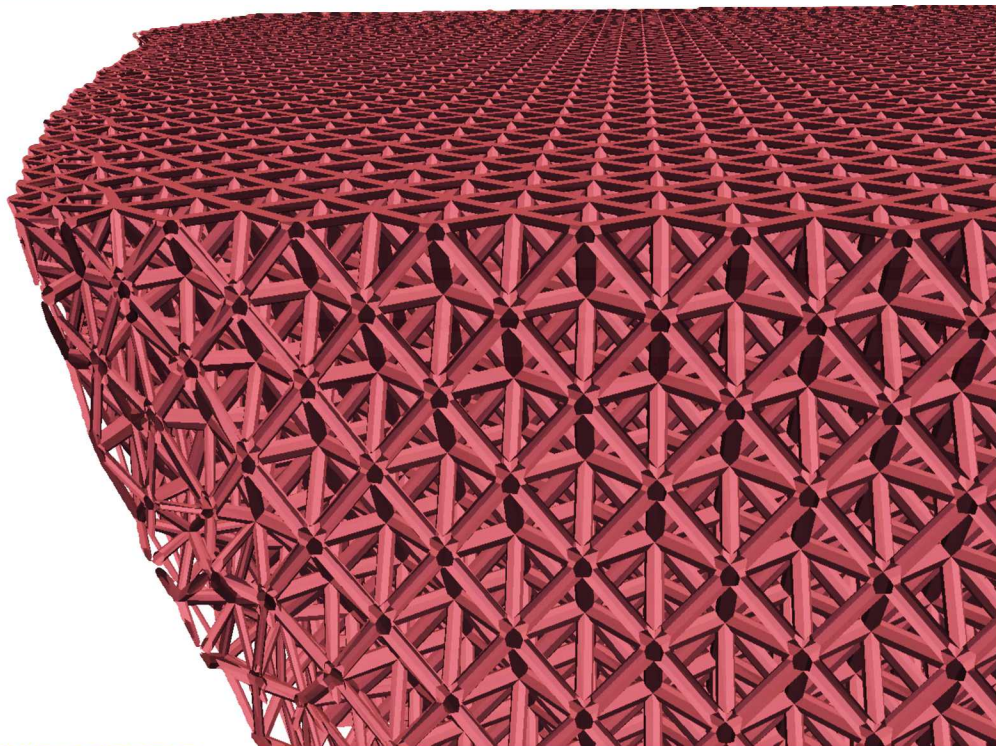
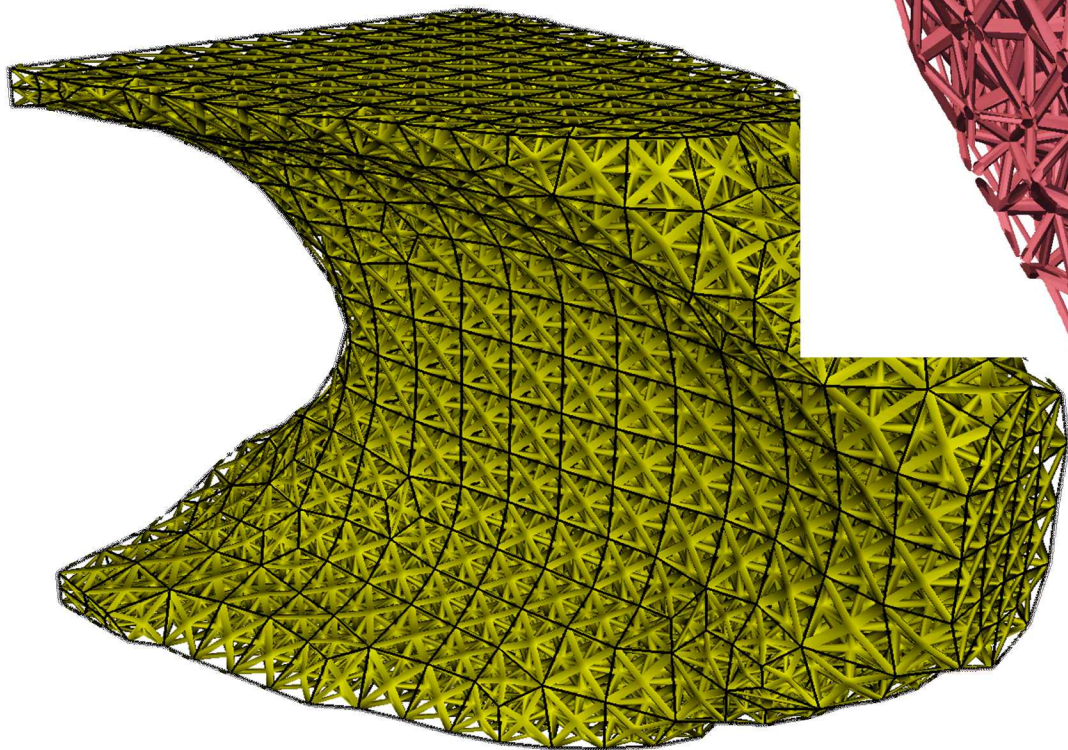
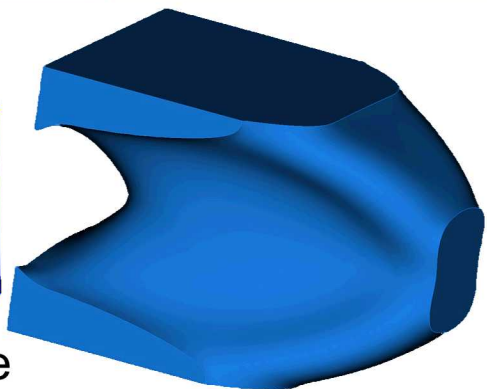
100% Dense

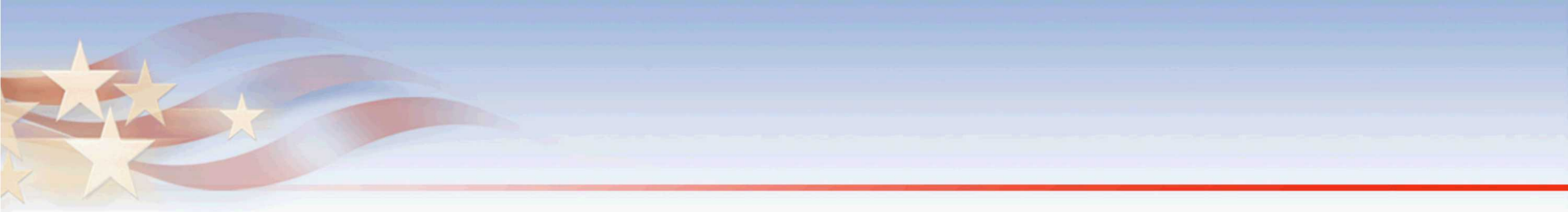


# Creating Curved Surfaces with no "Loose Ends"



10% Dense





# Materials Reliability

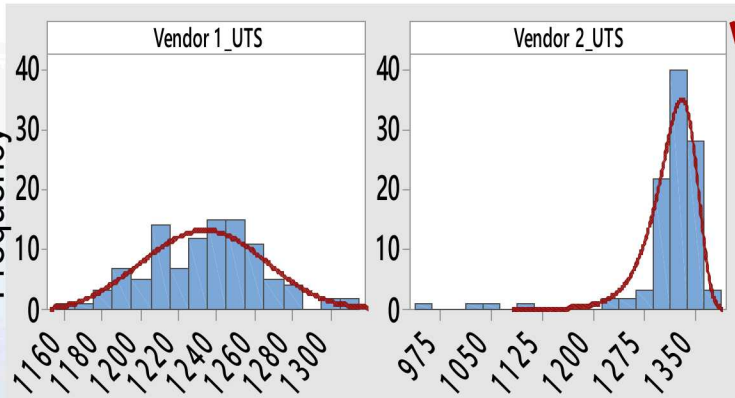


# Residual Stress, Materials Properties, and Variability are Important Issues

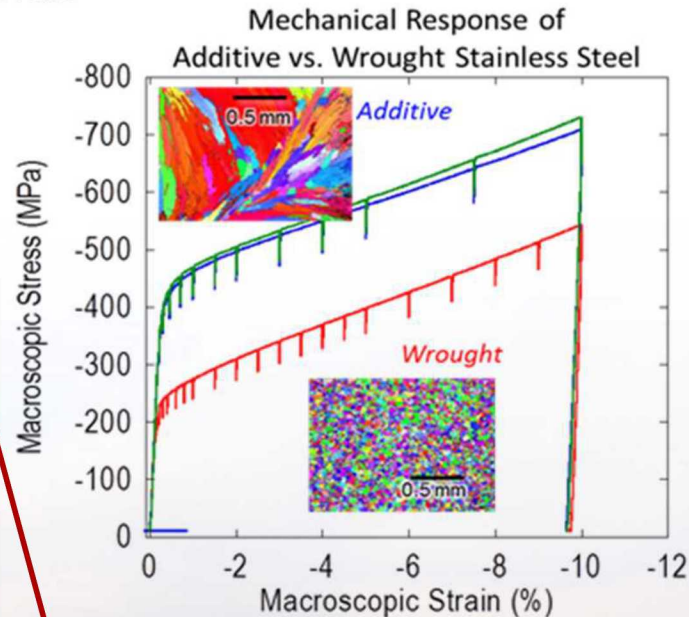
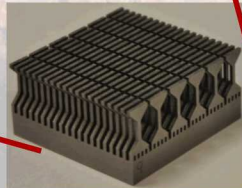
## AM Is Still an Evolving/Emerging Technology

- Residual Stress is a Significant Issue
- Limited Materials Property/Performance Data (no standards)
- Large Variability in Process and Materials

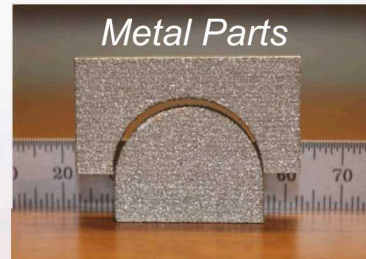
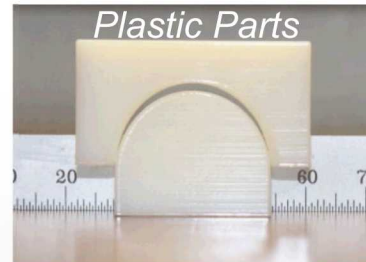
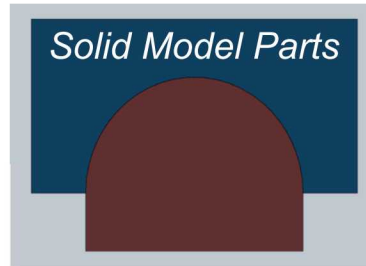
Large Variability in AM Materials Properties



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



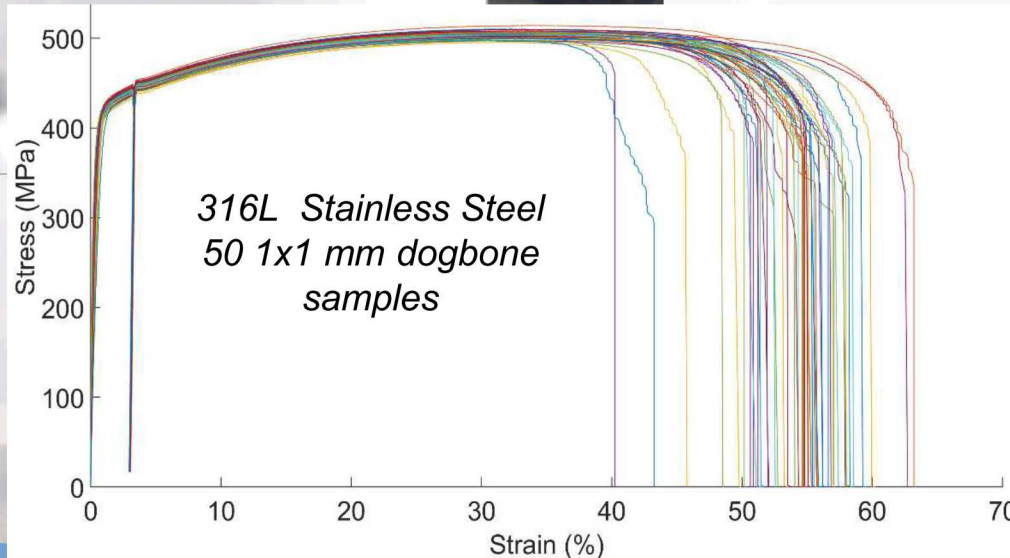
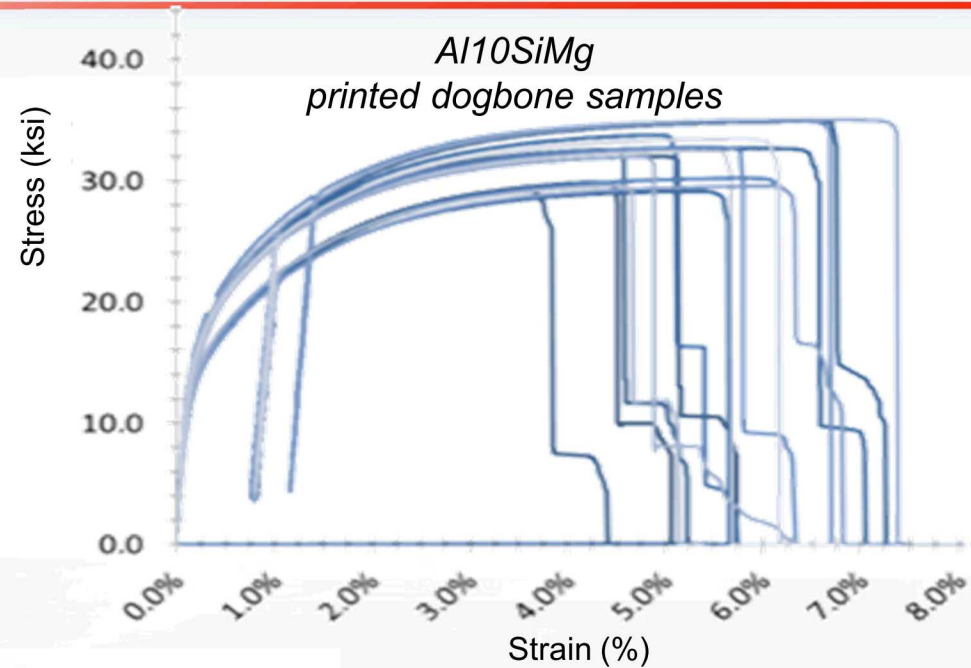
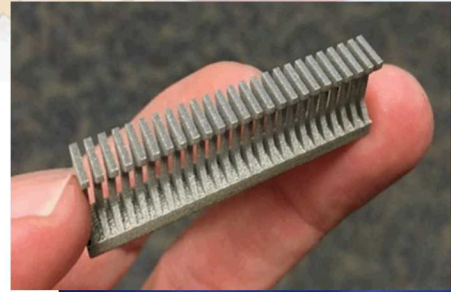
AM Metals are Unlike Cast or Wrought Metals



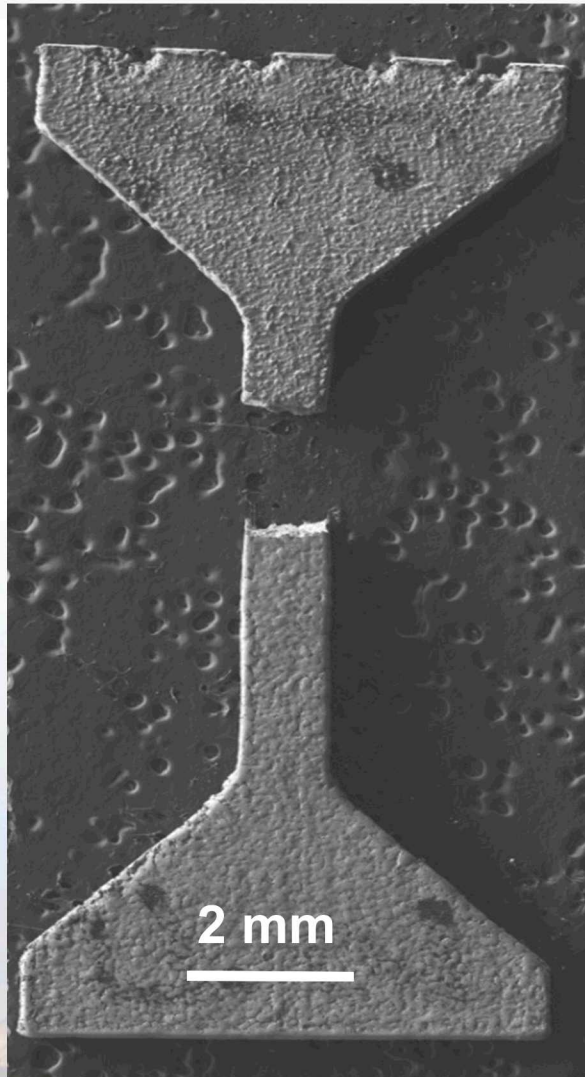
Shrinkage & Residual Stress Cause Dimensional Issues

# High-Throughput Testing Used to Address Variability

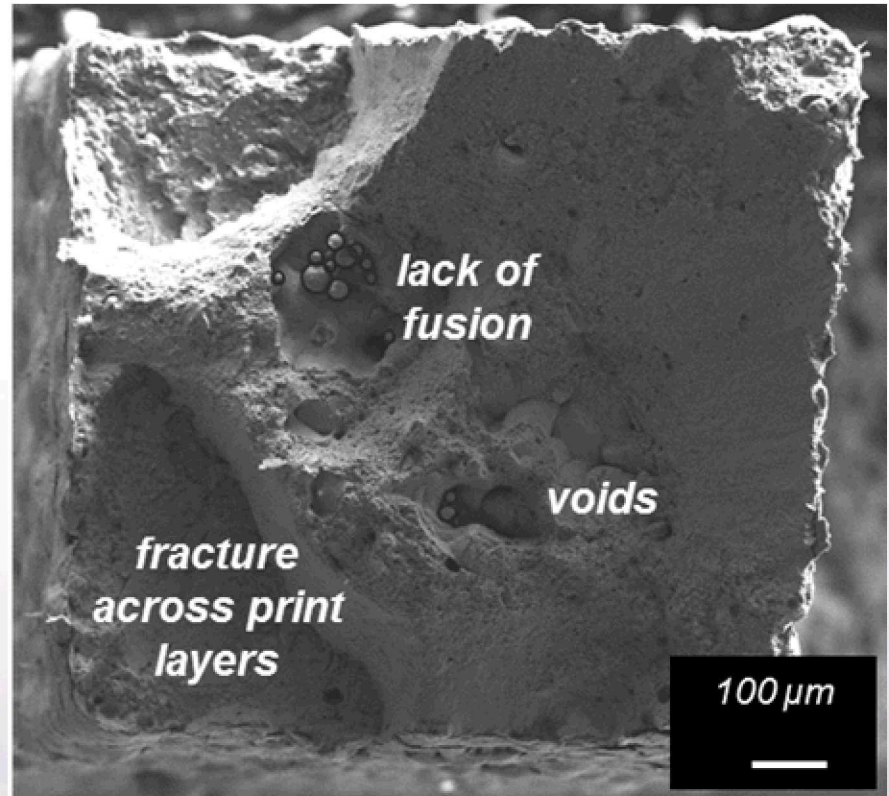
>100 Tests/Hr



# Common Types of Defects

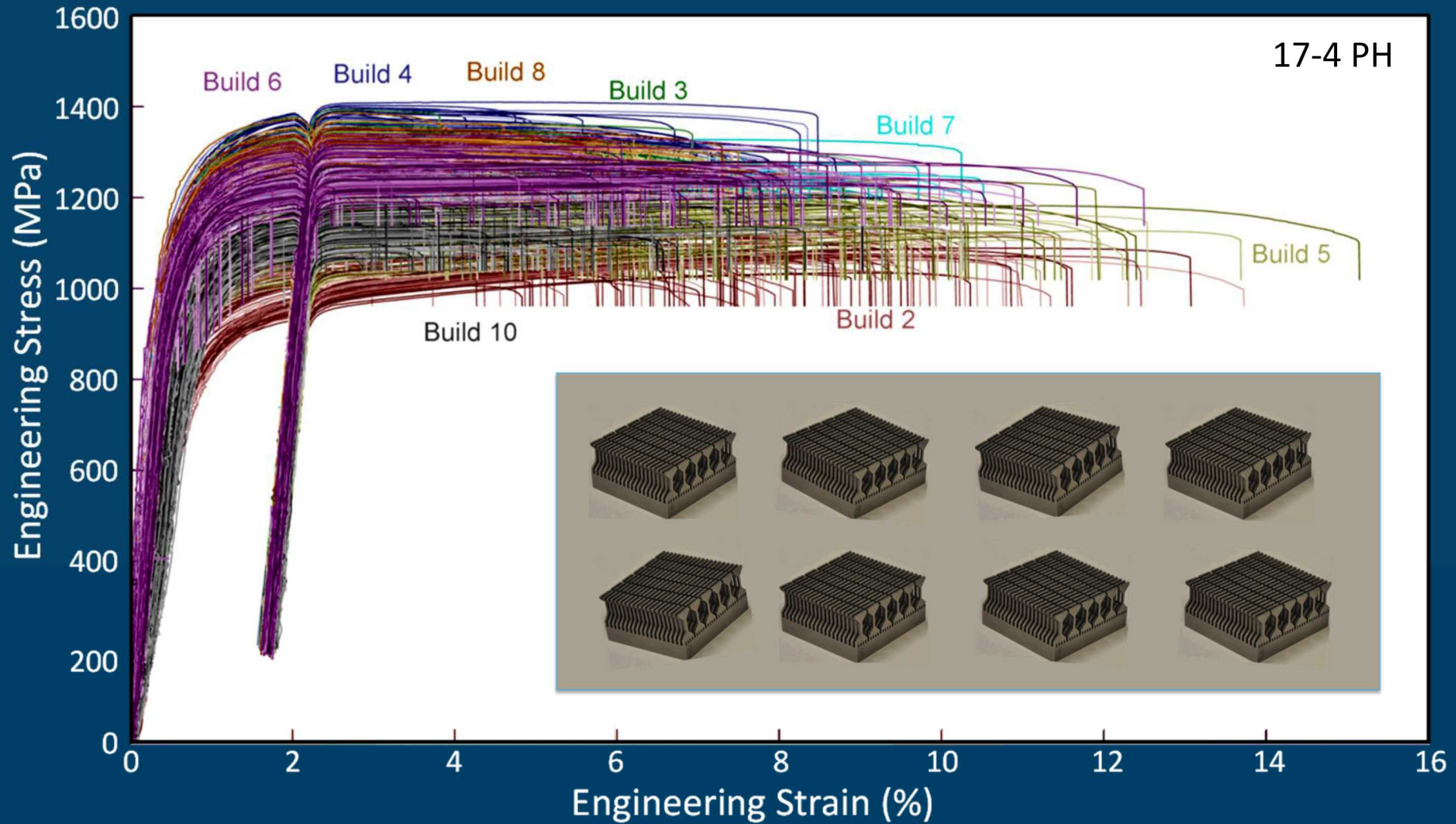


17-4 PH SS, H900 “brittle” fracture

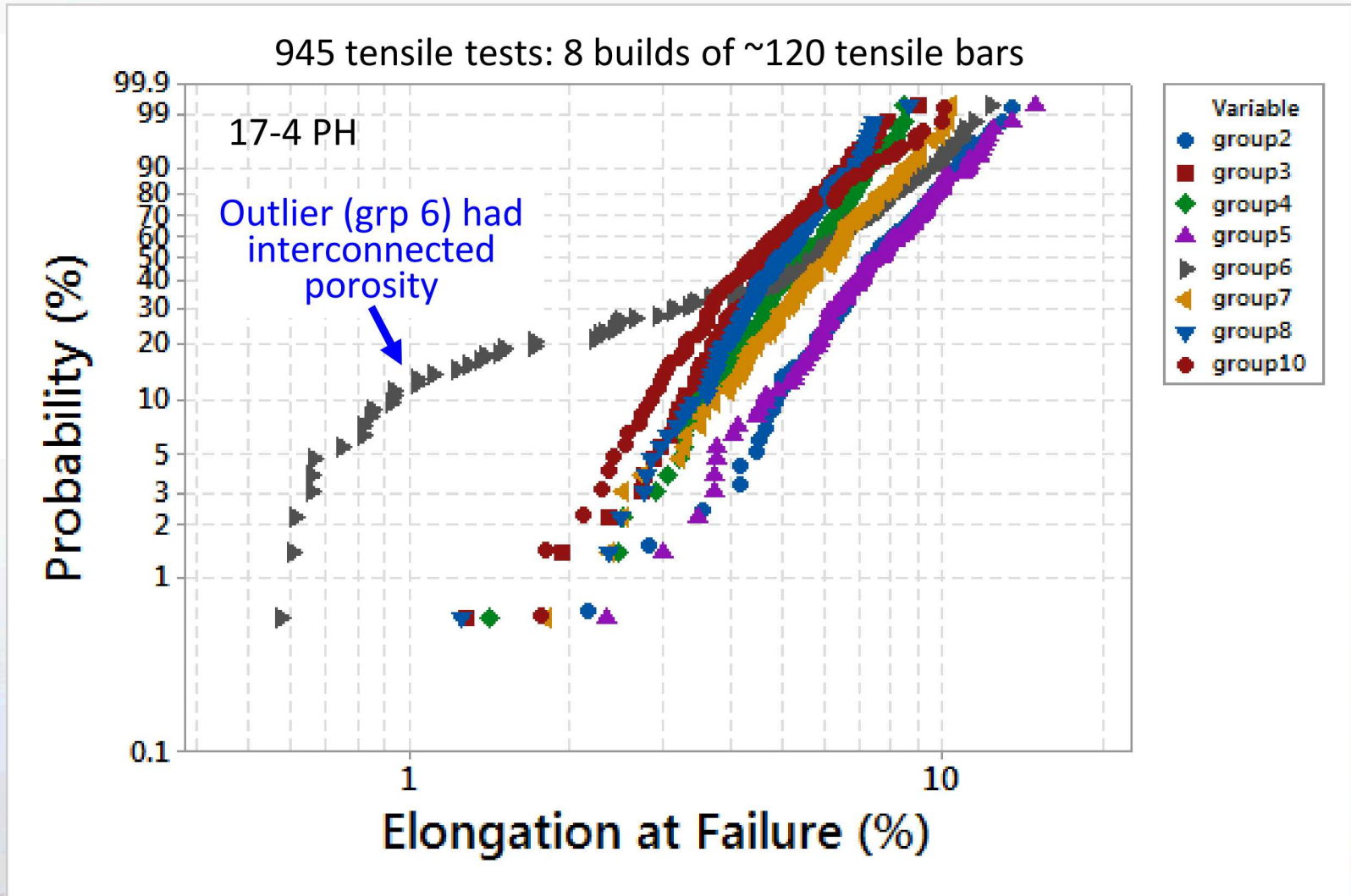


Failure at 2% elongation

# 945 Tensile Tests from 8 Nominally Identical 17-4 PH Builds

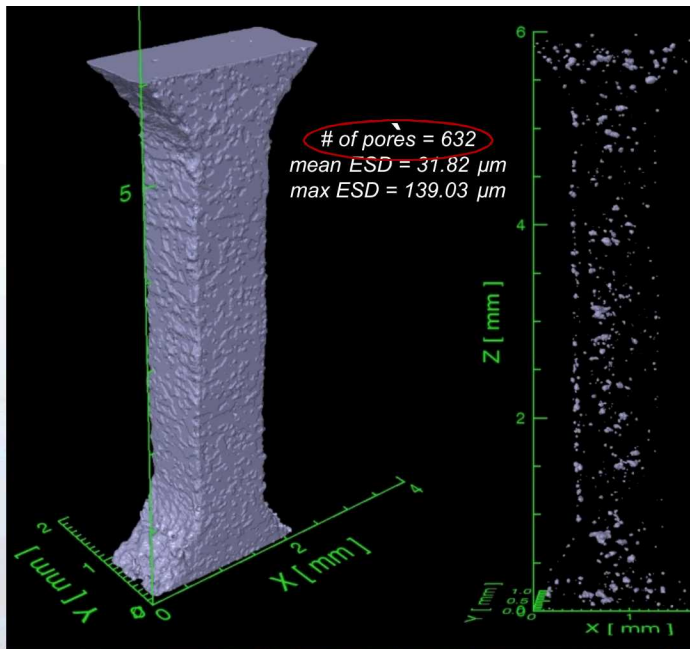
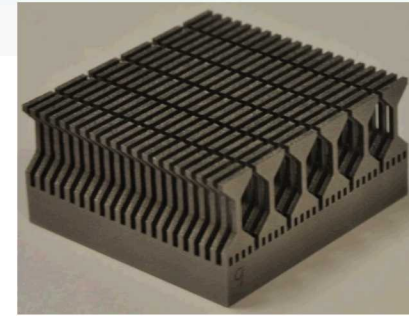


# Weibull Analysis of Variation in Ductility

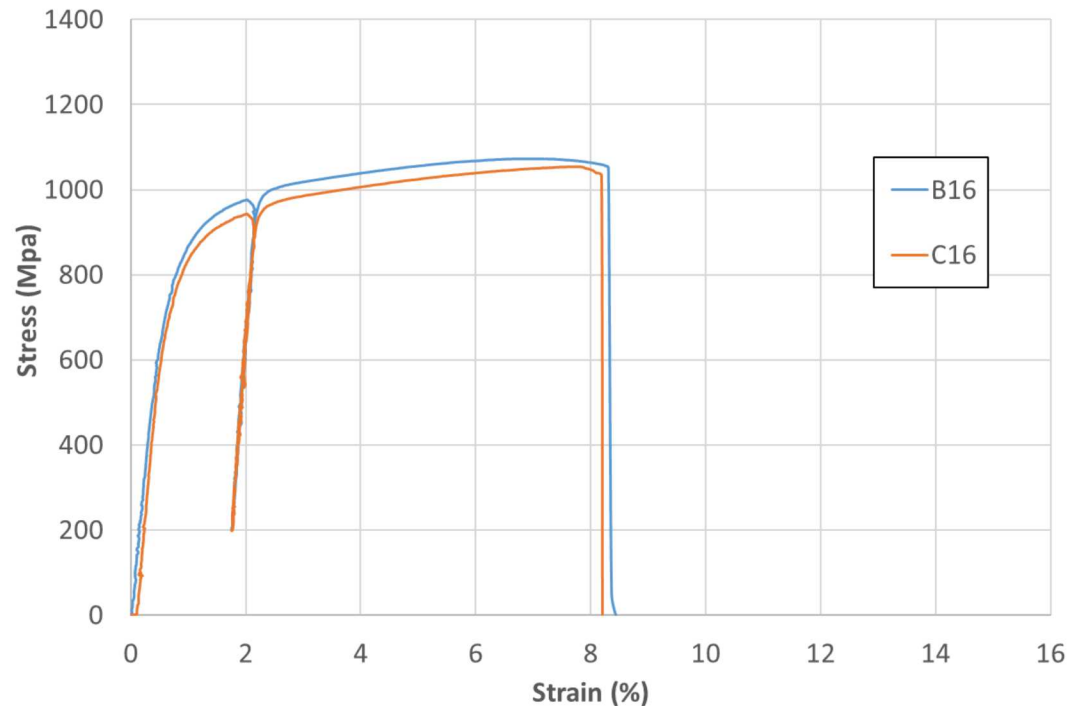


# R&D to Understand Defect Sensitivities and Failure Modes

- AlSi10Mg Dogbones (resolution  $\sim 7$  -10  $\mu\text{m}$  voxel edge length)
- 632 vs. 1124 similar size pores
- Very similar tensile test results; Why ???

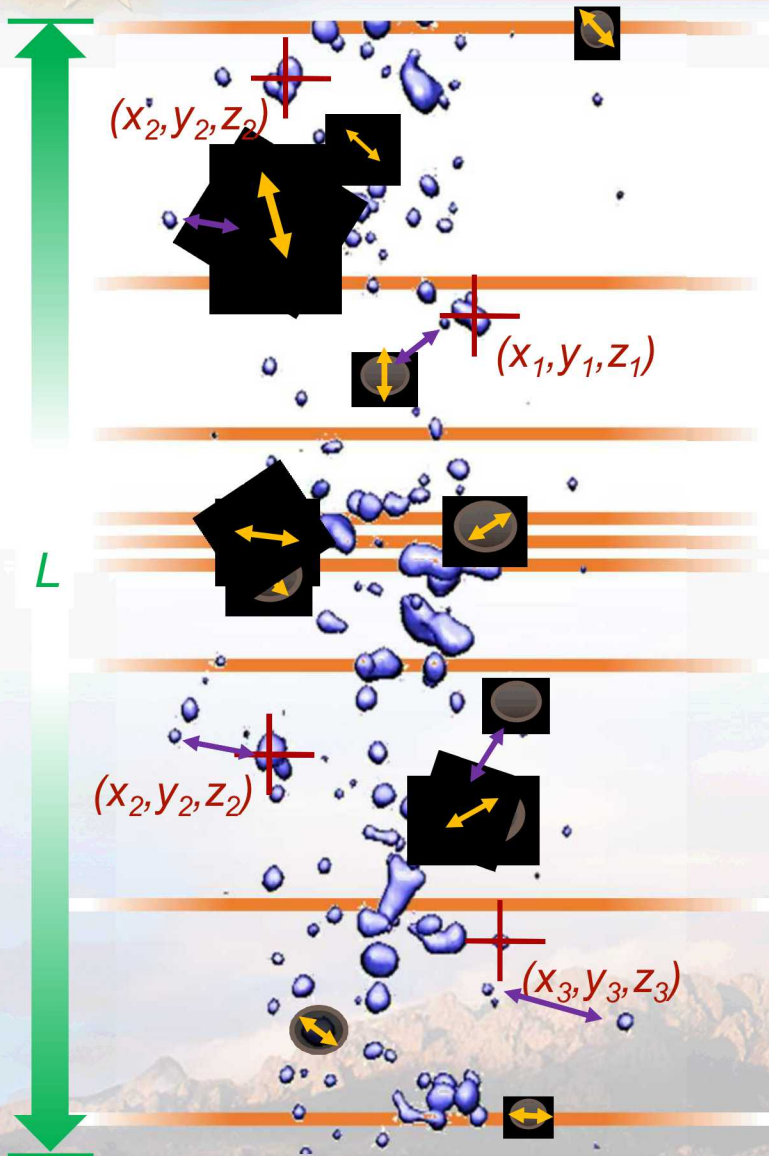


dogbone B,16 CT surface image (left), porosity map



ESD = equivalent spherical diameter

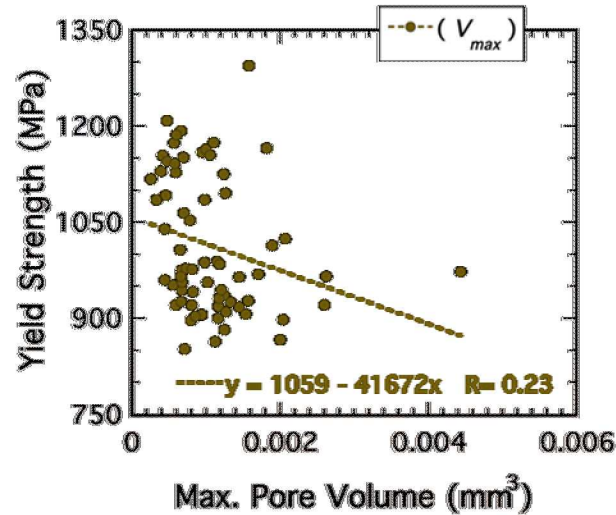
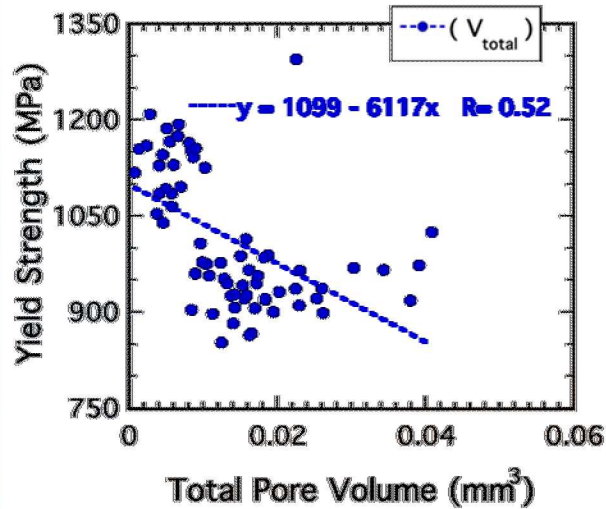
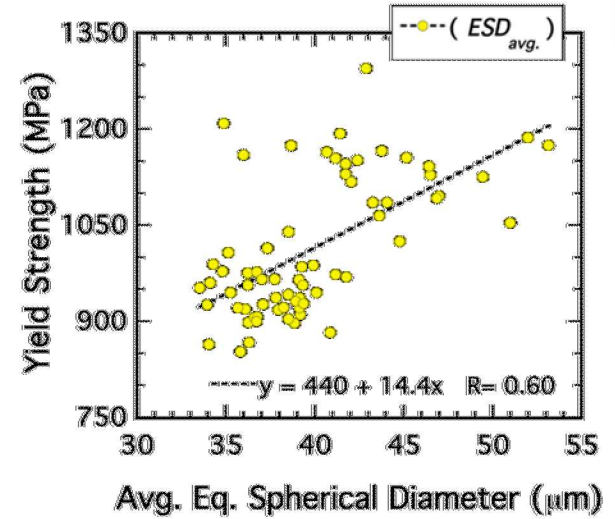
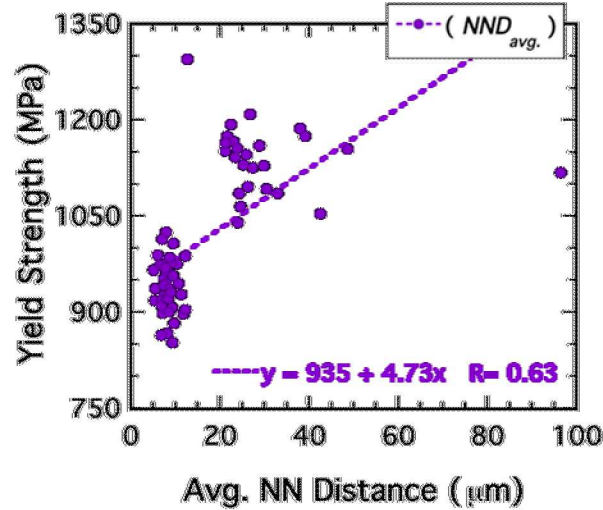
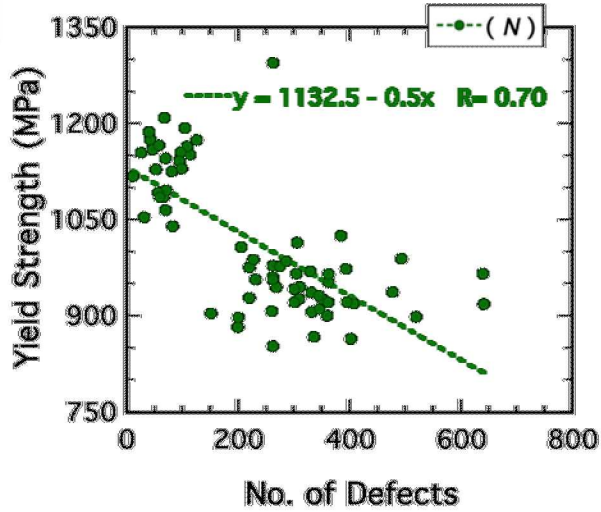
# Can We Find Defect/Property Correlations?



- Total Volume of Defects ( $V_{tot}$ )
- Pore Volume Fraction ( $V_{fract}$ )
- Spatial Location of Pores ( $x, y, z$ )
- Total Number of Defects ( $N$ )
- Total Defects/Length ( $N/L$ )
- Average Defect Volume ( $V_{avg.}$ )\*
- Average Equivalent Spherical Diameter ( $ESD_{avg.}$ )\*
- Average Cross-Sectional Area ( $CSA_{avg.}$ )\*
- Average Nearest Neighbor Distance ( $NND_{avg.}$ )\*

How do we *best* represent the defect populations present?

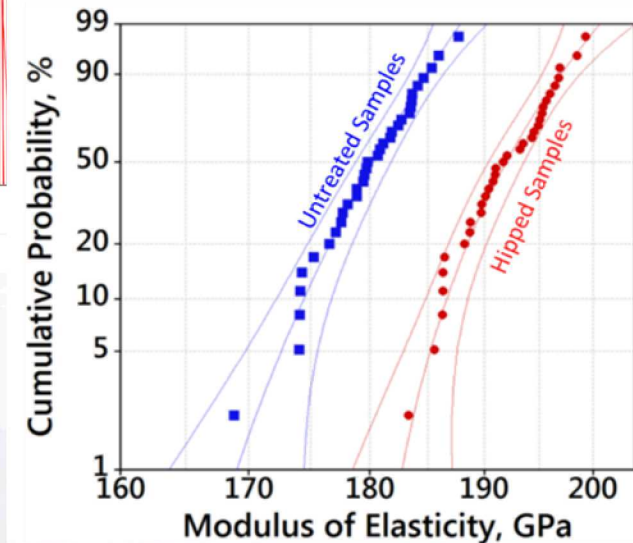
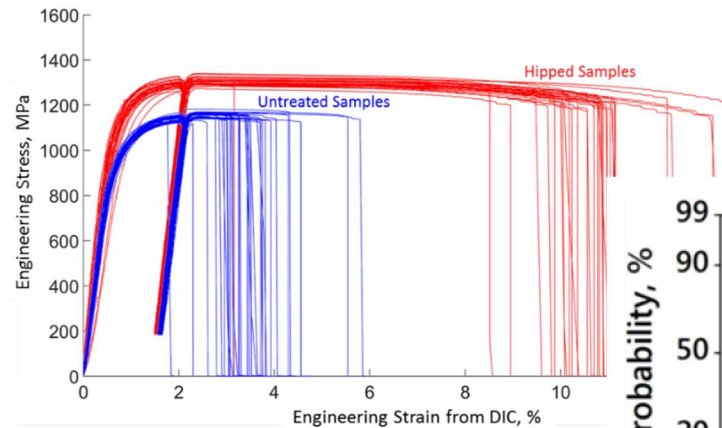
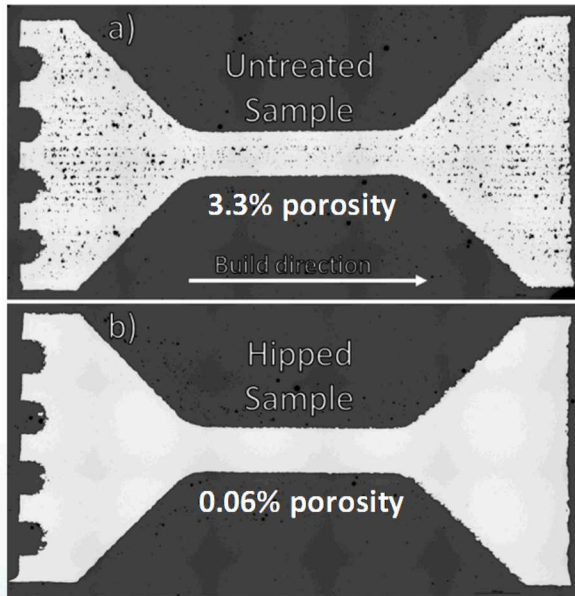
# Statistical Correlations Are Elusive



Measure	R <sup>2</sup>
No. of Defects	0.50
Avg. NN Distance (mm)	0.40
Avg. ESD (mm)	0.36
Max CSA Redux ( $\text{mm}^2$ )	0.38
Total Pore Volume ( $\text{mm}^3$ )	0.27
Avg. Defect Vol. ( $\text{mm}^3$ )	0.25
Max CSA Redux (%)	0.24
Maximum Pore Size	0.07
Seven factor multivariate regression	0.60

# HIP Process Improves Properties...

HIP Treatment: 1120°C+100MPa for 6 hr



A rule of mixtures model effectively predicts the average effect of porosity on modulus

$$E_p = E_0 * (1 - a * P)$$

$$a = 1.9 \text{ [Choren et al, J. Mater Sci, 2013]}$$

$$E_0 = 195 \text{ GPa}$$

$$\Rightarrow E_{0.06\%} = 195 \text{ GPa}$$

$$E_{3.3\%} = 183 \text{ GPa}$$

# Sandia Metal/Multi-Material AM Process R&D

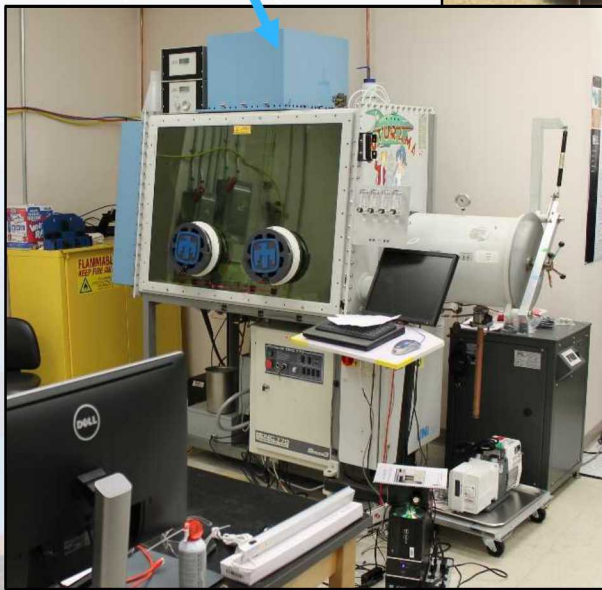
3D Systems ProX 200 Laser Metal Powder Bed Machine



Aspex Explorer SEM-based powder particle analyzer

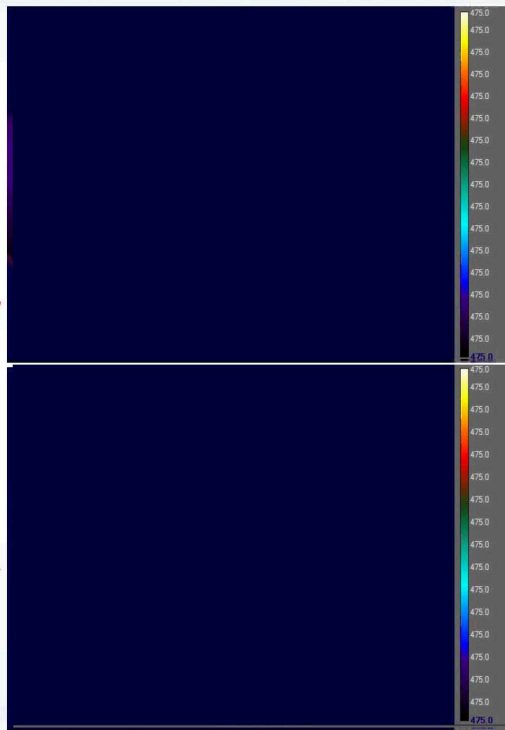
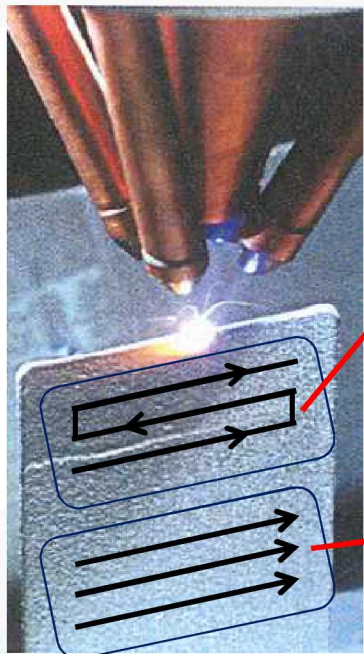


Next Generation Custom Built Hybrid LENS™ System

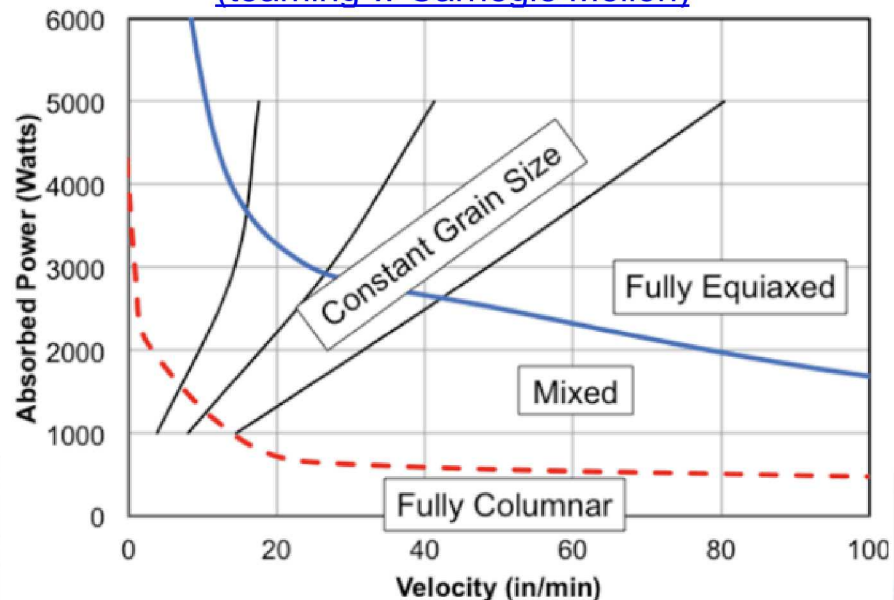


Haas VF2 mill-turn machine will be Modified for Multi-Material hybrid AM, including LENS™

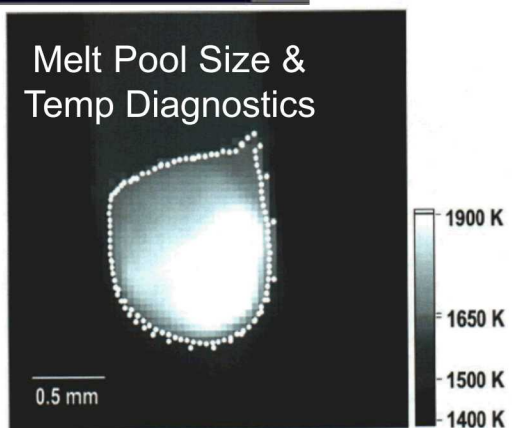
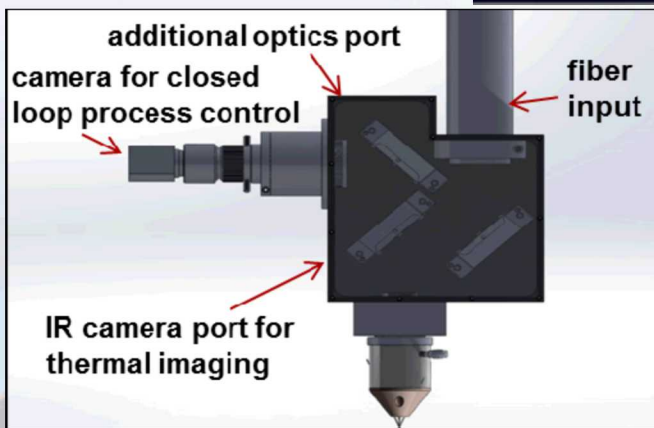
# Working to Understand LENS™ Processing-Microstructure Relationships



## Processing-Microstructure Relationships (teaming w Carnegie Mellon)



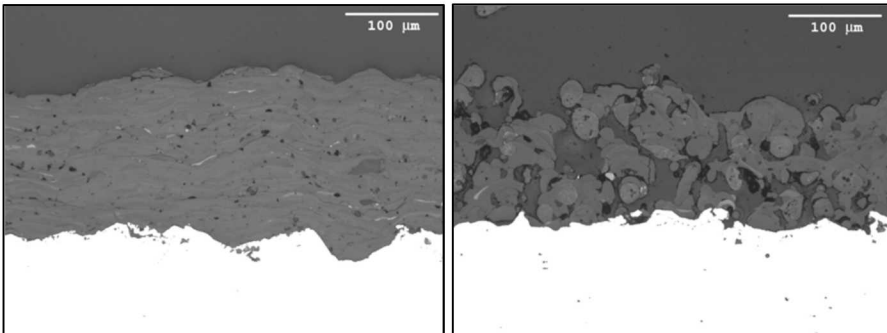
J. Gockel et al. / Additive Manufacturing 1-4 (2014) 119-126



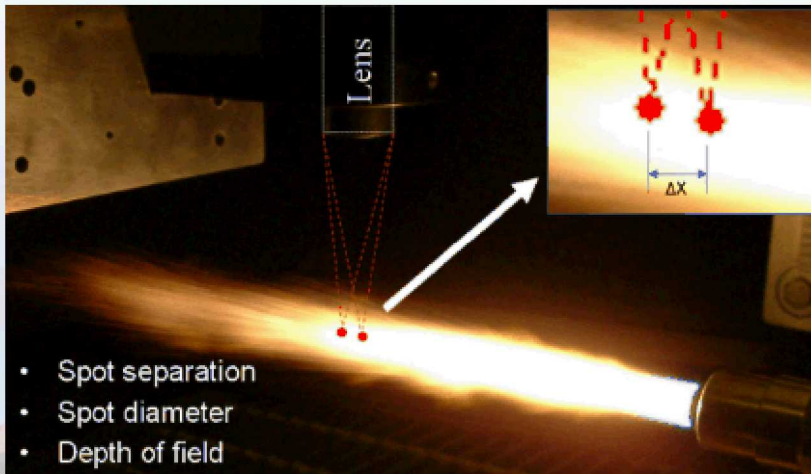
Control melt pool size & temperature to create desired microstructure and reduce variability

# Fundamental Process Understanding is Key to Controlling Variability

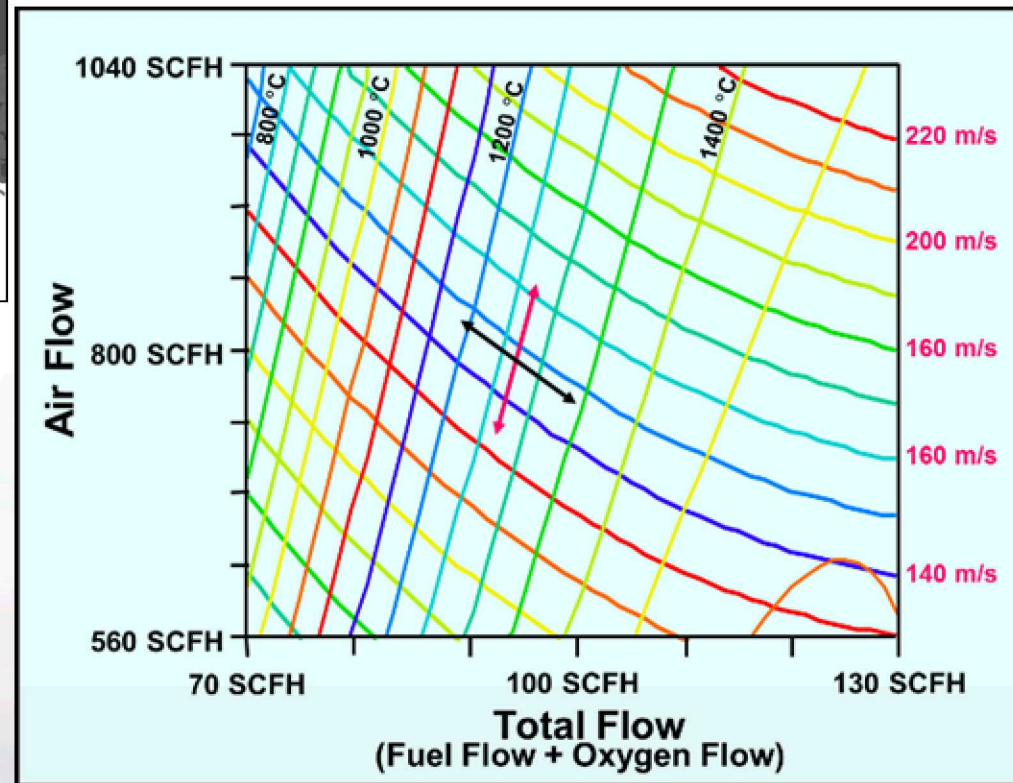
- Thermal spray process used to run open-loop with high variability in the resulting materials



- Experimental/computational R&D used to develop processing-microstructure-properties relationships



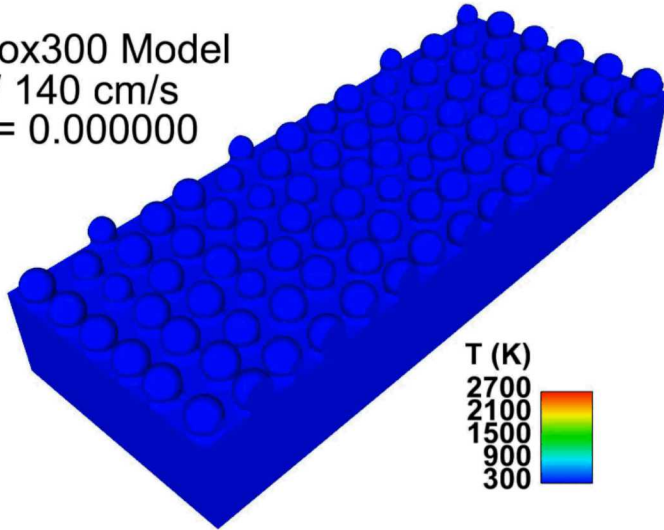
- Fundamental process understanding used to implement closed-loop control based on droplet temperature and velocity to reduce variability



Response surface showing relationships between Process Inputs (Air Flow, Fuel Flow, Oxygen Flow) and Critical Outputs (droplet temperature, droplet velocity)

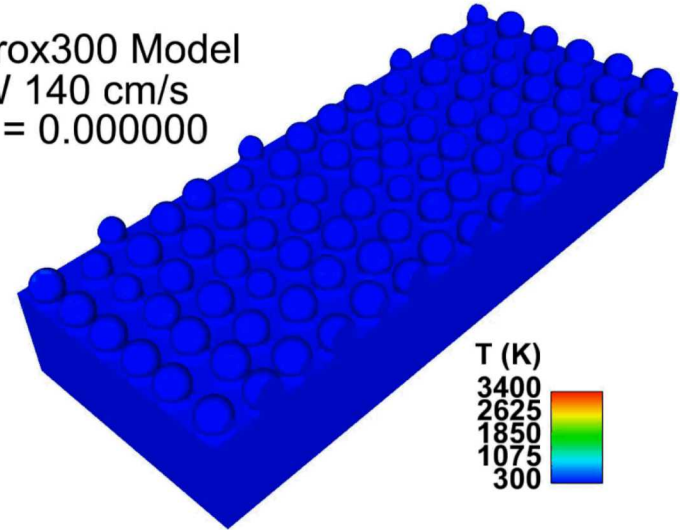
# Process Modeling Can Provide Useful Insights

SNL Prox300 Model  
25W 140 cm/s  
Time = 0.000000



Stainless steel 304L  
25 micron powder

SNL Prox300 Model  
50W 140 cm/s  
Time = 0.000000

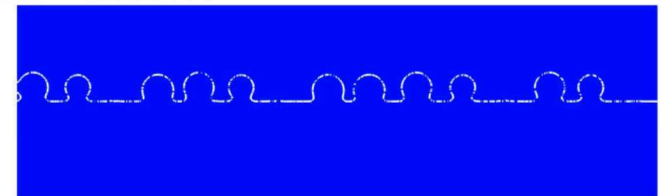


## Notes:

- 500 micron powder bed traversed in 357 microsec
- Sloshing-driven gas dynamics entrains ambient gas

## Gas and melt pool dynamics

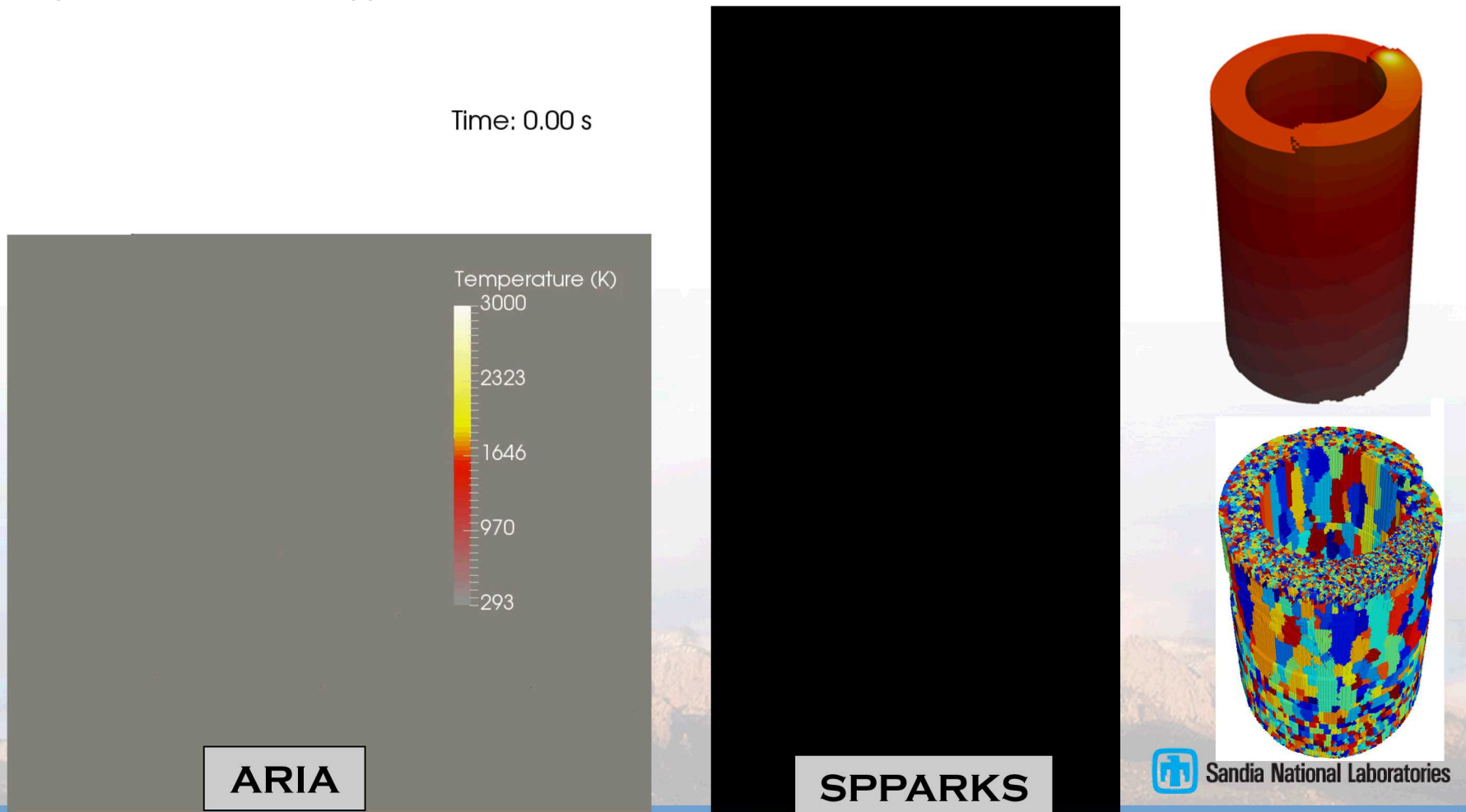
Time = 0.000000



T (K)  
3400  
2625  
1850  
1075  
300

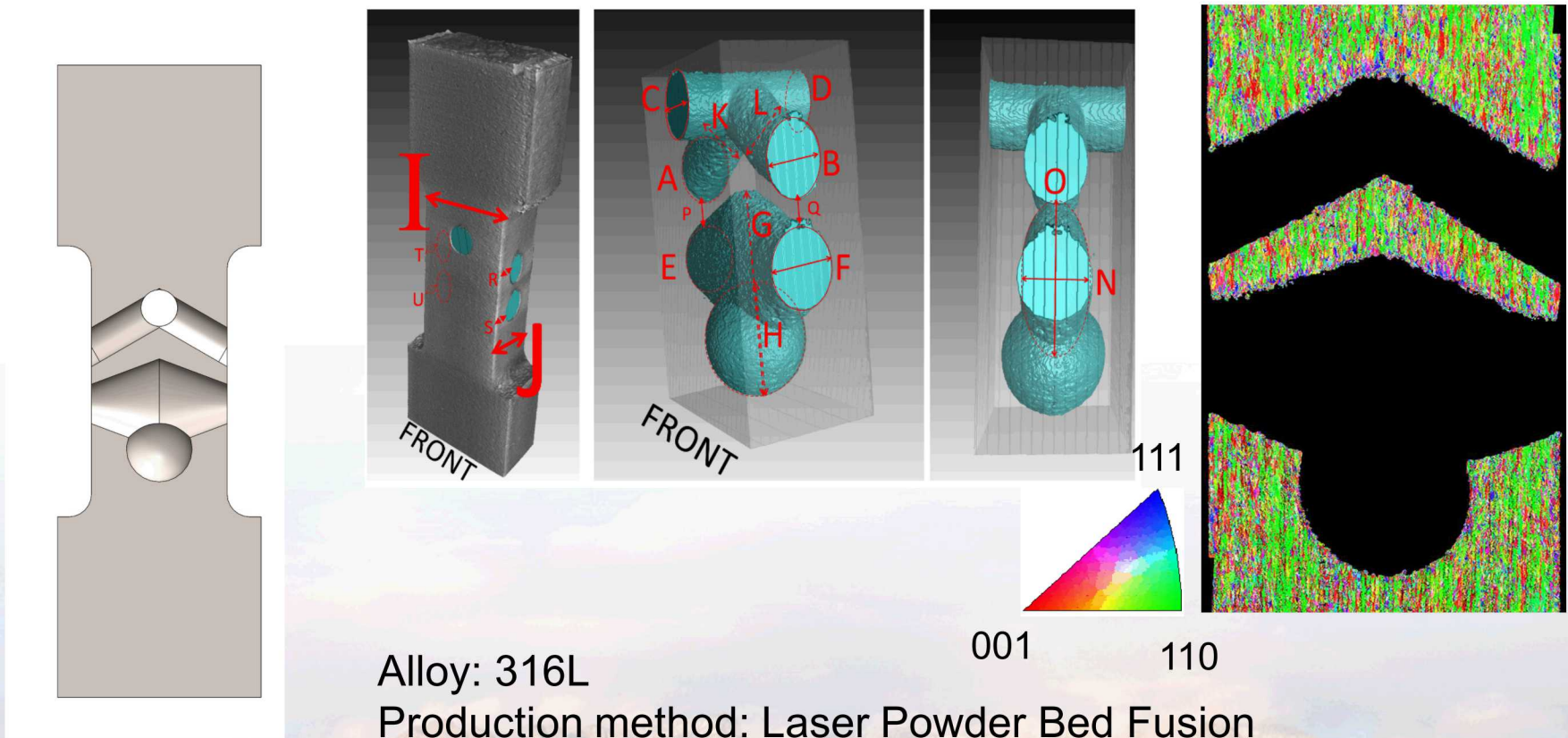
# Linking to Thermal Models

- Using thermal histories from SNL's ARIA code as an input, a modified Monte Carlo Potts model within SPPARKS is coupled to predict grain morphologies in an additive manufacturing build.
- This demonstrates an ability to predict grain morphology from a rigorous multi-physics model as opposed to a simplified and idealized approximation of the molten zone.



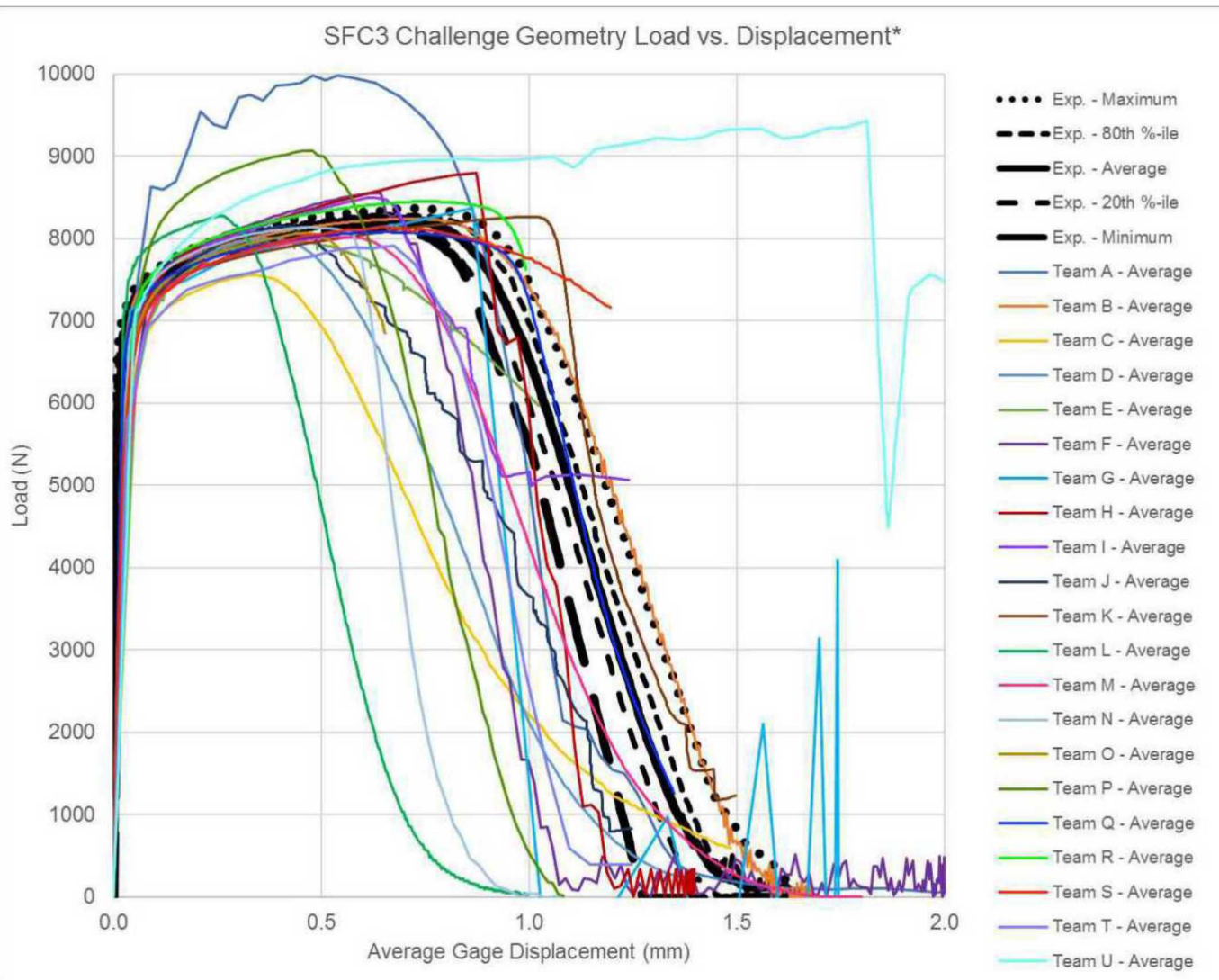
# Sandia's Reliability Prediction Competition "Fracture Challenge"

Provided with tensile data, CT data, roughness, microstructure, etc,  
**predict** the conditions (force, displacement) for fracture...



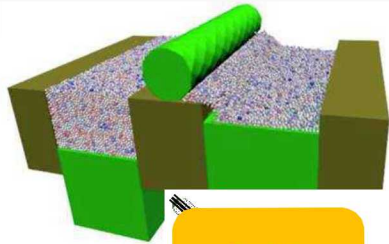
How well can standard methods (Finite Element) predict AM reliability?

# Only 2 of 21 Team Predictions Fell Within The Bounds of the Experimental Data (Teams B & Q)



- More teams under-predicted the failure displacement than over-predicted.
- Only two teams nominal prediction fell within the bounds of experimental data (Teams B and Q).

# Ultimate Vision is to Understand/Control Process → Microstructure → Properties → Performance



Particle packing

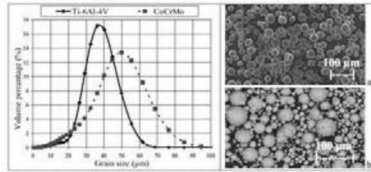
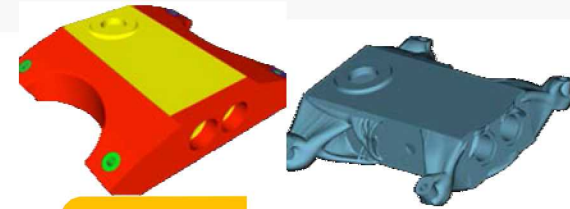
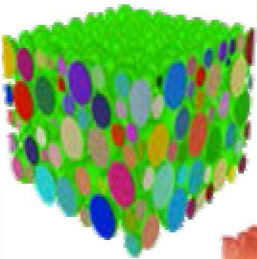


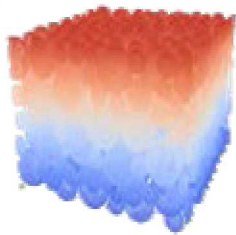
Fig. 1: Grain size distribution and micrographs of titanium (a) and cobalt-chromium (b) powder.



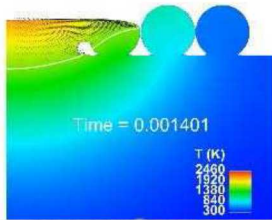
Topology Design



Heat Transfer

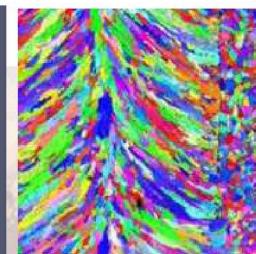
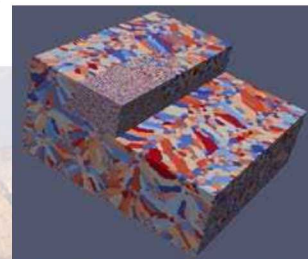
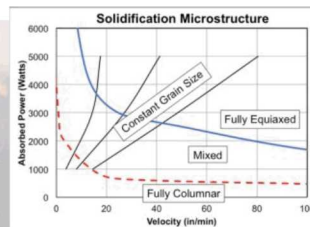


Partial melt & flow

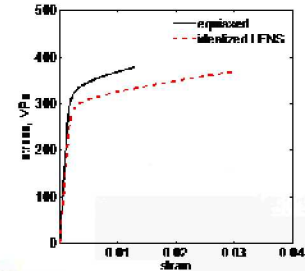


Molten pool dynamics

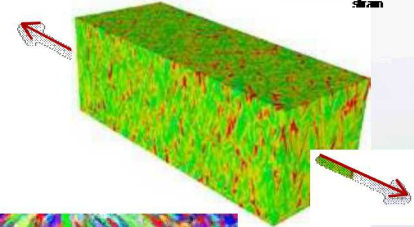
Solidification

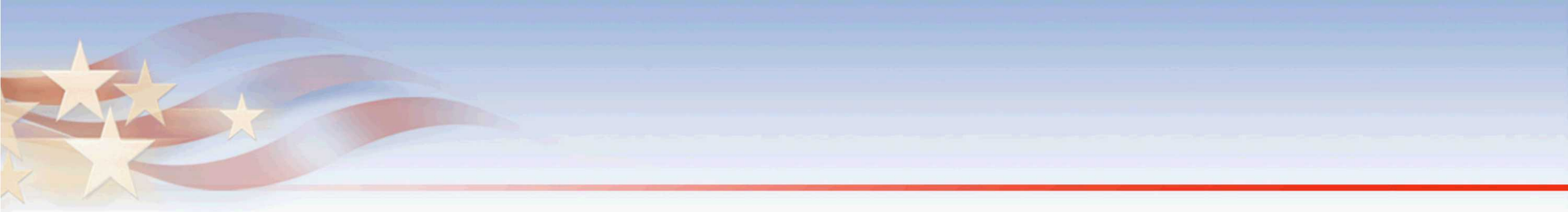


Property-Performance



Microstructure



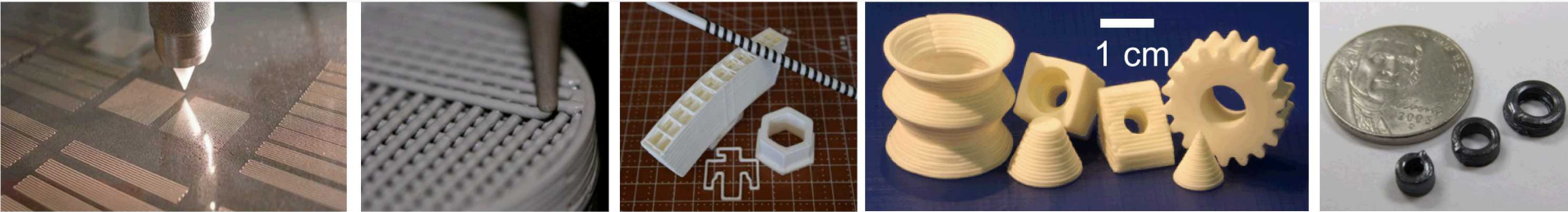


# Multi-Material AM

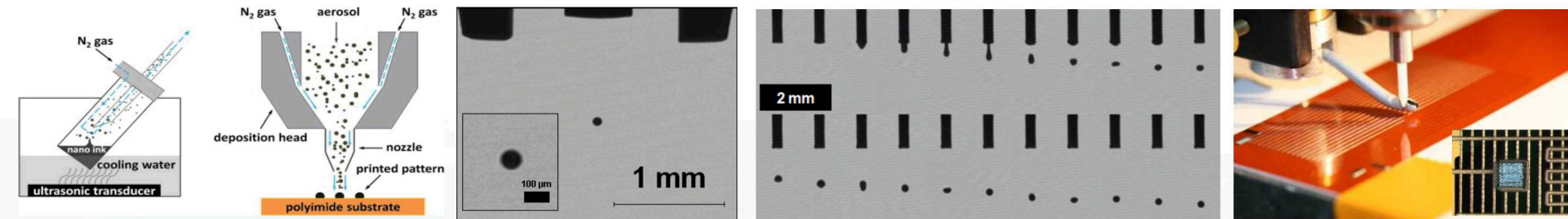


# Direct Write Technologies Enable Access To Materials Not Supported By Conventional Printing Processes

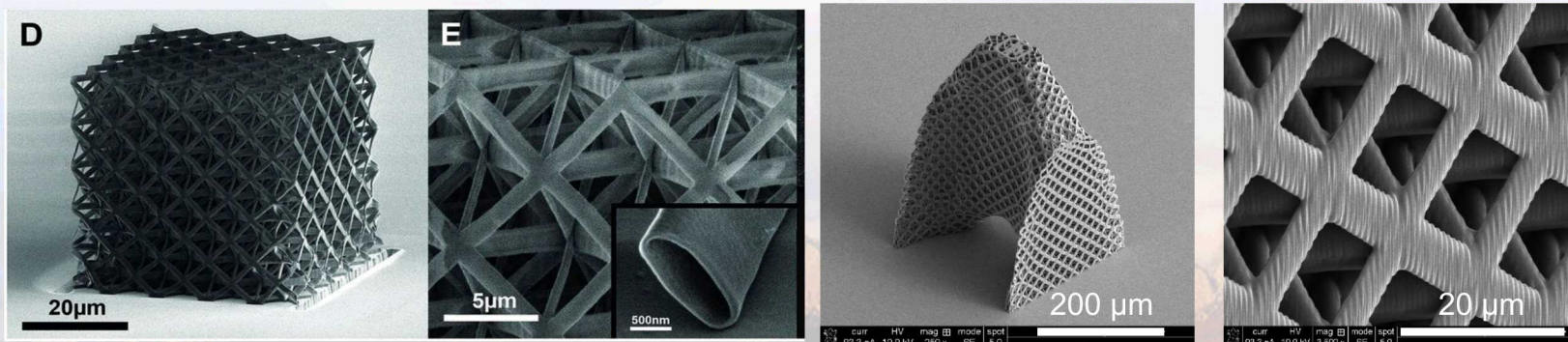
## Direct Write by Extrusion Casting (Robocasting)



## Direct Write by Aerosol & Ink Jet Deposition



## Direct Write by Laser Photo-Lithography



# From Nano-Materials to Components at the Sandia Advanced Materials Lab

Solution Precipitation



Solvothermal



Specialty Precursors

Specialized Nanomaterials

Specialty Inks

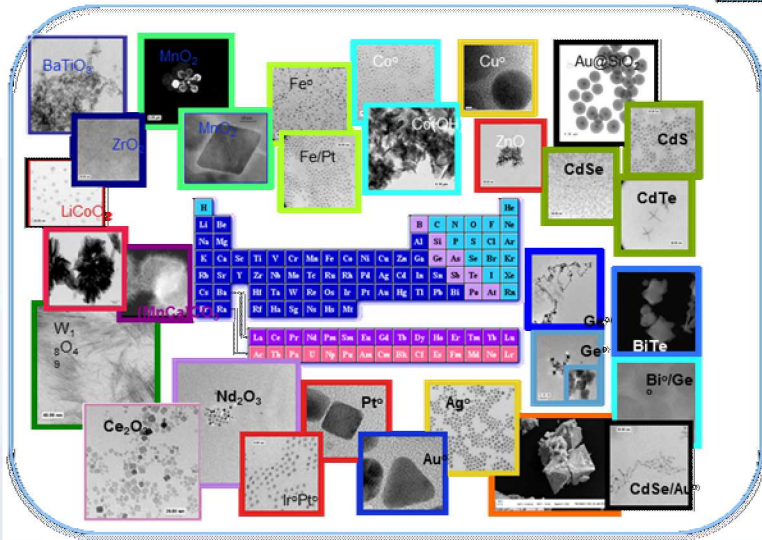
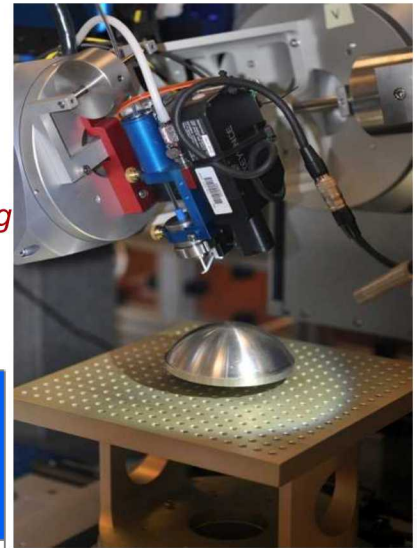


Colloidal Chemistry

Ink Characterization

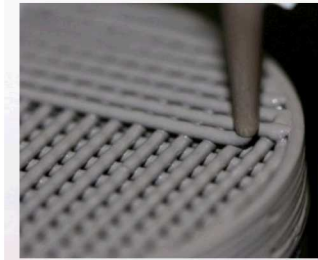
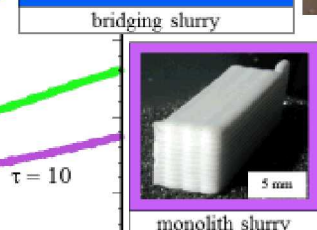
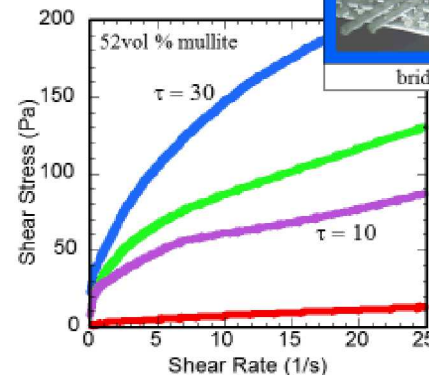
Process Engineering

Direct Write Printed Parts



Influence of paste rheology

Shear yield stress controls print morphology.







Rheology Tailoring

Aerosol, Inkjet, extrusion

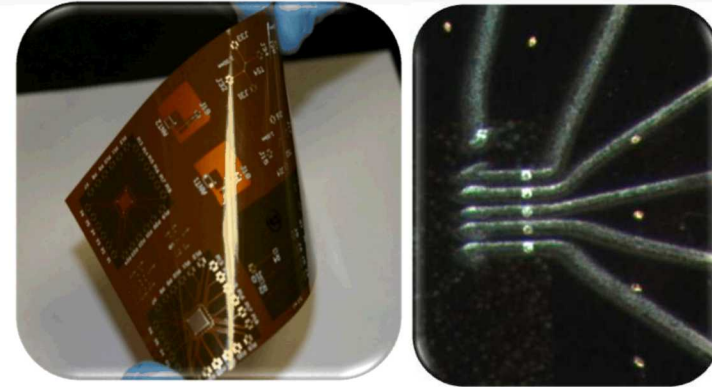
From specialized, tailored nano-materials to process-able inks requires chemical synthesis, colloidal chemistry, rheology/characterization, process engineering

# Sandia's Strong Capabilities/Expertise In Printed Electronics Extend to Device Level

-  Printed Encapsulant
-  Current Collector
-  Printable Separator
-  Printed Anode/Cathode

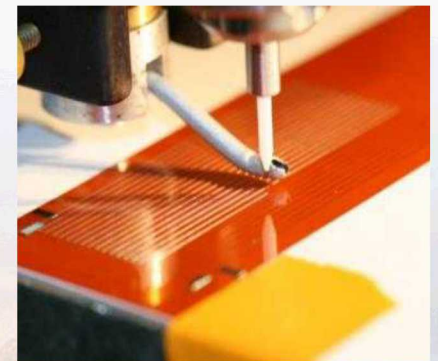
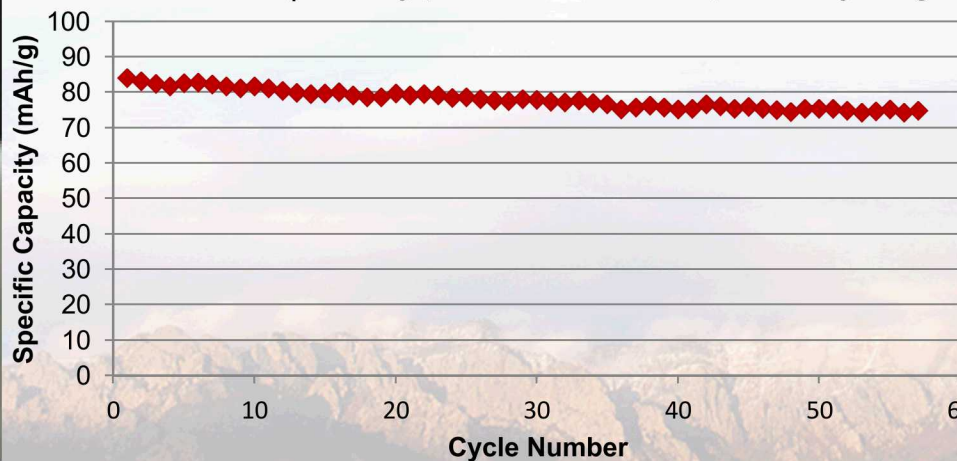
## Printed flexible battery

- Encapsulant (DW UV-curable epoxy)
- Current collector (DW carbon ink)
- Anode (DW graphite/carbon)
- Separator (DW mesoporous polymers)
- Cathode (DW LiFePO<sub>4</sub>)
- Current collector (DW copper ink)
- Substrate (polyimide)



"Flexible Chips" with printed wirebonds

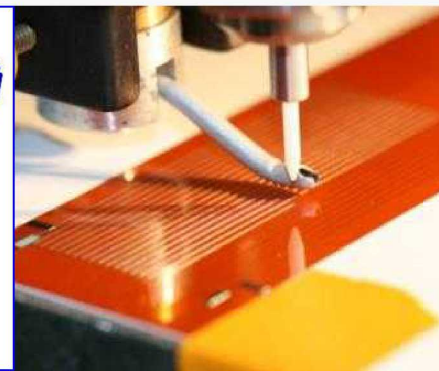
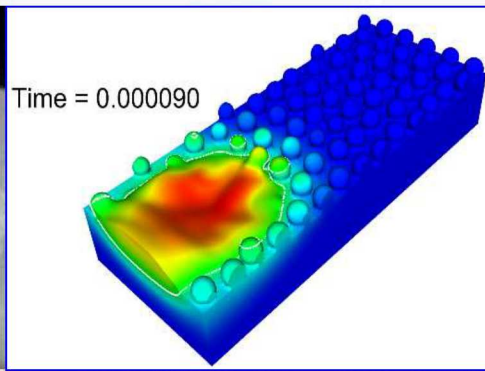
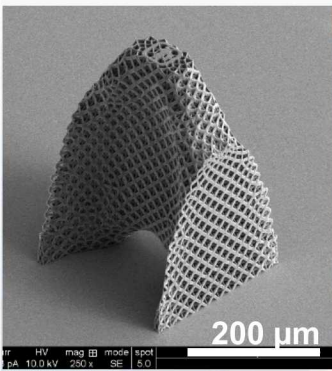
## LiFePO<sub>4</sub> Battery performs well in repeated cycling



Aerosol jet printing to 10 μm

# Summary

- Sandia has a rich history in AM technology development & commercialization
- Special interest in Design for AM, Materials Reliability, & Multi-Material AM
- Strong, uncommon, experimental and computational capabilities
- Strong interest in teaming with others in areas of mutual interest





# Questions???

Dr. Mark F. Smith

Deputy Director For Additive Manufacturing  
Material, Physical, & Chemical Sciences Center

Ph: 505-845-3256 [mfsmith@sandia.gov](mailto:mfsmith@sandia.gov)

