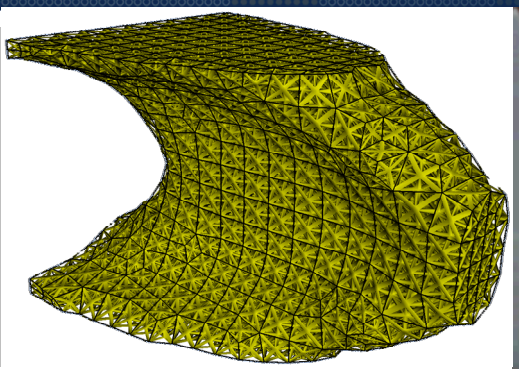
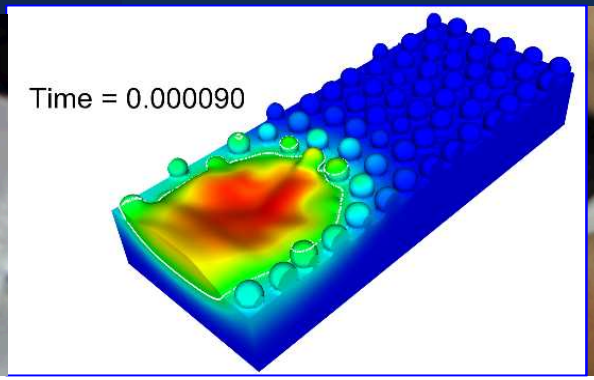
SAND2017-7087PE





Additive Manufacturing at Sandia

Dr. Mark F. Smith
Deputy Director For Additive Manufacturing
Materials Science & Engineering Center
Ph: 505-845-3256 mfsmith@sandia.gov

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

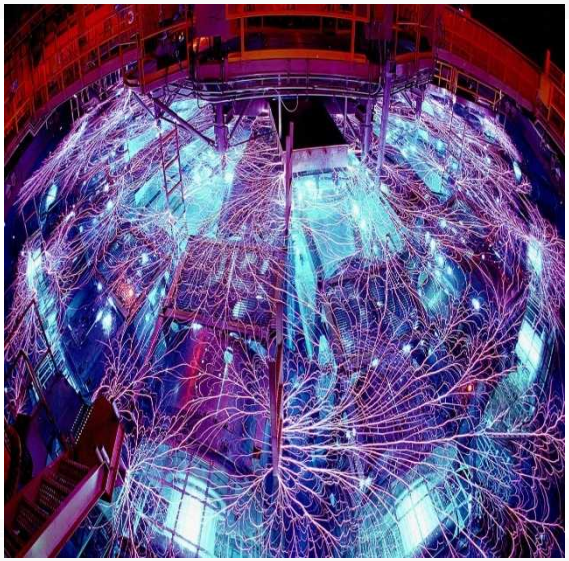
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia is a National Security Science and Engineering Laboratory

Sled Track Test

Albuquerque Labs

Z- Machine



- Historical mission -- non-nuclear components of nuclear weapons & weapon system integration
- Today, much broader mission in applied science & engineering for national security
- ~11,000 employees, ~$3B FY17 Budget

"We work on technologies at a scientific lab, but we must emphasize that science is not an end. The end is solving problems for the nation. Science is perhaps the best tool to achieve that end." C. Paul Robinson, SNL President 1995-2005

Sandia Materials & Process Science

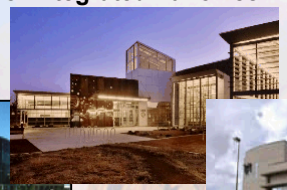
300+ Staff, ~$100M FY17

Activities Range from Basic R&D to Production Support

- *Materials Engineering Support*
  - Materials & process selection/optimization
  - Problem solving, production support
  - Understanding the margins
- *Materials & Process Advanced Development*
  - Advanced & exploratory materials & process development
  - Production process development & technology transfer
- *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

Multiple Large Materials R&D Facilities

Center for Integrated Nano Technologies



Adv. Materials & Processes Lab

Integrated Materials Research Lab

Advanced Materials Lab

Processing & Environmental Tech. Lab

Ion Beam Lab

Thermal Spray Research Lab

Sandia National Laboratories

30+ Years of Sandia AM Technology Development & Commercialization

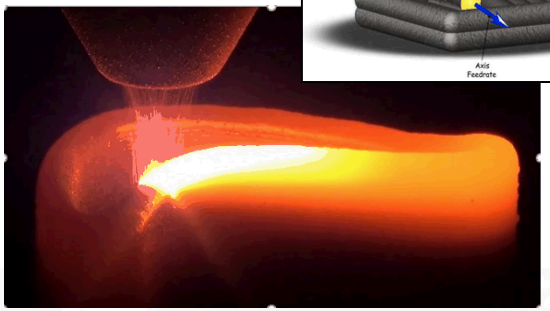
FastCast *

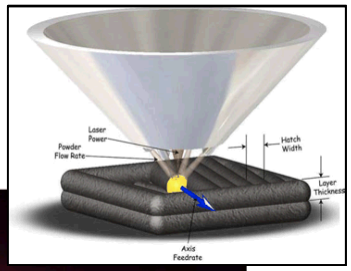
Development Housing

Laser Engineered Net Shaping *

LENS®

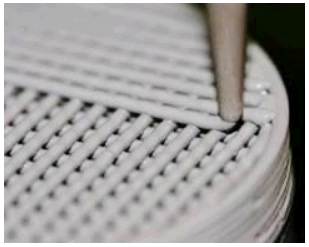
LENS Blade

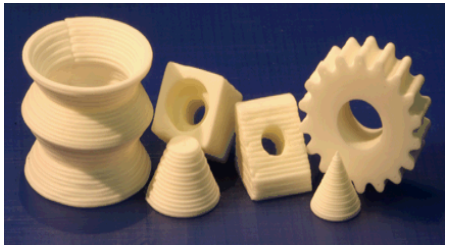




RoboCast *

Ceramic Parts

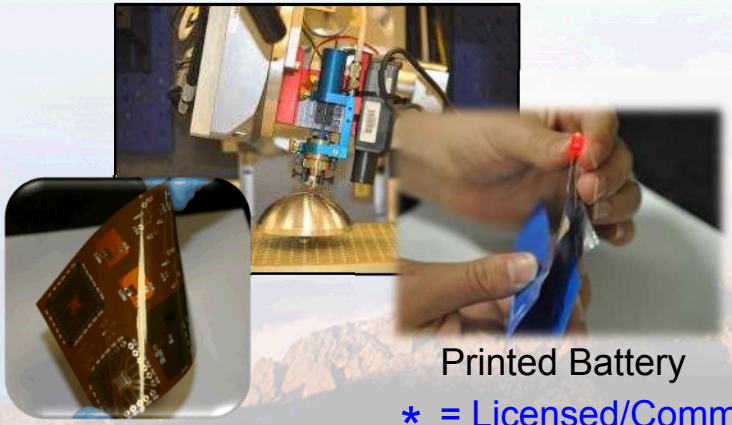




Energetic Materials

Direct Write

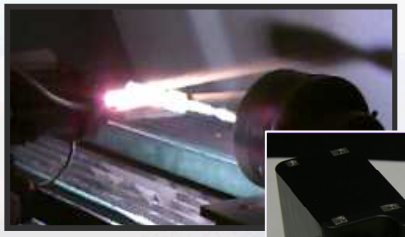
Conformal Printing



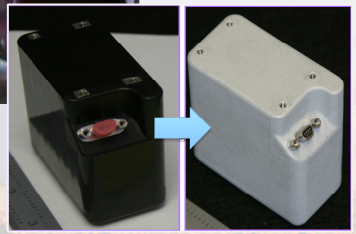
Flexible Electronics

Printed Battery

Thermal Spray



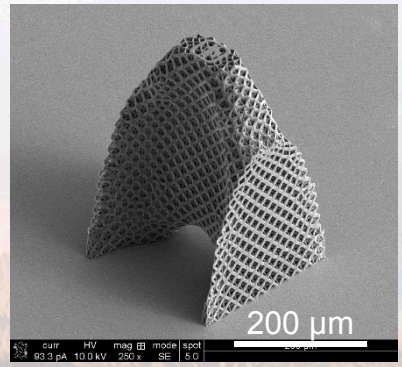
Spray-formed Rocket Nozzle



Metal on Plastic

Micro-Nano Scale AM

Lattice Structure



* = Licensed/Commercialized Sandia AM technologies

Underline = *Current Capability/Activity*

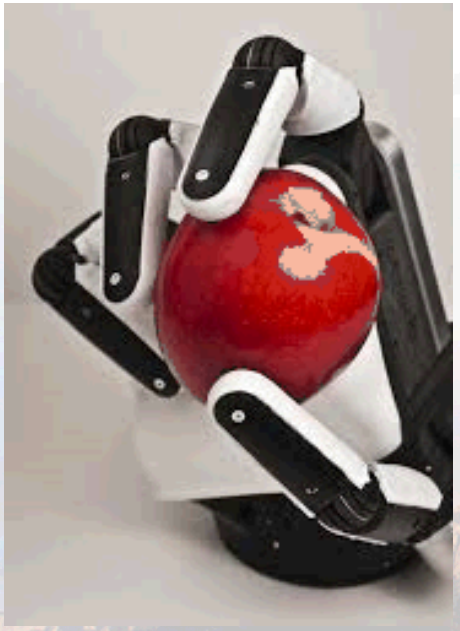
Sandia National Laboratories

Sandia Hand – AM Enabled Innovative Design and Substantial Cost Reduction

(~*50% of hand built with AM*)

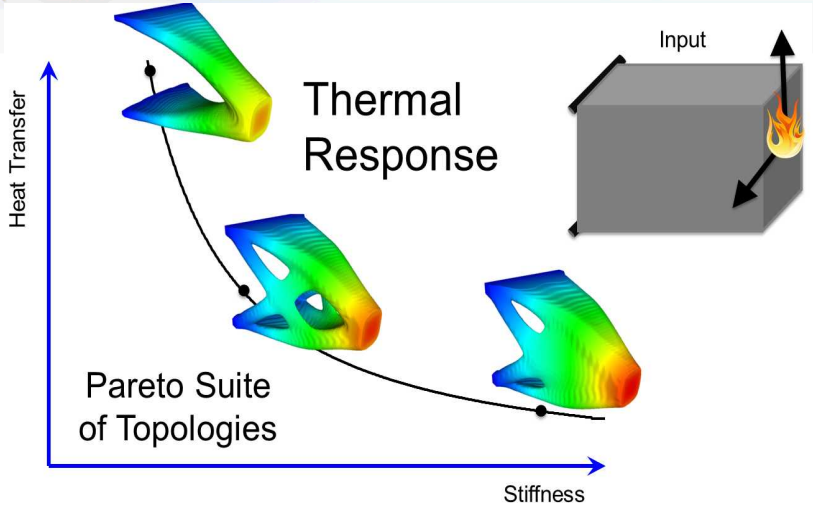
- Developed for bomb disablement
- AM Enabled rapid design iterations
- Cost $10k vs. ~$250k
- “Glove” controller
- One version has “touch” sensors

Fingers or other tools (e.g., drills) can be quickly magnetically attached in many configurations



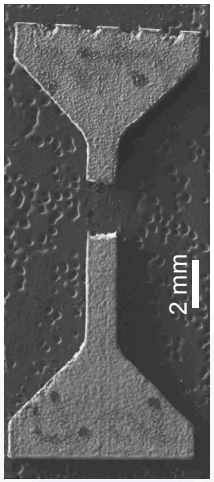
Sandia National Laboratories

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

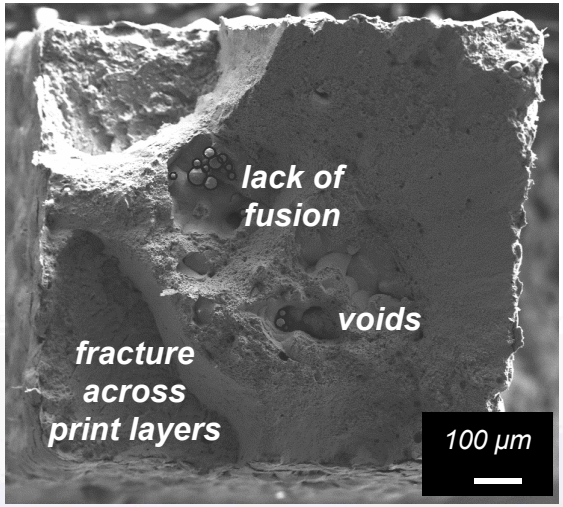


Engineering Analysis Driven Design

(Computer created/optimized AM design)



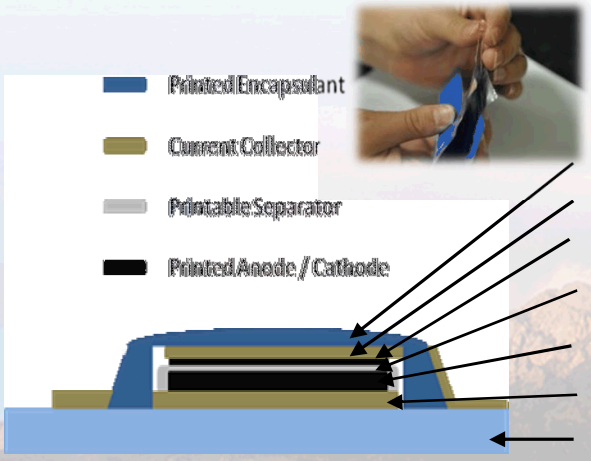
17-8 PH SS, H900, "brittle" fracture



Failure at 2% elongation

Material Assurance

(Assure/quantify reliability of AM materials)



Printed $LiFePO_4$ Battery

Encapsulant (DW UV-curable epoxy)
Current collector (DW carbon ink)
Anode (DW graphite/carbon)
Separator (DW mesoporous polymers)
Cathode (DW $LiFePO_4$)
Current collector (DW copper ink)
Substrate (polyimide)

Multi-Material Additive Manufacturing

(Printed electronics, packaging, ceramics,…)

Sandia National Laboratories

Analysis Driven Design

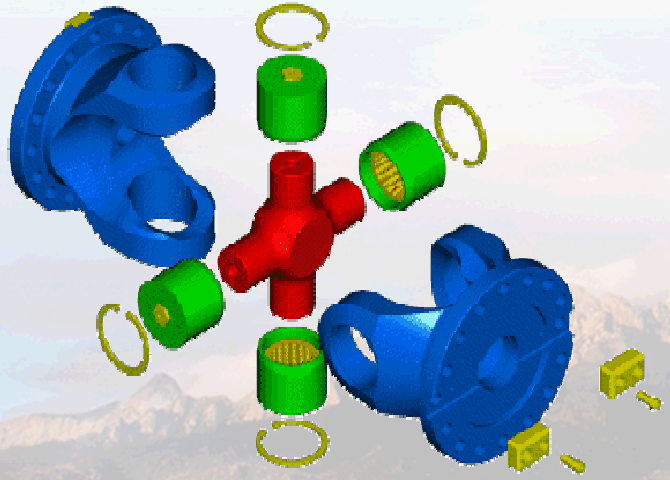
Analysis-Driven Design Optimization

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

"Titanium Cholla" 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!

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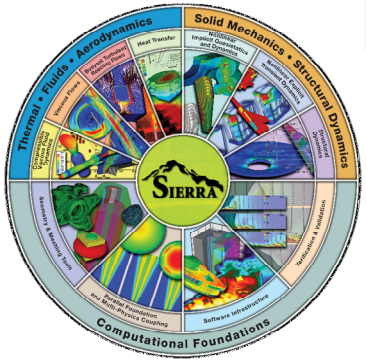
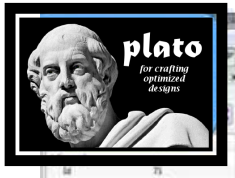
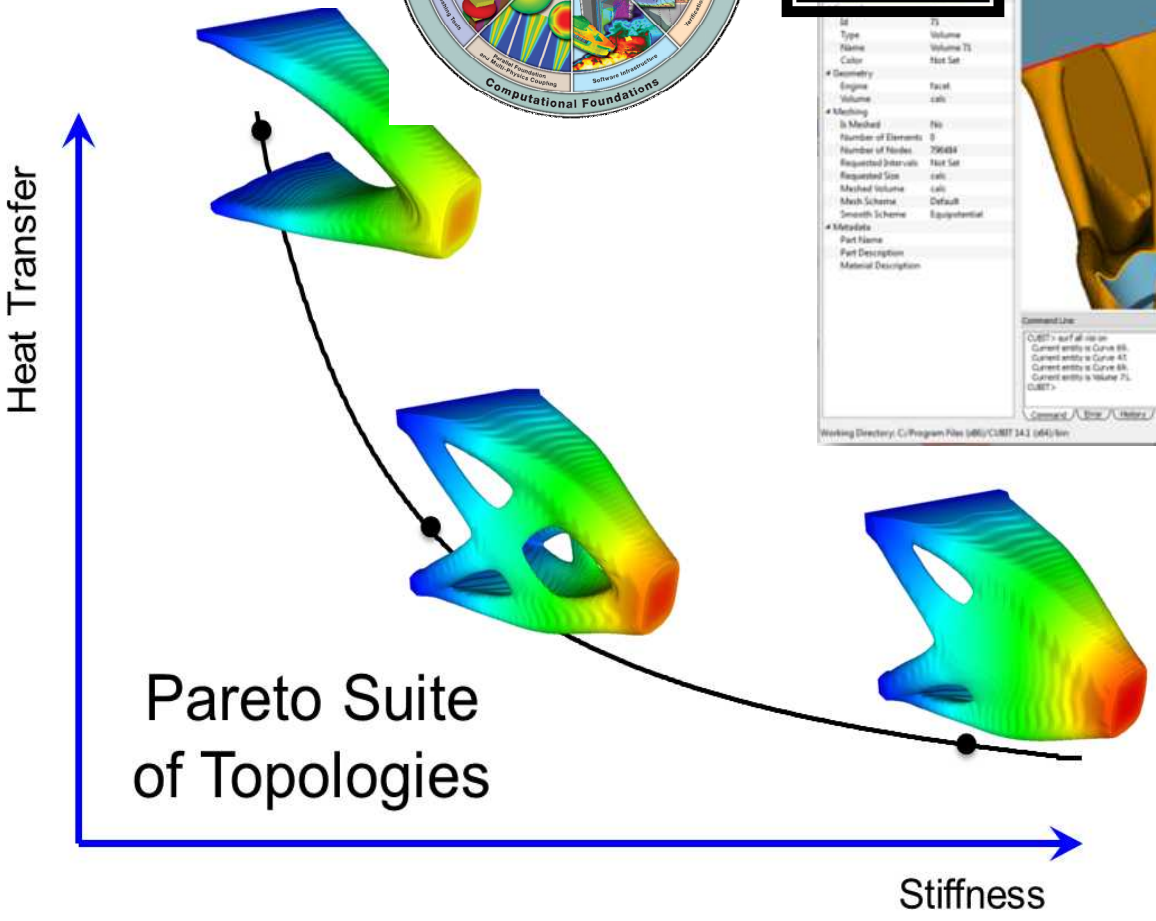
AM Design Via Functional Prioritization

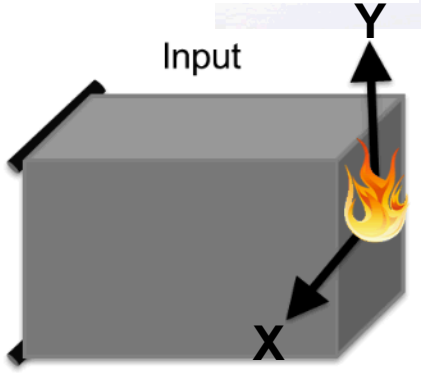


User-Friendly GUI Interface

PLATO - PLAtform for Topology Optimization







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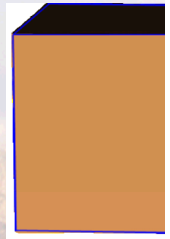
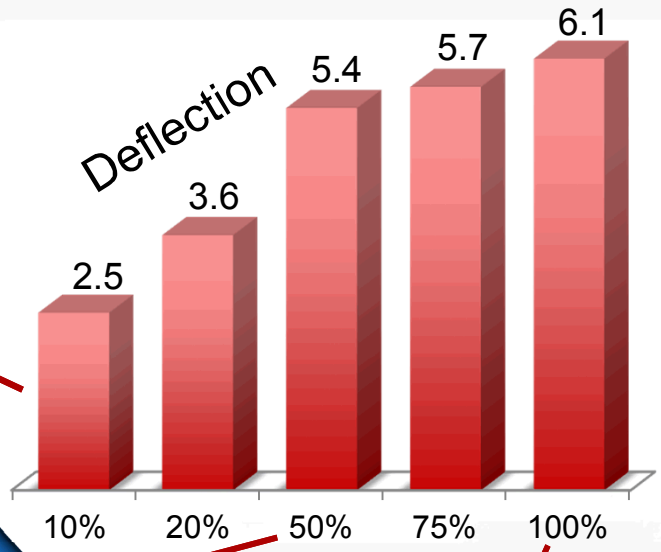
Optimizing Stiffness at Fixed Mass

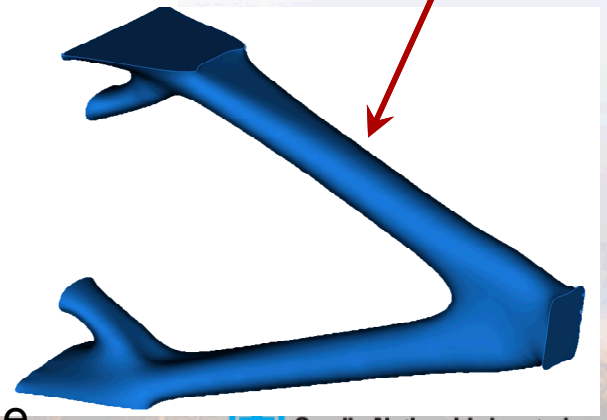
10% Dense

50% Dense



100% Dense





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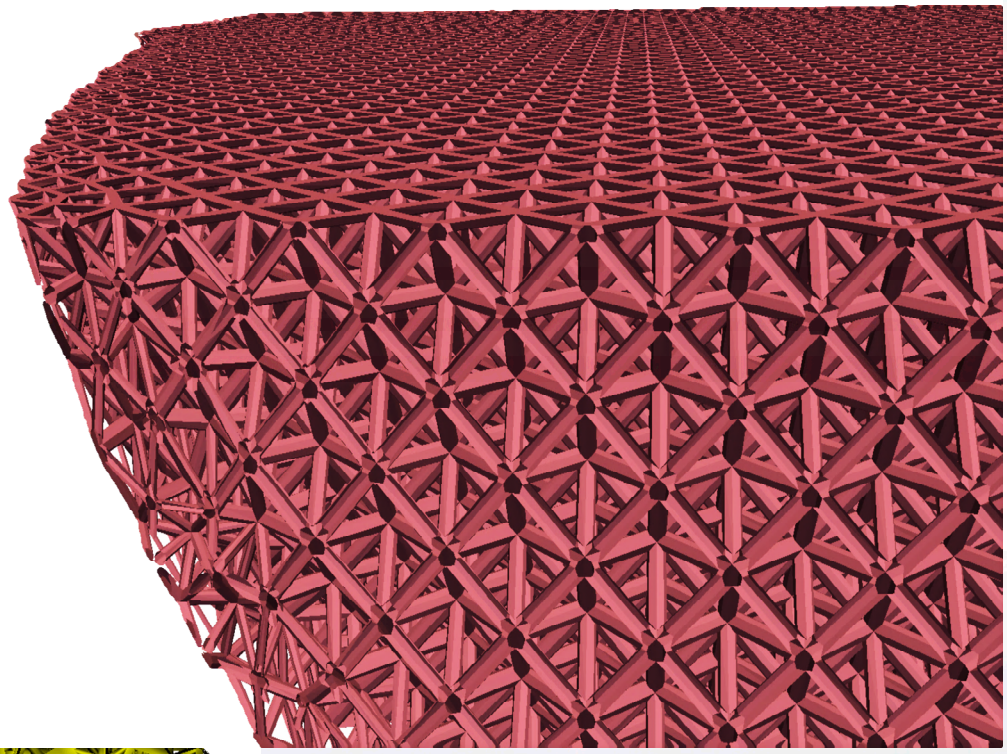
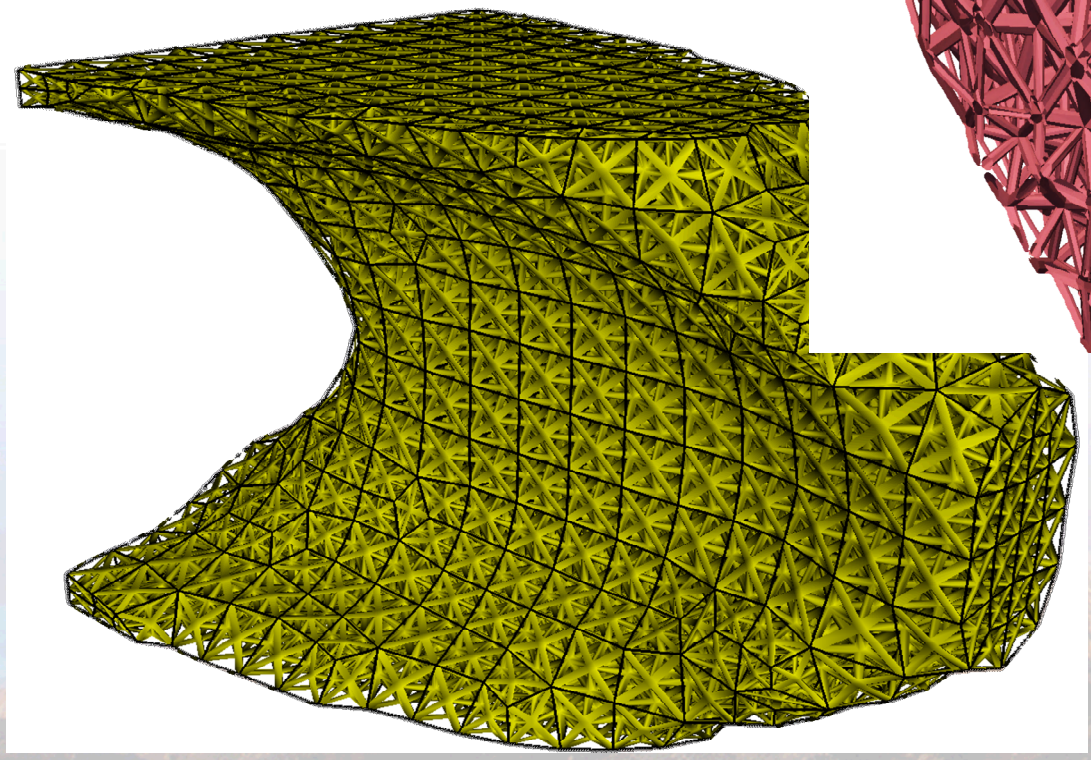
Creating Curved Surfaces with no "Loose Ends"

10% Dense





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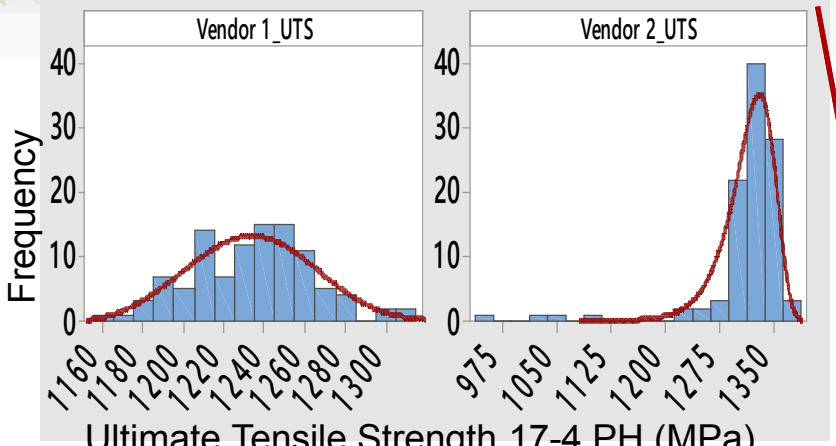
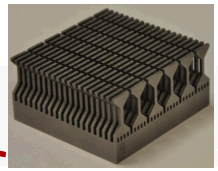
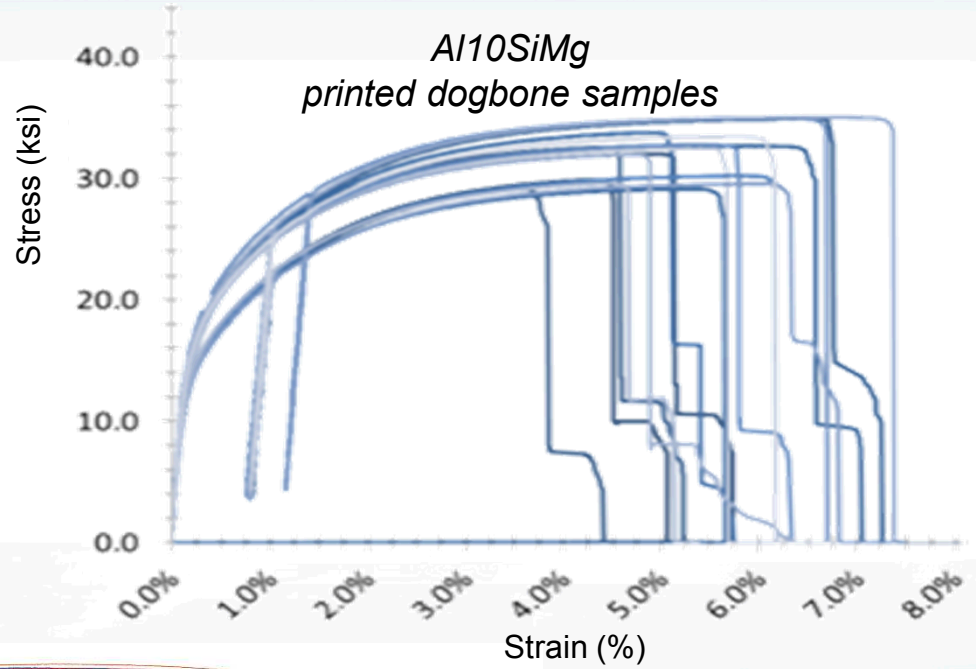
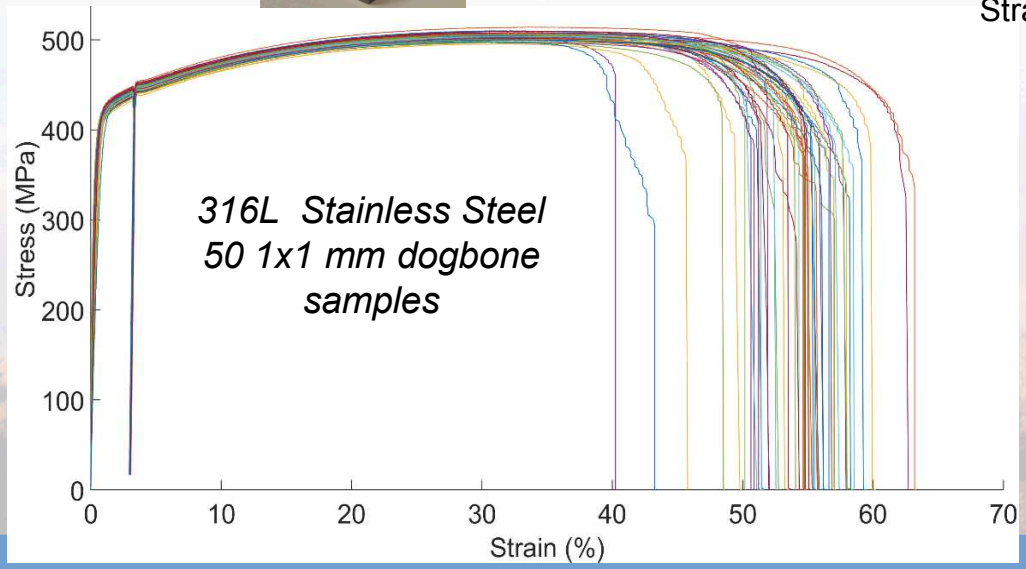
Materials Assurance

Examples of AM Variability









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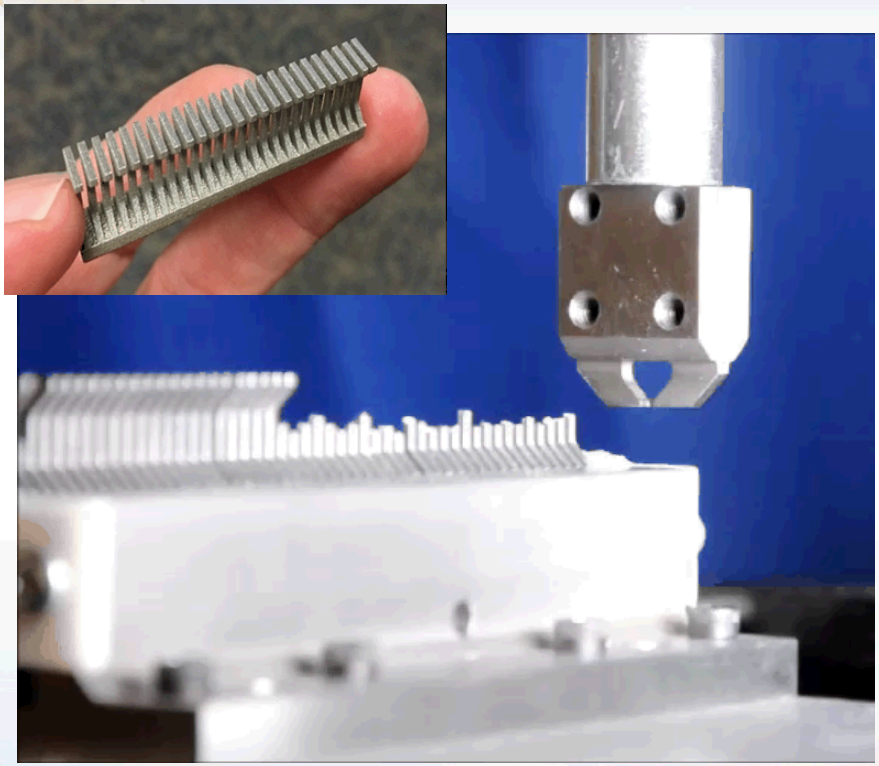
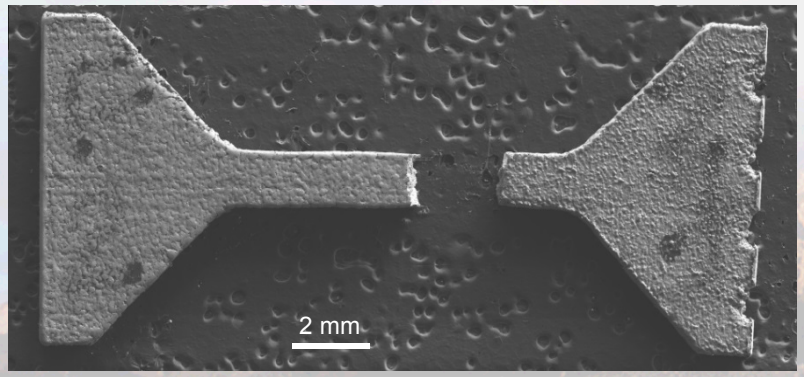
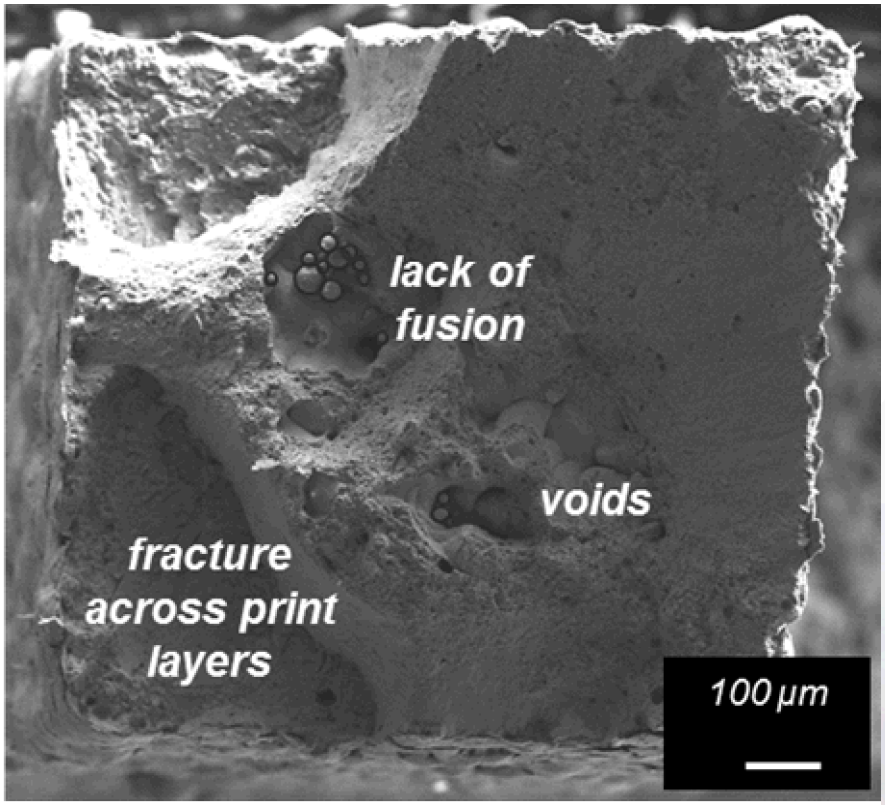
High-Throughput Tensile Testing





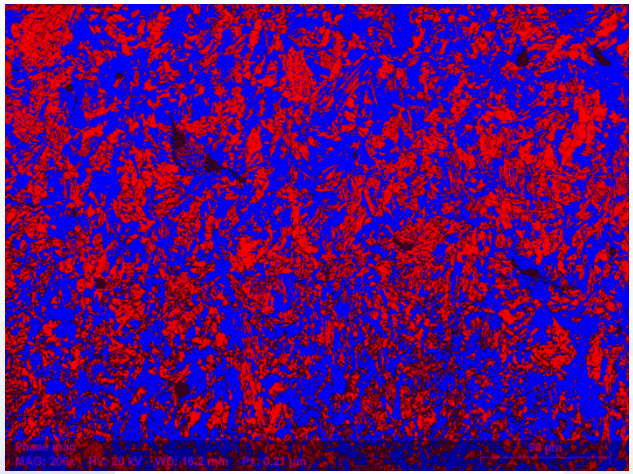
17-4 PH SS, H900 “brittle” fracture



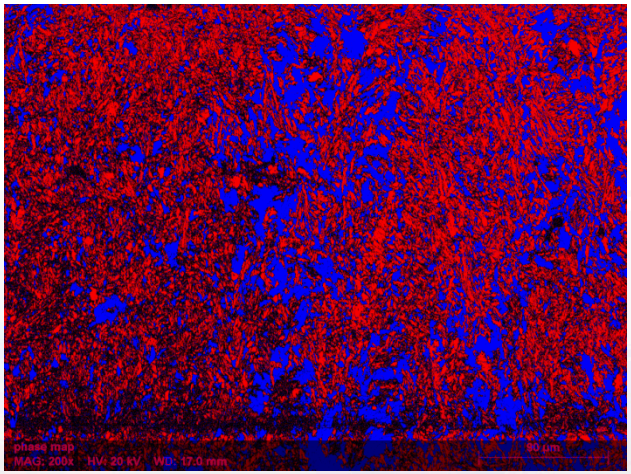
Failure at 2% elongation

Retained Austenite in 17-4 PH Stainless When Using Nitrogen Gas Atomized Powder

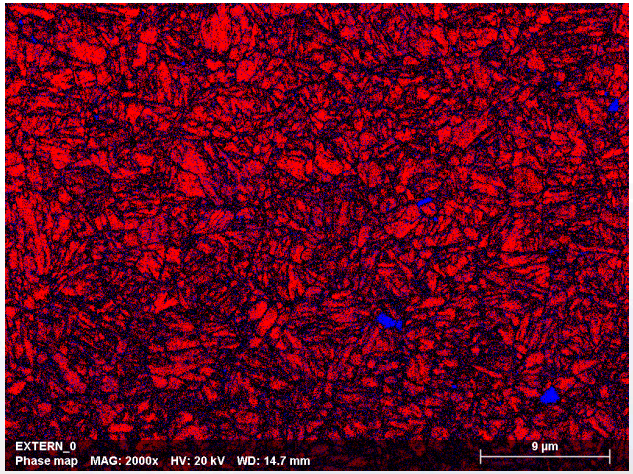
- Anomalous phase composition in AM vs. wrought 17-4 PH Stainless
  - Large fraction of retained austenite after solution heat treatment + H900 age
  - Cryo treatment to -196°C for 5 min still does not transform austenite



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*

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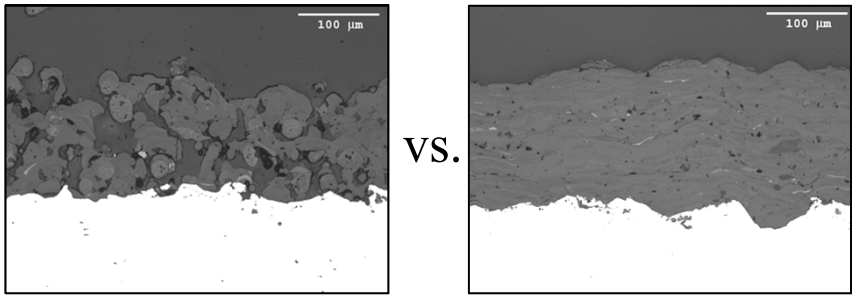
Fundamental Process Understanding is Key to Controlling Variability

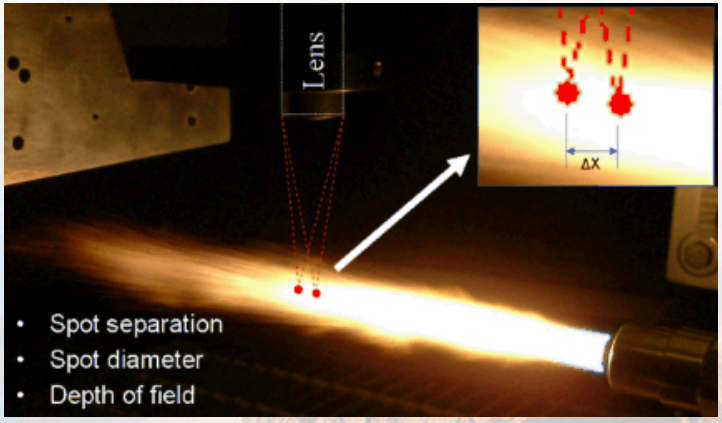
Prior Successful R&D with Thermal Spray

Same System, Same Feedstock,



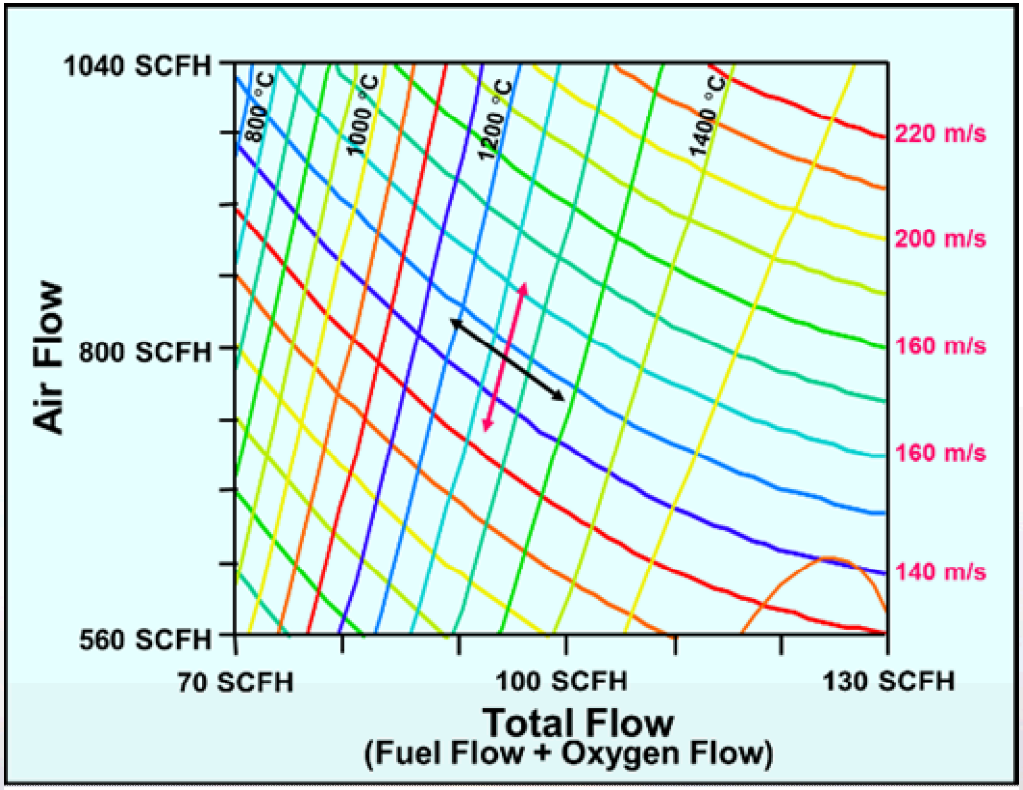
Very Different Results!

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



Process Diagnostics/Monitoring

Fundamental process understanding enables 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)

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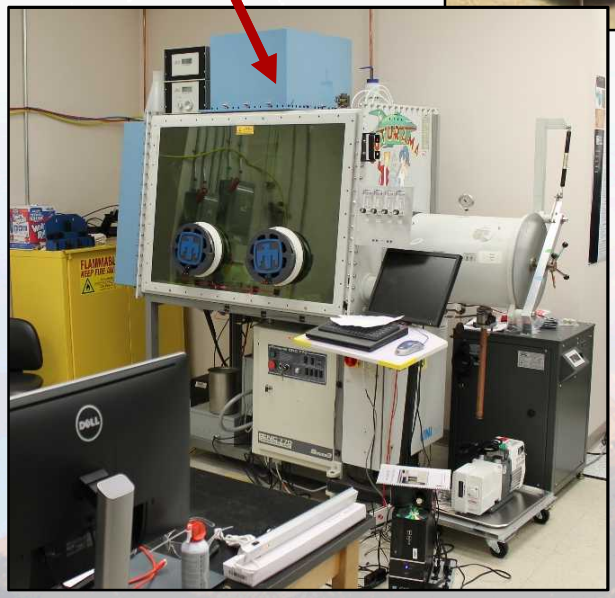
Sandia Metal/Multi-Material AM Process R&D Laboratory

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 Modified for Multi-Material hybrid AM

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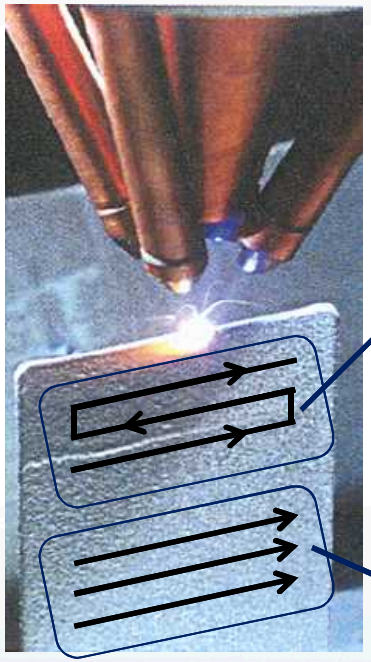
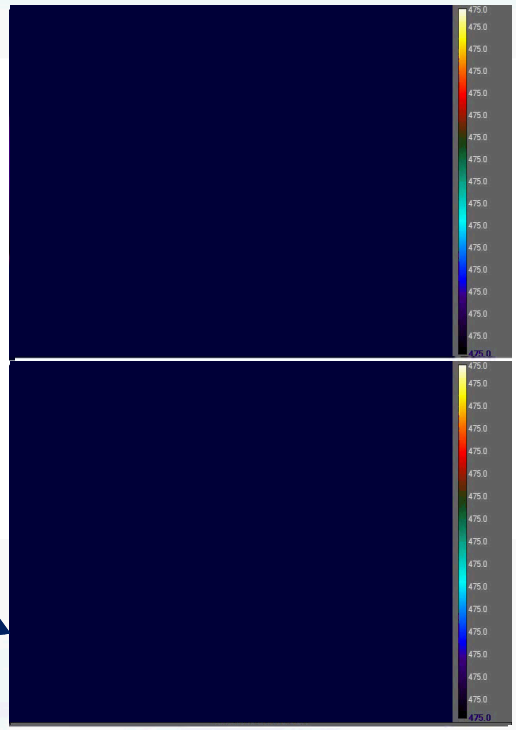
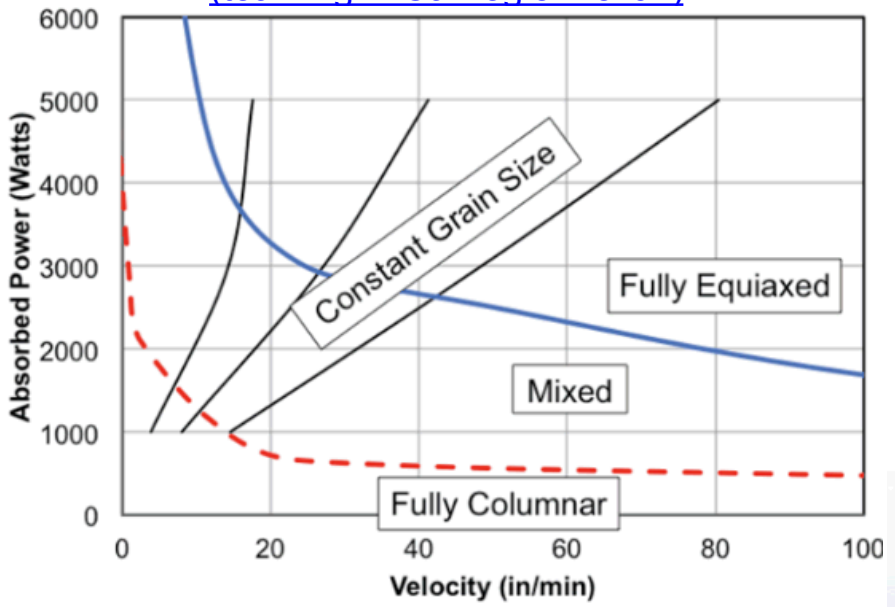
Working to Understand LENS™ Processing-Microstructure Relationships



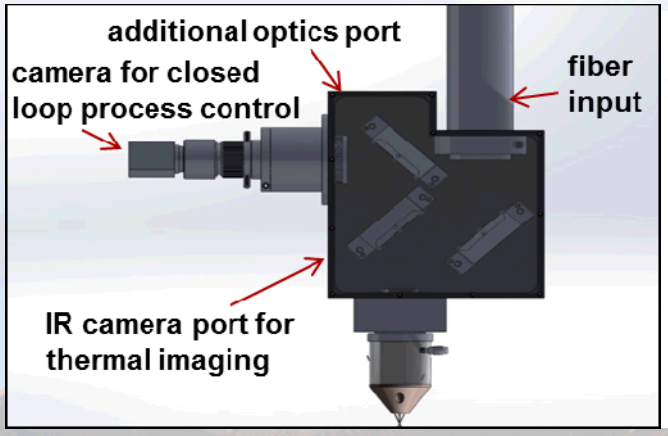


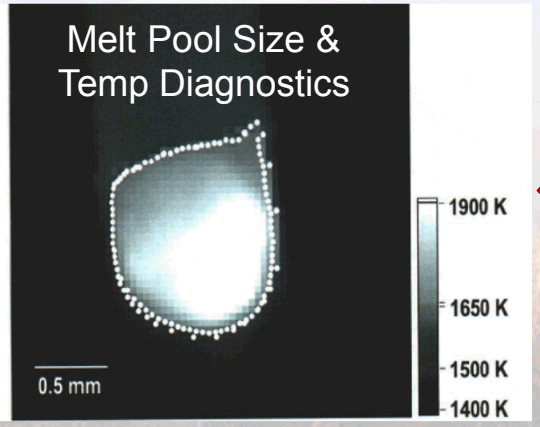
Processing-Microstructure Relationships

(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

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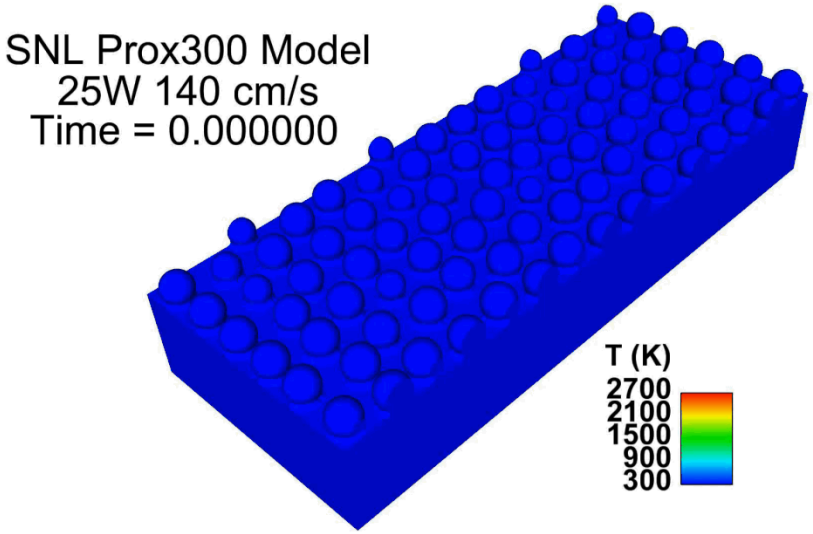
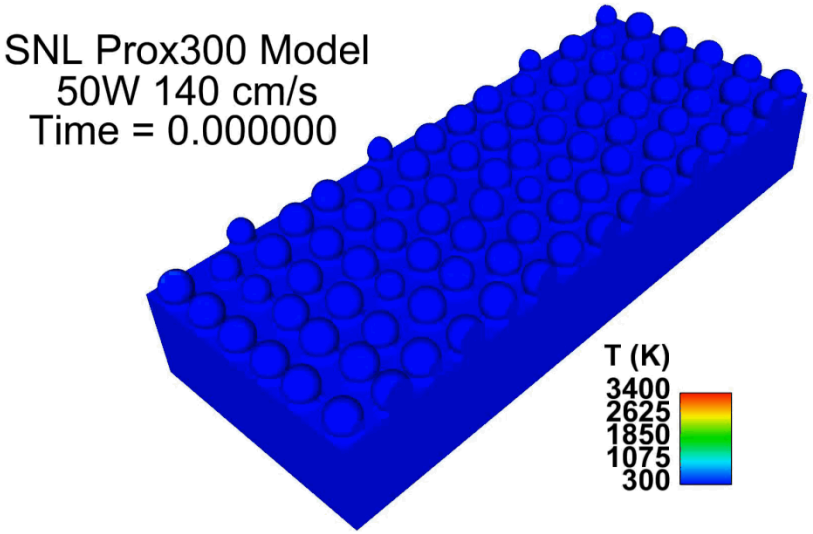
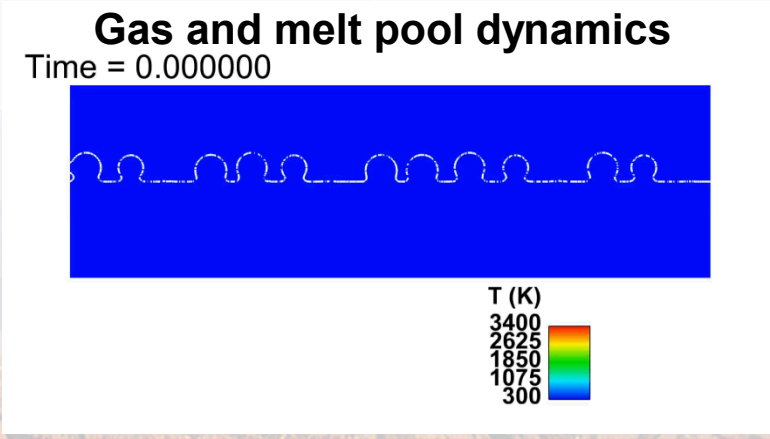
Process Modeling Can Provide Useful Insights





Stainless steel 304L
25 micron powder

Gas and melt pool dynamics



Notes:

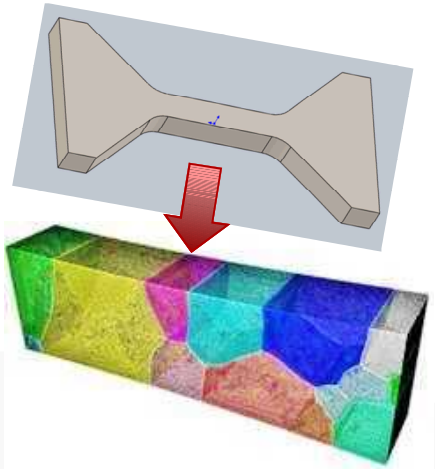
- 500 micron powder bed traversed in 357 microsec
- Sloshing-driven gas dynamics entrains ambient gas

Process Models by Mario Martinez

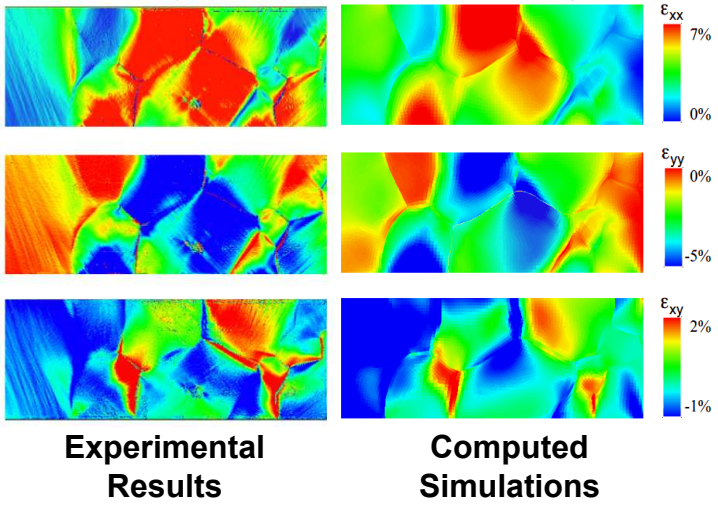
Leverage Sandia PPM to Investigate Variability/Defect Sensitivity

Sandia *Predicting Performance Margins (PPM)* initiative seeks to understand fundamental science of microstructural variability and defects and to quantitatively predict the resulting variability of materials properties.

Gauge Section of Wrought Ta Oligocrystal Tensile Specimen (1x3x5 mm)
(Use Electron Backscatter Diffraction & Digital Image Correlation)



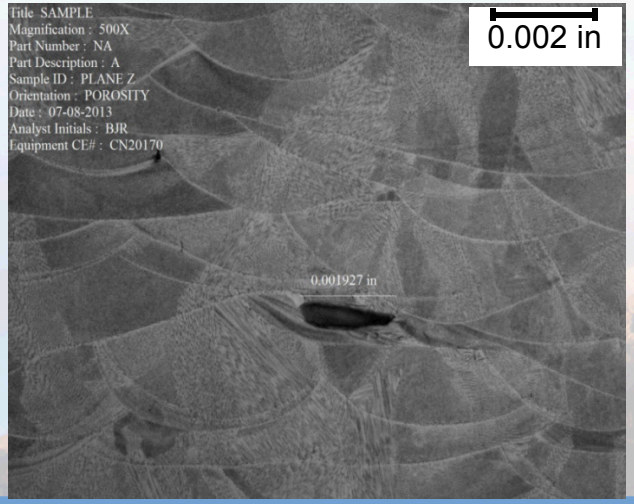
Oligocrystal experiments vs. crystal plasticity models (tensile loading)

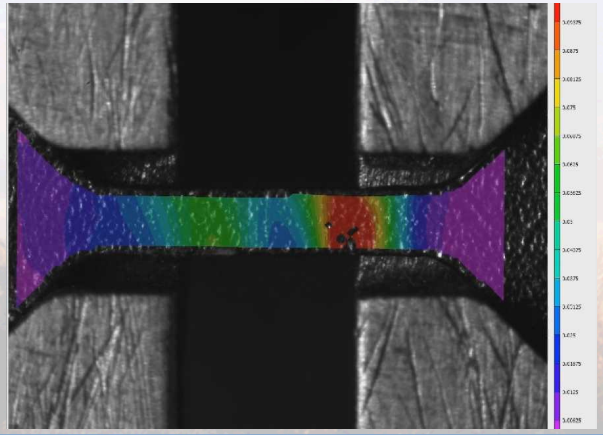


Key Questions:

What AM Defects Matter?

Can I detect them?





High-Throughput Tensile (HTT) Test with Digital Image Correlation

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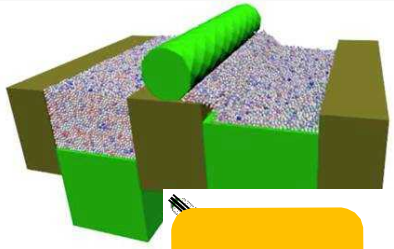
Ultimate Vision is to Understand/Control Process → Microstructure → Properties → Performance



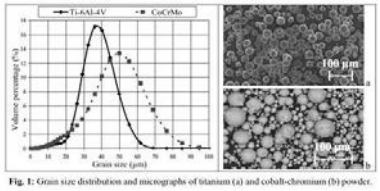
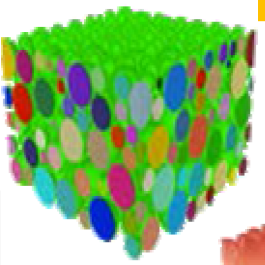
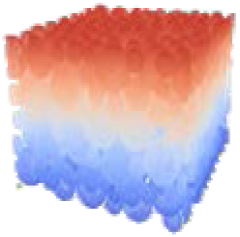


Fig. 1: Grain size distribution and micrographs of titanium (a) and cobalt-chromium (b) powder.

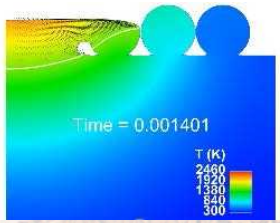
Particle packing



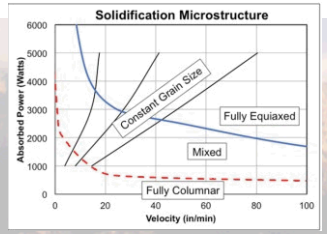
Heat Transfer



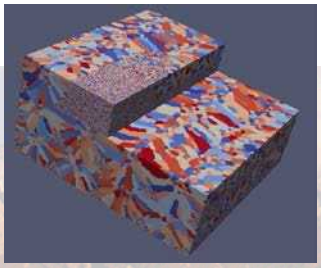
Partial melt & flow



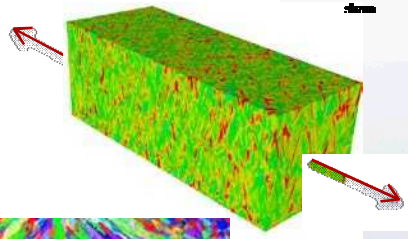
Molten pool dynamics



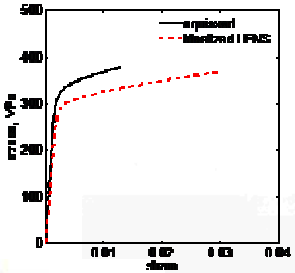
Solidification



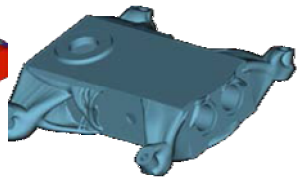
Microstructure



Property-Performance



Topology Design



- Process control
- Materials characterization
- Interfaces
- GRANTA database

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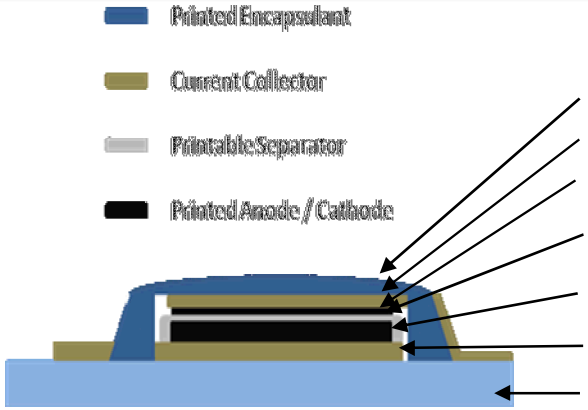
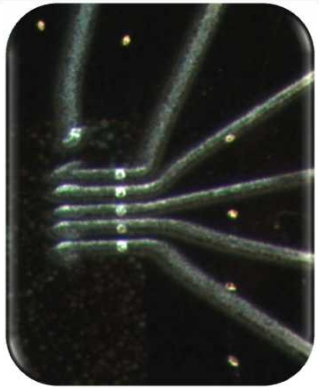
Multi-Material AM

Sandia has Strong Capabilities/Expertise In Printed Electronics

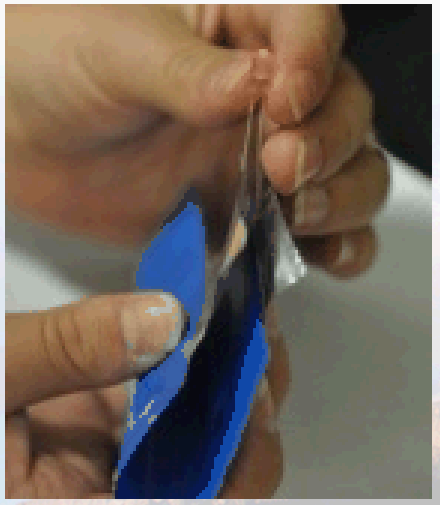


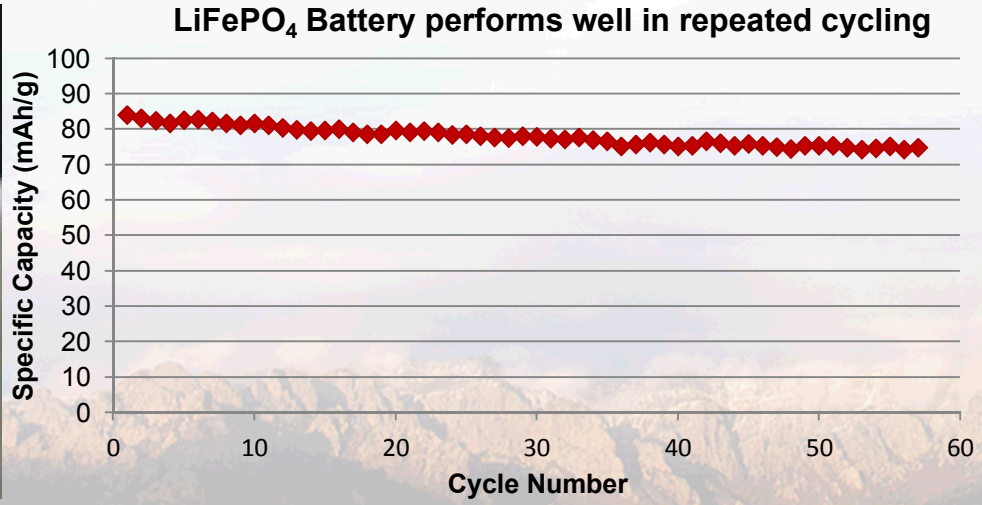
Printed flexible battery

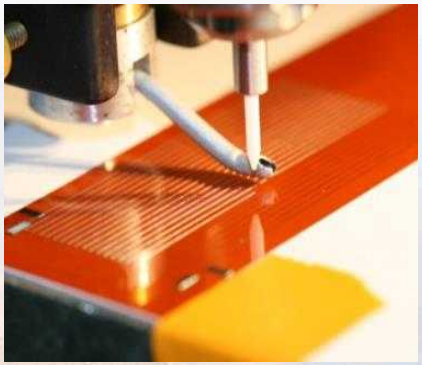
Encapsulant (DW UV-curable epoxy)
Current collector (DW carbon ink)
Anode (DW graphite/carbon)
Separator (DW mesoporous polymers)
Cathode (DW $LiFePO_4$)
Current collector (DW copper ink)
Substrate (polyimide)



"Flexible Chips" with printed wirebonds







Aerosol jet printing to 10 µm

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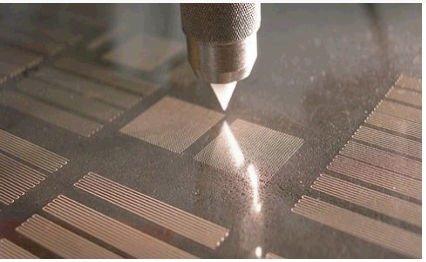
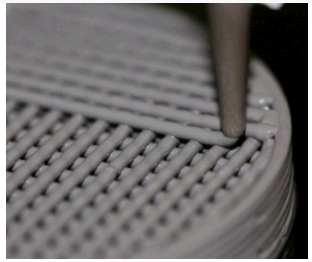
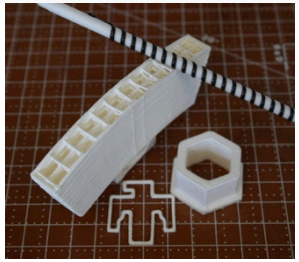
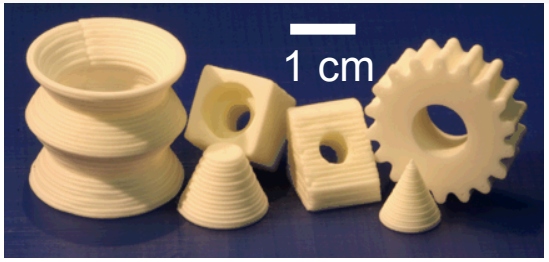
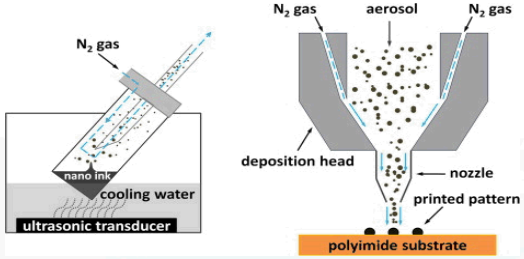
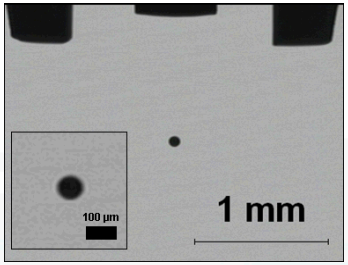
Direct Write Technologies Enable Access To Materials Not Supported By Conventional Printing Processes

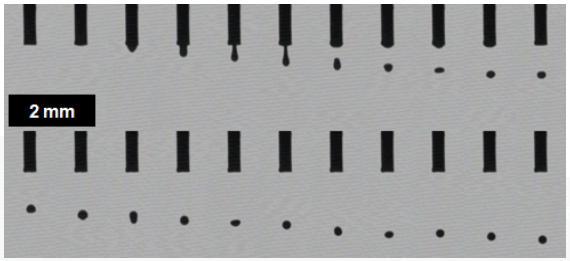
Direct Write by Extrusion Casting (Robocasting)

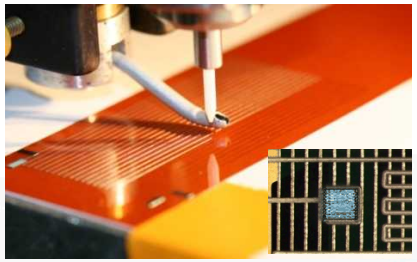





Direct Write by Aerosol & Ink Jet Deposition

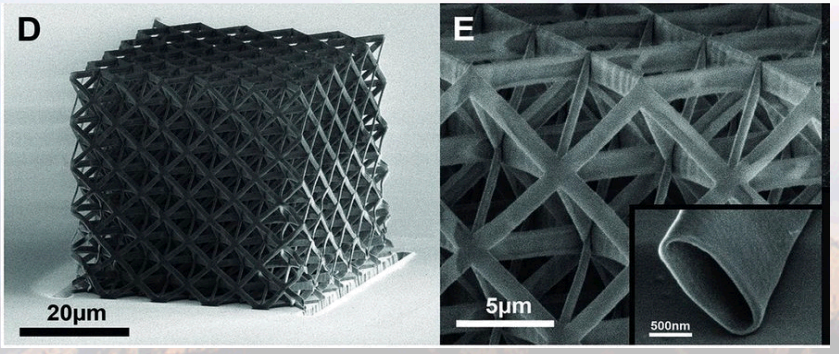


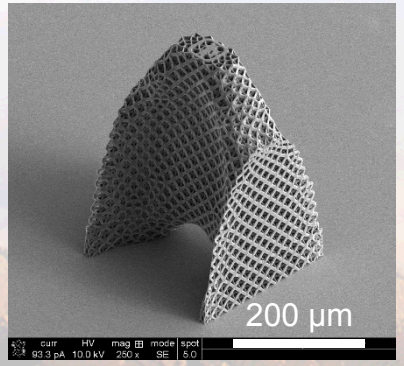


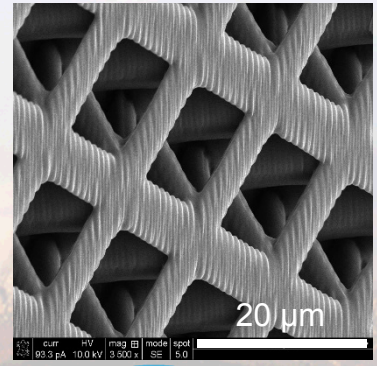




Direct Write by Laser Photo-Lithography NEW!







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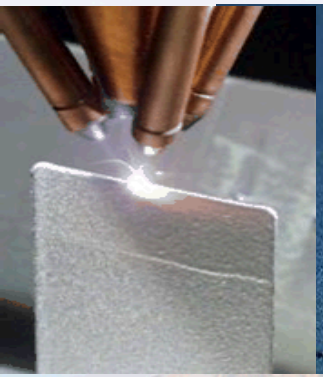
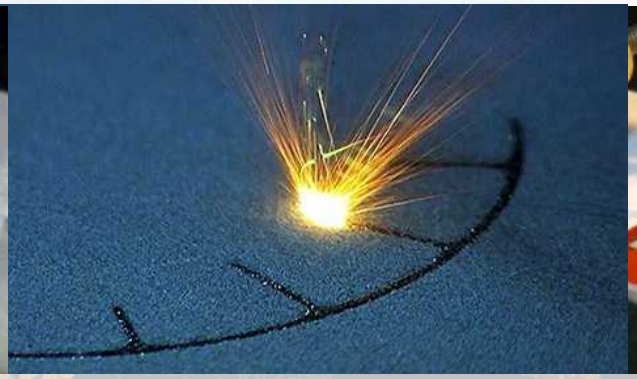
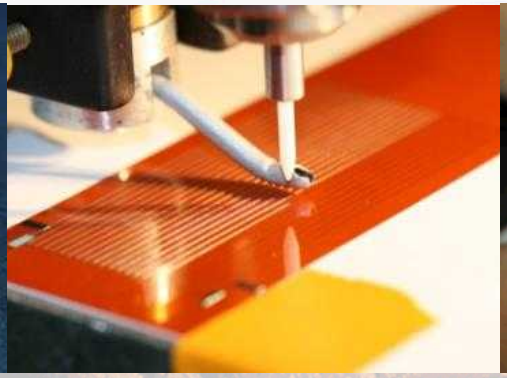
Summary

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


Questions?

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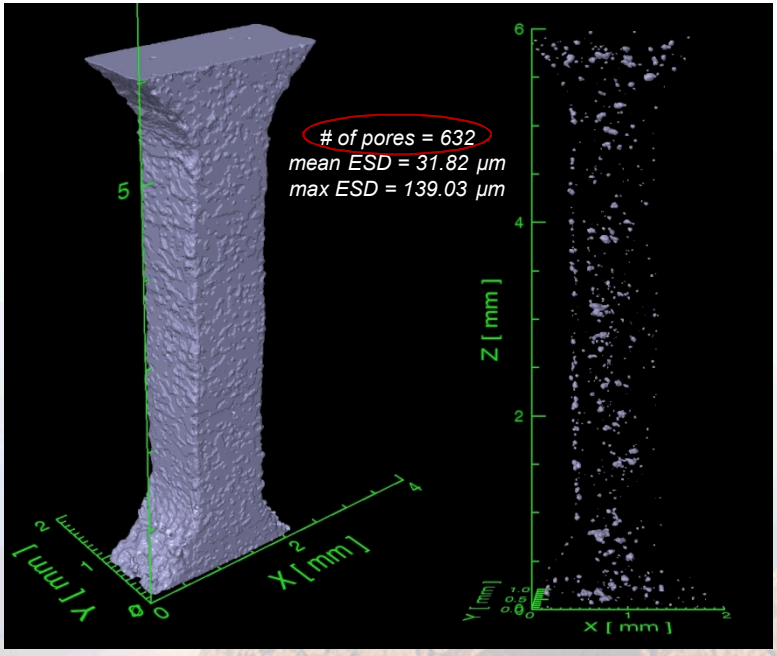
Ph: 505-845-3256
mfsmith@sandia.gov

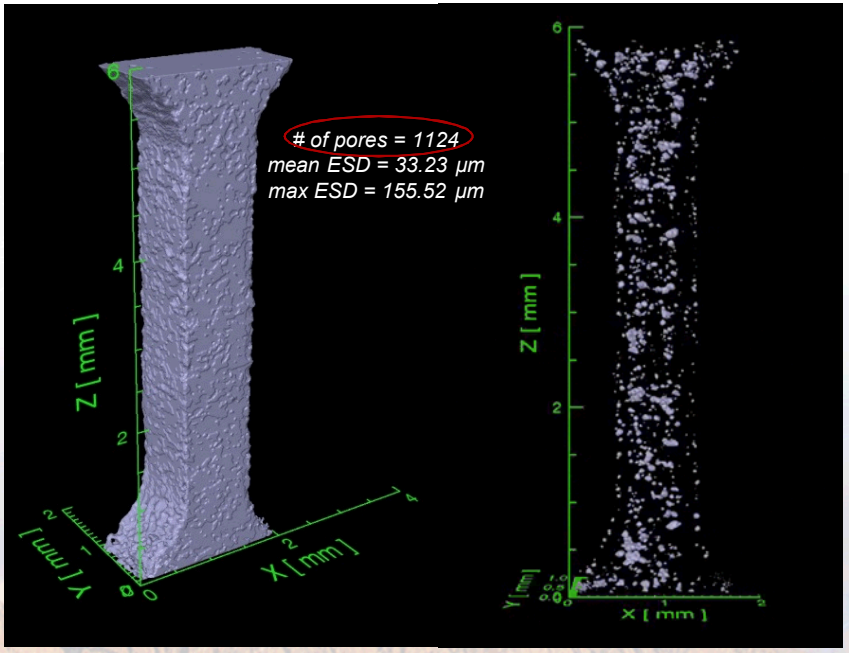
Backup Slides

Still Working to Understand Defects Sensitivities and Failure Modes

- AlSi10Mg Dogbones
  - Gage sections imaged w/resolution of ~10 µm voxel edge length
- Quantifying defect distributions
  - What can we see? Does it inform material behavior predictions?
  - Comparing w/serial sectioning (Robomet) & density (via Archimedes)
- 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

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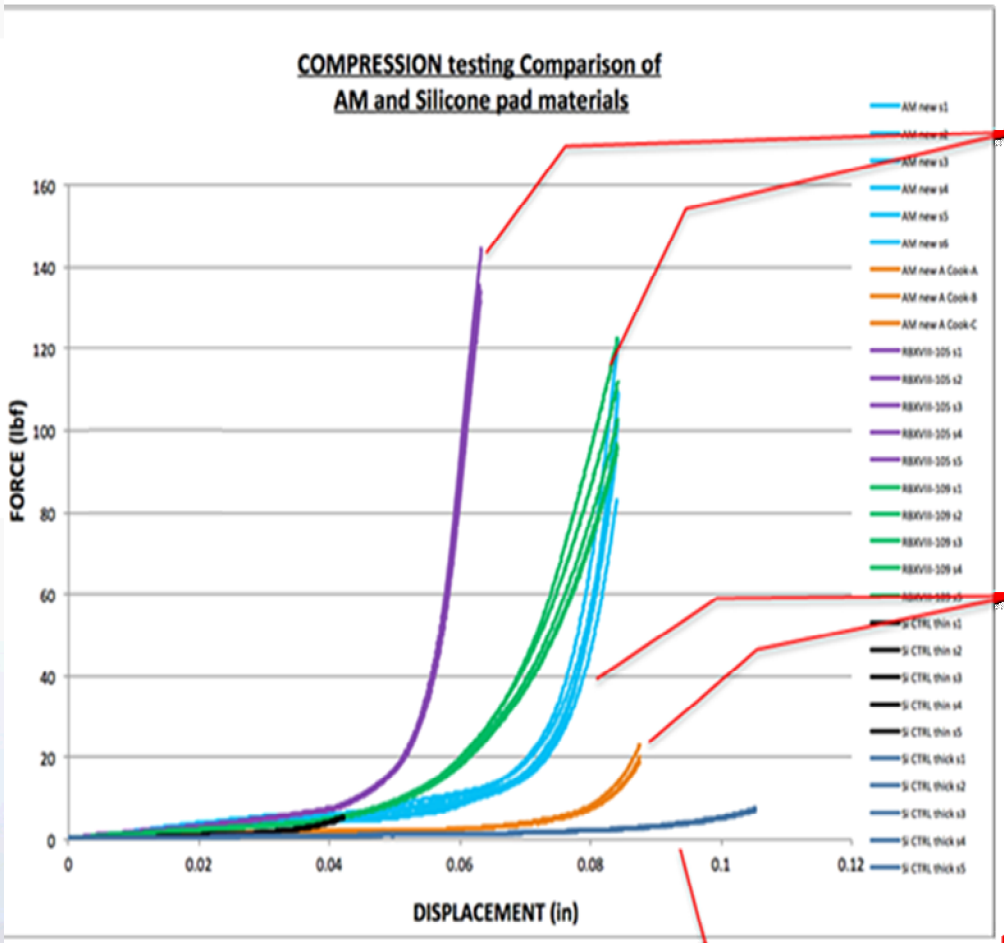
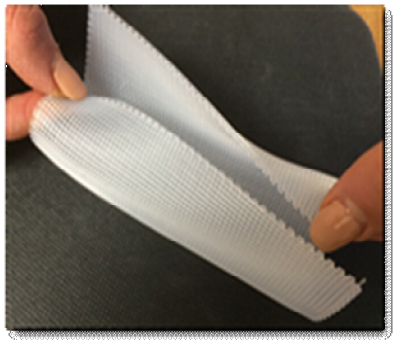
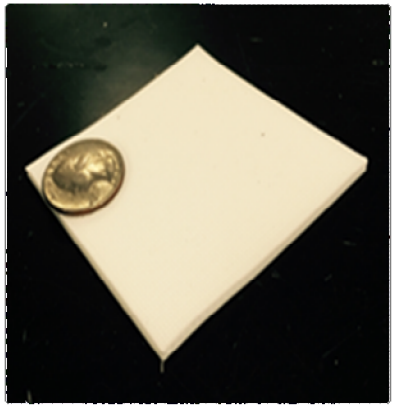
Tailorable Stress/Strain



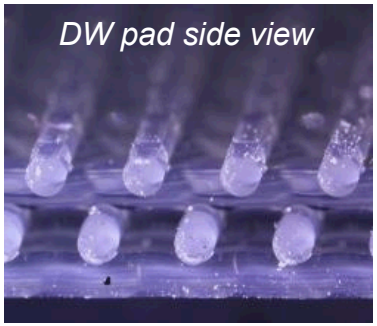


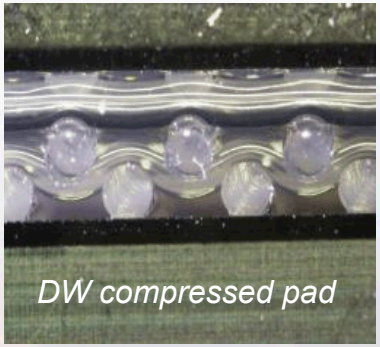
3D Printed Silicone (unmodified)



3D Printed Silicone (modified)

LEGACY MATERIAL





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