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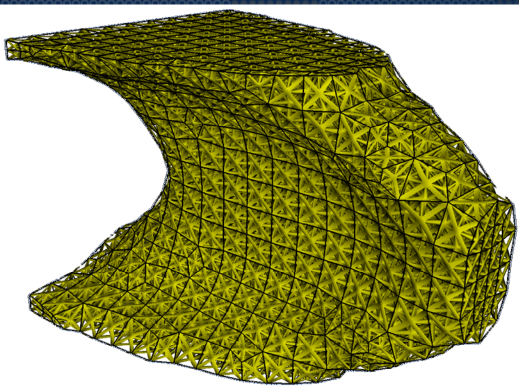

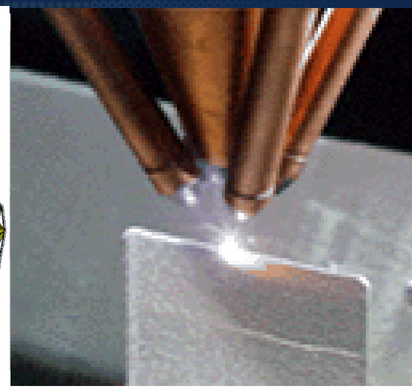

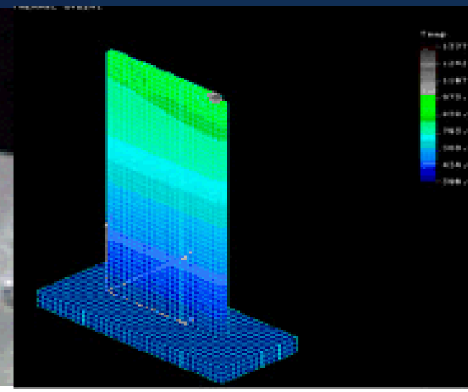

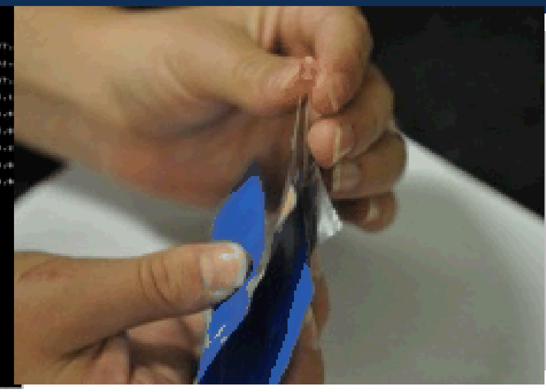

Additive Manufacturing --
A New World of Opportunities and Challenges

Mark F. Smith

Deputy Director for Additive Manufacturing

Materials Science & Engineering Center

Sandia National Laboratories

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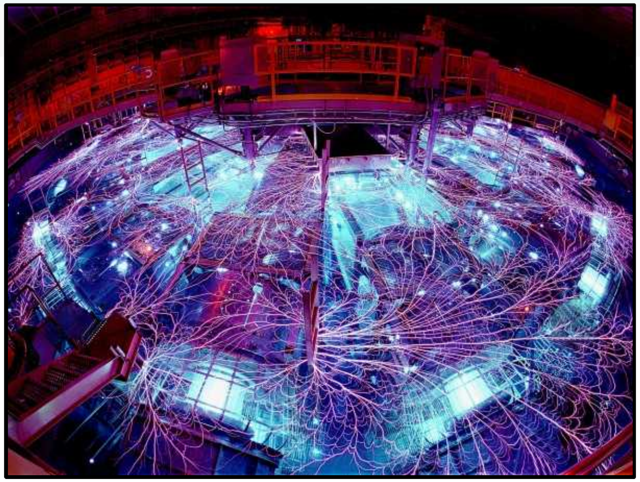
Sandia is a National Security Science and Engineering Laboratory

Weapon Drop Test



Energy R&D

Threat Test

- Historical mission -- non-nuclear components in nuclear weapons and nuclear weapon security
- Today, broader mission in science & engineering for U.S. national security

> *"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

Materials Science at Sandia

Three Major Areas of Materials R&D

- *Materials Engineering Support*
  - Problem solving, program support
  - Application of existing expertise
  - Point solutions
- *Materials & Process Advanced Development*
  - Advanced & exploratory materials & process development
  - Production process development & technology transfer
  - Understanding the margins
- *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
  - Created advanced materials analysis & process diagnostics tools

Center for Integrated Nano Technologies

Adv. Materials & Processes Lab

Ion Beam Lab

Advanced Materials Lab

Processing & Environmental Tech. Lab

Integrated Materials Research Lab

Thermal Spray Research Lab

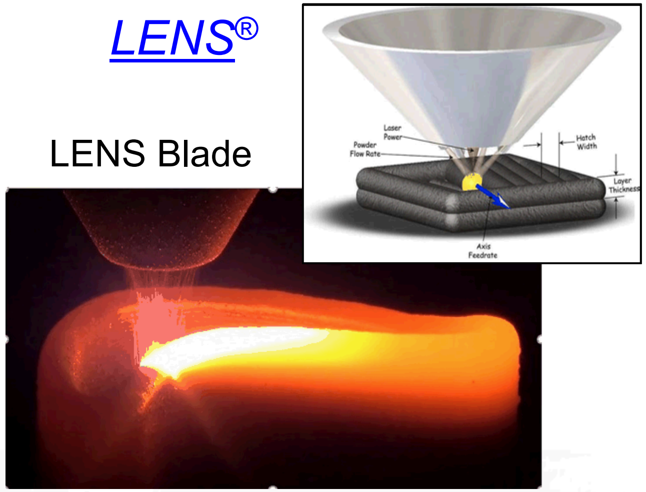
3

30+ Years of Sandia AM Technology Development & Commercialization

FastCast *
Development Housing

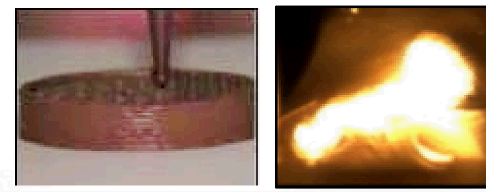
Laser Engineered Net Shaping *
LENS®

LENS Blade

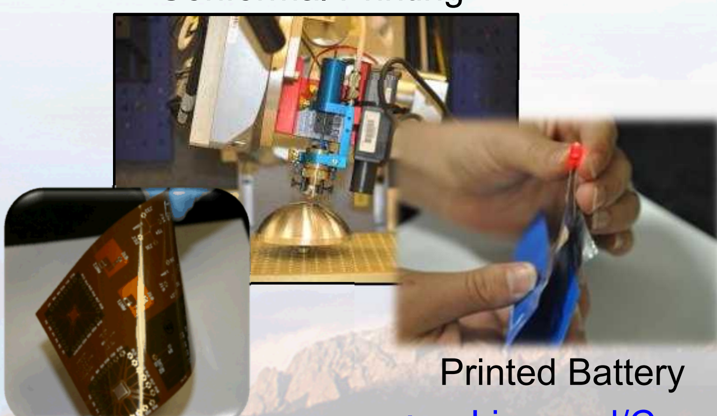


RoboCast *
Ceramic Parts

Energetic Materials



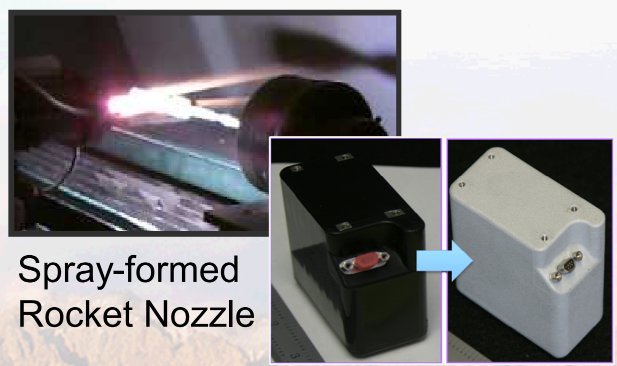
Direct Write
Conformal Printing



Printed Battery

Flexible Electronics

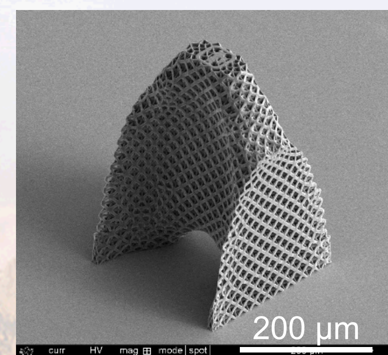
Thermal Spray



Spray-formed Rocket Nozzle

Metal on Plastic

Micro-Nano Scale AM
Lattice Structure



* = Licensed/Commercialized Sandia AM technologies

Underline = Current Capability/Activity

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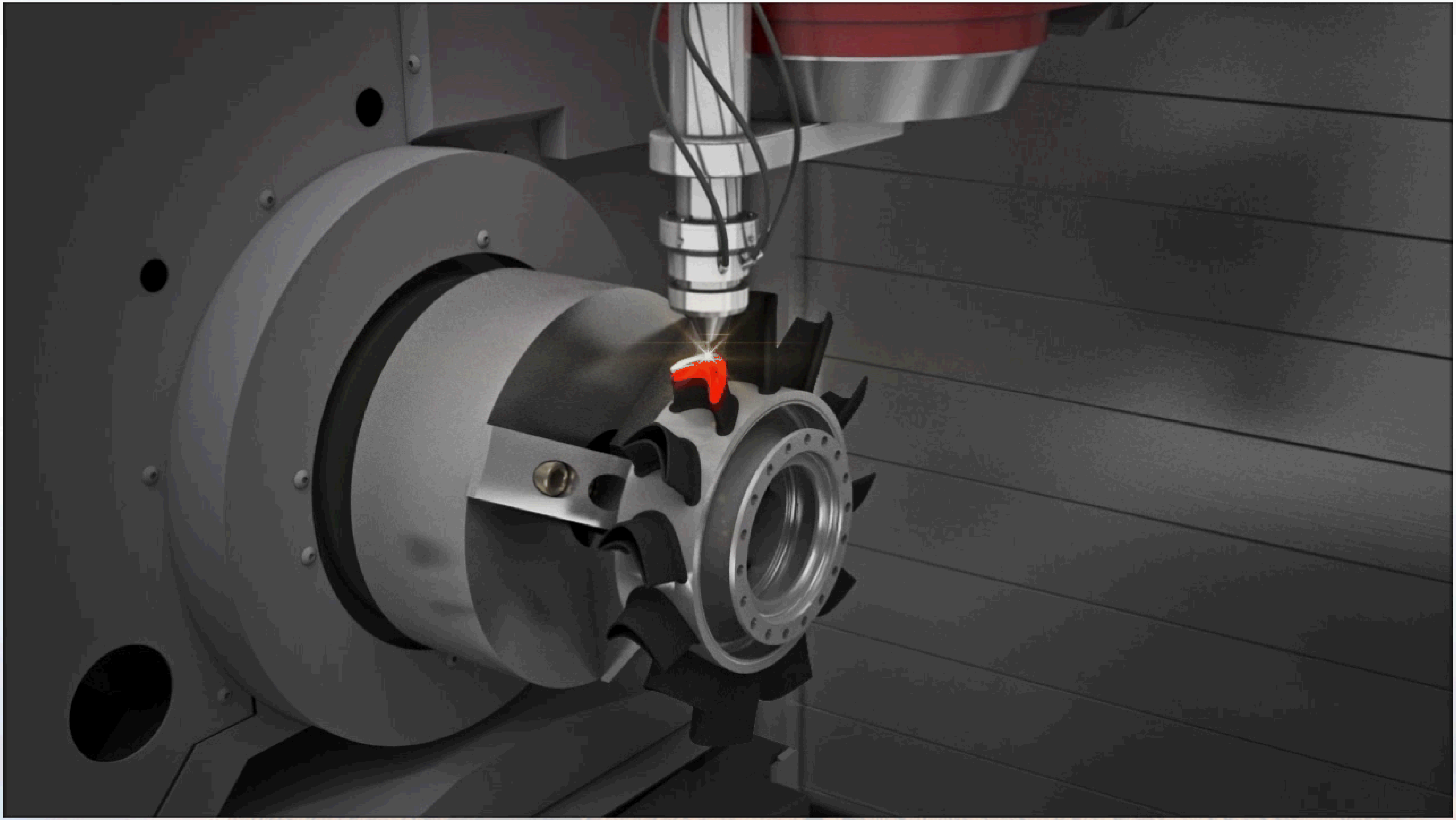
"Hybrid" Additive/Subtractive Machine Tools



Video Courtesy of DMG Mori (available on YouTube)

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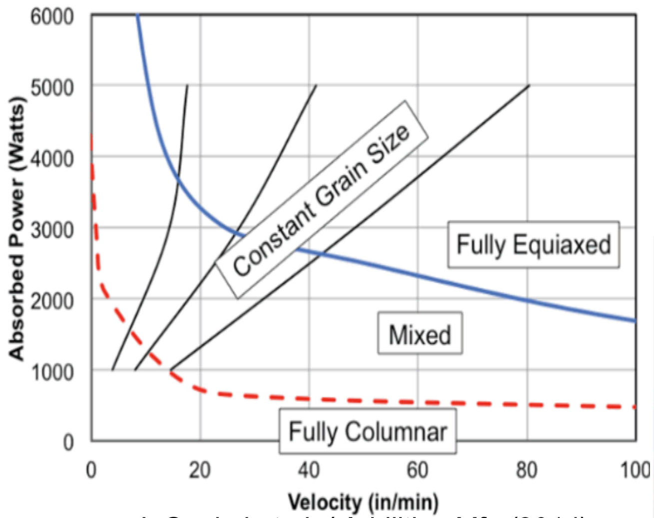
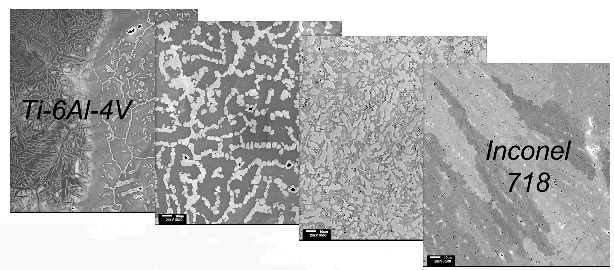
Why Use AM?
Some Potential Advantages

- Rapid/Inexpensive prototypes, cycles of learning, tooling, etc.
- Save Time, Money, Weight, Energy
- Design Freedom – shapes previously unachievable/impractical
- Print Integrated Assemblies
- Engineered Materials – special properties

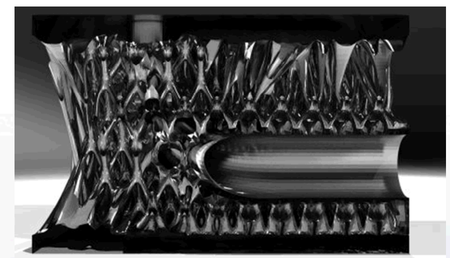


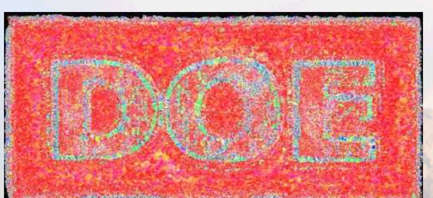
J. Gockel et al. / Addiitive Mfg.(2014)



LENS® functionally graded materials

New Design Possibilities
(Within Technologies)





Site specific control of the crystallographic orientation of grains within metal components
(Mfg. Demonstration Facility, ORNL)

Multi-Materials on a Single Printer

Printed Gear Assembly

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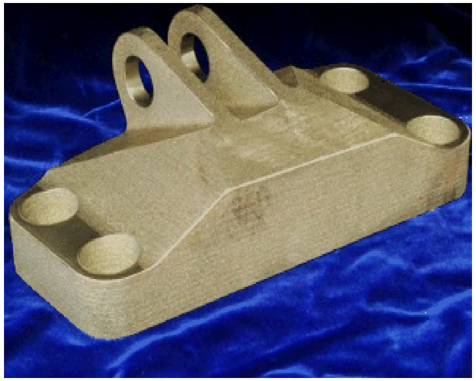
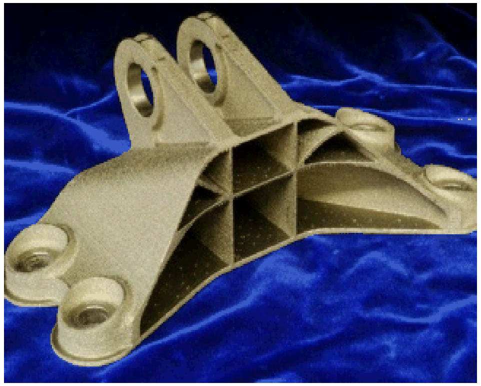
Commercial Aerospace Hardware

GE Additive Manufacturing Design Competition



Original Design 4.5 lb.



Winning AM Design 0.7 lb.

- ***84% wt. reduction***
- Performed well in load tests

CFM LEAP Engine Fuel Nozzle*

Additively Manufactured LEAP Fuel Nozzle

- ***Replaces 18 parts with 1 – ZERO joining operations***
- ***Internal geometry can't be built with traditional mfg.***
- ***25% lighter, 5x more durable, reduced NOX emissions***
- 19 fuel nozzles per engine
- Plan to build 40,000 nozzles/yr
- New $50M Mfg. Plant, Auburn, AL, Initial production in 2017

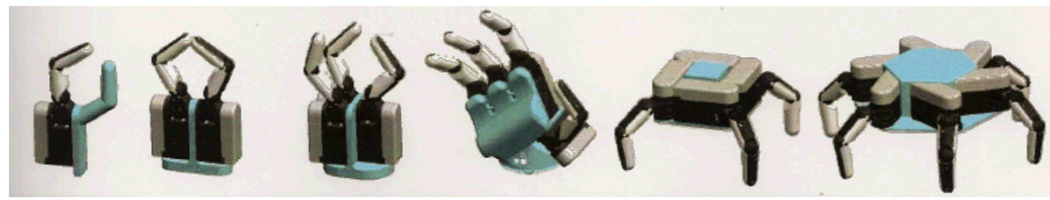
*CFM is a 50/50 Snecma/GE Company

Sandia Hand – AM Enabled Innovative Design and Substantial Cost Reduction

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

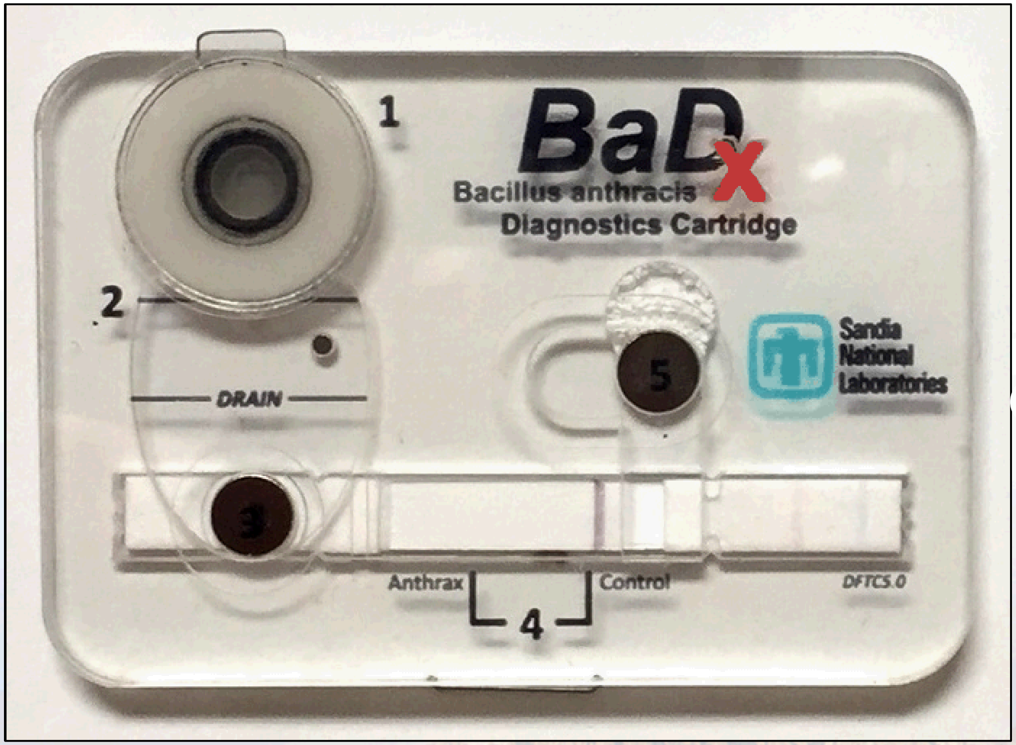
- Developed for bomb disablement
- AM Enabled rapid design iterations
- Cost $10k vs. ~$250k
- "Glove" controller
- Current version has "touch" sensors

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

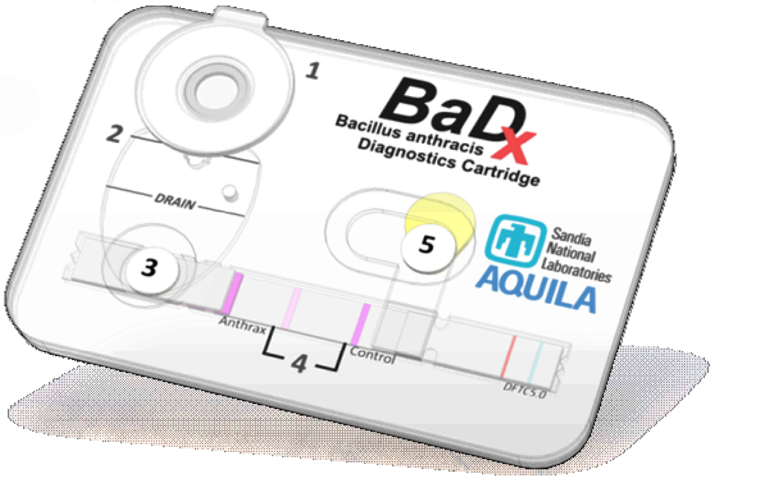


BaDx Anthrax Diagnostics Tool

- Microfluidic platform for *Ba*cterial *D*etection
- Rapid/inexpensive prototyping & design revisions
- Self-contained, credit card-sized "Lab in a Pocket"



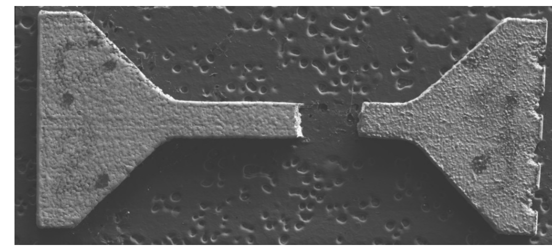
SNL Scientists Jason Harper, Melissa Finley, and Thayne Edwards



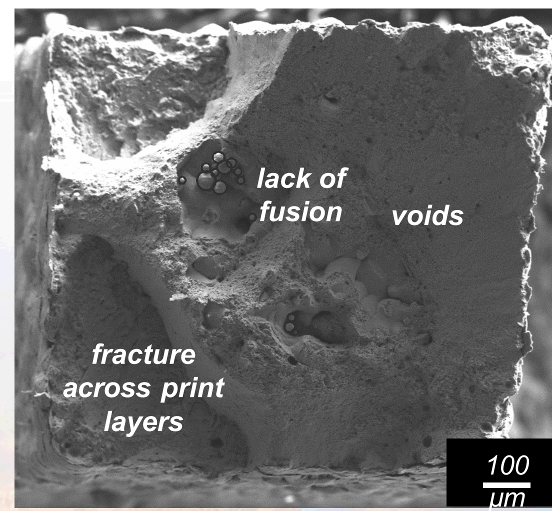
† Edwards *et al*. *Biomicrofluidics* **2011**, *5*, 044115.

Why Not Additive?
Some Potential Disadvantages/Limitations

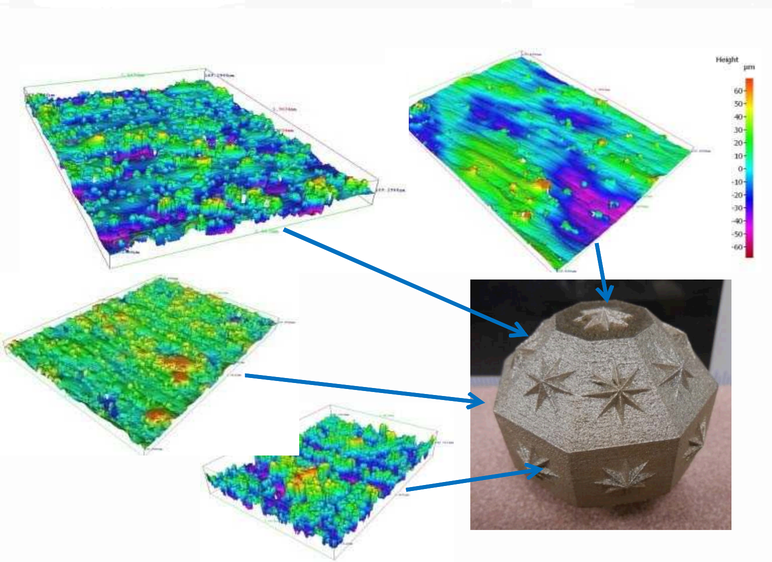
- AM Is Still an Evolving/Emerging Technology
- Many Sources of Variability – Most Machines Run "Open Loop"
- Material is "Built" Along with the Part – Is It Good?
- Lack of Engineering Data/Standards for Designers
- There ARE Design Constraints/Design Software Limitations
- Tolerances, Surface Finish, Residual Stress
- AM Isn't Always Faster/Cheaper

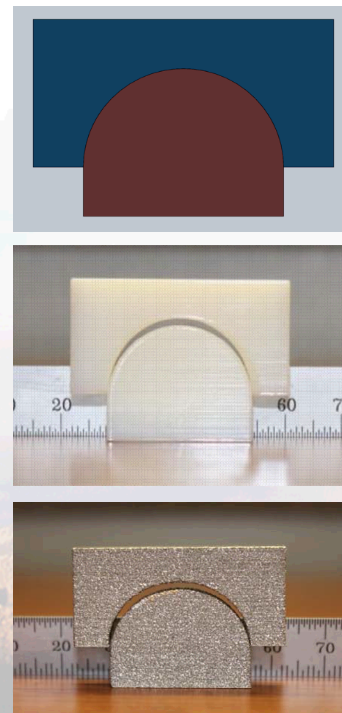


17-8 PH SS, H900, "brittle" fracture



Failure at 2% elongation





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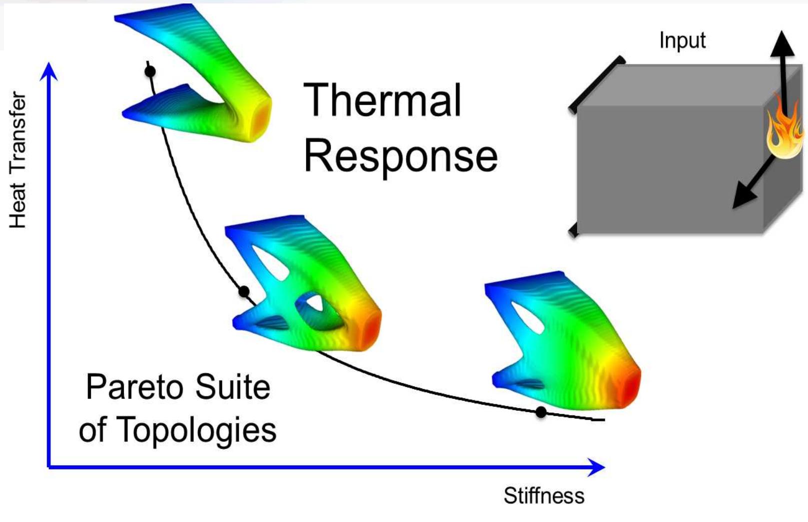
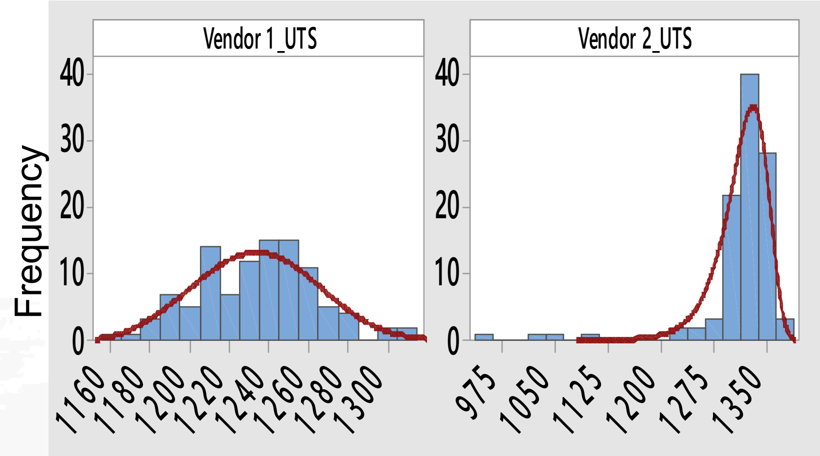
Three Areas of Emphasis in Ongoing Sandia AM R&D

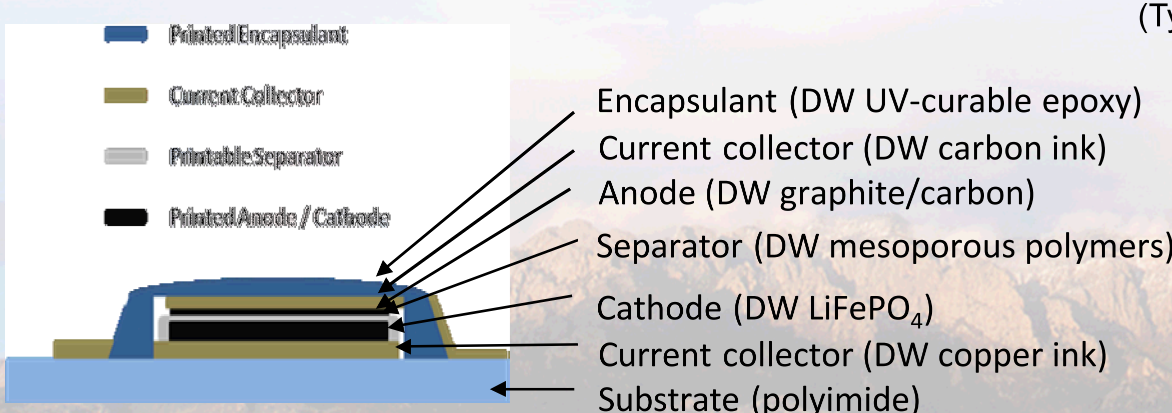


Engineering Analysis Driven AM Design



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

Materials Assurance



Multi-Material Additive Manufacturing

Sandia National Laboratories

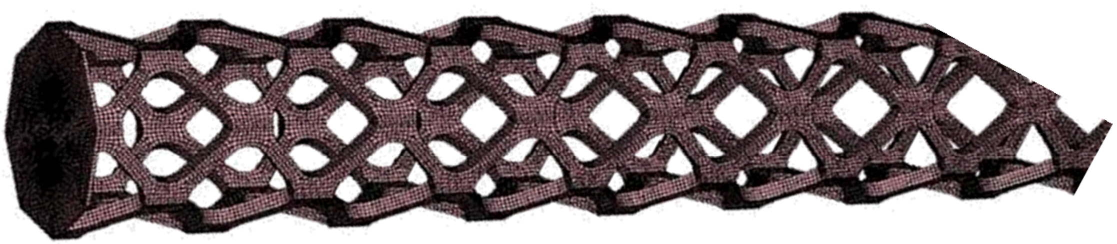
Analysis Driven Design

12

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

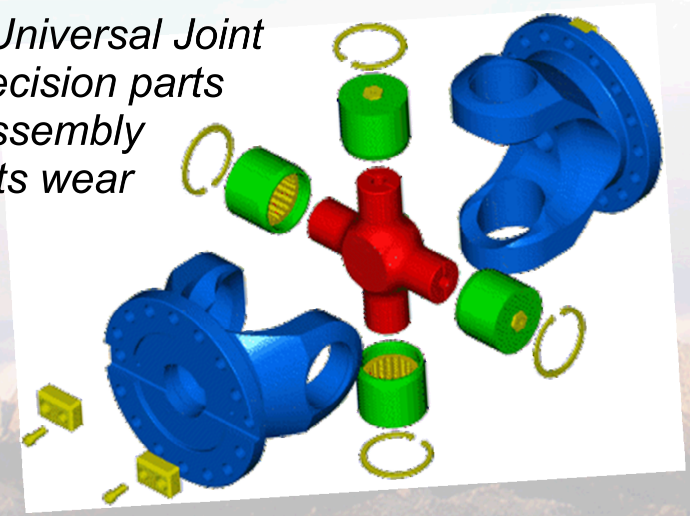


With AM it is faster and cheaper to build this optimized shaft than a solid shaft!

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

Conventional Universal Joint

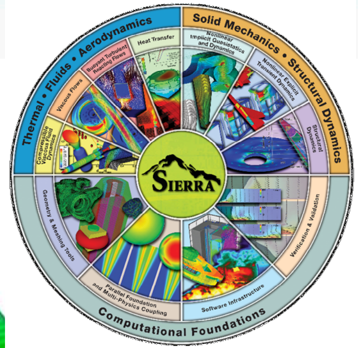
- *Many hi-precision parts*
- *Complex assembly*
- *Moving parts wear*



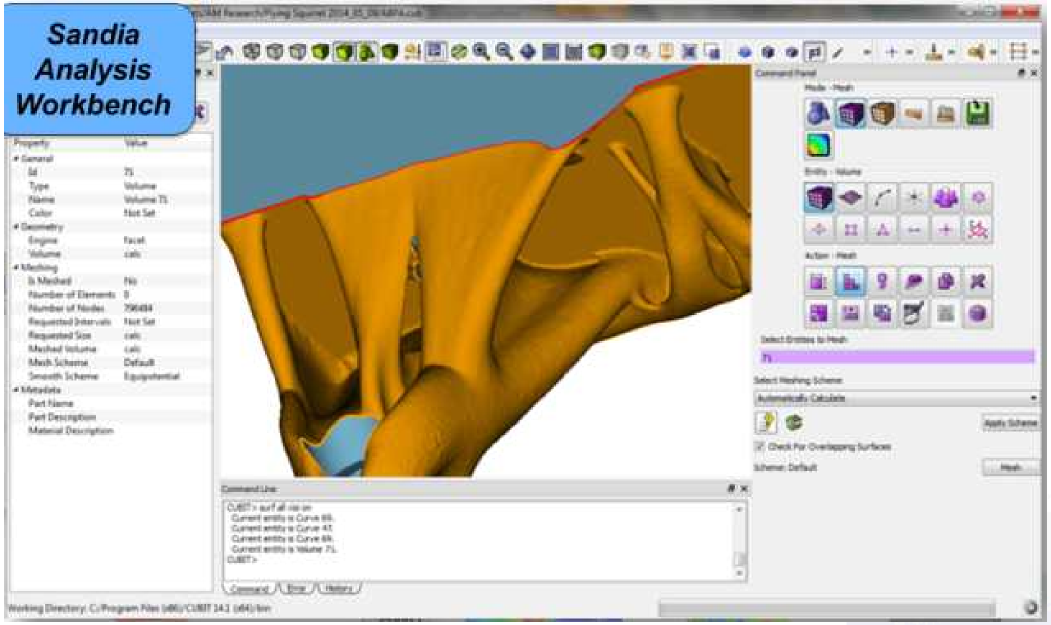
"Loxosphere"

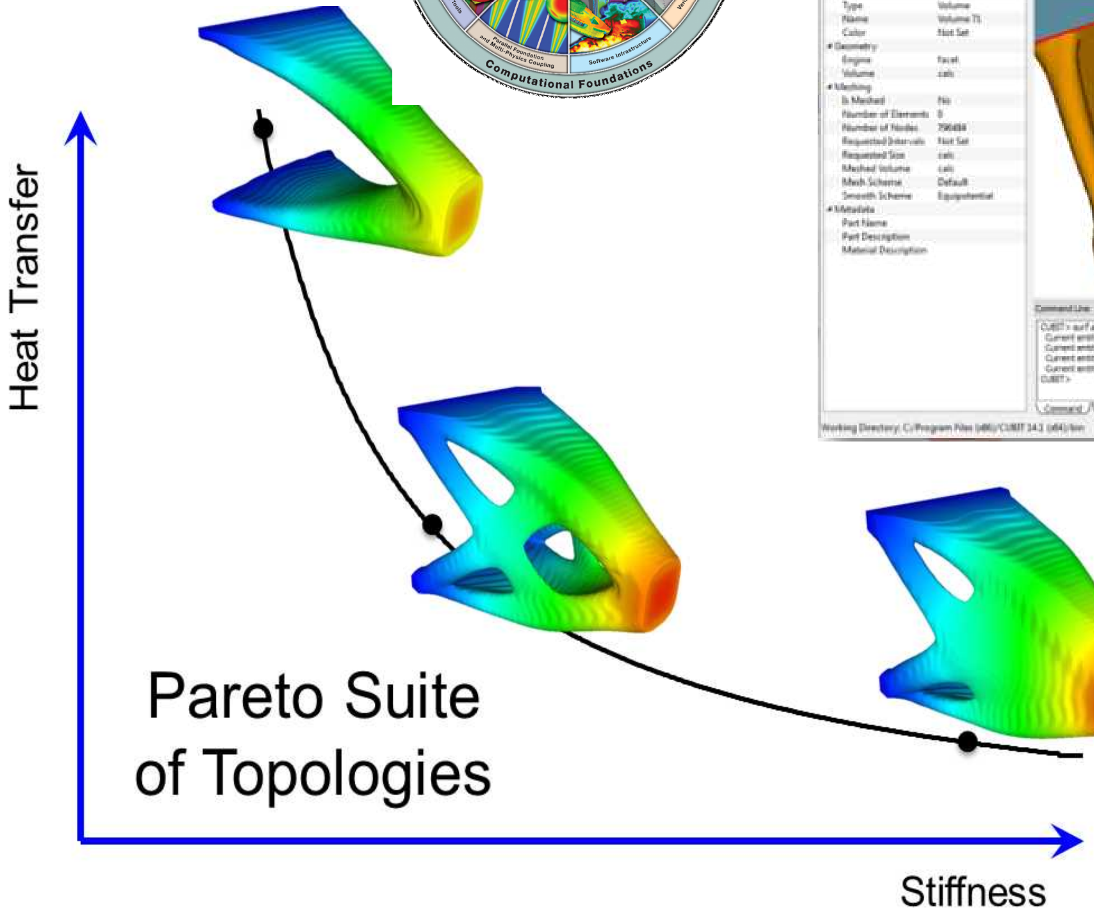
- *1 piece*
- *No assembly*
- *No moving parts*

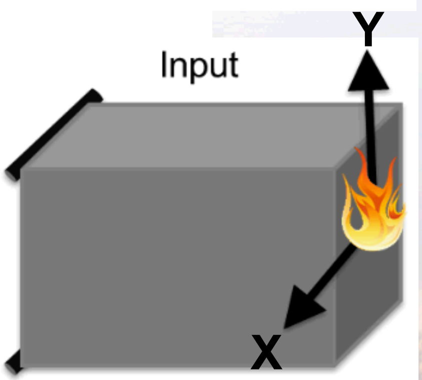
AM Design Via Functional Prioritization



User Friendly Interface







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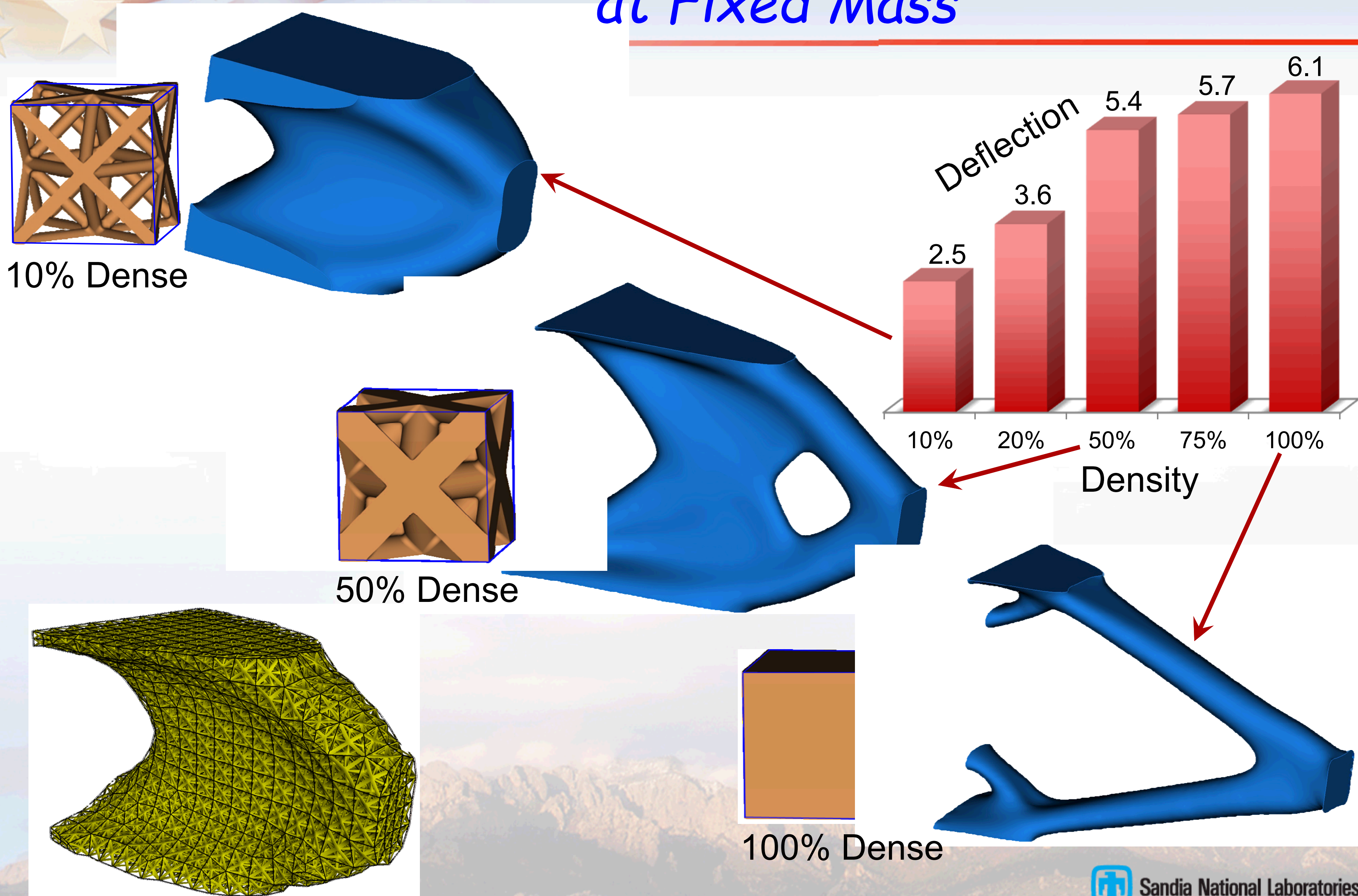
Optimizing Stiffness at Fixed Mass



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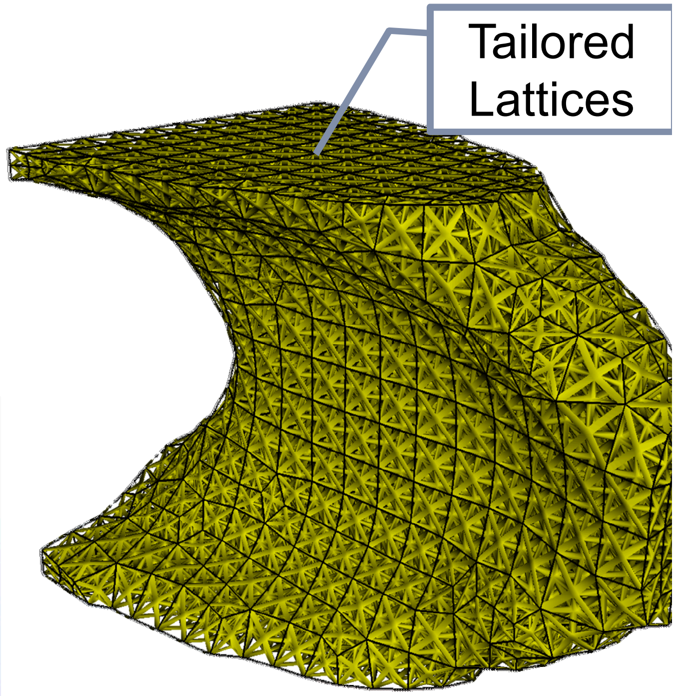
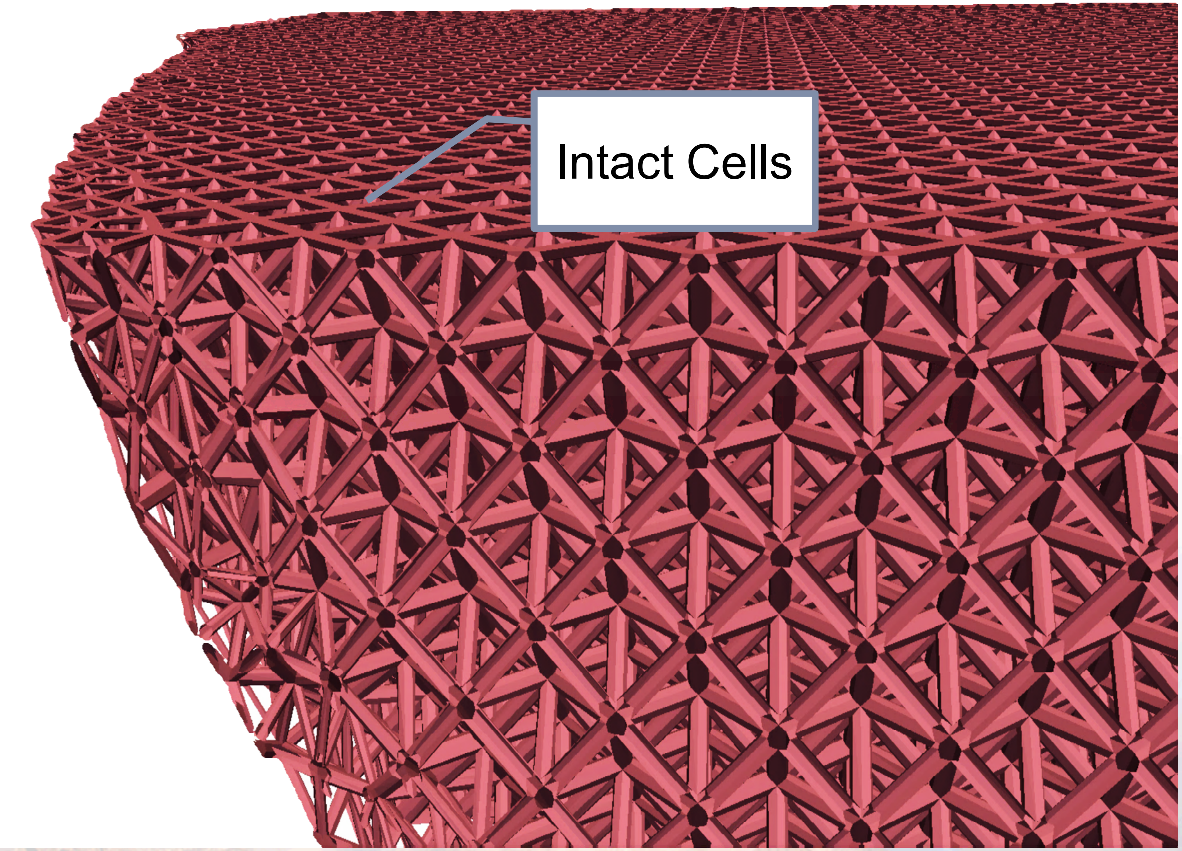
Tailored Lattice Geometries Avoid "Loose Ends"





Imagine a New Way of Designing & Realizing National Security Products

Requirements-Based, User-Friendly, Interactive, Analysis-Driven, Design Tools that Provide Test Guidance, Build Parameters, and Quantified Margins & Uncertainties

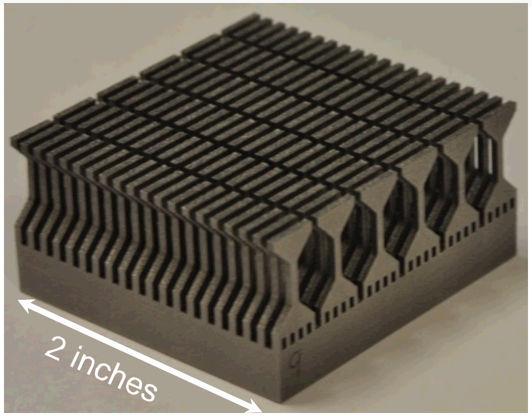
Seamless, Electronic, Agile, 3D Model-Based Manufacturing w Process Monitoring & Control

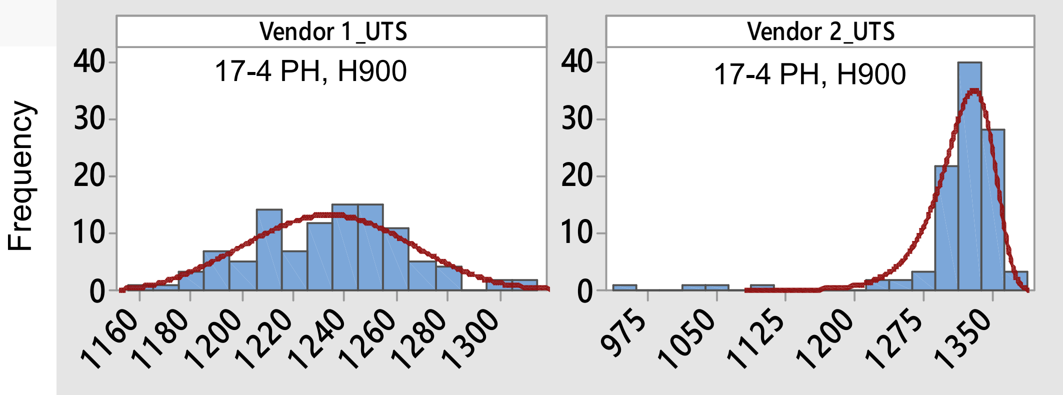
Final Products not Possible with Traditional Technologies; A New World of Possibilities!

Materials Assurance

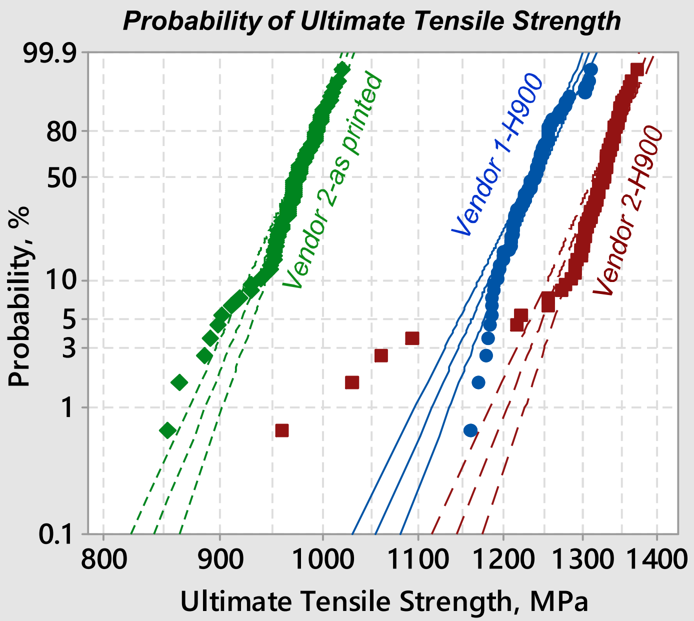
Data Variation Suggests Defect Dominated Failure Modes

High Throughput Tensile Testing





Ultimate tensile strength (MPa



- 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

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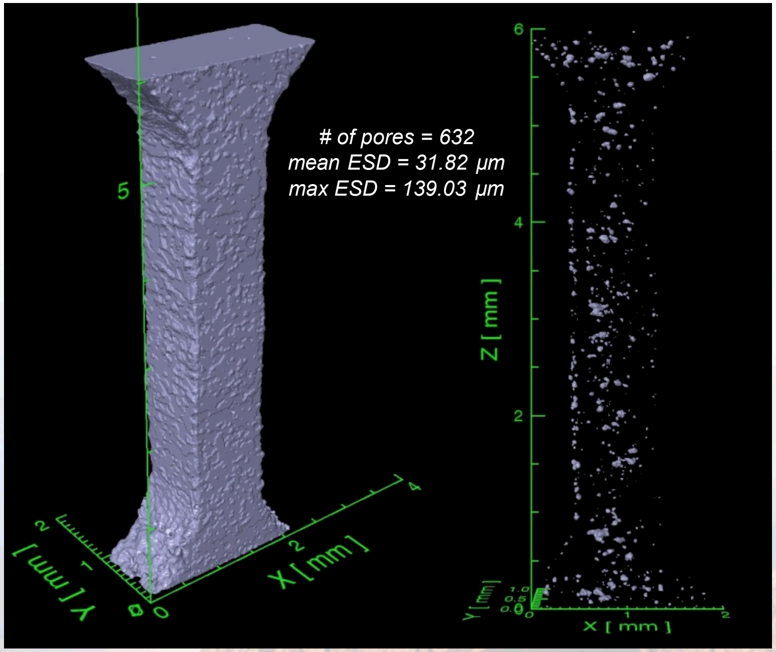
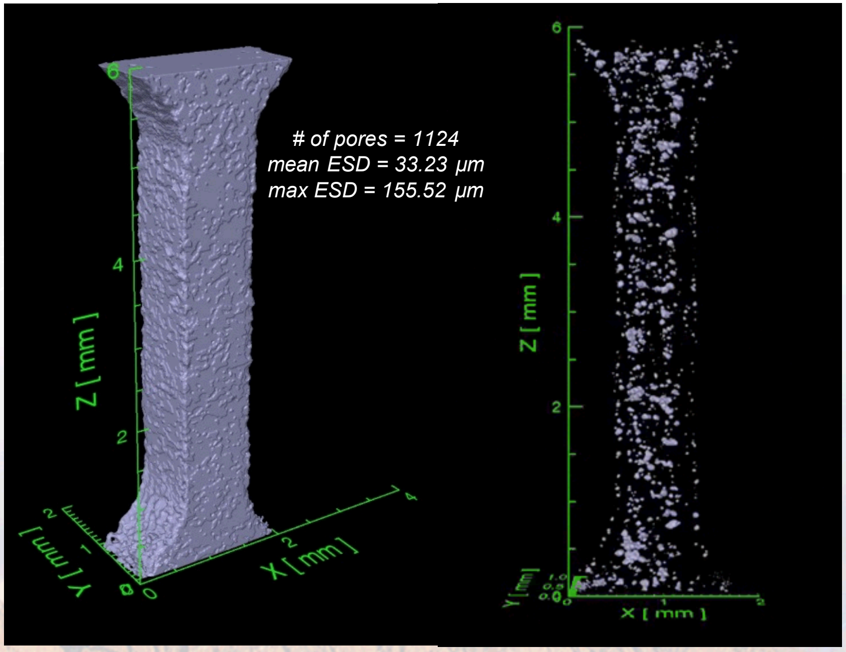
Still Working to Understand Defects Sensitivities and Failure Modes

- Dogbones
  - Gage sections imaged w/resolution of 7 or 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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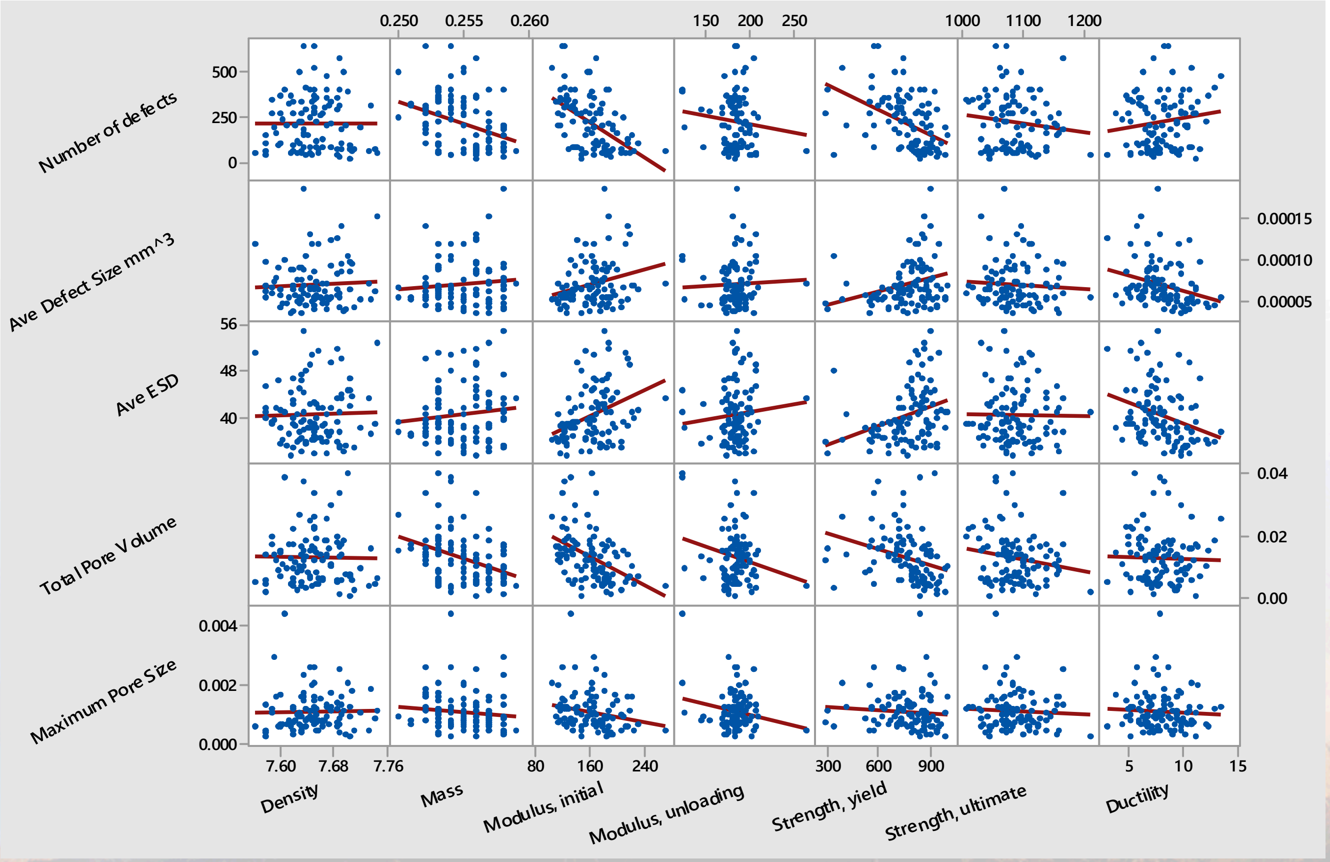
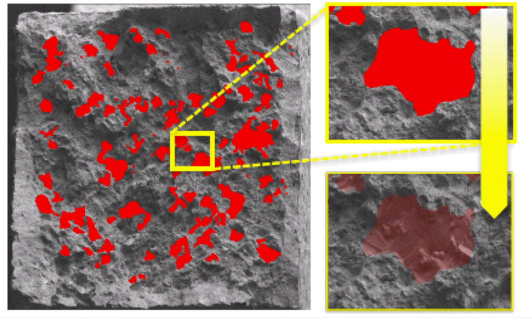
On-going Data Correlation Shows Few Strong Correlations

- Tools
  - Scatter plots, cluster analysis, spatial correlations, area fractions, …
- Metrics
  - Defect size, number, volume, density, void fractions
- Current effort exploring fractography, tomography, & FEA relationships



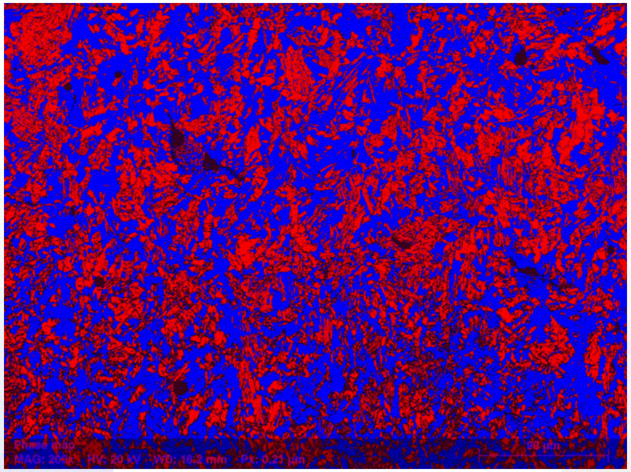
ESD = Equivalent Spherical Diameter



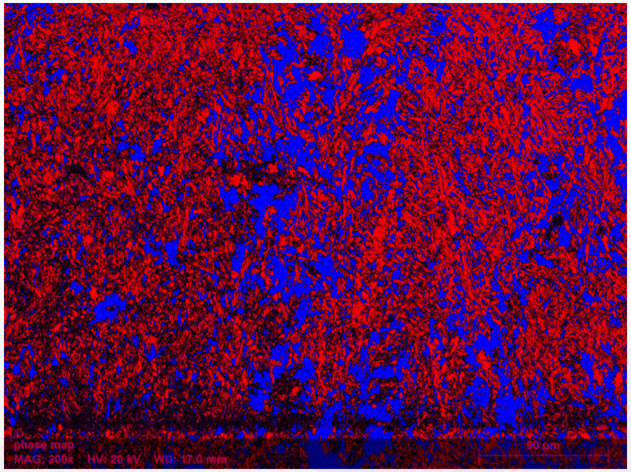
fracture surface w/highlighted void fractions

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

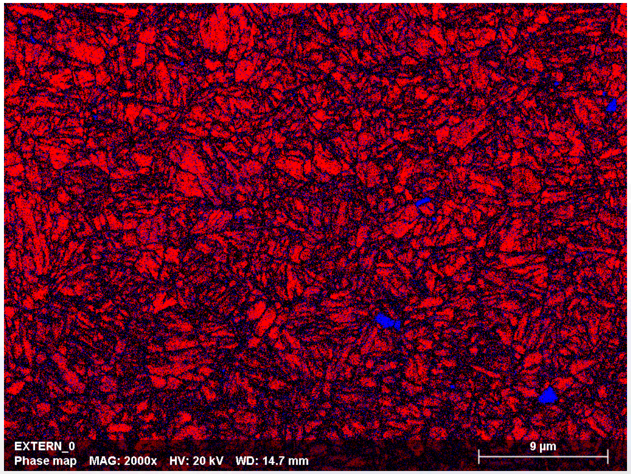
- Anomalous phase composition in AM vs. wrought 17-4 PH Stainless
  - Large fraction of retained austenite after solution heat treatment + H900 age
  - cryo treatment to -196^{o}C for 5 min still does not transform austenite



As-printed, 47% Austenite



SHT + H900 Age, 43% Austenite

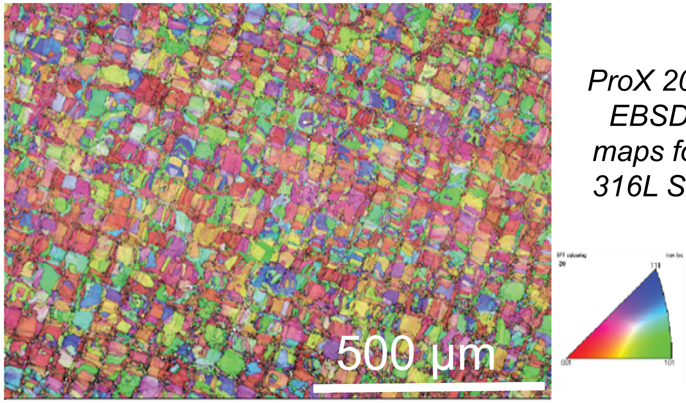


Wrought Sheet Shows Fine-grained Martensite

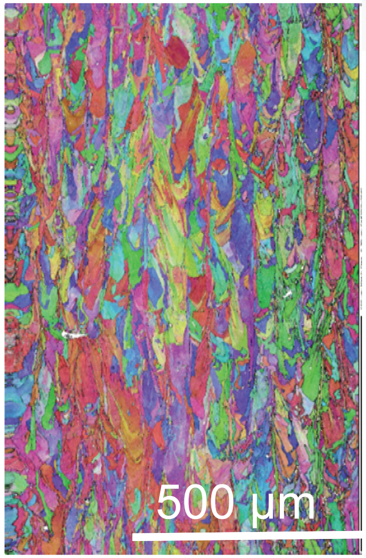
Blue *= austenite (FCC),* ***Red*** *= martensite / ferrite (BCC),* ***Black*** *= not indexed*

AM 316L Has Unique Microstructure with Reasonable, But Still Highly Variable Properties

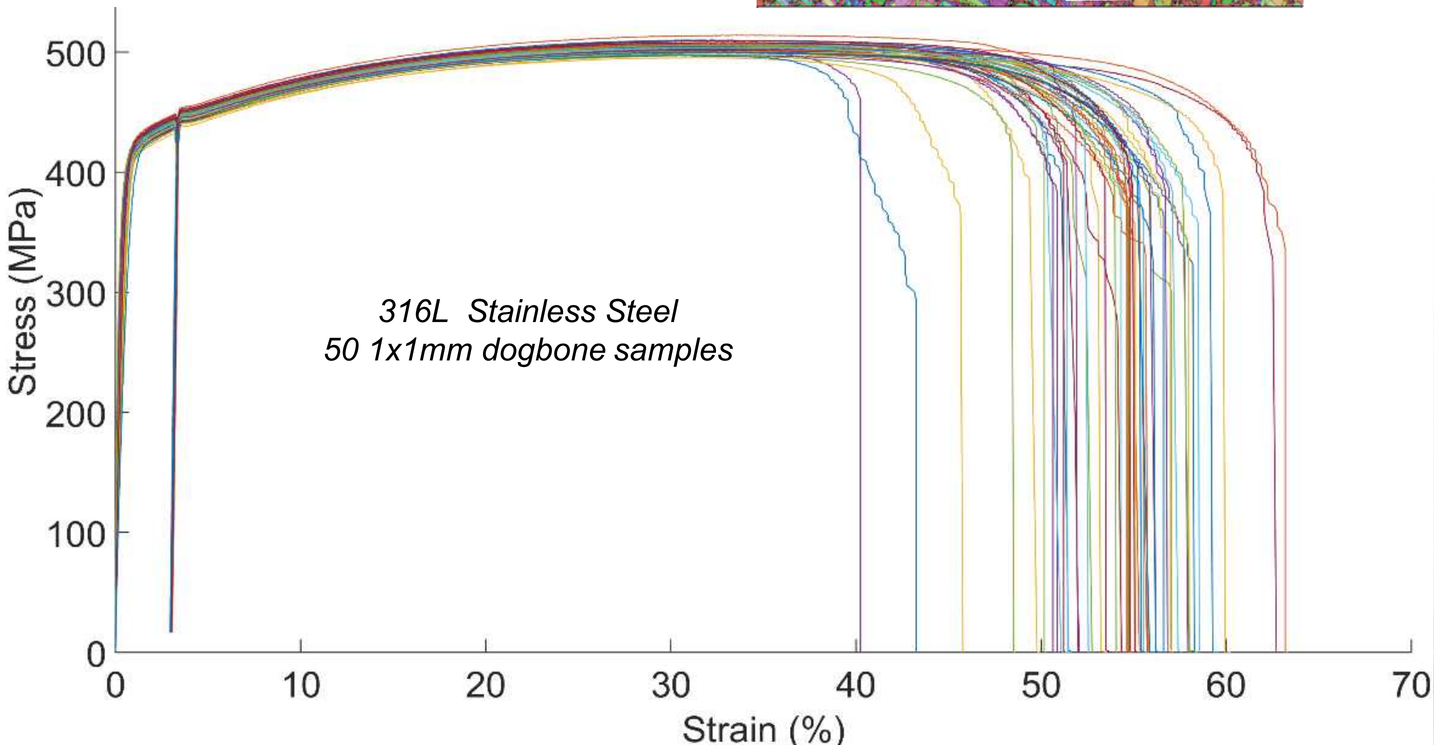
Top View
(Normal to Build Direction)



ProX 200 EBSD maps for 316L SS



Cross Section
(Parallel to Build Direction)



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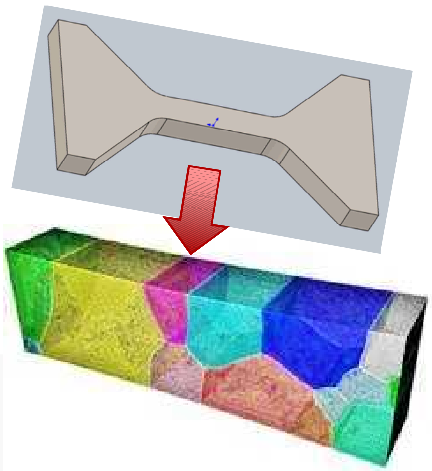
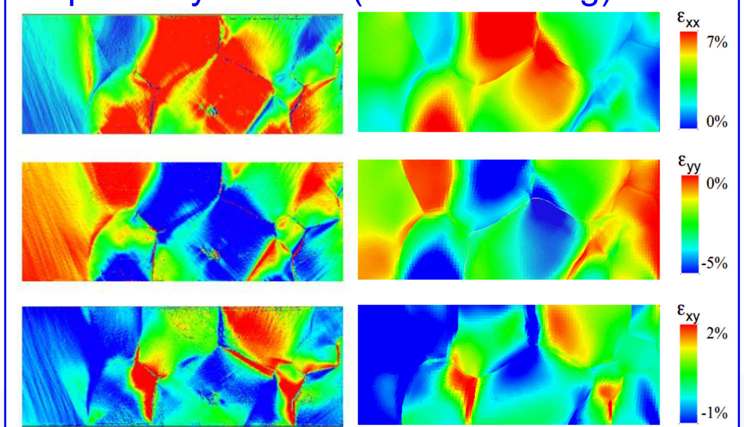
Leverage Sandia PPM to Investigate Variability/Defect Sensitivity

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)

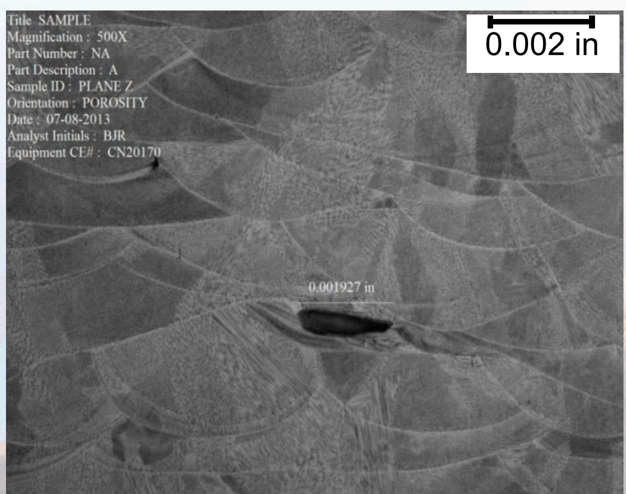


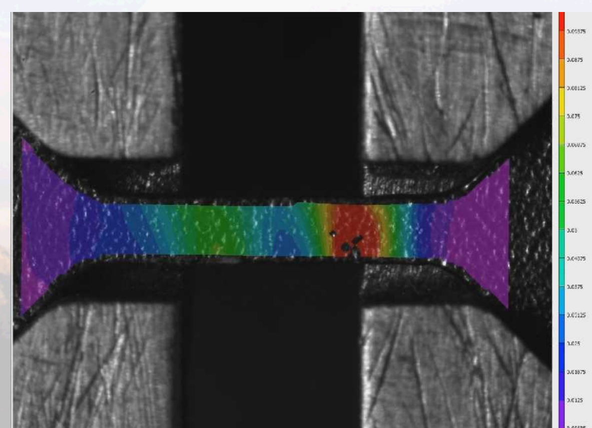
Experimental Results **Computed Simulations**

Key Questions:

What AM Defects Matter?

Can I detect them?





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

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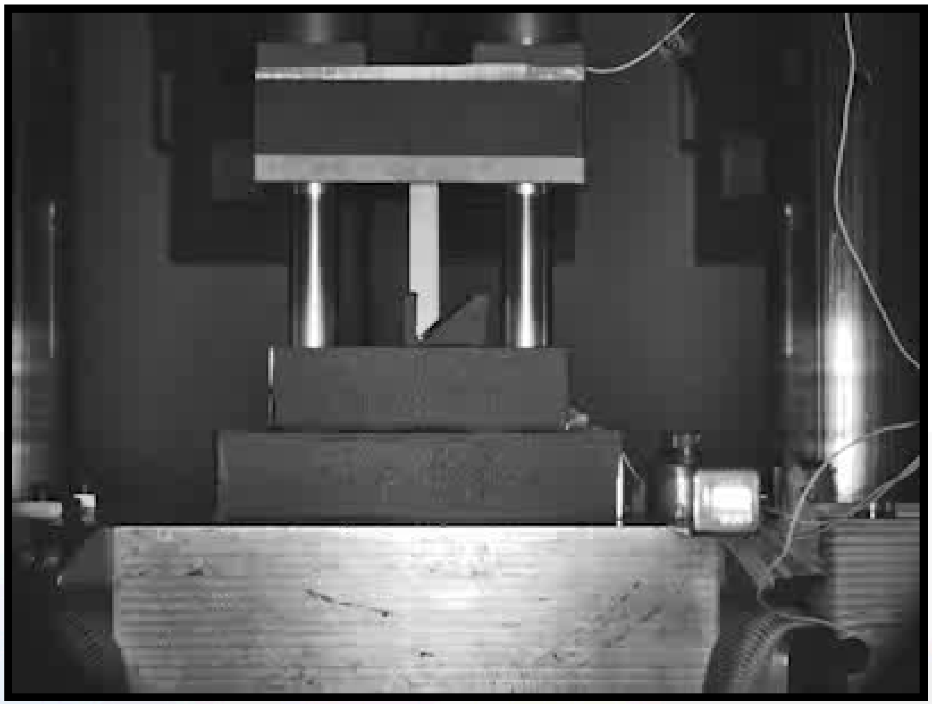
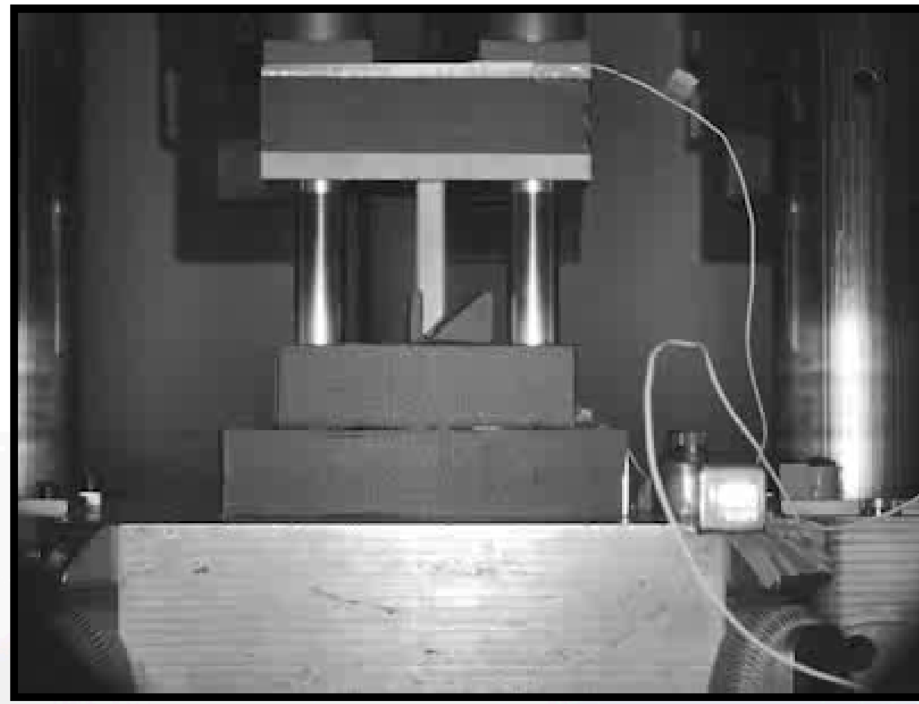
Despite Defects, AM Parts Can Offer Good Performance



Machined/Welded Housing
4047 Al alloy
weight = 45 grams



Additively Manufactured Housing
AlSi10Mg Al alloy
weight = 38 grams

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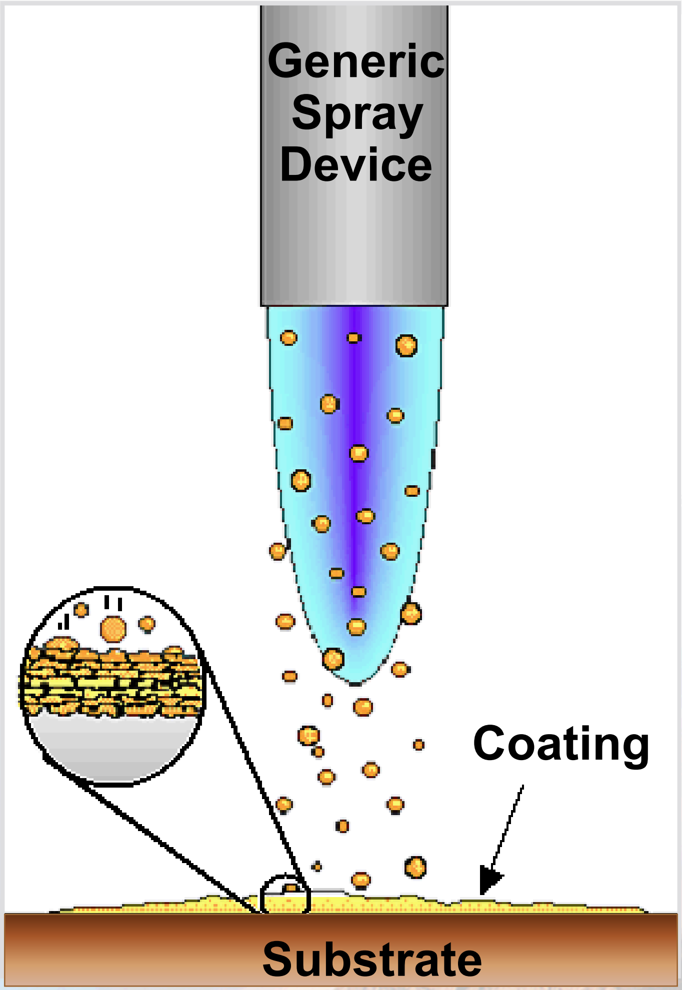
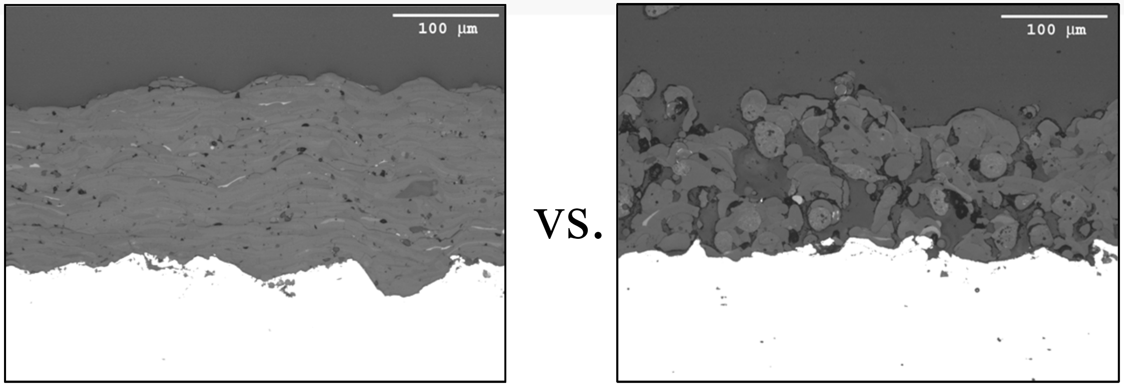
Build on Prior Success with Process Control of Another AM Process --Thermal Spray

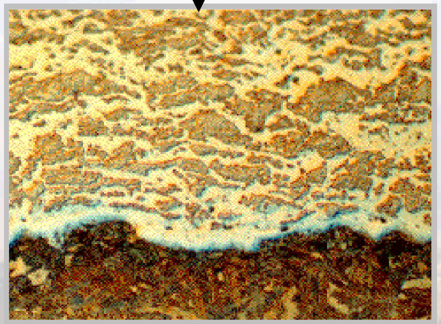


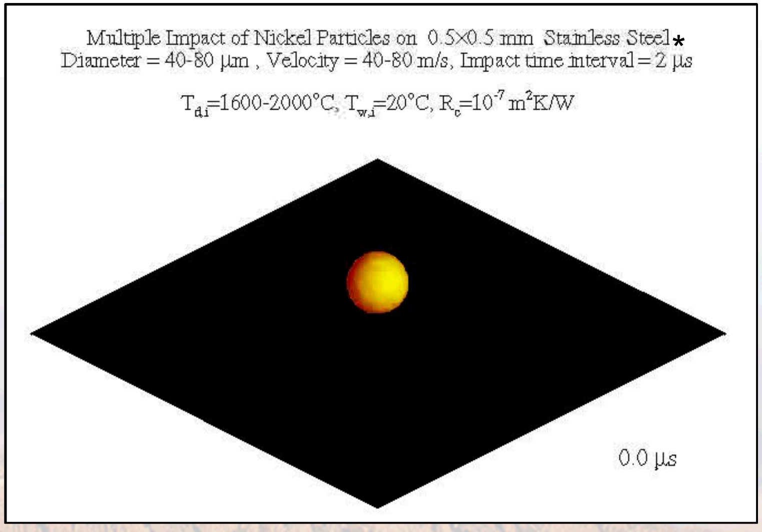
Same System, Same Feedstock,



Very Different Results

Cemented Carbide Coating On Steel





AM today is similar to Thermal Spray ~20 years ago

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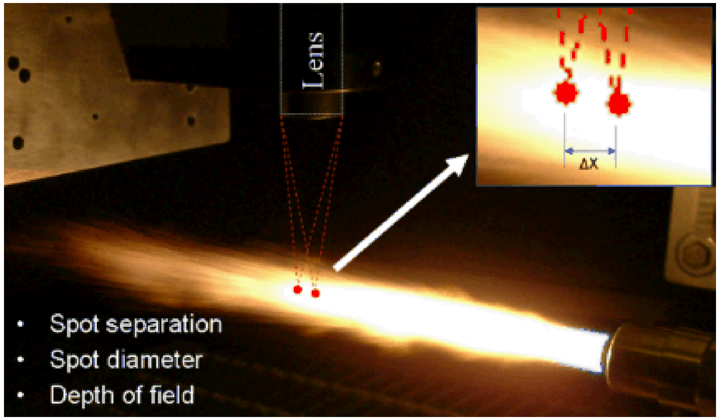
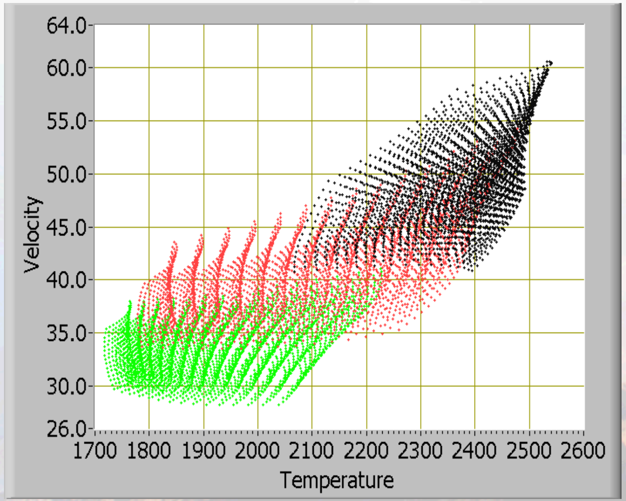
*Droplet Impact Simulation by Prof. J. Mostaghimi, et al. Univ. of Toronto

Fundamental Process Understanding is Key to Controlling Variability

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

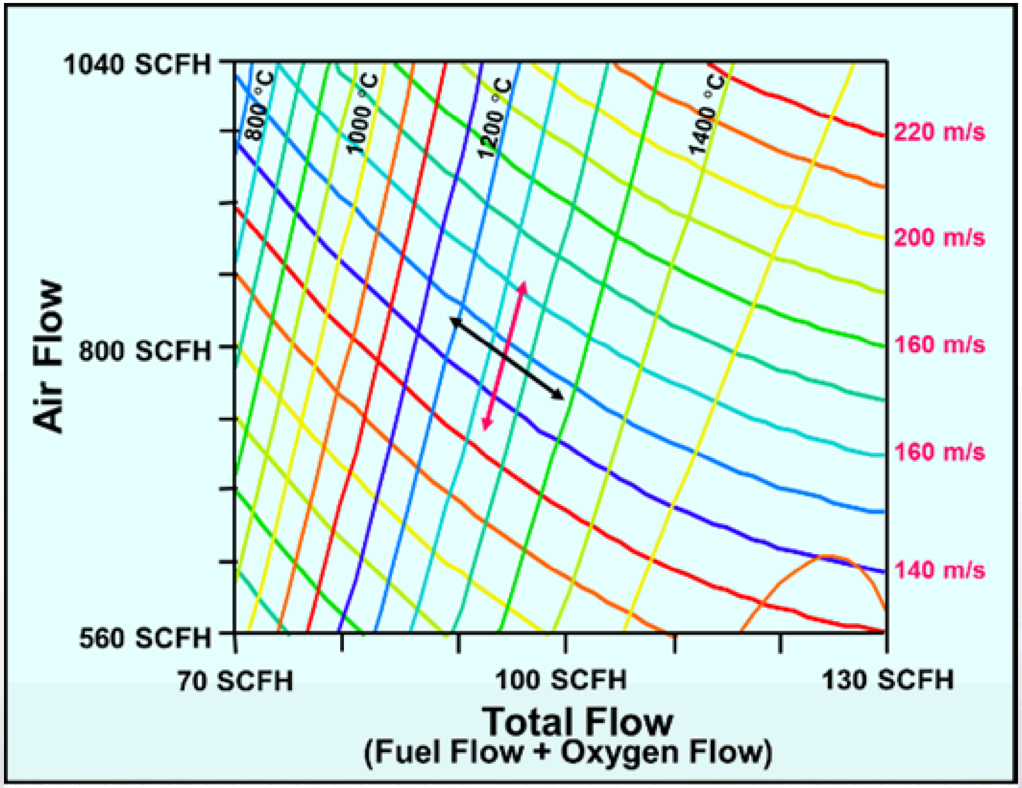


Process Diagnostics/Monitoring



Process Modeling
(All possible vel/temp regimes as a function of torch hardware)

- 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)

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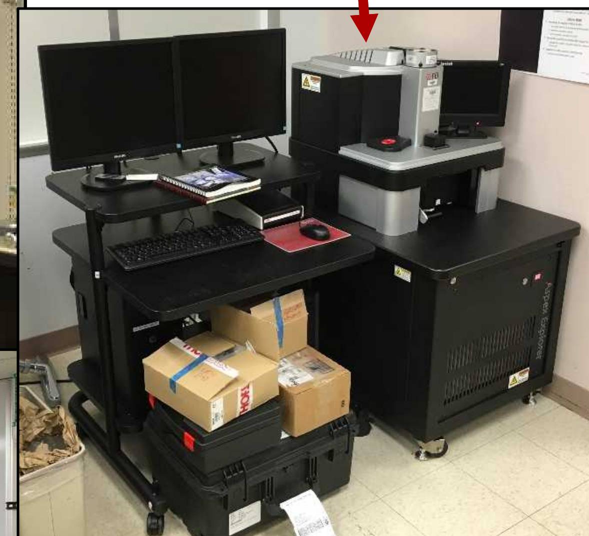
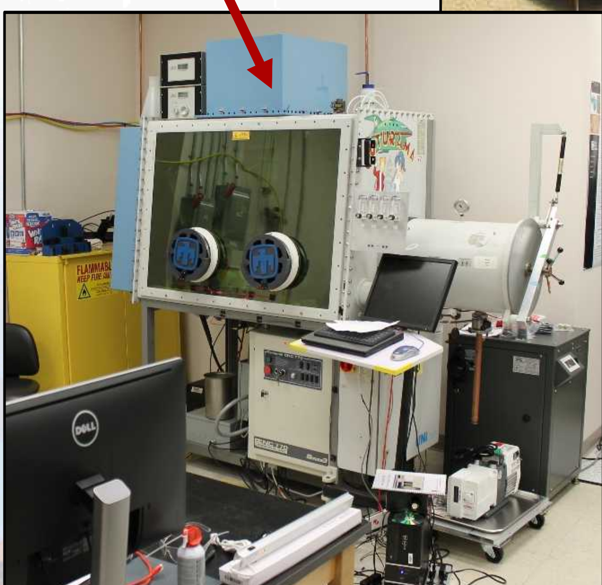
Sandia Metal/Multi-Material AM Process R&D Laboratory

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 will be Modified for Multi-Material hybrid AM, including LENS™

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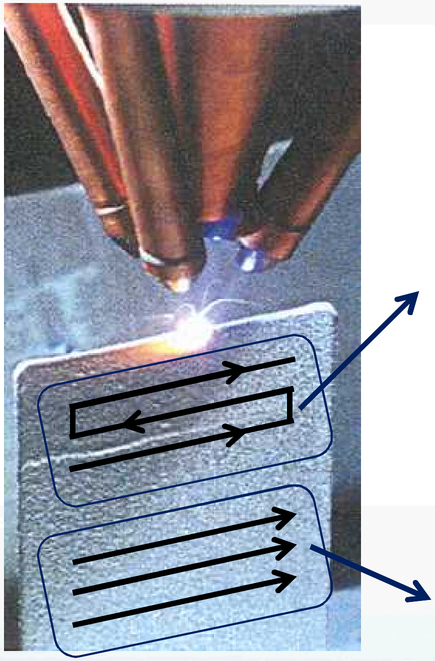
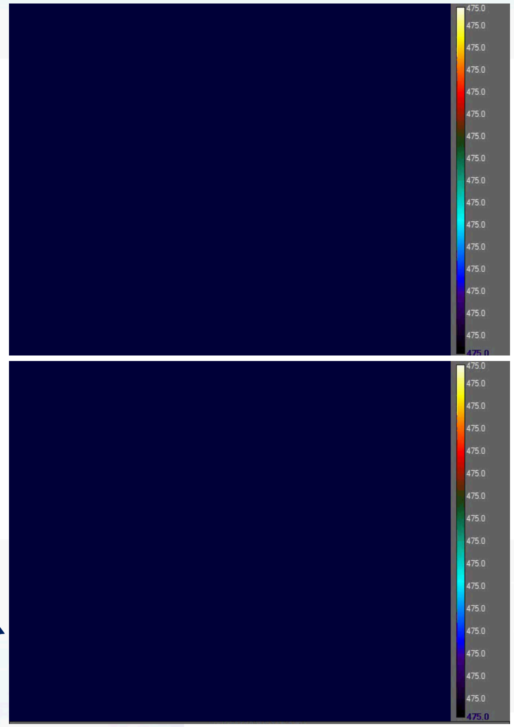
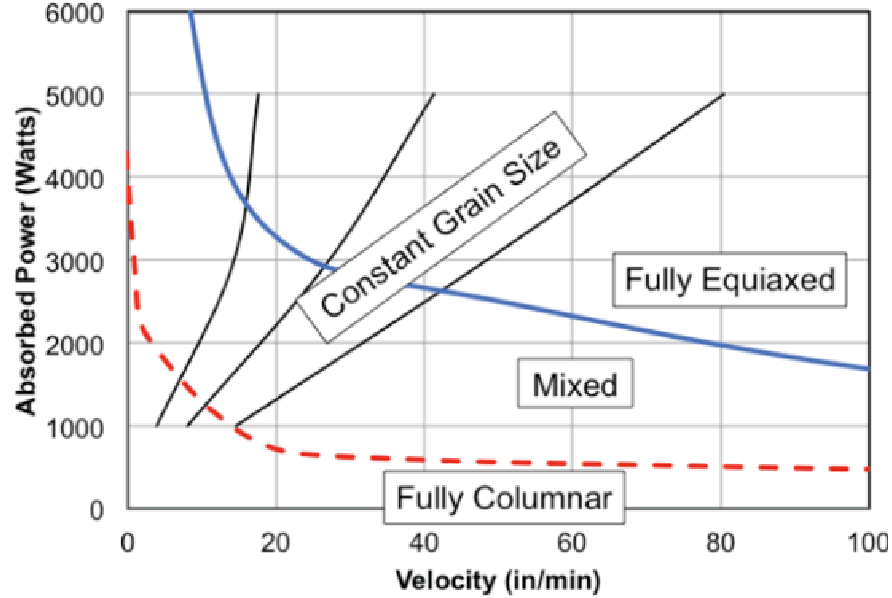
Working to Understand LENS™ Processing-Microstructure Relationships

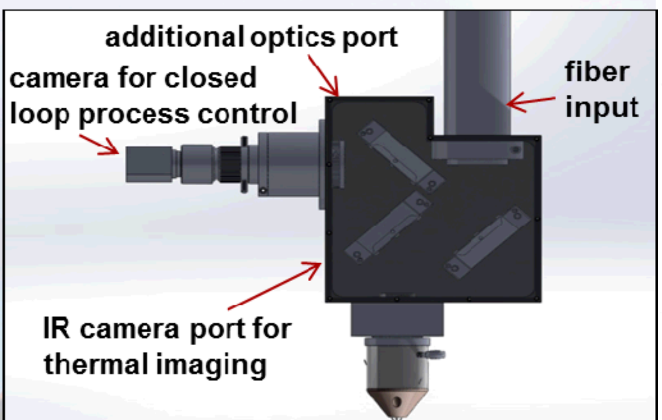


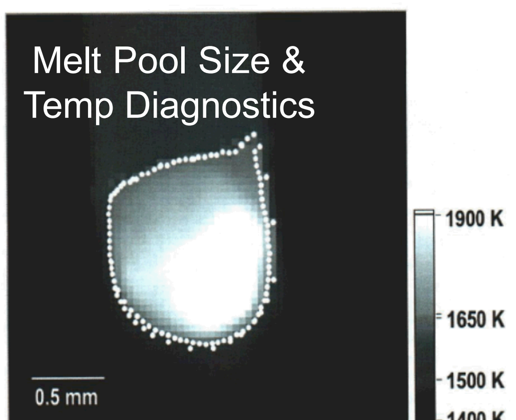


Processing-Microstructure Relationships
(teaming w Carnegie Mellon)



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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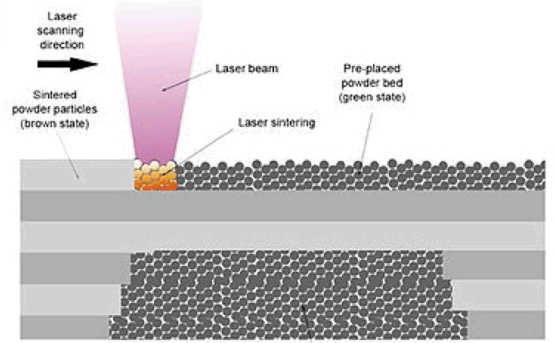
Process Models Involve Complex Physics

Goal: Link AM mesoscale processes to macroscale performance

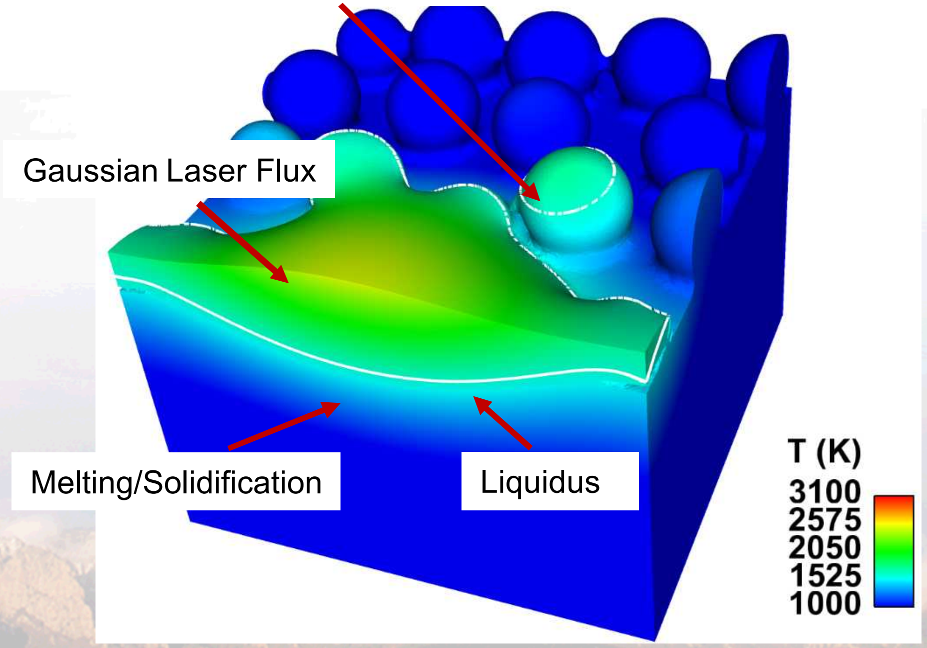
Method: Conformal level-set technology includes melt and ambient gas dynamics

- Laser energy coupling to particle packs
- Melt/solidification, capillary-driven flow, buoyant gas convection, solutal segregation
- Impact of laser setting: power, spot size, scan rate, hatch spacing, ...
- Laser schedule: edge modulation, variable power, variable spot,
- Beam overlap, remelt, porosity

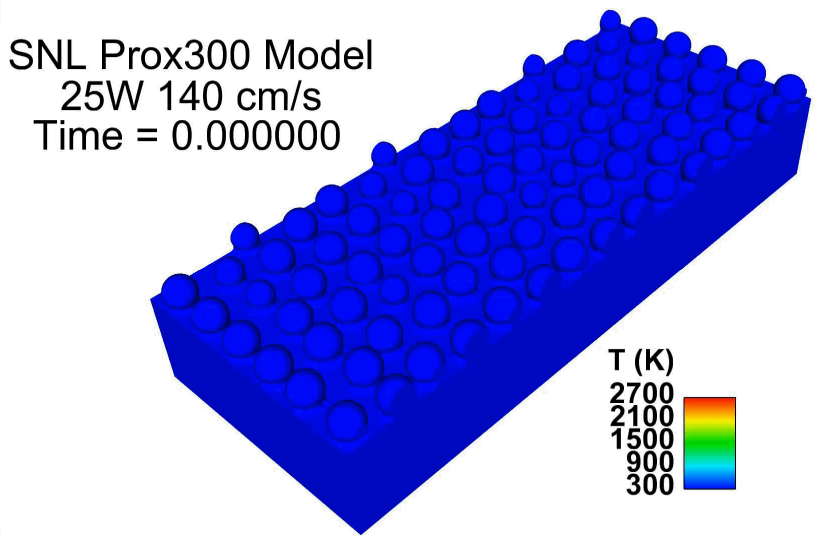
"Selective laser sintering", Wikipedia

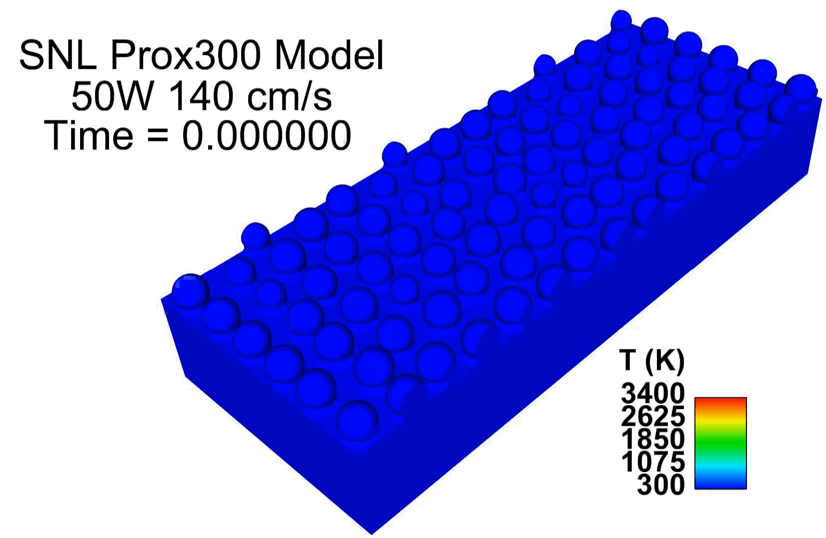


- Recoil Pressure
- Curvature & Maragoni Stress
- Ablative, Radiative & Convective Heat Loss

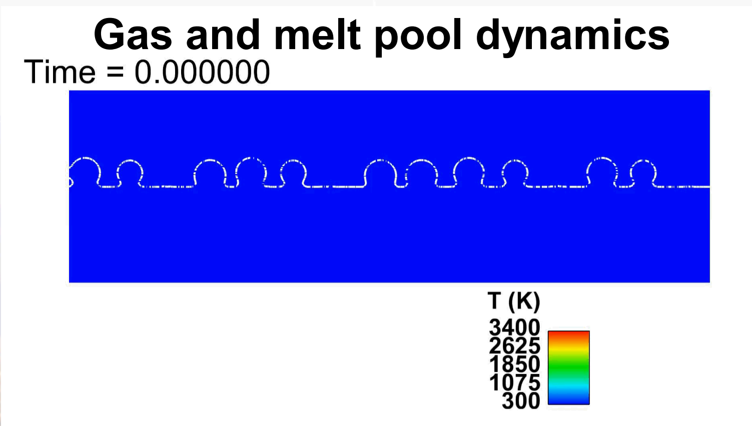


Process Modeling Can Provide Useful Insights





Stainless steel 304L
25 micron powder



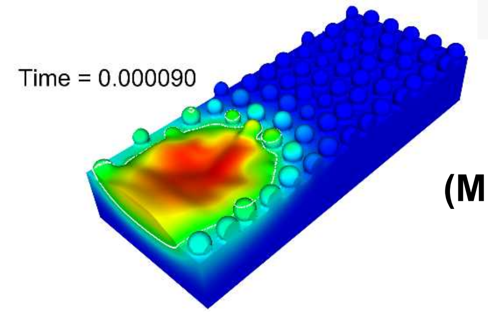
Notes:

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

Multiple Scale Powder Bed Modeling

Powder bed fusion model

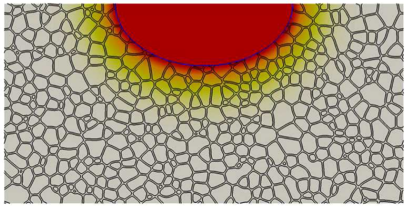
- High-fidelity melt-pool modeling
- Interactions of laser with powder bed, melt pool
- Solidification – grain morphology



(M. Martinez)

Phase field solidification model

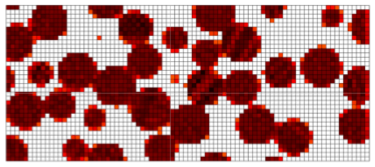
- Grain morphology



(F. Abdeljawad)

Atomistic model of thermal transport in nanoparticle powder beds

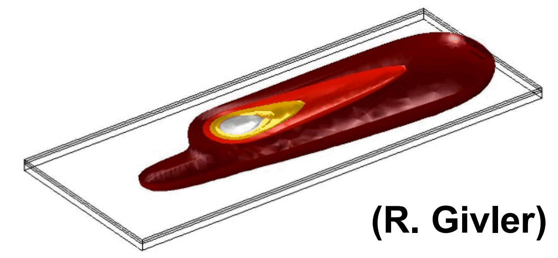
- Link to macroscale thermal model



(M. Wilson & M. Chandross)

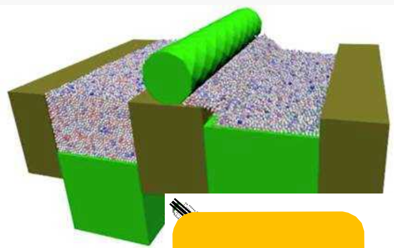
Macroscale powder bed model

- Methods for modeling part-scale PBF process
- Optimization of laser paths (100's of passes)



(R. Givler)

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



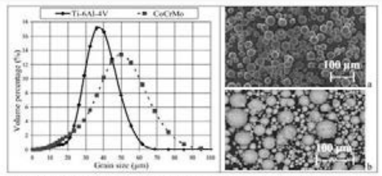
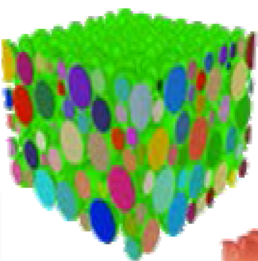
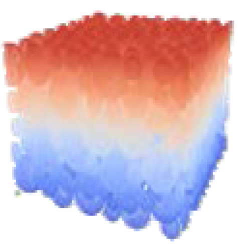
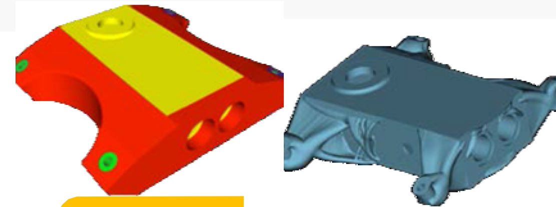
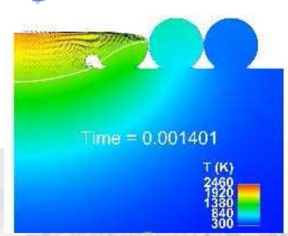


Fig. 1: Grain size distribution and micrographs of titanium (a) and cobalt-chromium (b) powder.



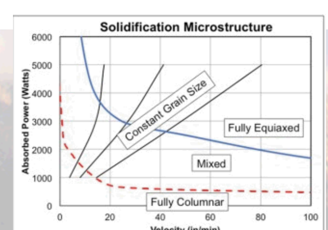


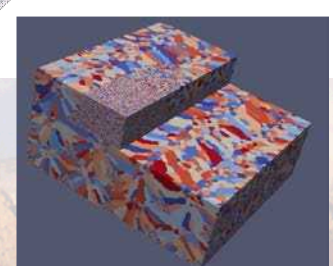


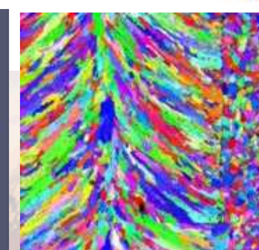


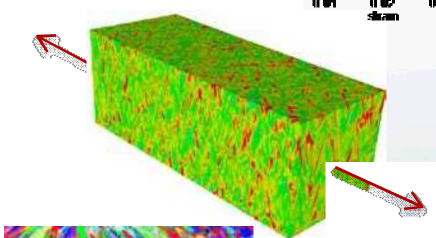
Particle packing → *Heat Transfer* → *Partial melt & flow* → *Molten pool dynamics* → *Solidification* → *Microstructure* → *Property-Performance* → *Topology Design*

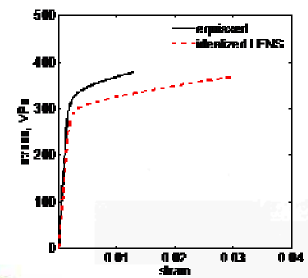
- Process control
- Materials characterization
- Interfaces
- GRANTA database











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Multi-Material AM

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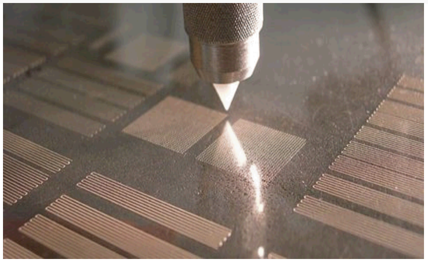
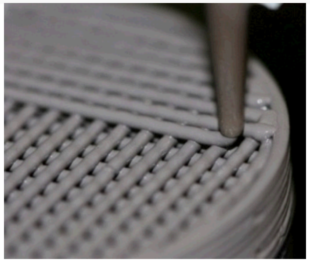
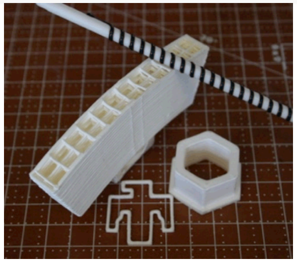
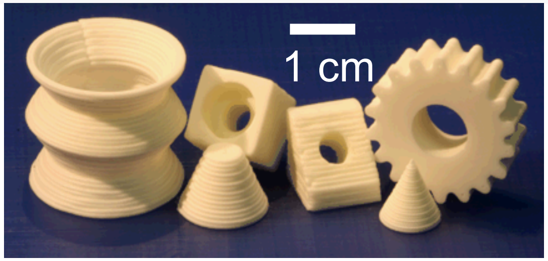
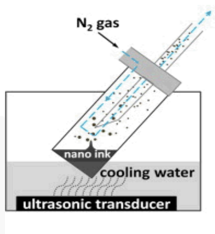
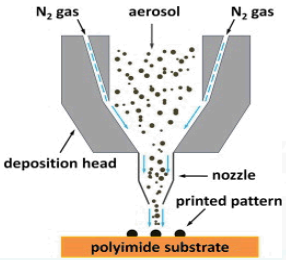
Direct Write Technologies Enable Access To Materials Not Supported By Conventional Printing Processes

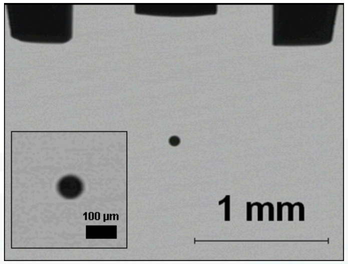
Direct Write by Extrusion Casting (Robocasting)

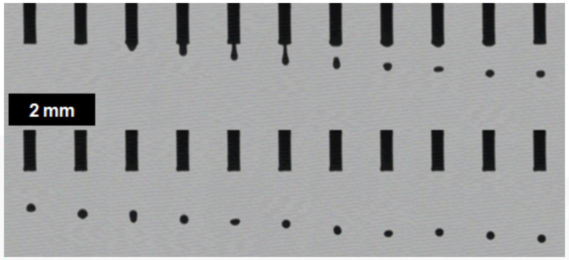





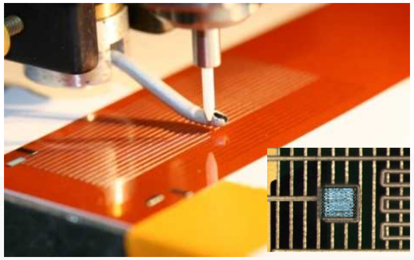
Direct Write by Aerosol & Ink Jet Deposition



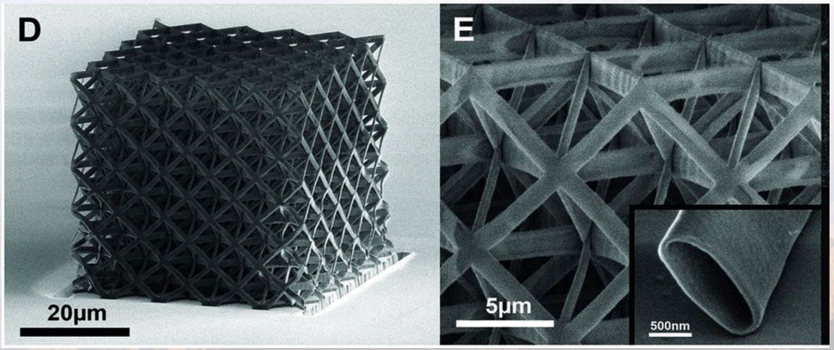


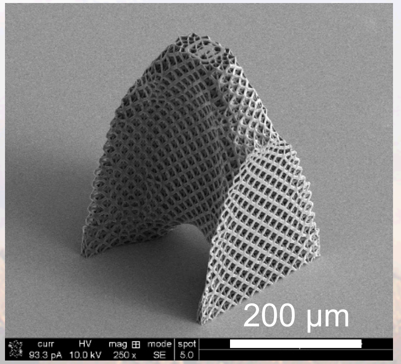


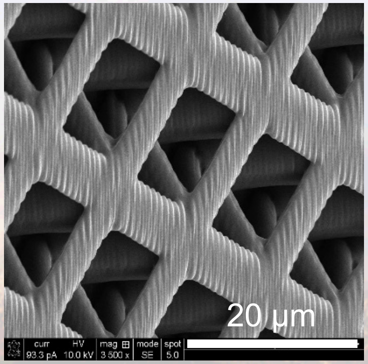




Direct Write by Laser Lithography







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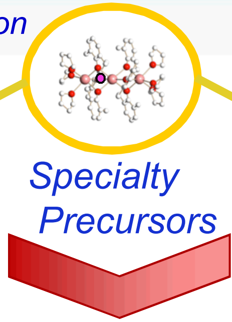
From Nano-Materials to Components at the Sandia Advanced Materials Lab

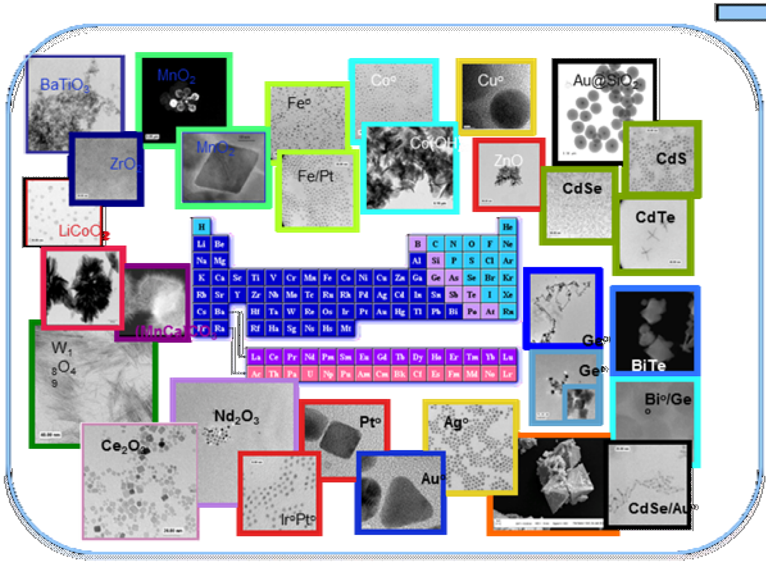
Solution Precipitation



Specialty Precursors

Solvothermal

Speicalized Nanomaterials



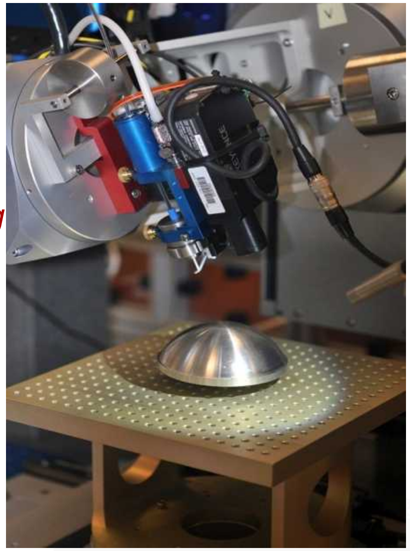
Specialty Inks

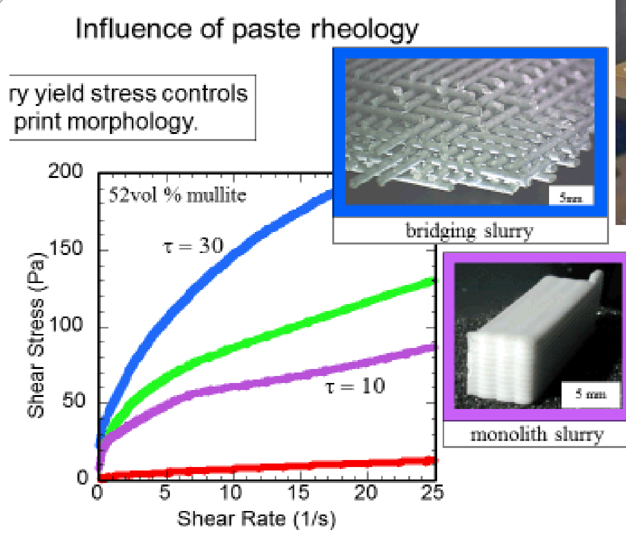
Colloidal Chemistry

Ink Characterization

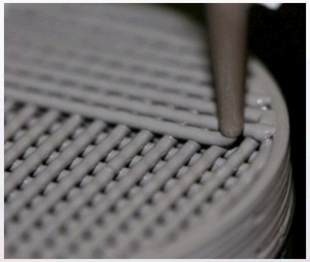
Process Engineering

Direct Write Printed Parts





Rheology Tailoring



Aerosol, Inkjet, extrusion

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

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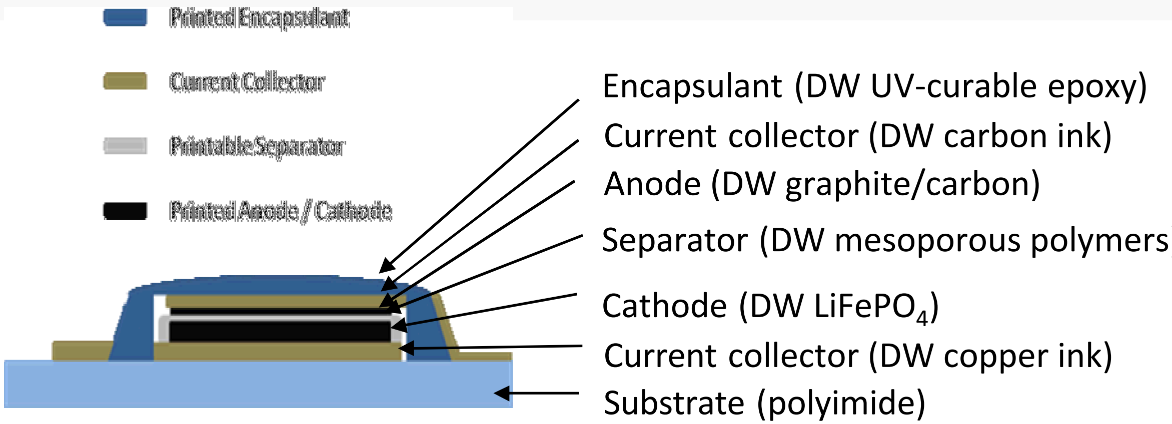
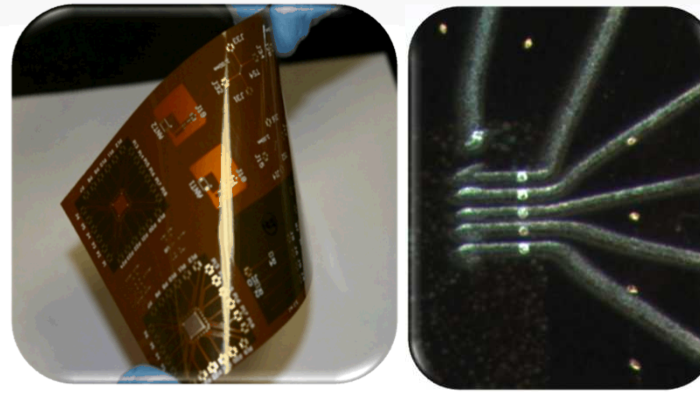
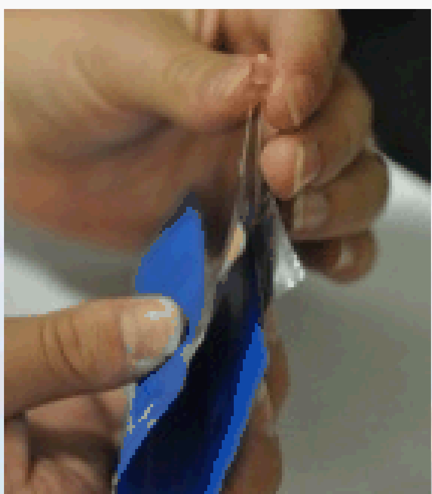
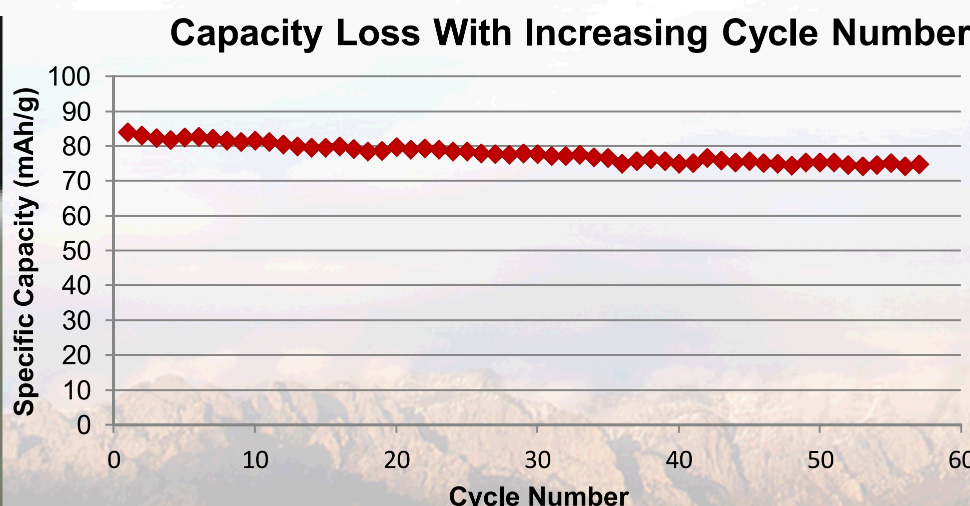
Printed Electronics

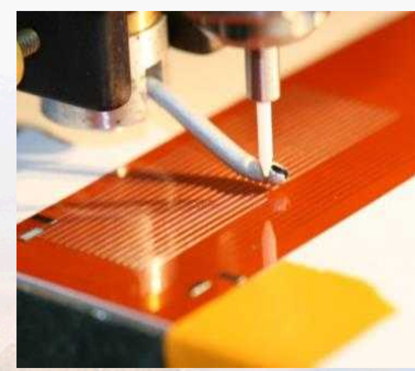




"Flexible Chips" with
Printed Wirebonds







Aerosol jet printing to 10 μm

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Summary

- Sandia has a rich history in AM technology development & commercialization
- AM offer great new opportunities, but it is still immature and there is need for R&D
- Sandia AM R&D emphasizes:
  - Engineering Analysis Driven AM Design
  - Materials Assurance (reliability)
  - Multi-Material AM
- Sandia is very interested in working with others to advance AM technology