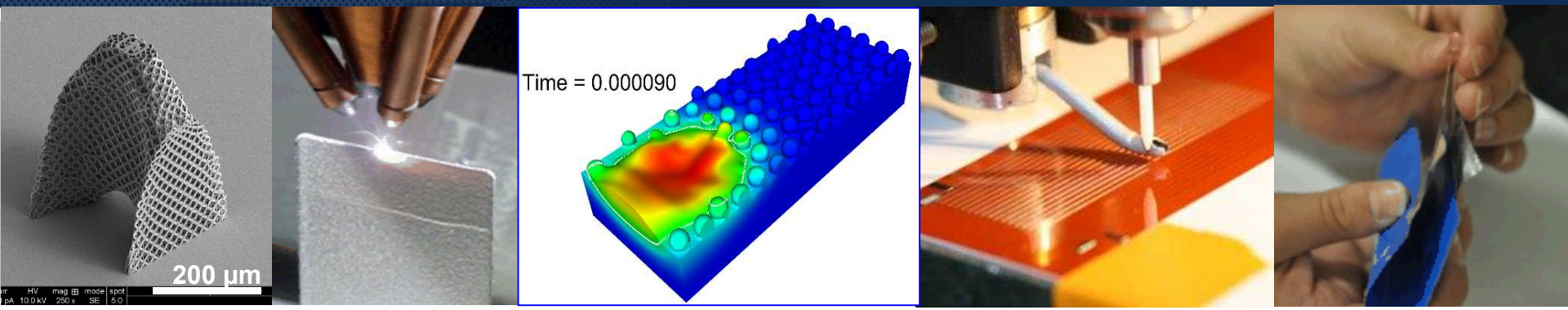
SAND2017-5094PE



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

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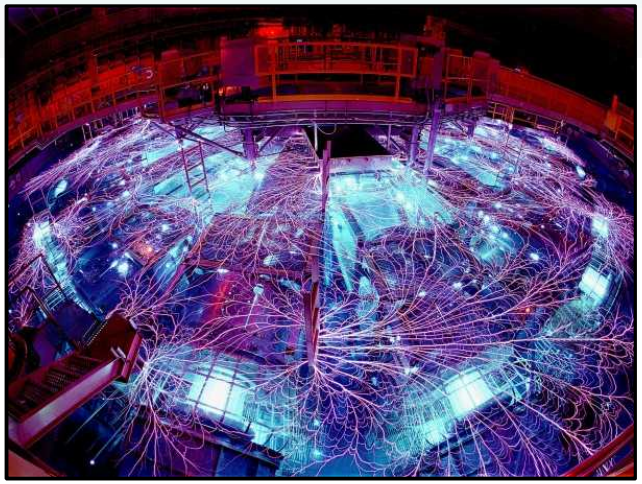
Sandia is a National Security Science and Engineering Laboratory

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

Materials Science Objective: Materials R&D conducted at Sandia will enable mission delivery now and in the future and advance the frontiers of science and engineering.

Three Major Areas of Materials R&D

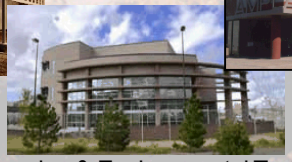
- *Materials Engineering Support*
  - Problem solving, program support
  - Application of existing expertise
  - Point solutions
- *Materials & Process Advanced Development*
  - Advanced & exploratory materials & process development
  - Production process development & technology transfer
  - Understanding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

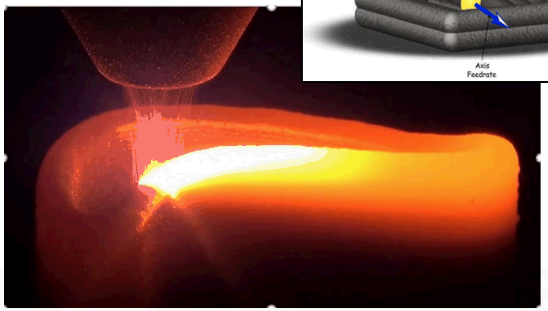
30+ Years of Sandia AM Technology Development & Commercialization

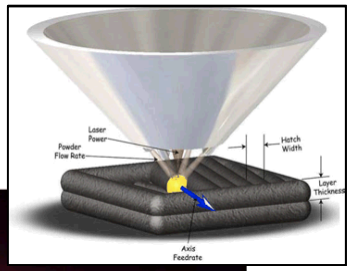
FastCast *
Development Housing

Laser Engineered Net Shaping *

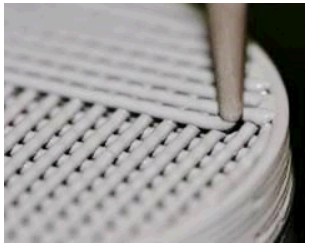
LENS®

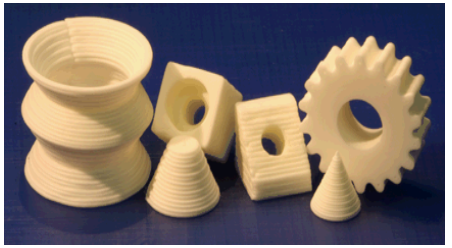
LENS Blade





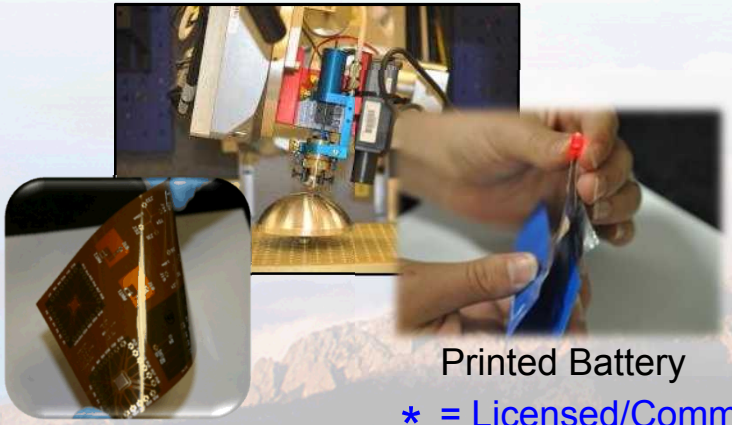
RoboCast *
Ceramic Parts





Energetic Materials

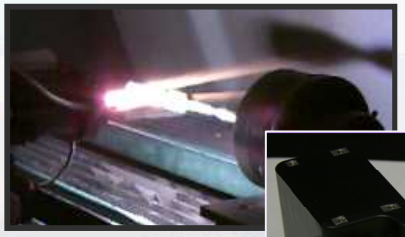
Direct Write
Conformal Printing



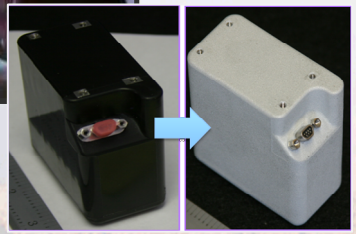
Flexible Electronics

Printed Battery

Thermal Spray

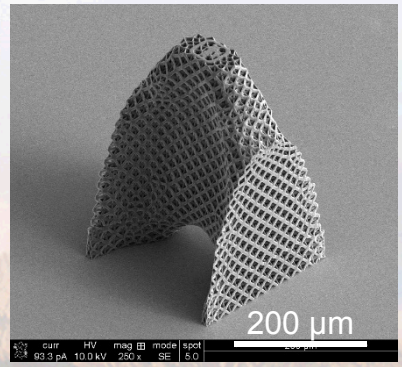


Spray-formed Rocket Nozzle



Metal on Plastic

Micro-Nano Scale AM
Lattice Structure



* = Licensed/Commercialized Sandia AM technologies

Underline = *Current Capability/Activity*

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Example Applications

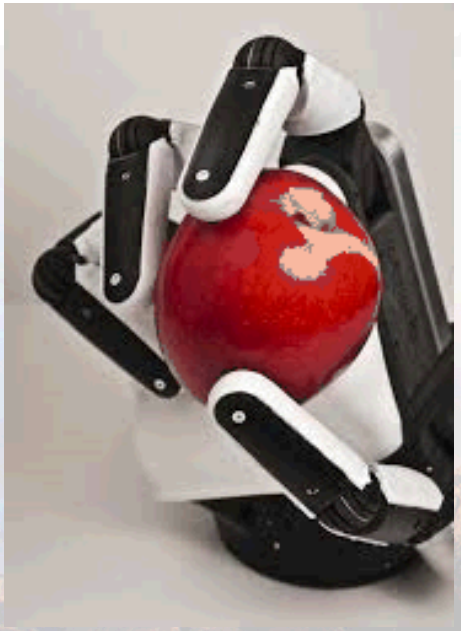
Sandia Hand – AM Enabled Innovative Design and Cost Reduction

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

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

DARPA

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



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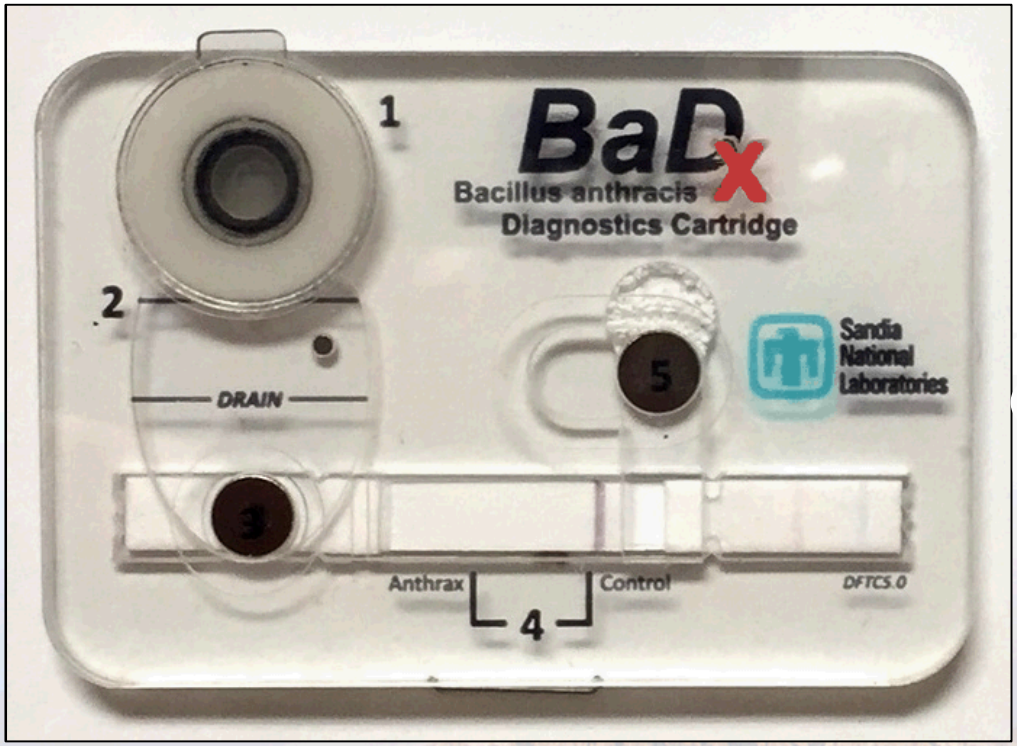
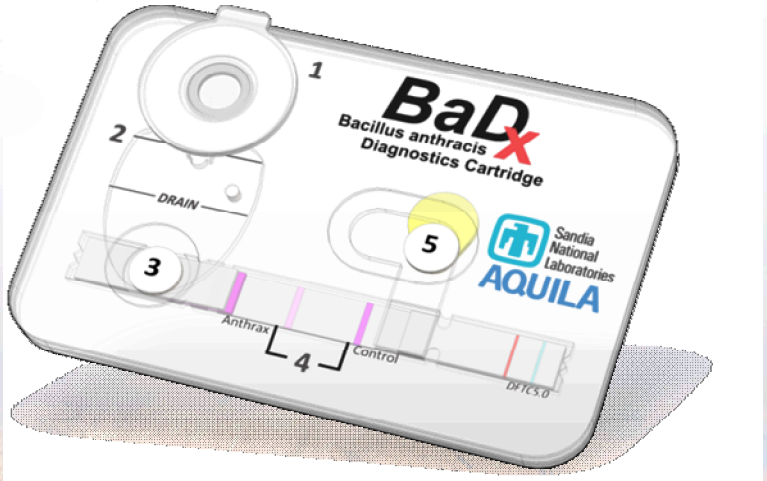
BaDx Anthrax Diagnostics Tool

- Microfluidic platform for bacterial detection
- 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.

Design/Analysis Tools

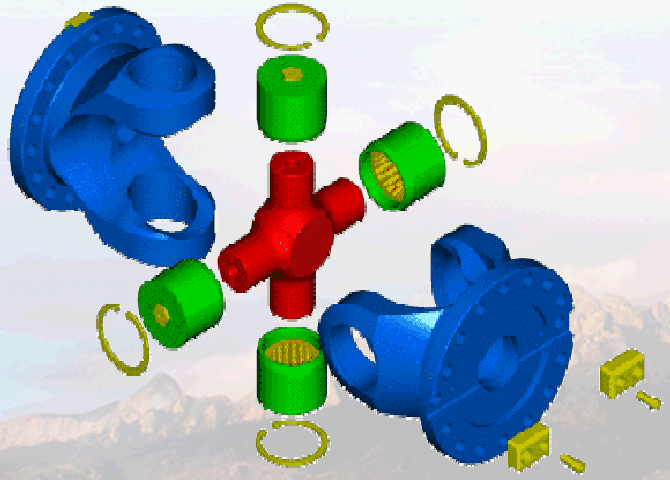
Analysis-Driven Design Optimization

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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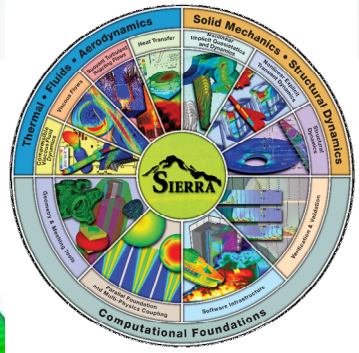
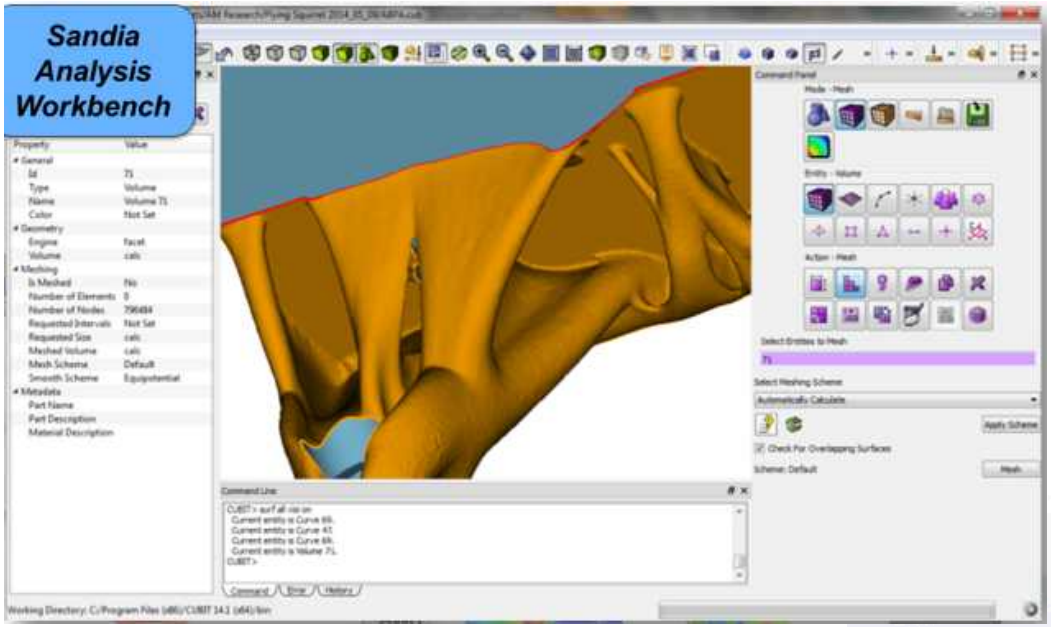
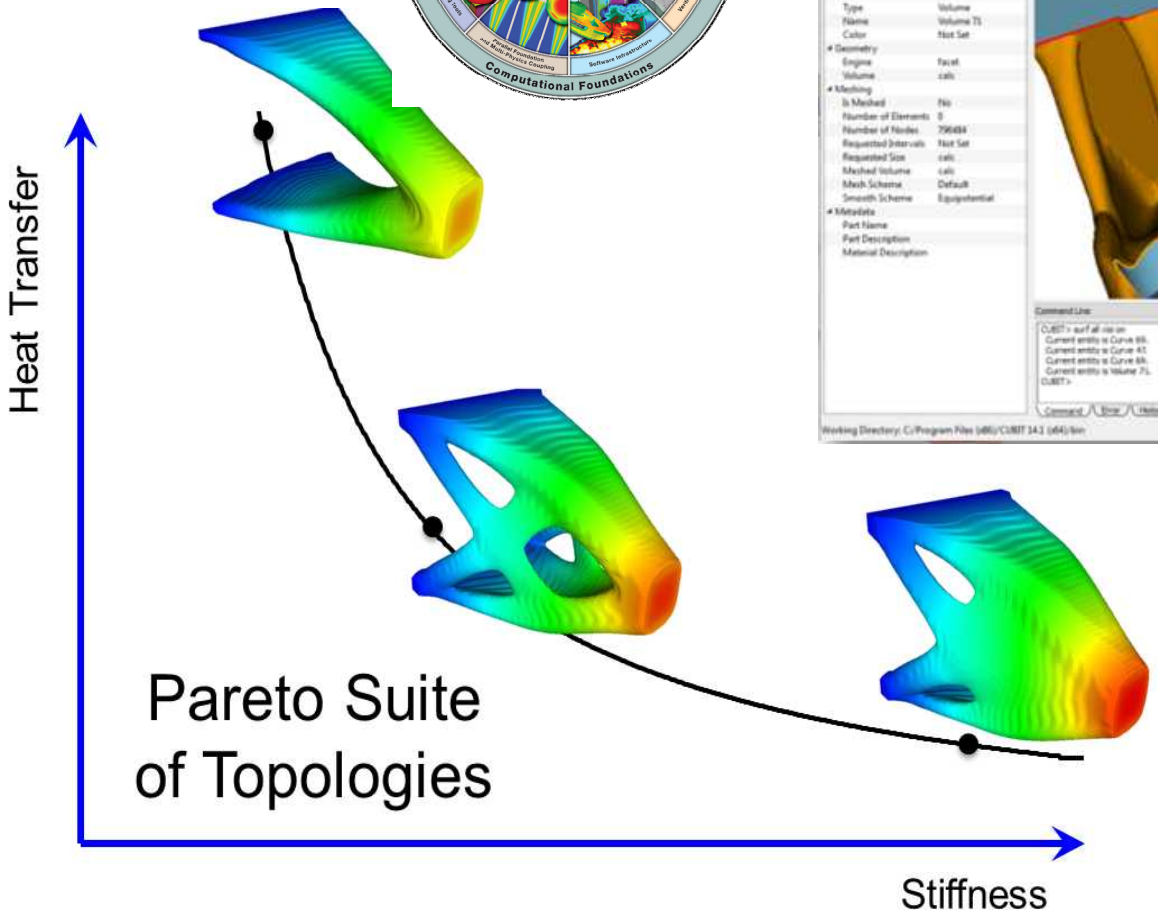
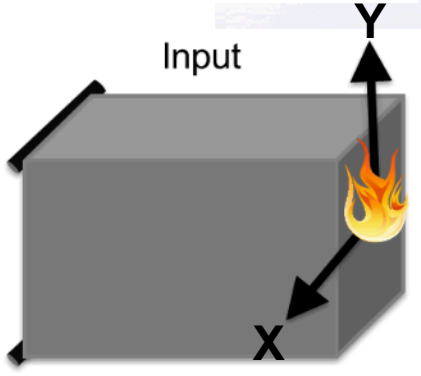
AM Design Via Functional Prioritization



User Friendly Interface







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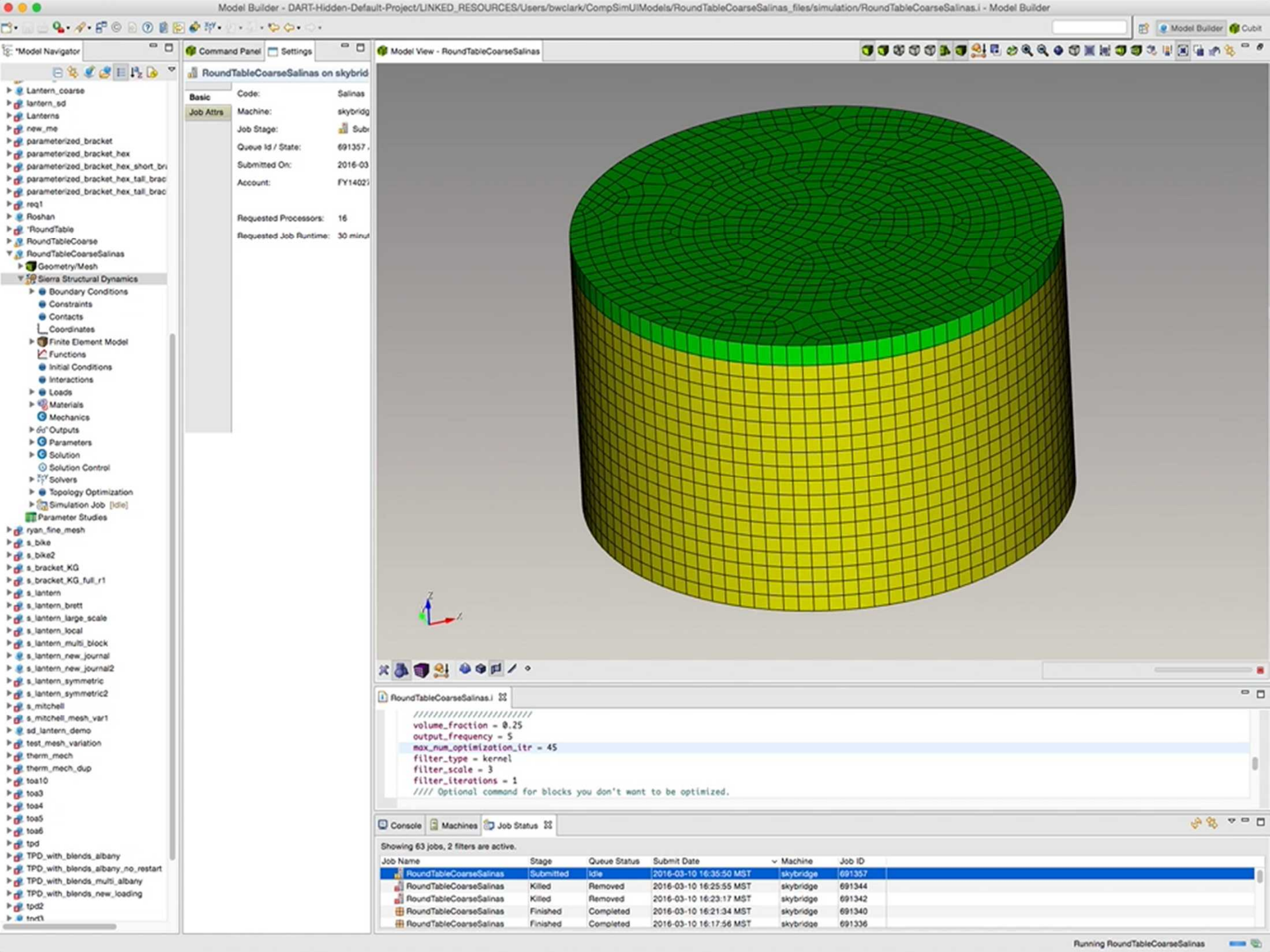
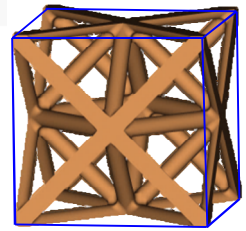
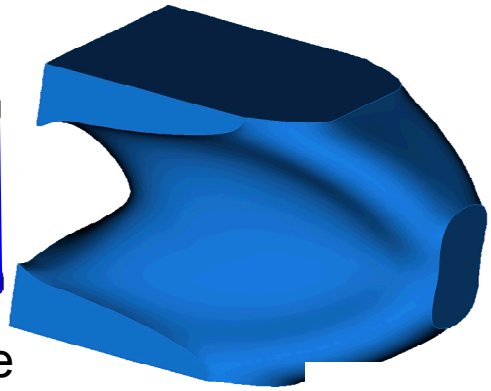
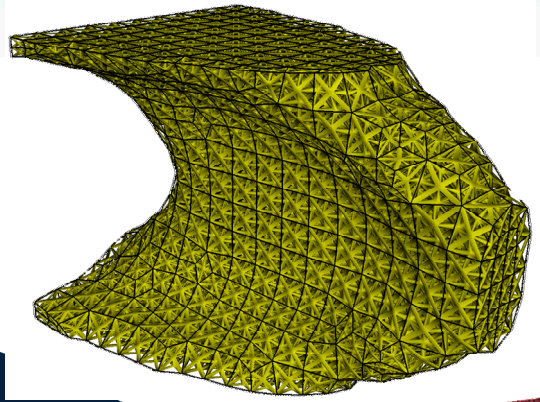

Model Builder - DART-Hidden-Default-Project/LINKED_RESOURCES/Users/bwclark/CompSimUIModels/RoundTableCoarseSalinas_files/simulation/RoundTableCoarseSalinas.i - Model Builder
*Model Navigator
Lantern_coarse
lantern_sd
Lanterns
new_me
parameterized_bracket
parameterized_bracket_hex
parameterized_bracket_hex_short_bri
parameterized_bracket_hex_tall_brac
parameterized_bracket_hex_tall_brac
req1
Roshan
*RoundTable
RoundTableCoarse
RoundTableCoarseSalinas
Geometry/Mesh
Sierra Structural Dynamics
Boundary Conditions
Constraints
Contacts
Coordinates
Finite Element Model
Functions
Initial Conditions
Interactions
Loads
Materials
Mechanics
Outputs
Parameters
Solution
Solution Control
Solvers
Topology Optimization
Simulation Job [Idle]
Parameter Studies
ryan_fine_mesh
s_bike
s_bike2
s_bracket_KG
s_bracket_KG_full_r1
s_lantern
s_lantern_brett
s_lantern_large_scale
s_lantern_local
s_lantern_multi_block
s_lantern_new_journal
s_lantern_new_journal2
s_lantern_symmetric
s_lantern_symmetric2
s_mitchell
s_mitchell_mesh_var1
sd_lantern_demo
test_mesh_variation
therm_mech
therm_mech_dup
toa10
toa3
toa4
toa5
toa6
tpd
TPD_with_blends_albany
TPD_with_blends_albany_no_restart
TPD_with_blends_multi_albany
TPD_with_blends_new_loading
tpd2
Command Panel
Settings
RoundTableCoarseSalinas on skybrid
Basic
Job Attrs
Code: Salinas
Machine: skybridg
Job Stage: Subi
Queue Id / State: 691357
Submitted On: 2016-03
Account: FY1402
Requested Processors: 16
Requested Job Runtime: 30 minut
Model View - RoundTableCoarseSalinas
RoundTableCoarseSalinas.i
volume_fraction = 0.25
output_frequency = 5
max_num_optimization_itr = 45
filter_type = kernel
filter_scale = 3
filter_iterations = 1
//// Optional command for blocks you don't want to be optimized.
Console
Machines
Job Status
Showing 63 jobs, 2 filters are active.
Job Name | Stage | Queue Status | Submit Date | Machine | Job ID
RoundTableCoarseSalinas | Submitted | Idle | 2016-03-10 16:35:50 MST | skybridge | 691357
RoundTableCoarseSalinas | Killed | Removed | 2016-03-10 16:25:55 MST | skybridge | 691344
RoundTableCoarseSalinas | Killed | Removed | 2016-03-10 16:23:17 MST | skybridge | 691342
RoundTableCoarseSalinas | Finished | Completed | 2016-03-10 16:21:34 MST | skybridge | 691340
RoundTableCoarseSalinas | Finished | Completed | 2016-03-10 16:17:56 MST | skybridge | 691336
Running RoundTableCoarseSalinas

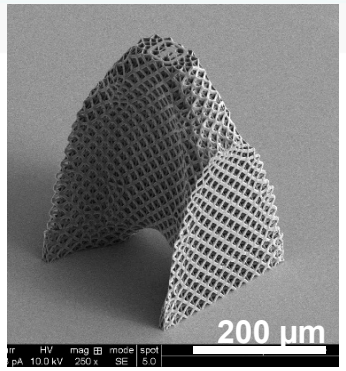
Optimizing Stiffness at Fixed Mass

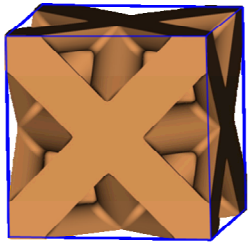


10% Dense

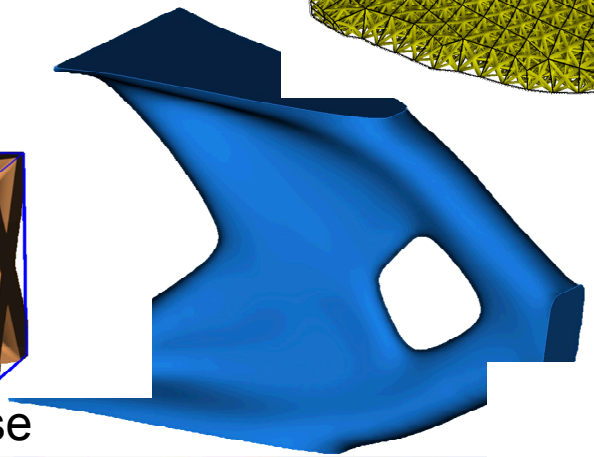


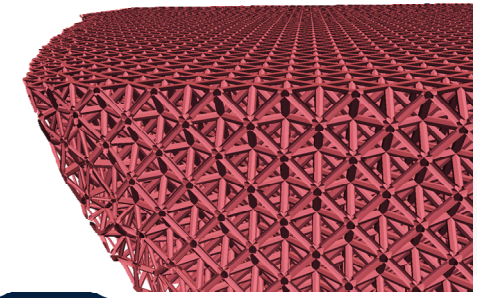




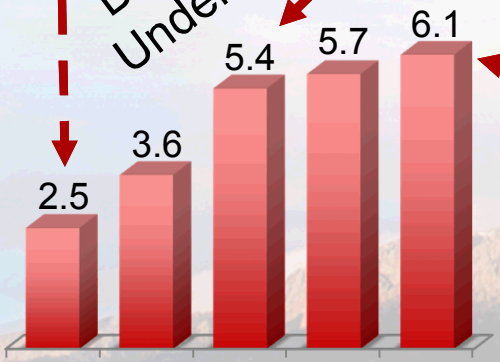


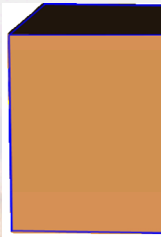
50% Dense



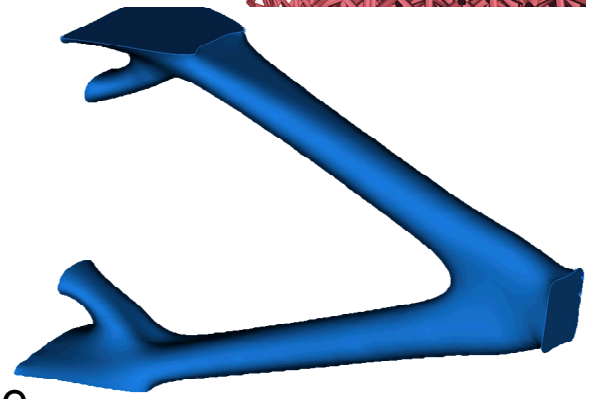


Deflection Under Load





100% Dense



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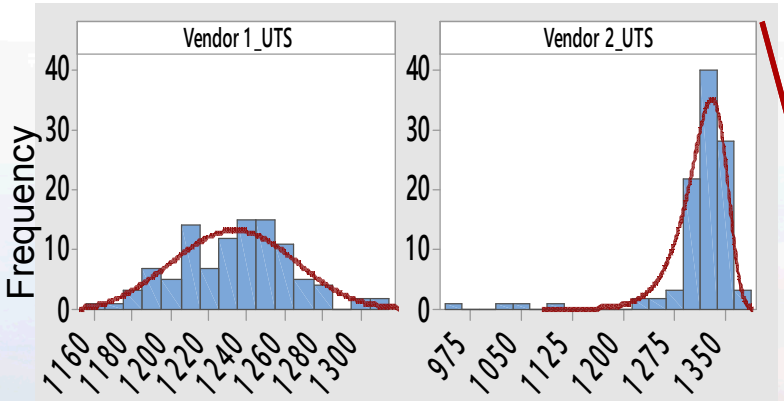
Materials Assurance

Residual Stress, Materials Properties, and Variability are Important Issues

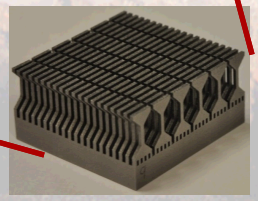
AM Is Still an Evolving/Emerging Technology

- Residual Stress is a Significant Issue
- Little Available Materials Property/Performance Data (no standards)
- Large Variability in Process and Materials
- Both Experimental & Modeling R&D in-progress

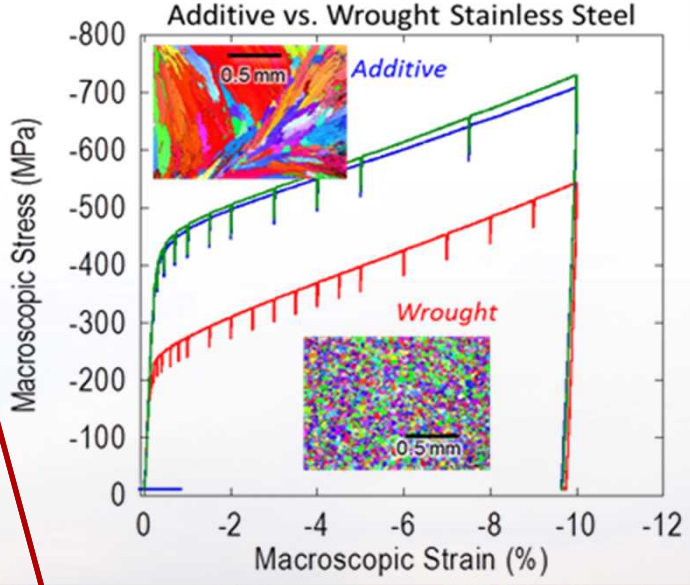
Large Variability in AM Materials Properties



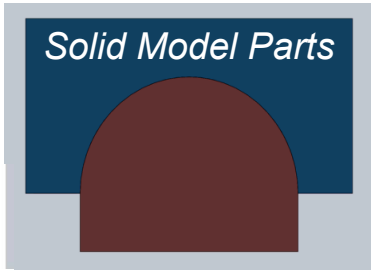
Ultimate Tensile Strength 17-4 PH (MPa)
(Typical wrought H900 ~ 1450 MPa)

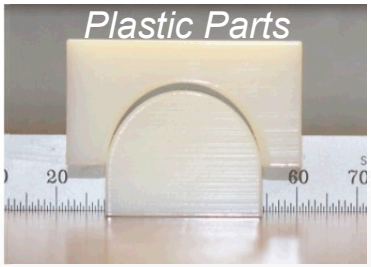


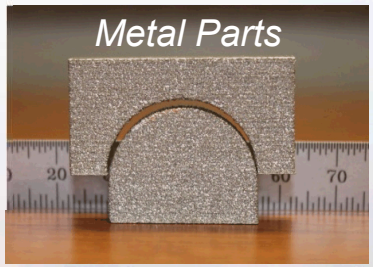
Mechanical Response of Additive vs. Wrought Stainless Steel



AM Metals are Unlike Cast or Wrought Metals







Residual Stress Causes Parts to "Move"

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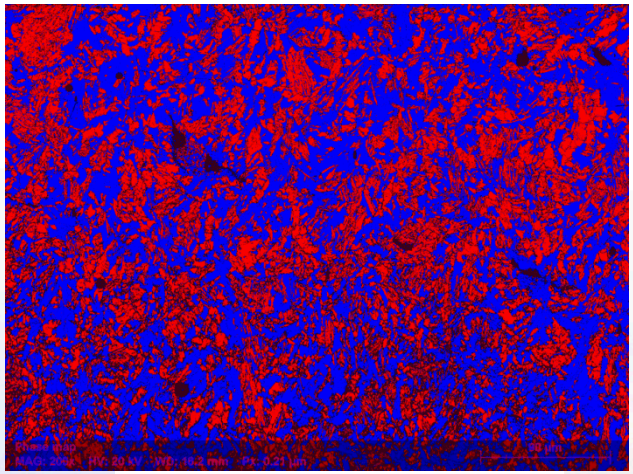
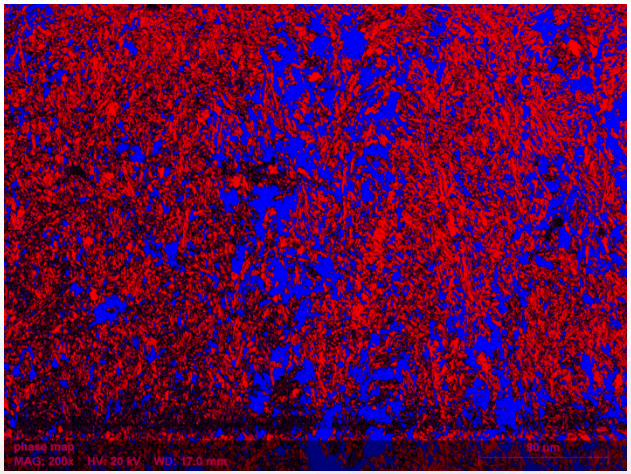
Retained Austenite in 17-4 PH Stainless When Using Nitrogen Gas Atomized Powder

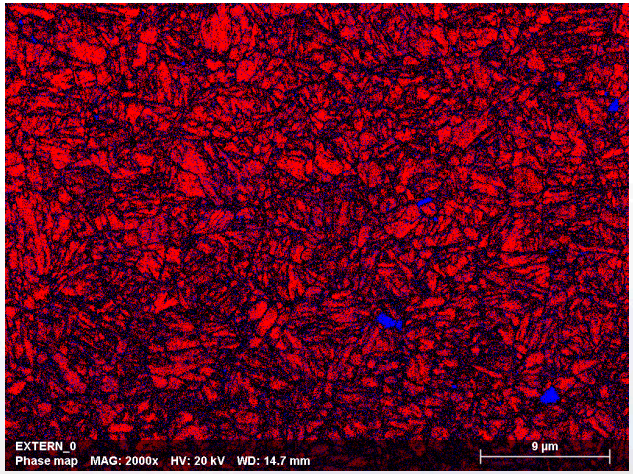
- Anomalous phase composition in AM vs. wrought 17-4 PH Stainless
  - Large fraction of retained austenite after solution heat treatment + H900 age
  - Cryo treatment to -196°C for 5 min still does not transform austenite



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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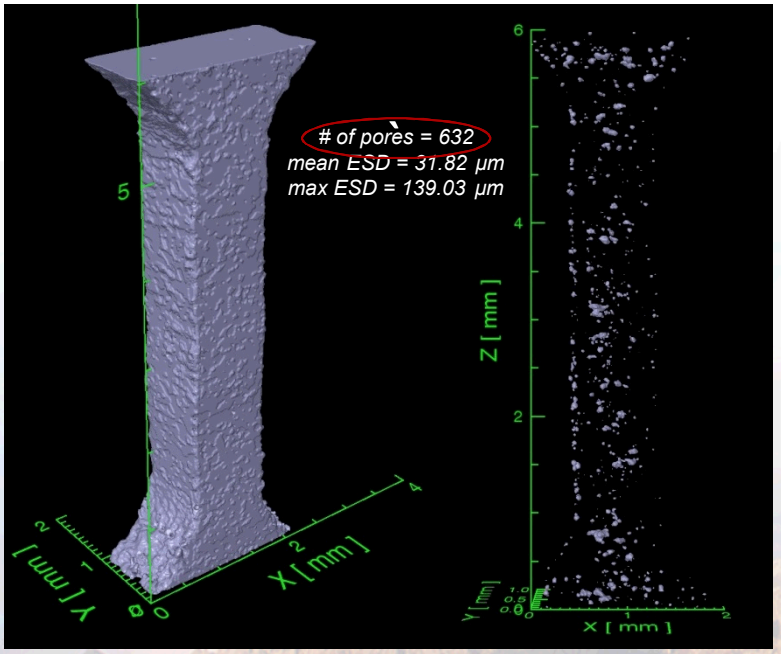
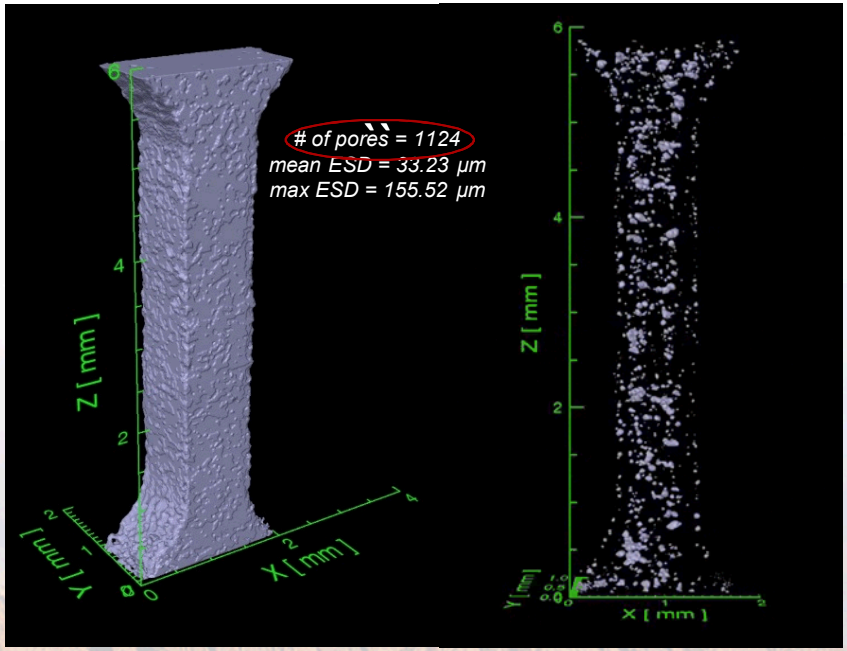
Still Working to Understand Defect Sensitivities and Failure Modes

- AlSi10Mg Dogbones
  - Gage sections imaged with resolution of 7 or 10 µm voxel edge length
- Quantifying defect distributions
  - What can we see? Does it inform material behavior predictions?
  - Comparing with serial sectioning (Robomet) & density (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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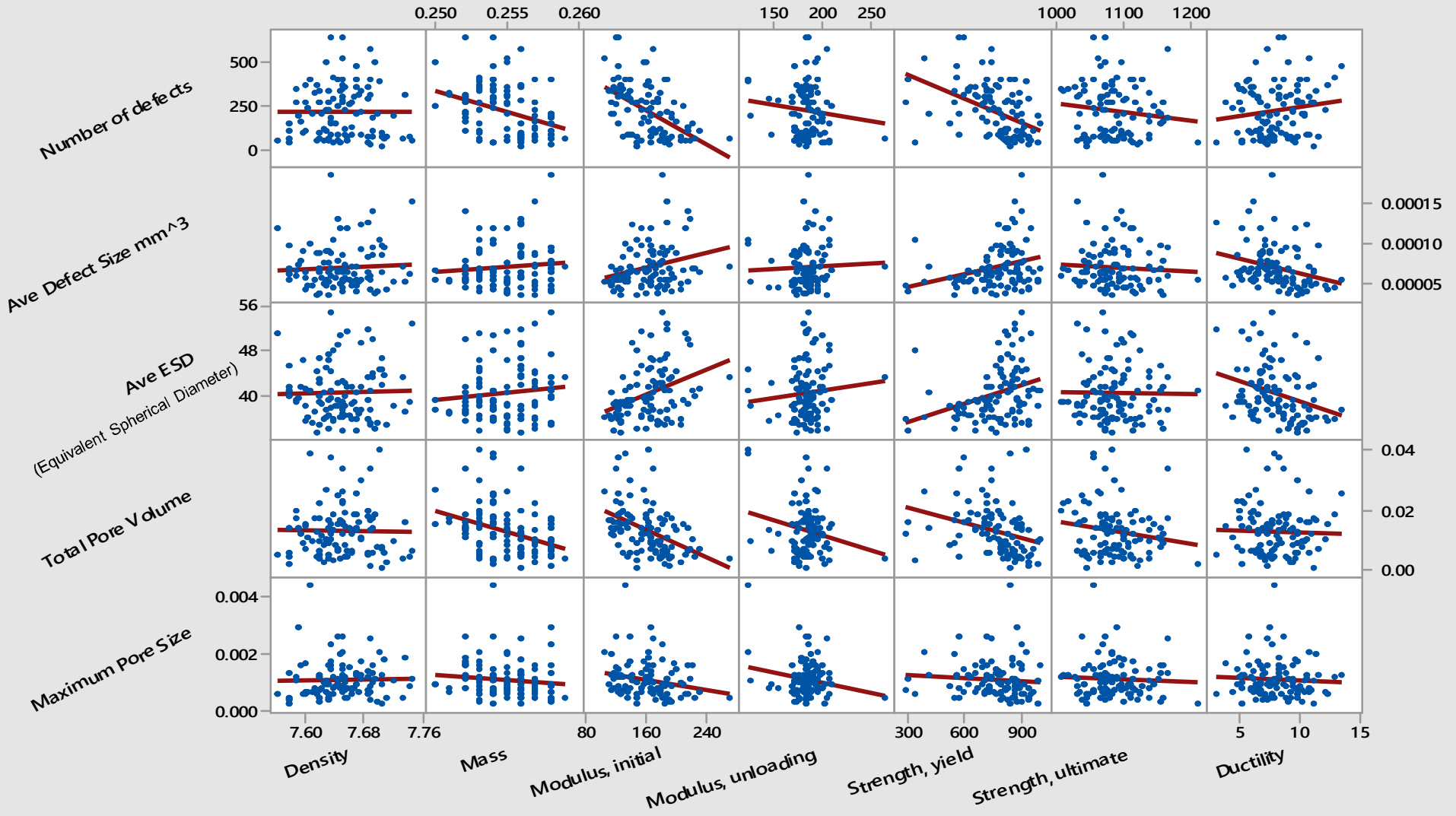
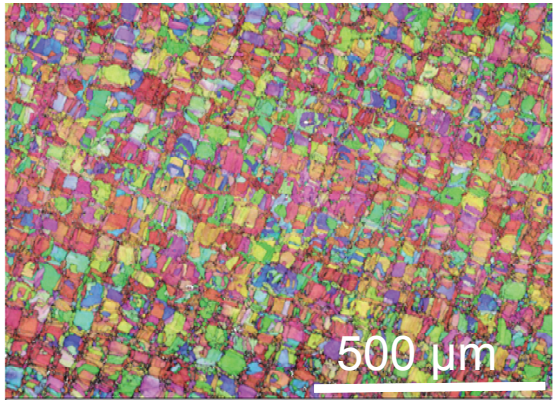
On-going Data Analytics Studies To Investigate Potential Relationships



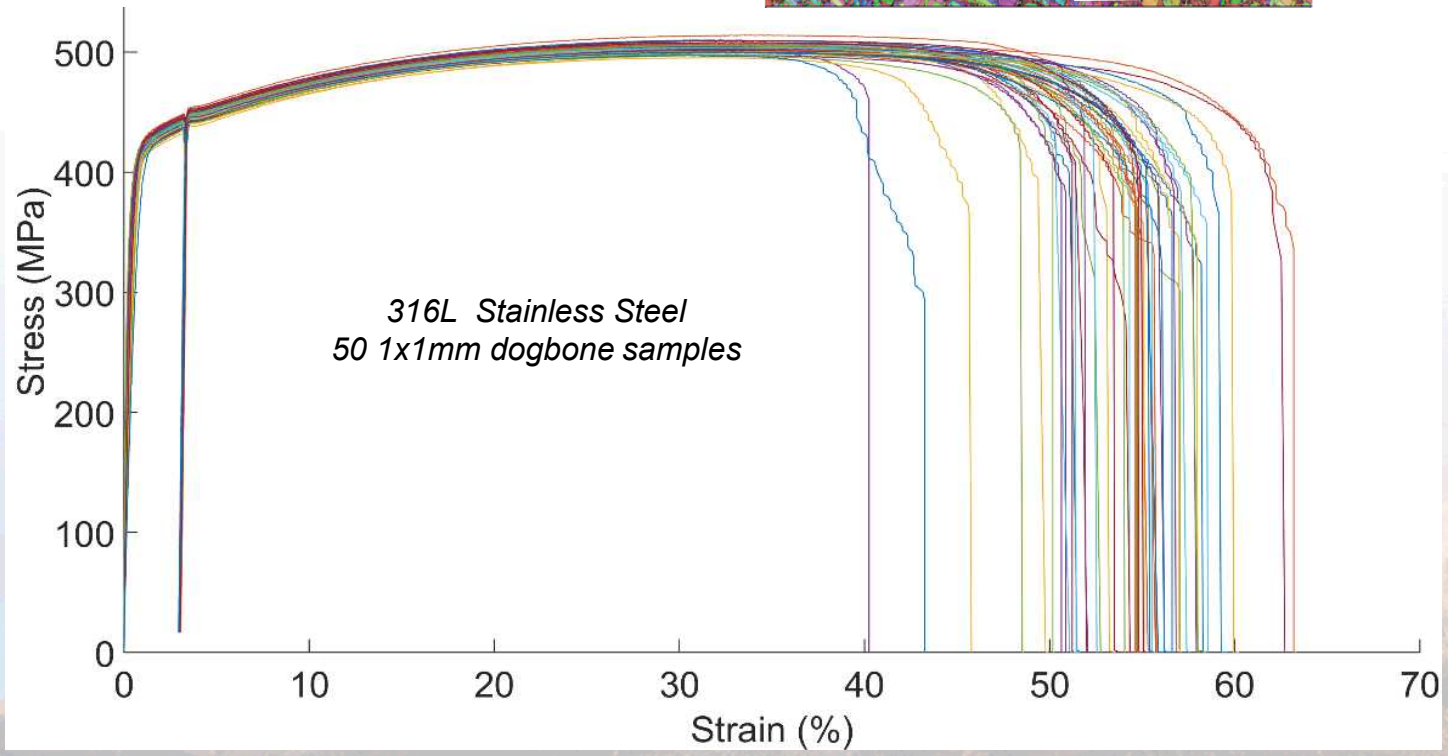
AM 316L Has Unique Microstructure with Reasonable, But Still Highly Variable Properties

Top View
(Normal to Build Direction)



ProX 200 EBSD maps for 316L SS

Cross Section
(Parallel to Build Direction)

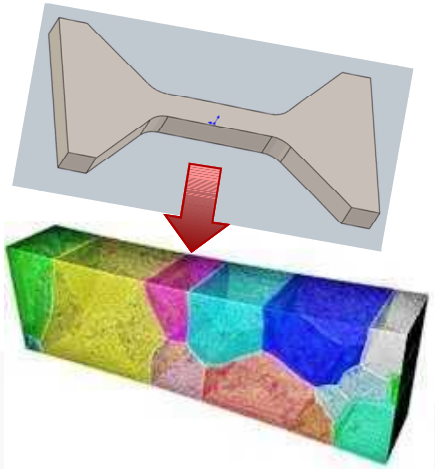


Sandia National Laboratories

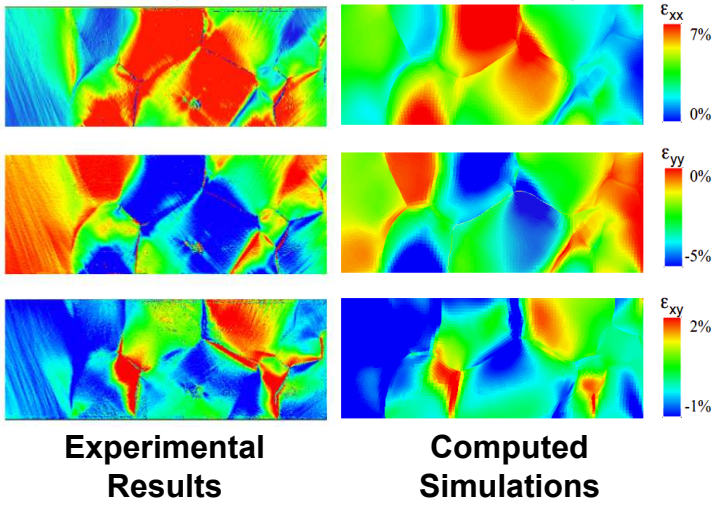
Leverage Sandia PPM to Investigate Variability/Defect Sensitivity

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)

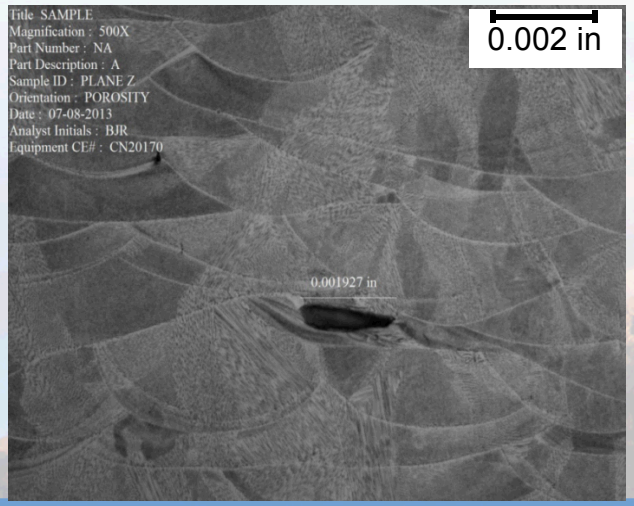


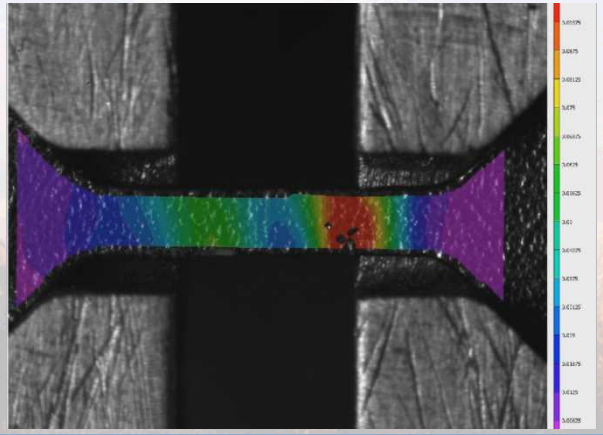
Experimental Results | **Computed Simulations**

Key Questions:

What AM Defects Matter?

Can I detect them?





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

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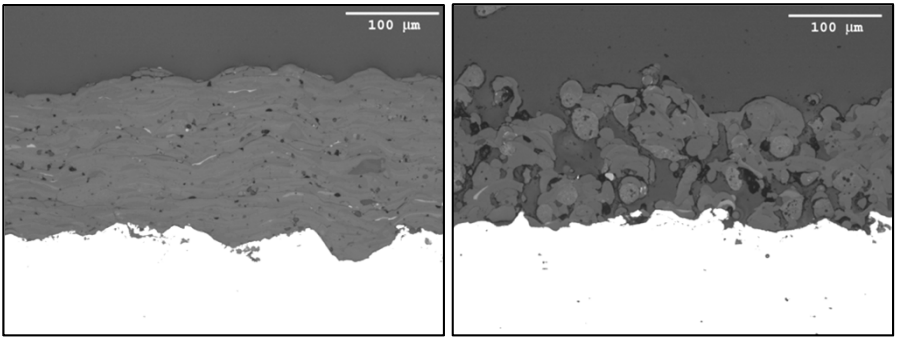
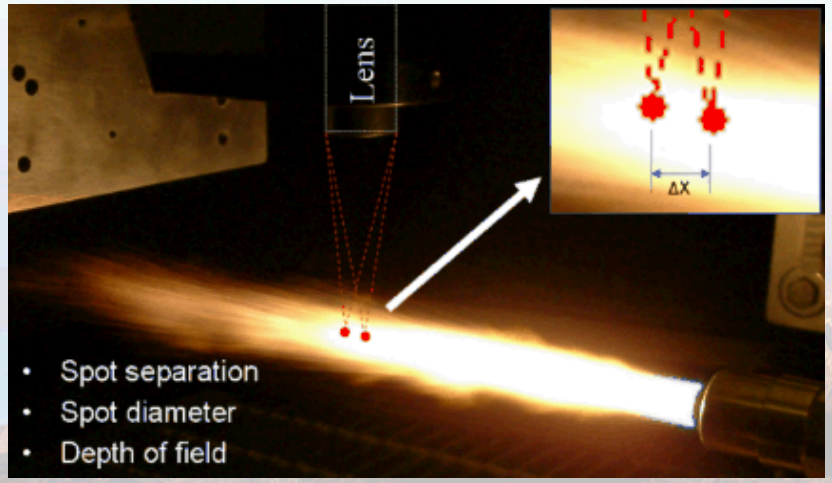
Fundamental Process Understanding is Key to Controlling Variability

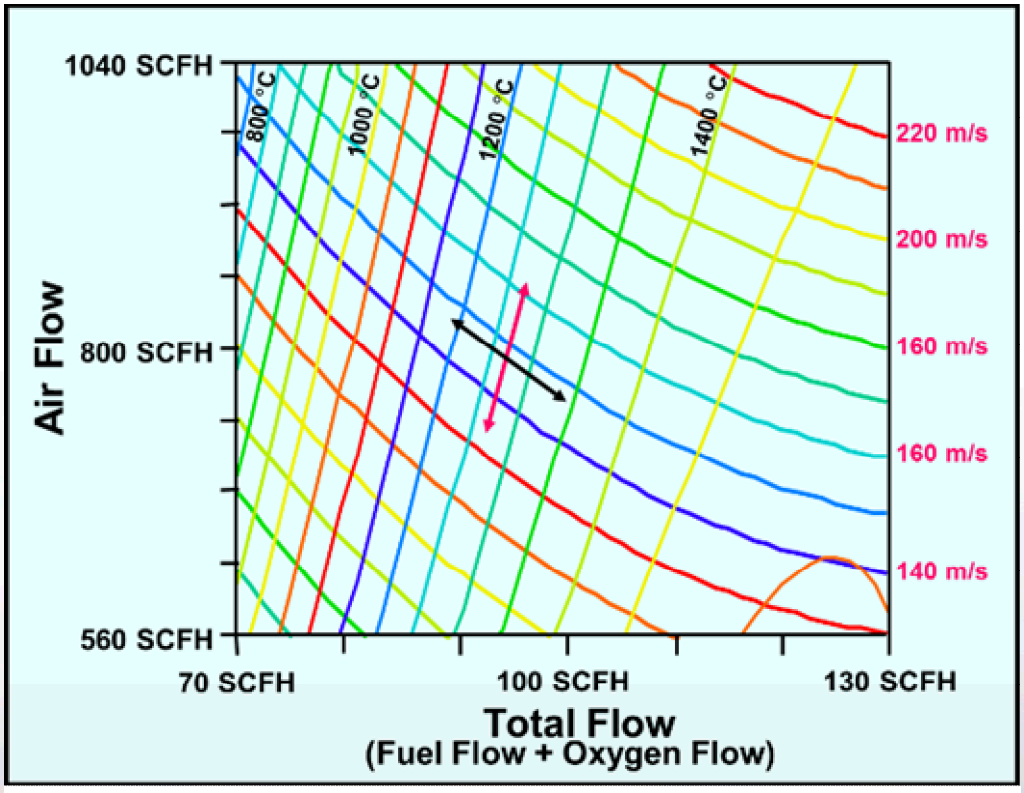
- Thermal spray process used to run open-loop with high variability in the resulting materials



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



- Fundamental process understanding used to implement <u>closed-loop control</u> based on droplet *<u>temperature</u>* and *<u>velocity</u>* to <u>reduce *variability*</u>



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

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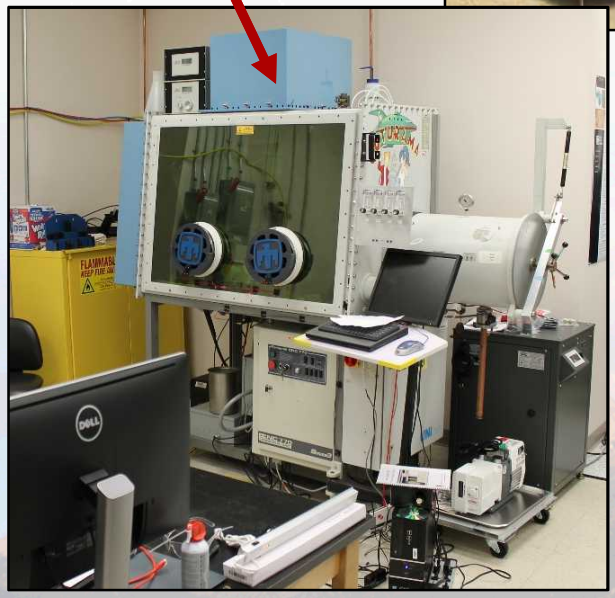
Sandia Metal/Multi-Material AM Process R&D

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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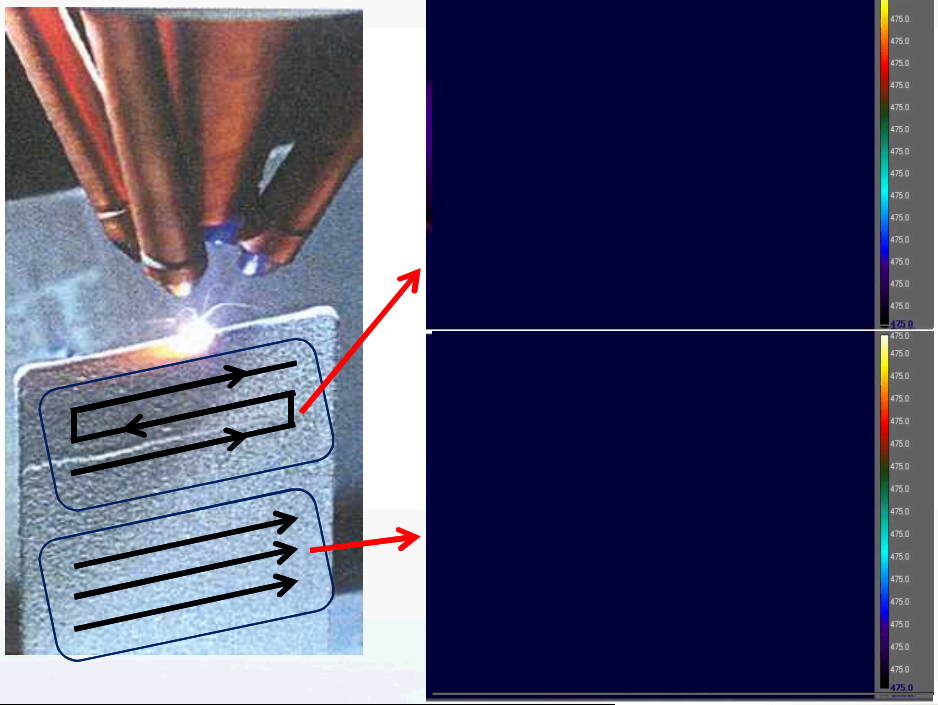
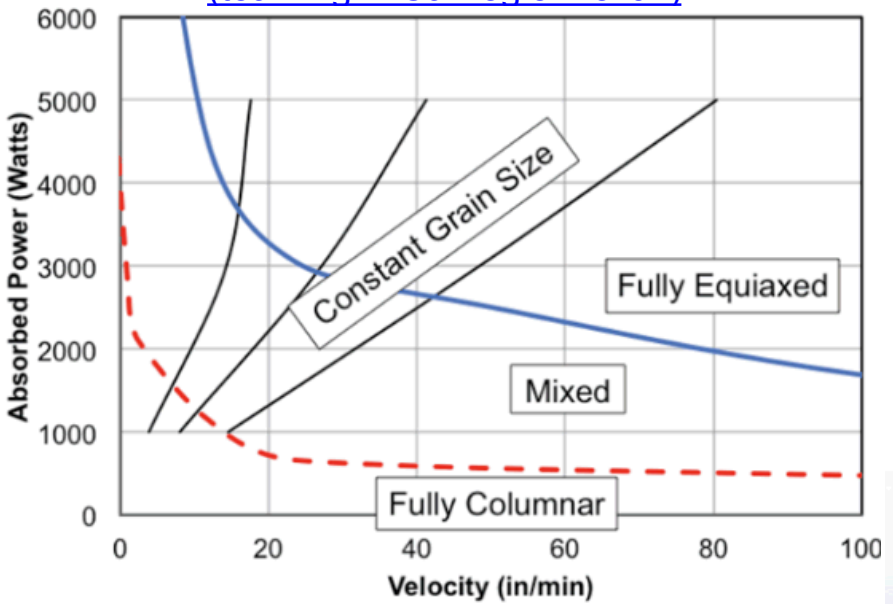
Working to Understand LENS™ Processing-Microstructure Relationships

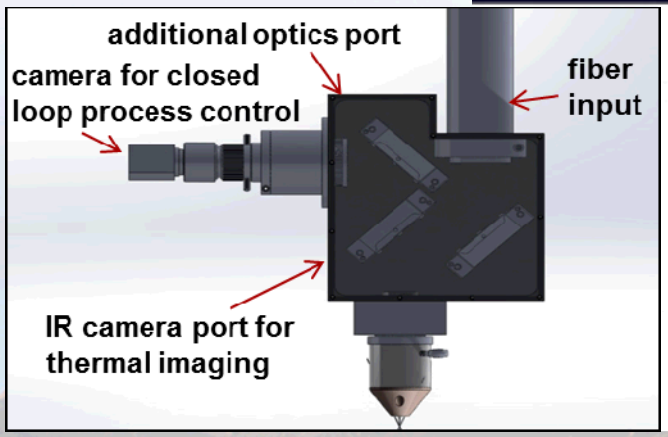


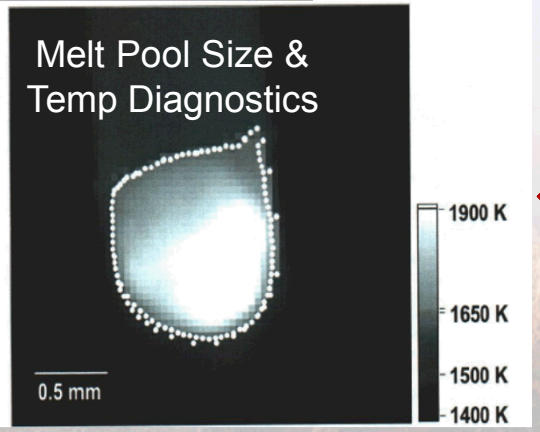
Processing-Microstructure Relationships

(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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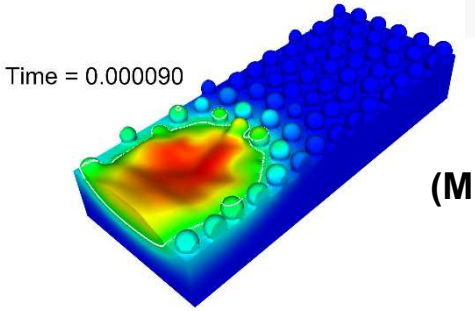
Multiple Scale Powder Bed Modeling

Powder bed fusion model

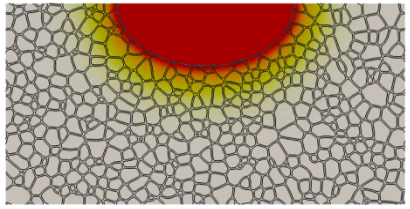
- High-fidelity melt-pool modeling
- Interactions of laser with powder bed, melt pool
- Solidification – grain morphology



(M. Martinez)

Phase field solidification model

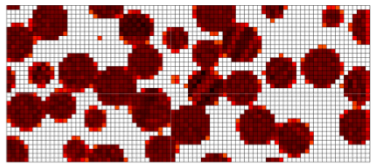
- Grain morphology



(F. Abdeljawad)

Atomistic model of thermal transport in nanoparticle powder beds

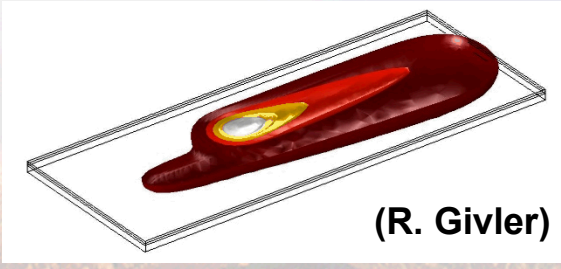
- Link to macroscale thermal model



(M. Wilson & M. Chandross)

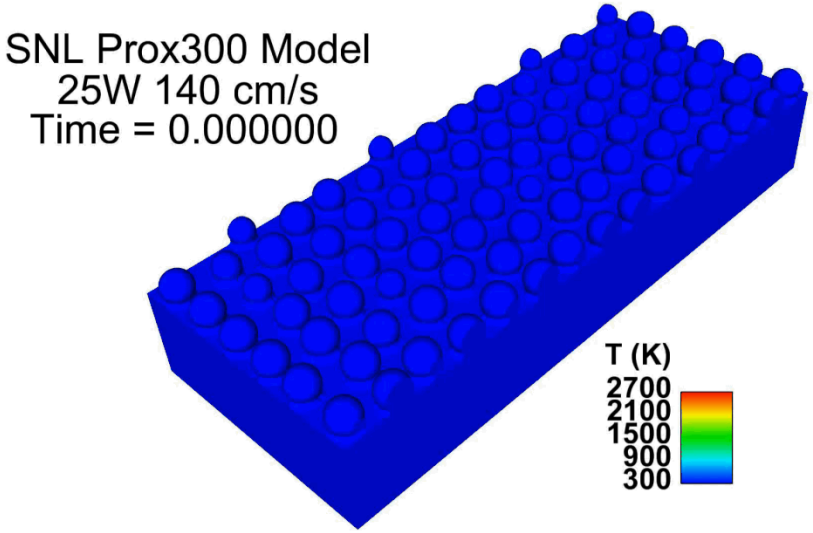
Macroscale powder bed model

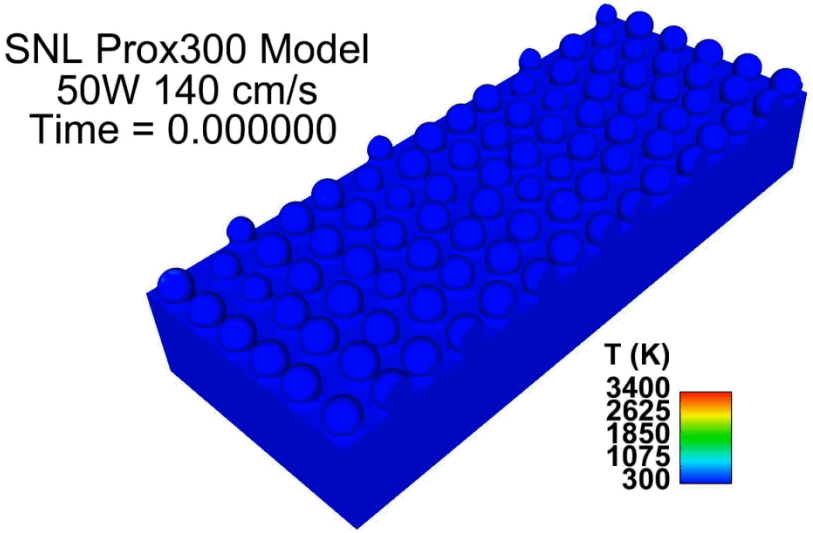
- Methods for modeling part-scale PBF process
- Optimization of laser paths (100's of passes)



(R. Givler)

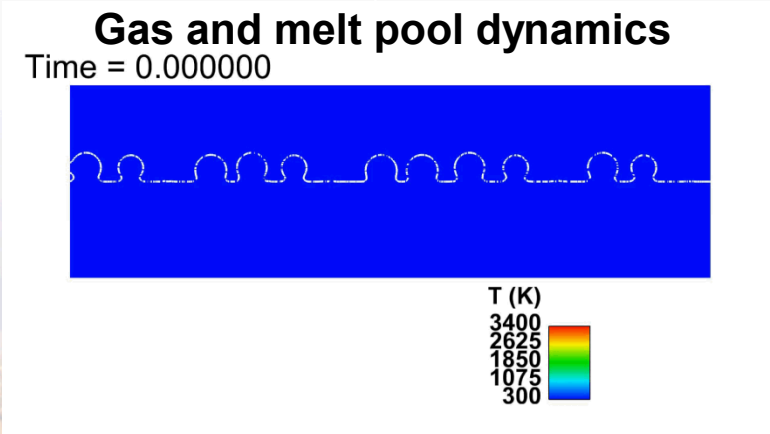
Process Modeling Can Provide Useful Insights





Stainless steel 304L
25 micron powder

Gas and melt pool dynamics

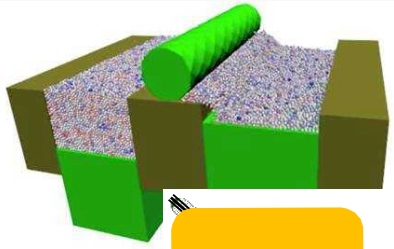


Notes:

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

Process Models by Mario Martinez

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



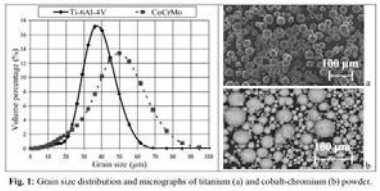
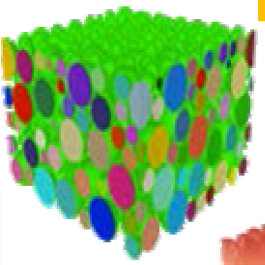
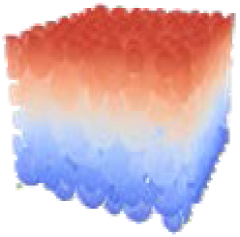


Fig. 1: Grain size distribution and micrographs of titanium (a) and cobalt-chromium (b) powder.

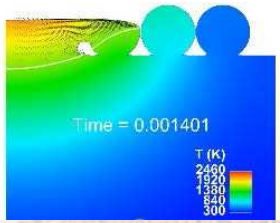
Particle packing



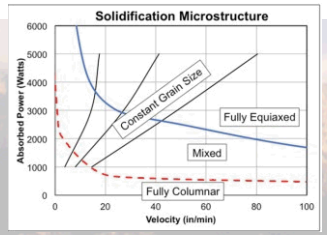
Heat Transfer



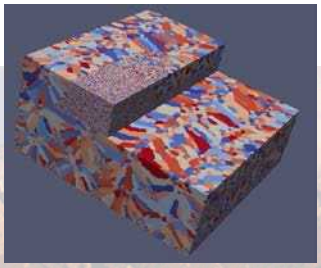
Partial melt & flow

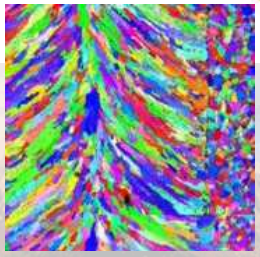


Molten pool dynamics

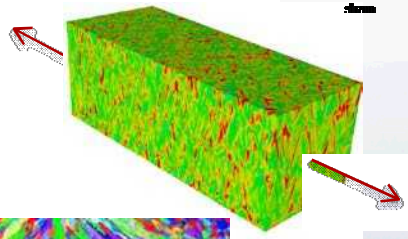


Solidification

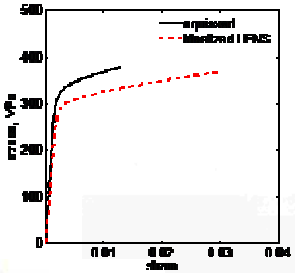




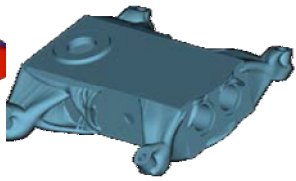
Microstructure



Property-Performance



Topology Design



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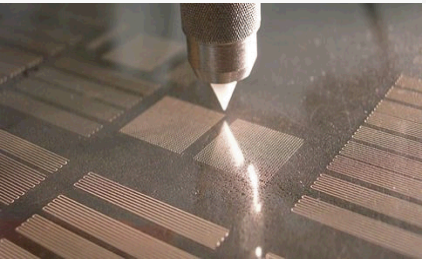
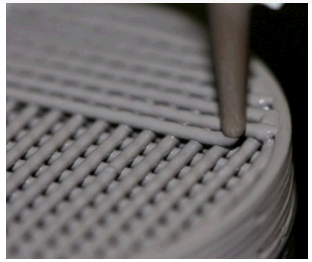
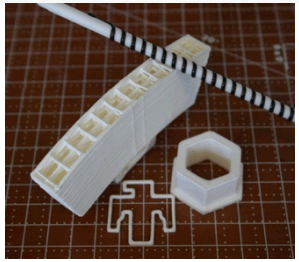
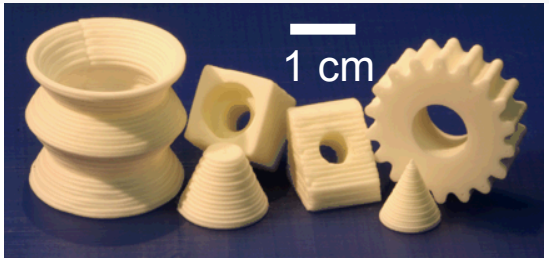
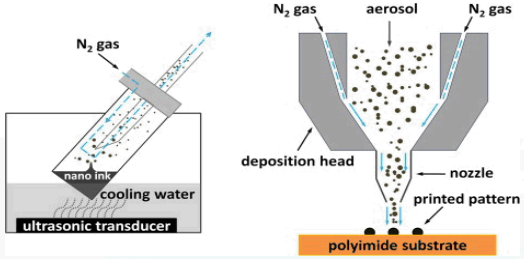
Multi-Material AM

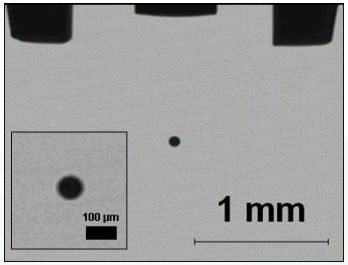
Direct Write Technologies Enable Access To Materials Not Supported By Conventional Printing Processes

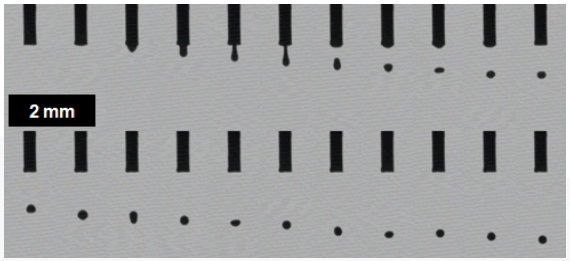
Direct Write by Extrusion Casting (Robocasting)

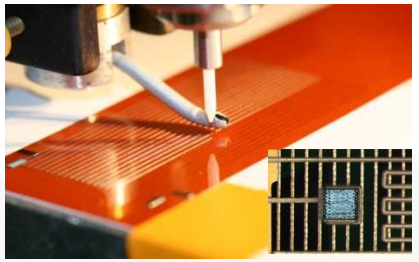





Direct Write by Aerosol & Ink Jet Deposition

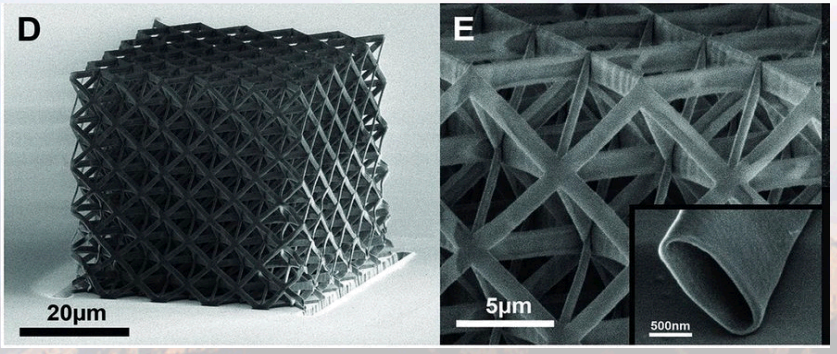


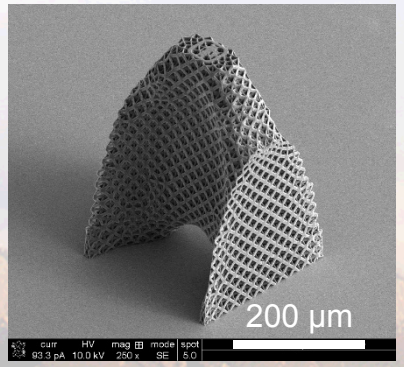


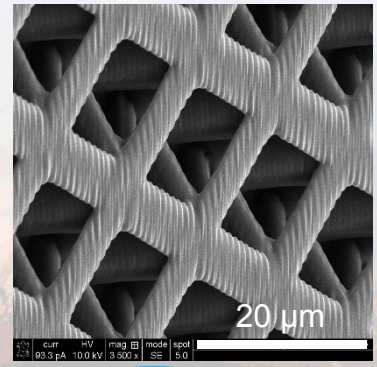




Direct Write by Laser Photo-Lithography







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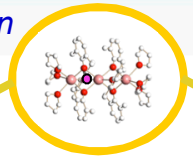
From Nano-Materials to Components at the Sandia Advanced Materials Lab

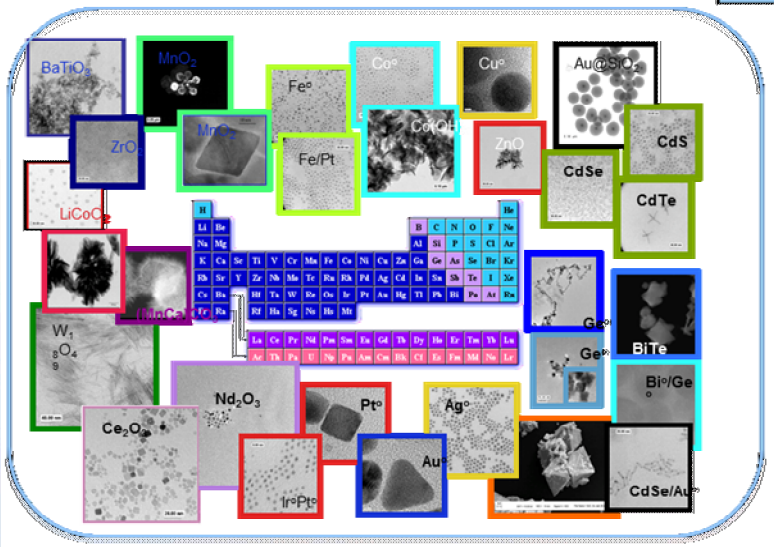
Solution Precipitation



Specialty Precursors

Solvothermal

Specialized Nanomaterials



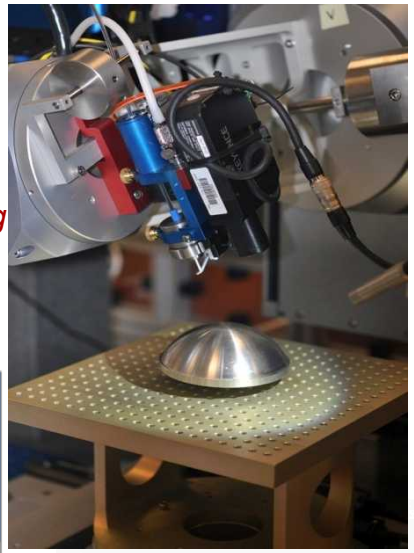
Specialty Inks

Colloidal Chemistry

Process Engineering

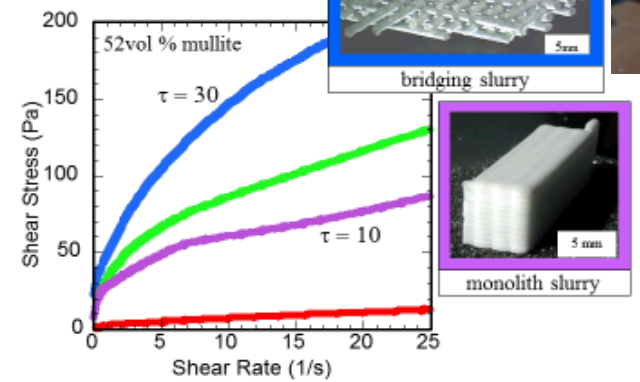
Ink Characterization

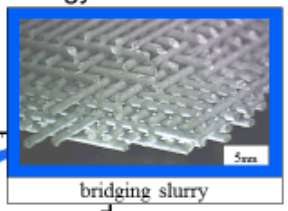
Direct Write Printed Parts



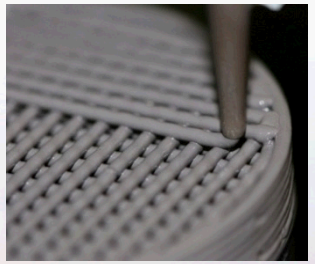
Influence of paste rheology

ry 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

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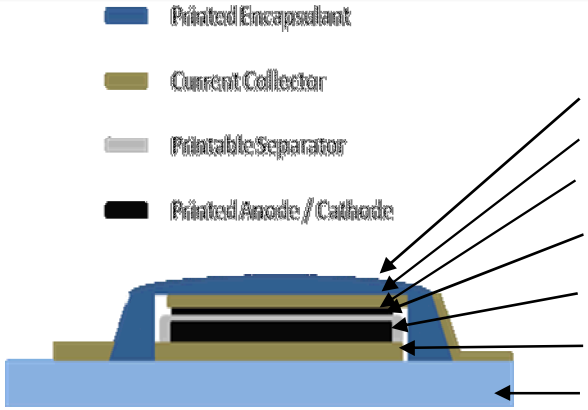
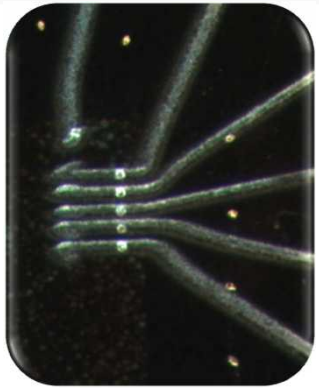
Sandia has Strong Capabilities/Expertise In Printed Electronics

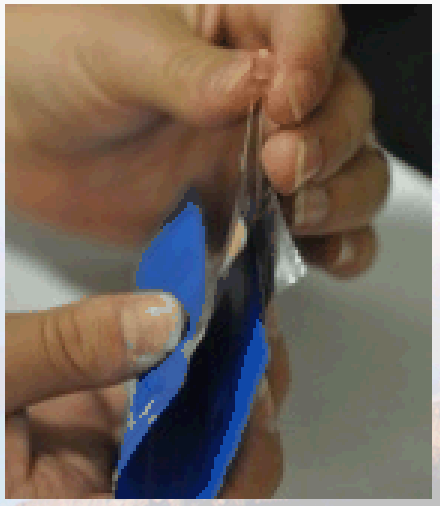


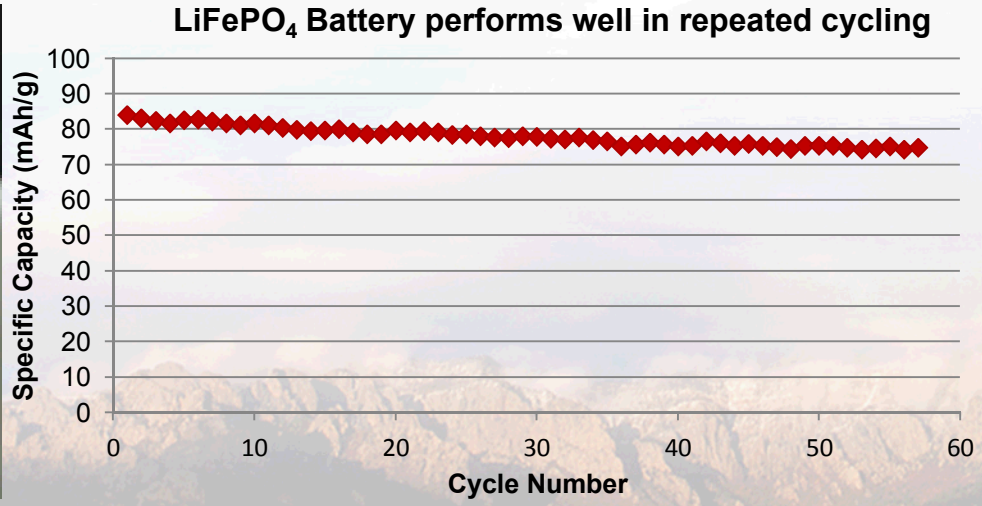
Printed flexible battery

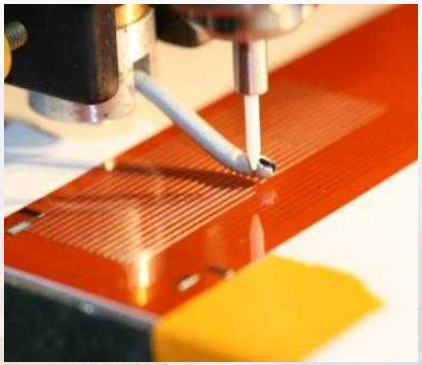
Encapsulant (DW UV-curable epoxy)
Current collector (DW carbon ink)
Anode (DW graphite/carbon)
Separator (DW mesoporous polymers)
Cathode (DW $LiFePO_4$)
Current collector (DW copper ink)
Substrate (polyimide)



"Flexible Chips" with printed wirebonds







Aerosol jet printing to 10 µm

Sandia National Laboratories

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