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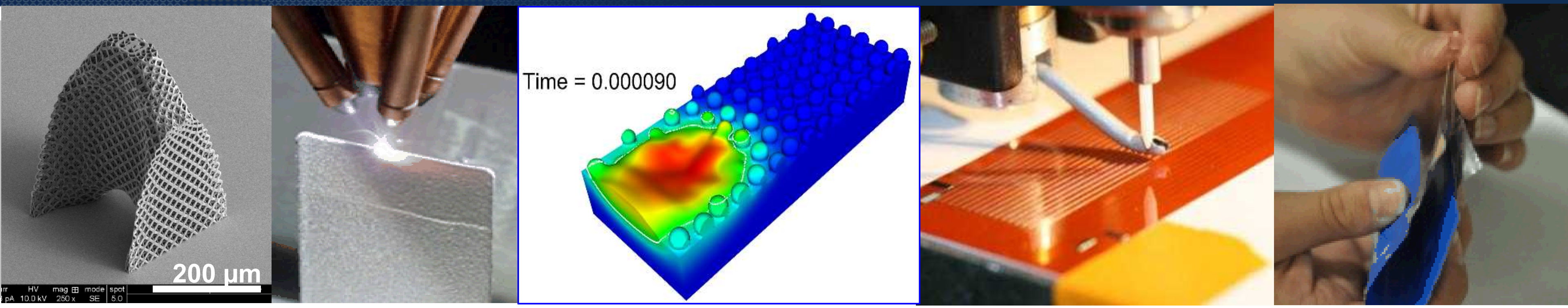


Additive Manufacturing at Sandia -- New Opportunities & Technical Challenges

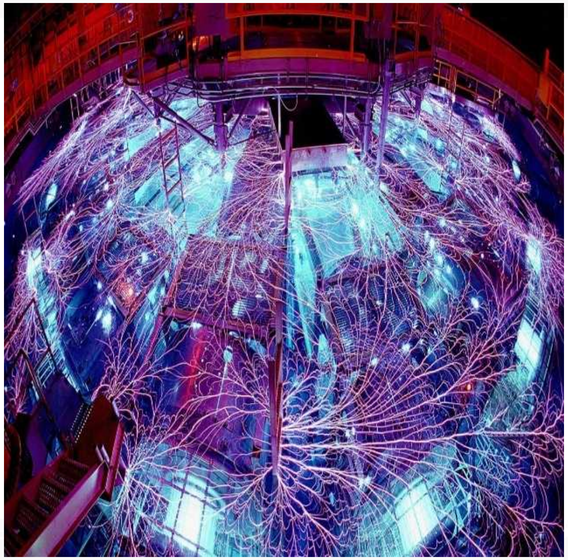
Dr. Mark F. Smith
Deputy Director For Additive Manufacturing
Material, Physical, & Chemical Sciences Center
Ph: 505-845-3256 mfsmith@sandia.gov

Sandia is a US DOE National Security Science and Engineering Laboratory

Sled Track Test

Albuquerque Labs

Z- Machine



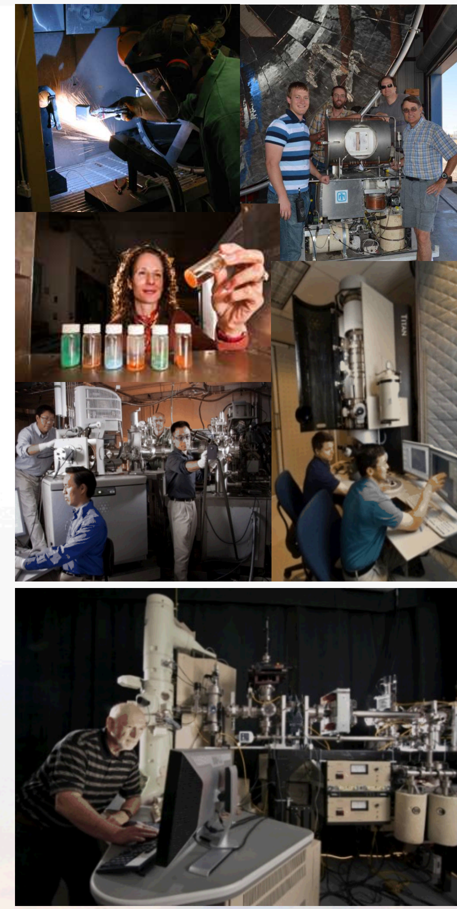
- ~11,000 employees, ~$3.2B FY17 Budget
- Historical mission -- non-nuclear components of nuclear weapons & weapon system integration
- Today, much broader mission in applied science & engineering for national security

> *"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

Sandia Materials & Process Science

Activities Range from Basic R&D to Specialized Production

300+ Staff, ~$100M FY17



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

<u>Multiple Large Materials R&D Facilities</u>

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

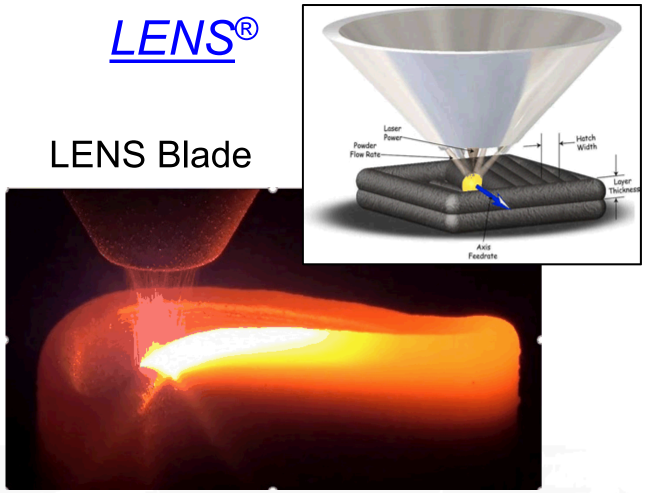
FastCast *

Development Housing

Laser Engineered Net Shaping *

LENS®

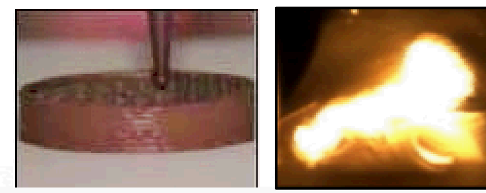
LENS Blade



RoboCast *

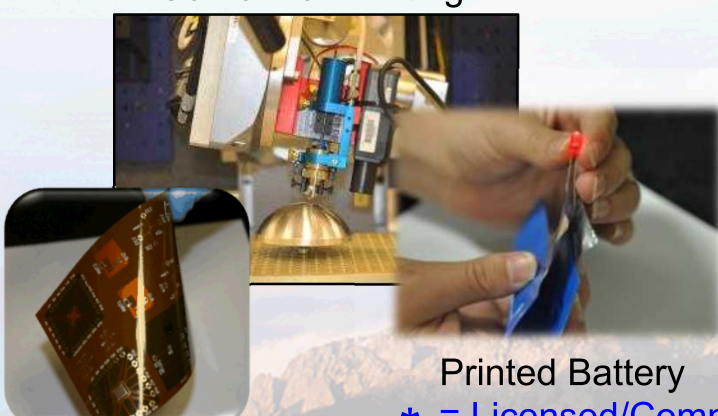
Ceramic Parts

Energetic Materials



Direct Write

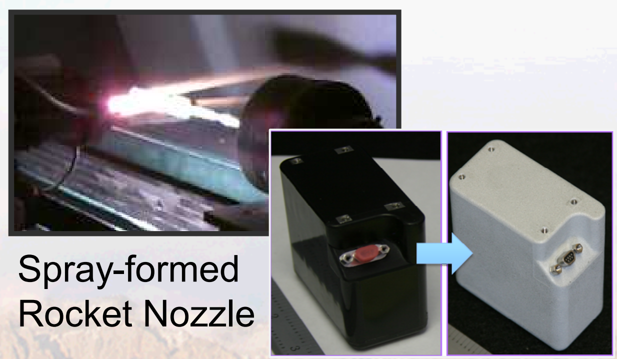
Conformal Printing



Printed Battery

Flexible Electronics

Thermal Spray

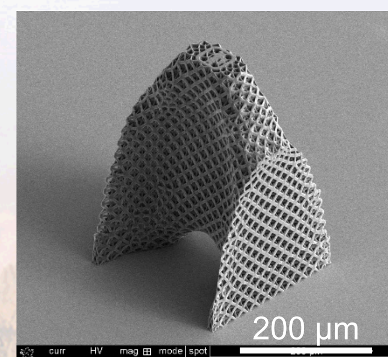


Spray-formed Rocket Nozzle

Metal on Plastic

Micro-Nano Scale AM

Lattice Structure



* = Licensed/Commercialized Sandia AM technologies

Underline = Current Capability/Activity

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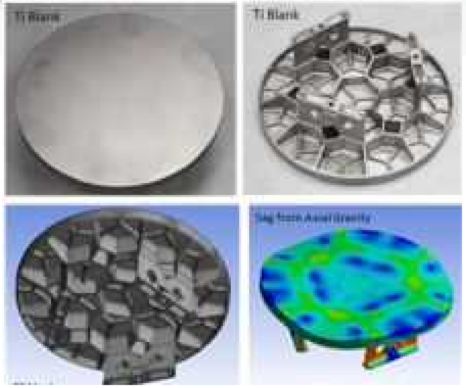
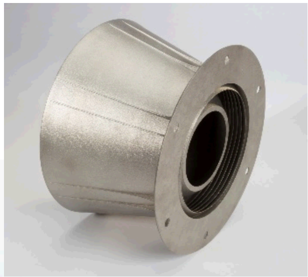
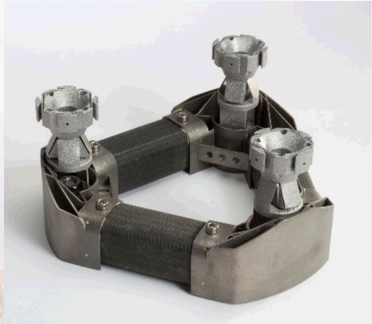
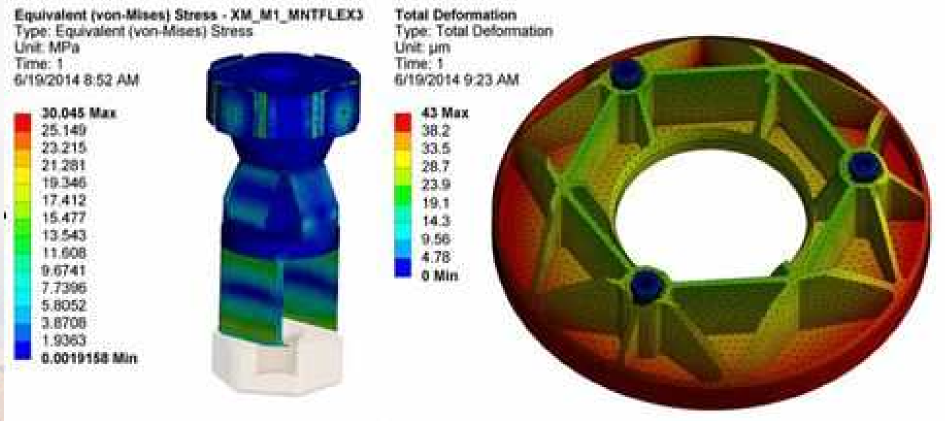
Lightweight Telescope Demonstrator









- More than 80 AM parts in the final assembly
- Additional 20+ parts for tooling, fixturing, rapid development

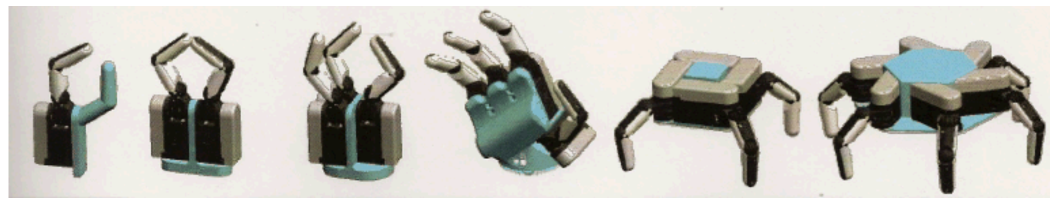
Sandia National Laboratories

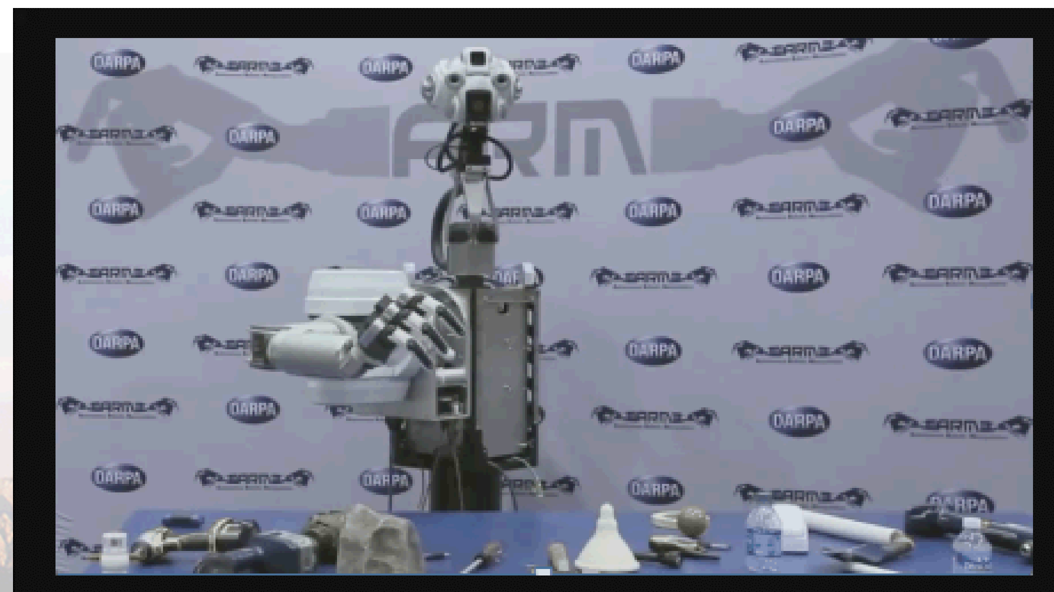
Sandia Hand – AM Enabled Innovative Design and Substantial Cost Reduction

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

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

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

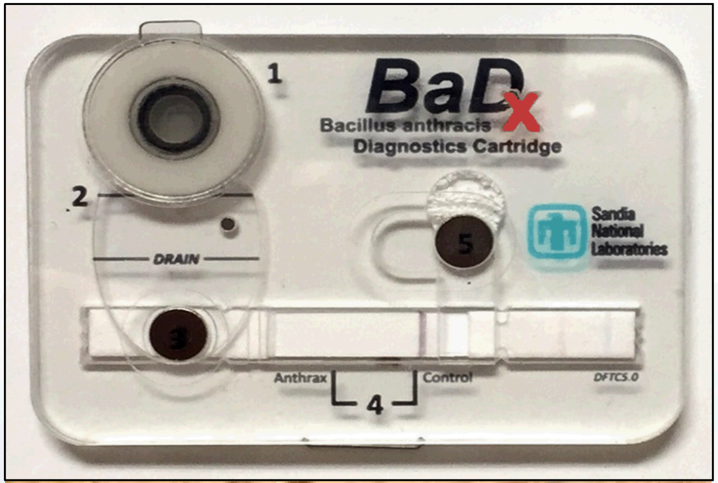




Inexpensive/Portable Chem Labs

BaDx Anthrax Tester

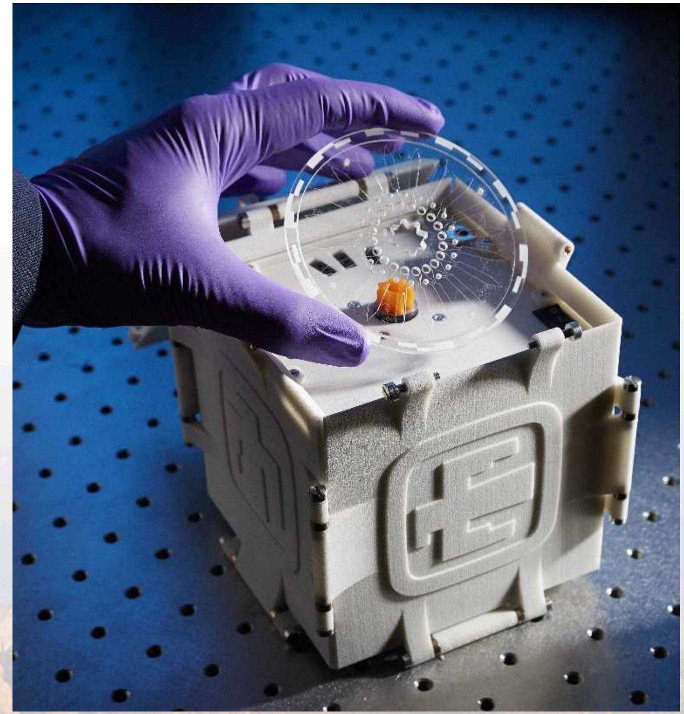
- Microfluidic platform for bacterial detection
- AM enabled rapid/inexpensive design iterations
- Self-contained, credit card-sized "Lab in a Pocket"



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

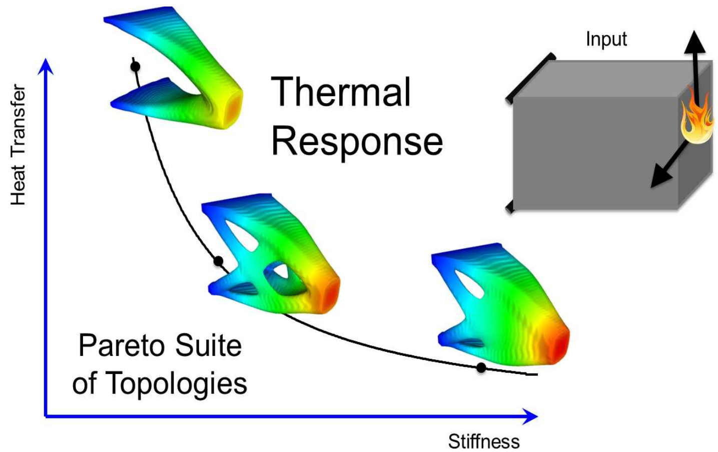
SpinDx "Lab on a Disk"

- Broad applications -- detection of drugs, food & water safety, medical diagnostics, and bio-agent detection
- Licensed to Lifleloc Technologies Inc. for commercialization



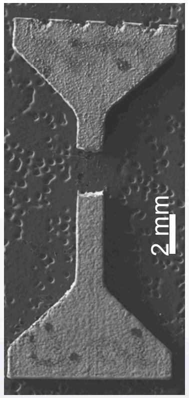
Three Primary Areas of Emphasis in Ongoing Sandia AM R&D

FY17 Sandia AM: >80 Projects, ~$20M Total Investment, ~50/50 R&D vs. Applications

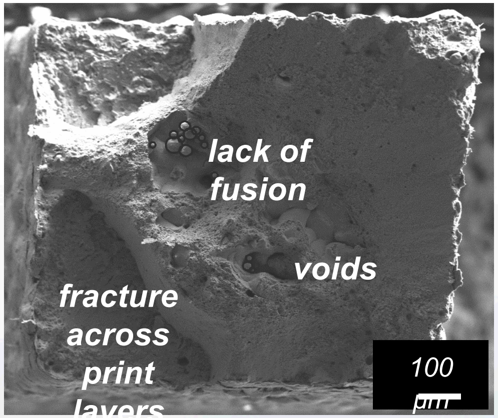


Engineering Analysis Driven Design
(Computer created/optimized AM design - PLATO)

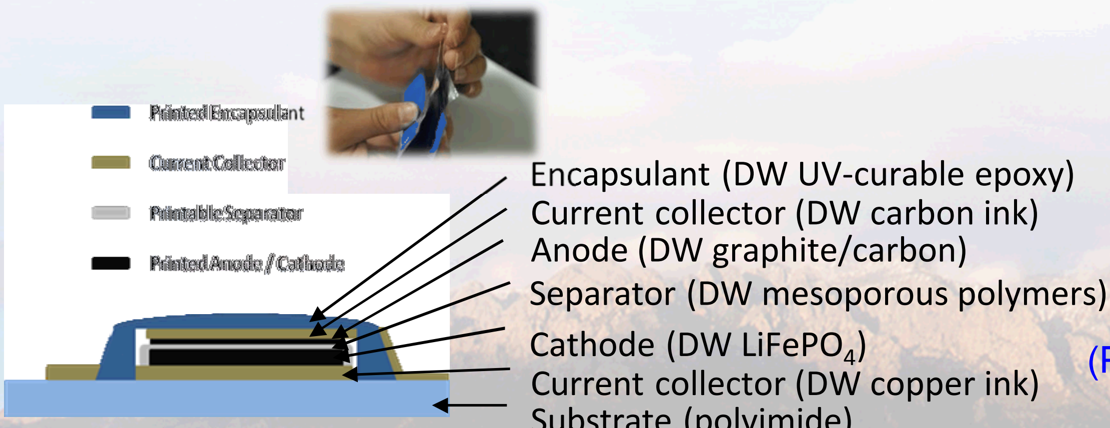
Materials Reliability
(Assure/quantify reliability of AM materials)



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



Failure at 2% elongation



Printed $LiFePO_4$ Battery

Multi-Material Additive Manufacturing
(Printed electronics, packaging, ceramics, …)

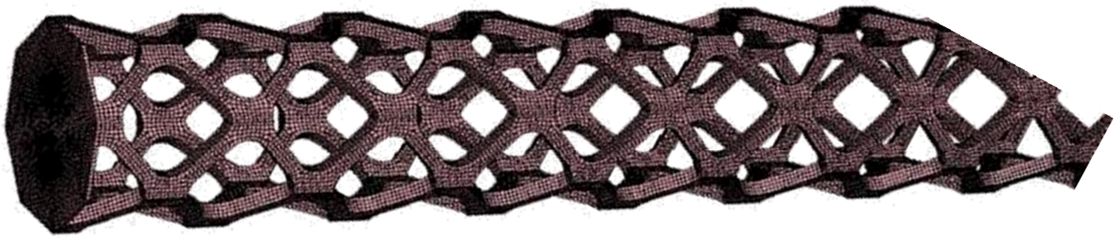
Sandia National Laboratories

Design/Analysis Tools

Analysis-Driven Design Optimization

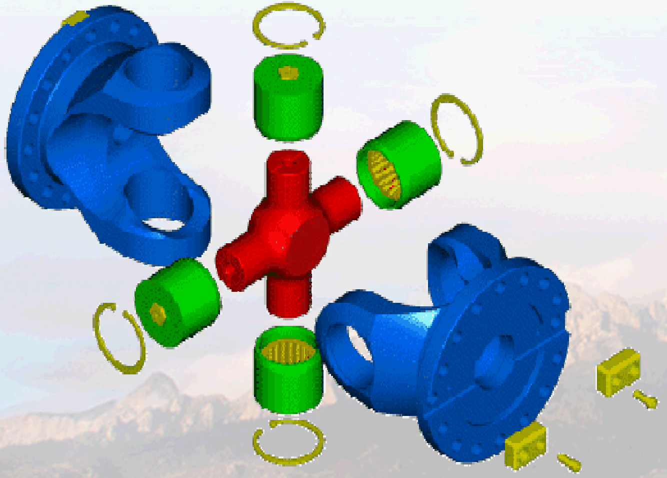
We combined Topological Optimization (TO) with eXtended Finite Element Modeling (X-FEM) & LENS® to optimize selected properties, e.g., strength/weight ratio

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



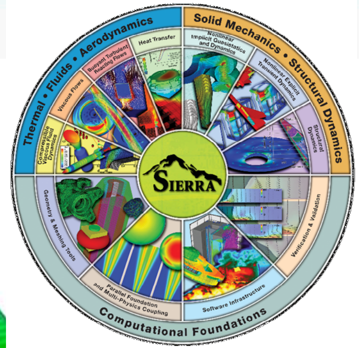
With AM it is faster and cheaper to build this optimized shaft than a solid shaft!

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

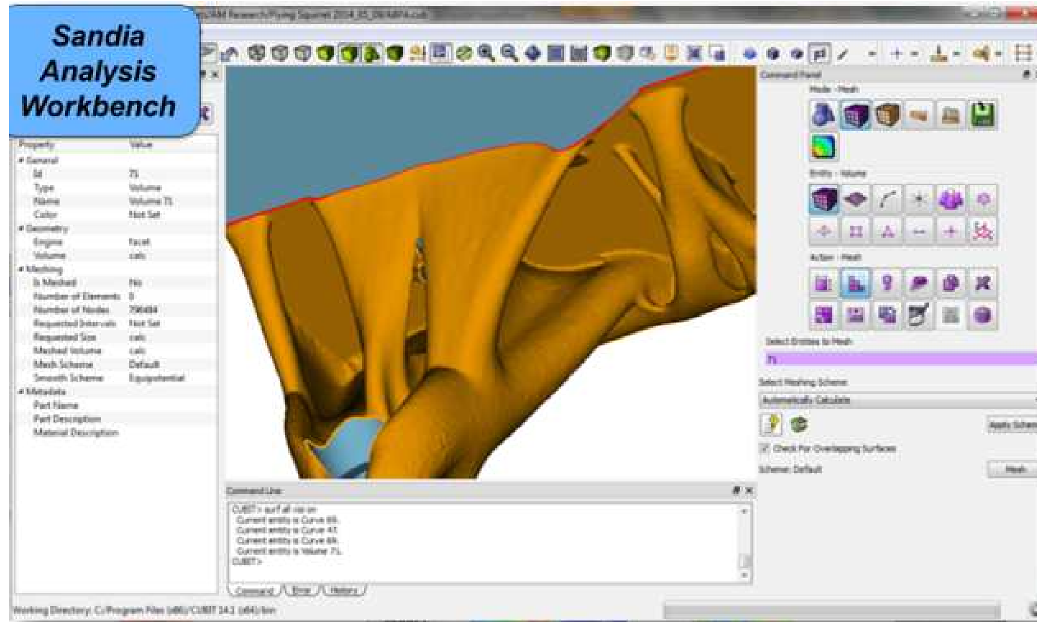


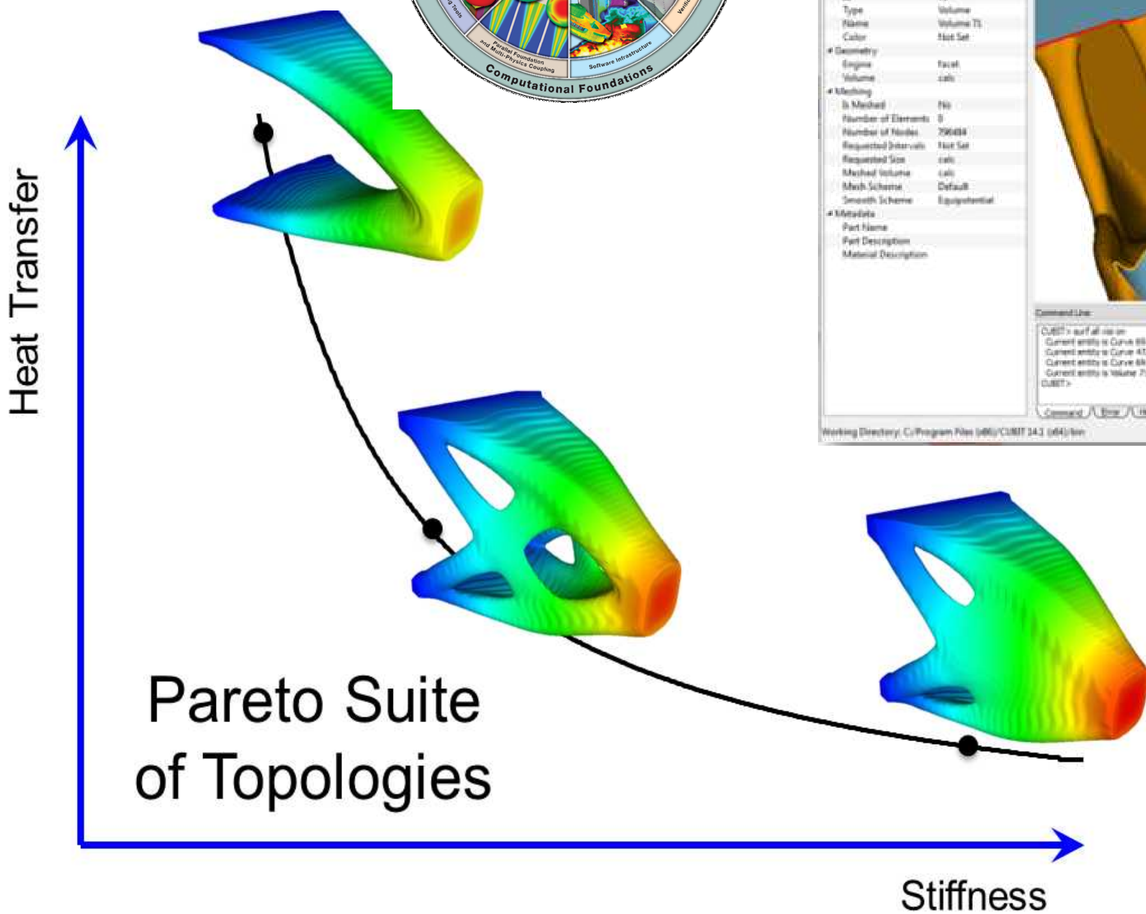
"Loxosphere" Universal Joint printed as a single integrated assembly –fewer parts, no assembly, no frictional wear!

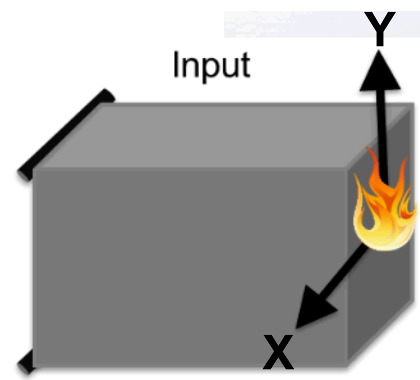
AM Design Via Functional Prioritization



User Friendly Interface







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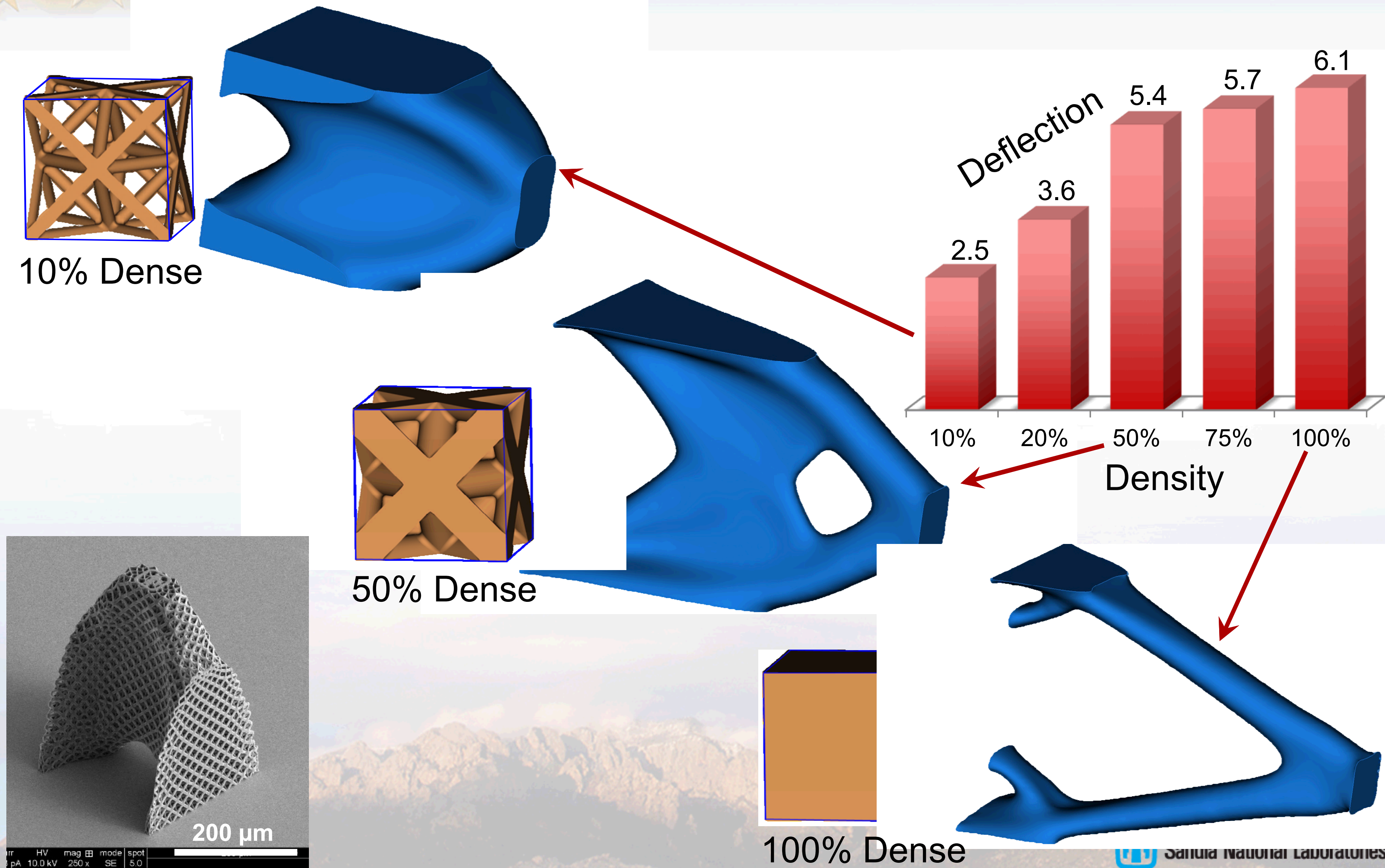
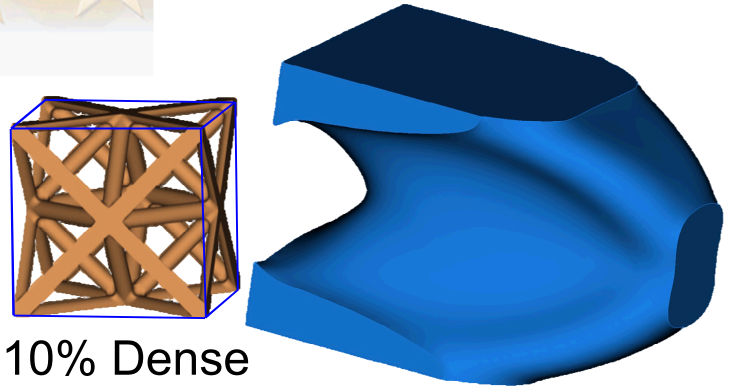
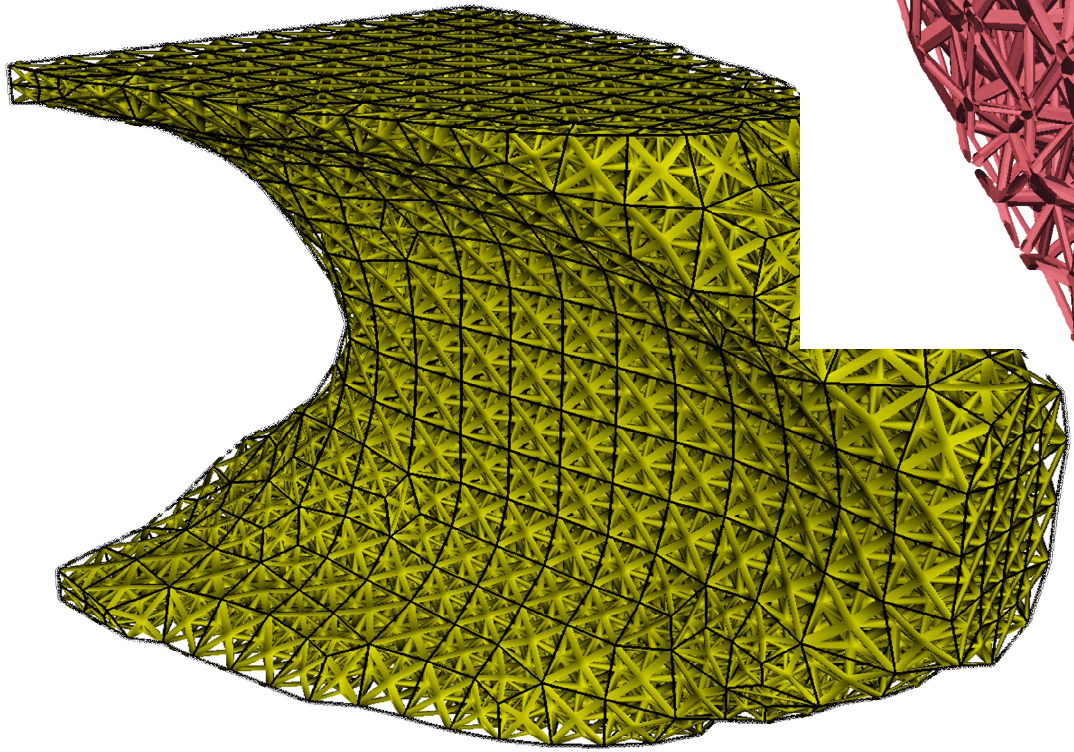
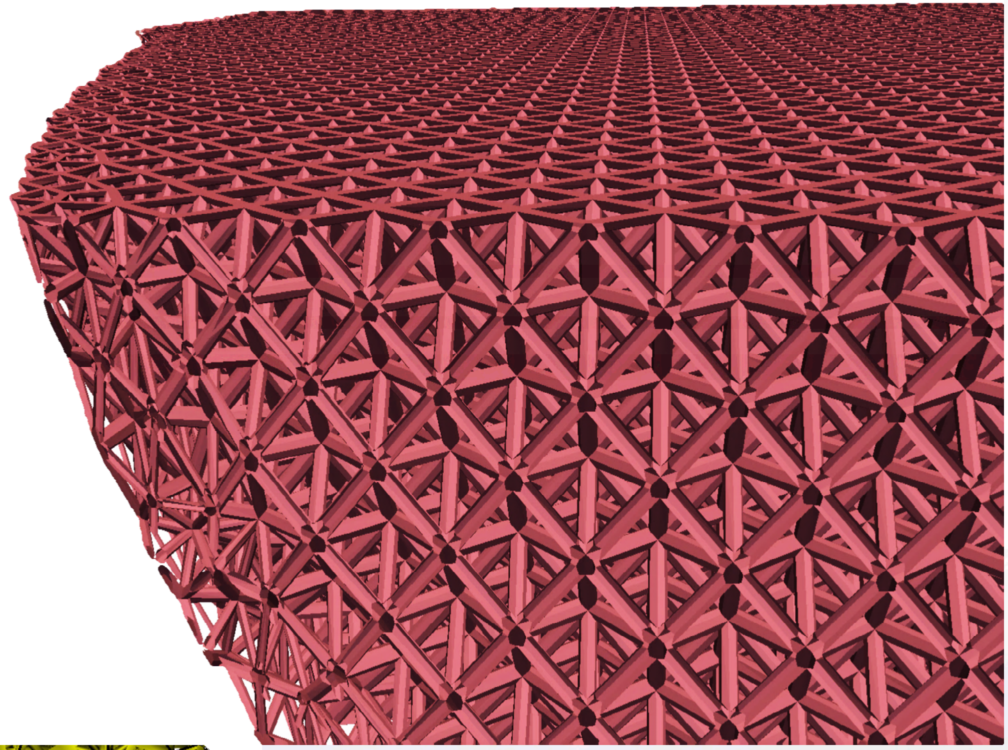
Optimizing Stiffness at Fixed Mass



Creating Curved Surfaces with no "Loose Ends"







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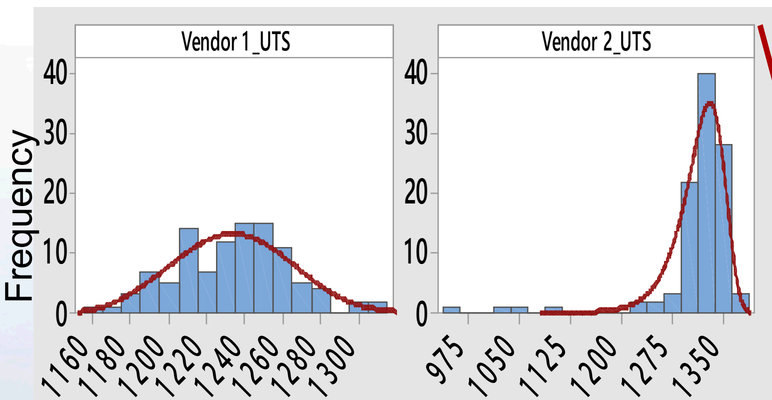
Materials Reliability

Residual Stress, Materials Properties, and Variability are Important Issues

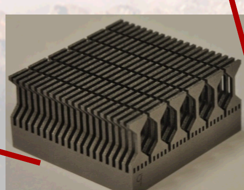
AM Is Still an Evolving/Emerging Technology

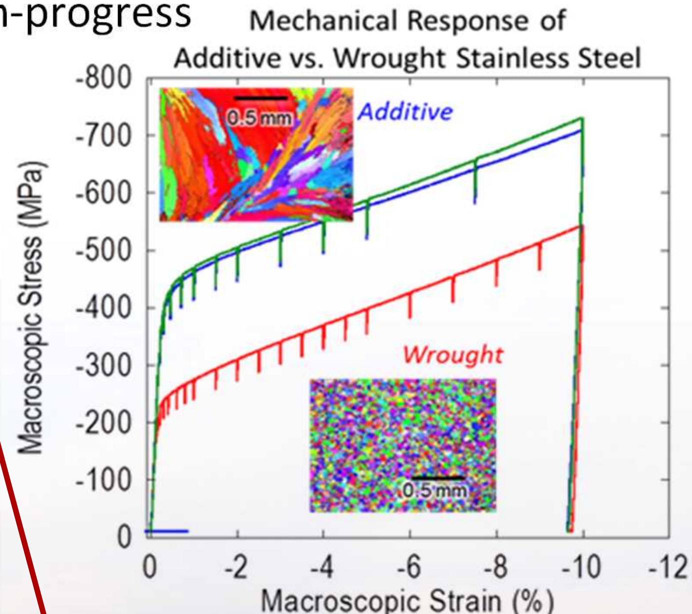
- Residual Stress is a Significant Issue
- Little Available Materials Property/Performance Data (no standards)
- Large Variability in Process and Materials
- Both Experimental & Modeling R&D in-progress

Large Variability in AM Materials Properties

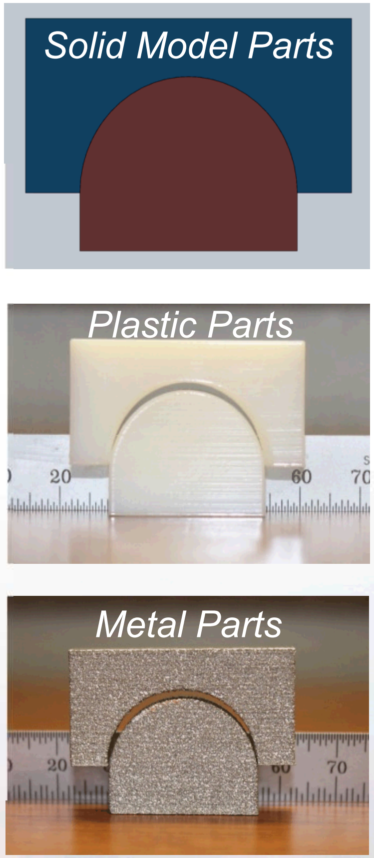


Ultimate Tensile Strength 17-4 PH (MPa)
(Typical wrought H900 ~ 1450 MPa)





AM Metals are Unlike Cast or Wrought Metals



Residual Stress Causes Parts to "Move"

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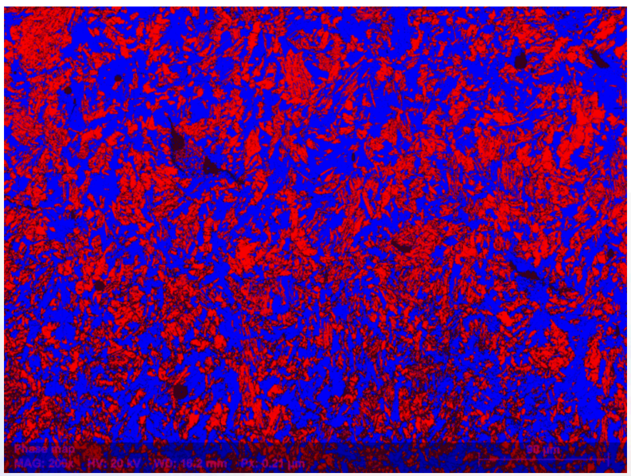
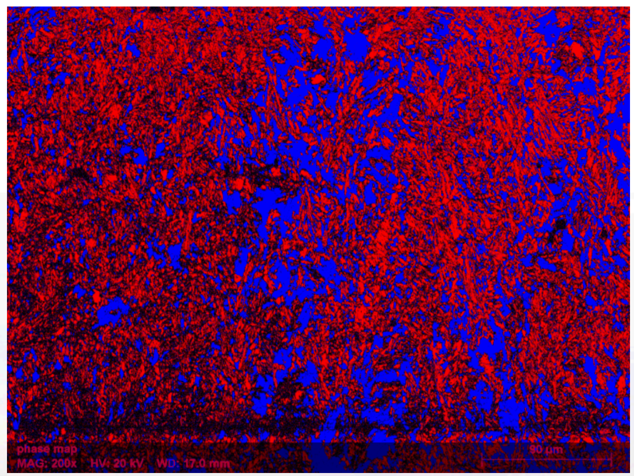
Retained Austenite in 17-4 PH Stainless When Using Nitrogen Gas Atomized Powder

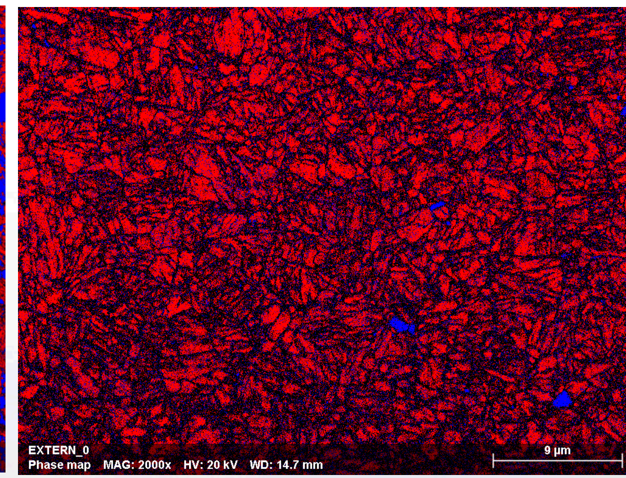
- Anomalous phase composition in AM vs. wrought 17-4 PH Stainless
  - Large fraction of retained austenite after solution heat treatment + H900 age
  - Cryo treatment to -196^{o}C for 5 min still does not transform austenite



As-printed, 47% Austenite



SHT + H900 Age, 43% Austenite



Wrought Sheet is Predominantly Fine-grained Martensite

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

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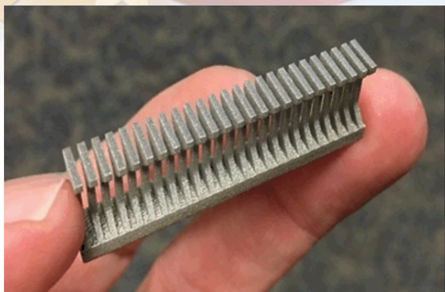
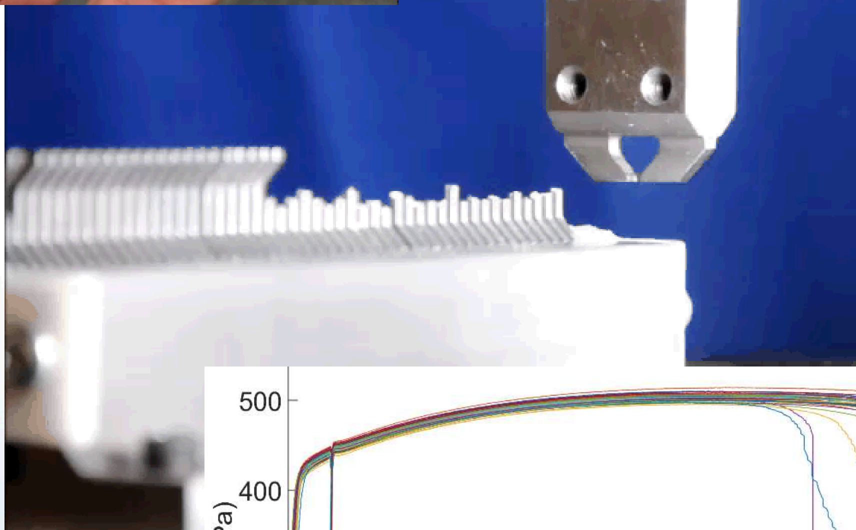
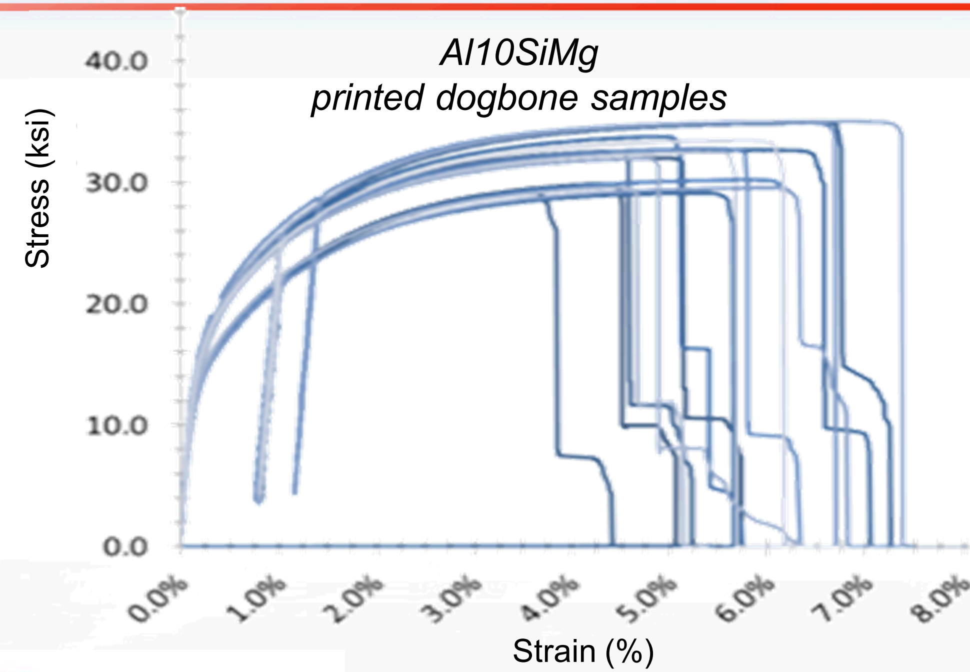
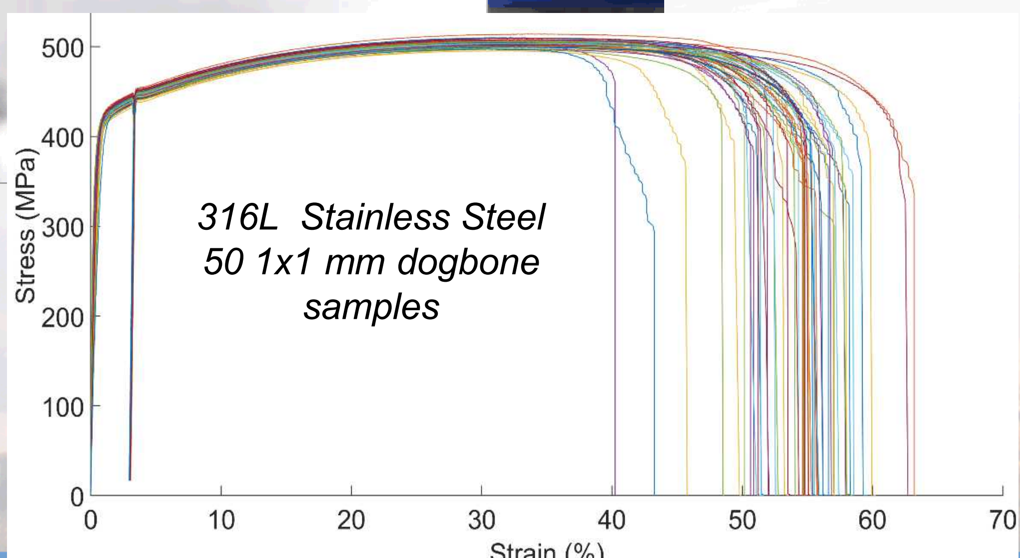
High-Throughput Testing Used to Address Variability



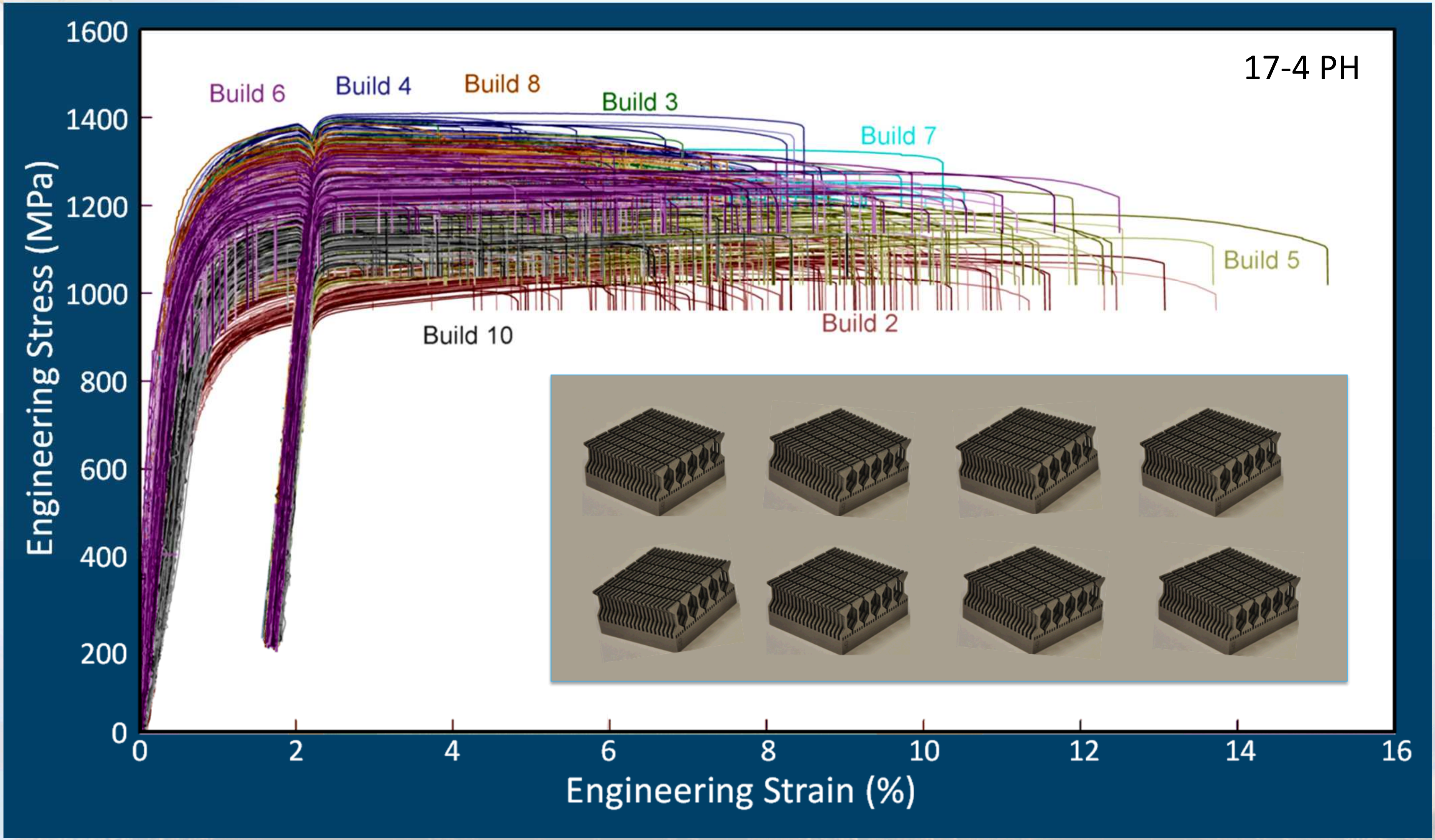
>100 Tests/Hr



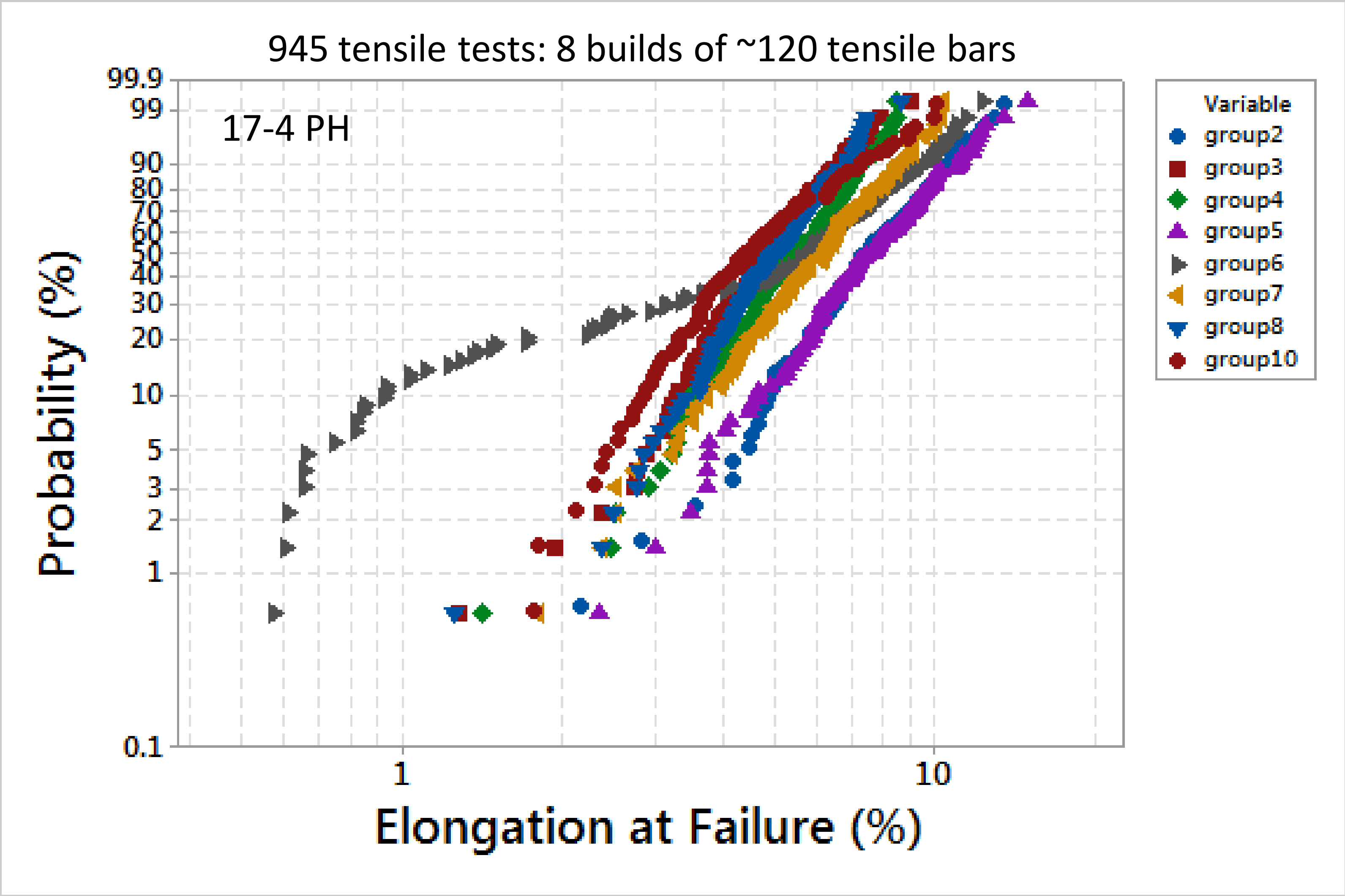




945 Tensile Tests from 8 Nominally Identical Builds



Weibull Analysis of Variation in Ductility



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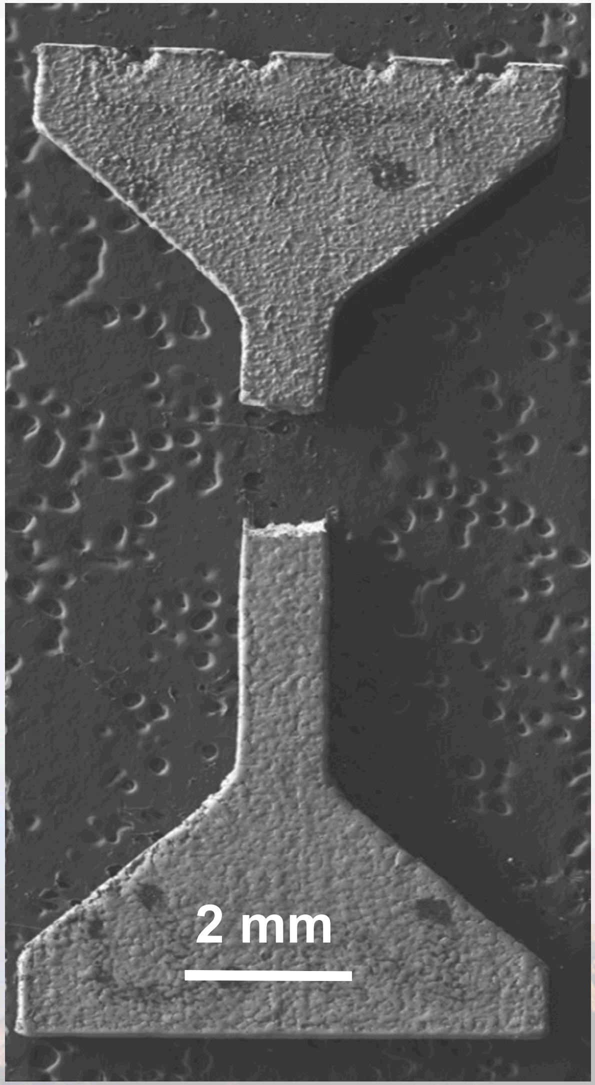
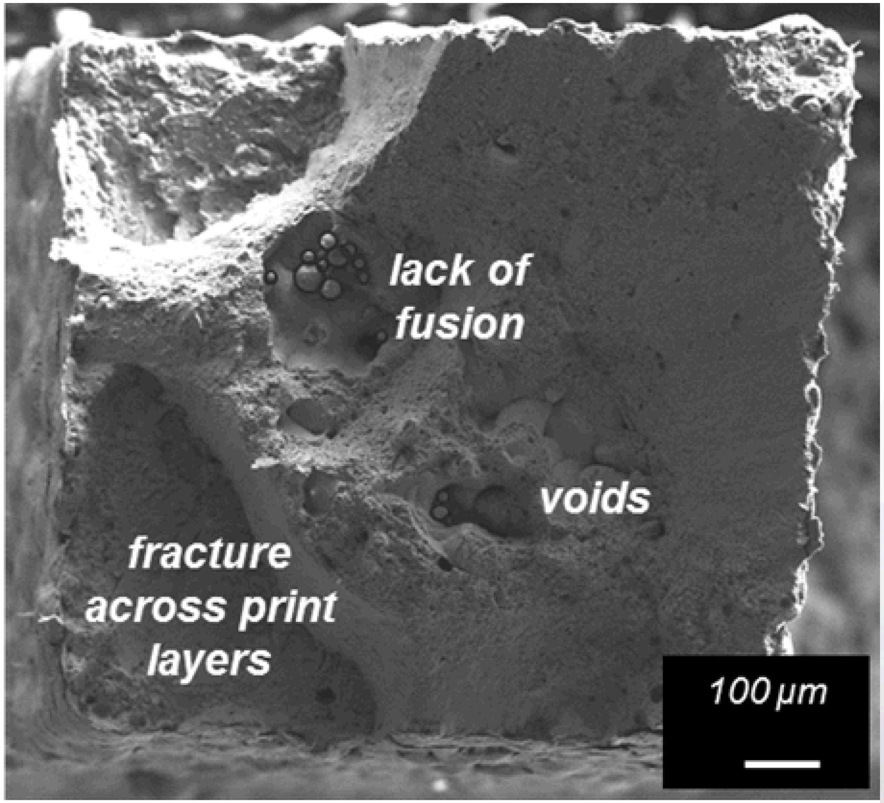
Common Types of Defects



17-4 PH SS, H900 “brittle” fracture



Failure at 2% elongation

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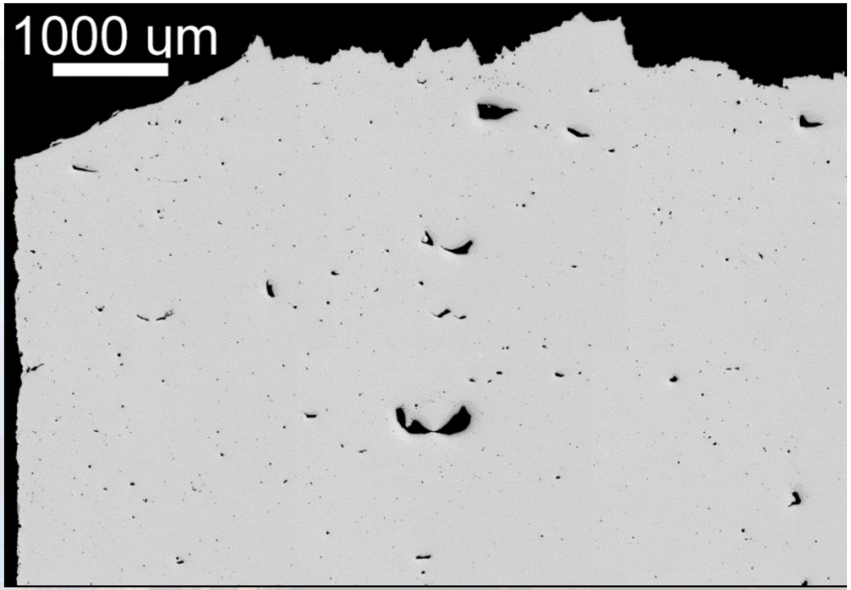
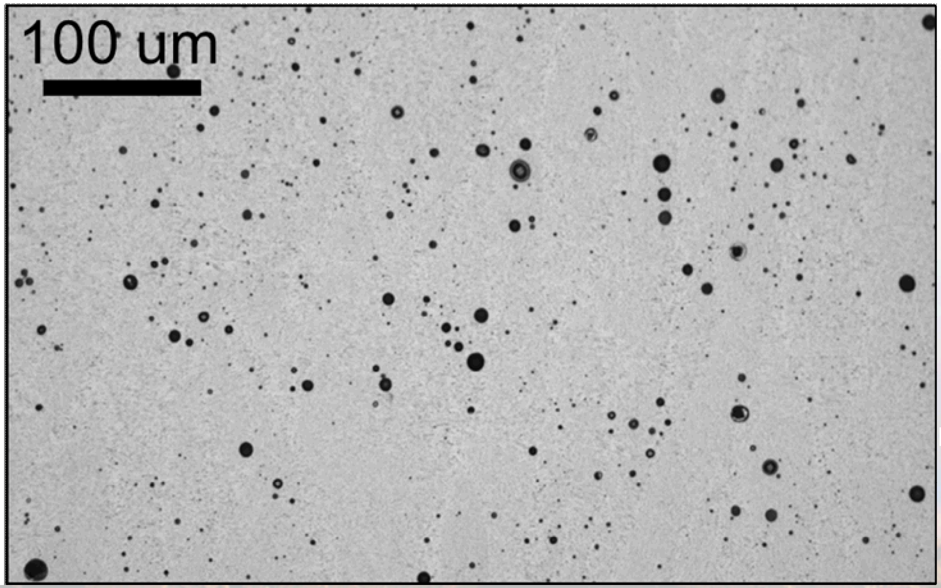
Metallographic Porosity (RoboMET.3D™)

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

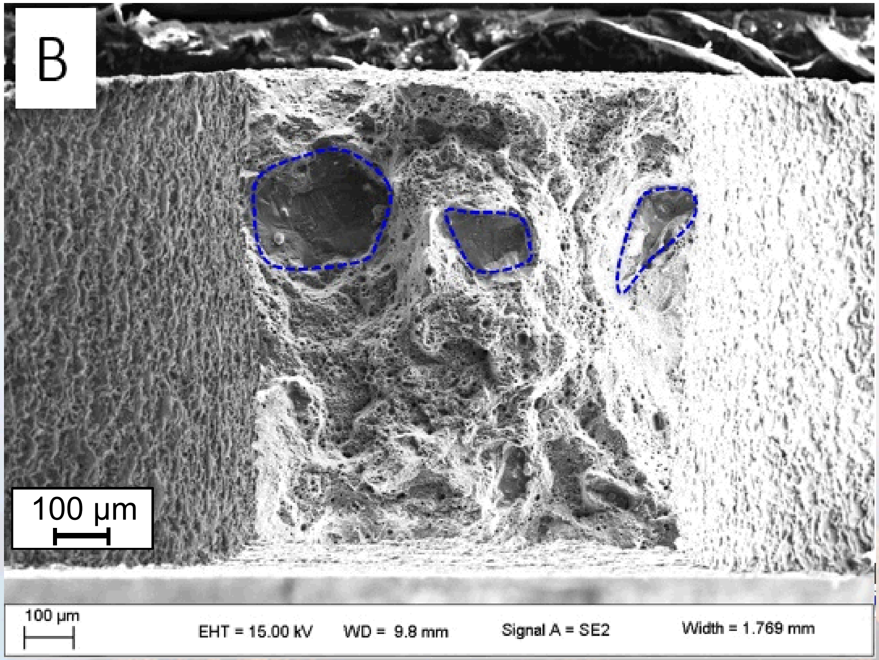


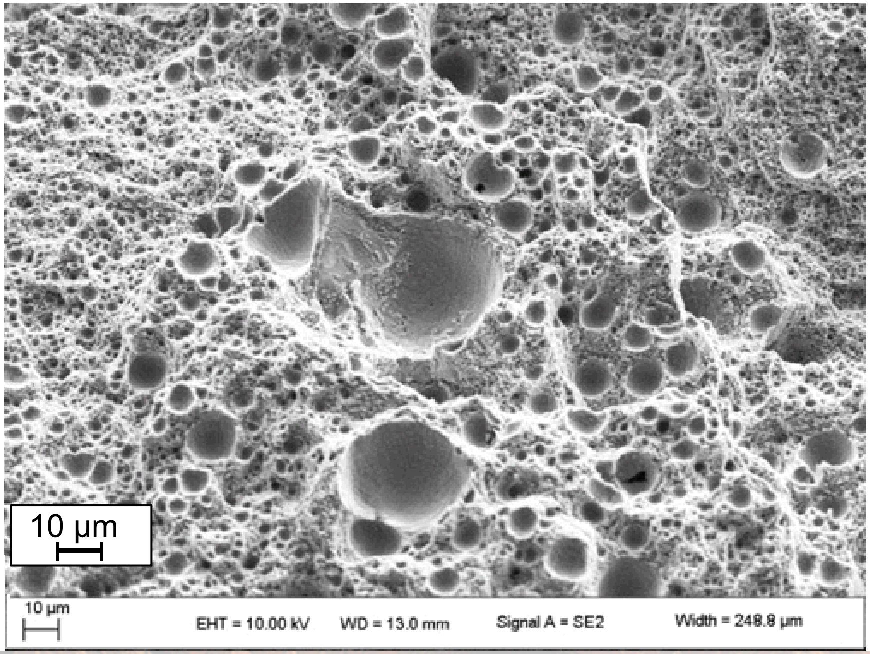


(note 10X difference in magnification between these two images)

Fracture Surface Porosity

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





D.F. Susan, T.B. Crenshaw, & J.S. Gearhart, *J Mat'ls Eng & Perf* 24(8), pp. 2917-2924, June 2016.

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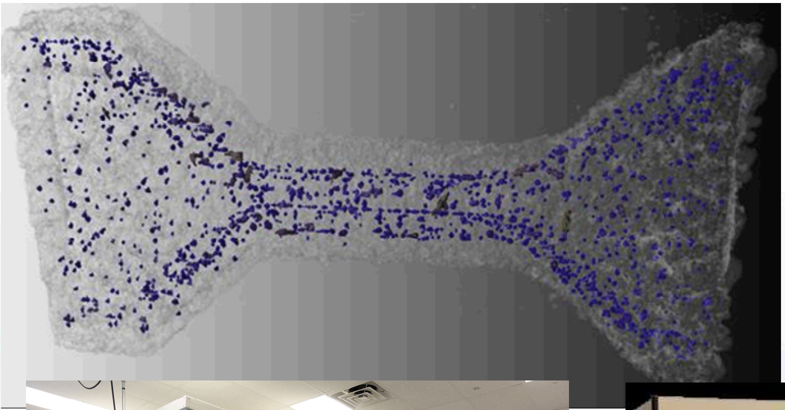
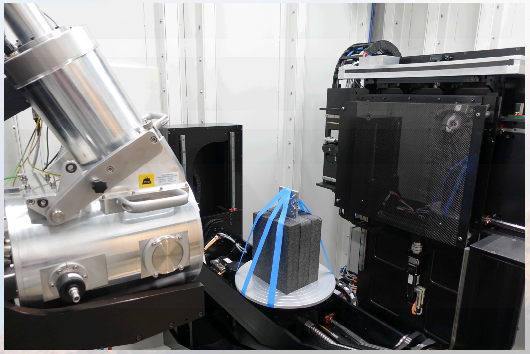
Computed Tomography Porosity

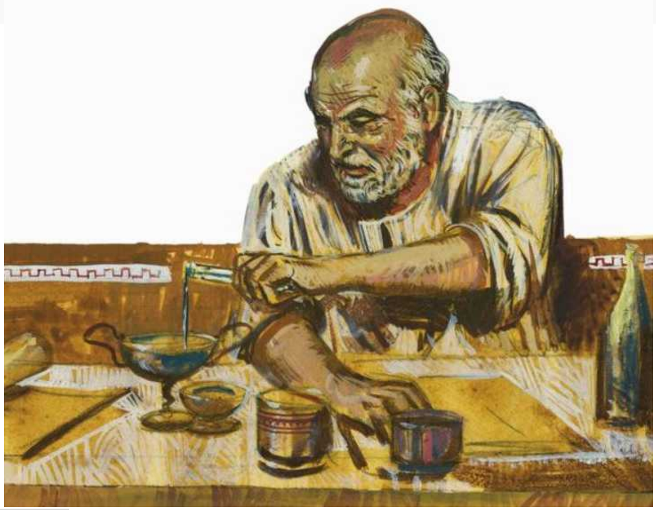
- Technique characteristics
  - Nondestructive
  - Amenable sample – X-rays have to be able to penetrate
  - Resolution/time can be issues; i.e., resolution/speed tradeoff
  - May not detect very small (gas) porosity or pores filled with unmelted powder

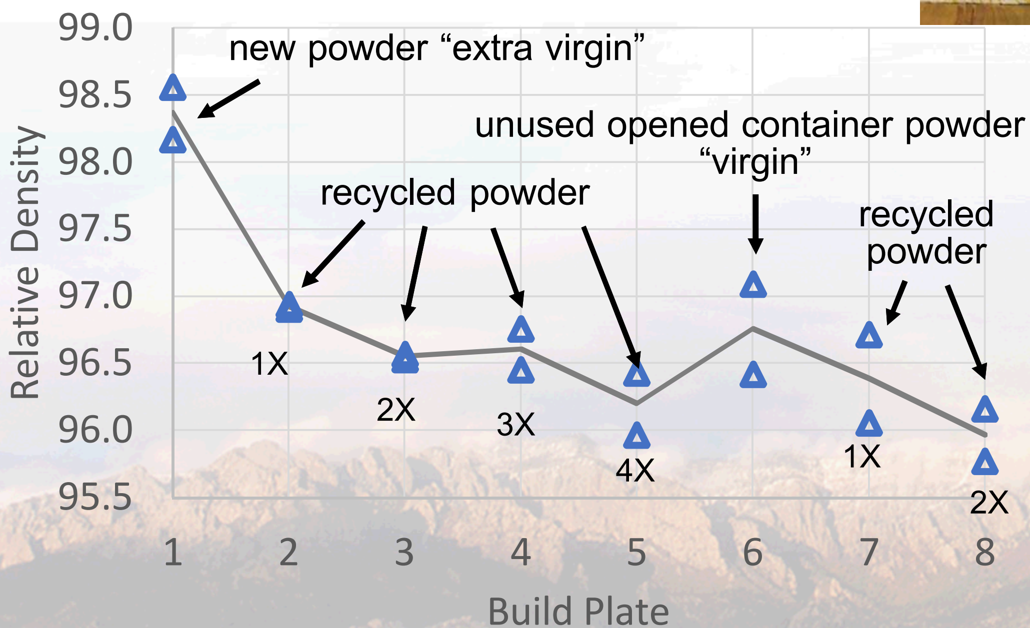




Density – Archimedes Porosity

- Technique characteristics
  - Nondestructive
  - Quick and inexpensive
  - Immersion of part
  - Surface voids/wetting can bias results
  - Won't account for pores filled w unmelted powder





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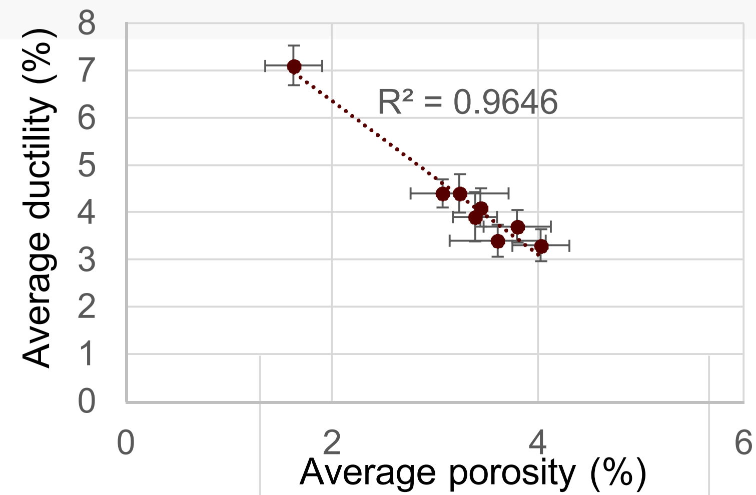
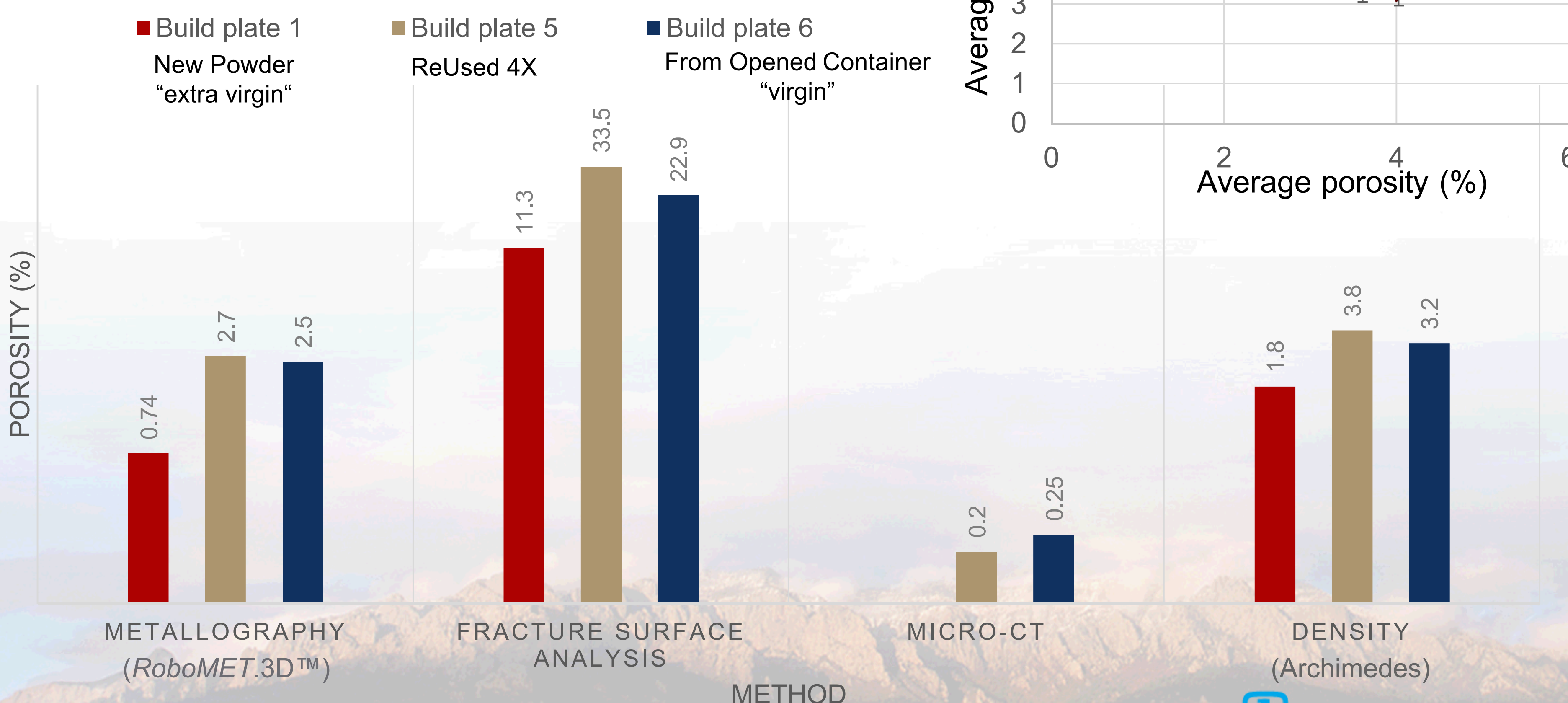
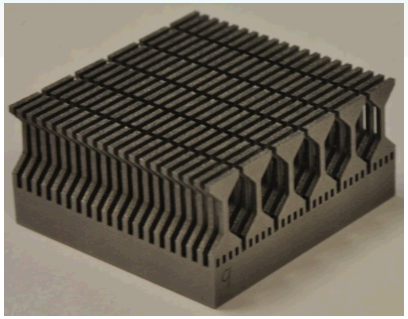
Results Vary With Measurement Method

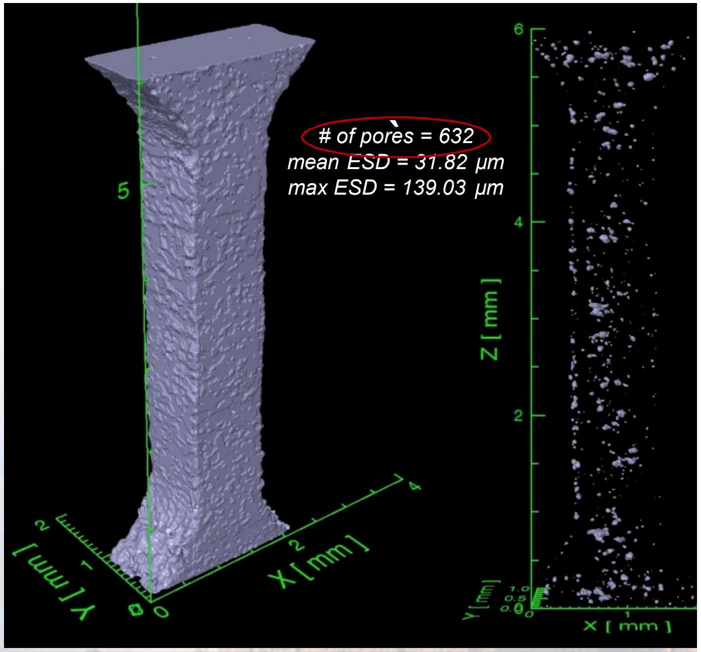


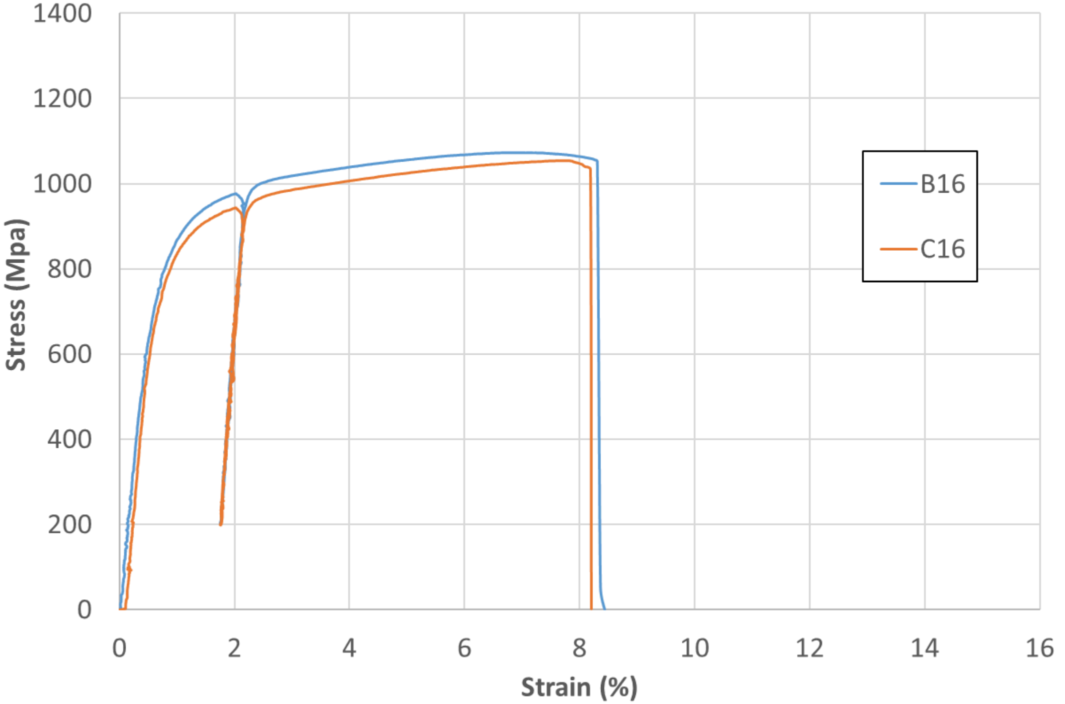


R&D to Understand Defect Sensitivities and Failure Modes

- AlSi10Mg Dogbones (Imaged w resolution ~ 7 -10 µm voxel edge lengt
- 632 vs. 1124 similar size pores
- Very similar tensile test results; Why ???



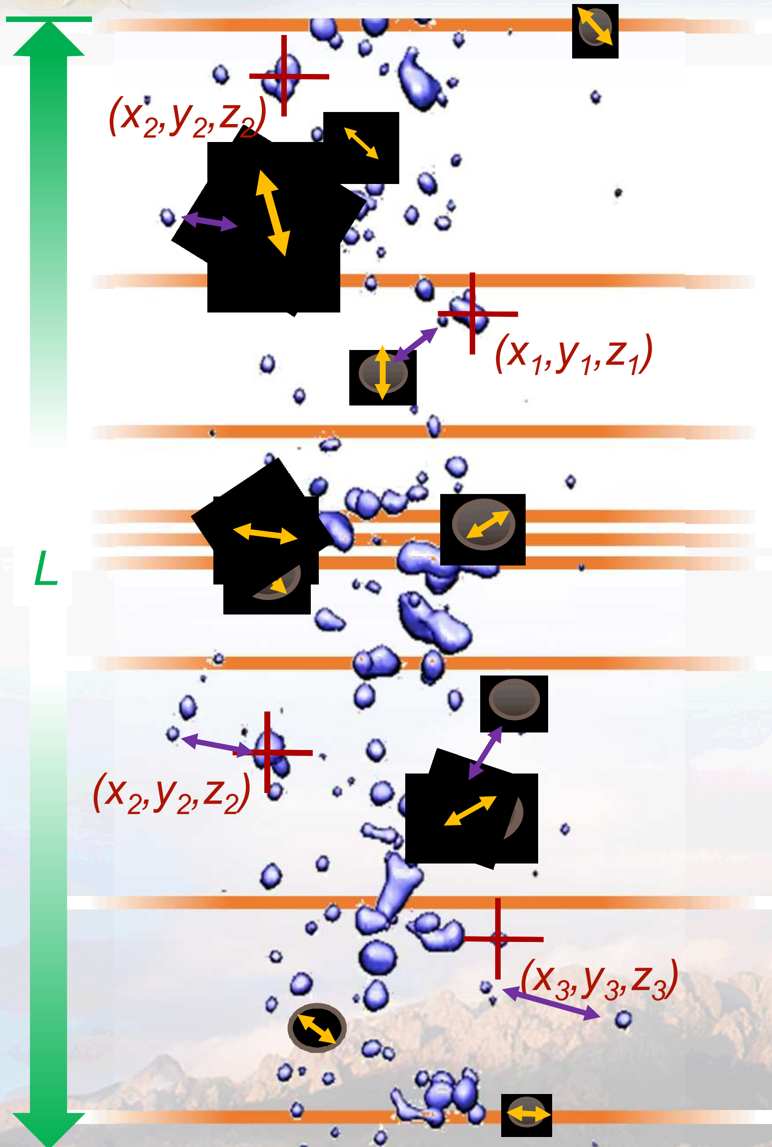




dogbone B,16 CT surface image (left), porosity map (

ESD = equivalent spherical diameter

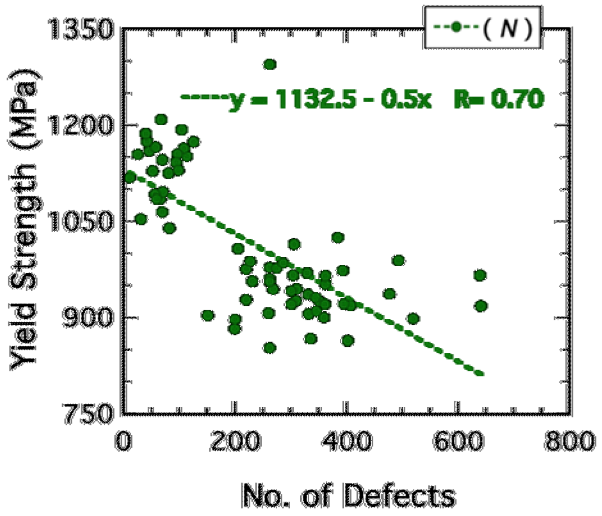
Can We Find Defect/Property Correlations?

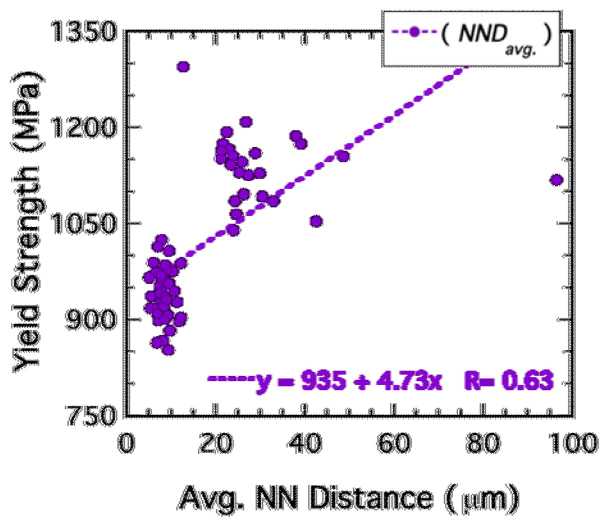


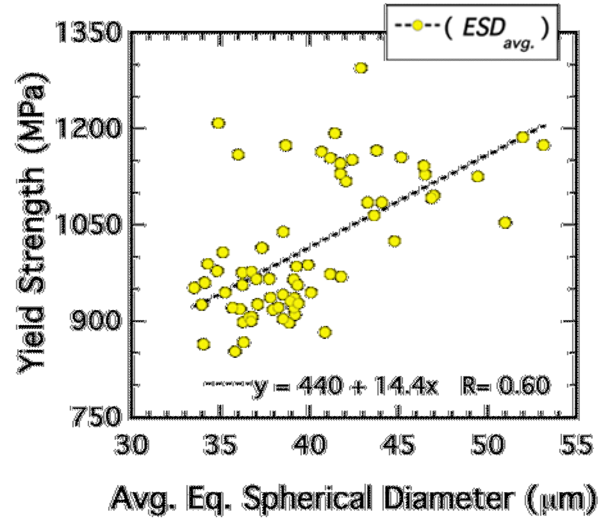
- Total Volume of Defects *(V_{tot})*
- Pore Volume Fraction *(V_{fract})*
- Spatial Location of Pores *(x, y, z)*
- Total Number of Defects *(N)*
- Total Defects/Length *(N/L)*
- Average Defect Volume ($V_{avg.}$)*
- Average Equivalent Spherical Diameter ($ESD_{avg.}$)*
- Average Cross-Sectional Area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

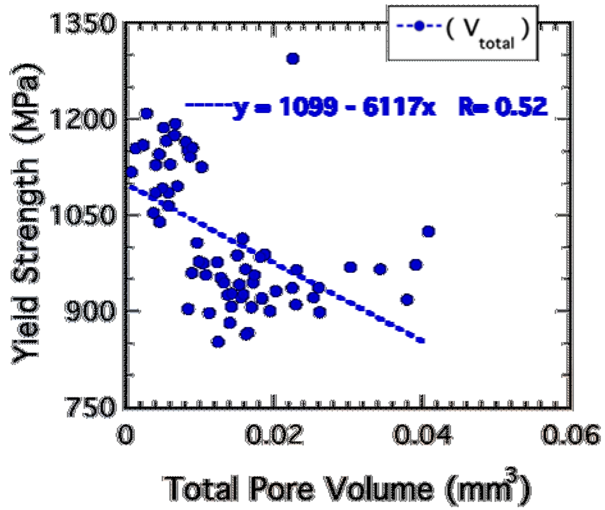
How do we *best* represent the defect populations present?

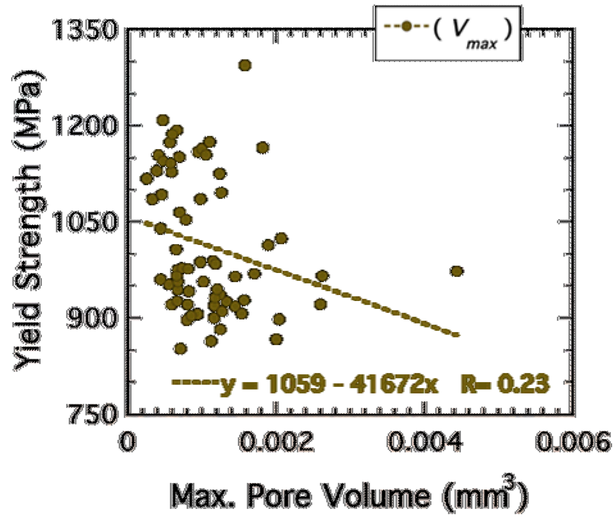
Statistical Correlations Are Elusive







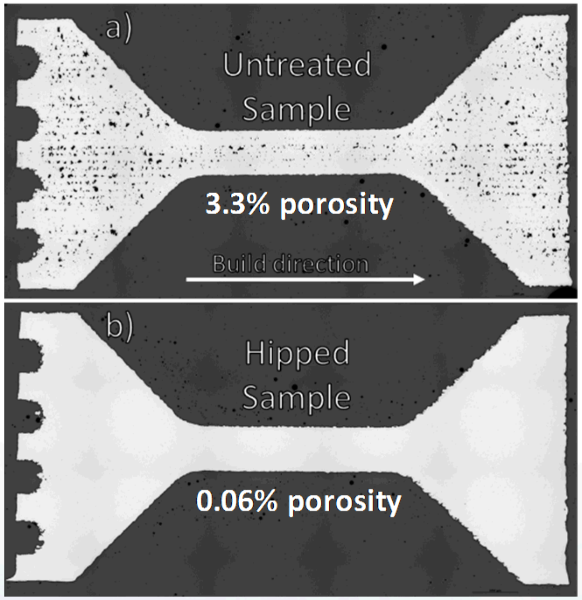


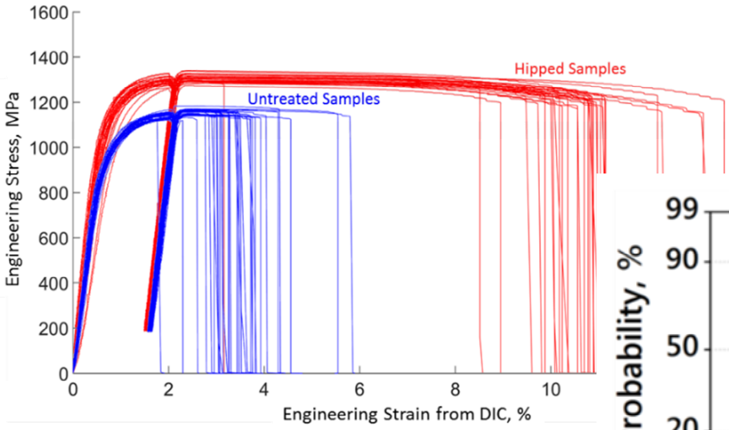


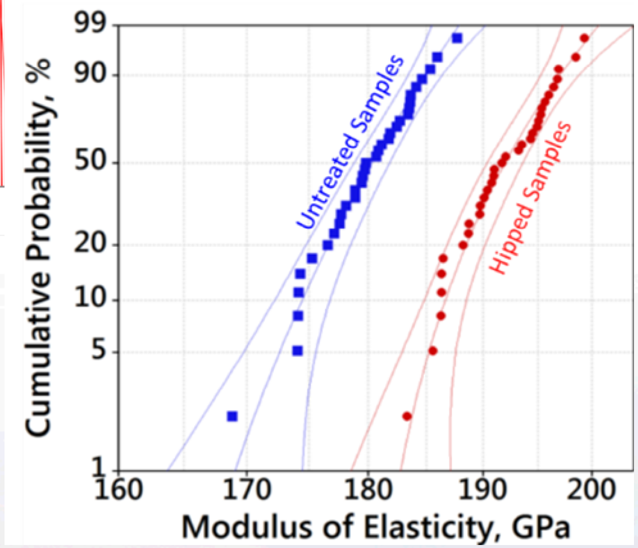
Measure	R^2
No. of Defects	0.50
Avg. NN Distance (mm)	0.40
Avg. ESD (mm)	0.36
Max CSA Redux (mm^2)	0.38
Total Pore Volume (mm^3)	0.27
Avg. Defect Vol. (mm^3)	0.25
Max CSA Redux (%)	0.24
Maximum Pore Size	0.07
Seven factor multivariate regression	0.60

HIP Process Improves Properties…

HIP Treatment: **1120°C+100MPa for 6 hr**







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

$$E_p = E_0 * (1 - a * P) \qquad a = 1.9 \text{ [Choren et al, J. Mater Sci, 2013]}$$

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

$$\Longrightarrow E_{0.06\%} = 195 \text{ Gpa}$$

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

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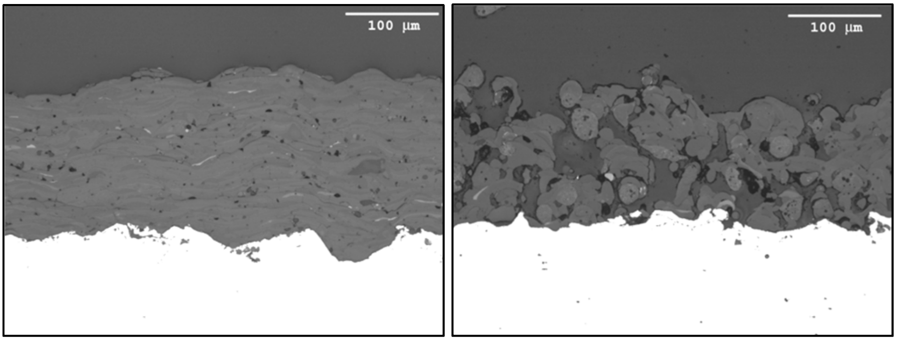
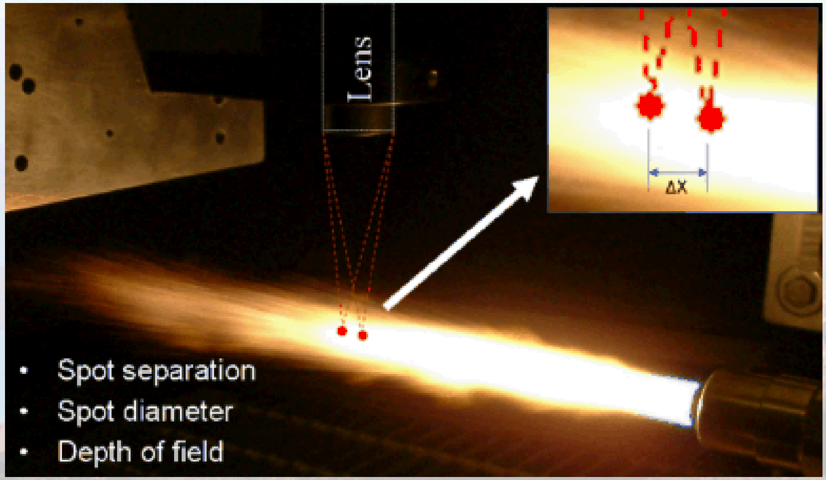
Fundamental Process Understanding is Key to Controlling Variability

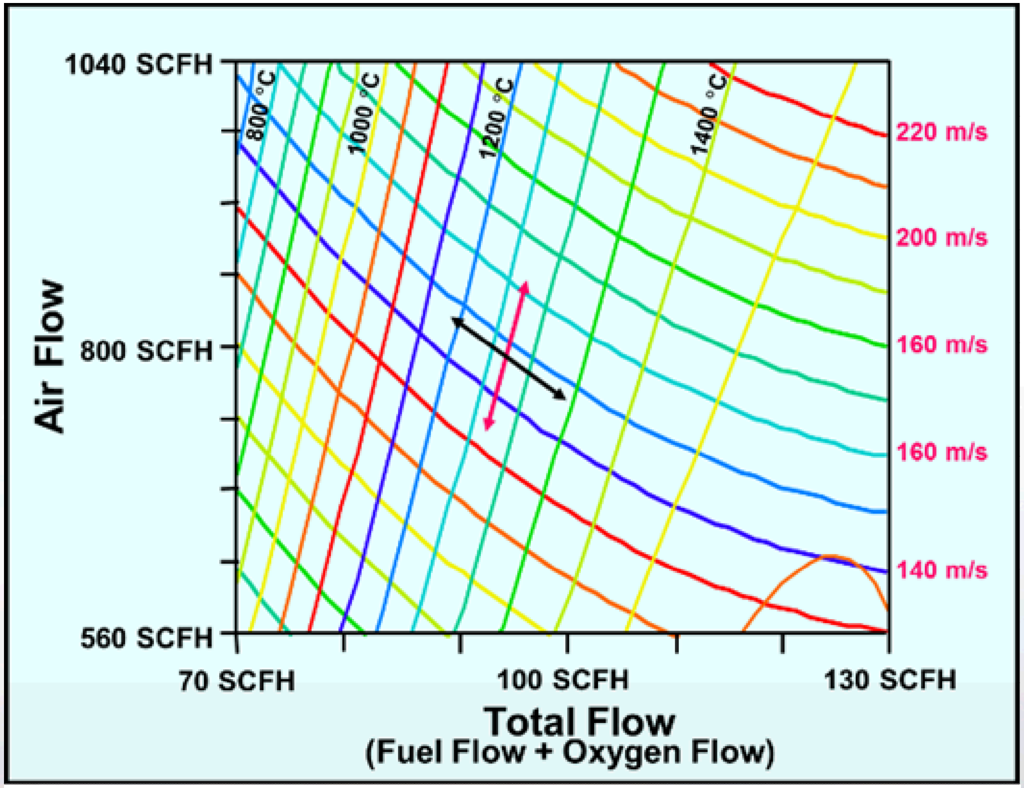
- Thermal spray process used to run open-loop with high variability in the resulting materials



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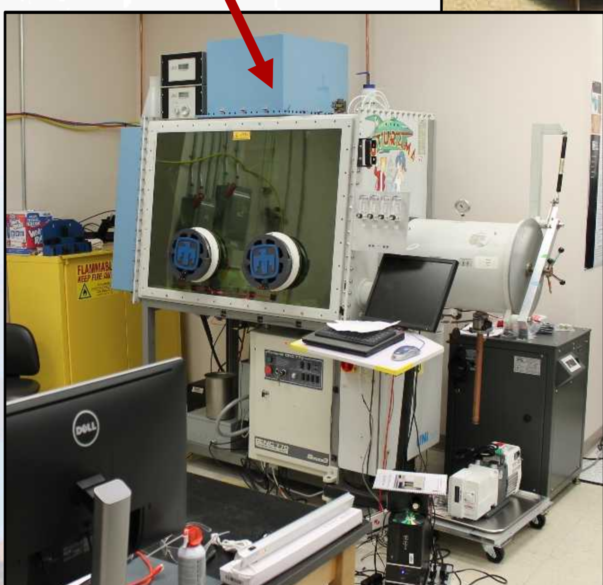
Sandia Metal/Multi-Material AM Process R&D

3D Systems ProX 200 Laser Metal Powder Bed Machine

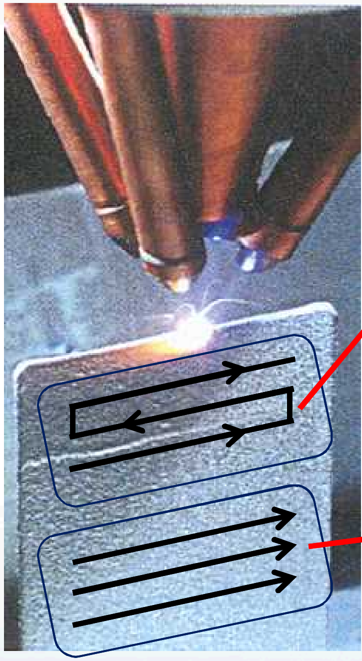
Aspex Explorer SEM-based powder particle analyzer

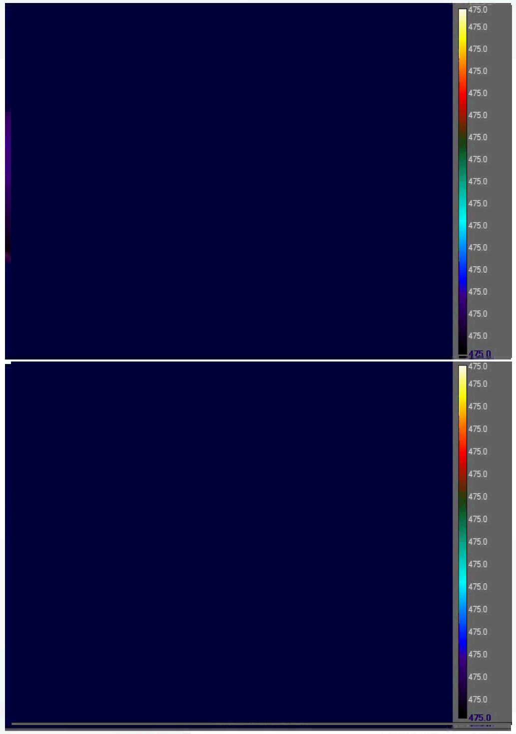
Next Generation Custom Built Hybrid LENS™ System



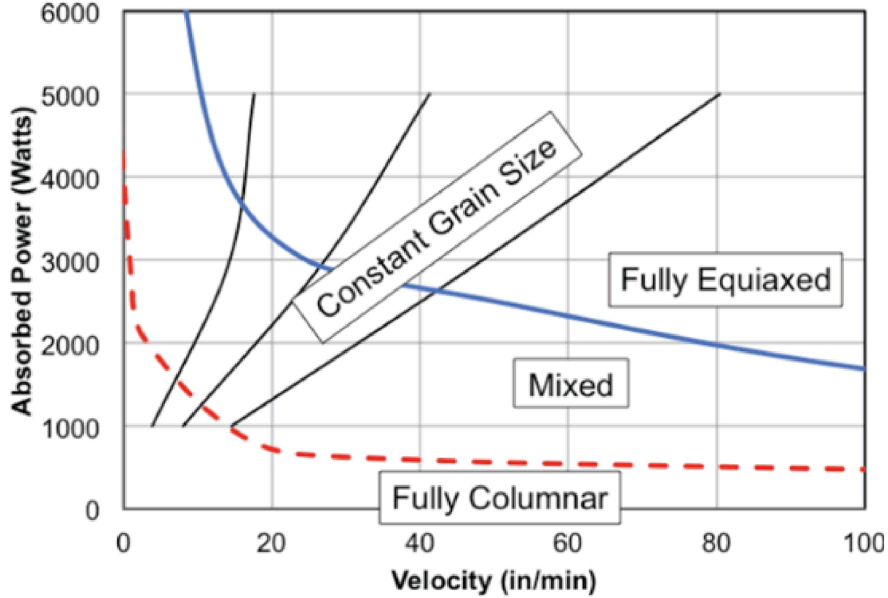
Haas VF2 mill-turn machine will be Modified for Multi-Material hybrid AM, including LENS™

Working to Understand LENS™ Processing-Microstructure Relationships

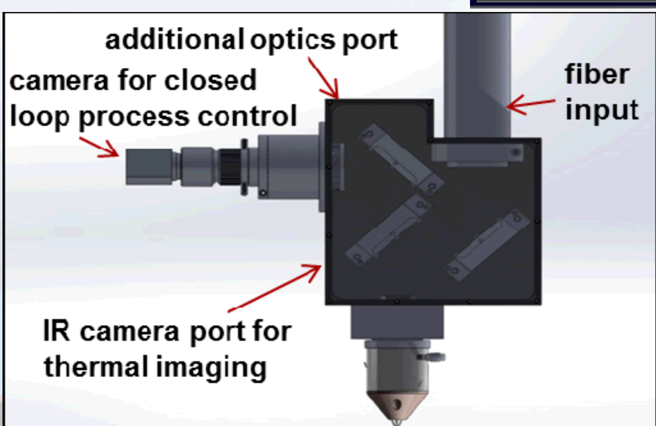


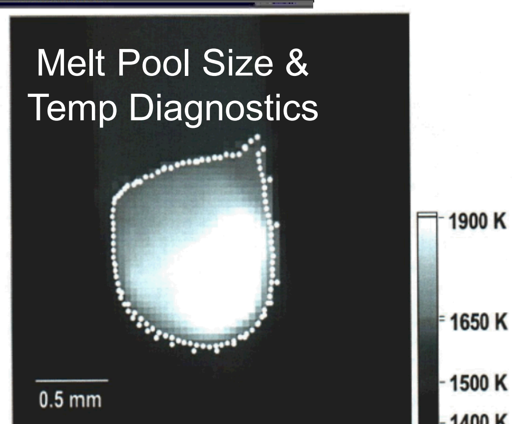


Processing-Microstructure Relationships (teaming w Carnegie Mellon)



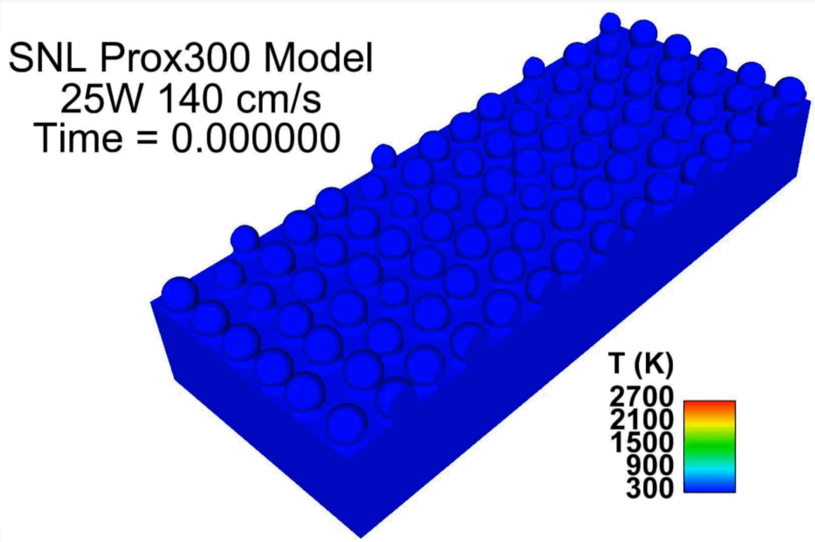
J. Gockel et al. / Additive Manufacturing 1–4 (2014) 119–126

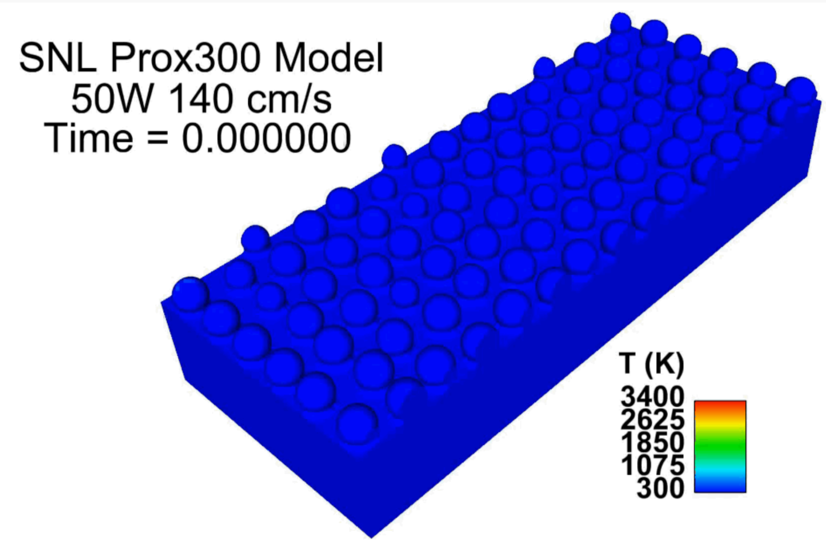




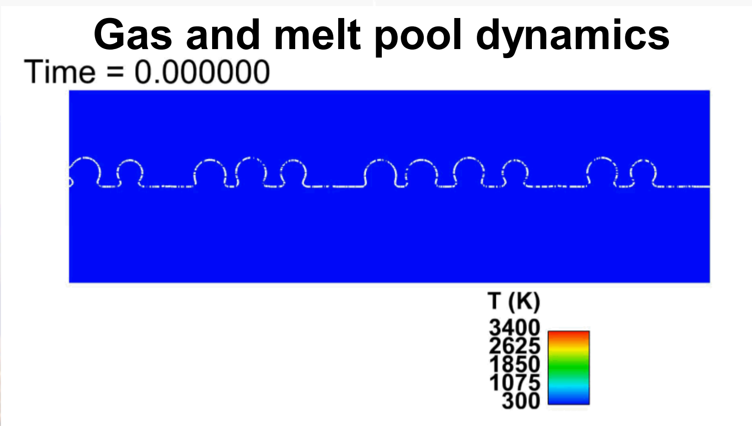
Control melt pool size & temperature to create desired microstructure and reduce variability

Process Modeling Can Provide Useful Insights





Stainless steel 304L
25 micron powder



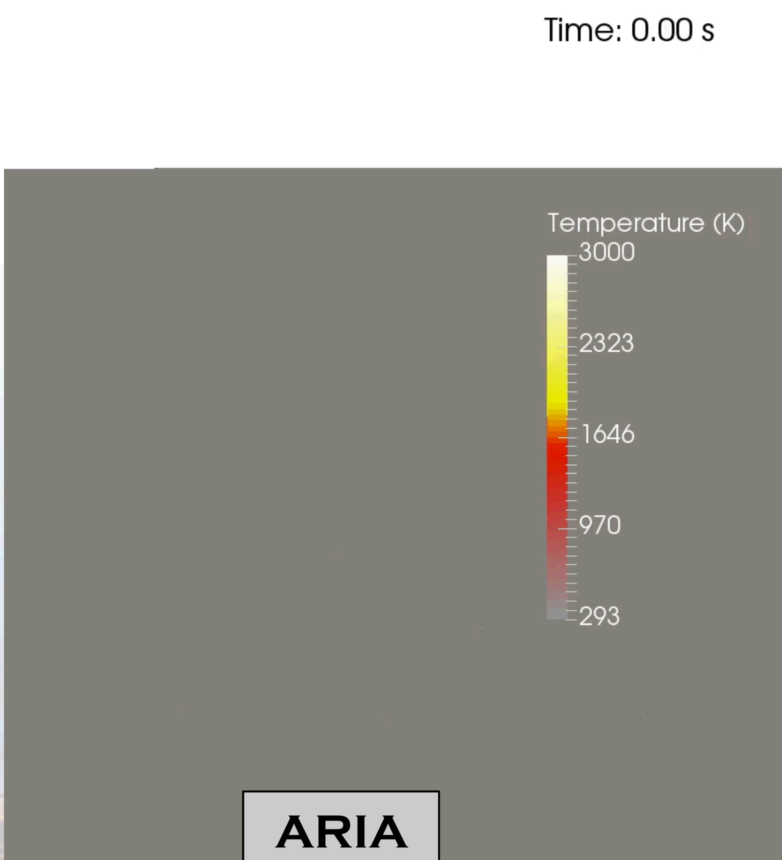
Notes:

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

Process Models by Mario Martinez

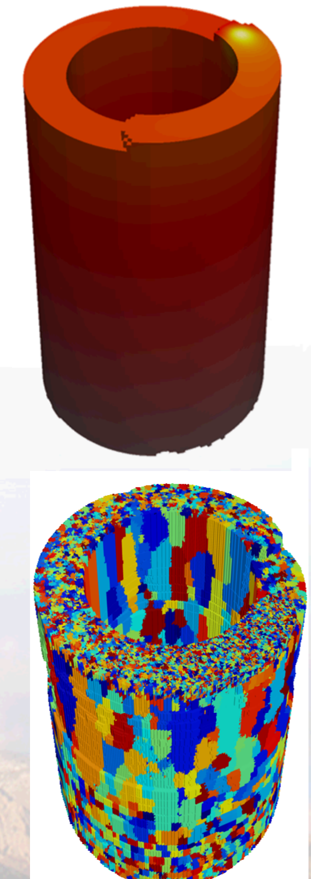
Linking to Thermal Models

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



ARIA

SPPARKS



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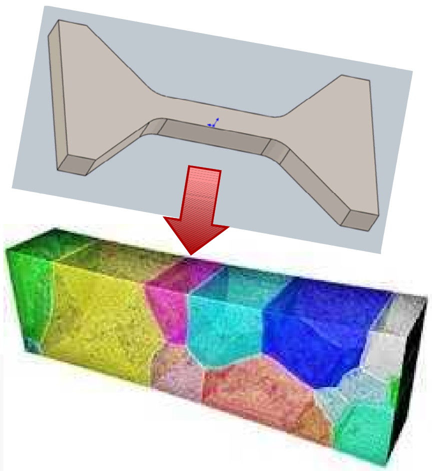
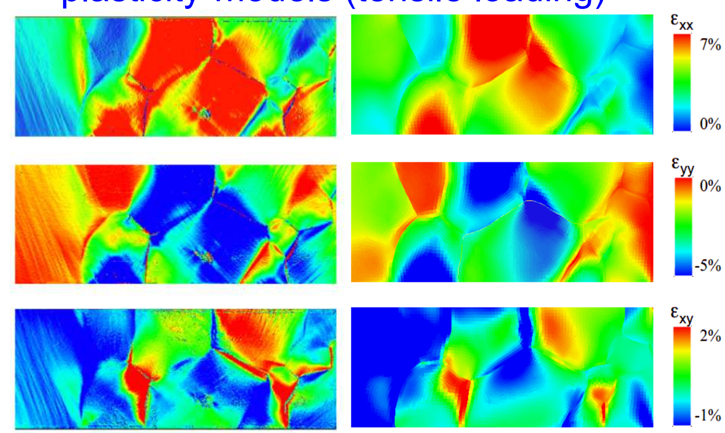
Leverage Sandia PPM to Investigate Variability/Defect Sensitivity

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)

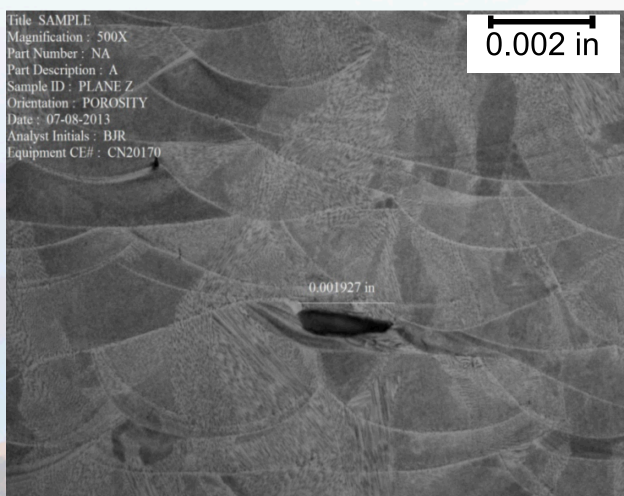


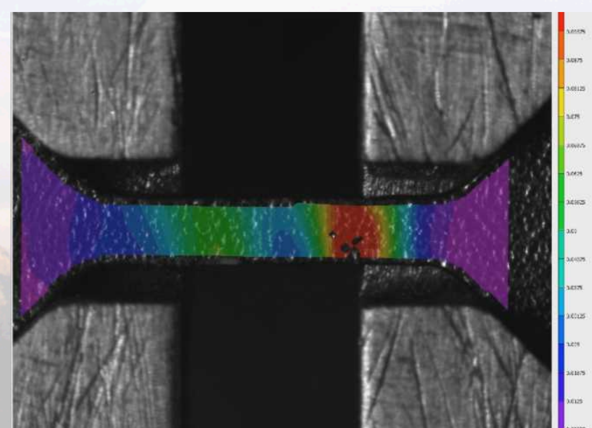
Experimental Results | **Computed Simulations**

Key Questions:

What AM Defects Matter?

Can I detect them?





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

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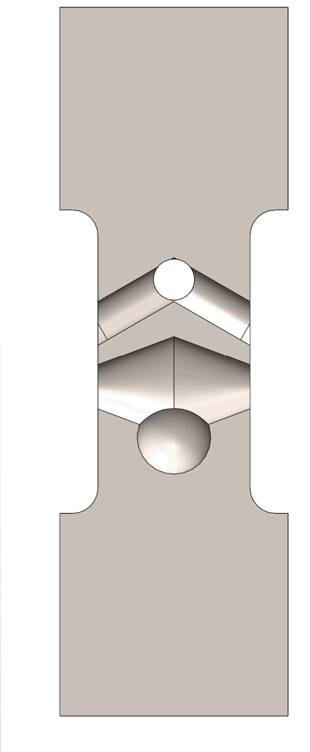
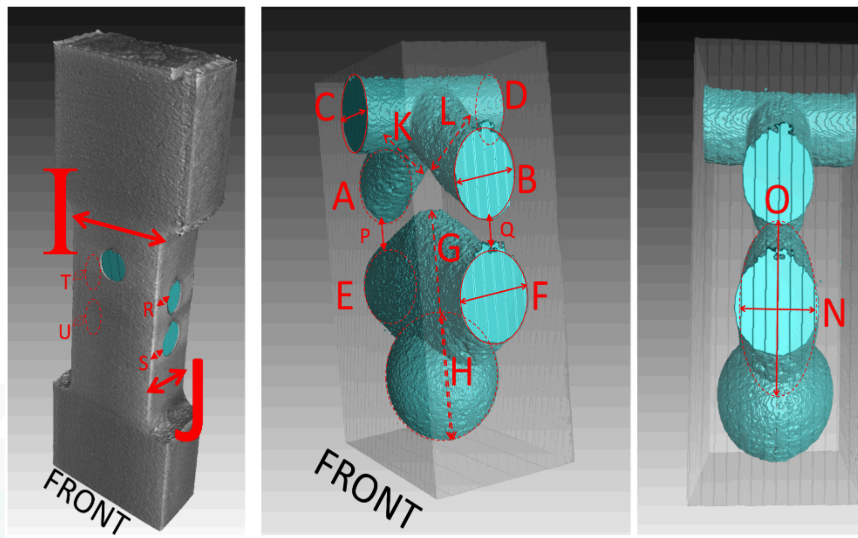
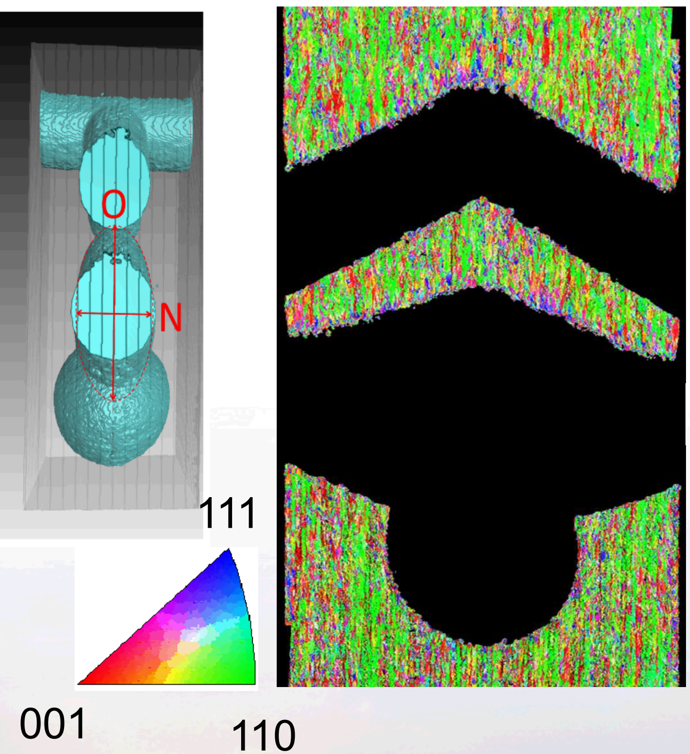
Sandia's Reliability Prediction Competition

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







Alloy: 316L
Production method: Laser Powder Bed Fusion

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

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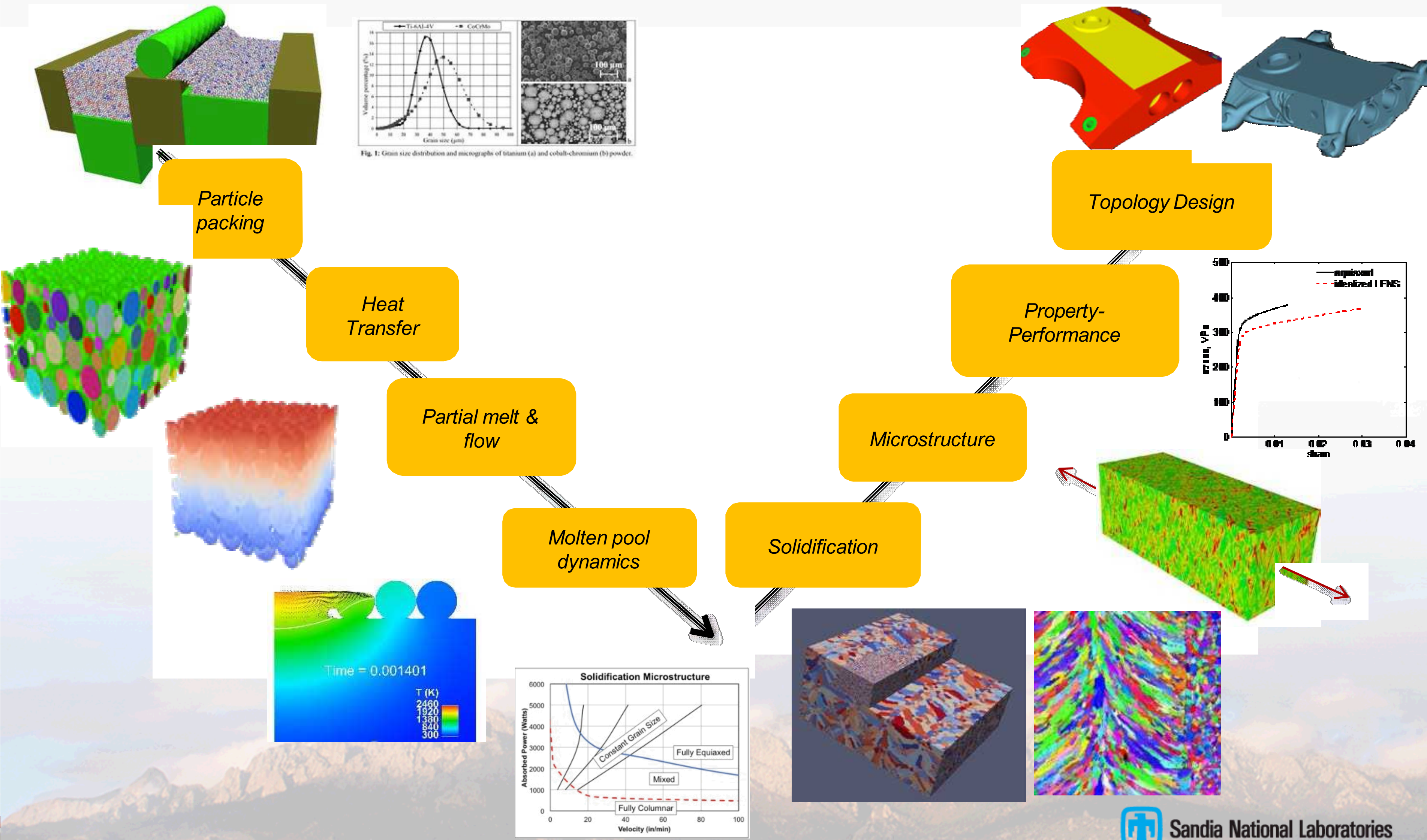
Ultimate Vision is to Understand/Control
Process → Microstructure → Properties → Performance



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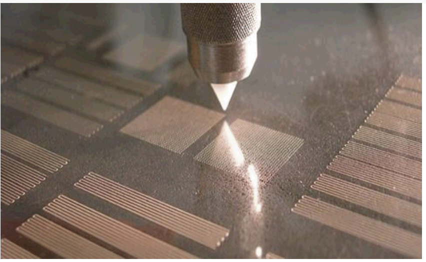
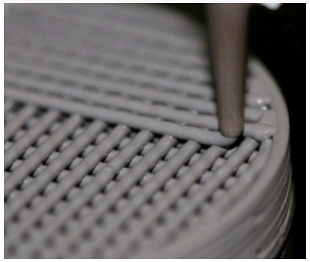
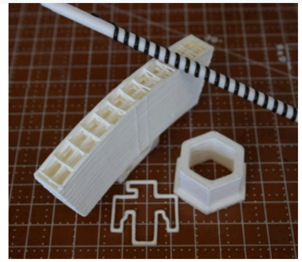
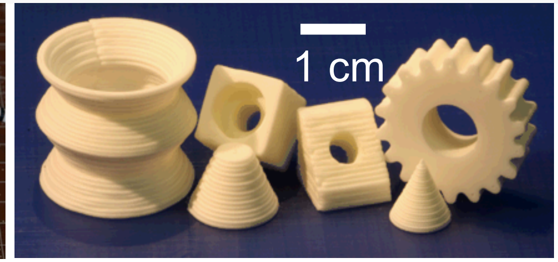
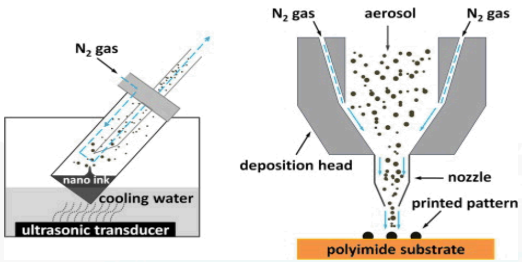
Multi-Material AM

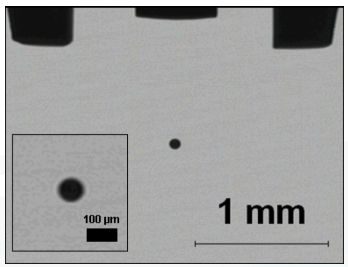
Direct Write Technologies Enable Access To Materials Not Supported By Conventional Printing Processes

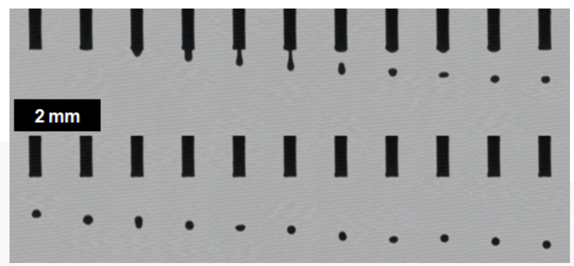
Direct Write by Extrusion Casting (Robocasting)

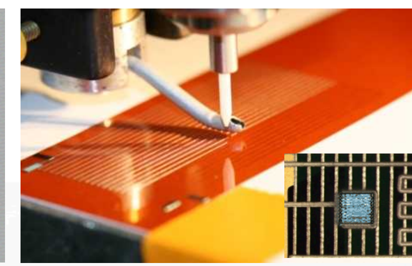





Direct Write by Aerosol & Ink Jet Deposition

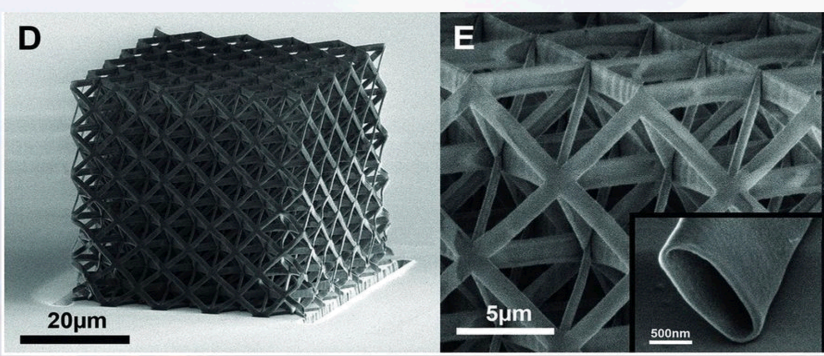


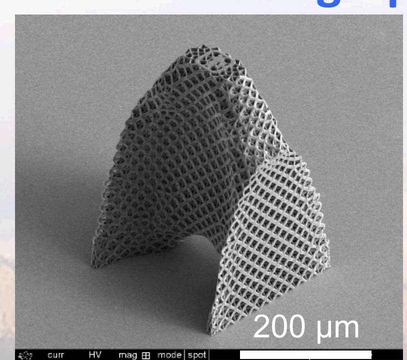


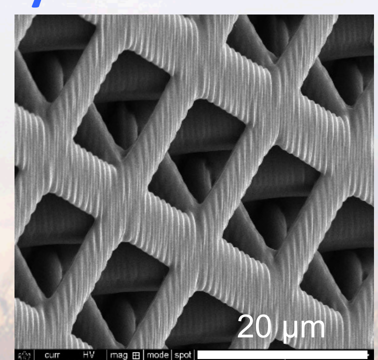




Direct Write by Laser Photo-Lithography







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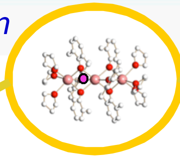
From Nano-Materials to Components at the Sandia Advanced Materials Lab

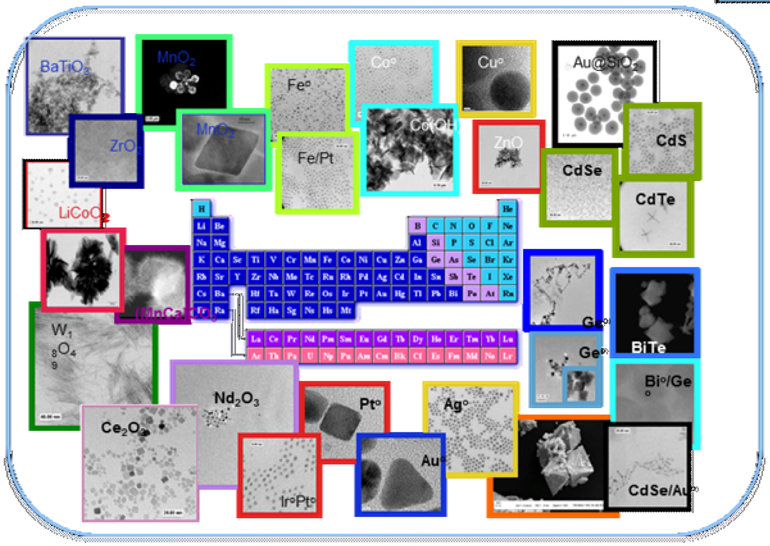
Solution Precipitation



Specialty Precursors

Solvothermal

Speicalized Nanomaterials



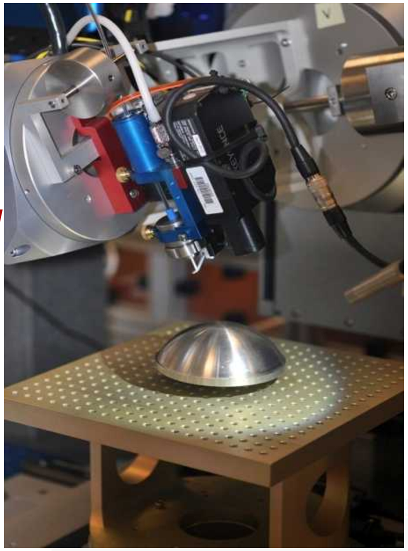
Colloidal Chemistry

Specialty Inks

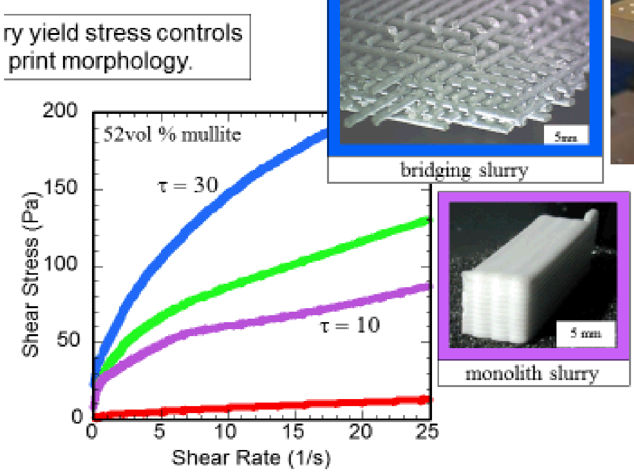
Ink Characterization

Process Engineering

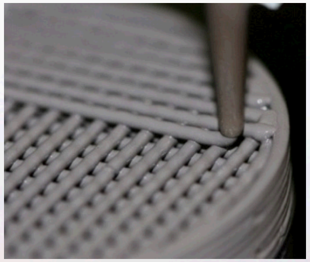
Direct Write Printed Parts



Influence of paste rheology



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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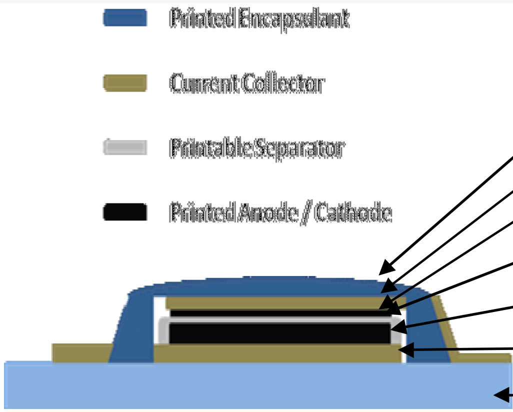
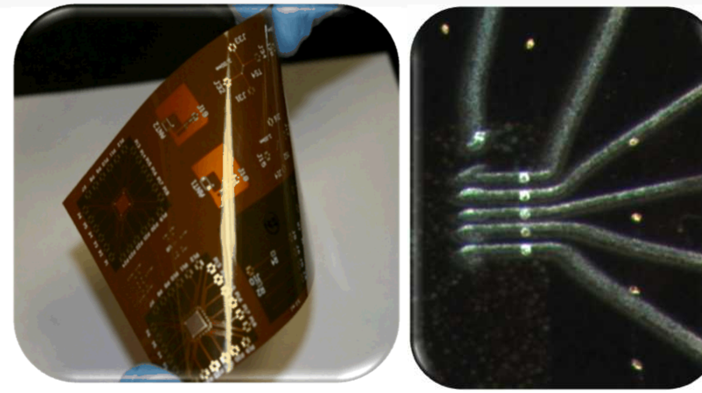
Sandia has Strong Capabilities/Expertise In Printed Electronics

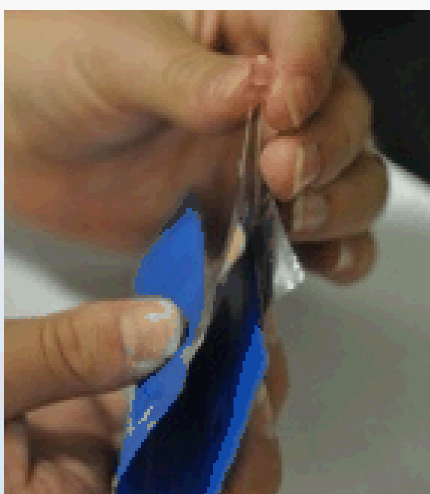


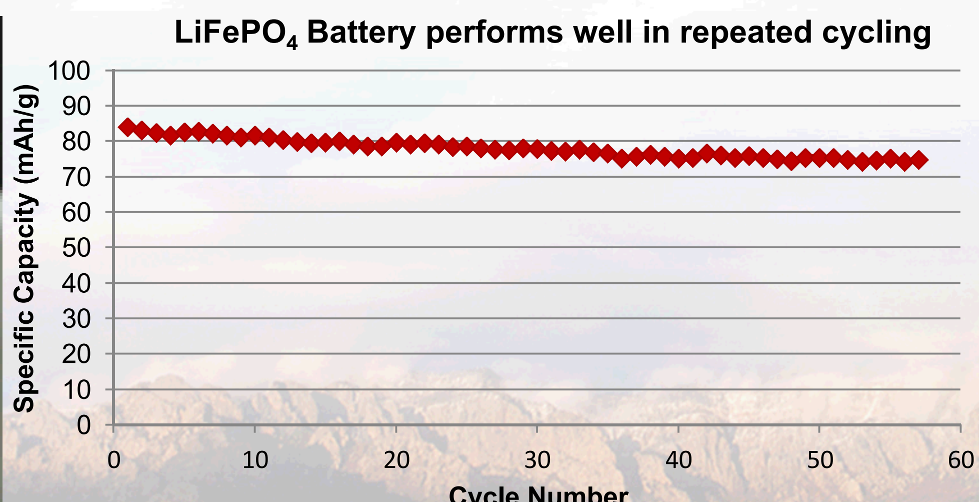
Printed flexible battery

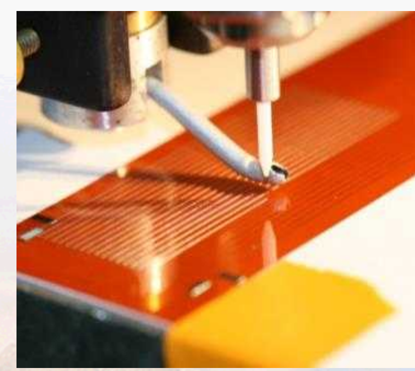
- Encapsulant (DW UV-curable epoxy)
- Current collector (DW carbon ink)
- Anode (DW graphite/carbon)
- Separator (DW mesoporous polymers)
- Cathode (DW $LiFePO_4$)
- Current collector (DW copper ink)
- Substrate (polyimide)



"Flexible Chips" with printed wirebonds



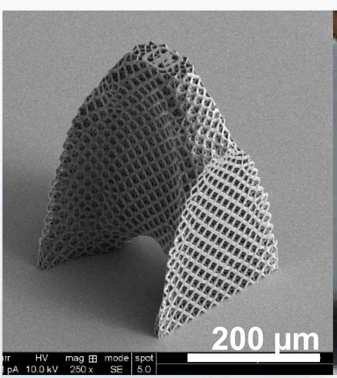


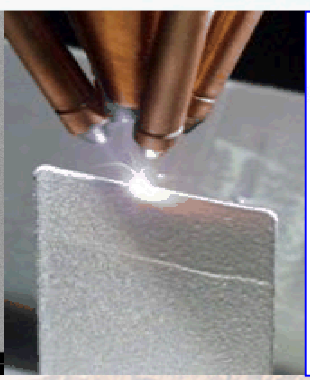
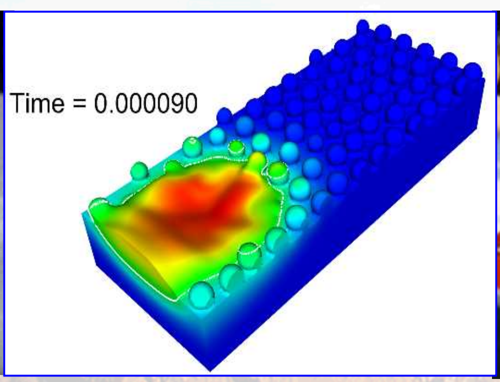


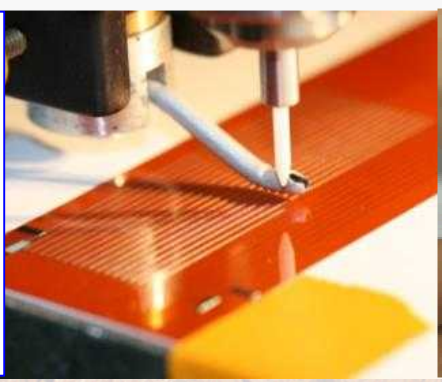
Aerosol jet printing to 10 μm

Summary

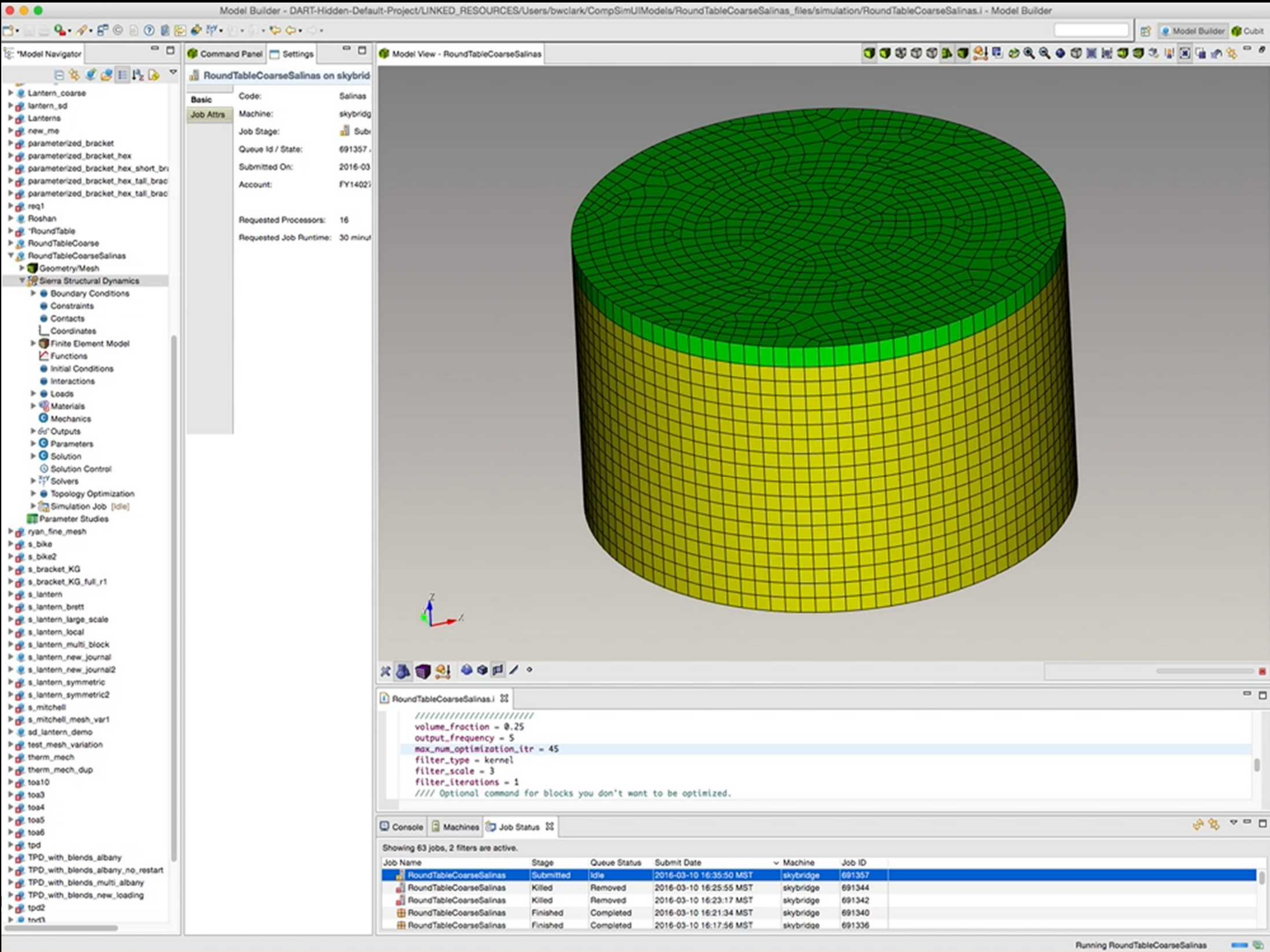
- Sandia has a rich history in AM technology development & commercialization
- Special interest in Design for AM, Materials Reliability, & Multi-Material AM
- Strong, uncommon, experimental and computational capabilities
- Strong interest in teaming with others in areas of mutual interest



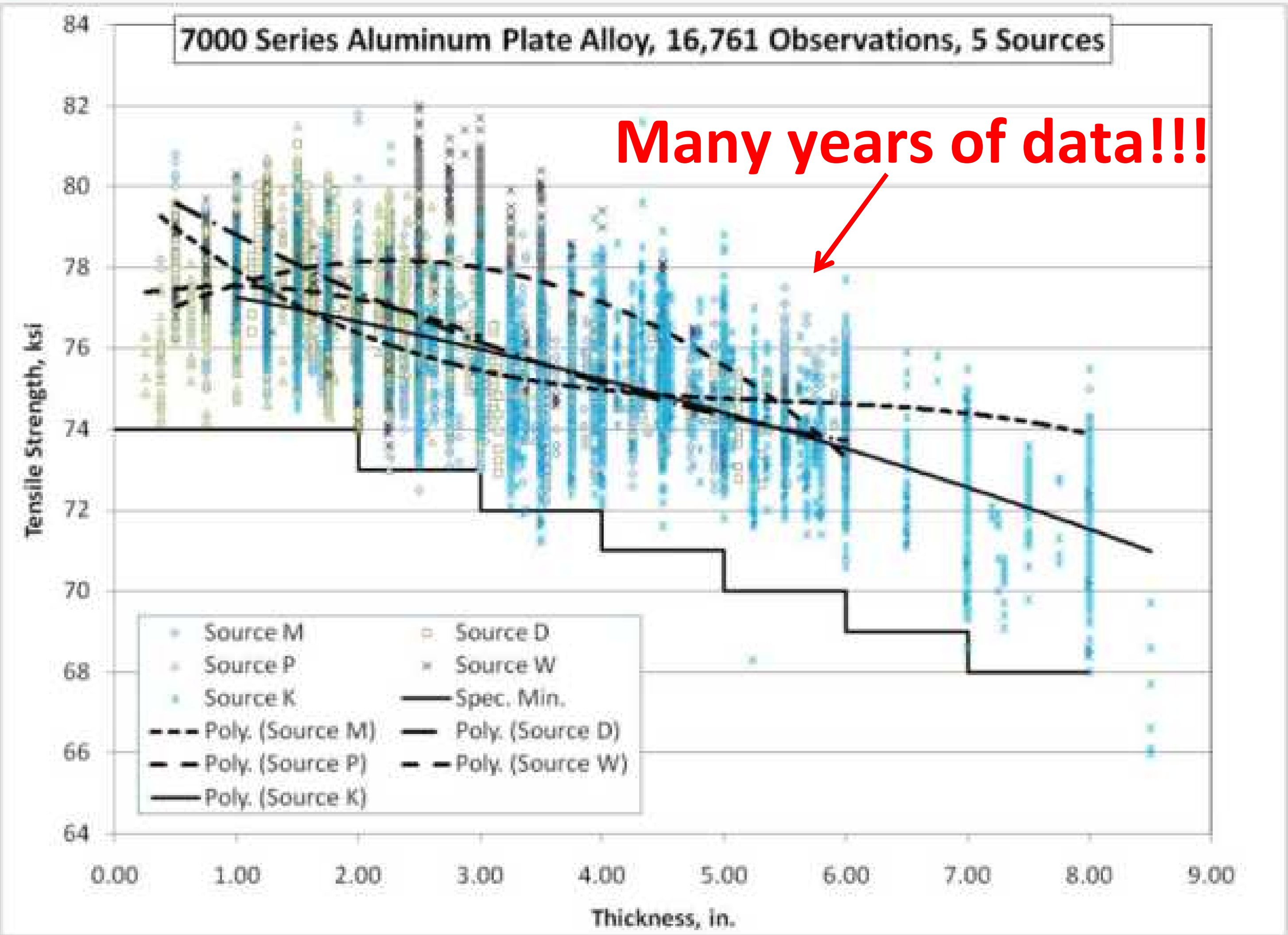



Backup Slides


Model Builder - DART-Hidden-Default-Project/LINKED_RESOURCES/Users/bwclark/CompSimUIModels/RoundTableCoarseSalinas_files/simulation/RoundTableCoarseSalinas.i - Model Builder
Model Builder
Cubit
*Model Navigator
Lantern_coarse
lantern_sd
Lanterns
new_me
parameterized_bracket
parameterized_bracket_hex
parameterized_bracket_hex_short_br
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: Sub
Queue Id / State: 691357
Submitted On: 2016-03
Account: FY1402
Requested Processors: 16
Requested Job Runtime: 30 minu
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

Conversion to Geometric CAD

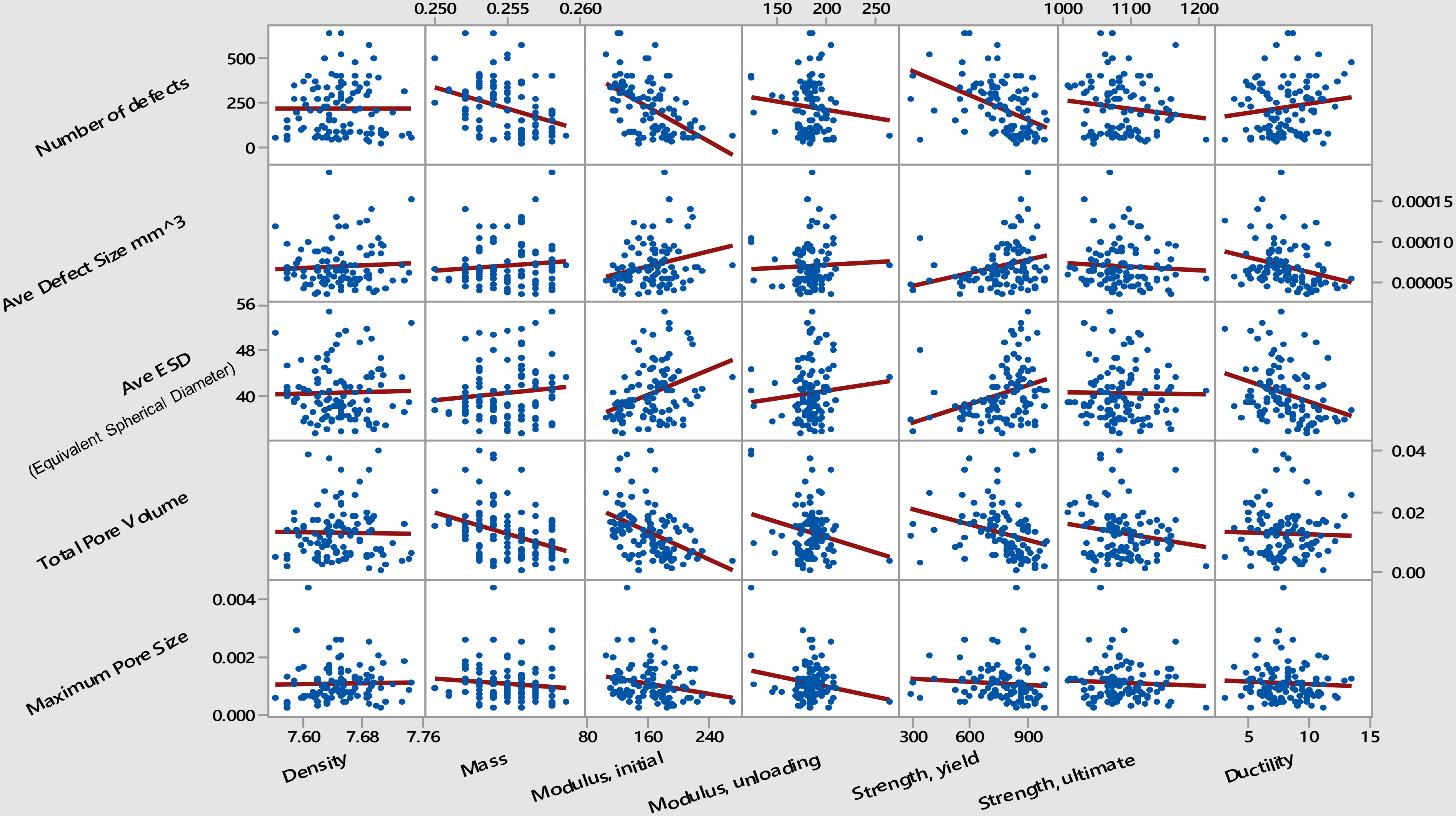
Conventional Materials Qualification



How can we qualify AM materials?

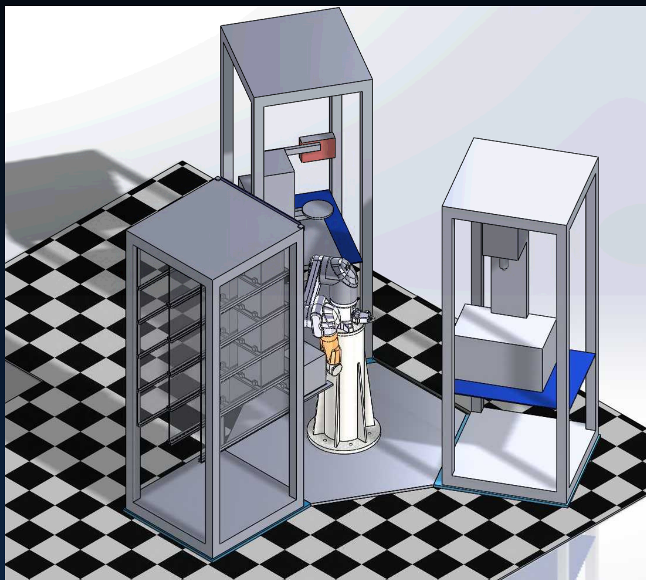
Sandia National Laboratories

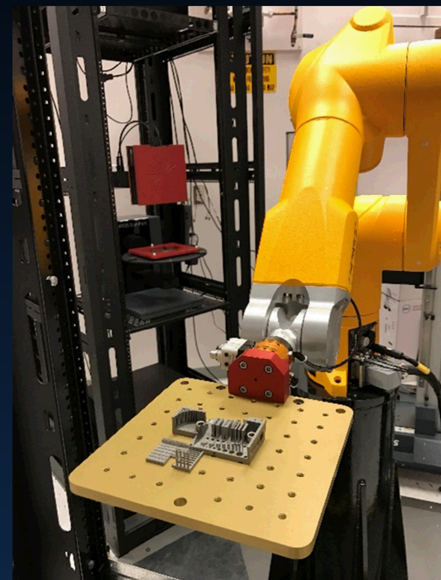
On-going Data Analytics Studies To Investigate Potential Relationships

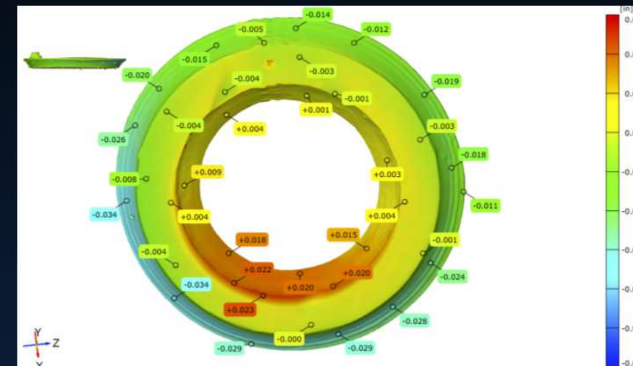


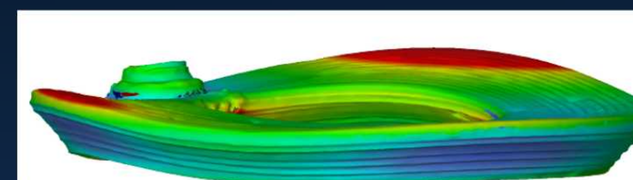
The Alinstante Modular Inspection Robot

Extensive material+part data in minutes, not months









Properties	**Structure**	**Post-Processing**
Tensile strength	Geometry	Surface remediation
Ductility	Porosity	Heat treatment
Toughness	Chemistry	Subtractive machining
Electrical performance	Microstructure	Joining
etc.	etc.	etc.

A diagnostic artifact provides an inspection surrogate and a process monitor…

Material & Structural Properties

Mechanical Properties
Arrays of tensile bars used to investigate stochastic tensile properties. Arrays of two different-sized tensile bars allow exploration of size-dependent mechanical properties

Structural Dynamics
Several cantilever beams of two heights can be used to test the resonance frequency of the material.

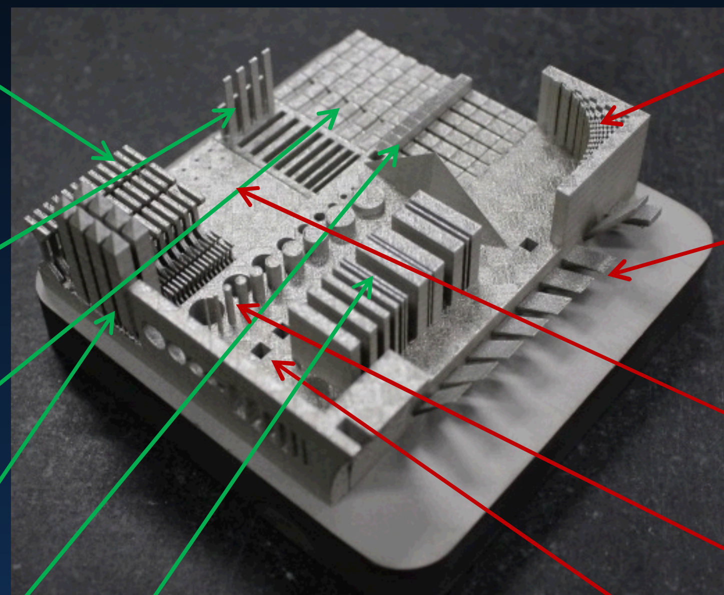
Notched Features
Arrays of notched features intended to explore stress-concentration effects on reliability and develop break-away coupons

Material Chemistry
Coupons to readily verify the composition and monitor contaminant levels.

Surface Roughness
Several features explore the interplay between geometry and the resulting surface roughness

Residual Stresses
Several features may be used to quantify the stress-induced warpage. Also, regions of the part exacerbate internal residual stresses to be measured by x-ray/ neutron diffraction or hole drilling.

Sandia Artifact printed in stainless steel alloy 17-4PH using a commercial vendor (Fineline) with a ConceptLaser Mlab Printer



Printability Limits & Metrology

Minimum Feature Dimensions
Evaluate printability and dimensional accuracy for a wide range of feature types including theoretical sharp corners

Overhangs & Bridges
Incrementally sized features intended to determine the maximum dimension that will maintain structural integrity of the part. Features push printer to failure point.

Internal voids
Intentional internal void arrays of varying dimension allow inspectability assessment

Aspect Ratios
A wide range of aspect ratios explores the printability limits of positive and negative features

Consistency features
Arrays of nominally identical features allow evaluation of repeatability

Most existing artifacts (e.g. NIST AM artifact) emphasize dimensional metrology and ignore material/structural properties. This compact array employs many dual-purpose features and many arrays of features for statistical repeatability analysis.