SAND2015-4907PE

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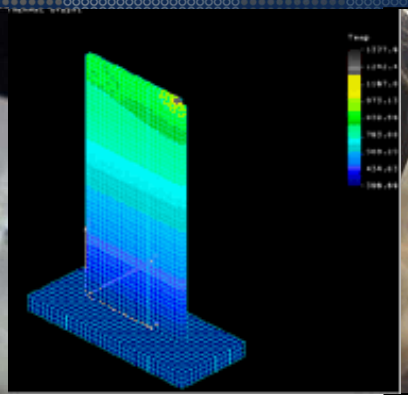

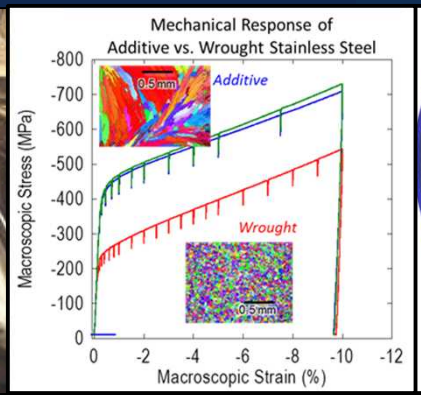

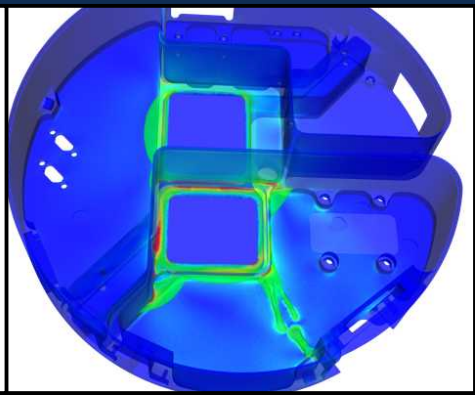

Additive Manufacturing at Sandia

Mark F. Smith
Senior Manager
Materials Science & Engineering Center

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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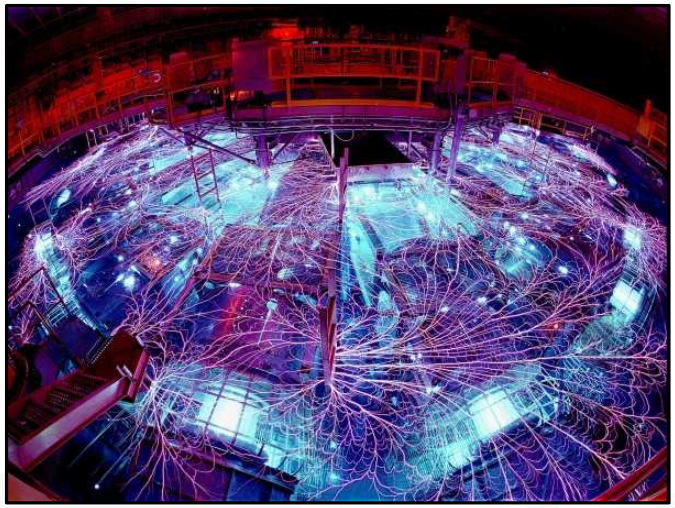
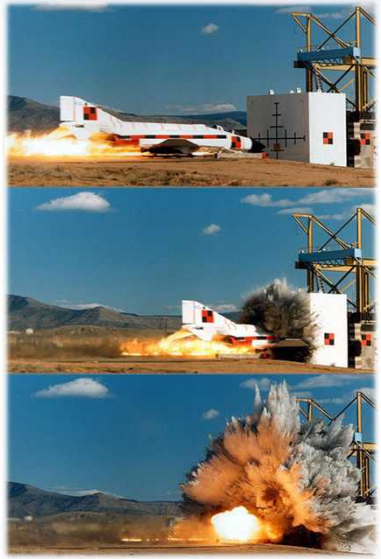
Sandia is a National Security Science and Engineering Laboratory

Weapon Drop Test



Energy R&D



Threat Test

- Historical mission -- non-nuclear component design and full system integrator for all US 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

Sandia National Laboratories Sites

Albuquerque, New Mexico

Livermore, California

Kauai, Hawaii

Waste Isolation Pilot Plant, Carlsbad, New Mexico

Pantex Plant, Amarillo, Texas

Tonopah, Nevada

All sites: 12,000 employees, $2.8B annual budget

Sandia National Laboratories

Sandia Additive Mfg. Tech Development & Commercialization

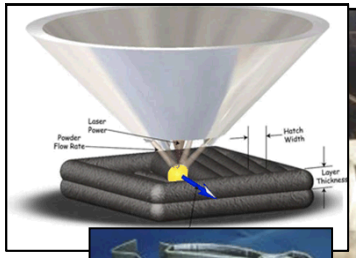
30+ yrs of Pioneering Process/Materials R&D

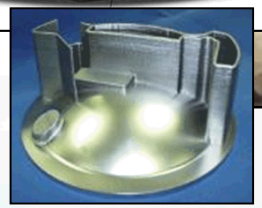
FastCast *

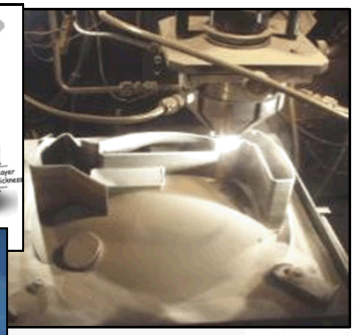
Development housing

Laser Engineered Net Shaping LENS® *

Stainless housing

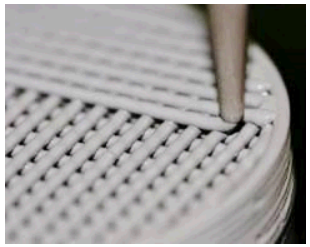


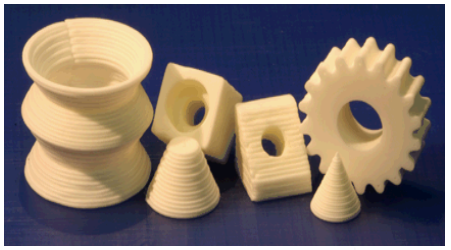




RoboCast *

Ceramic Parts

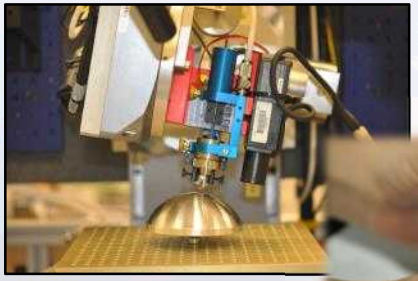




Energetic Materials

Direct Write

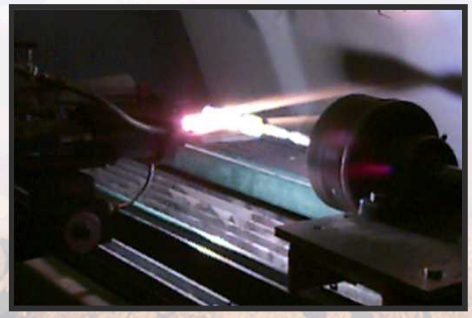
Conformal electronics



Printed battery

Spray Forming

Rocket nozzle



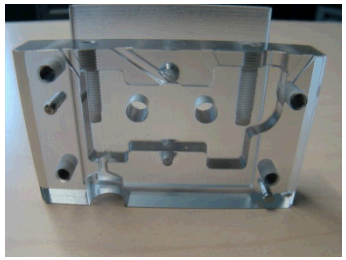
* Licensed/Commercialized Sandia AM technologies

Current Capability/Activity

Why AM at Sandia? – Mission Drivers

- Potential Cost/Schedule/Design/Risk Benefits
- Optimize for Performance, Not Machinability
  - Revolutionary new design possibilities
  - Engineering analysis driven designs
- Engineered Materials
  - Multi-material and graded material parts
  - Potential for microstructural control

50% Cost Reduction for Neutron Generator Tooling 1st Yr

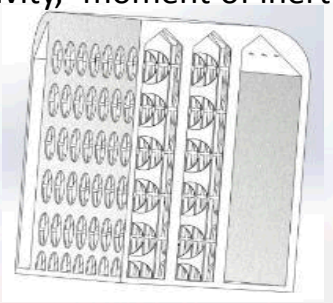


Connector Mold

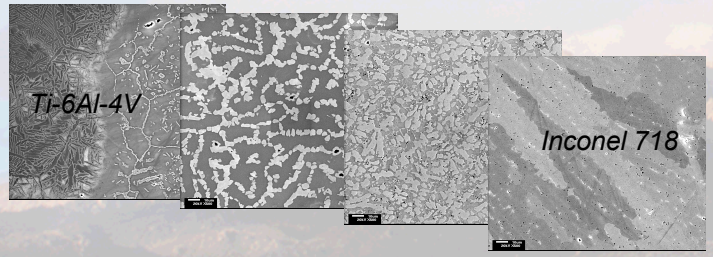
Forming Tool

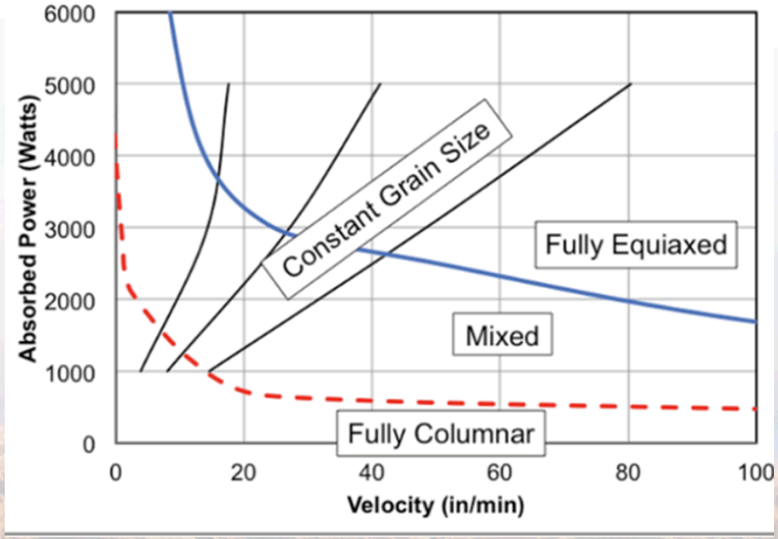
Electronic Component Mass Mock

Customize mass, center of gravity, moment of inertia



LENS® Functionally Graded Materials





LENS® Microstructure Control

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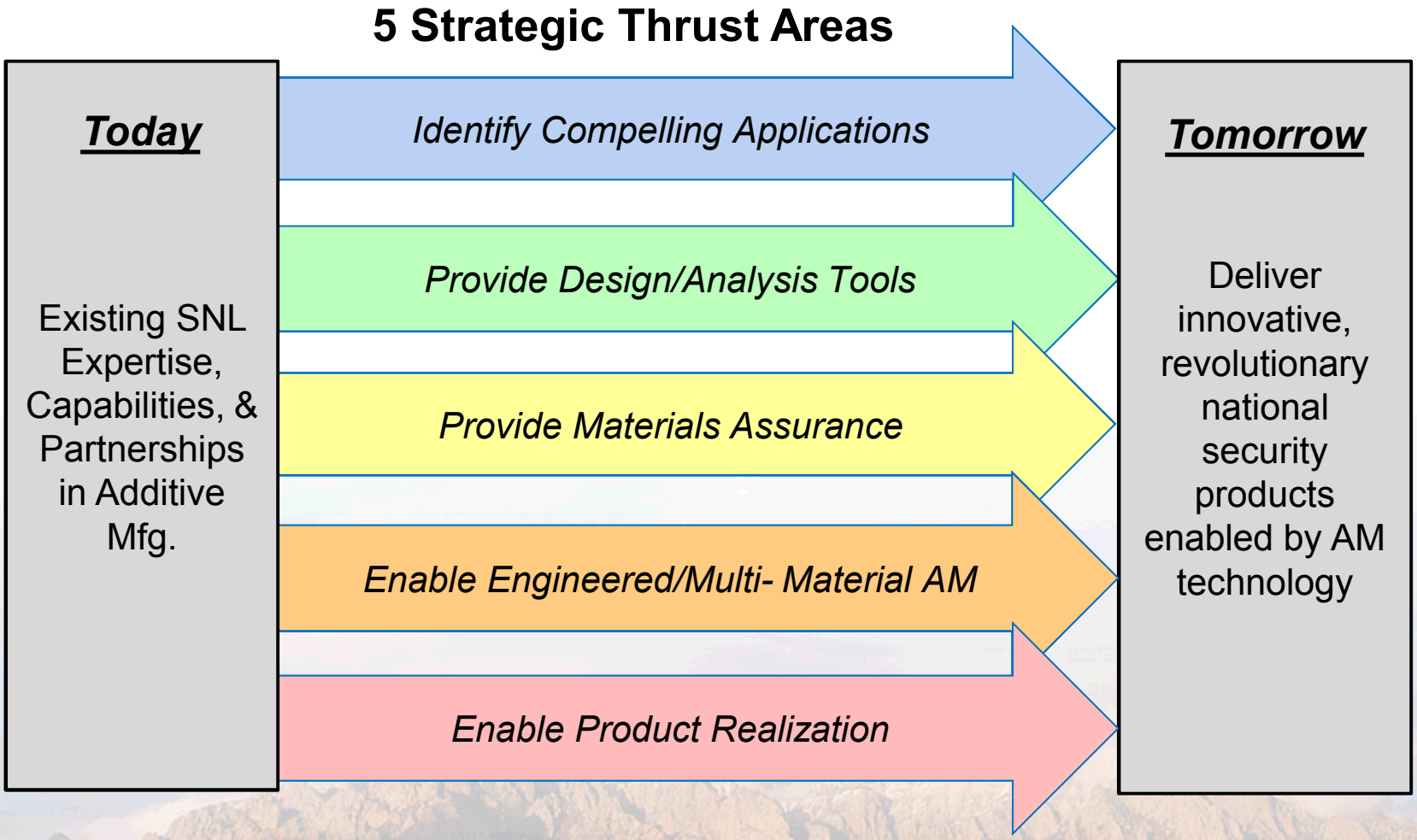
Sandia Additive Manufacturing Strategy



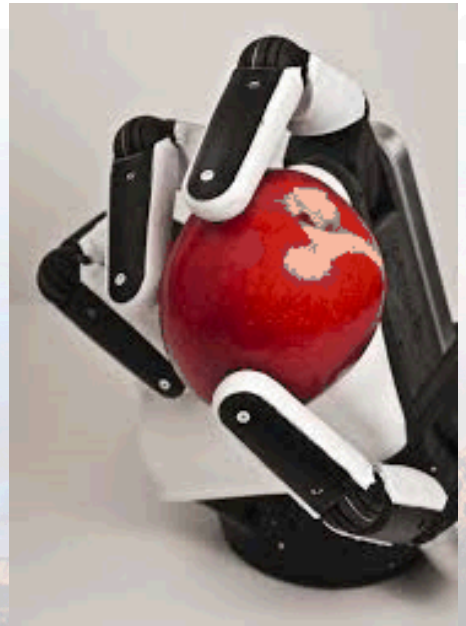
Example Applications

Sandia Hand – AM Enabled Innovative Design and Substantial Cost Reduction

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

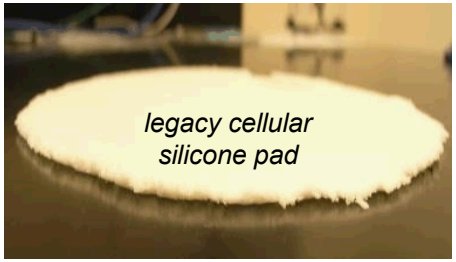
- Developed for bomb disablement
- Enabled rapid design iterations
- Cost $10k vs. ~$250k
- “Glove” controller
- Current version includes “touch” sensors

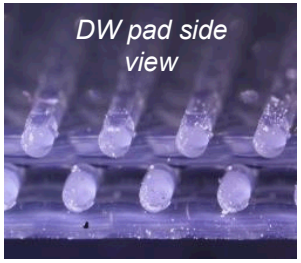
Fingers or other tools (e.g., drills) can be quickly magnetically attached in many configurations

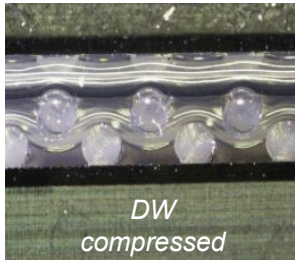


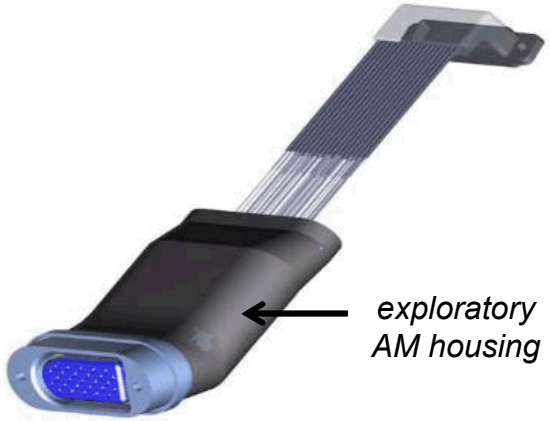
Example High Design Margin AM Applications

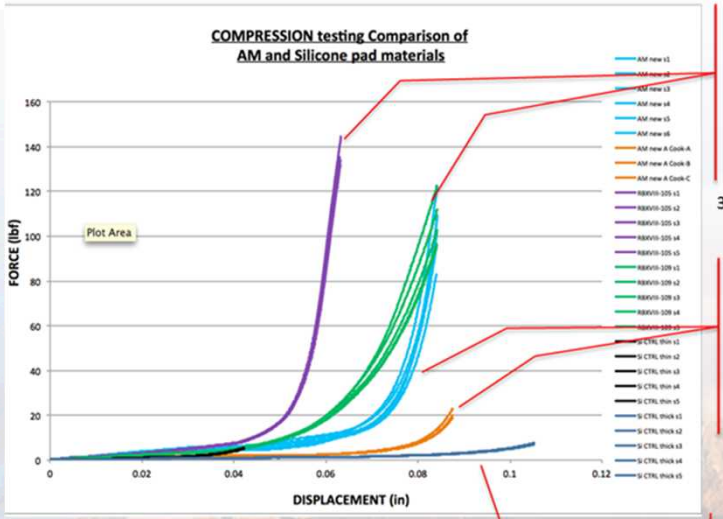
- Value Proposition to Replace Foam with Direct Write Pads
  - Prior manufacturing issues w legacy foam
  - Potential $2M cost & 90% mfg. floorspace savings @ NSC
  - Ability to custom tailor stress-strain response



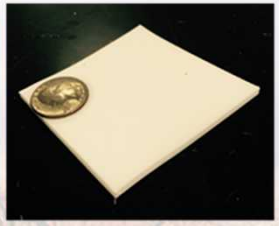




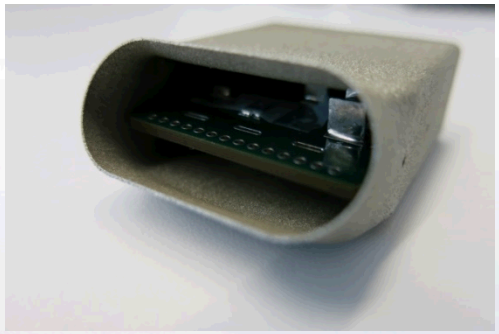





3D Printed Silicone (unmodified) NSC


3D Printed Silicone (modified) SNL

LEGACY MATERIAL



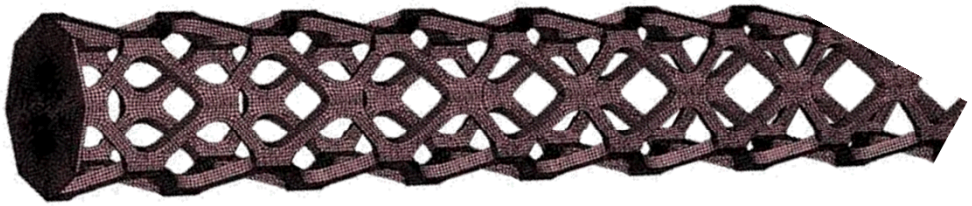
- AM Offers Potential Advantages for Complex, Thin-Walled Shape

Design/Analysis Tools

Engineering Analysis Driven Design & Margins

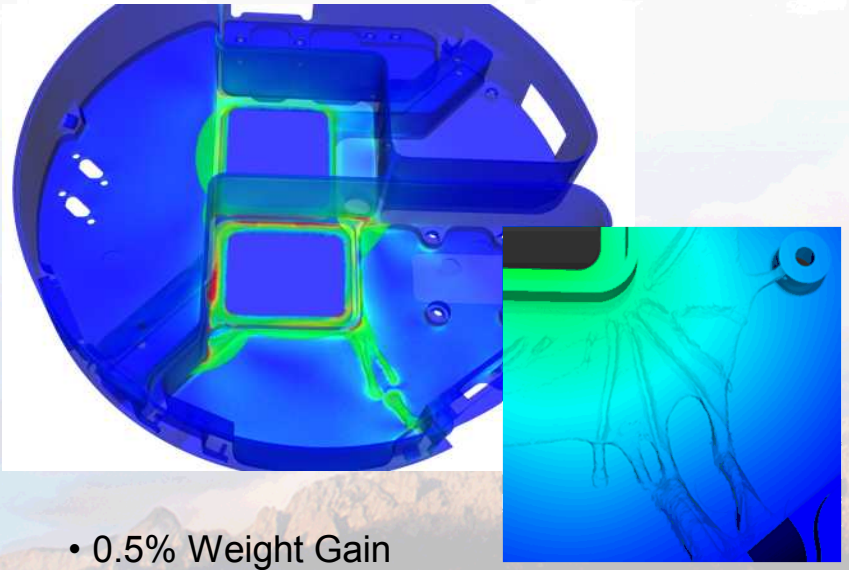
We combine Topology Optimization (TO) with eXtended Finite Element Modeling (X-FEM) & LENS® to optimize selected properties, e.g., strength/weight ratio.

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

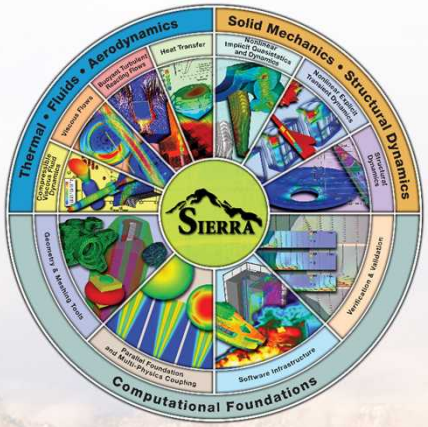


With AM it is faster and cheaper to build this optimized shaft than a solid shaft

Core of a dead Cholla cactus (bio-mimicry)



- 0.5% Weight Gain
- 52% Less Deflection Under Load



- NNSA lead lab for engineering code development
- Leverage extensive HPC codes/capabilities for AM

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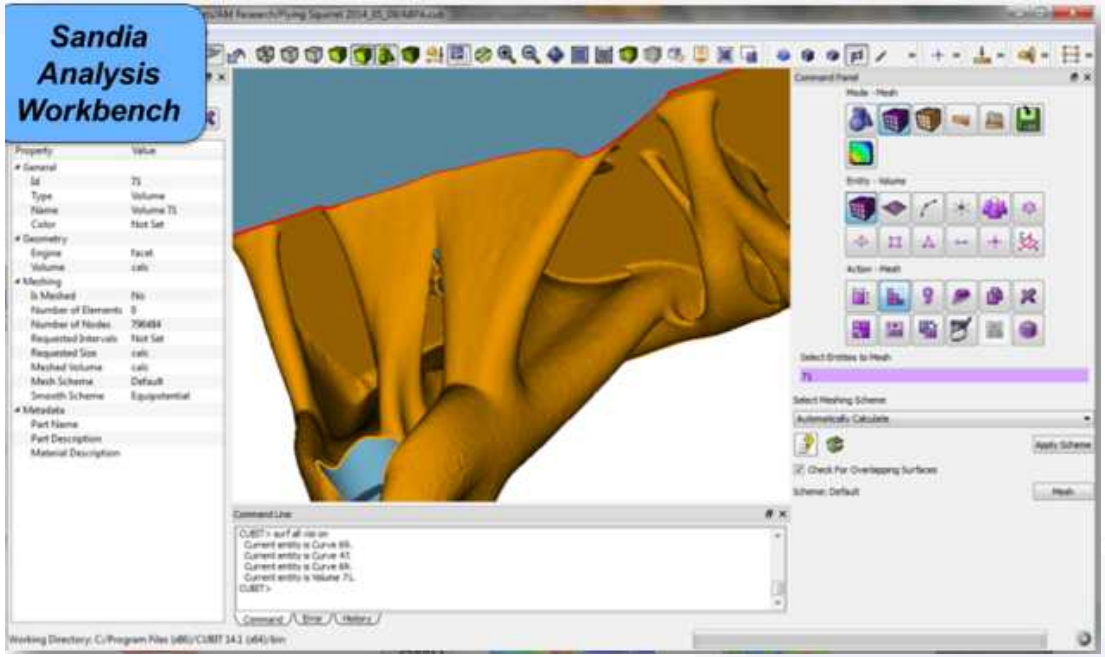
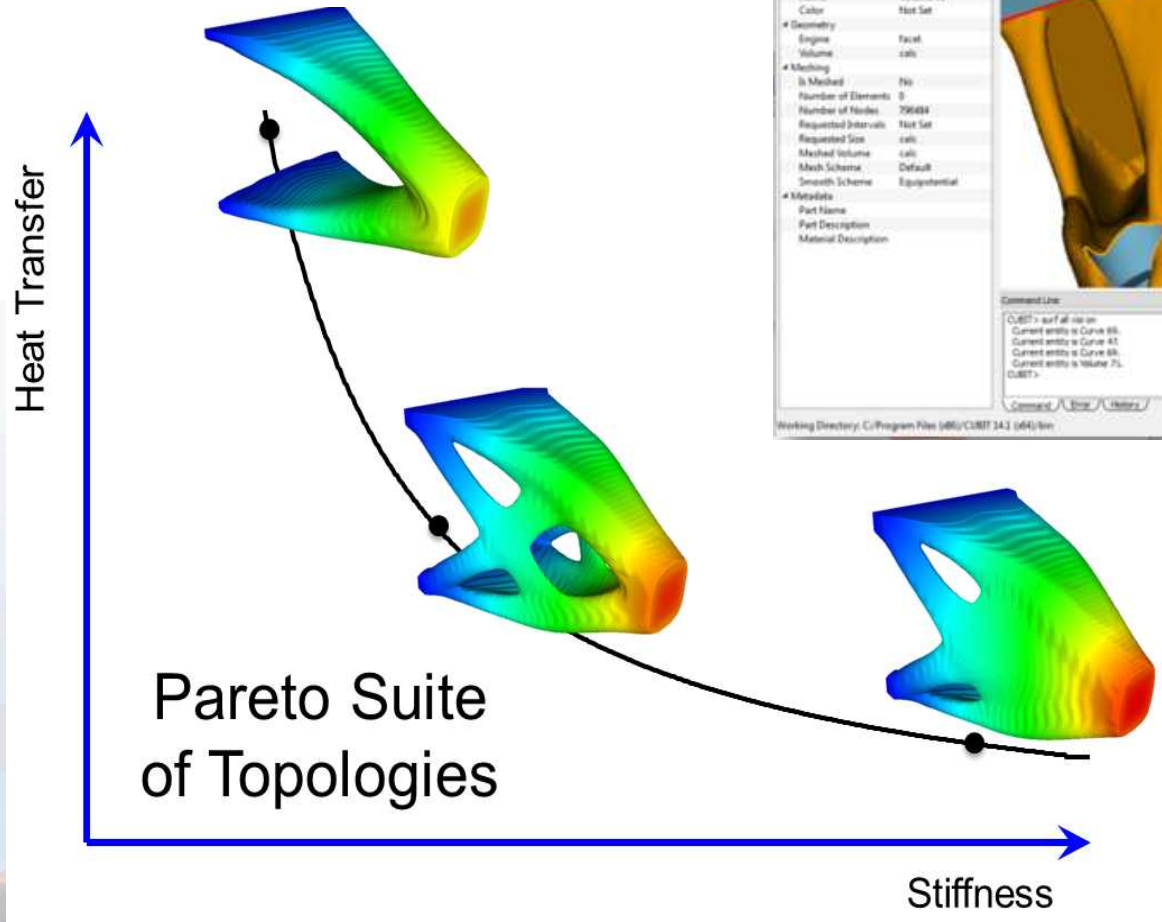
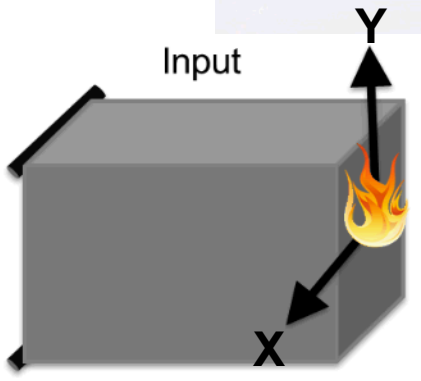
AM Design Via Functional Prioritization

User Friendly Interface







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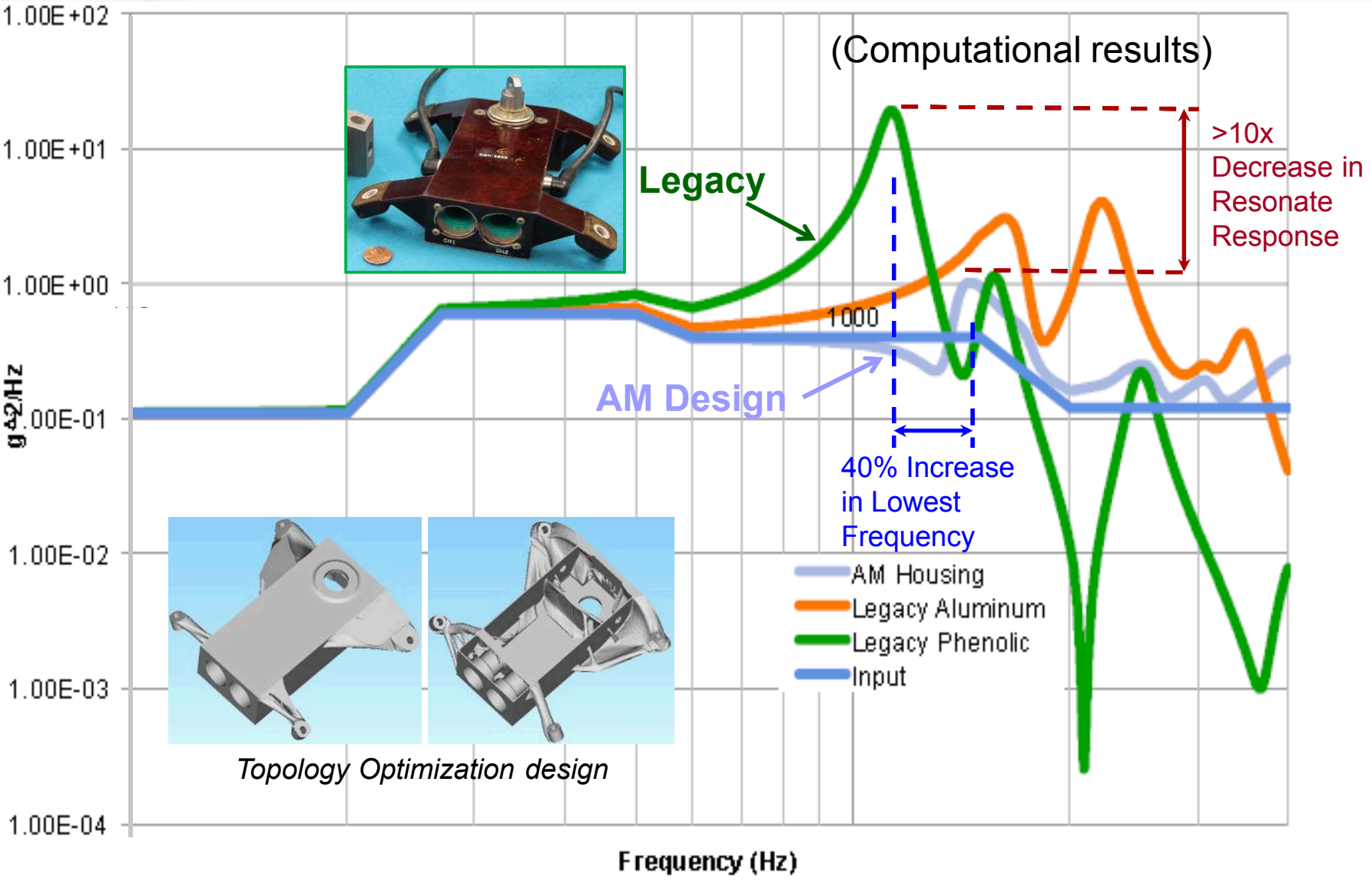
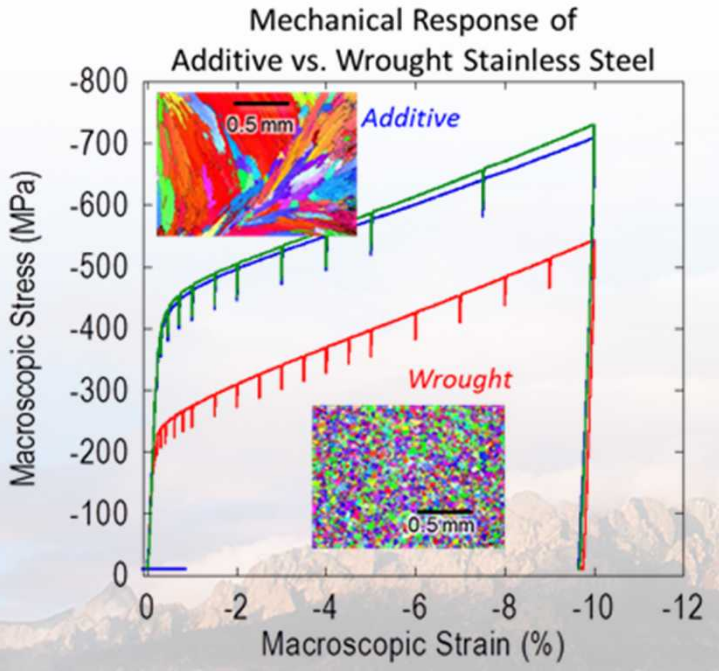
Improved Vibrational Response with Topology Optimized Housing Design



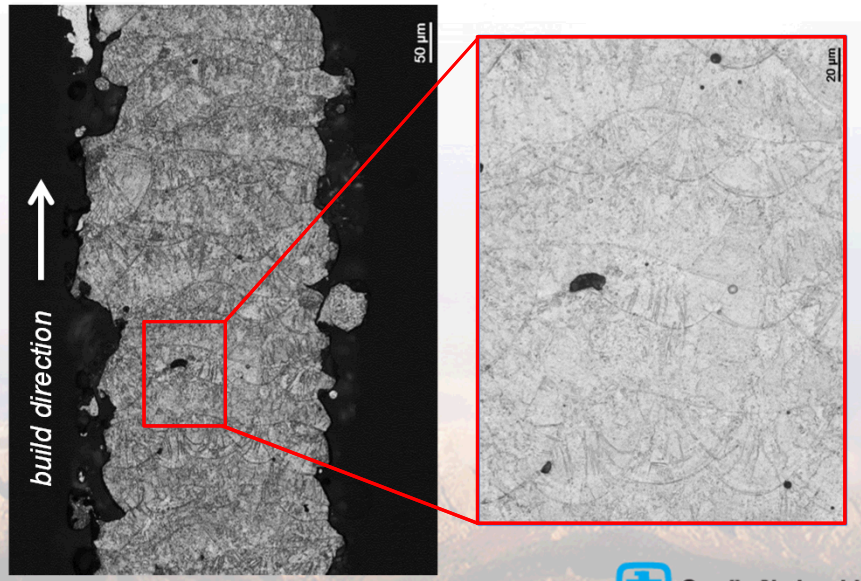
Materials Assurance

Materials Assurance -- a Key Challenge for AM

- AM Materials Are Unlike Traditional Materials
  - Little data on AM materials properties, including variability & long-term reliability
  - No official materials standards
- AM Materials Are "Built" Along with the Part
  - Qualifying starting material is not sufficient
  - Technology is immature – high variability, defects common
  - How to detect defects, assure microstructure/properties?



Surface & Interior Defects in 17-4 PH Stainless Steel



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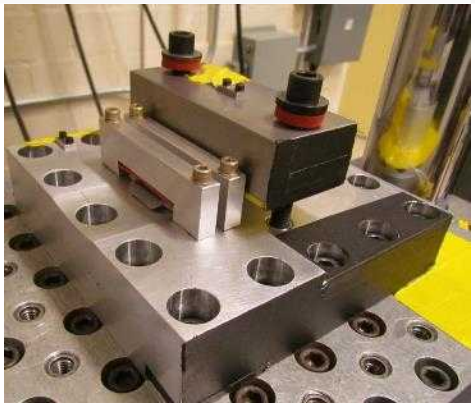
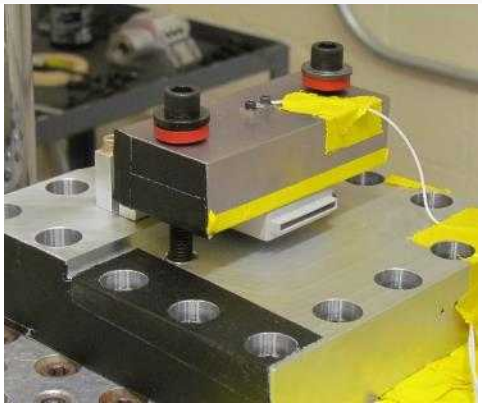
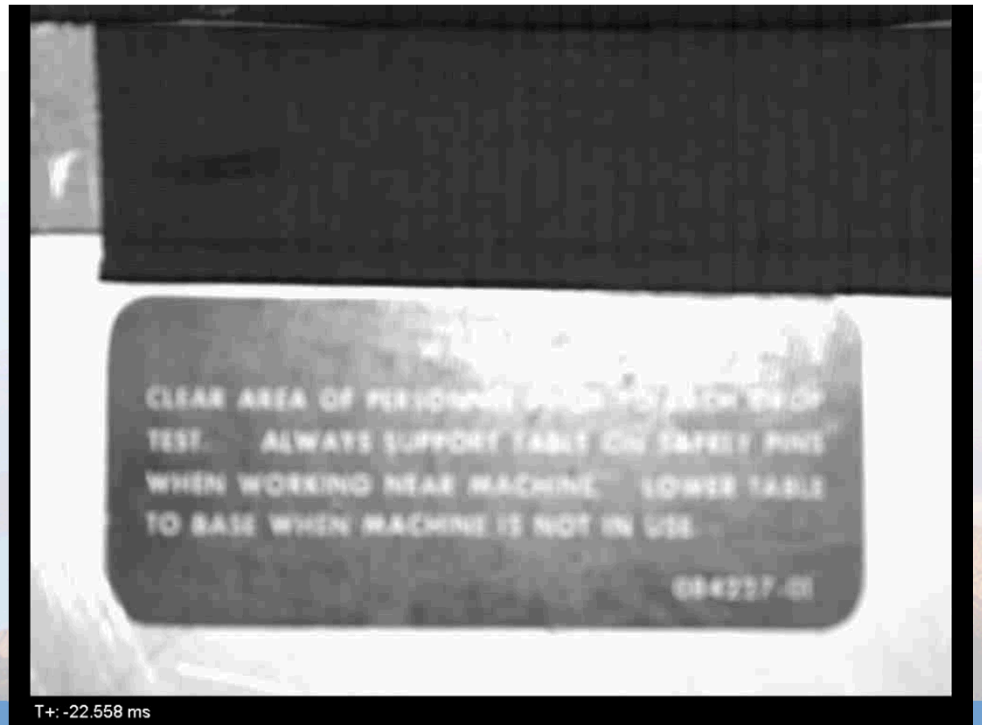
AM Hardware Included in Development Tests

Impact Tests of 3 Al housings at 32 ft/sec (3500 lb. impact force)

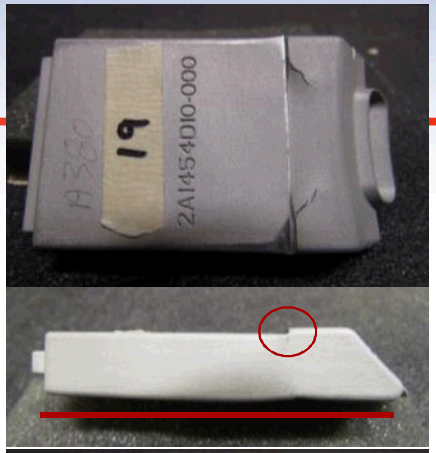






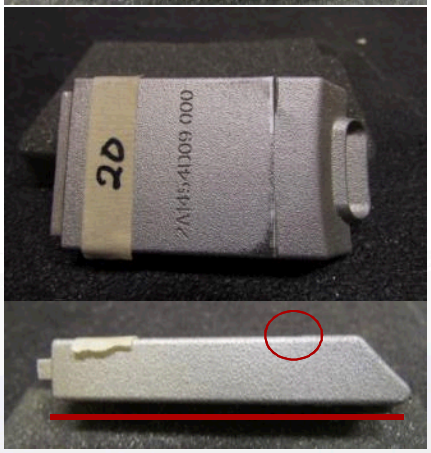
Cast, A380
1 pc, 38 g

- cracked
- buckled



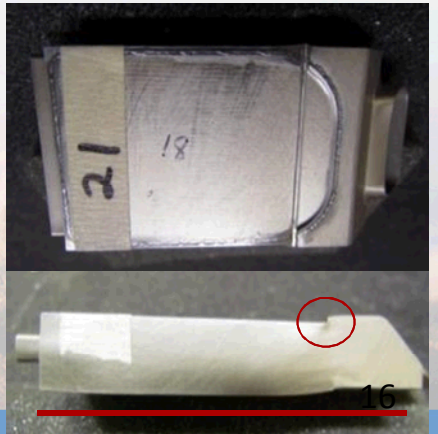
AM, AlSi10Mg
1 pc, 38 g

- slight indent
- still straight



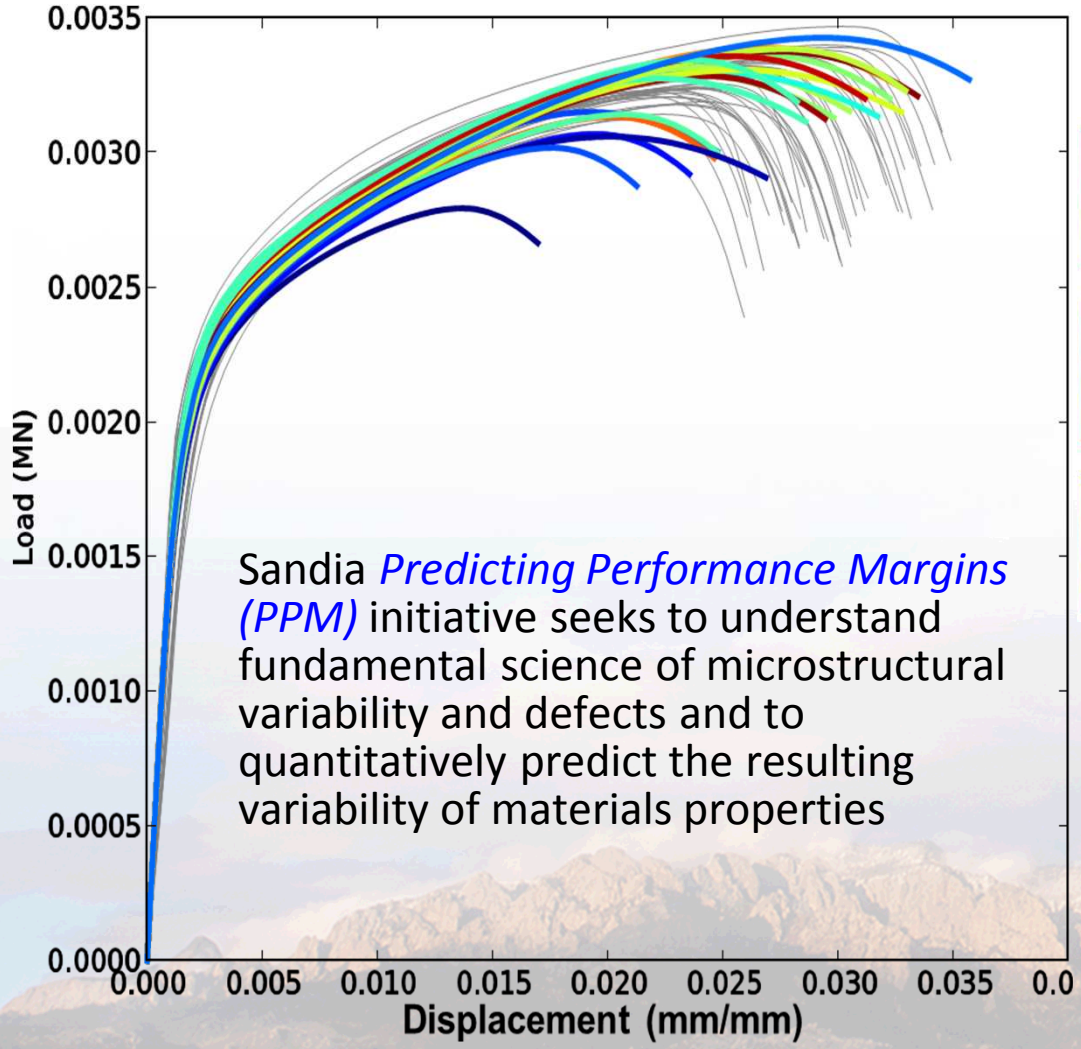
Machined 4047
2 pc assy, 45 g
(Baseline Design)

- weld cracks?
- buckled



Leverage Sandia PPM to Quantify Variability/Defect Sensitivity

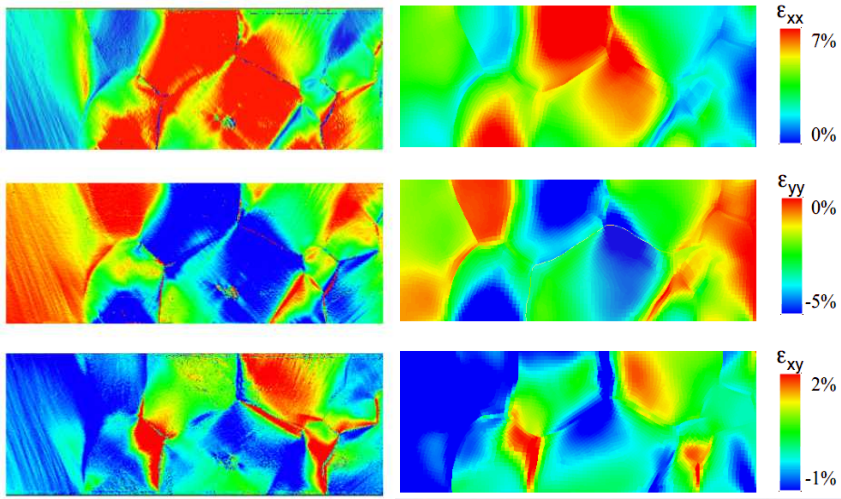
Predicted (color) vs. measured (grey) responses for laser welds (PPM)



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

Promising agreement of experimental vs. computational results

Oligocrystal experiments vs. crystal plasticity models (tensile loading)



Differential Interference Contrast Experimental Measurements

Computed Simulations

Gauge Section of Oligocrystal Tensile Specimen (1x3x5 mm)

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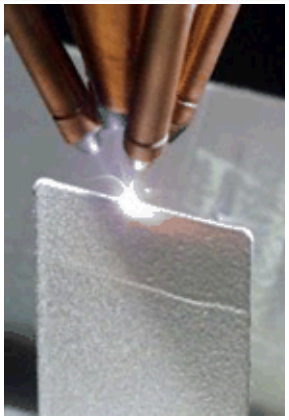
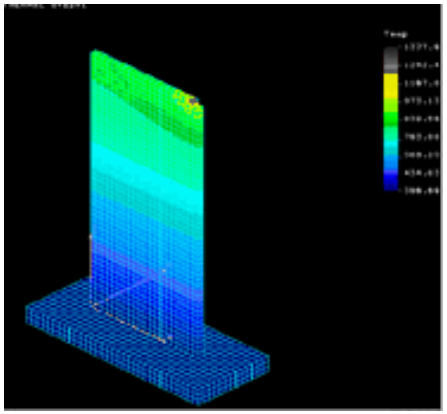
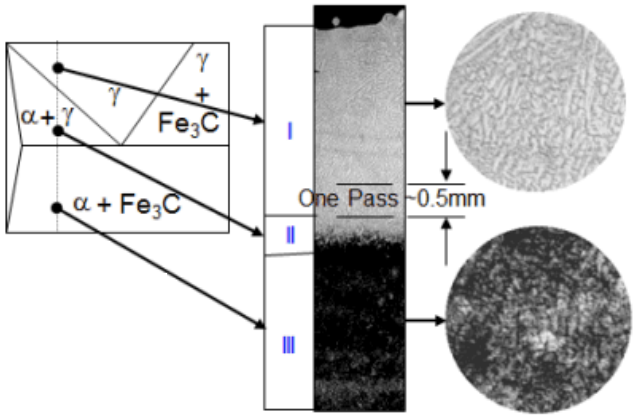
LENS® Process & Materials R&D

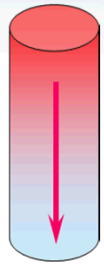
Process characterization/modeling





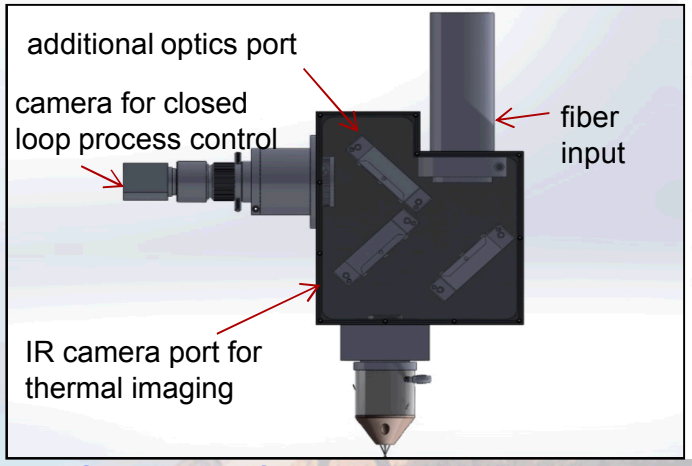


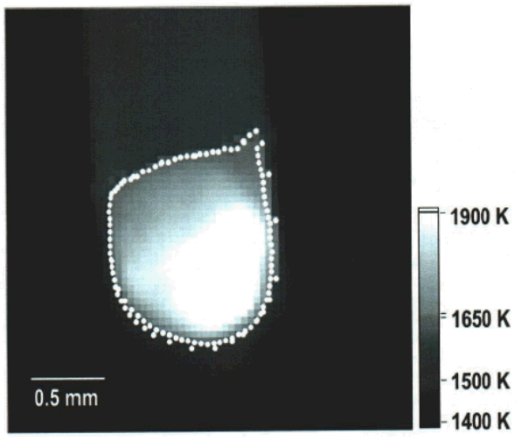
Part heats up during the build & heat flow changes -- so microstructure & properties in the top (I), middle (II), & base (III) may differ

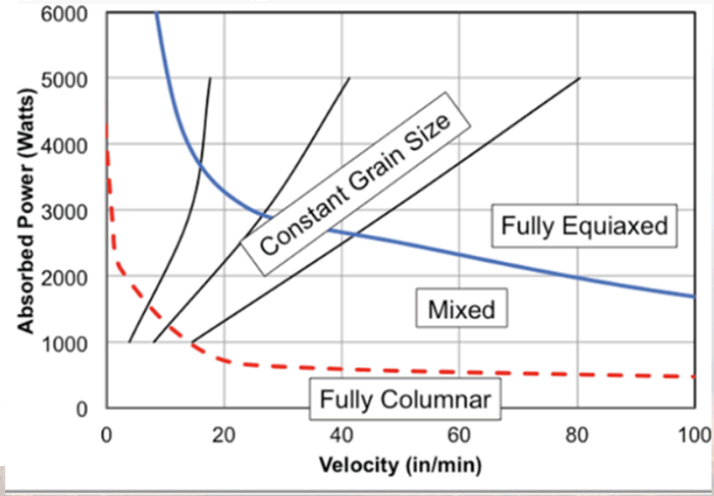


Uni-directional Solidification

- Built narrow "wires" to achieve 1-D heat flow
- Simplified comparison with model predictions







Successfully demonstrated control of melt pool size & temperature to control microstructure and reduce variability

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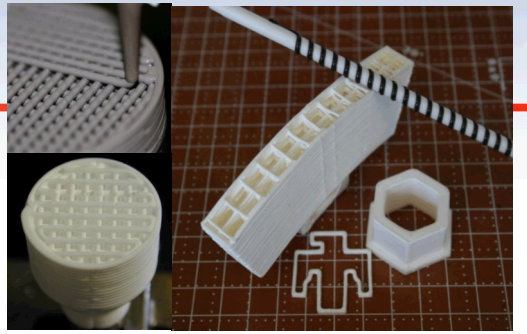
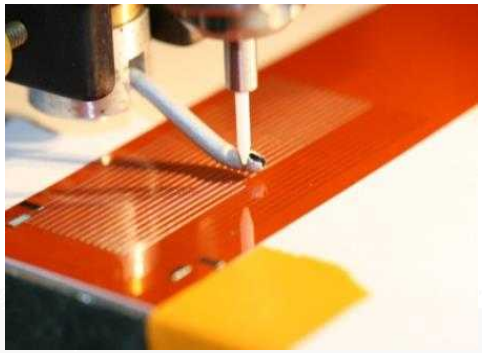
Multi-Material AM

Direct Write, A Versatile, Multi-Material Process

- **Materials**
  - Print: ceramics, metallics, polymerics, energetics, multi-phase
  - Substrates: ceramics, metals, plastics, polyimide, encapsulants, FR4, glass, paper
- **Example Applications**
  - DC & RF interconnects, antennas
  - Flexible electronics
  - Sensor networks / structural health (strain, crack, temperature, …)
  - Electronic package integration (resistors, capacitors, inductors, transistors, batteries)
  - Conformal printing

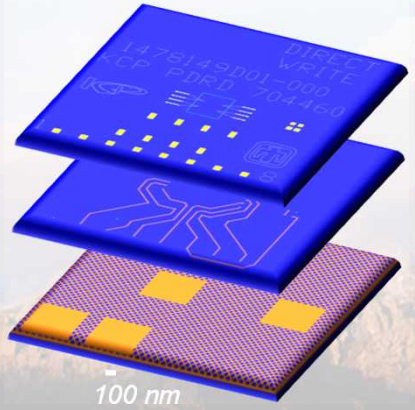


Extrusion casting (Robocasting)

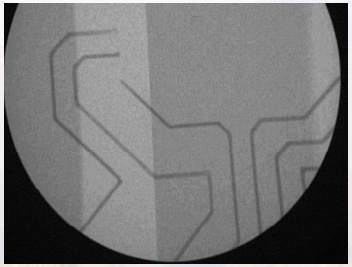


Aerosol jet printing to 10 μm

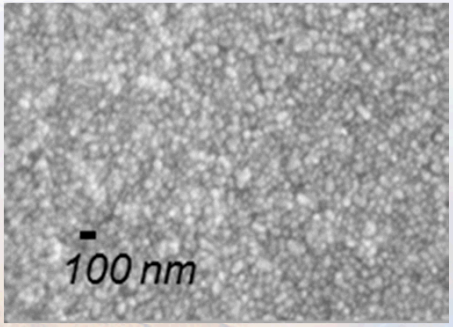
DW circuit fabrication



Multi-level circuit



X-ray of 4 layer composite system, 200 μm conductors



Nano-particle Ag inks for conductive pathways

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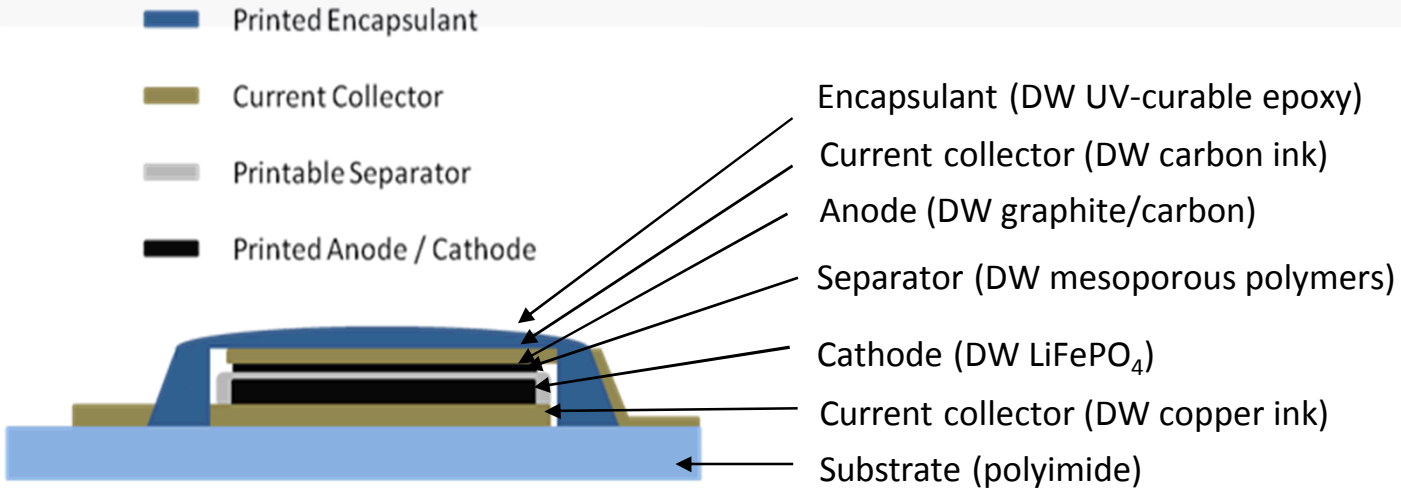
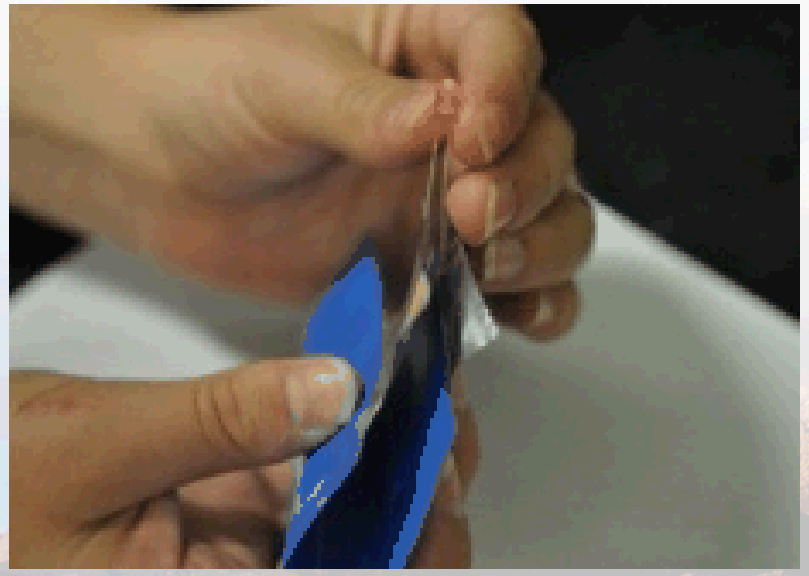
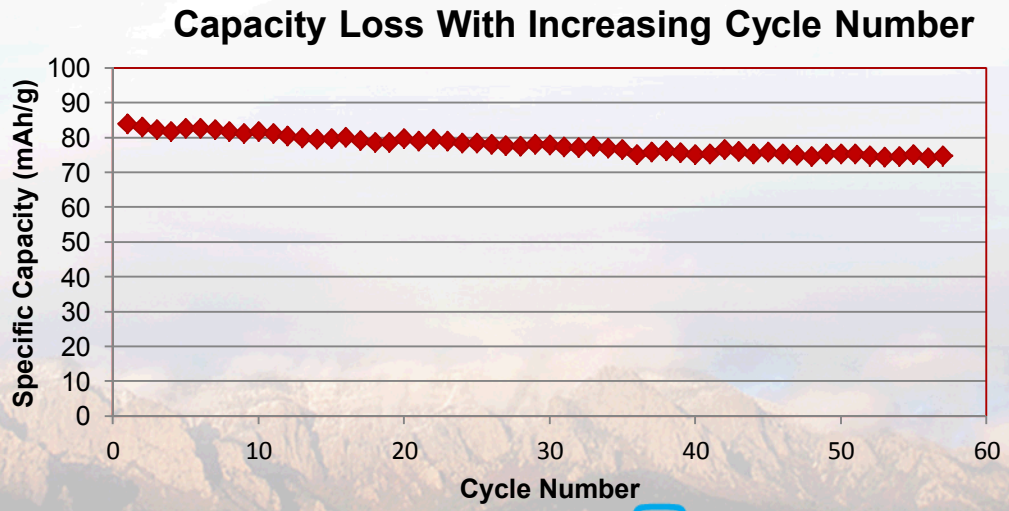
Direct Write Lithium Iron Phosphate Battery Performed Well



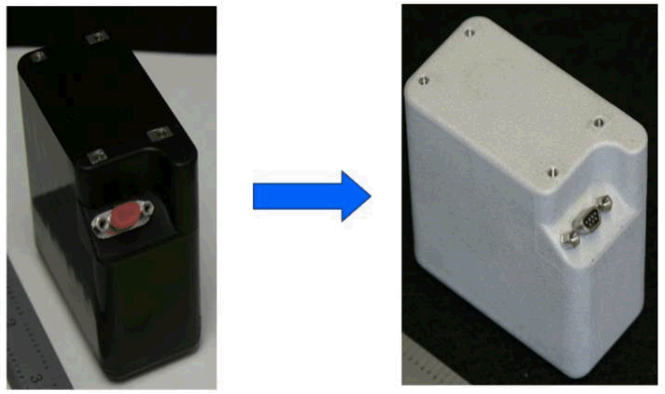




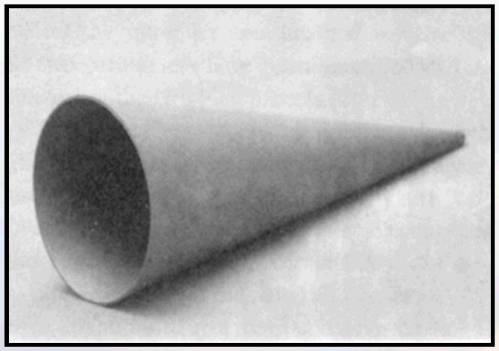
Sandia National Laboratories

World Class Capabilities in Thermal Spray/Cold Spray

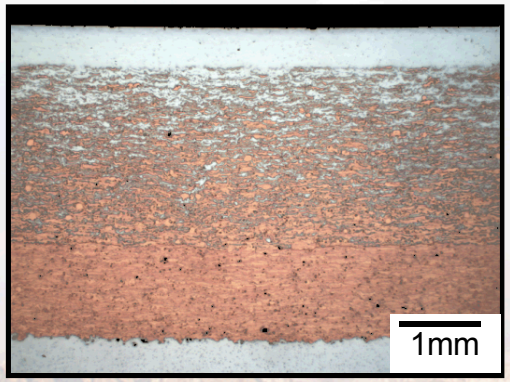
- High Deposition Rates
- Wide Choice of Materials
  "anything that melts"
- Combine Highly Dissimilar Materials
- Unique Microstructures / Properties



Metal Sprayed onto Plastic for Electromagnetic Shielding



Spray-Formed B_4C Cone†



Graded Density Cu→Al Spray-Formed Flyer Plate

AlSi / Polyester Composite

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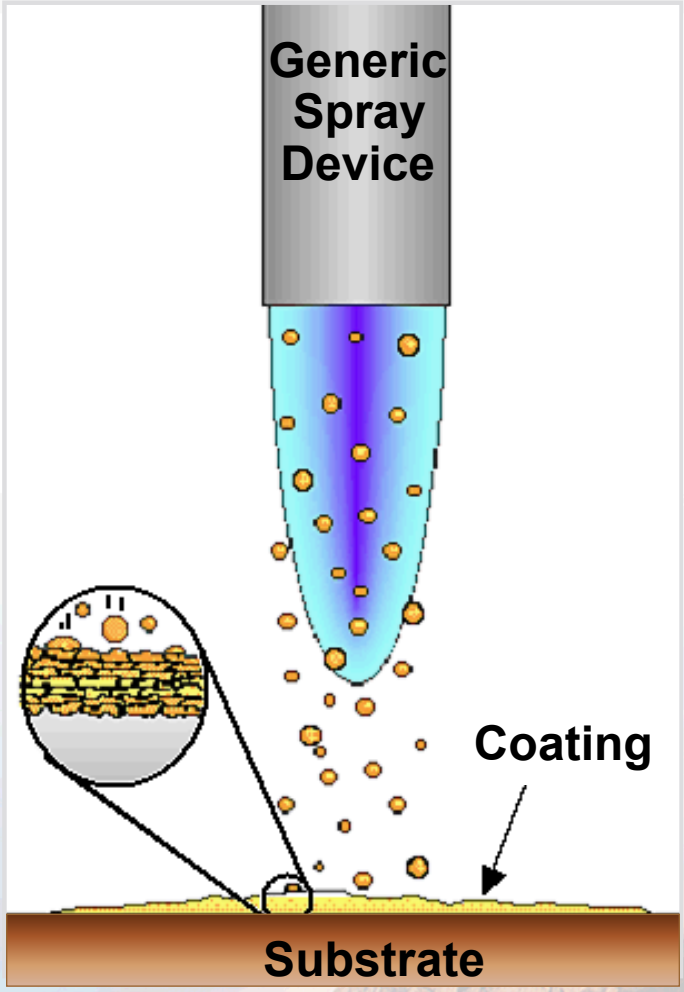
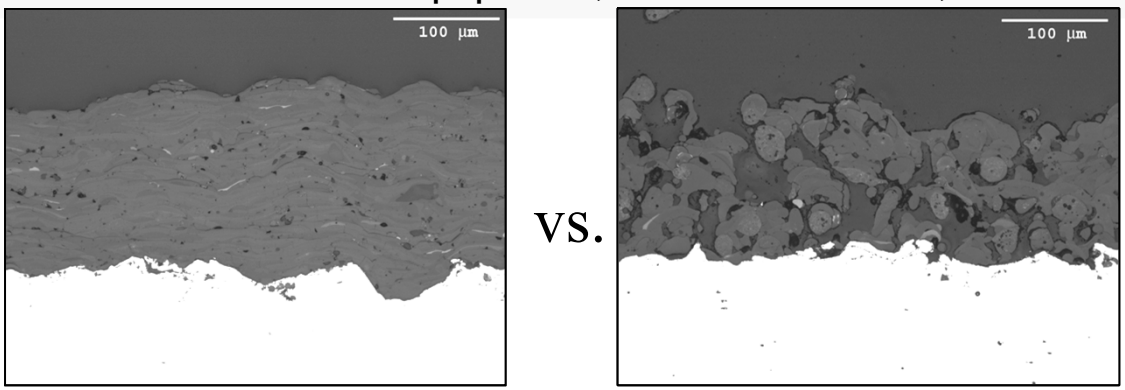
† From, Freslon, Proc. 1995 Intl. Thermal Spray Conf.

Prior Success with Qualification for Thermal Spray Production

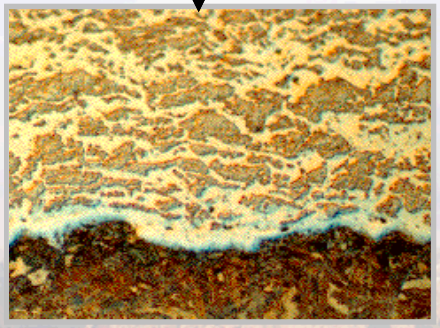


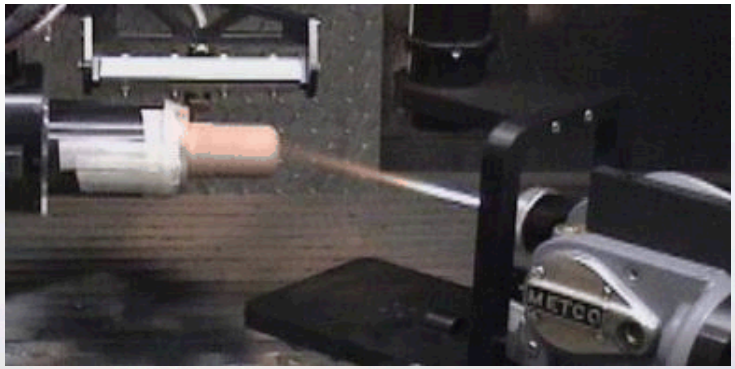
Same Equipment, Same Feedstock,



Very Different Results

Cemented Carbide Coating On Steel





Sandia Thermal Spray Production

- Final step, ~$100k/part
- No re-work

AM today is similar to Thermal Spray ~20 years ago

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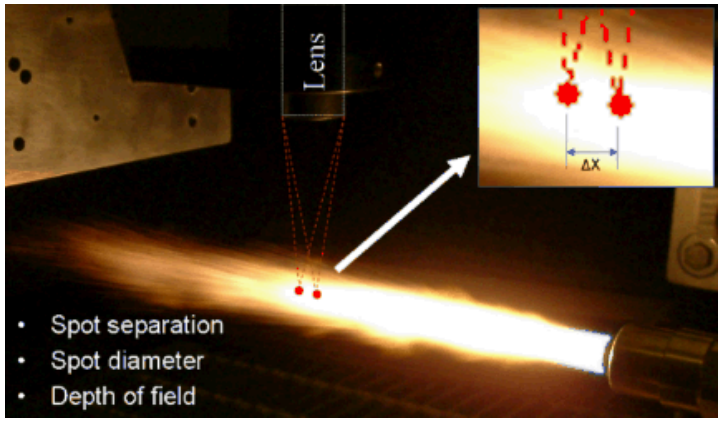
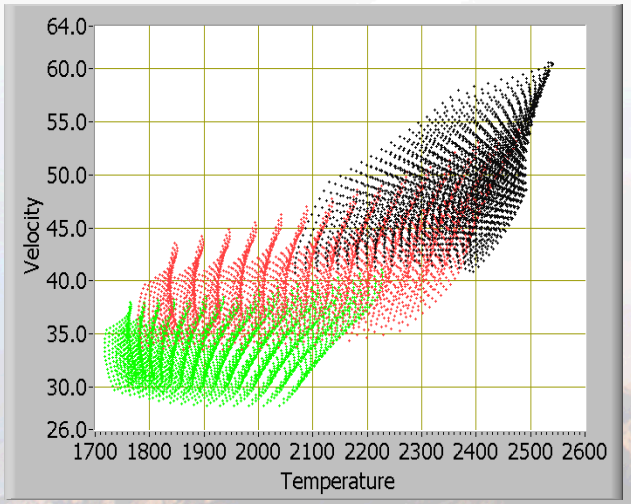
Fundamental Process Understanding is Key to Controlling Variability

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



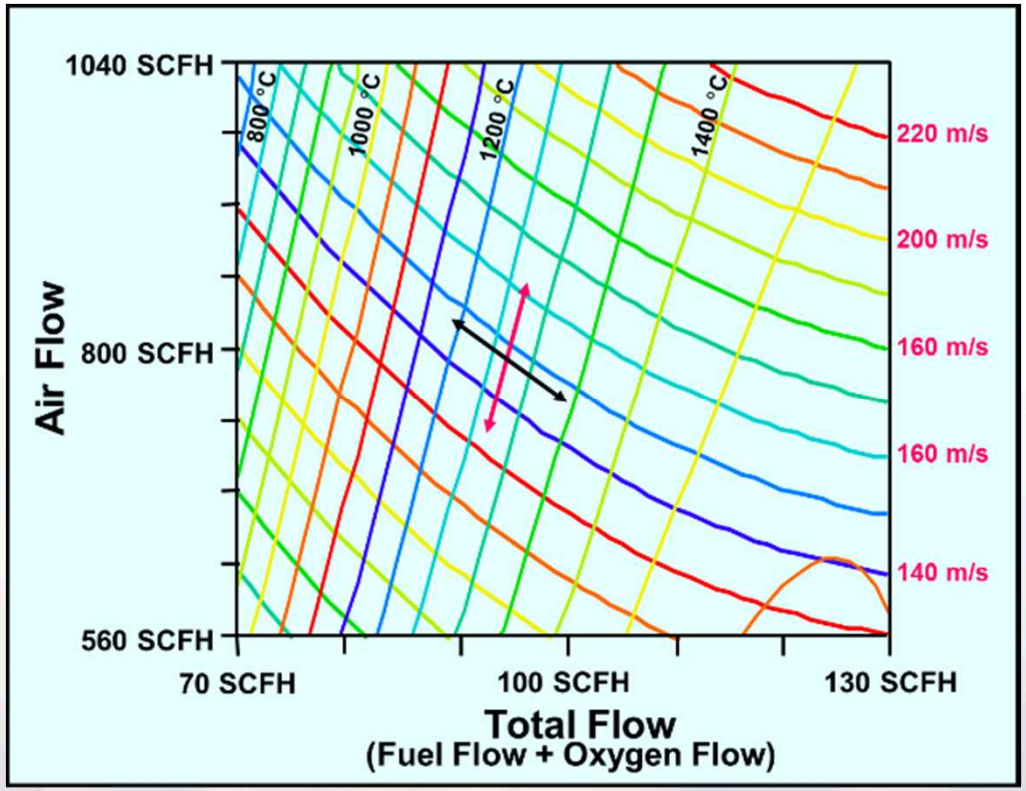
Process Diagnostics/Monitoring



Process Modeling

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

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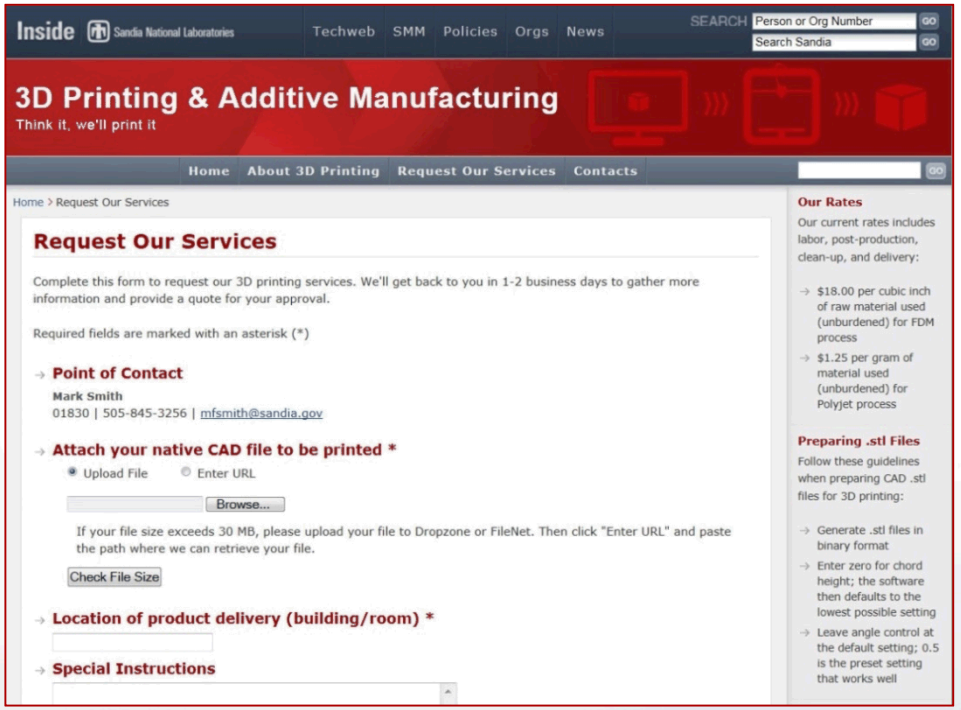
AM Equipment

Plastic AM Machines

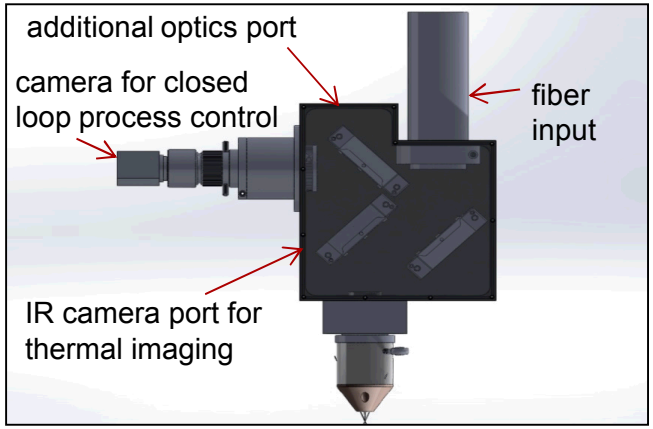
- ~ 100 Plastic AM machines at Sandia
- Web-based Central AM Printing Service

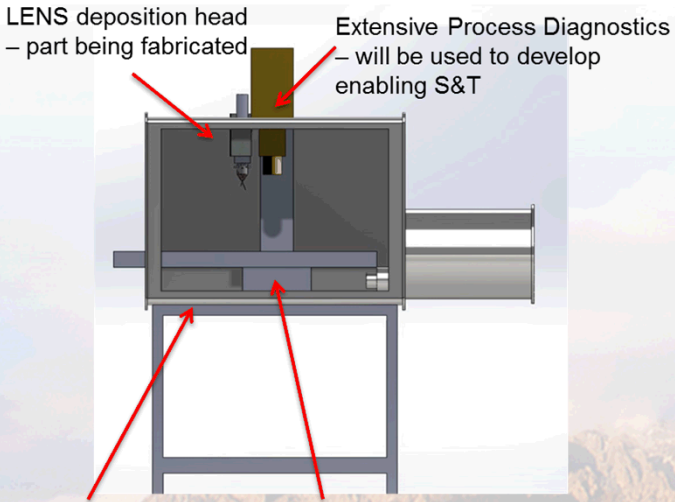


"You Think It, We'll Print It!"

Metal AM Machines

Custom Built Aditive/Subtractive LENS® System





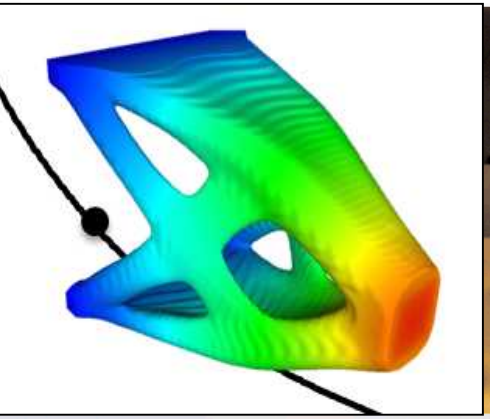
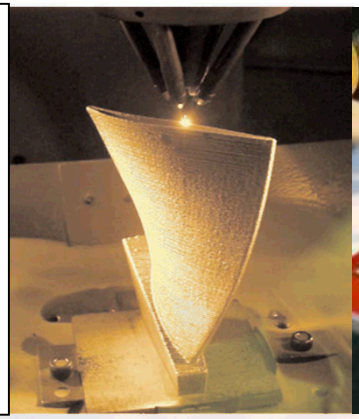
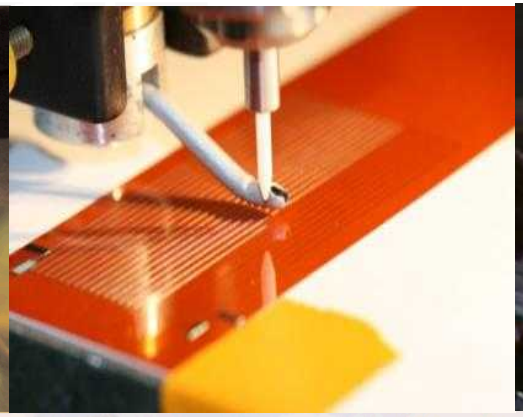
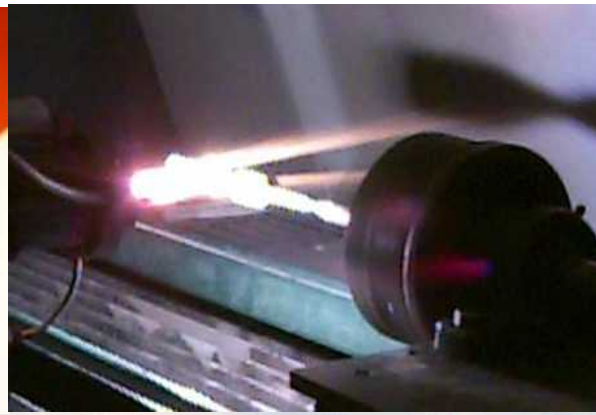
Commercial Powder Bed Laser Systems

- Two 3D Systems ProX 300
- One 3D Systems ProX 200
- 9.8 x 9.8 x 11.8 inches build volume
- Many metals, some ceramics?

Sandia National Laboratories

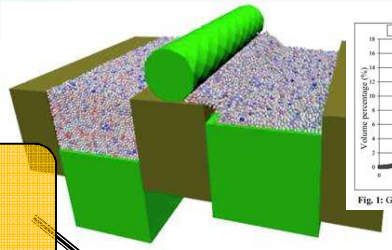
Summary

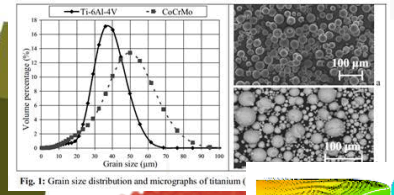
- Sandia has a Rich History in AM technology development & commercialization
- We are especially interested in Design for AM and Materials Assurance
- We have strong High Performance Computing & Experimental Capabilities
- We have strong expertise in Multi-Material AM & Spray Technology
- We are very interested in working with others to advance AM technology

Backup Slides

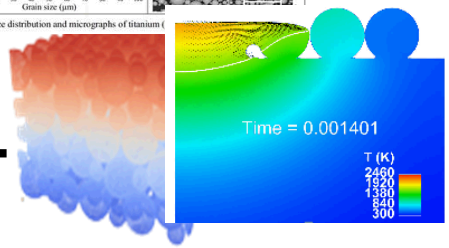
Working to Model Process → Microstructure

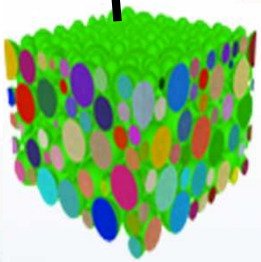




Particle packing

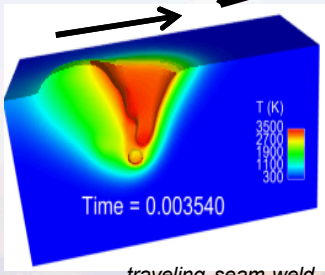
Particle heating





Partial melt & flow

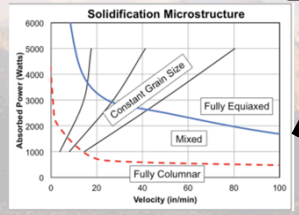
Molten pool dynamics



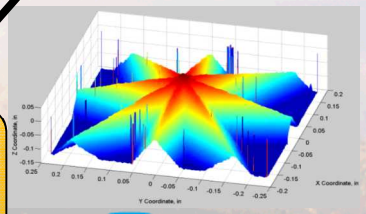
traveling seam weld

Solidification

Microstructure



Topology issues & surface finish



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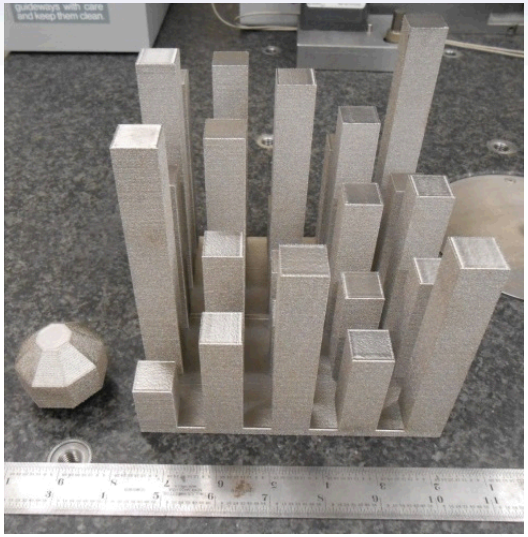
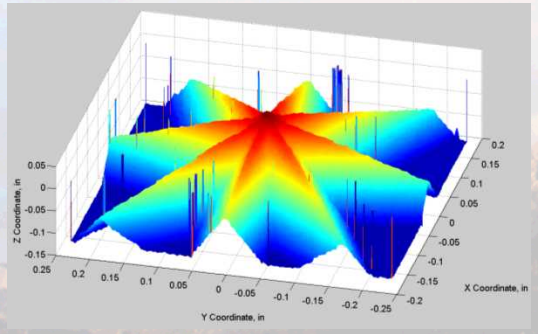
Metrology for AM Is Also A Key Challenge

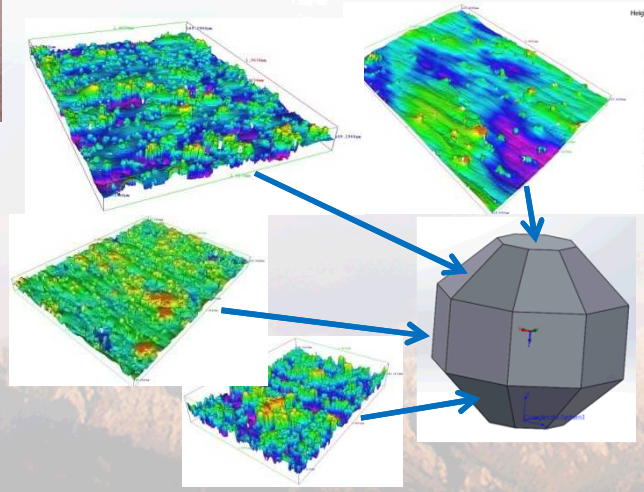
- Family of artifacts designed, 3D printed, & measured
  - Sandia Primary Standards Lab working w NIST to develop better AM metrology artifacts
- Unique challenges for process/equip. characterization
  - Tolerance/Surface Finish/Properties vary with machine, material, print orientation, support structures, post-processing,…)



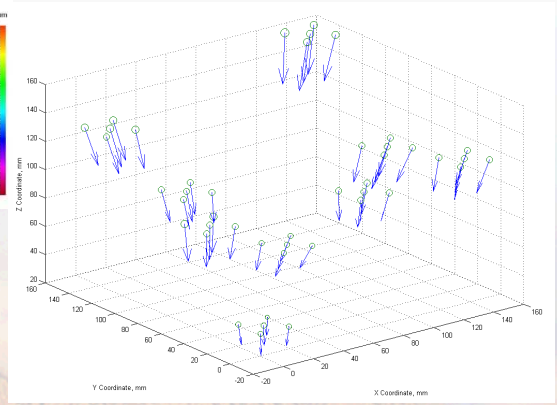
Ti-6Al-4V polyhedron & "Manhattan" artifacts for MPE (maximum permissible error)

Siemens star geometries for resolution evaluation





17-4PH polyhedron texture anisotropy map



Ti "Manhattan" error map

Sandia National Laboratories

Partnering to Leverage Our AM Efforts/Investments

- **Nuclear Security Enterprise, DOE, Other Federal Agencies**
  - Ongoing, strong NSE AM Partnerships with NSC, LLNL, LANL
  - Interacting w AWE thru monthly VTC's, JOWOG meetings, & Joint Tech Demonstrator
  - Actively working potential partnerships with ORNL/MDF, AFRL, NIST
- **Academic / Industry Involvement**
  - *America Makes* project with 3D Systems, Lockheed Martin, & Univ. of Delaware
  - Currently negotiating AM CRADA with US-based AM supplier
  - Active & potential collaborations with several universities
    - U of Pennsylvania
    - UC Davis
    - University of Colorado
    - University of Wisconsin
    - = Active Partnerships
    - Carnegie Mellon
    - Case Western Reserve
    - UT Austin
    - Univ. of Louisville
    - UT El Paso
    - = Active Discussions
- **Other External AM-Related Activities**
  - Tech landscape survey of Topology Optimization, Materials Assurance, and Multi-Material AM
  - Exploring joint SNL/CA – LLLN AM facility at Livermore Valley Open Campus