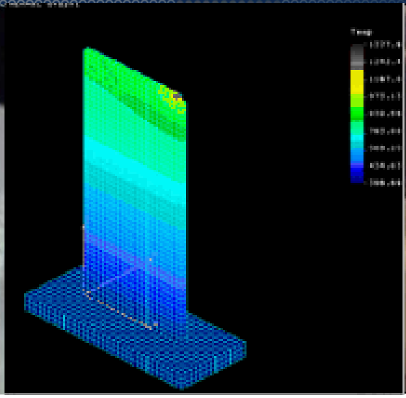
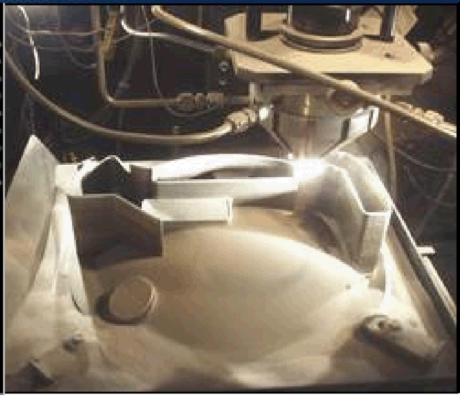
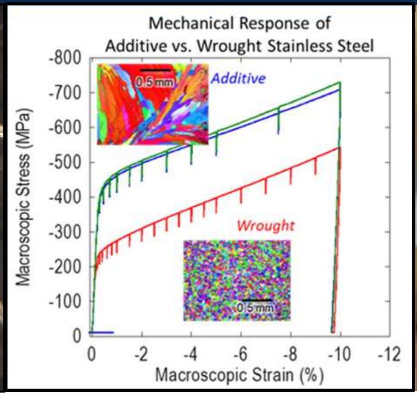
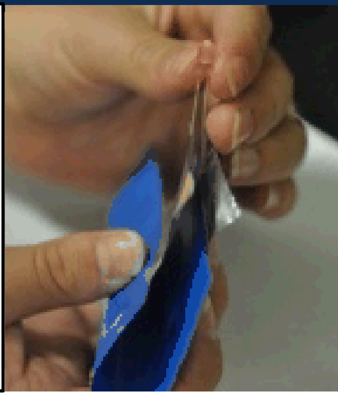
SAND2016-1129PE

Exceptional service in the national interest

Sandia National Laboratories



Additive Manufacturing at Sandia

Dr. Mark F. Smith

Deputy Director for Additive Manufacturing

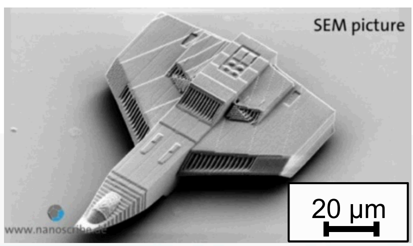
Materials Science & Engineering Center

U.S. DEPARTMENT OF ENERGY

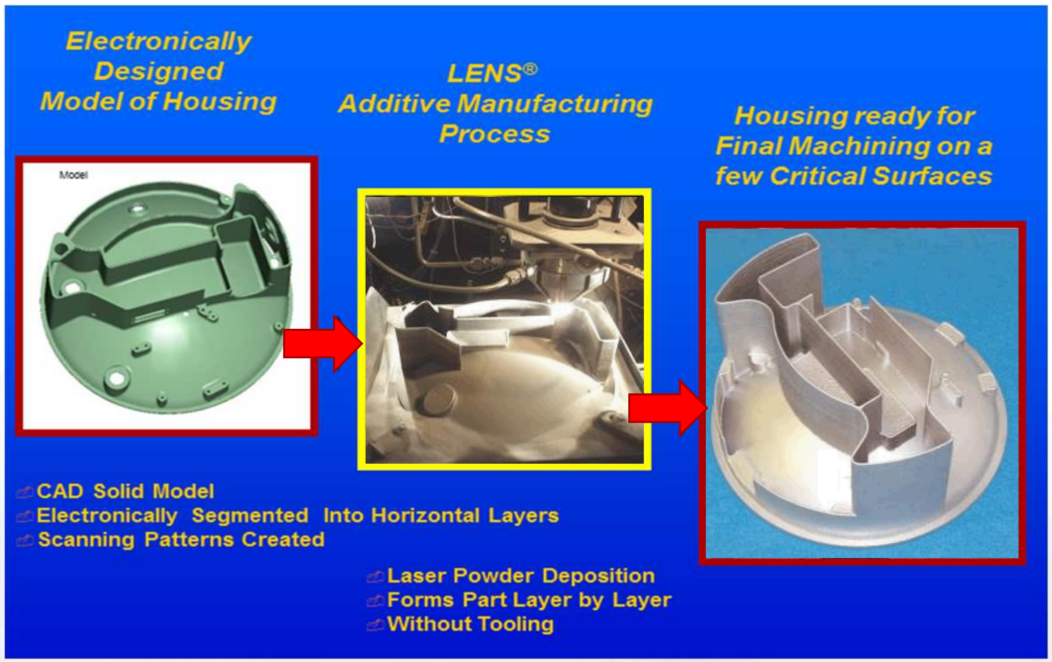
NNSA National Nuclear Security Administration

What is Additive Manufacturing (AM)?

ASTM F2792: *“A process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies”*



Laser Photopolymerization
(Nanoscribe GmbH)



Electron Beam Freeform Fabrication
(Accleron Inc.)

Many Different AM (3D Printing) Process Technologies

- *Plastics* – Relatively Mature
- *Metals* – Less Mature, but Rapidly Evolving
- *Ceramics* – Relatively Limited at Present, but in Commercial Use
- *Multi-Material* – Great Potential, Needs Further Development

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Sandia Additive Mfg.
Tech Development & Commercialization

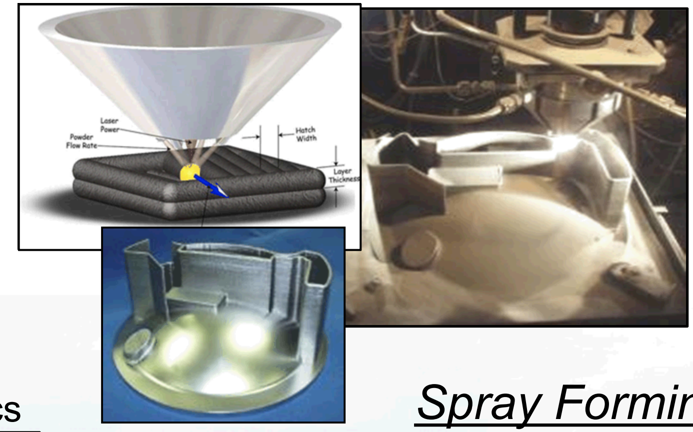
30+ yrs of Pioneering Process/Materials R&D

FastCast *

Development Housing

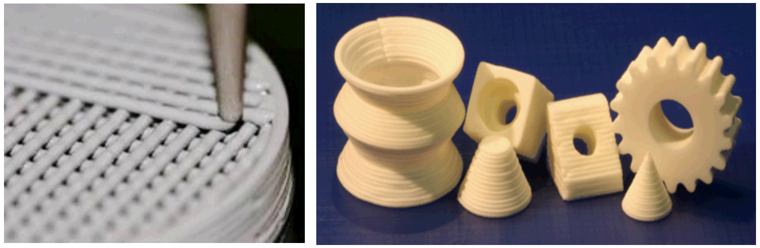
Laser Engineered Net Shaping * LENS®

Stainless Housing



RoboCast *

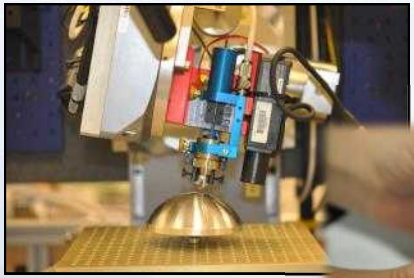
Ceramic Parts



Energetic Materials

Direct Write

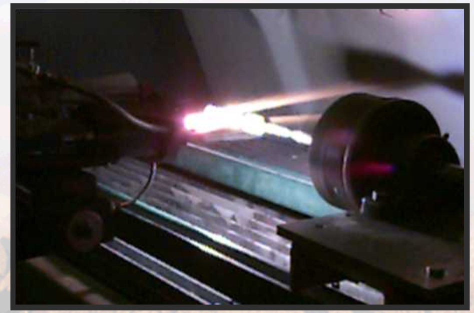
Conformal Electronics



Printed Battery

Spray Forming

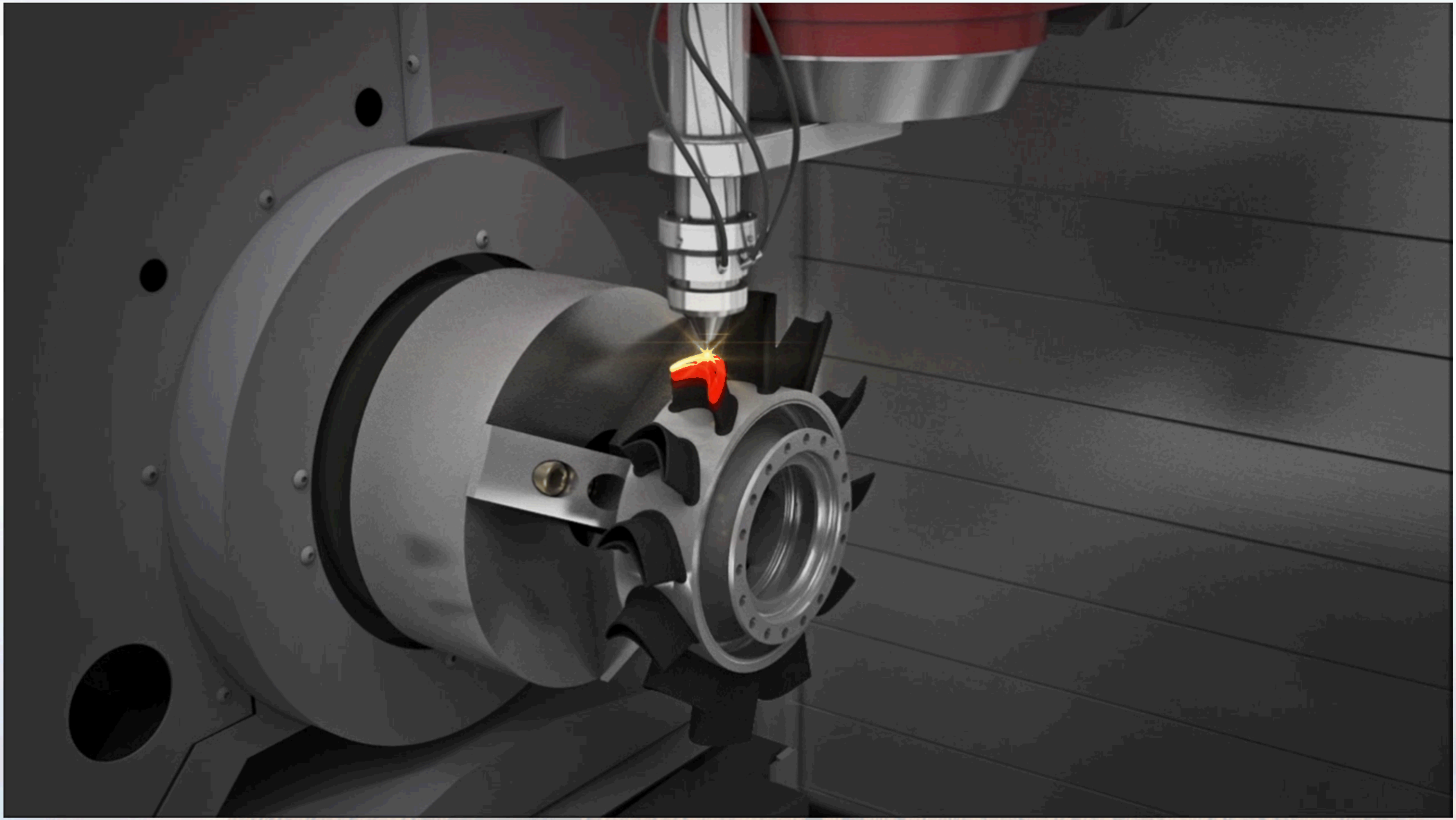
Rocket Nozzle



* = Licensed/Commercialized Sandia AM technologies

Underline = Current Capability/Activity

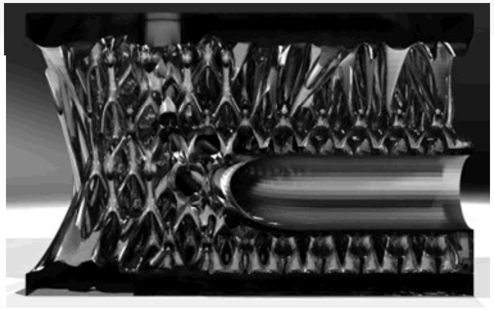
"Hybrid" Additive/Subtractive Machine Tools



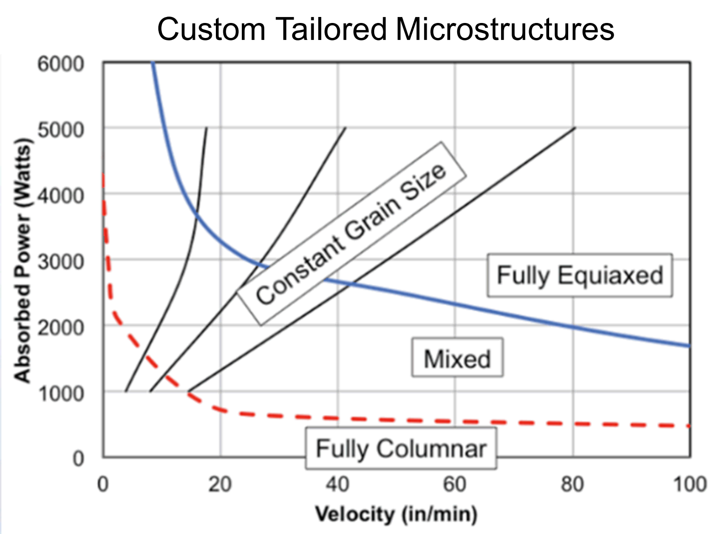
Video Courtesy of DMG Mori

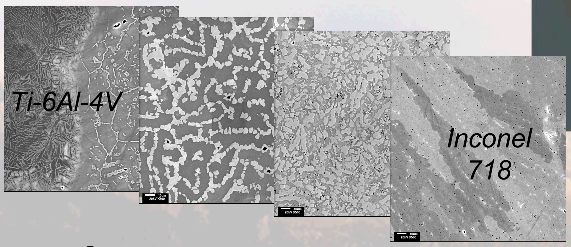
Why Use AM?
Some Intriguing Possibilities

- Design Freedom – shapes previously unachievable/impractical
- Print Integrated Assemblies
- Engineered Materials – special properties
- Save Weight, Time, Money
- Reduce Waste & Design Risk



Within Technologies

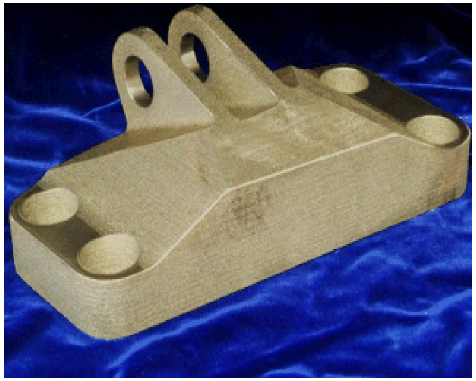




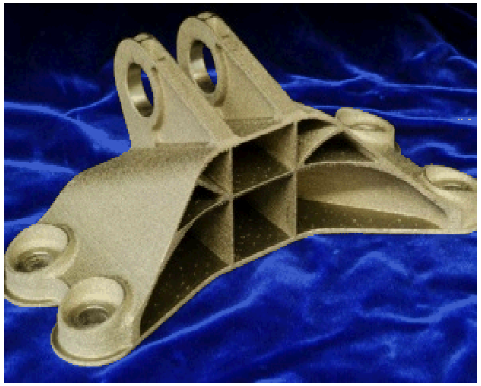
LENS® functionally graded materials

Commercial Aerospace Hardware

GE Additive Manufacturing Design Competition



Original Design 4.5 lb.



Winning AM Design 0.7 lb.

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

CFM LEAP Engine Fuel Nozzle*

Additively Manufactured LEAP Fuel Nozzle

- Internal geometry can’t be built with traditional technology
- 5x lifetime, 25% lighter
- Replaces 20 parts with 1 -- eliminates joining operations
- 19 fuel nozzles per engine
- New $50M Mfg. Plant, Auburn, AL, to build 40,000 nozzles/yr

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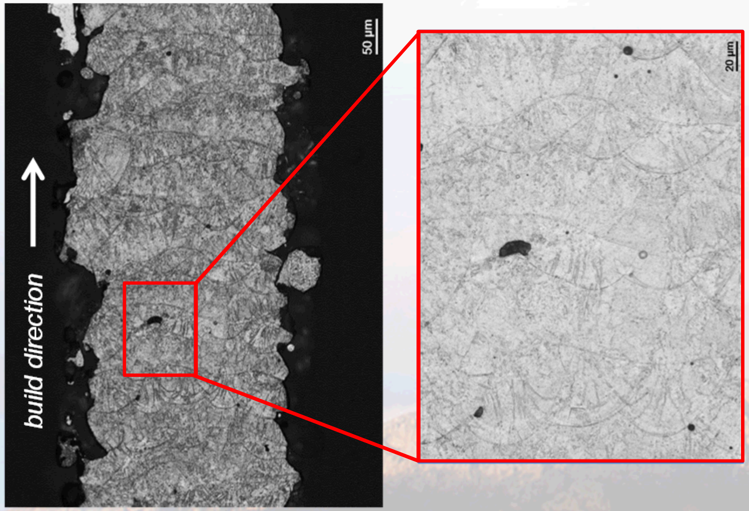
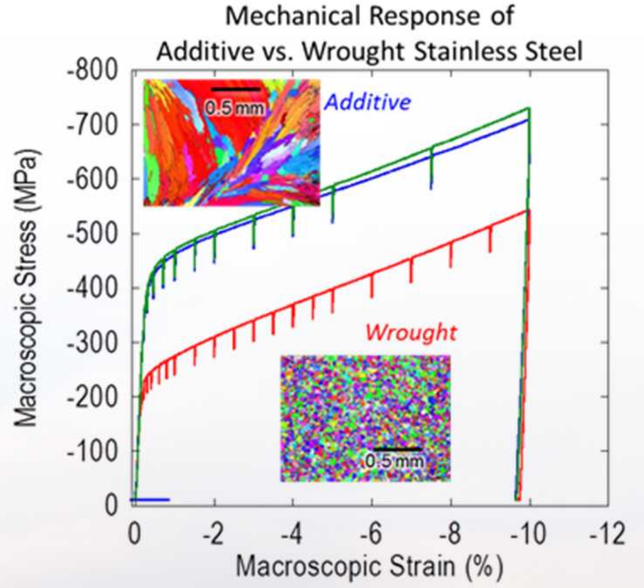
*CFM is a 50/50 Snecma/GE Company

Some Technical Challenges

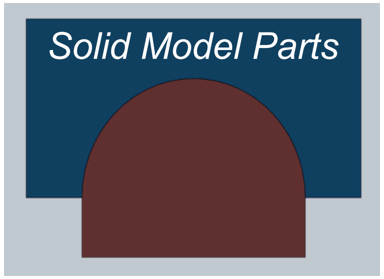
- Current Design Software Poorly Suited to AM
  - Need to Develop Requirements-Based / Analysis-Driven Design Tools
  - Need User-Friendly Interface / Reasonable Computing Resources
- AM Is Still an Evolving/Emerging Technology
  - Understand Material Properties / Create Standards
  - Understand & Control Variability
- Need to Address Production Issues
  - Model-Based Manufacturing
  - Inspection / Acceptance Methods

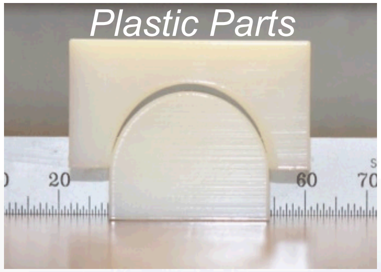


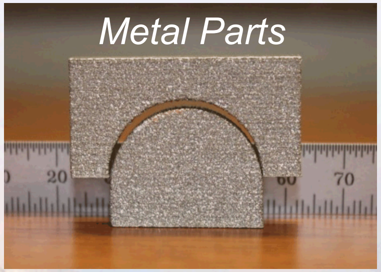
Surface & Interior Defects in 17-4 PH Stainless Steel



AM Metals are Unlike Cast or Wrought Metals







Residual Stress is an Issue

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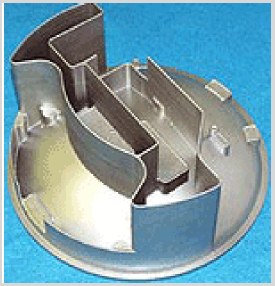
Sandia Additive Manufacturing Strategy

5 Strategic Thrust Areas

Today

Existing SNL Expertise, Capabilities, & Partnerships in Additive Mfg.



Identify Compelling Applications

Provide Analysis Driven Design Tools

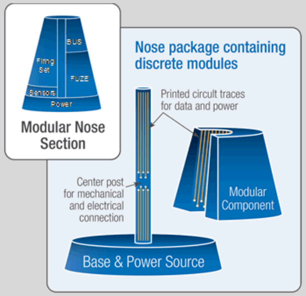
Provide Materials Assurance

Enable Engineered/Multi- Material AM

Enable Product Realization

Tomorrow

Deliver innovative, revolutionary national security products enabled by AM technology



FY16 ~$16M, 80 Projects

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Example Applications

Sandia Hand – AM Enabled Innovative Design and Substantial Cost Reduction

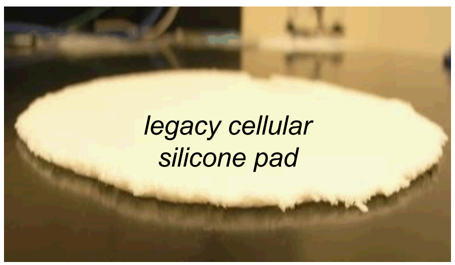
(~*50% of hand built with AM*)

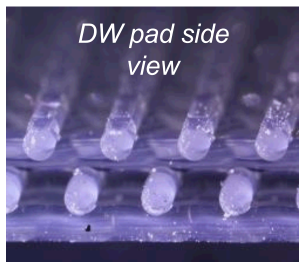
- Developed for bomb disablement
- AM Enabled rapid design iterations
- Cost $10k vs. ~$250k
- “Glove” controller
- Current version has “touch” sensors

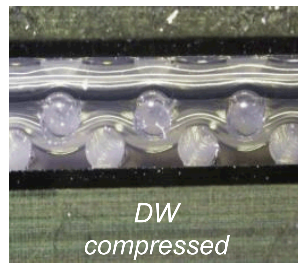
Fingers or other tools (drills, lights, …) can be quickly magnetically attached in many configurations

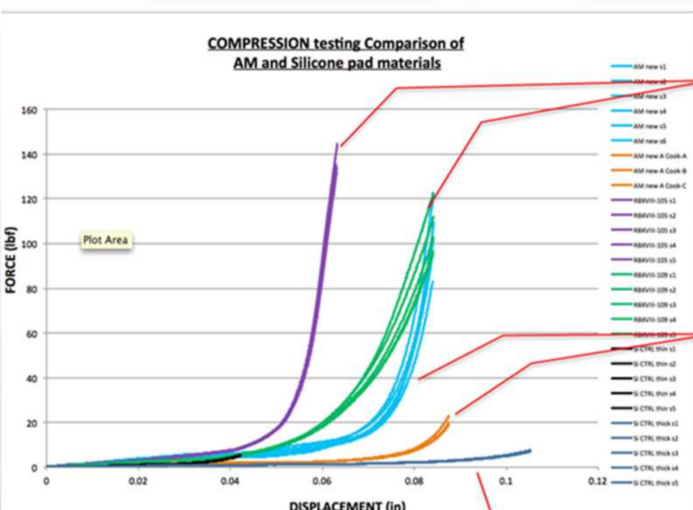
Example High Design Margin AM Applications

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





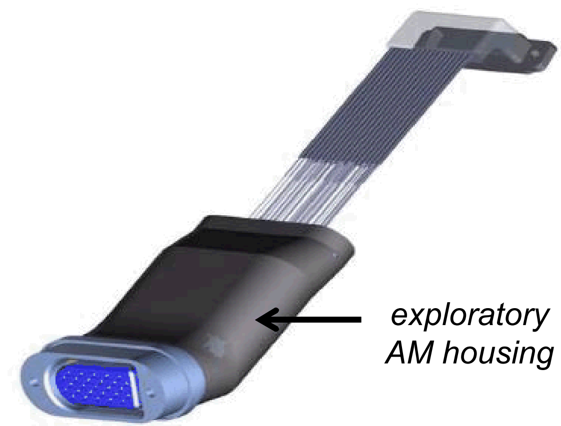


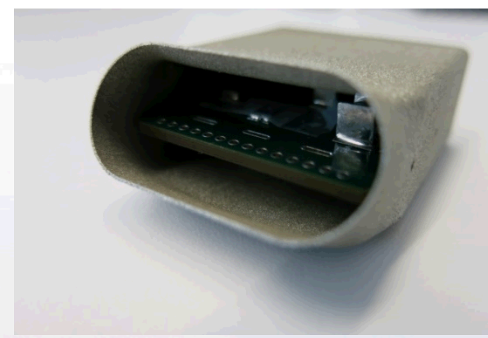


3D Printed Silicone (unmodified) NSC

3D Printed Silicone (modified) SNL

LEGACY MATERIAL





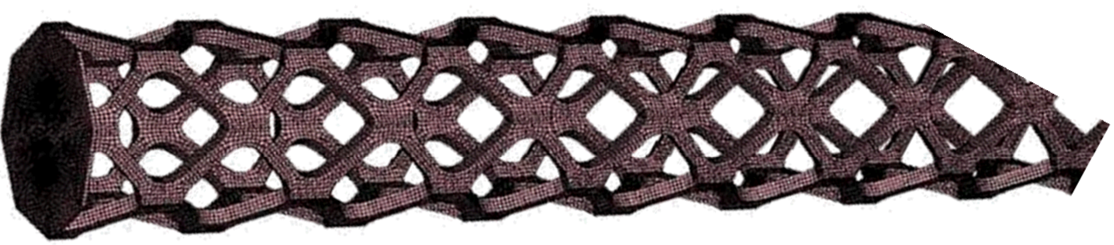
- AM Offers Potential Advantages for Complex, Thin-Walled Shape

Analysis Driven Design

Analysis-Driven Design Optimization

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

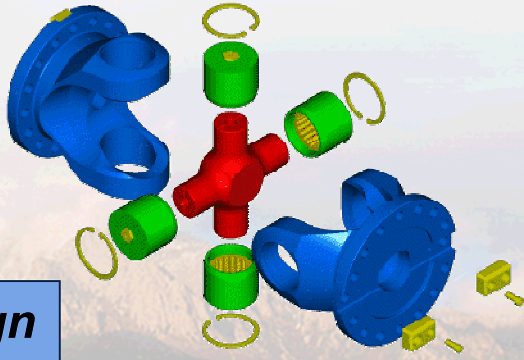
"Titanium Cholla" -- Minimum Weight, Maximum Strength, Rapidly Manufactured!



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

Core of a dead Cholla cactus. It is interesting that optimized designs often resemble natural structures (bio-mimicry).

"Loxosphere" Universal Joint printed as a single integrated assembly – far fewer parts, no complex assembly required!



How can we use AM to achieve design objectives in revolutionary new ways?

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Imagine a New Way of Designing & Realizing National Security Products

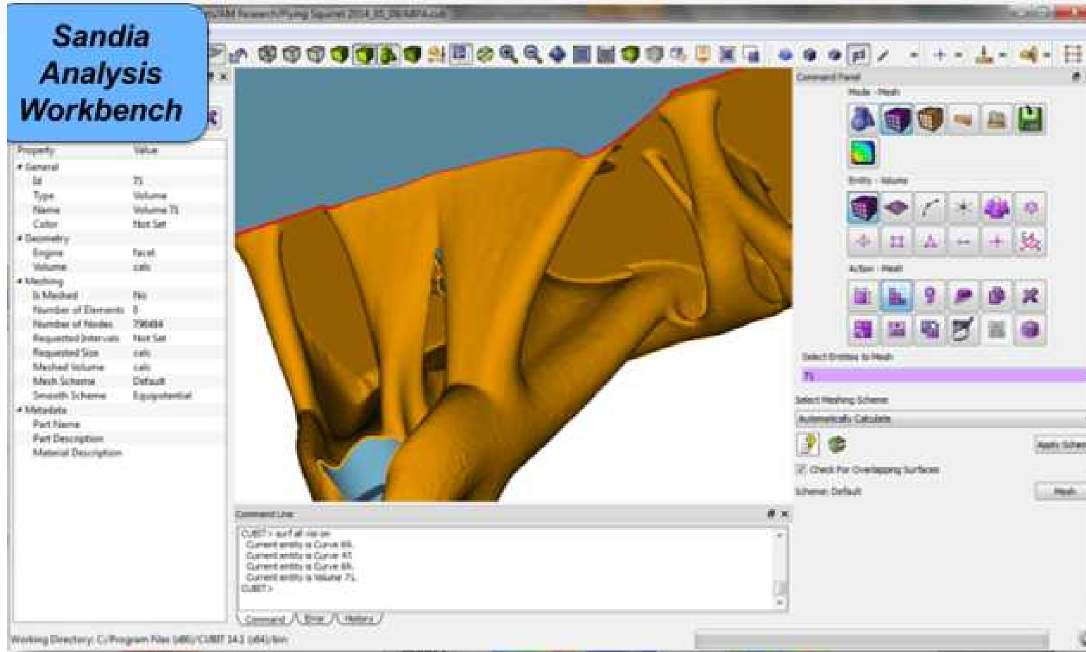
Requirements-Based, User-Friendly, Interactive, Analysis-Driven, Design Tools that Provide Test Guidance, Build Parameters, and Quantified Margins & Uncertainties

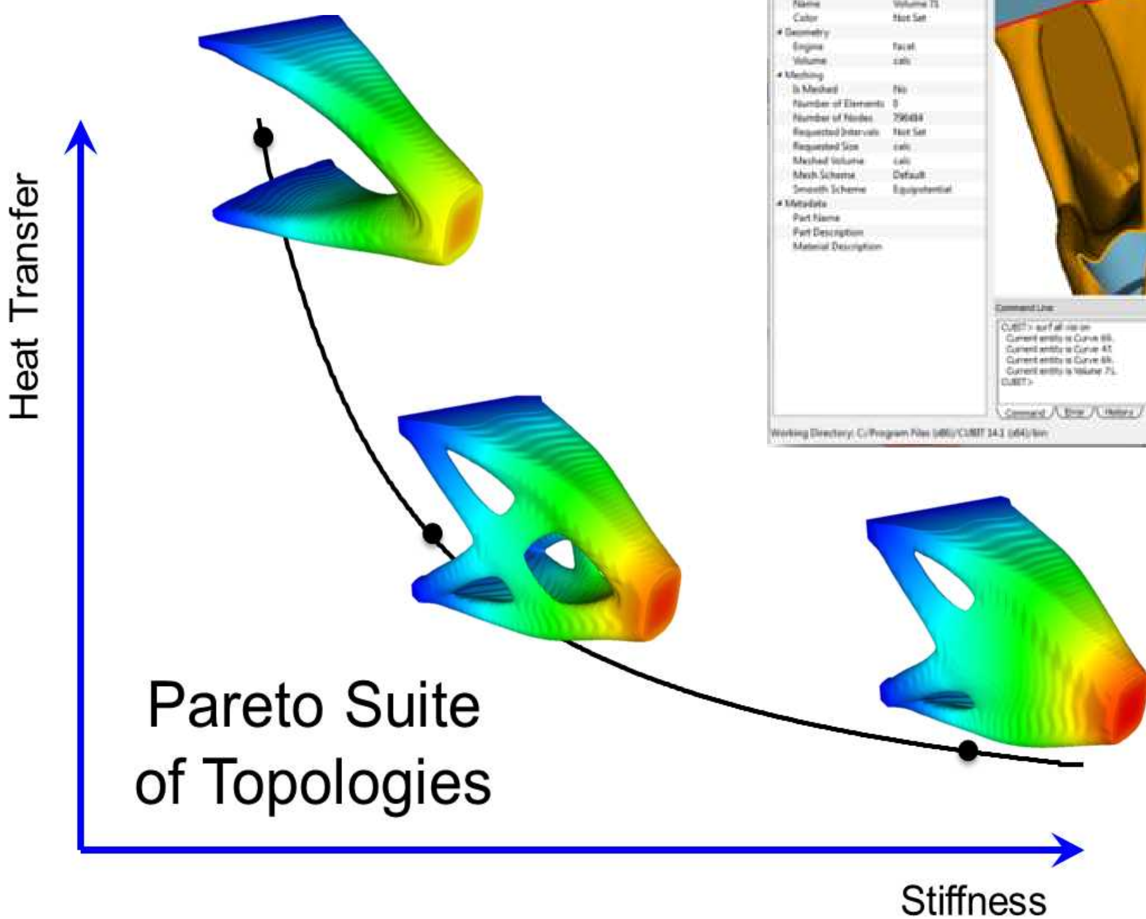
Seamless, Electronic, Agile, 3D Model-Based Manufacturing w Process Monitoring & Control

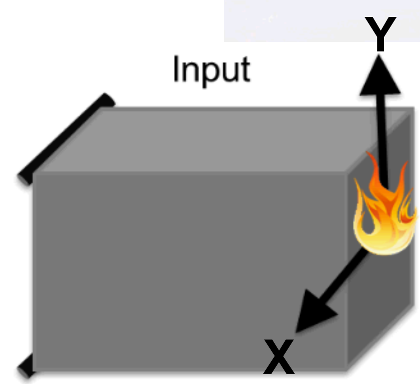
Final Products not Possible with Traditional Technologies; A New World of Possibilities!

AM Design Via Functional Prioritization

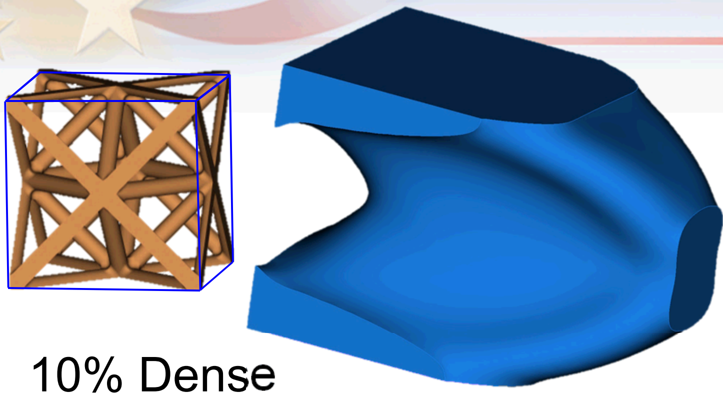
User Friendly Interface



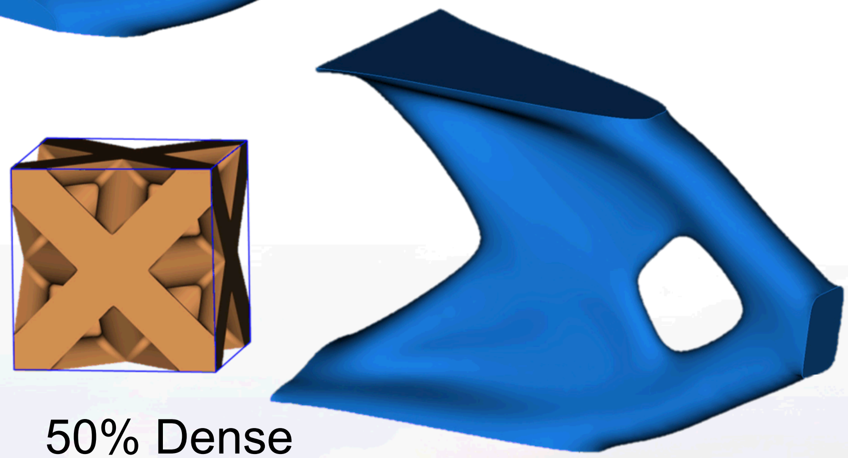




Optimizing Stiffness at Fixed Mass

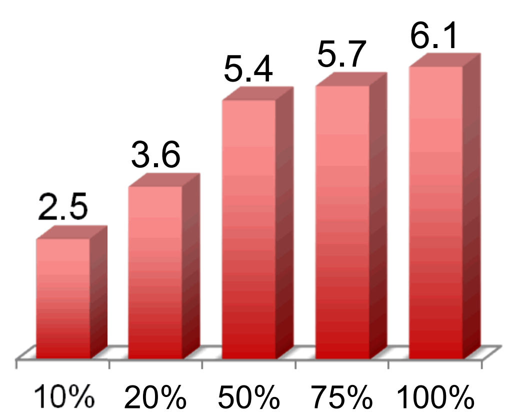


10% Dense

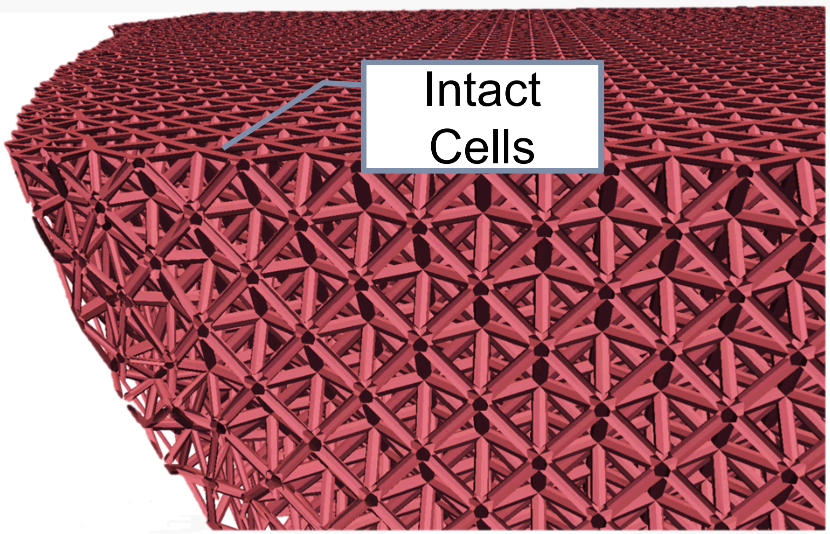


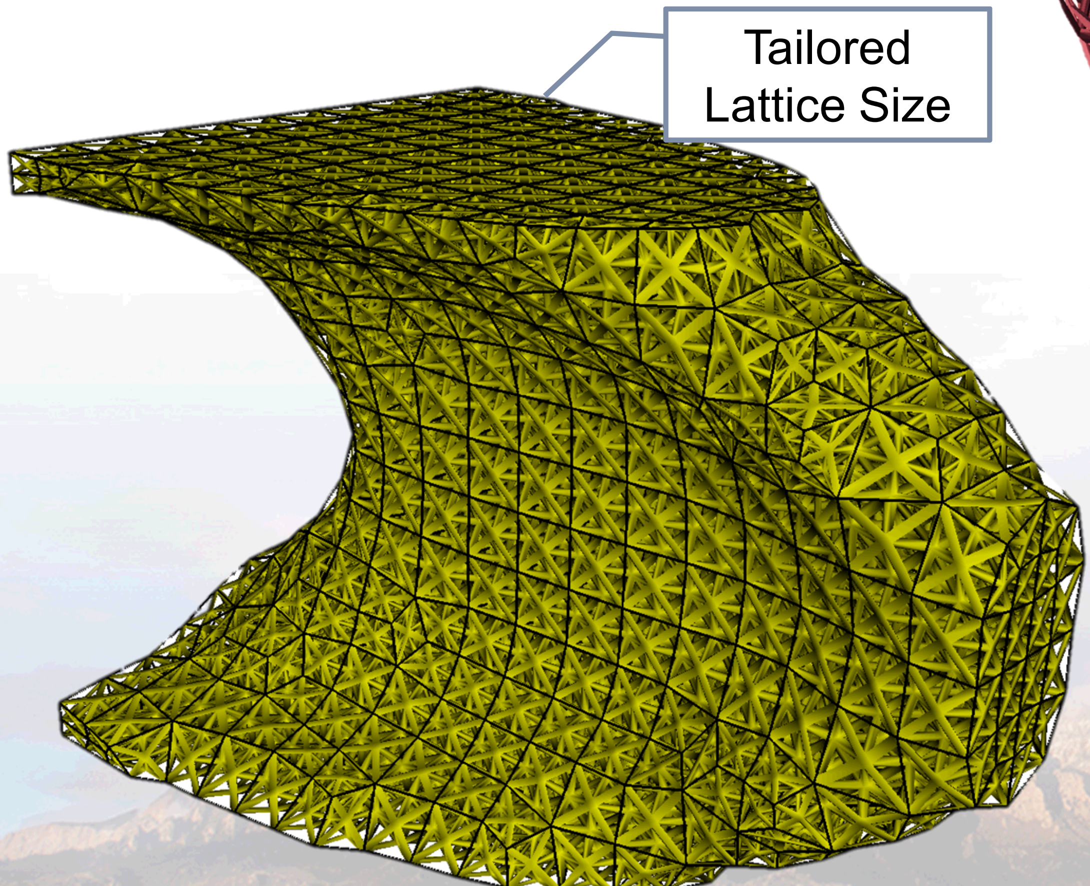
50% Dense

100% Dense



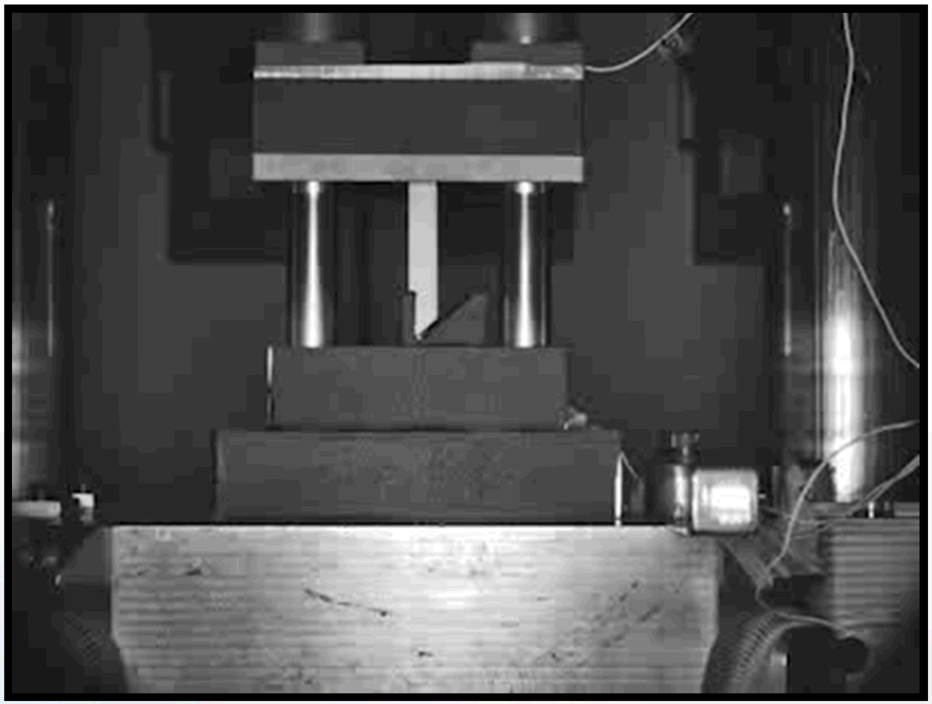
Tailored Geometry Avoids "Loose Ends"



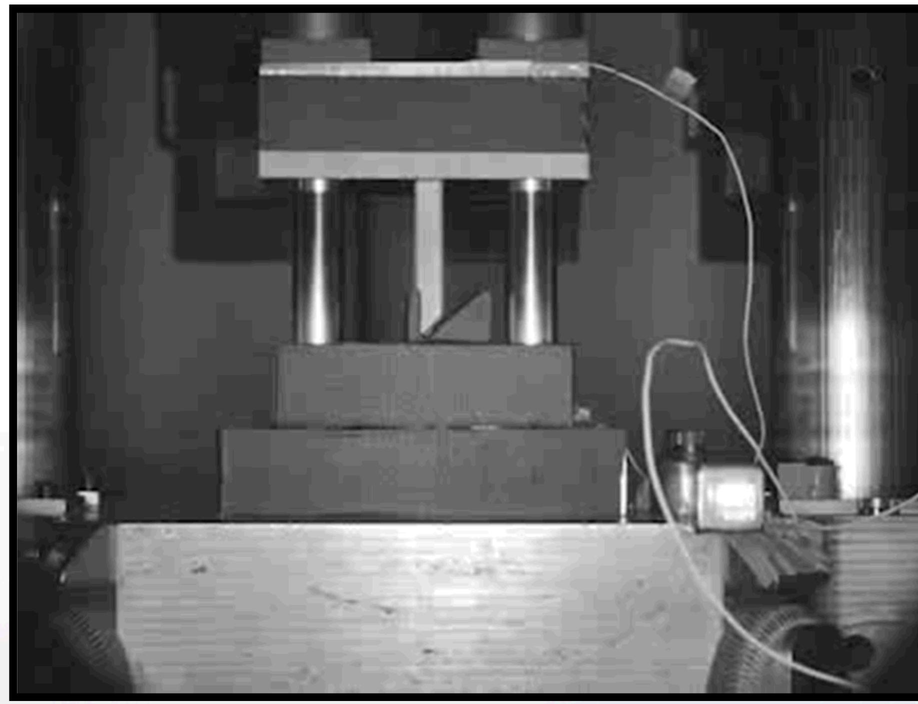


Materials Assurance

Longitudinal Impact Test



Machined/Welded Housing
4047 Al alloy
weight = 45 grams



Additively Manufactured Housing
AlSi10Mg Al alloy
weight = 38 grams

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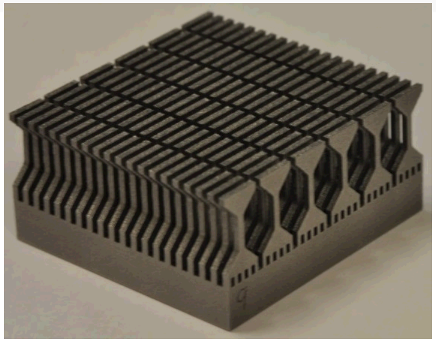
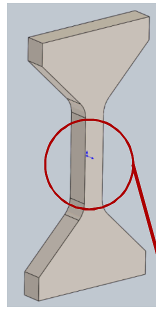
Leverage Sandia PPM to Quantify Variability/Defect Sensitivity

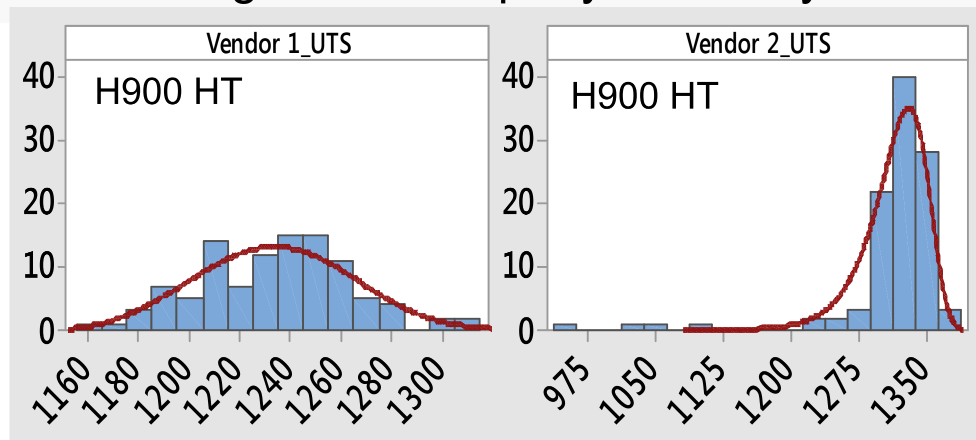


120 AM 17-4 PH SS tensile bars enable rapid, economical testing



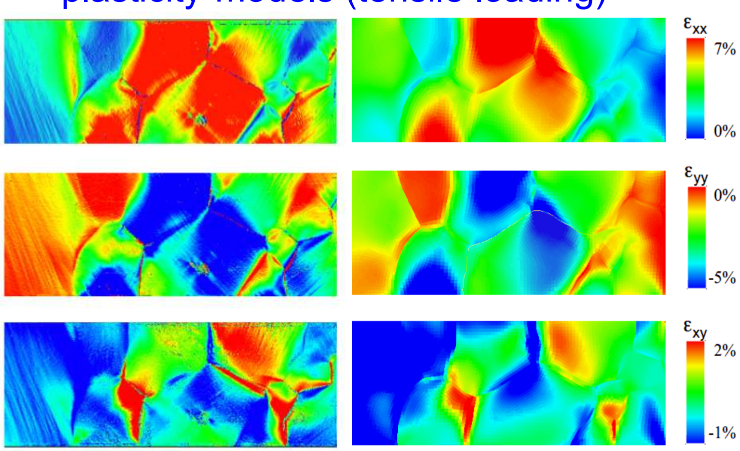
1x1 mm gage section sample

Significant Property Variability



Ultimate Tensile Strength (Mpa)

Oligocrystal experiments vs. crystal plasticity models (tensile loading)



Experimental Results

Computed Simulations

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 Oligocrystal Tensile Specimen (1x3x5 mm)
(Use Electron Backscatter Diffraction & Digital Image Correlation)

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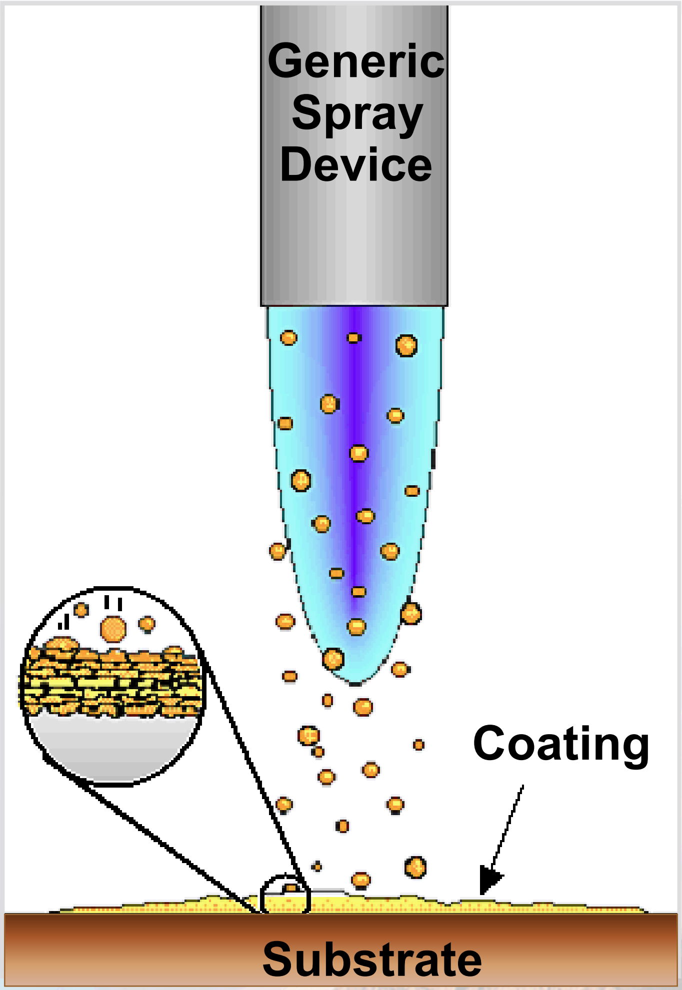
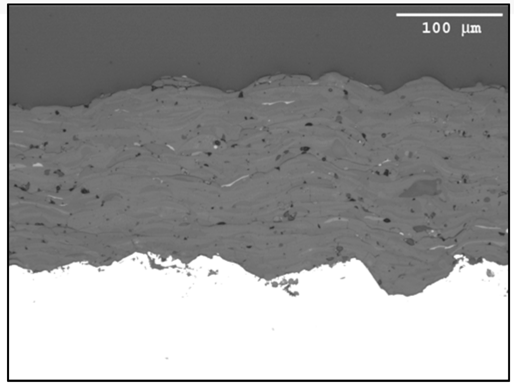
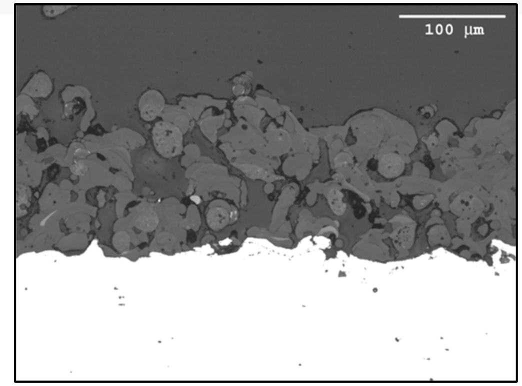
Build on Prior Success with Process Control of Another AM Process --Thermal Spray



Same System, Same Feedstock,

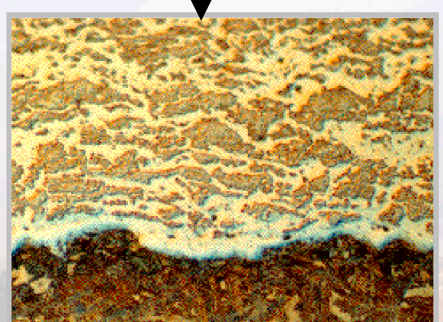


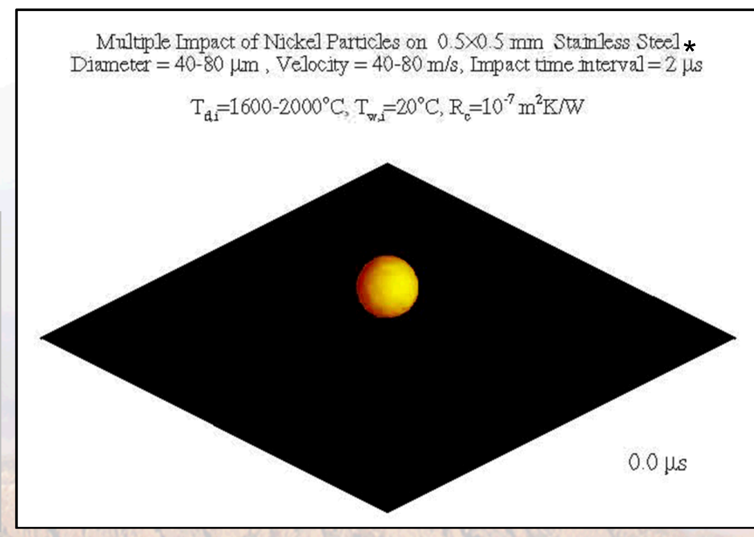
vs.



Very Different Results

Cemented Carbide Coating On Steel





AM today is similar to Thermal Spray ~20 years ago

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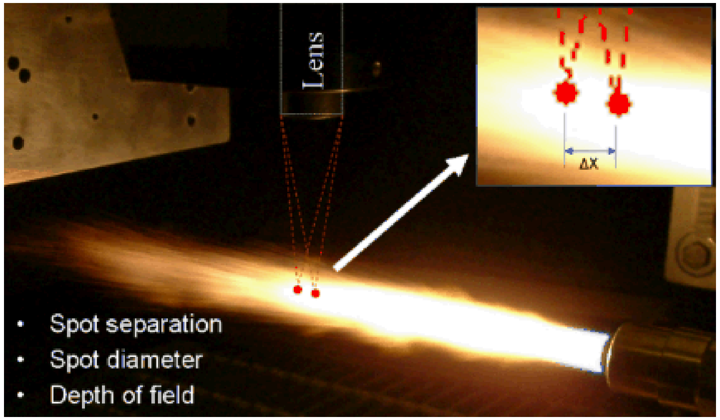
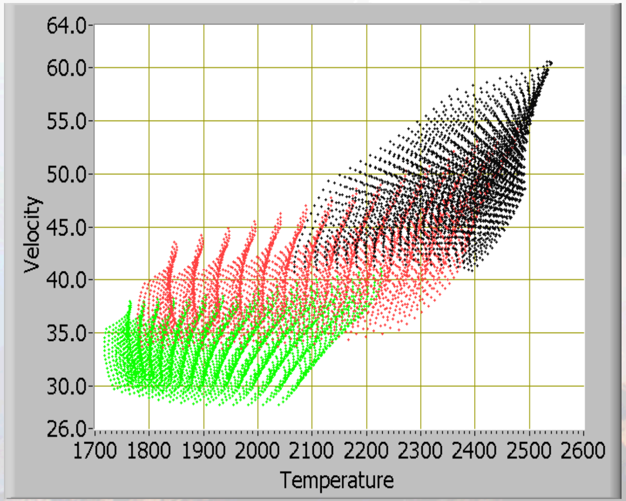
*Droplet Impact Simulation by Prof. J. Mostaghimi, et al, Univ. of Toronto

Fundamental Process Understanding is Key to Controlling Variability

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

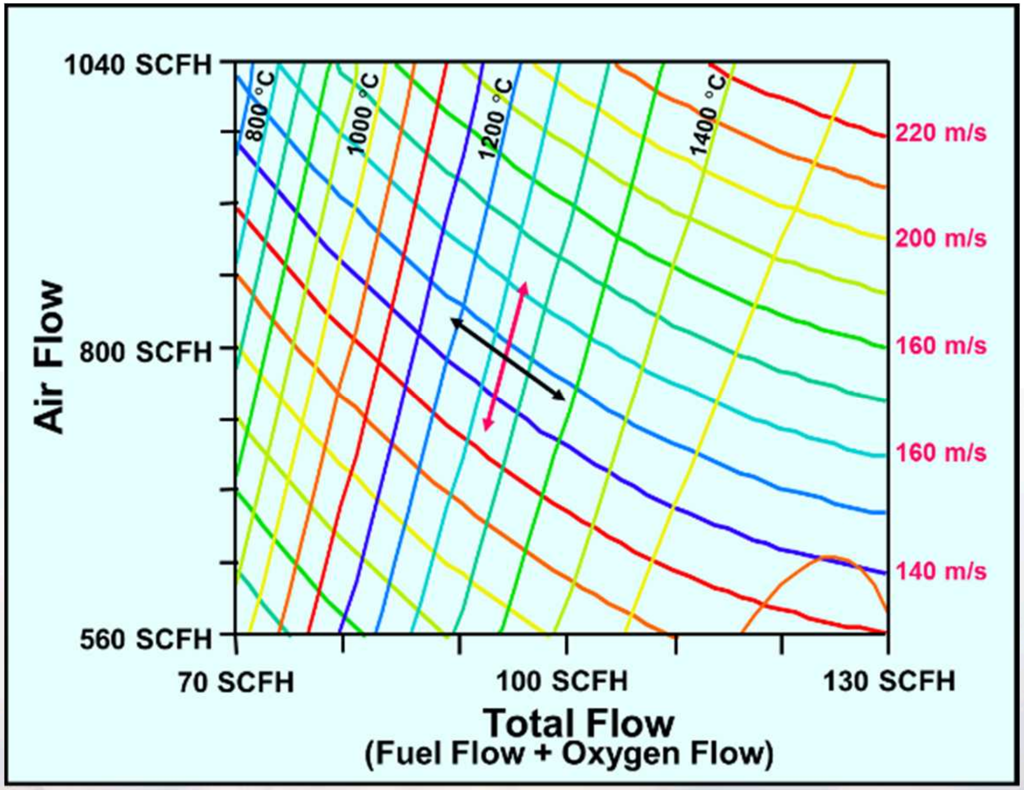


Process Diagnostics/Monitoring



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

- Fundamental process understanding used to implement <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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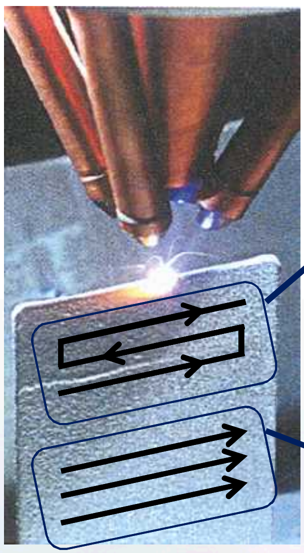
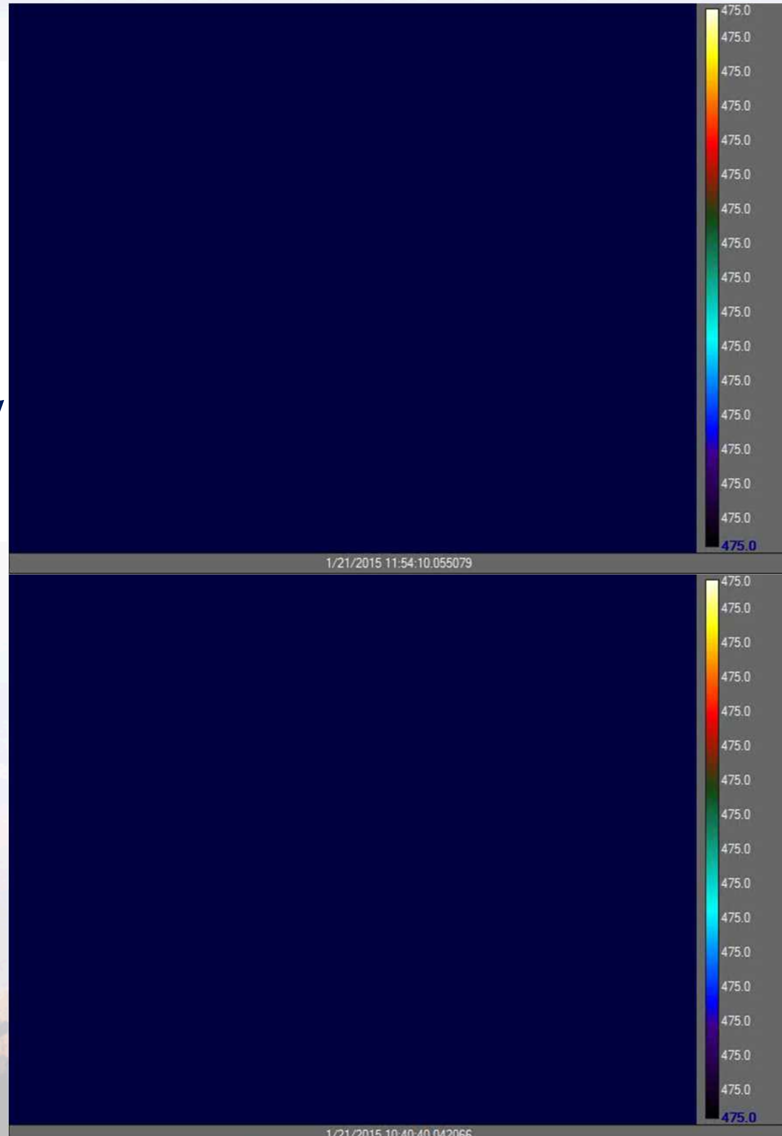
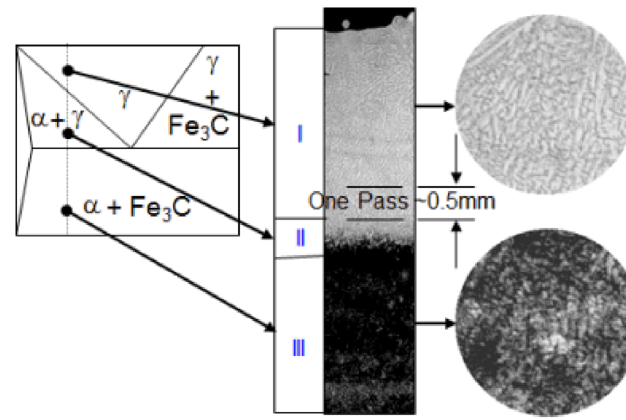
Processing Strongly Affects AM Material Properties

Thermal history during <u>bi</u>directional metal additive deposition



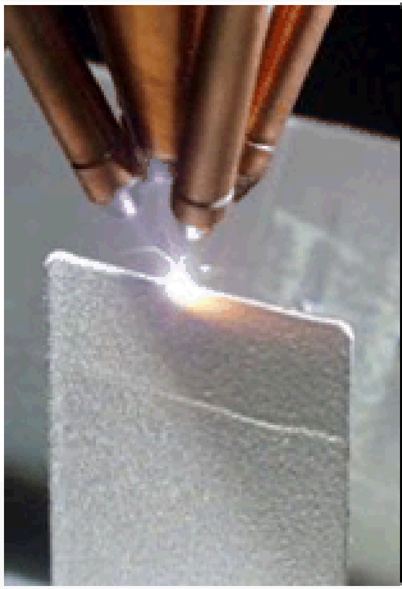
Thermal history during <u>uni</u>directional metal additive deposition

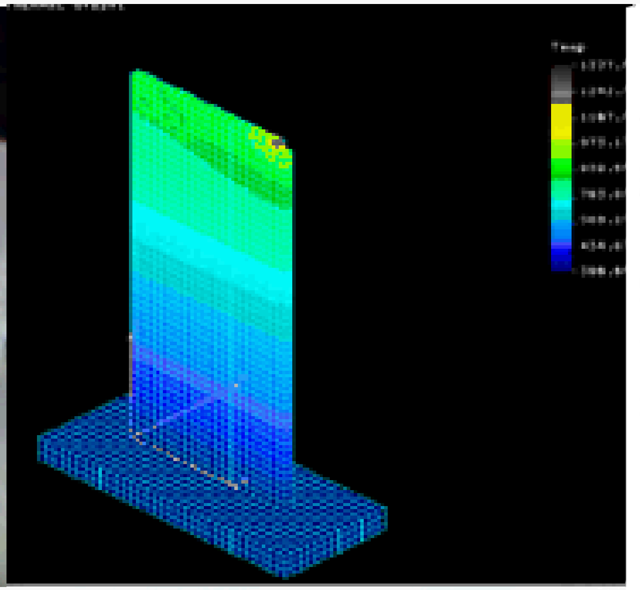


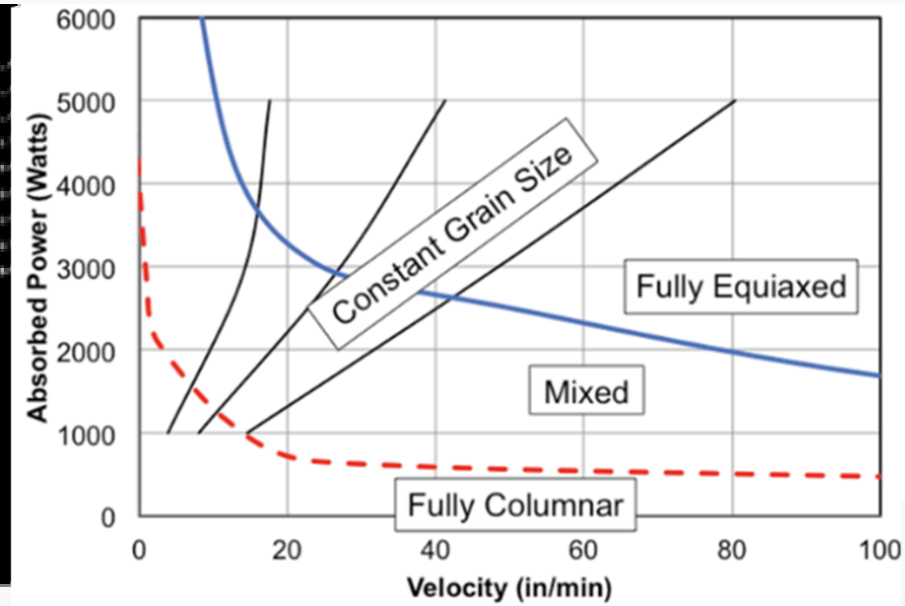


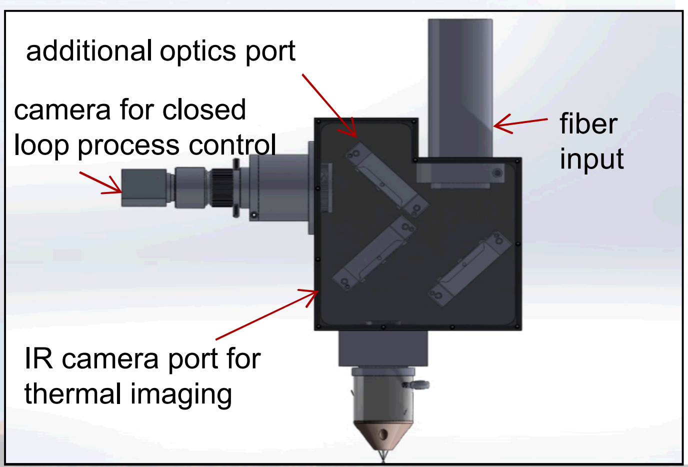
LENS® Process & Materials R&D

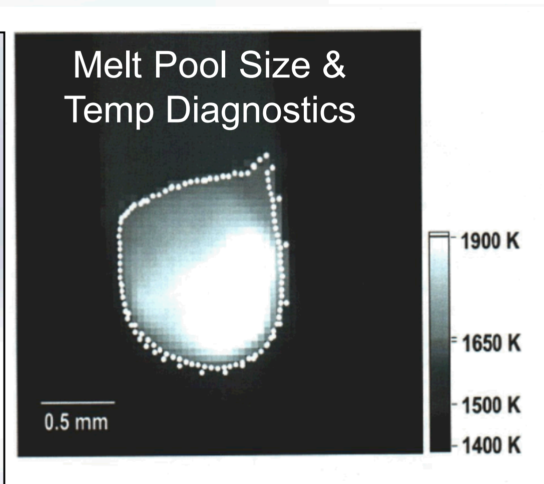
Process characterization/modeling





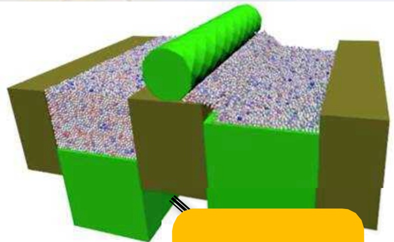


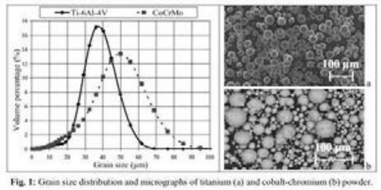


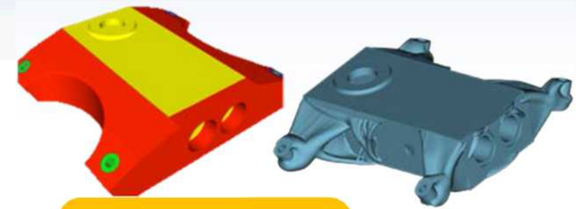


Successfully demonstrated control of melt pool size & temperature to control microstructure and reduce variability

Working to Understand/Control
Process → Microstructure → Properties → Performance

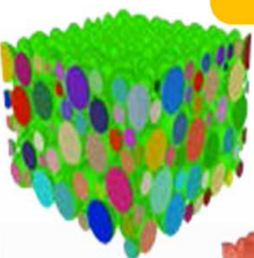


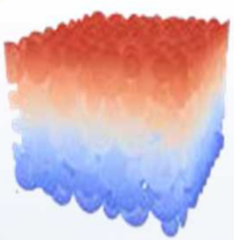


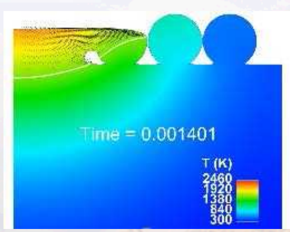


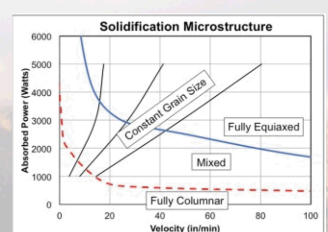
- Process control
- Materials characterization
- Interfaces
- GRANTA database

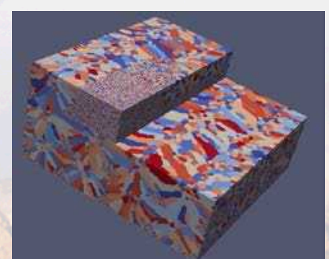
Particle packing → Heat Transfer → Partial melt & flow → Molten pool dynamics → Solidification → Microstructure → Property-Performance → Topology Design

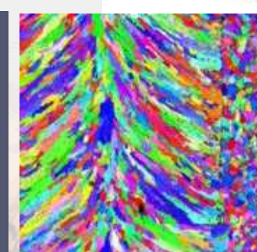


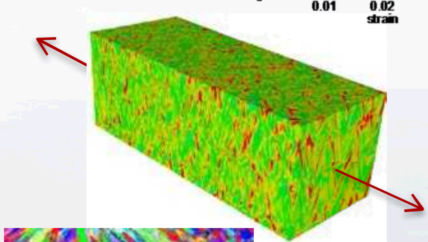


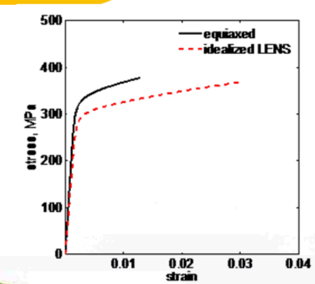






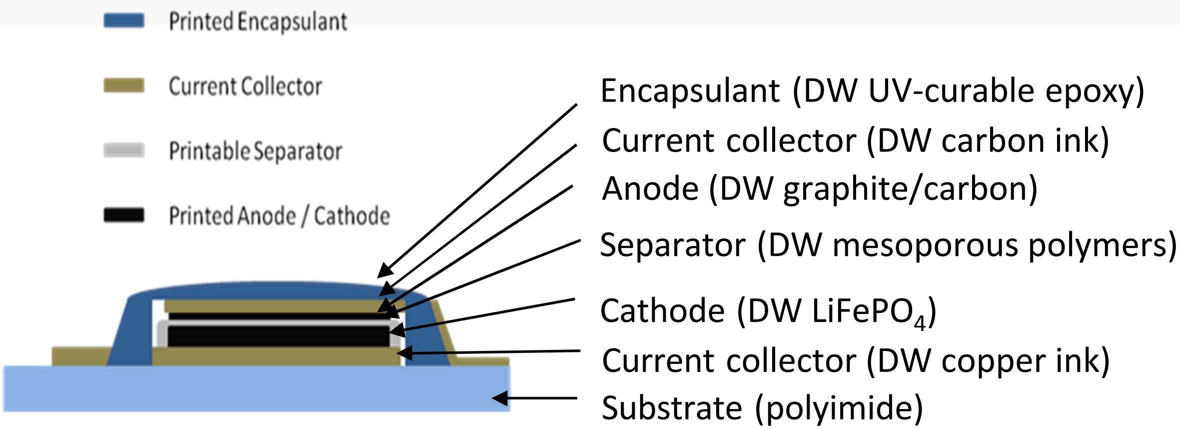


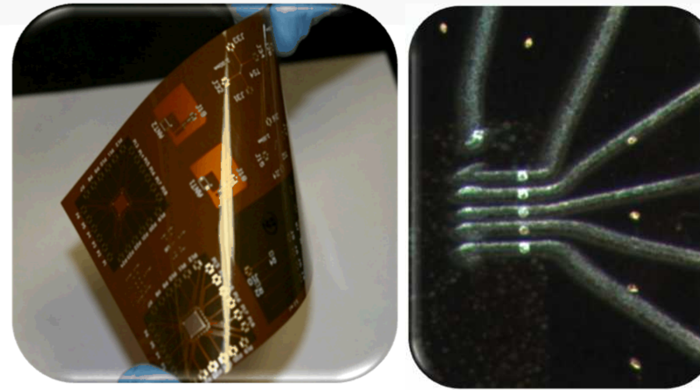




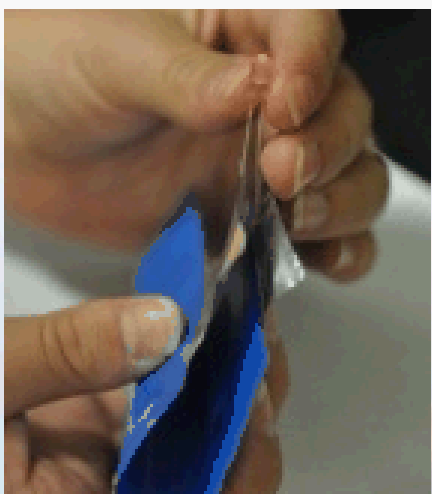
Multi-Material AM

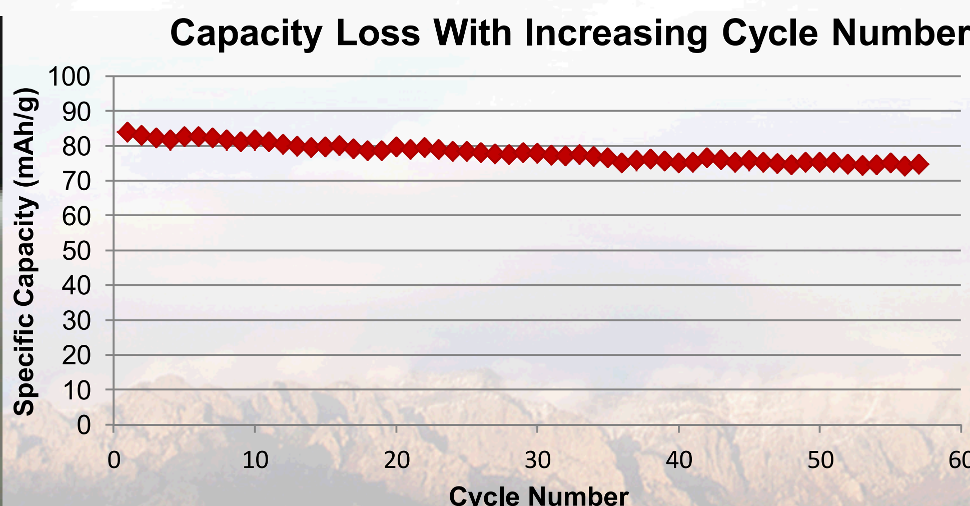
Printed Electronics

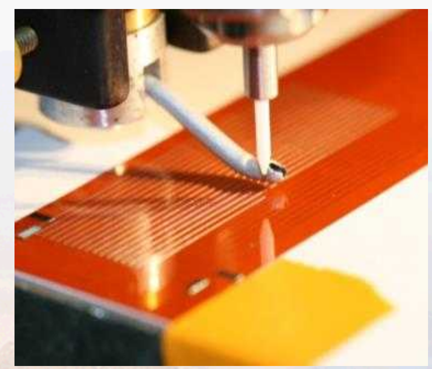




"Flexible Chips" with Printed Wirebonds







Aerosol jet printing to 10 μm

Sandia National Laboratories

Summary

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