SAND2016-2670PE

Exceptional service in the national interest

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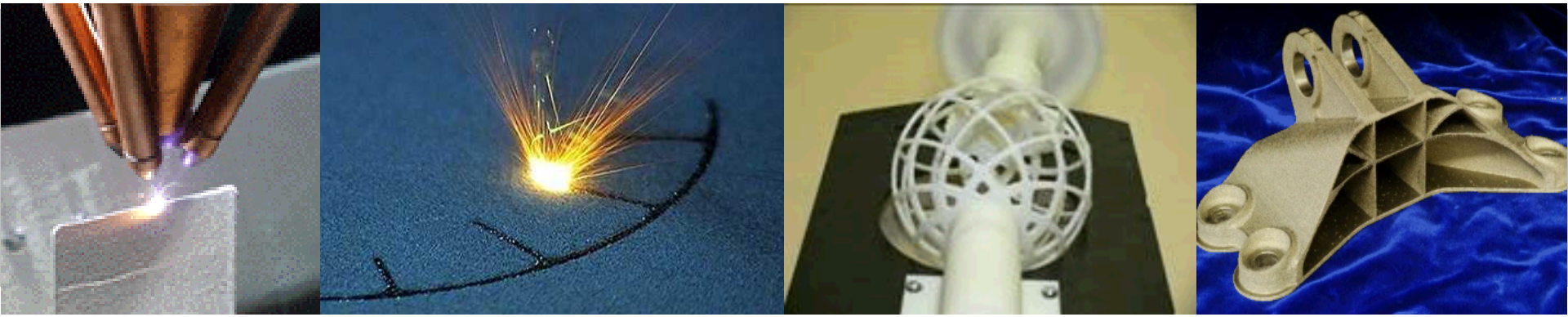

Additive Manufacturing at Sandia -- A New World of Possibilities and Challenges

Mark F. Smith

Materials Science & Engineering Center

Sandia National Laboratories

Dec. 2015

Presented by Hy D. Tran, Primary Standards Laboratory

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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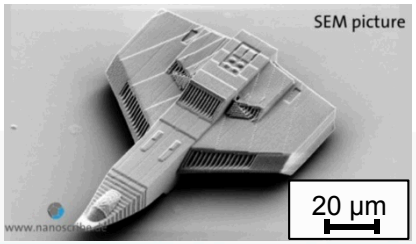
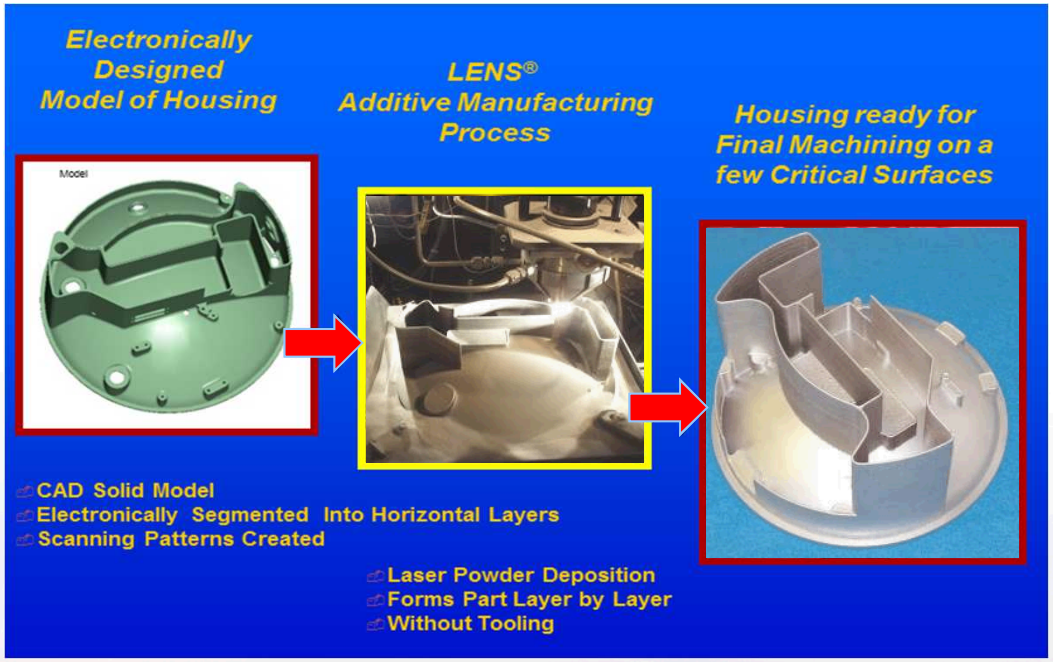
What is Additive Manufacturing (AM)?

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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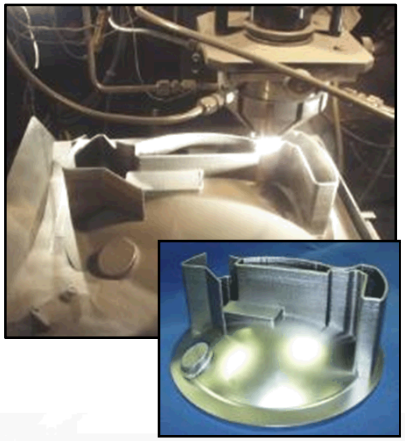
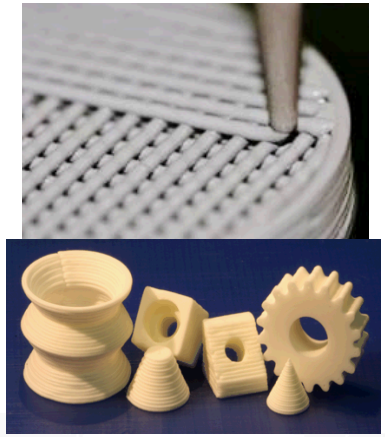
30+ yrs of Pioneering Sandia AM Tech Development & Commercialization

*FastCast**
Development Housing

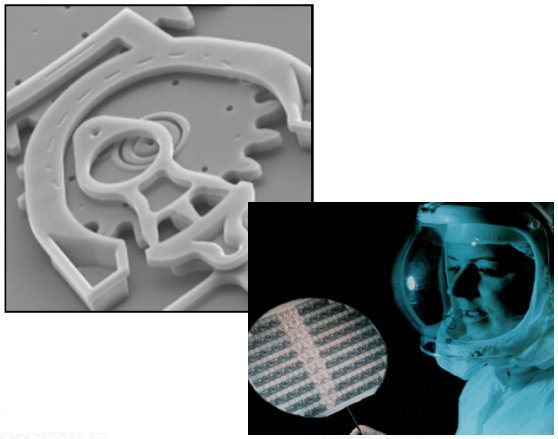
*LENS®**
Stainless Housing



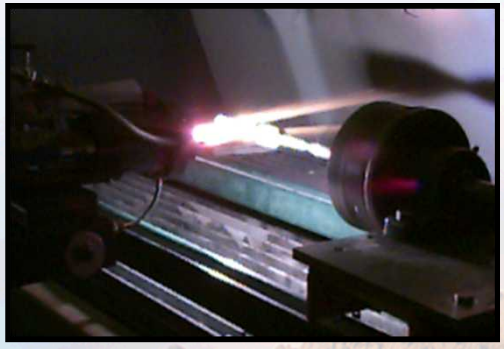
*RoboCast **
Ceramic Parts



*MEMS SUMMIT™ **
Micro Gear Assembly

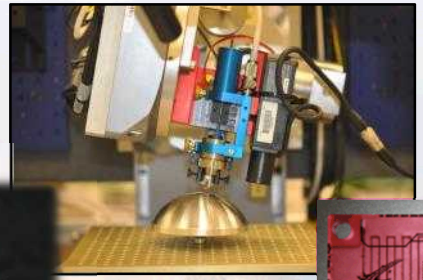


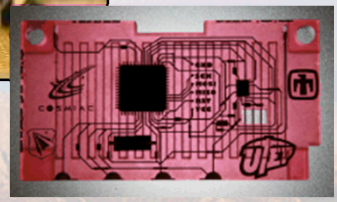
Thermal Spray Forming
Rocket Nozzle



LIGA
Miniature Spring

Direct Write
Conformal Electronics





Printed Battery/Wiring Board

* = Licensed/Commercialized SNL AM technologies
Underlined = Existing SNL Capability

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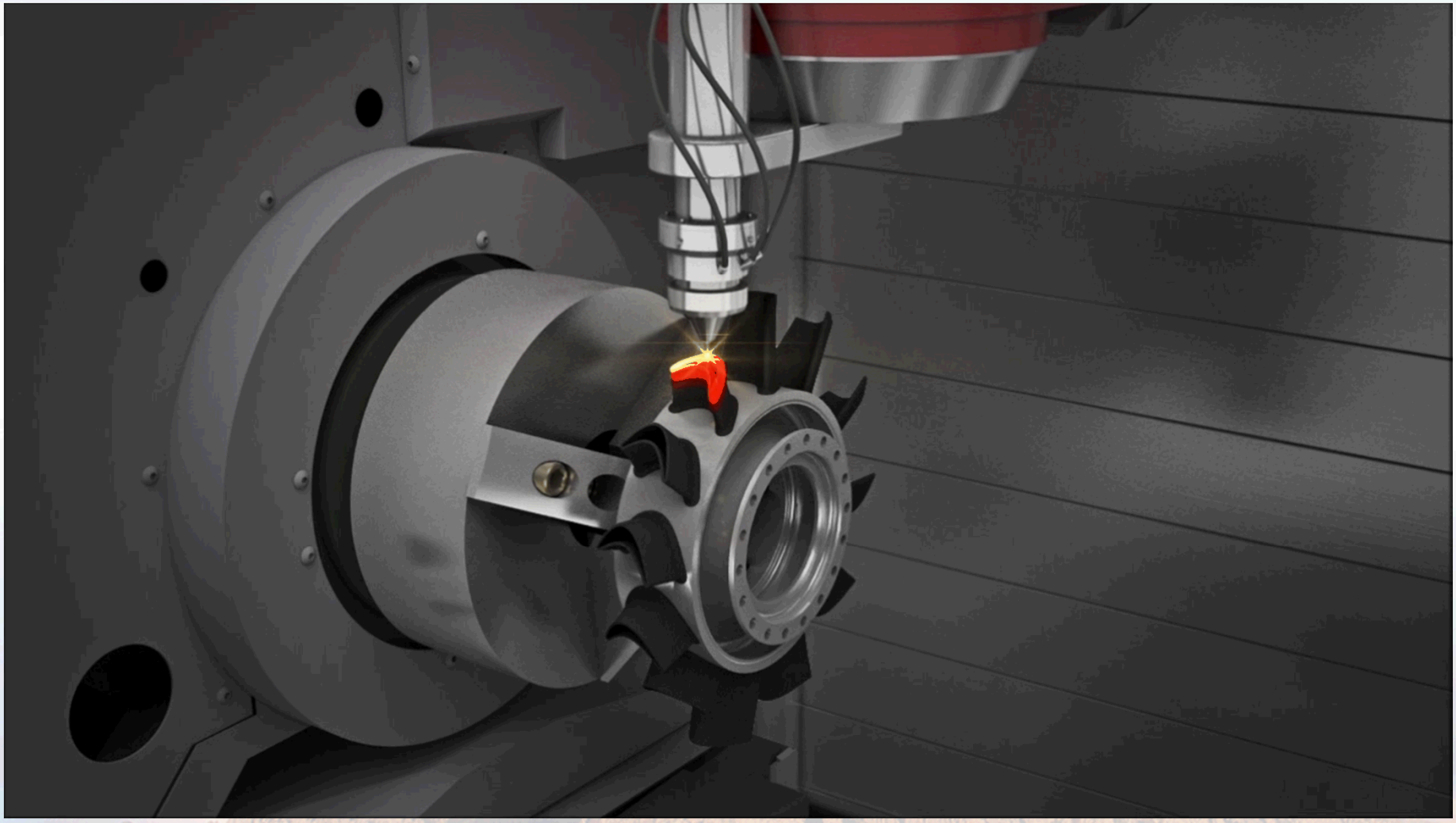
"Hybrid" Additive/Subtractive Machine Tools



Video Courtesy of DMG Mori

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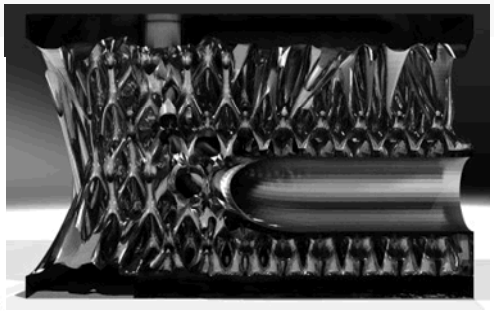
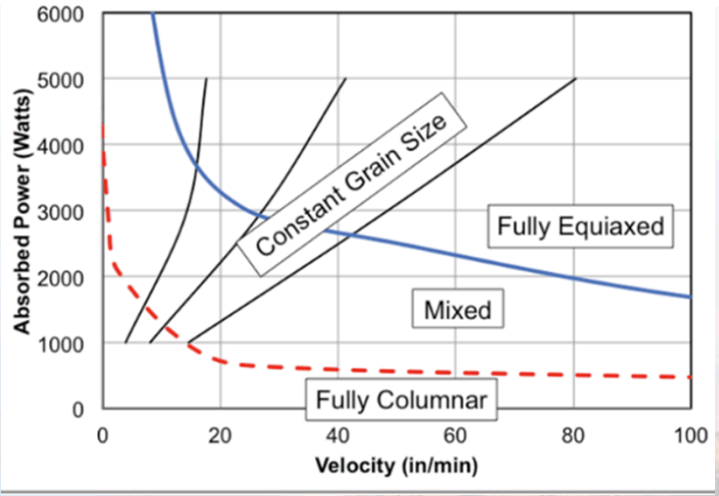
Why Use AM?
Some Intriguing Possibilities

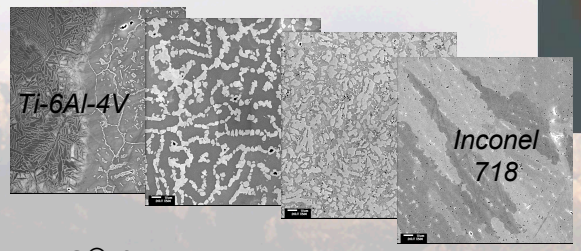
- Design Freedom – shapes previously unachievable/impractical
- Print Integrated Assemblies
- Engineered Materials – special properties
- Save Weight, Time, Money
- Reduce Waste & Design Risk



Within Technologies

Custom Tailored Microstructures





LENS® functionally graded materials

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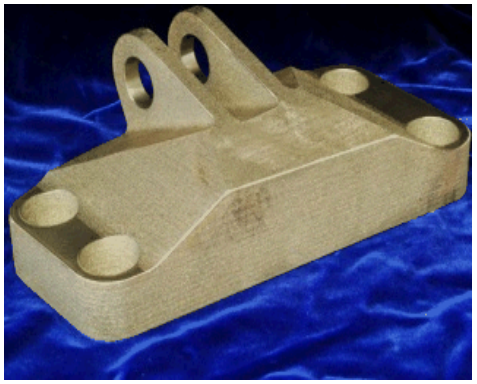
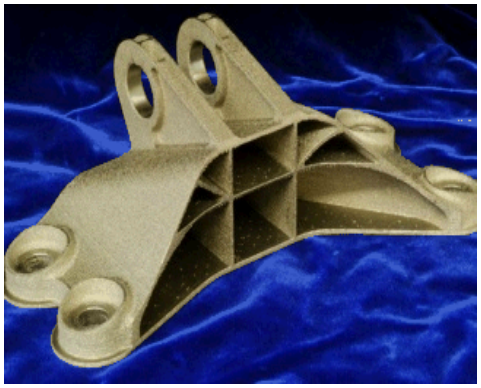
Commercial Aerospace Hardware

GE Additive Manufacturing Design Competition



Original Design 4.5 lb.



Winning AM Design 0.7 lb.

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

CFM LEAP Engine Fuel Nozzle*

Additively Manufactured LEAP Fuel Nozzle

- 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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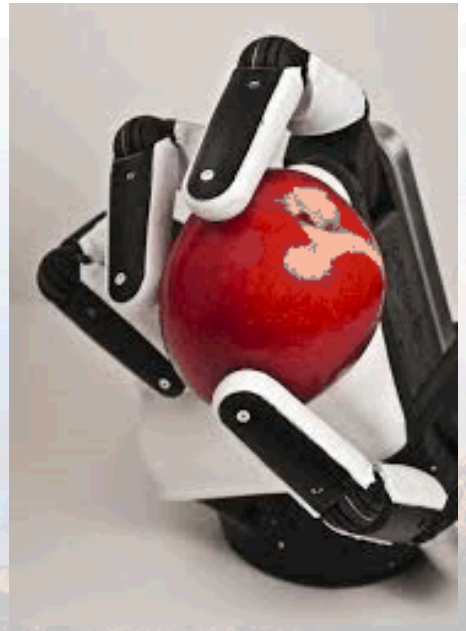
*CFM is a 50/50 Snecma/GE Company

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



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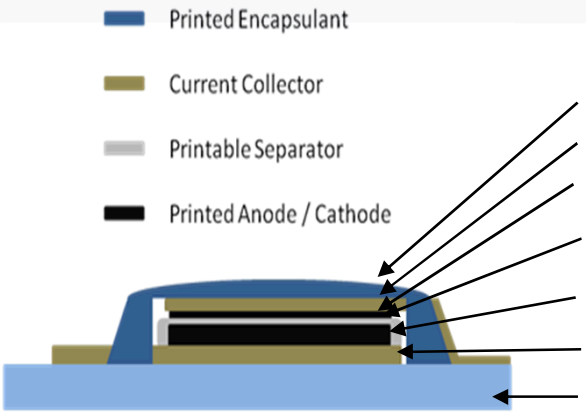
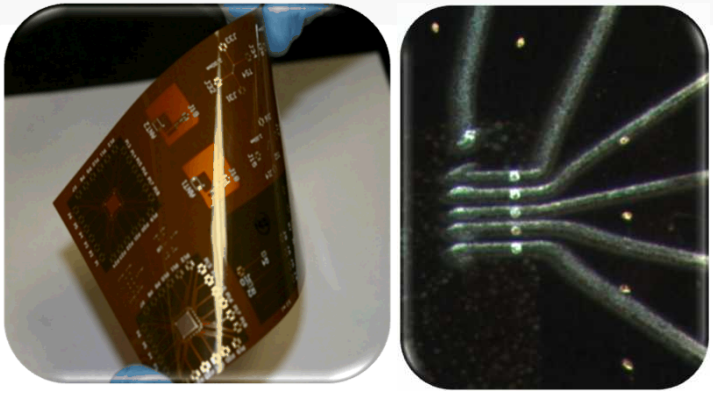
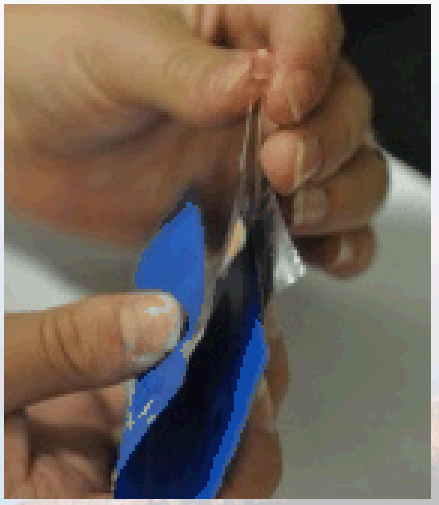
Printed Electronics

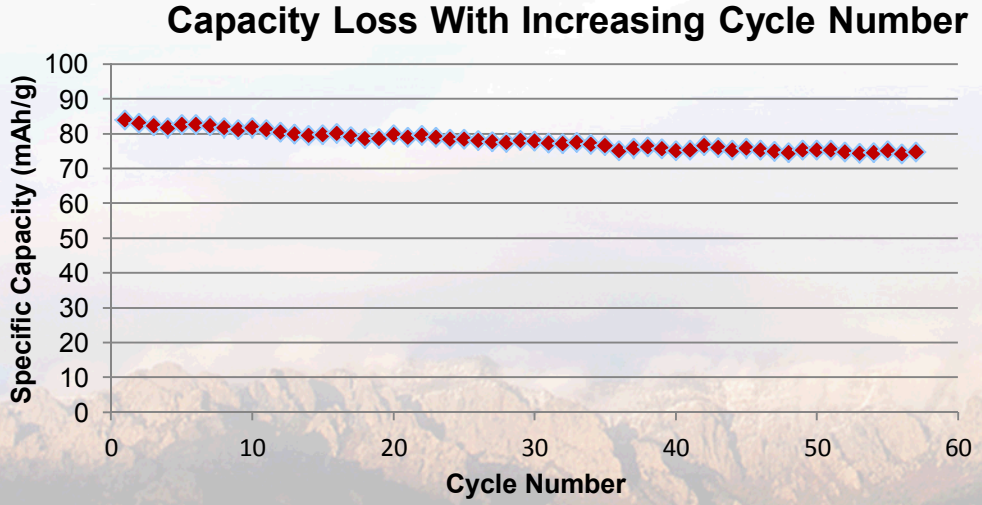


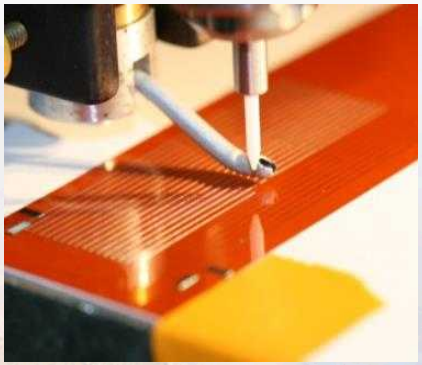
Encapsulant (DW UV-curable epoxy)
Current collector (DW carbon ink)
Anode (DW graphite/carbon)
Separator (DW mesoporous polymers)
Cathode (DW $LiFePO_4$)
Current collector (DW copper ink)
Substrate (polyimide)



"Flexible Chips" with Printed Wirebonds







Aerosol jet printing to 10 μm

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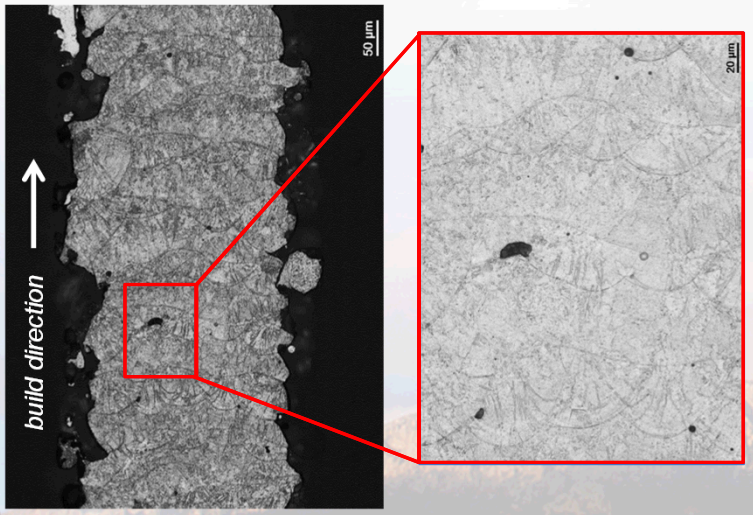
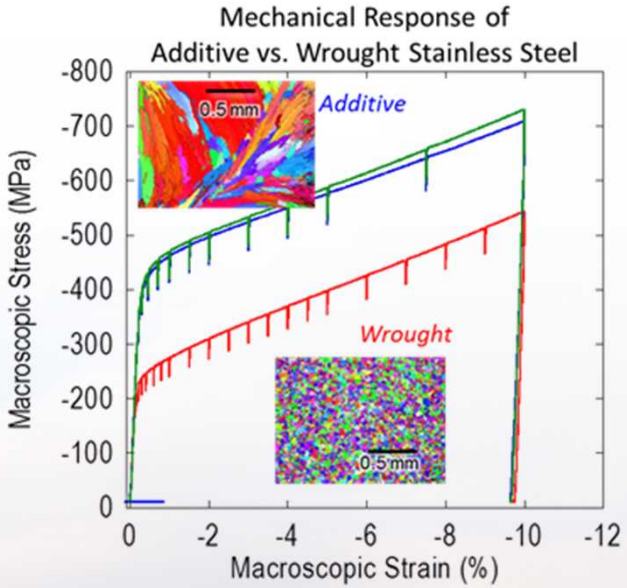
Some Technical Challenges

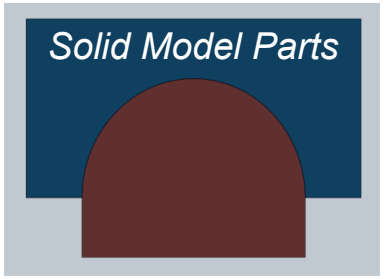
- Current Design Software Poorly Suited to AM
  - Move to Requirements-Based / Analysis-Driven Designs (Topology Optimization)
  - Need User Friendly Interface / Reasonable Computing Resources
- AM Is Still an Evolving/Emerging Technology
  - Understand Material Properties / Create Standards
  - Understand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

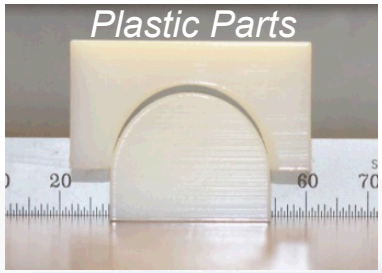


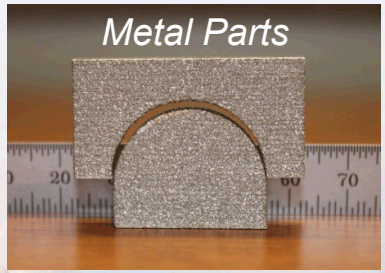
Surface & Interior Defects in 17-4 PH Stainless Steel



AM Metals are Unlike Cast or Wrought Metals







Residual Stress is an Issue

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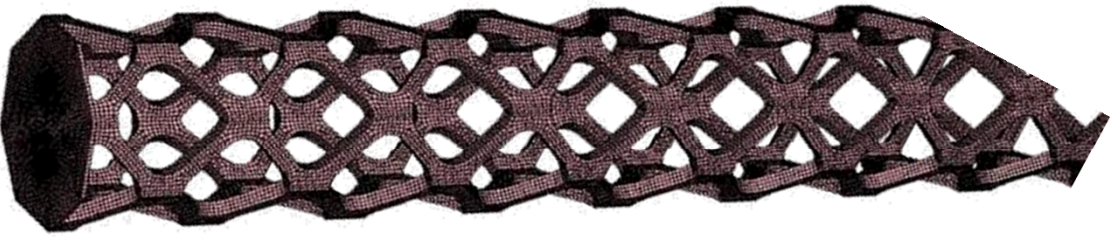
Analysis-Driven Design Optimization

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

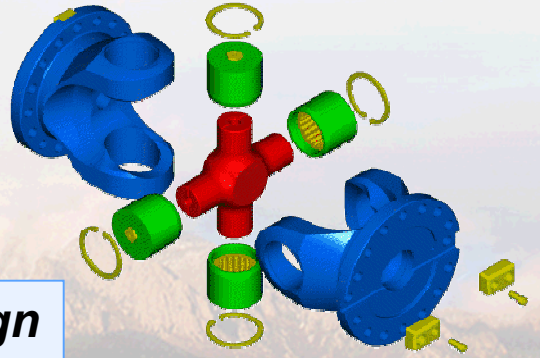
"Titanium Cholla" -- Minimum Weight, Maximum Strength, Rapidly Manufactured!



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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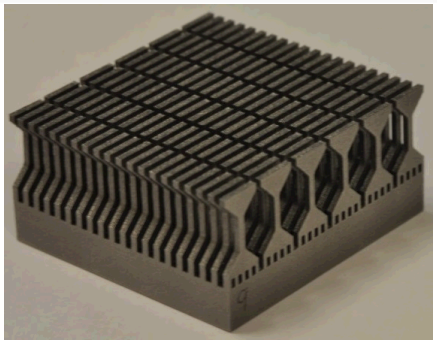
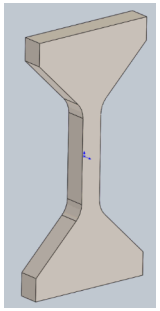
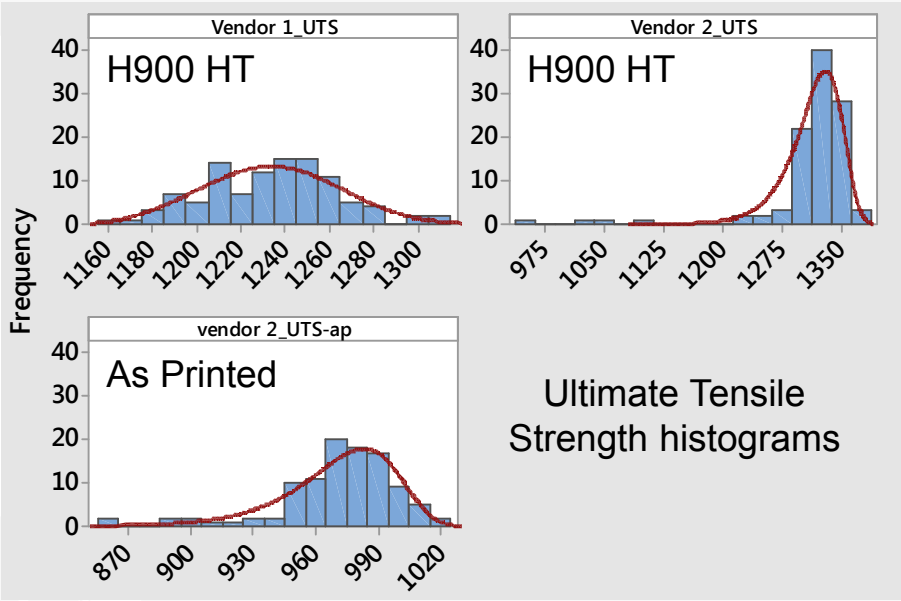
Leverage Sandia PPM to Quantify Variability/Defect Sensitivity



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

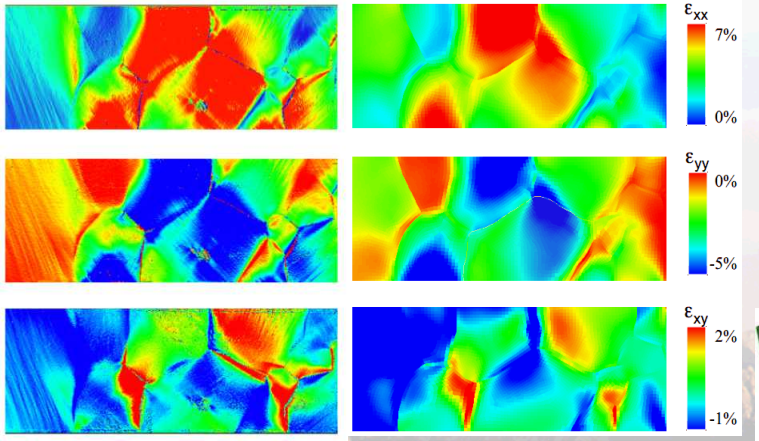


1x1 mm gage section sample



Ultimate Tensile Strength histograms

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)

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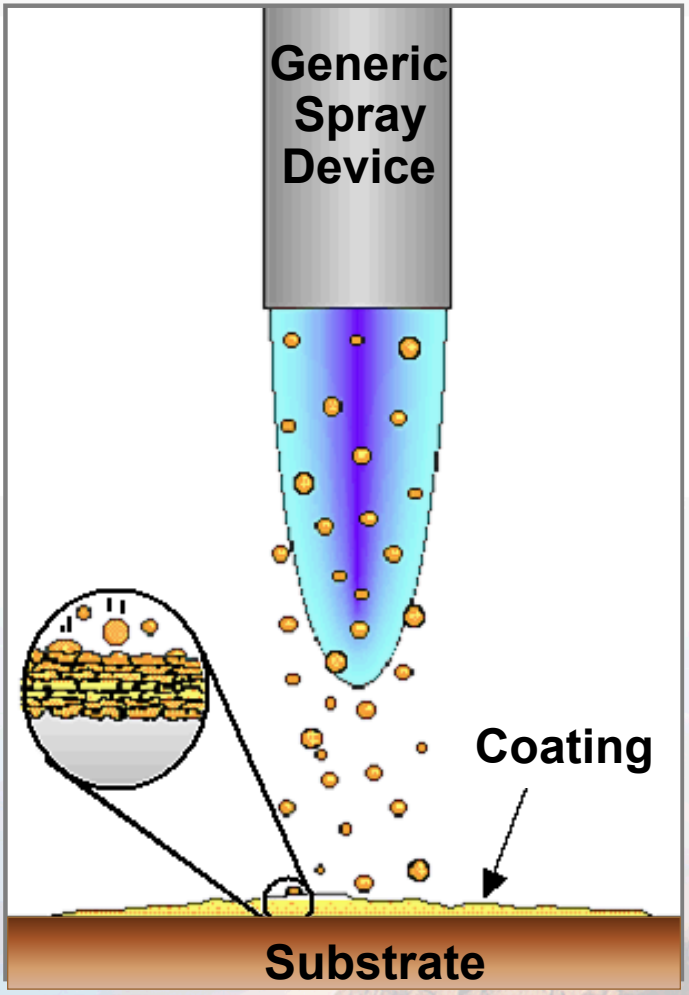
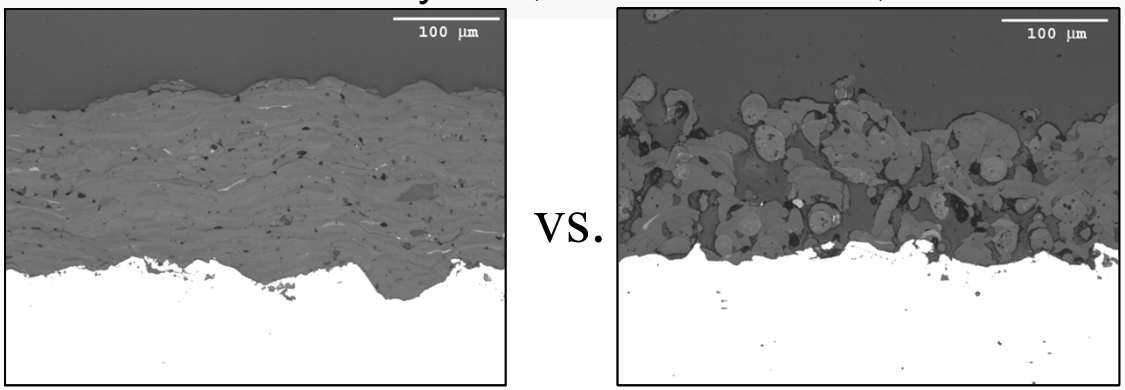
Build on Prior Success with Qualification of Another AM Process --Thermal Spray

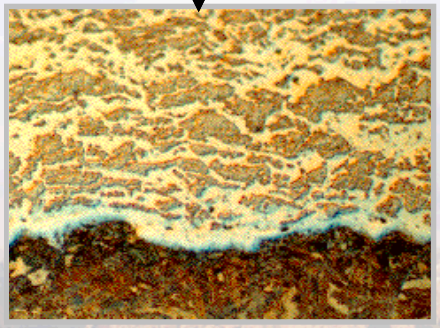


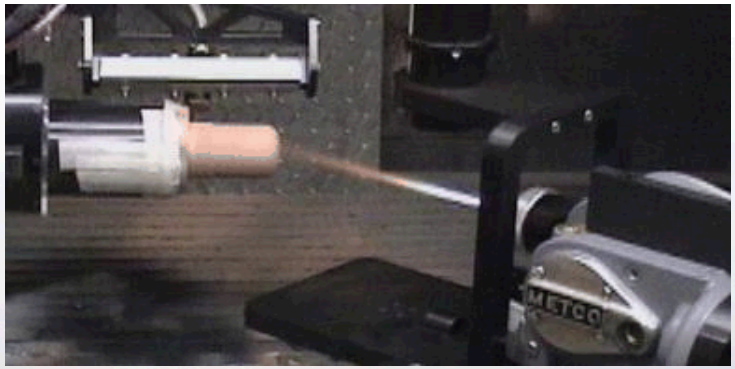
Same System, Same Feedstock,



Very Different Results

Cemented Carbide Coating On Steel





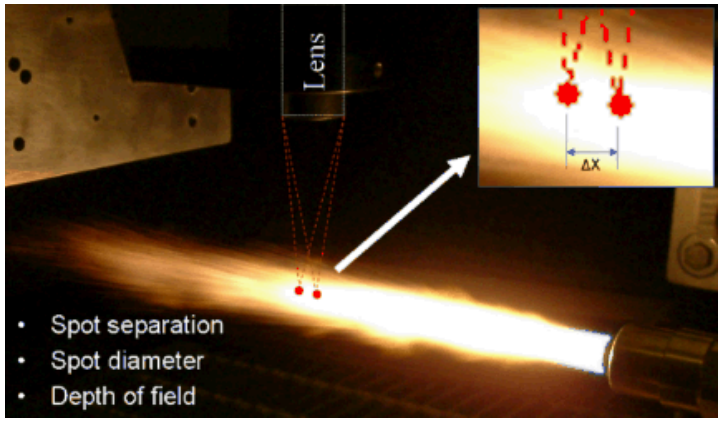
Sandia Thermal Spray Production

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

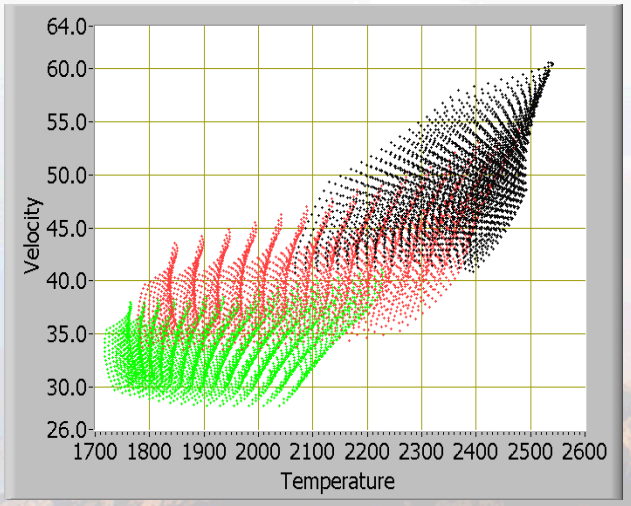
AM today is similar to Thermal Spray ~20 years ago

Fundamental Process Understanding is Key to Controlling Variability

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



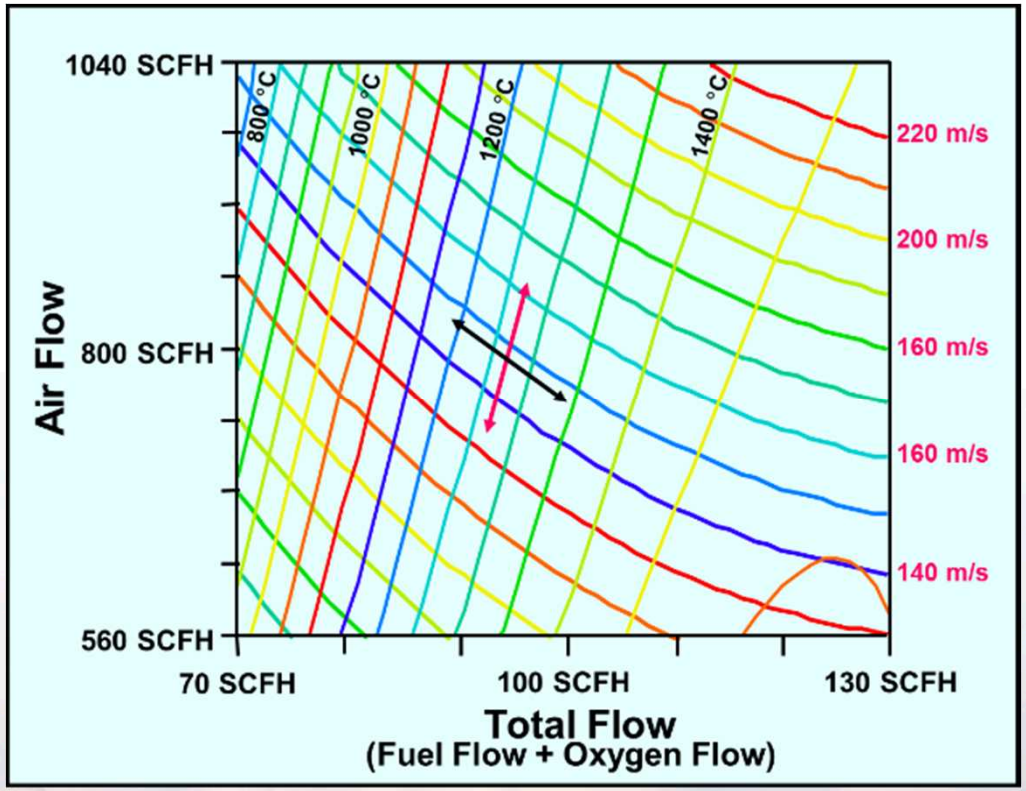
Process Diagnostics/Monitoring



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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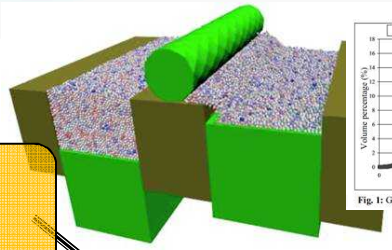
Working to Model Process → Microstructure



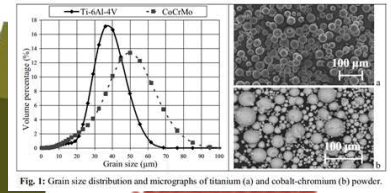
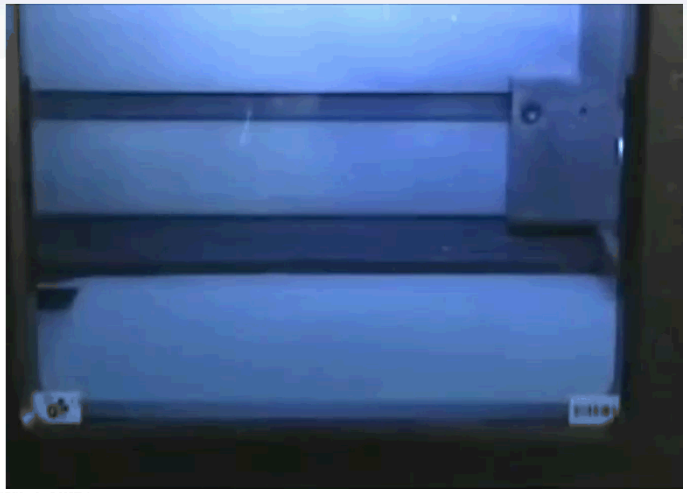
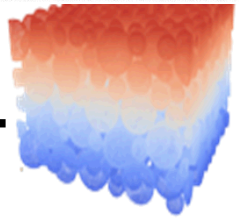


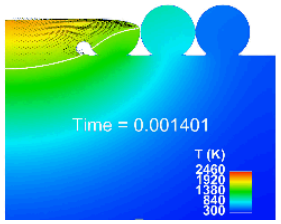
Fig. 1: Grain size distribution and micrographs of titanium (a) and cobalt-chromium (b) powder.

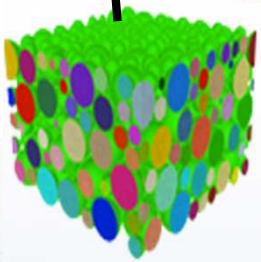


Particle packing

Particle heating

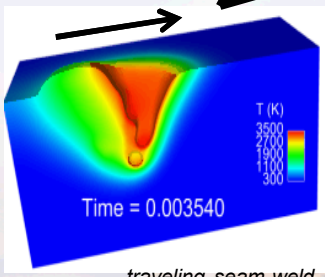






Partial melt & flow

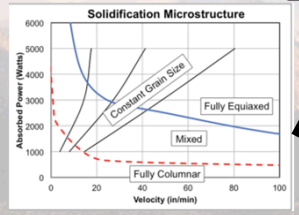
Molten pool dynamics



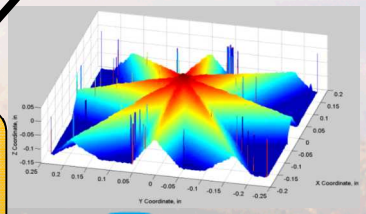
traveling seam weld

Solidification

Microstructure



Topology issues & surface finish



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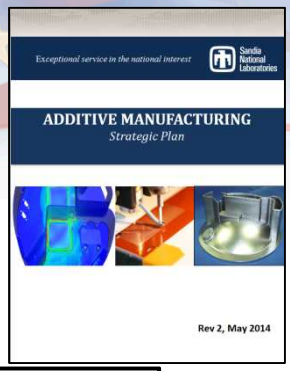
Sandia Additive Manufacturing Strategy



5 Strategic Thrust Areas

Identify Compelling Applications

Provide Design/Analysis Tools

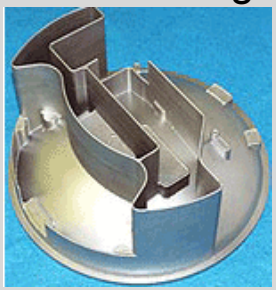
Provide Materials Assurance

Enable Engineered/Multi- Material AM

Enable Product Realization

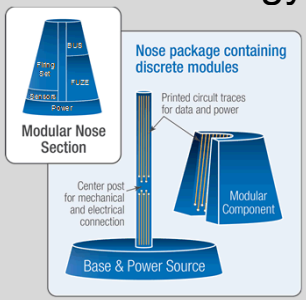
Today

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



Tomorrow

Deliver innovative, revolutionary national security products enabled by AM technology

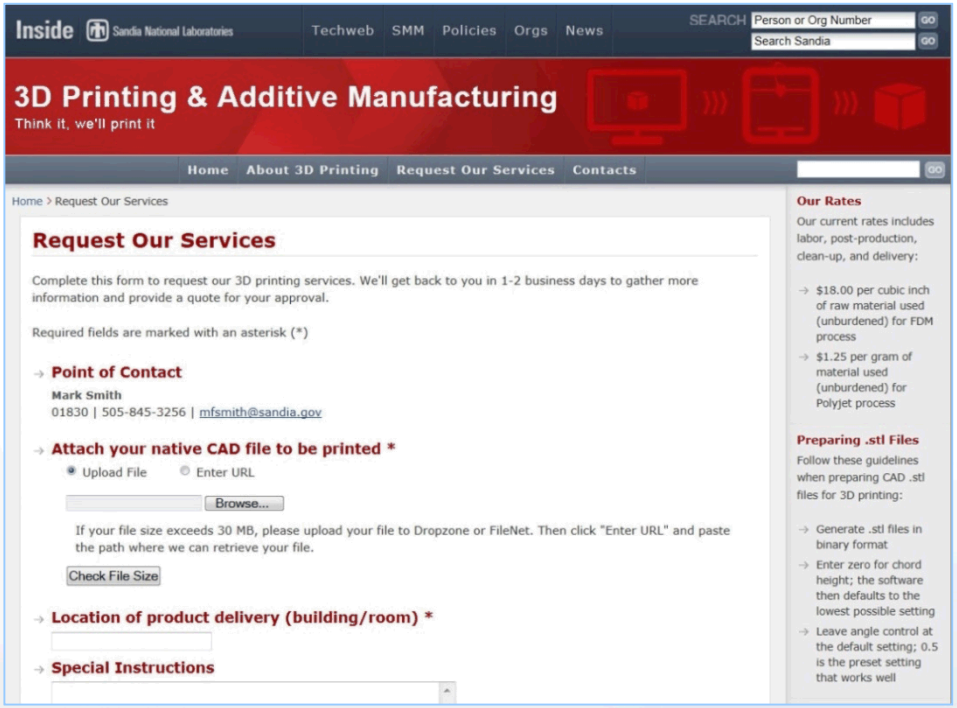


Sandia National Laboratories

Plastic AM Machines

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

http://3dprinting.sandia.gov/



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

Sandia National Laboratories

Metal &Multi-Material AM Machines

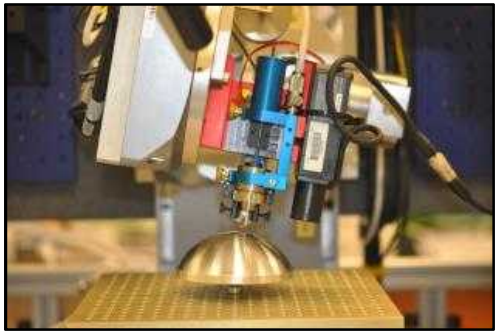
Commercial LENS® & Custom Built Additive/Subtractive LENS® Systems

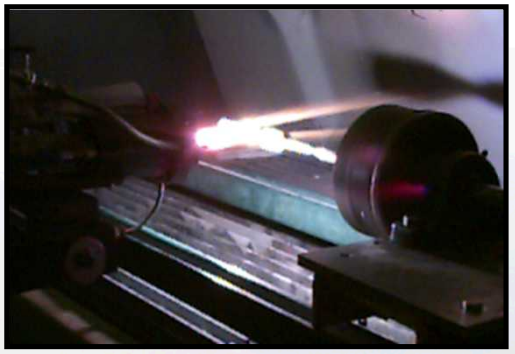
- Graded or layered metals
- High degree of microstructure control

Commercial Metal Powder Bed Laser Systems

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

Multi-axis Direct Write & MicroJet Systems + Spray Form





- Organics/Metals/Ceramics
- Energetic Materials
- Shapes, Sensors, Wiring Boards, Electronics, …

Sandia National Laboratories

Snapshot of activities at Sandia

Sandia National Laboratories

- Large variety of rapid prototyping across many departments at Sandia; used for design, training, prototyping, tooling
- Thermal spray processes—both used for custom Sandia products with quality requirements; R&D including alumina deposition, gradient interfaces
- Microelectronics, MEMS, optical/acousto-optical—both production and R&D activities
- LENS and metal powder bed—R&D including integration of modeling, design/topological optimization, materials science, qualification & uncertainty quantification, verification, validation
- R&D funded both through program (higher technological readiness level and directed by customer) and LDRD (competitive internal program, ~6% of total SNL budget for all LDRD areas)