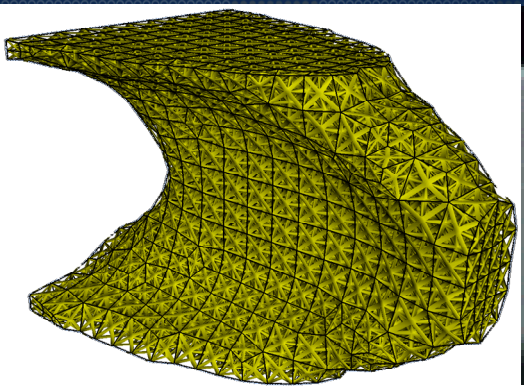
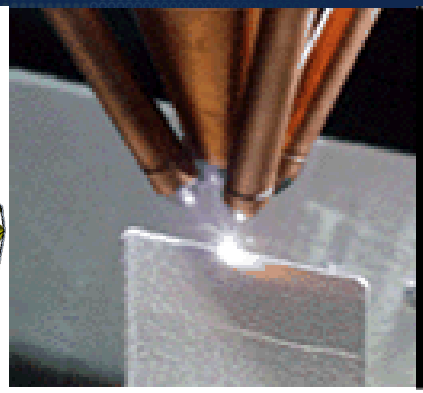
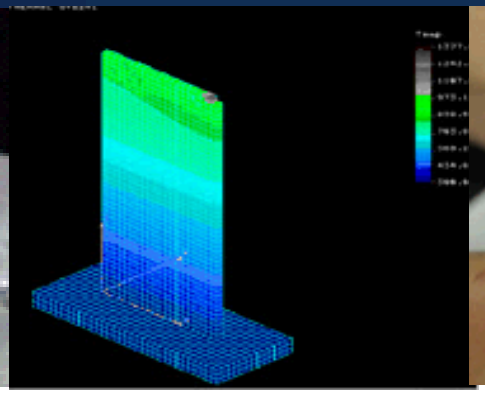
SAND2017-5897C


Additive Manufacturing -- A New World of Opportunities and Challenges

Mark F. Smith
Deputy Director for Additive Manufacturing
Materials Science & Engineering Center
Sandia National Laboratories
ph: 505-845-3256 email: mfsmith@sandia.gov

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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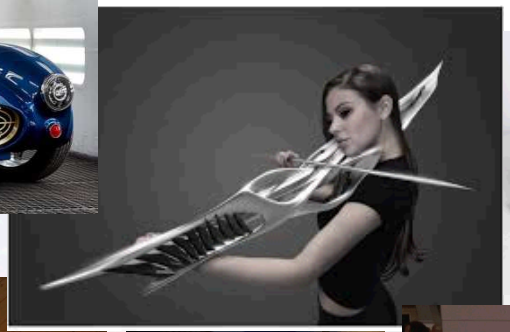
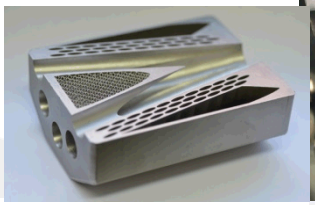
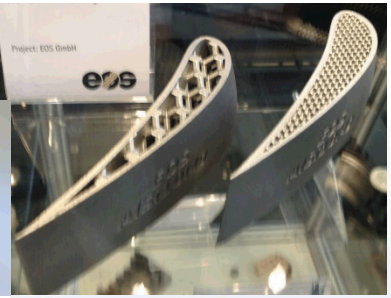
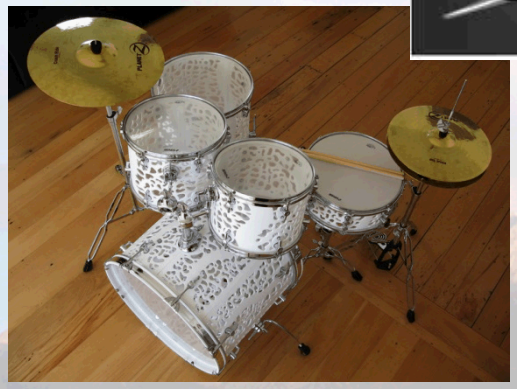
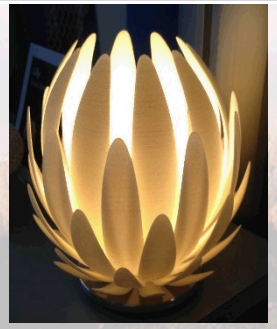
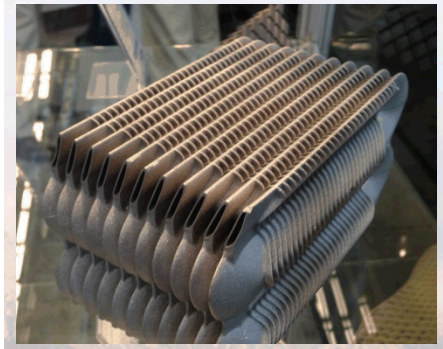
Overview

- *Additive Manufacturing in the Global Marketplace*
- *Additive Manufacturing Processes*
- *Potential Advantages*
- *Potential Limitations*
- *A Brief Look to the Future*

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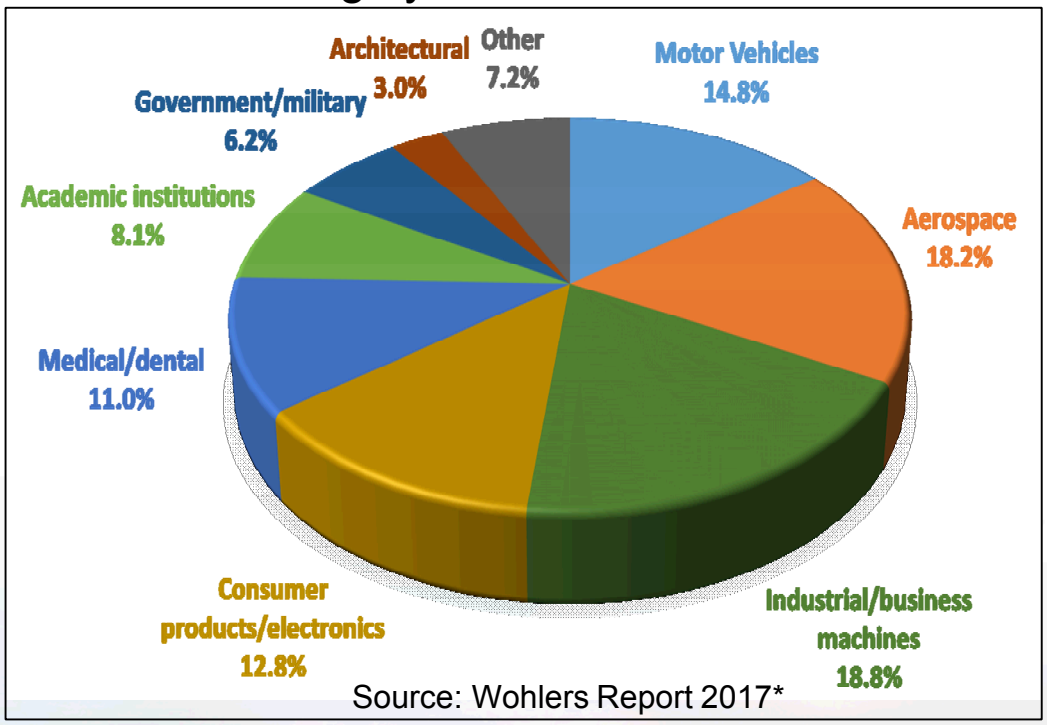
The Market for AM is Broad & Growing

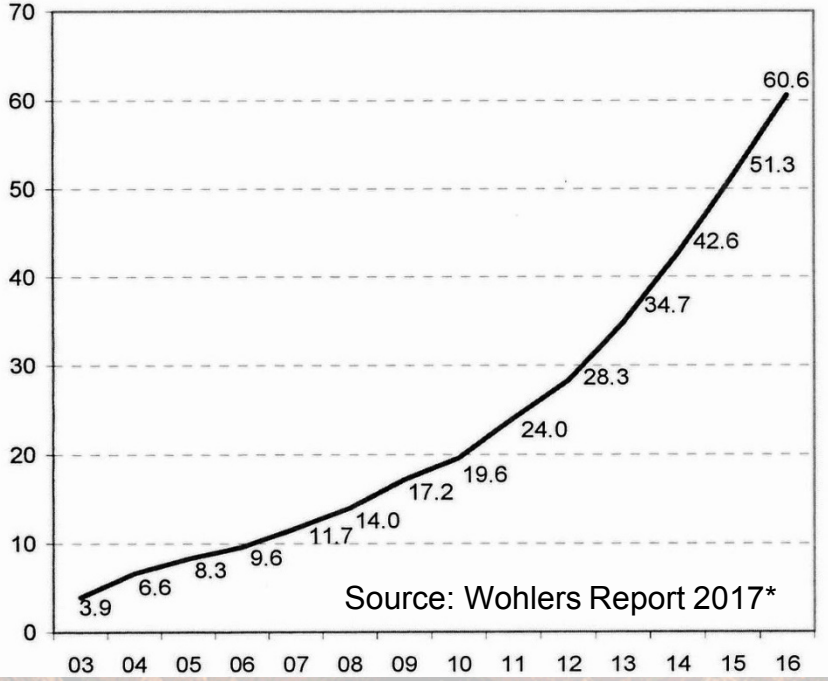
AM Has A Highly Diversified Market Base



Source: Wohlers Report 2017*

Use of AM for Part *Production* Grew More Than15 Fold From 2003 to 2016

(% of total AM product/service revenue)



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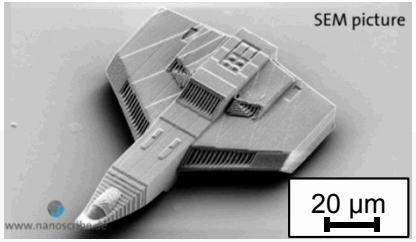
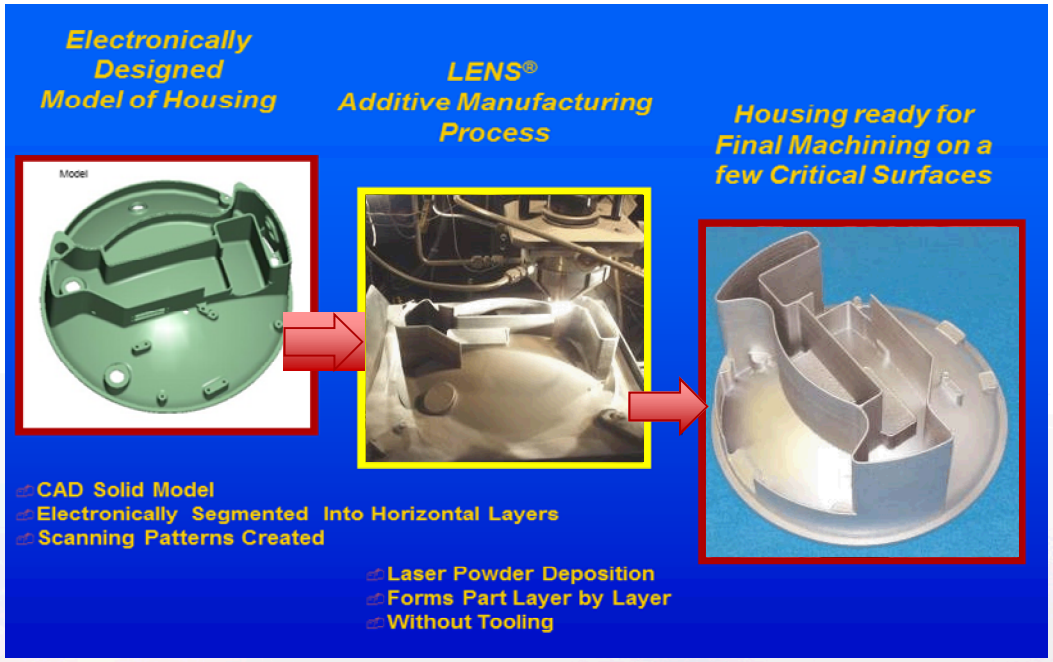
Additive Manufacturing -- A Wide Range of Processes, Sizes, & Materials

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* – Commercial Use, Relatively Mature
- *Metals* – Commercial Use, But Still Relatively Immature & Rapidly Evolving
- *Ceramics* – Commercial Use, but Limited Applications at Present
- *Multi-Material* – Great Potential, Needs Further Development

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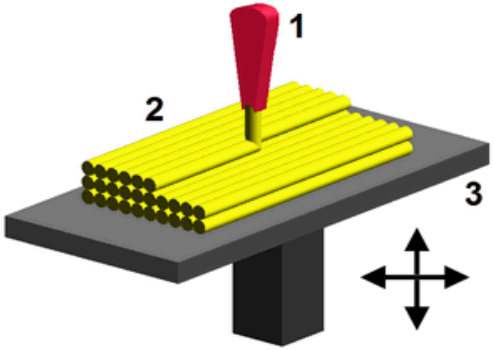
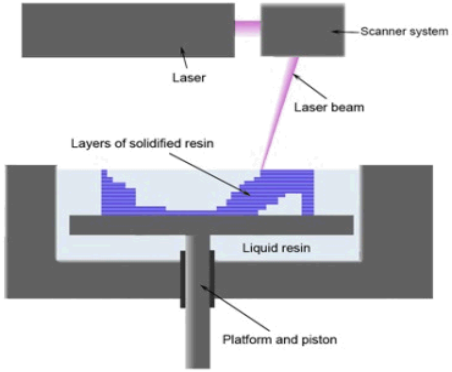
7 ASTM Additive Manufacturing "Process Categories"

Material Extrusion (e.g., FDM, Direct Write)
Thermoplastics, Metal/Ceramic Inks



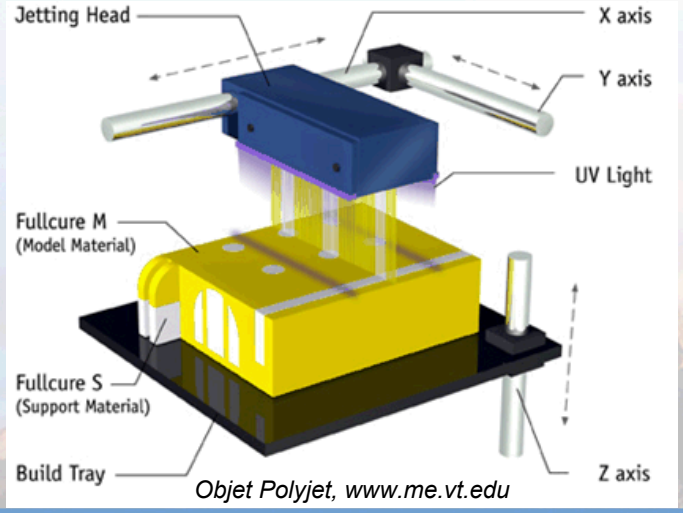
"Fused Deposition Modelling", Wikipedia

Vat Photo-Polymerization (e.g., SLA, Stereolithography)
Photopolymers, Epoxies (Investment Casting Patterns)



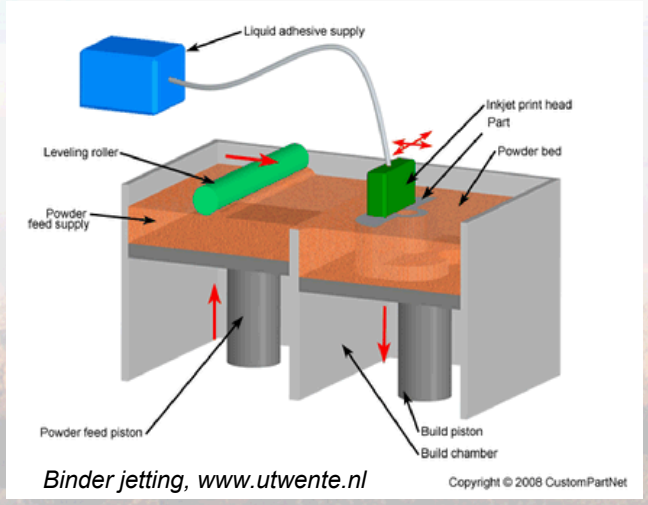
"Stereolithography", Wikipedia

Material Jetting (e.g., "ink jetting" plastic)
UV Cure Photopolymers



Objet Polyjet, www.me.vt.edu

Binder Jet (2 step process, Print then Infuse)
Plastics, Metals (composite)



Binder jetting, www.utwente.nl

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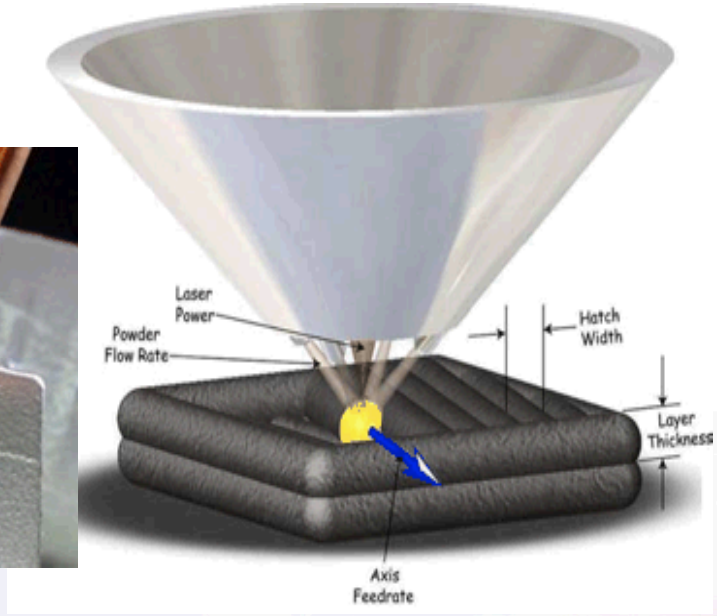
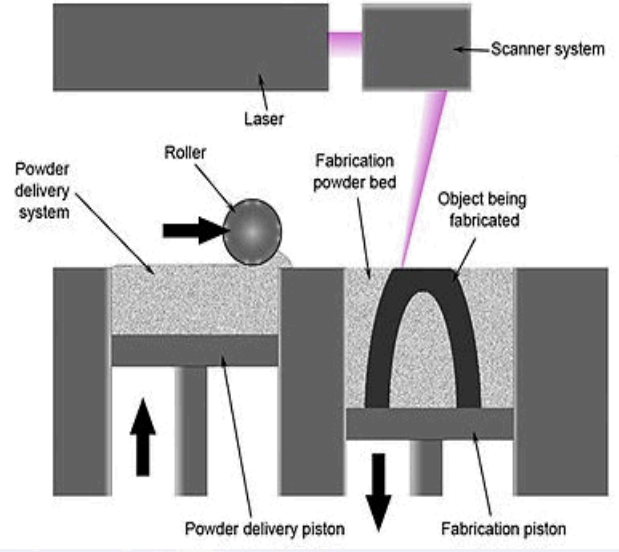
7 ASTM Additive Mfg. "Process Categories"

Directed Energy Deposition (e.g., LENS®)
Metals, Ceramics?

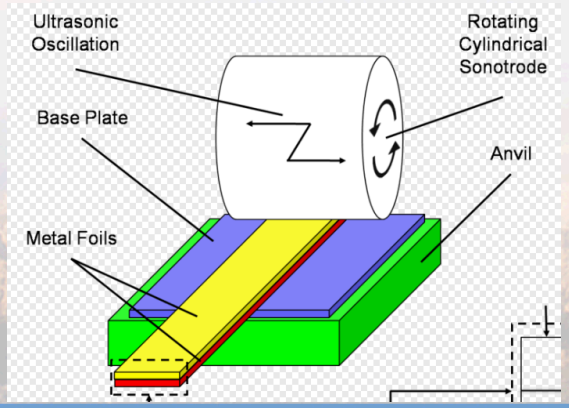


Powder Bed Fusion (Laser or e-Beam)
Thermoplastics, Metals, Ceramics?



"Selective laser melting", Wikipedia

Sheet Lamination (Ultrasonic, low temp)
Multi-Material Composites



"Ultrasonic consolidation", Wikipedia

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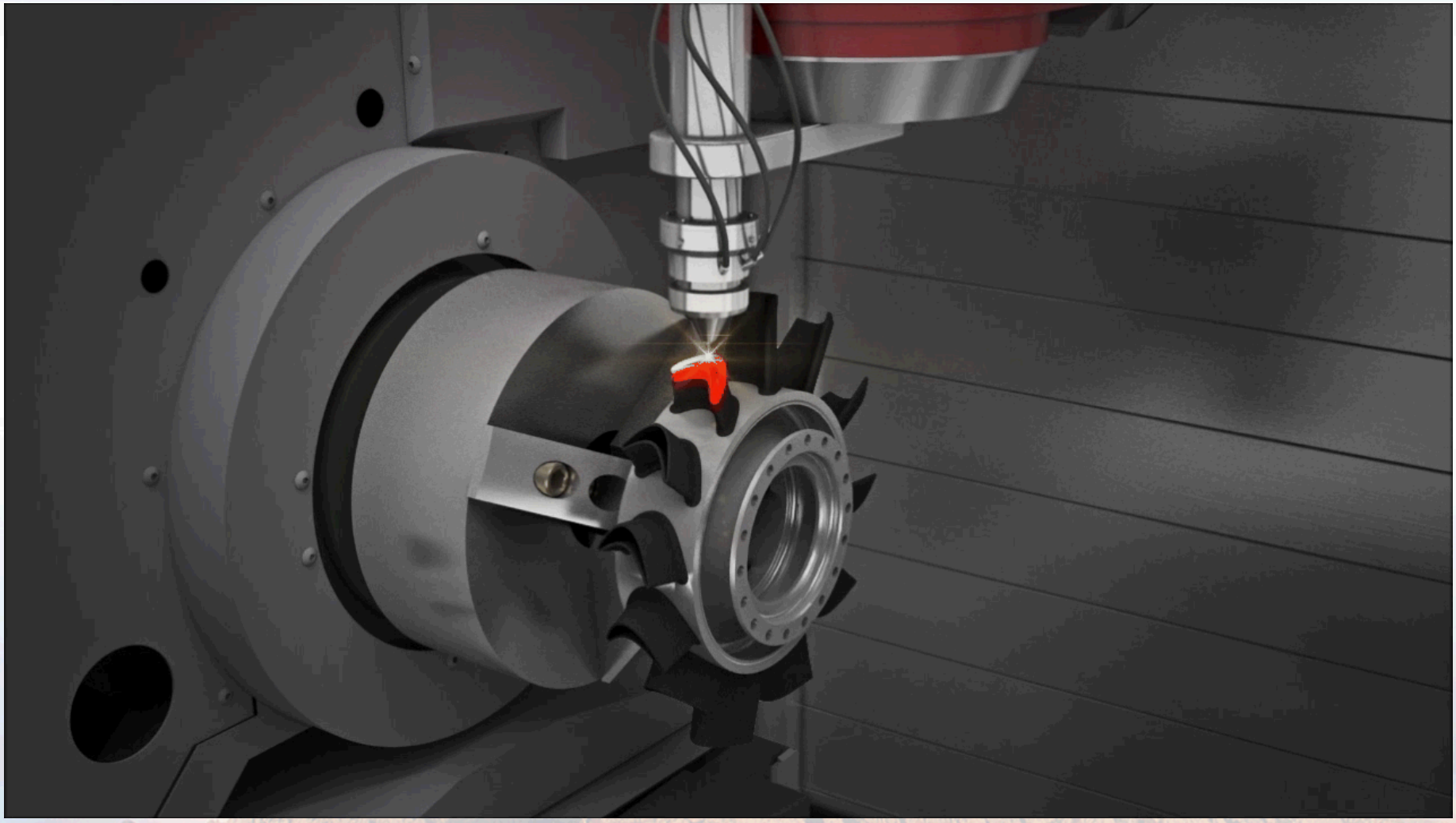
"Hybrid" Additive/Subtractive Machine Tools



Video Courtesy of DMG Mori

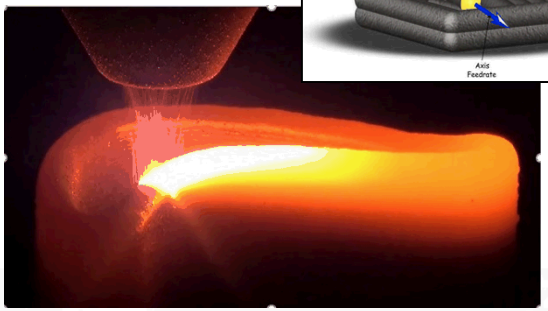
30+ Years of Sandia AM Technology Development & Commercialization

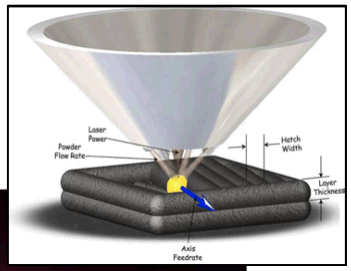
FastCast *
Development Housing

Laser Engineered Net Shaping *

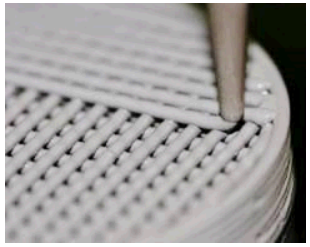
LENS®

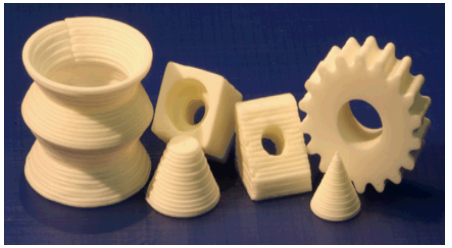
LENS Blade





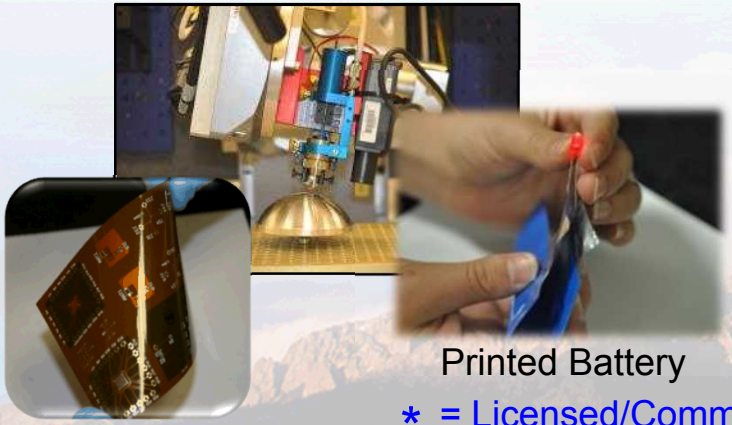
RoboCast *
Ceramic Parts





Energetic Materials

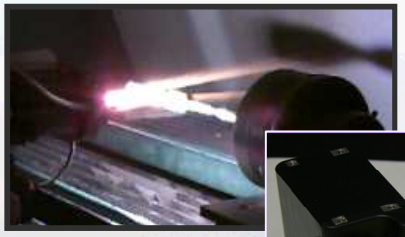
Direct Write
Conformal Printing



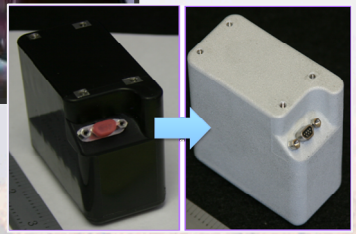
Flexible Electronics

Printed Battery

Thermal Spray

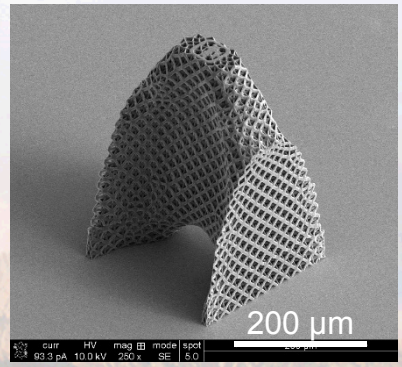


Spray-formed Rocket Nozzle



Metal on Plastic

Micro-Nano Scale AM
Lattice Structure



* = Licensed/Commercialized Sandia AM technologies

Underline = *Current Capability/Activity*

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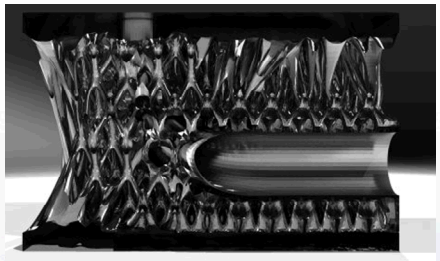
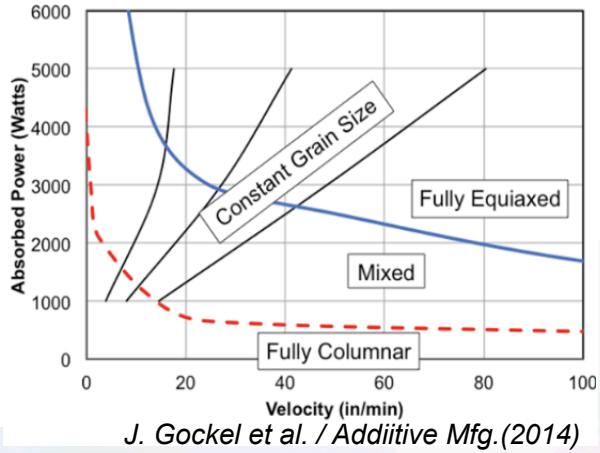
Why Use AM?
Some Potential Advantages

- Rapid/Inexpensive prototypes, cycles of learning, tooling, etc.
- Save Time, Money, Weight, Energy
- Design Freedom – shapes previously unachievable/impractical
- Print Integrated Assemblies
- "Designer" Materials – custom engineer material properties

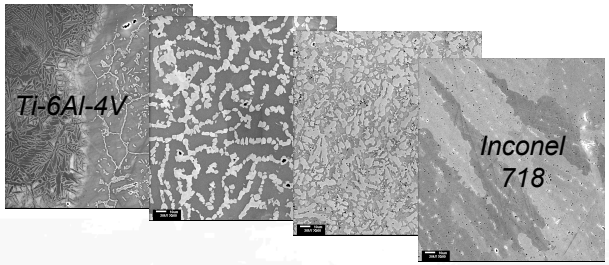
New Design Possibilities
(Within Technologies)



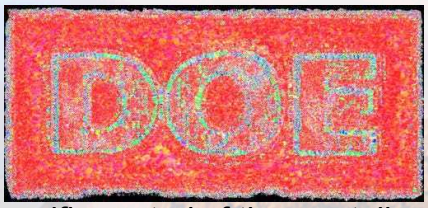


J. Gockel et al. / Additive Mfg.(2014)

Locally Control Grain Size & Morphology



LENS® functionally graded materials



Site specific control of the crystallographic orientation of grains within metal components
(Mfg. Demonstration Facility, ORNL)

Multi-Materials on a Single Printer

Printed Gear Assembly

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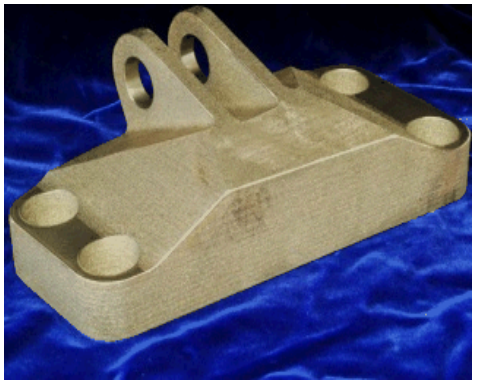
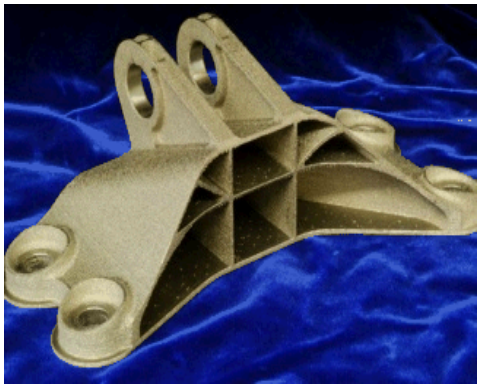
Commercial Aerospace Hardware

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

- ***Replaces 18 parts with 1 – ZERO joining operations***
- ***Internal geometry can't be built with traditional mfg.***
- ***25% lighter, 5x more durable, reduced NOX emissions***
- 19 fuel nozzles per engine, Plan to build 40,000 nozzles/yr
- New $50M Mfg. Plant, Auburn, AL

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*CFM is a 50/50 Snecma/GE Company

3D Printed Automobiles

Oak Ridge National Lab/Cincinnati Inc.
50th Anniversary "BAAM" Shelby Cobra

Local Motors
Design Competition
Winner

Local Motors
"Rally Fighter"

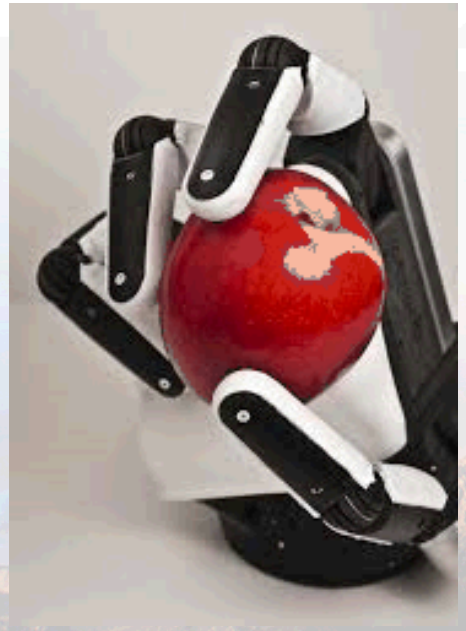
Sandia National Laboratories

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
- Current version has “touch” sensors

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



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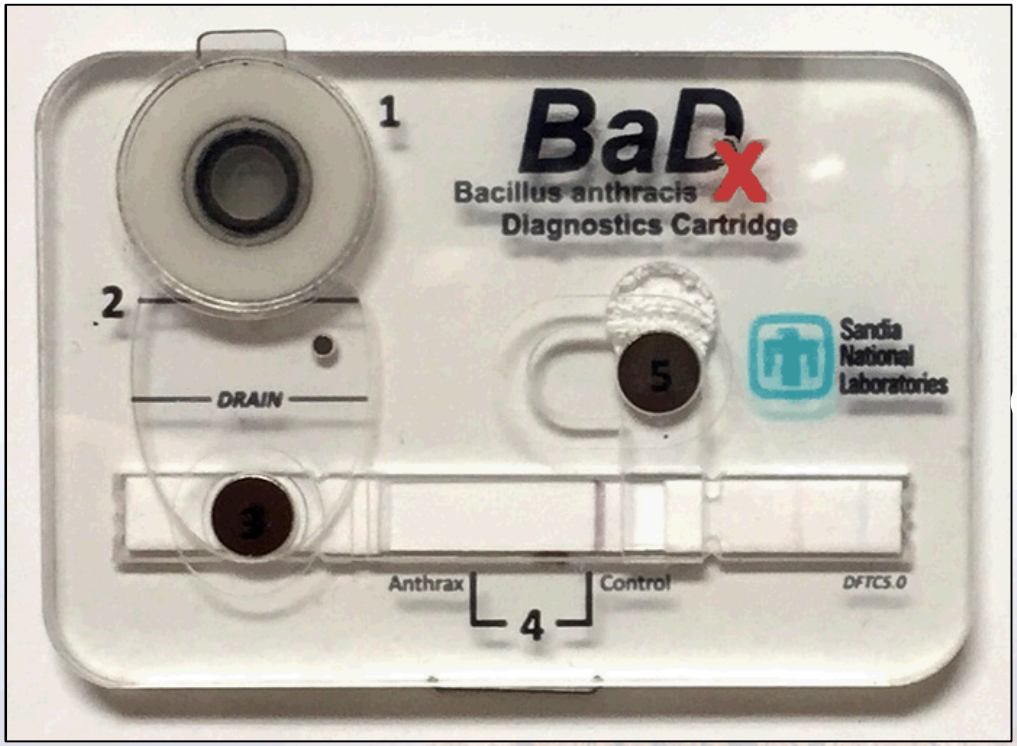
BaDx Anthrax Diagnostics Tool

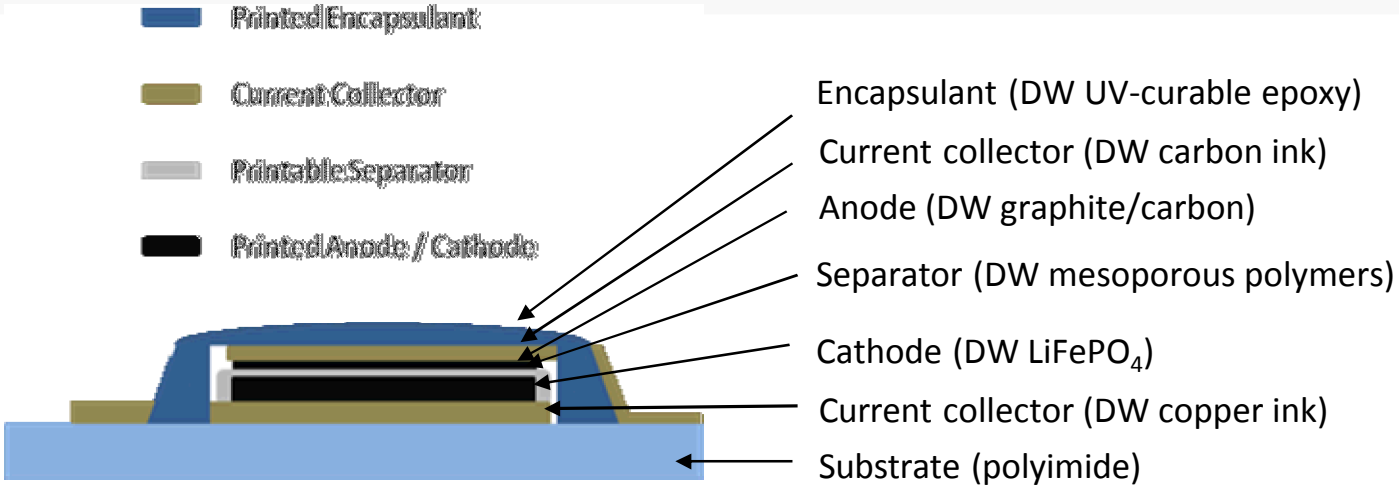
- Microfluidic platform for bacterial detection
- Rapid/inexpensive prototyping & design revisions
- Self-contained, credit card-sized “Lab in a Pocket”



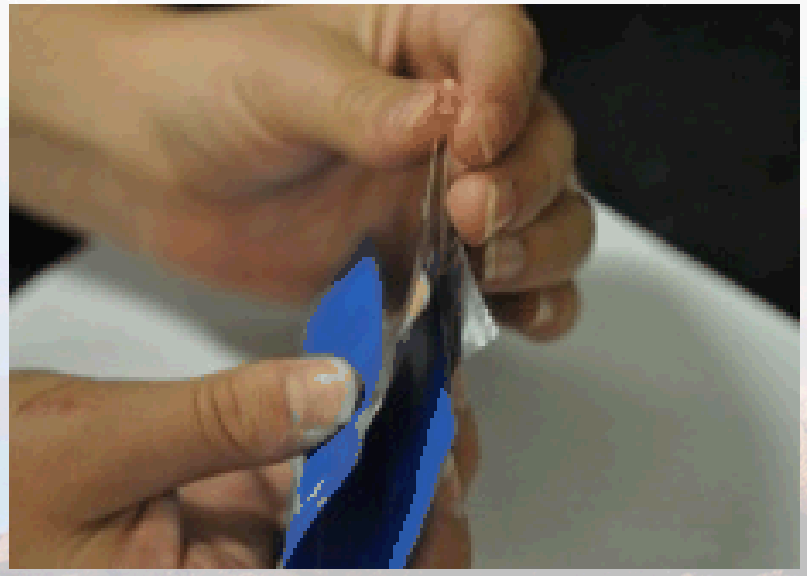
SNL Scientists Jason Harper, Melissa Finley, and Thayne Edwards

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

3D Printed Flexible Battery



Roll-to-Roll Printed Electronics



Cleveland Clinic Prosthetics

ALLELES Design Studio, CA

Sandia National Laboratories

Analysis Driven Design

Analysis-Driven Design Optimization

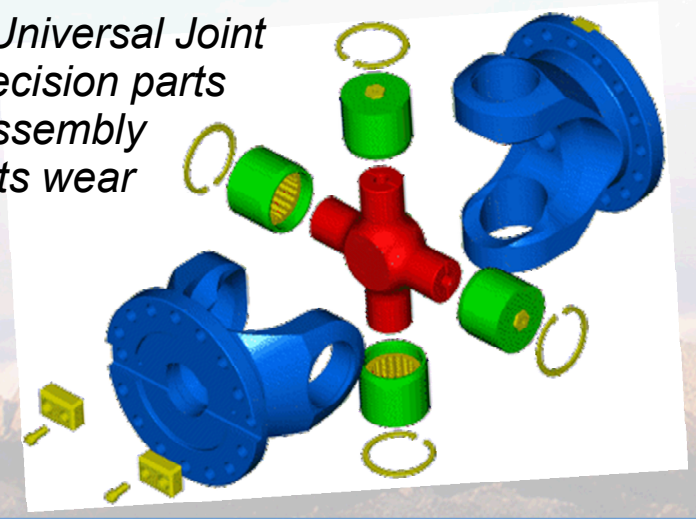
We combined Topological Optimization (TO) with eXtended Finite Element Modeling (X-FEM) & LENS® to optimize selected properties, e.g., strength/weight ratio.

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

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

Dead Cholla cactus. TO designs often resemble natural structures (bio-mimicry).

Conventional Universal Joint
- *Many hi-precision parts*
- *Complex assembly*
- *Moving parts wear*



"Loxosphere"
- *1 piece*
- *No assembly*
- *No moving parts*

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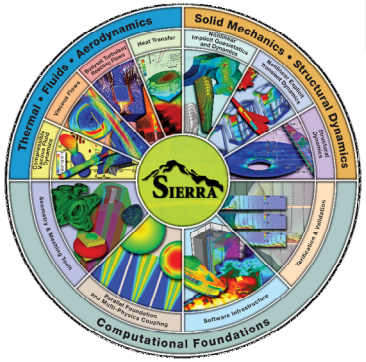
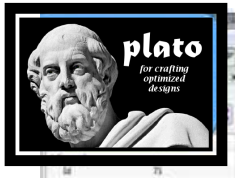
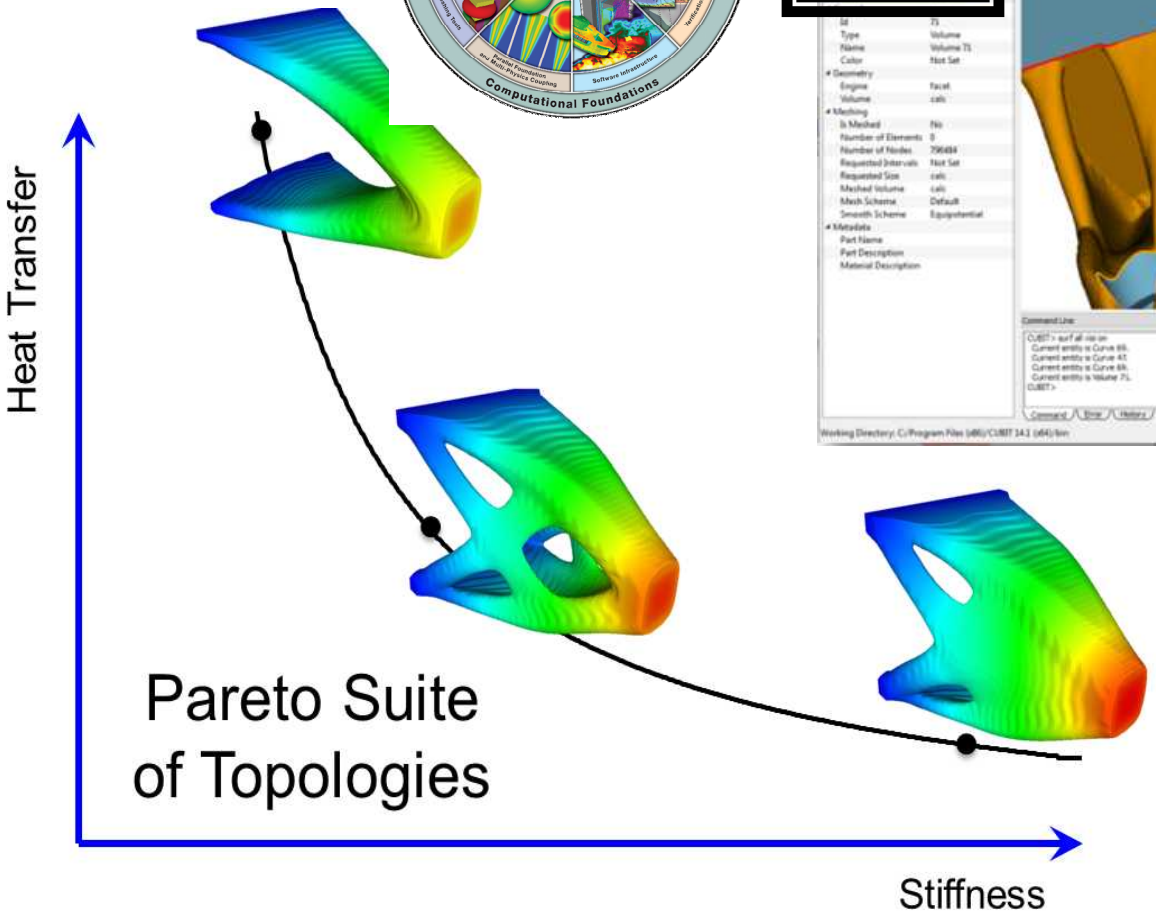
AM Design Via Functional Prioritization

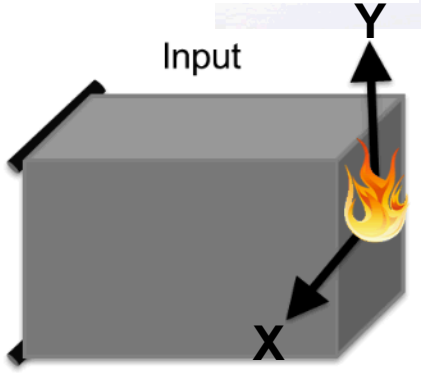


User-Friendly GUI Interface

PLATO - PLAtform for Topology Optimization







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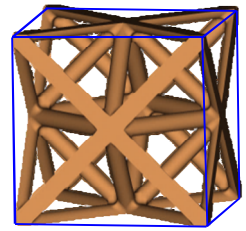
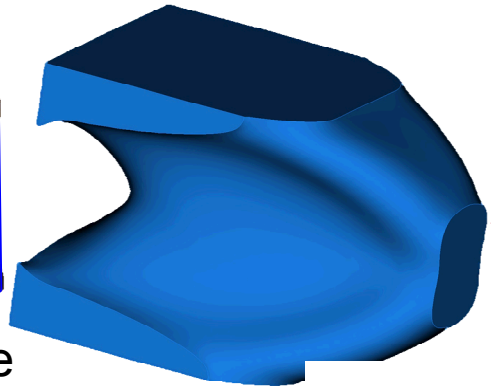
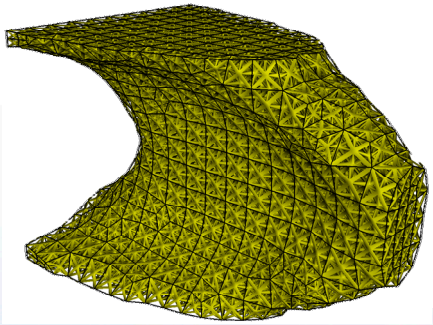
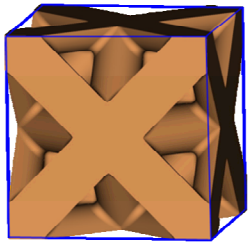
Optimizing Stiffness at Fixed Mass



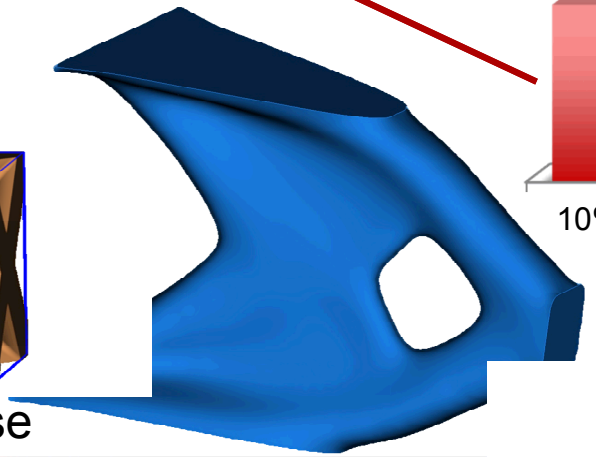


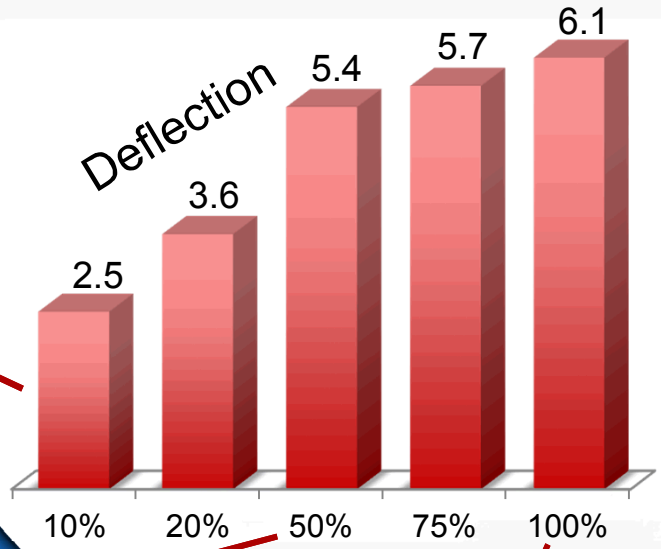
10% Dense

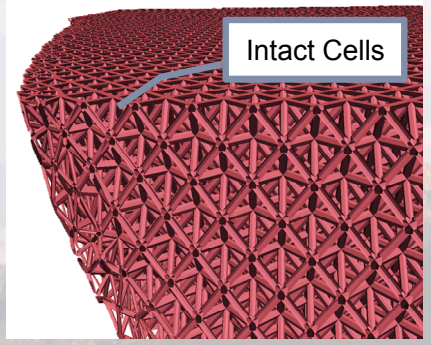


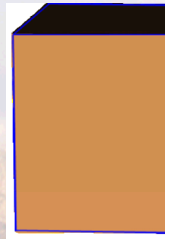


50% Dense

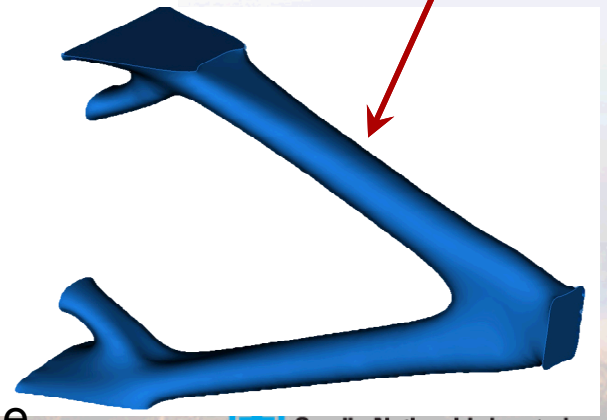








100% Dense



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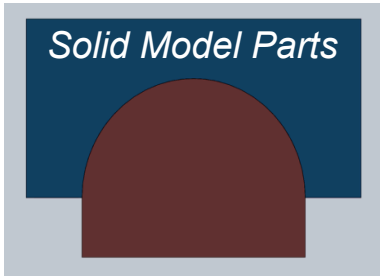
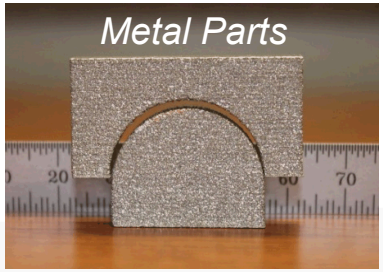
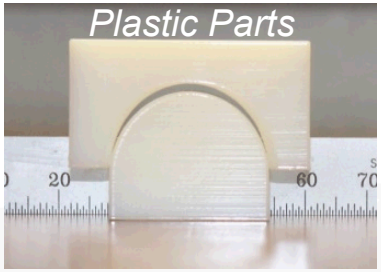
Why Not Additive?
Some Potential Disadvantages/Limitations

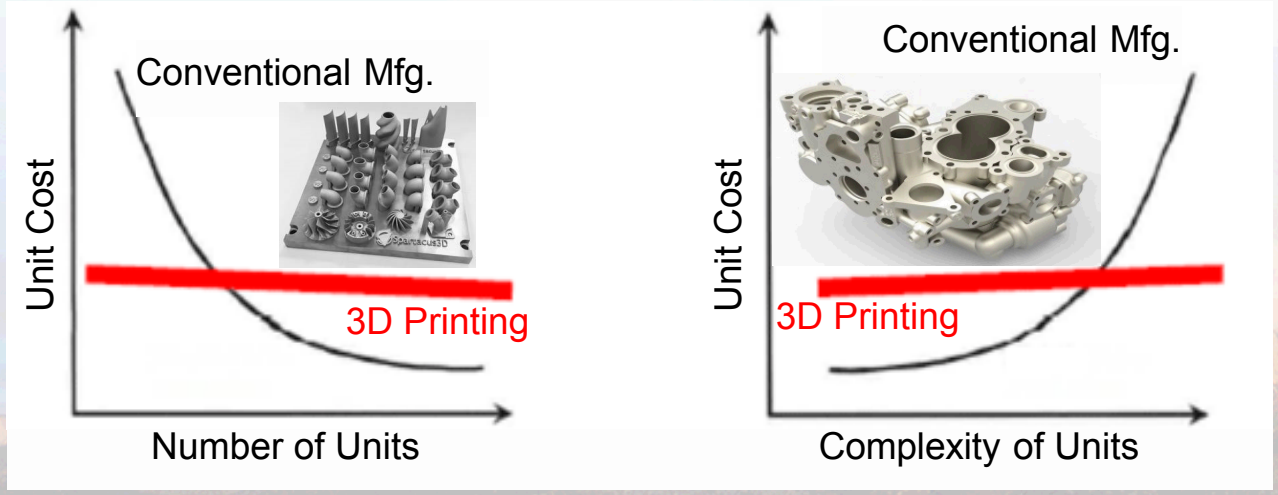
- AM Is Still an Evolving/Emerging Technology
- Many Sources of Variability – Most Machines Run "Open Loop"
- Material is "Built" Along with the Part – Is It Good?
- Lack of Engineering Data/Standards for Designers
- There ARE Design Constraints/Design Software Limitations
- Inspection, Tolerances, Surface Finish, Residual Stress
- Additional Support Equipment Req'd
- AM Isn't Always Faster/Cheaper







Notional Cost vs. Volume & Cost vs. Complexity Charts



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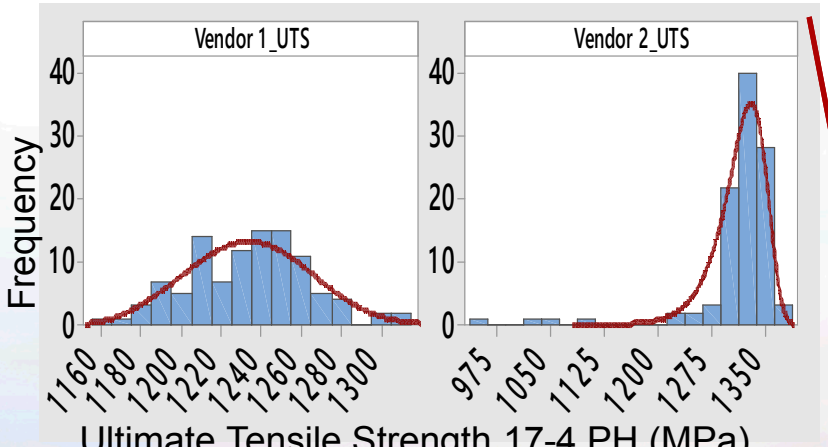
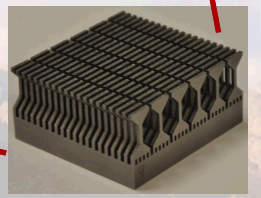
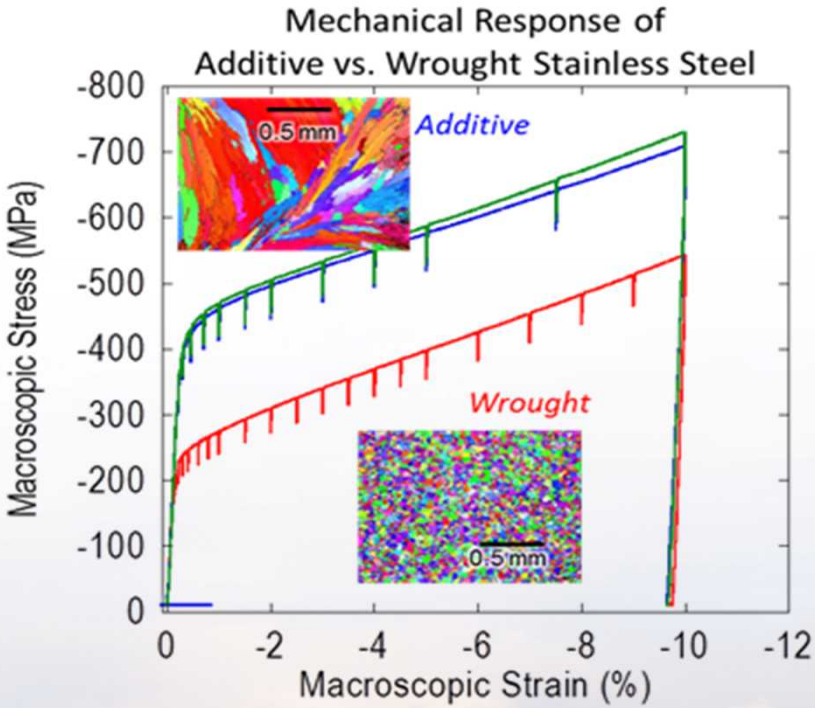
Materials Properties, Residual Stress, and Tolerances are Important Issues

- Materials Properties/Reliability Are Important Issues
  - Little Available Materials Property/Performance Data (no standards)
  - Large Variability in Process and Materials

Variability in Materials Properties







AM Metals are Unlike Cast or Wrought Metals

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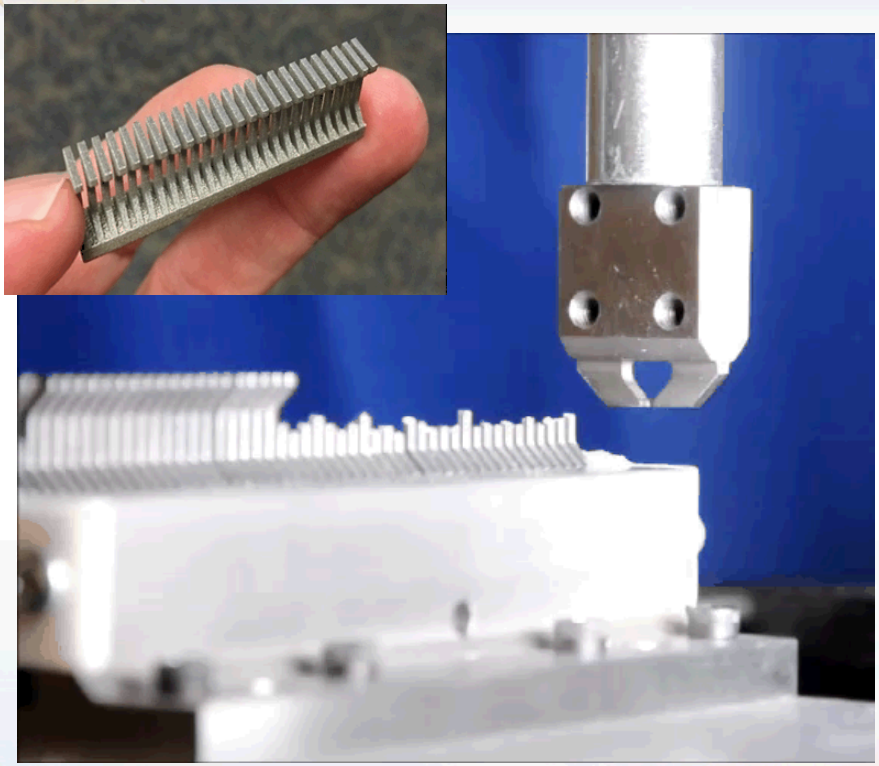
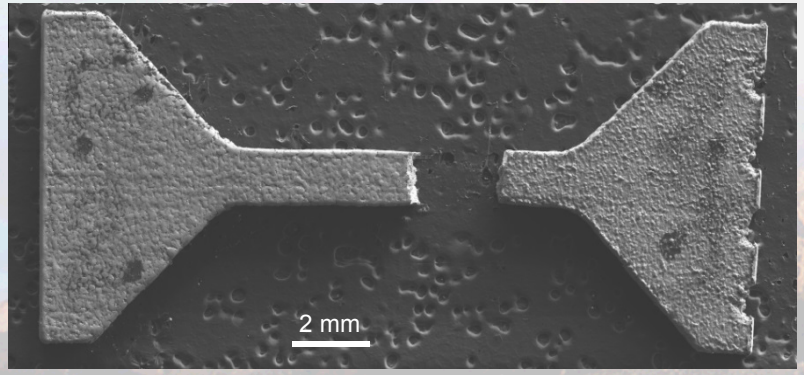
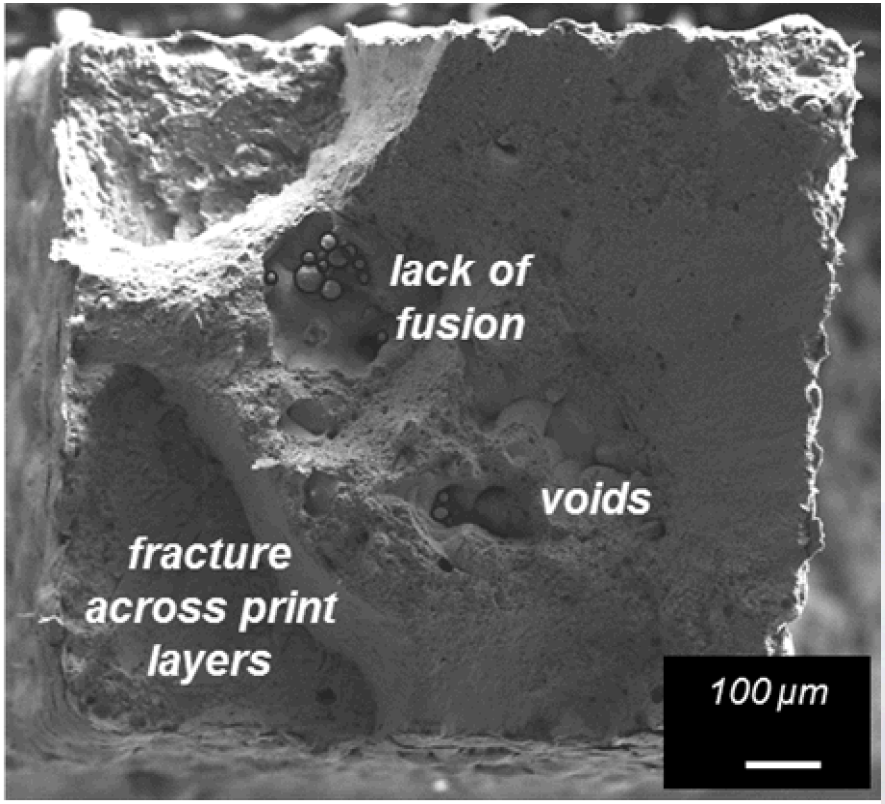
Materials Assurance

High-Throughput Tensile Testing





17-4 PH SS, H900 “brittle” fracture



Failure at 2% elongation

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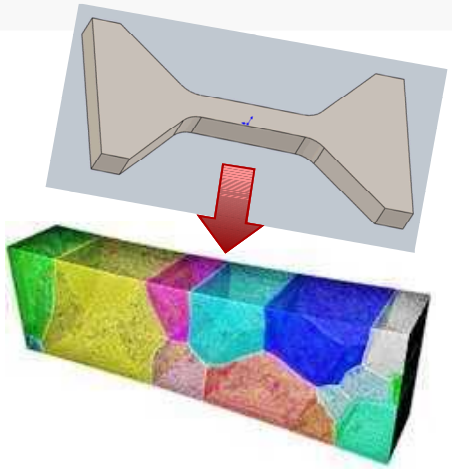
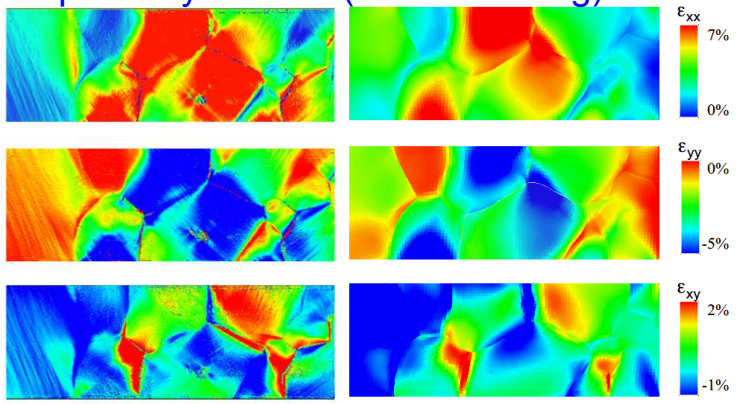
R&D to Investigate AM Material Variability/Defect Sensitivity

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)

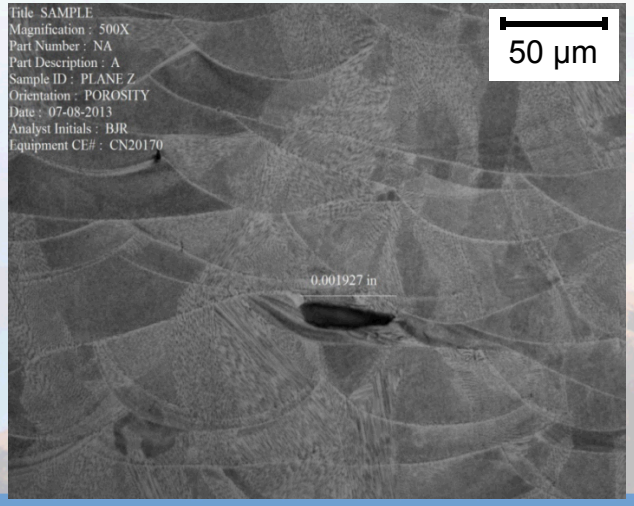


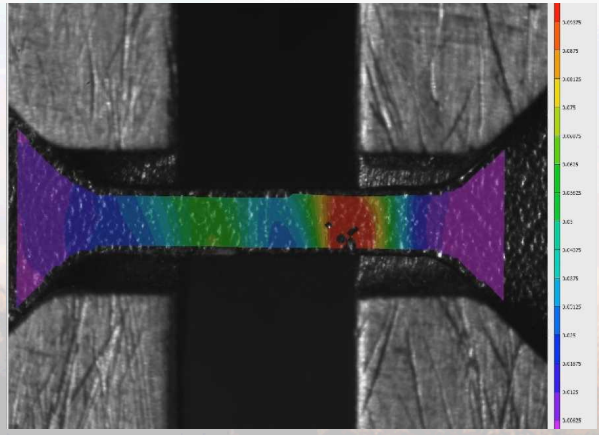
Experimental Results | **Computed Simulations**

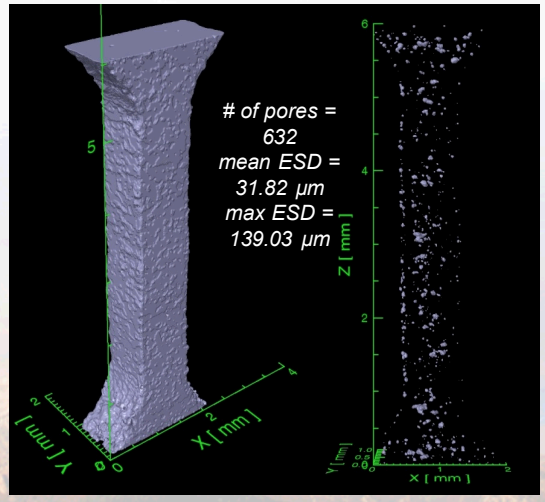
Key Questions:

What AM Defects Matter?

Can I detect them?







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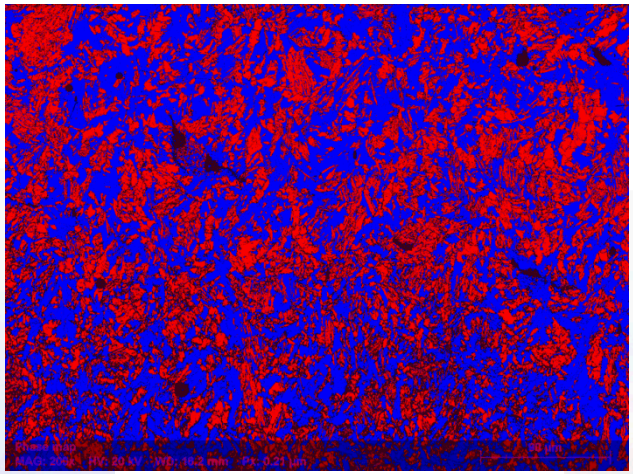
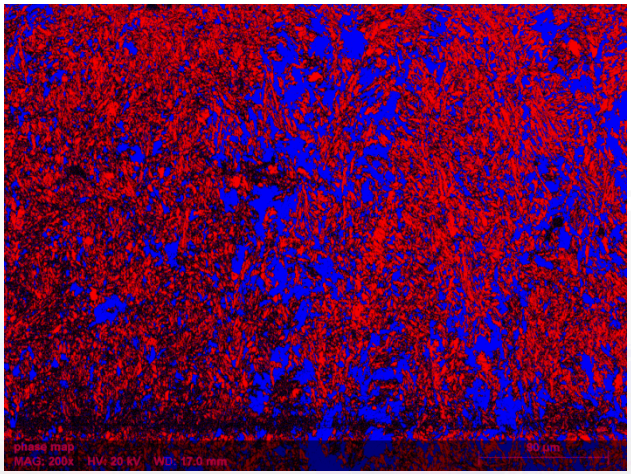
Retained Austenite in 17-4 PH Stainless When Using Nitrogen Gas Atomized Powder

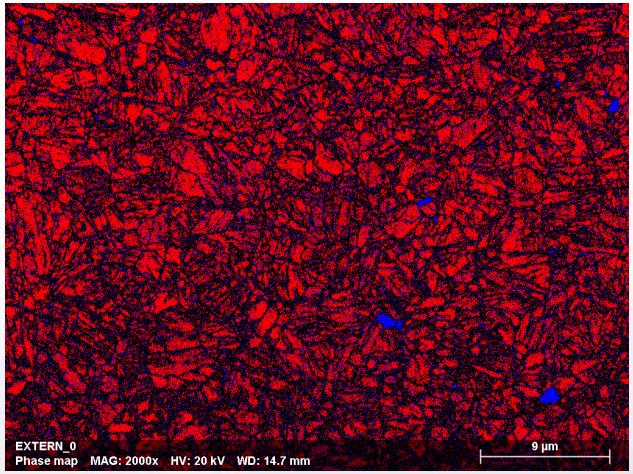
- Anomalous phase composition in AM vs. wrought 17-4 PH Stainless
  - Large fraction of retained austenite after solution heat treatment + H900 age
  - Cryo treatment to -196°C for 5 min still does not transform austenite



As-printed, 47% Austenite



SHT + H900 Age, 43% Austenite



Wrought Sheet Shows Fine-grained Martensite

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

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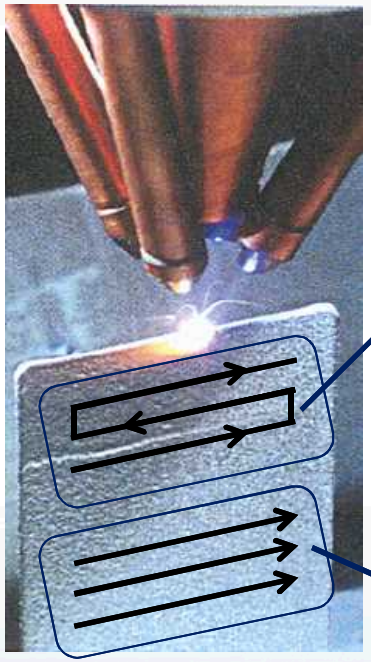
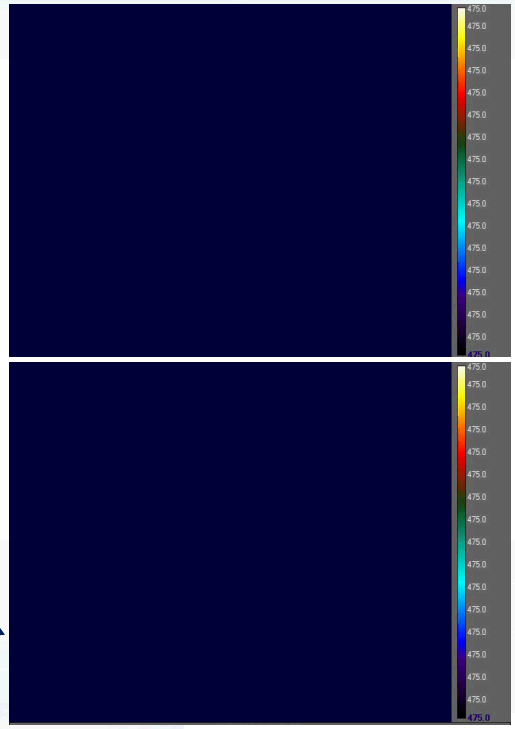
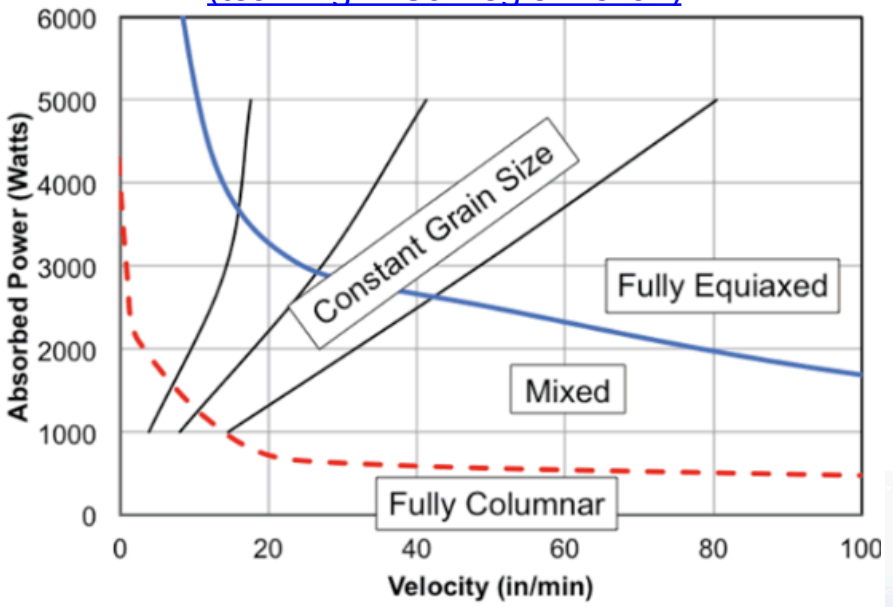
Working to Understand LENS™ Processing-Microstructure Relationships



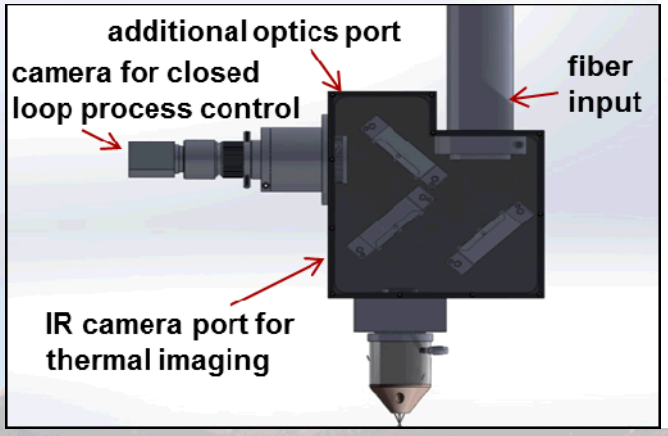


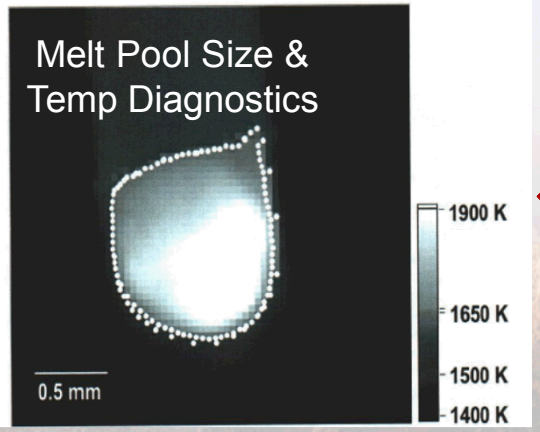
Processing-Microstructure Relationships

(teaming w Carnegie Mellon)



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





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

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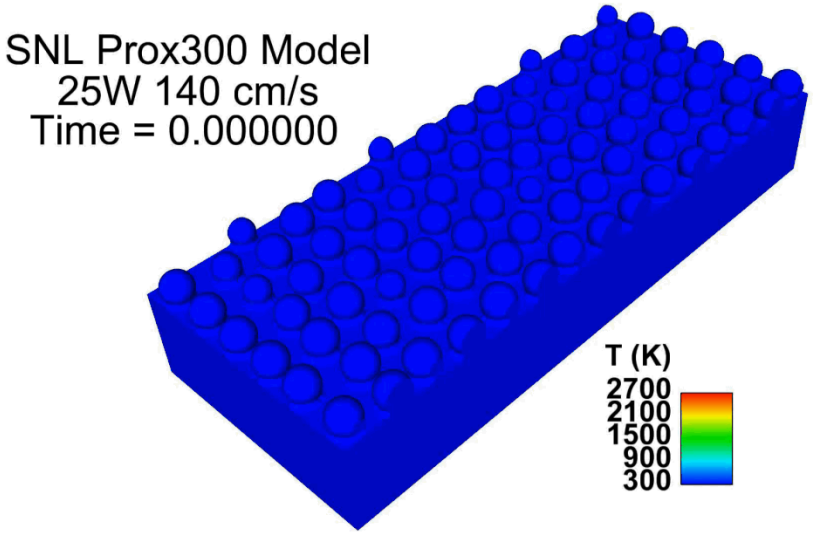
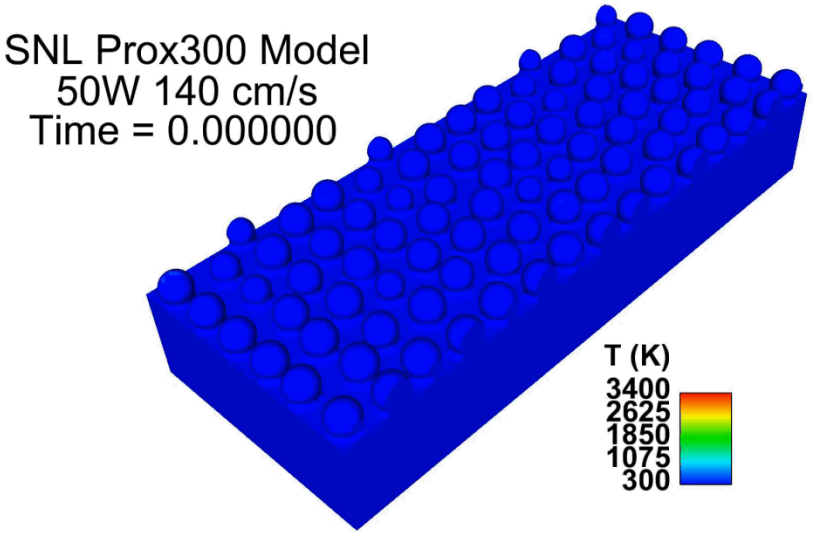
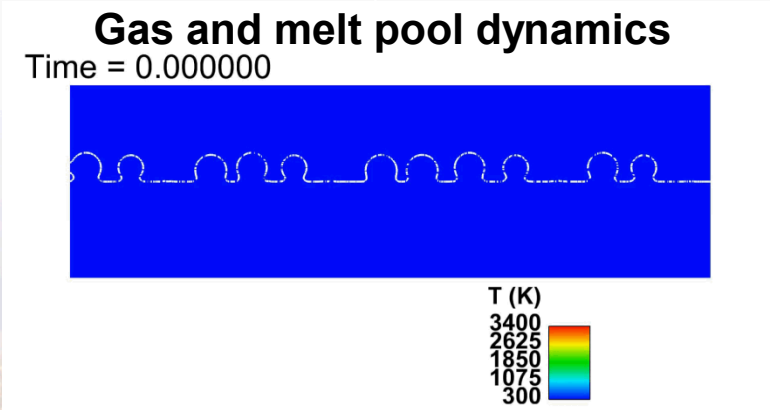
Process Modeling Can Provide Useful Insights



Stainless steel 304L
25 micron powder



Gas and melt pool dynamics



Notes:

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

Process Models by Mario Martinez

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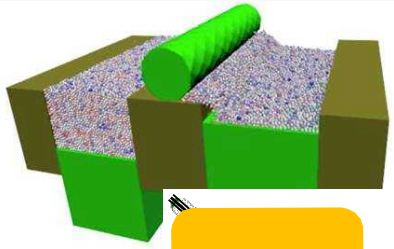
Ultimate Vision is to Understand/Control
Process → Microstructure → Properties → Performance



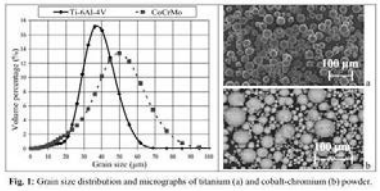
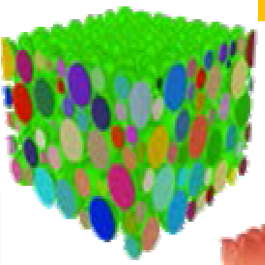
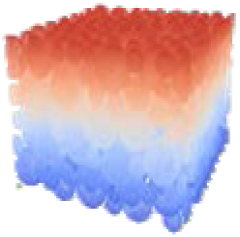


Fig. 1: Grain size distribution and micrographs of titanium (a) and cobalt-chromium (b) powder.

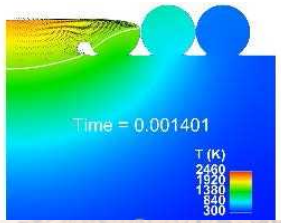
Particle packing



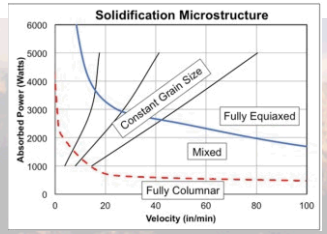
Heat Transfer



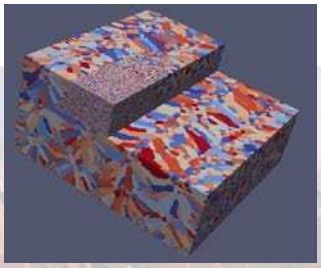
Partial melt & flow

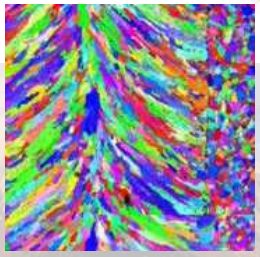


Molten pool dynamics

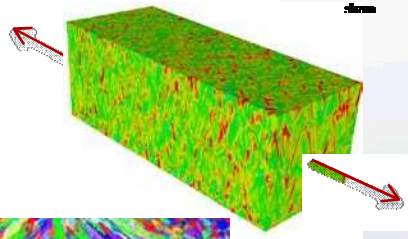


Solidification

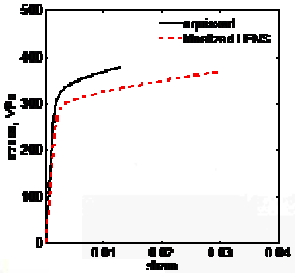




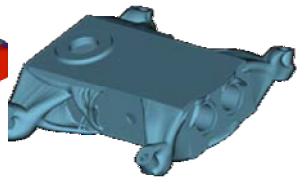
Microstructure



Property-Performance



Topology Design



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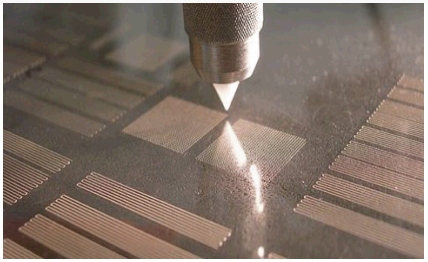
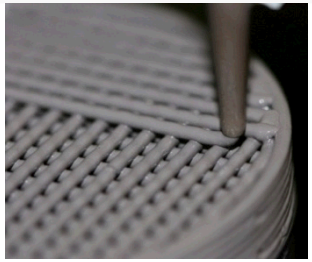
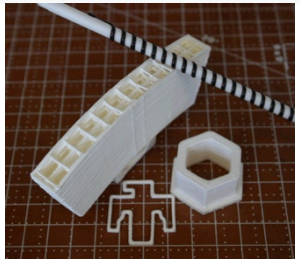
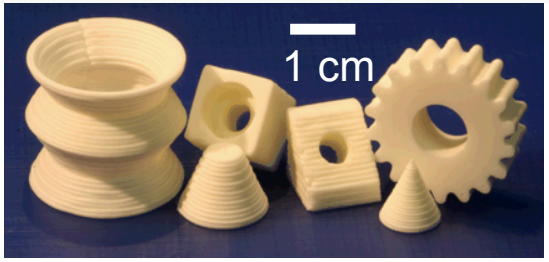
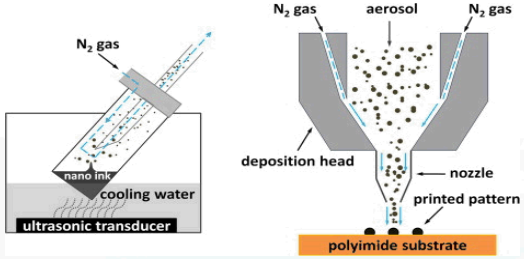
Multi-Material AM

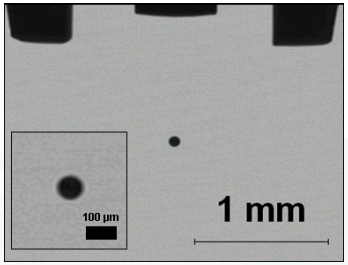
Direct Write Technologies Enable Access To Materials Not Supported By Conventional Printing Processes

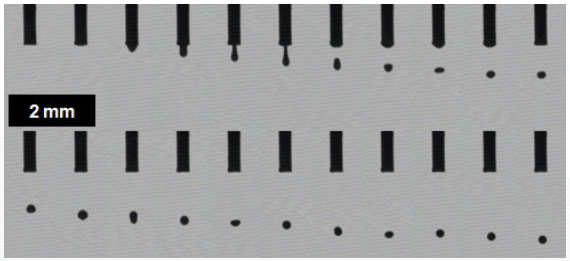
Direct Write by Extrusion Casting (Robocasting)

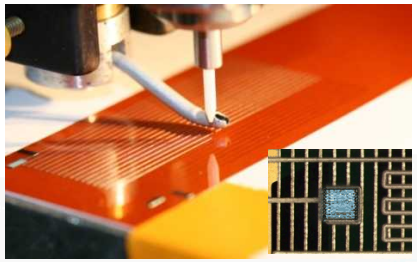





Direct Write by Aerosol & Ink Jet Deposition

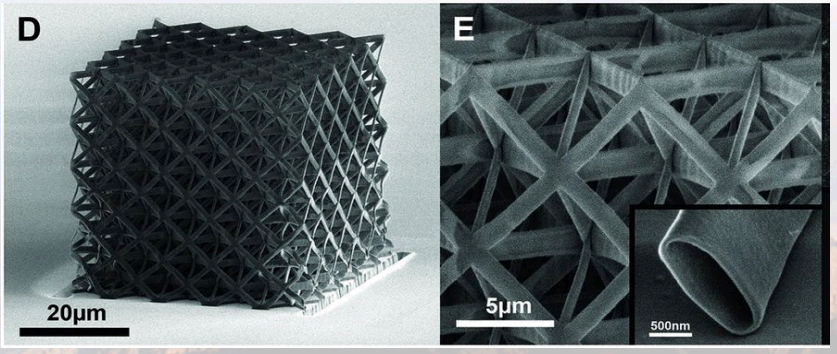


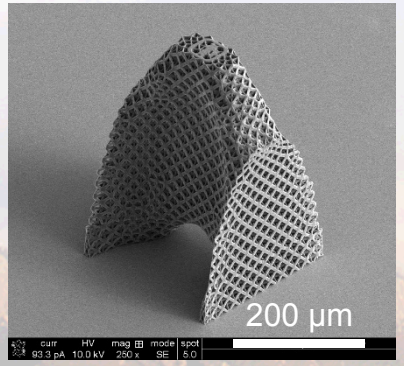


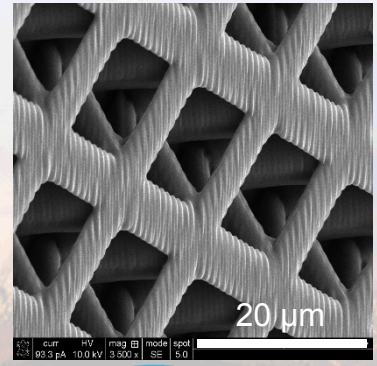




Direct Write by Laser Lithography







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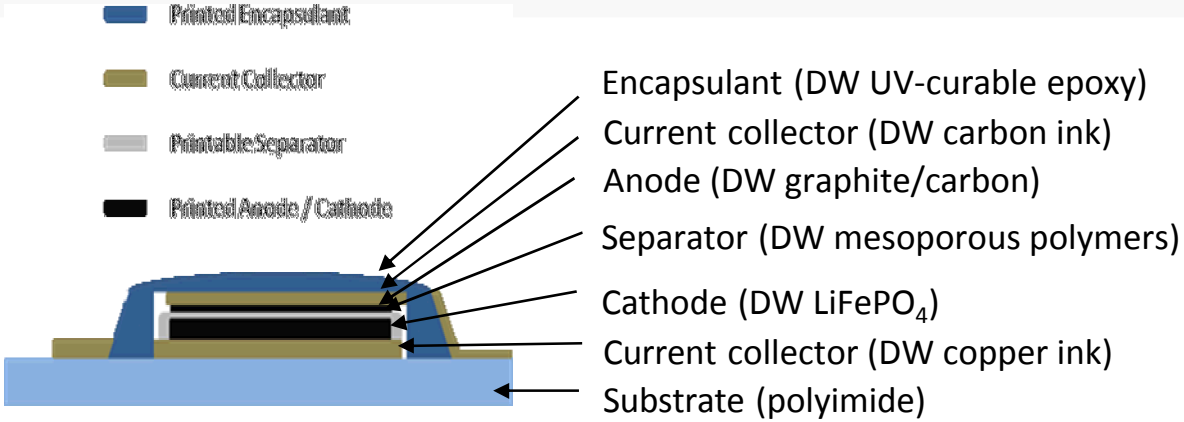
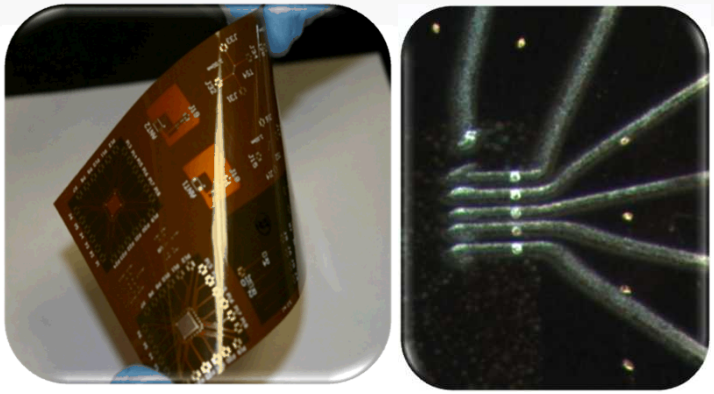
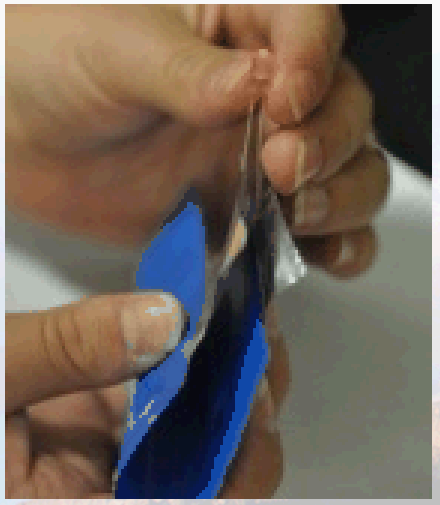
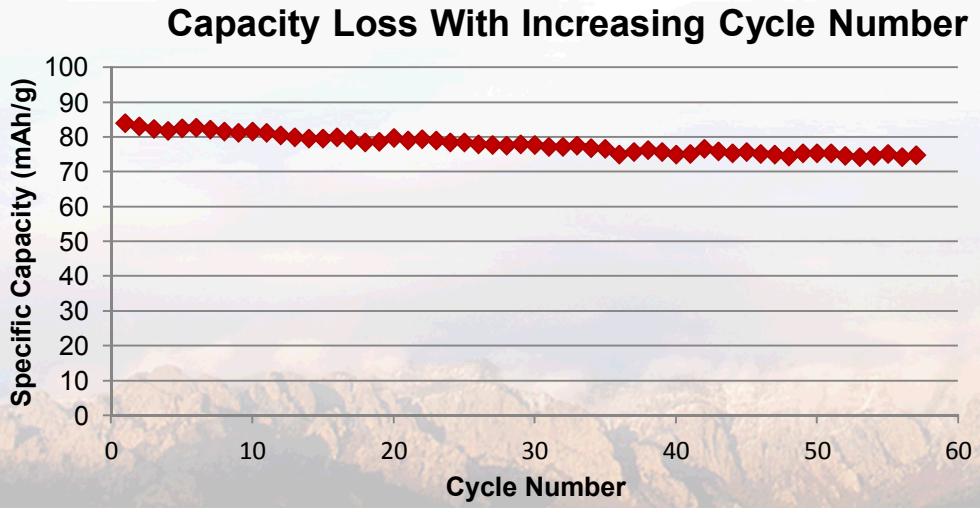
Printed Electronics

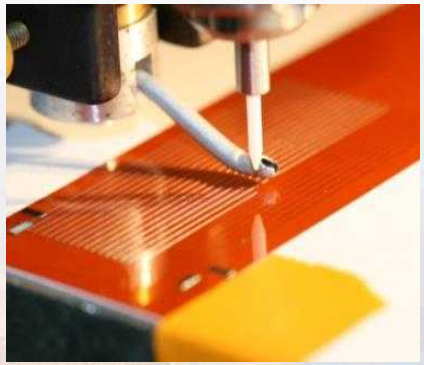




"Flexible Chips" with Printed Wirebonds







Aerosol jet printing to 10 μm

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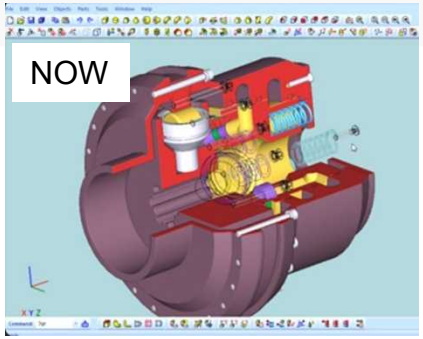
A New Way of Designing & Manufacturing Innovative Products?

Computer "Aided" Design

- Didn't Really "Automate" Design
- Still a "Human" Design
- Manufacturing Limitations



Engineering Analysis Driven AM Design

- New Manufacturing/Design Possibilities
- Computer Generated Design
- Potential to Optimize Both Structure & Materials

Traditional Drafting Design

- Purely Manual Process
- 100% Reliant on the Designer
- Limitations of 2D Representations
- Manufacturing Limitations

3D Model-Based Manufacturing

- Highly Flexible/Agile
- Process Monitoring/Control
- Process/Model Based Acceptance

Products Impossible or Impractical with Traditional Technologies

A New World of Possibilities!

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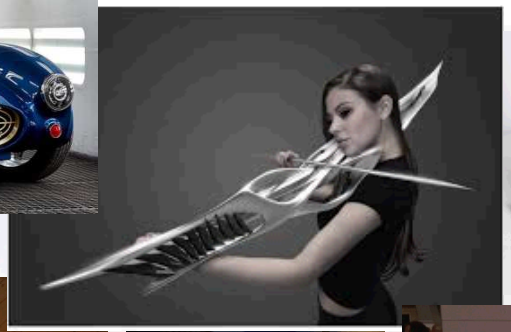
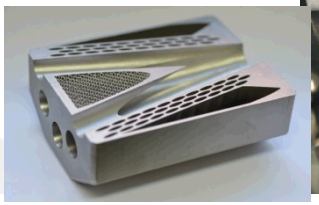
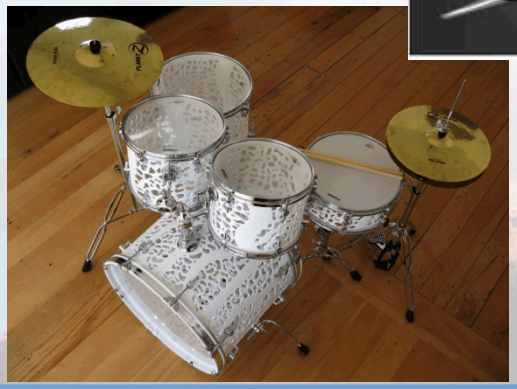
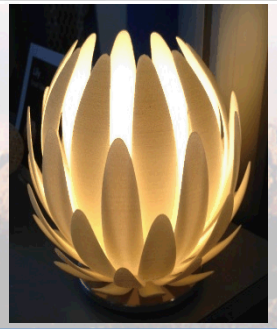
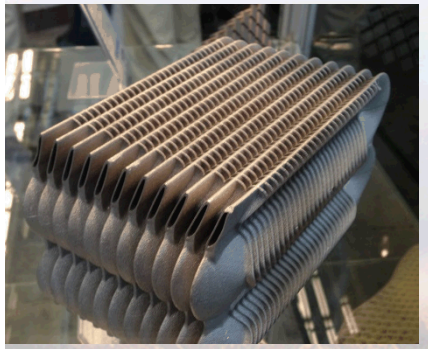
Closing Remarks

- Additive Mfg/3D Printing offers revolutionary new design/mfg possibilities
- It is *NOT* a panacea, but is a very important and extremely versatile new mfg. tool
- Commercial AM technology is still evolving, but it is maturing rapidly
- There are many opportunities to contribute to the advancement of this technology



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