SAND2016-3662PE

Exceptional service in the national interest

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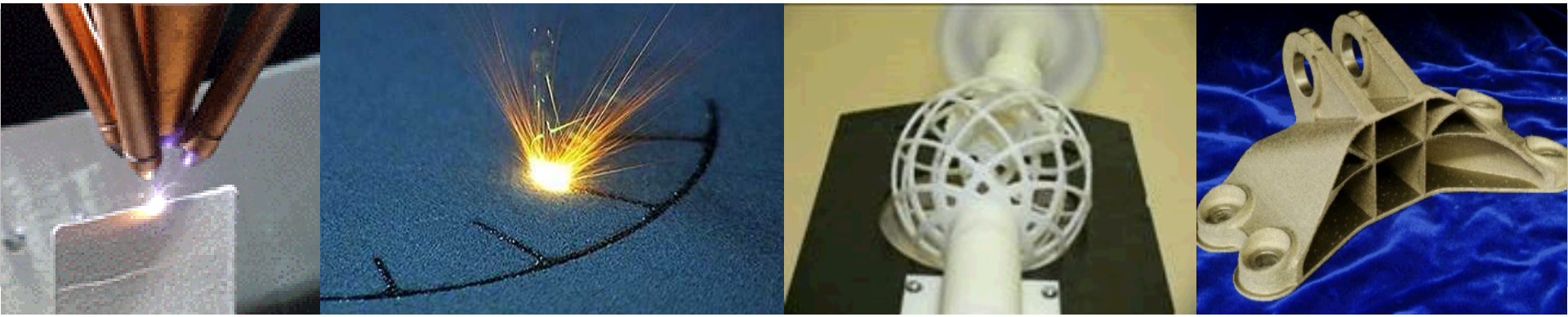

Additive Manufacturing -- A New World of Opportunities and Challenges

Mark F. Smith
Materials Science & Engineering Center
Sandia National Laboratories

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

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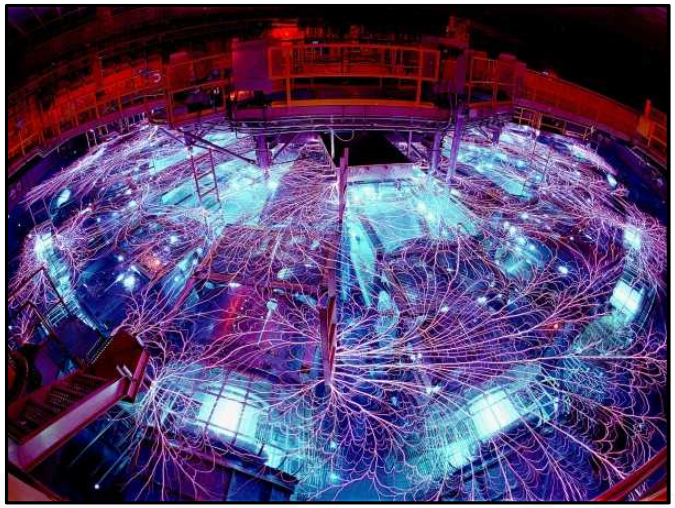
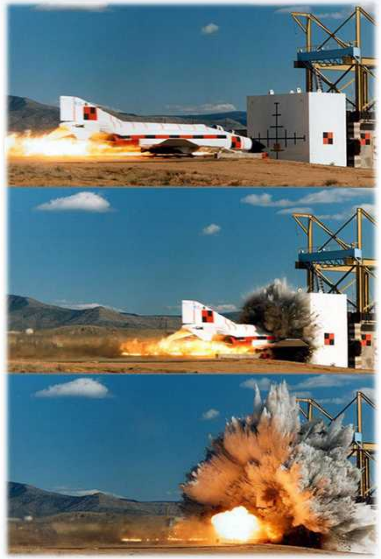
Sandia is a Dept. of Energy National Security Science and Engineering Laboratory

Weapon Drop Test



Energy R&D



Threat Test

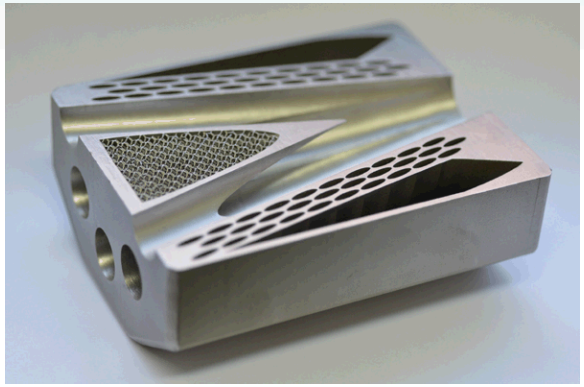
- Historical mission -- non-nuclear component design and full system integrator for all US nuclear weapons and nuclear weapon security
- Today, broader mission in science & engineering for U.S. national security

"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

A Balanced Overview of Additive Manufacturing

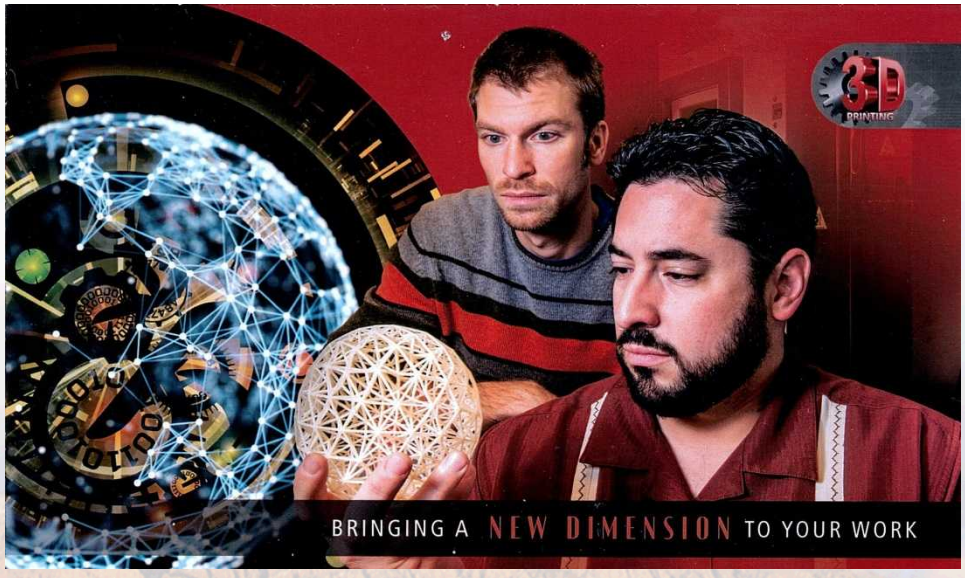
- *Additive Manufacturing Processes*
- *Potential Advantages*
- *Potential Limitations*
- *Some Emerging Trends/Opportunities*



3D Systems LayerWise

Commercial Metal AM Machine

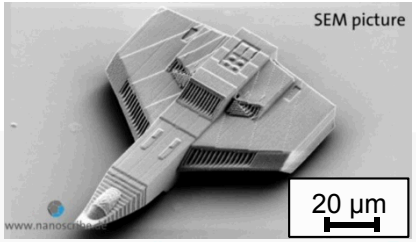
Sandia Hand



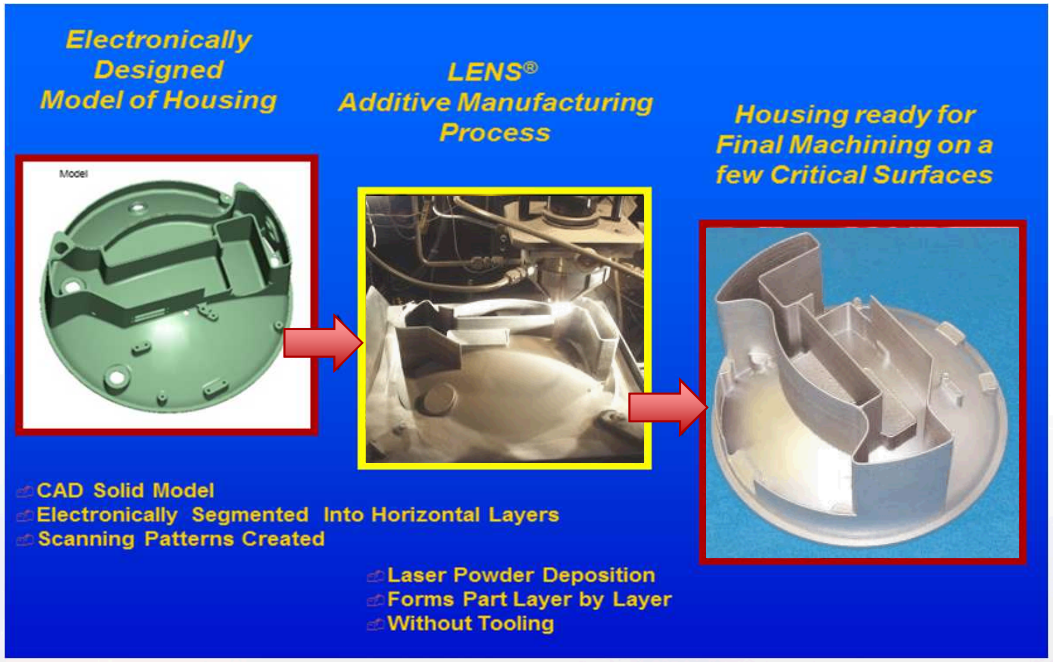
Sandia Web-based 3D Printing Service

Additive Manufacturing -- A Wide Range of 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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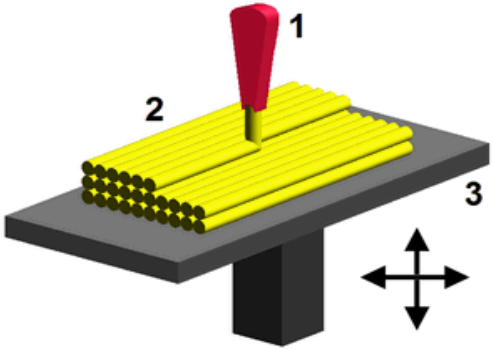
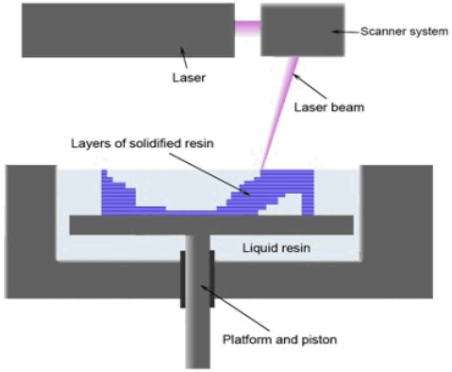
7 ASTM Additive Manufacturing "Process Categories"

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



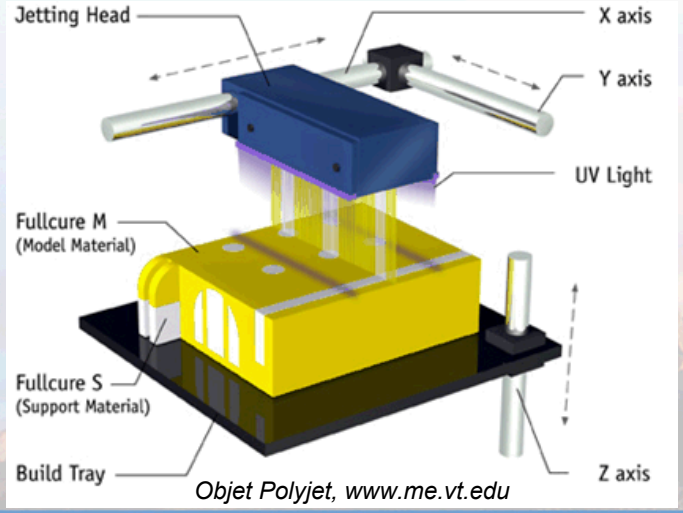
"Fused Deposition Modelling", Wikipedia

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



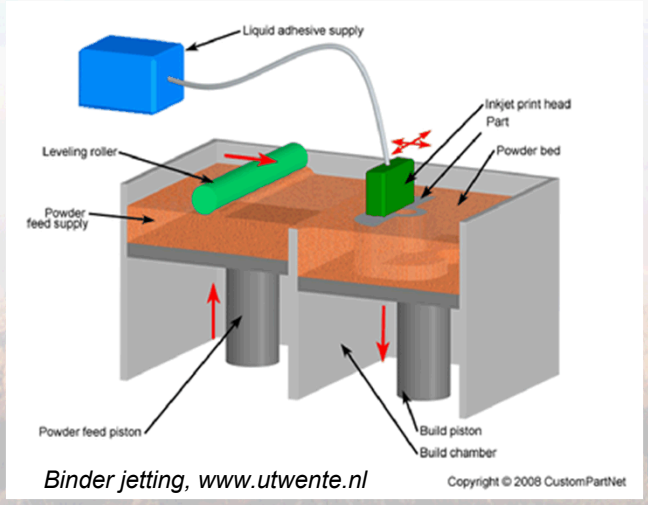
"Stereolithography", Wikipedia

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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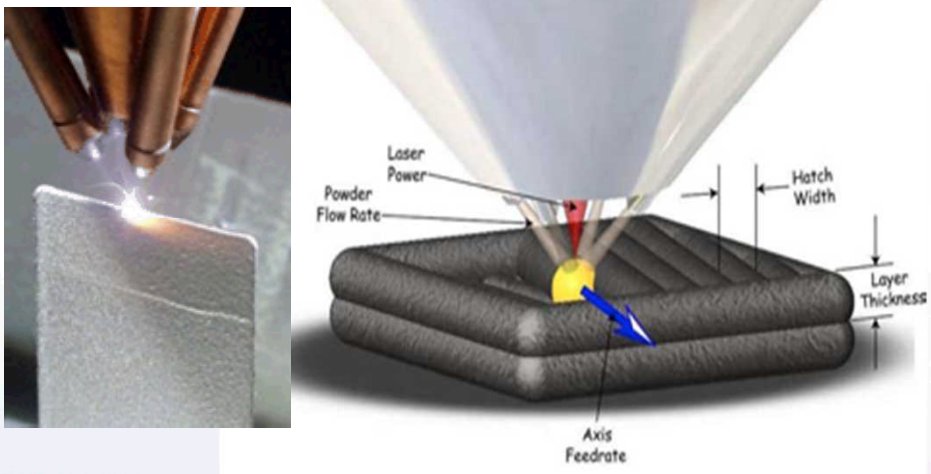
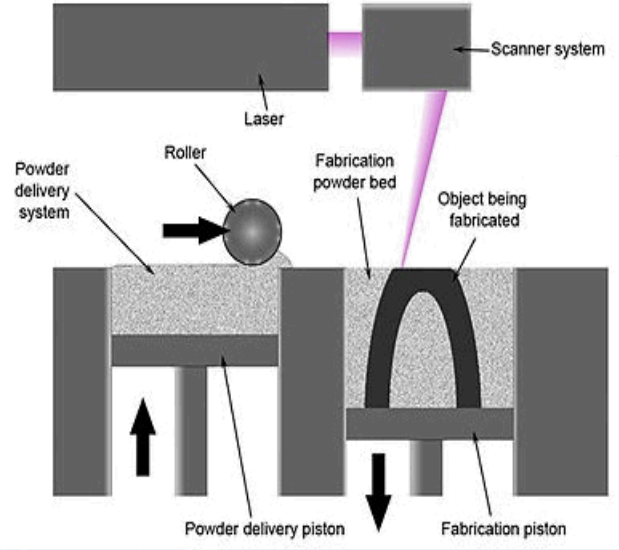
7 ASTM Additive Mfg. "Process Categories"

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

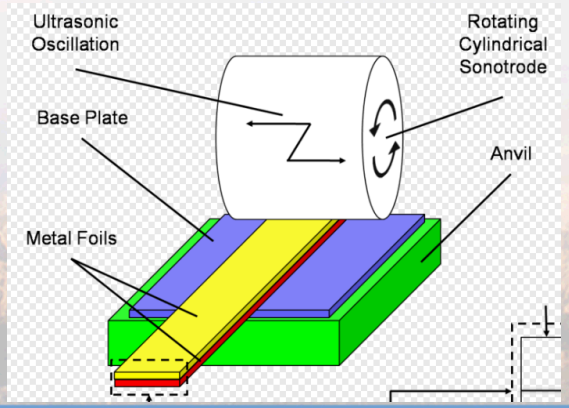


Powder Bed Fusion (Laser or e-Beam)
Thermoplastics, Metals, Ceramics



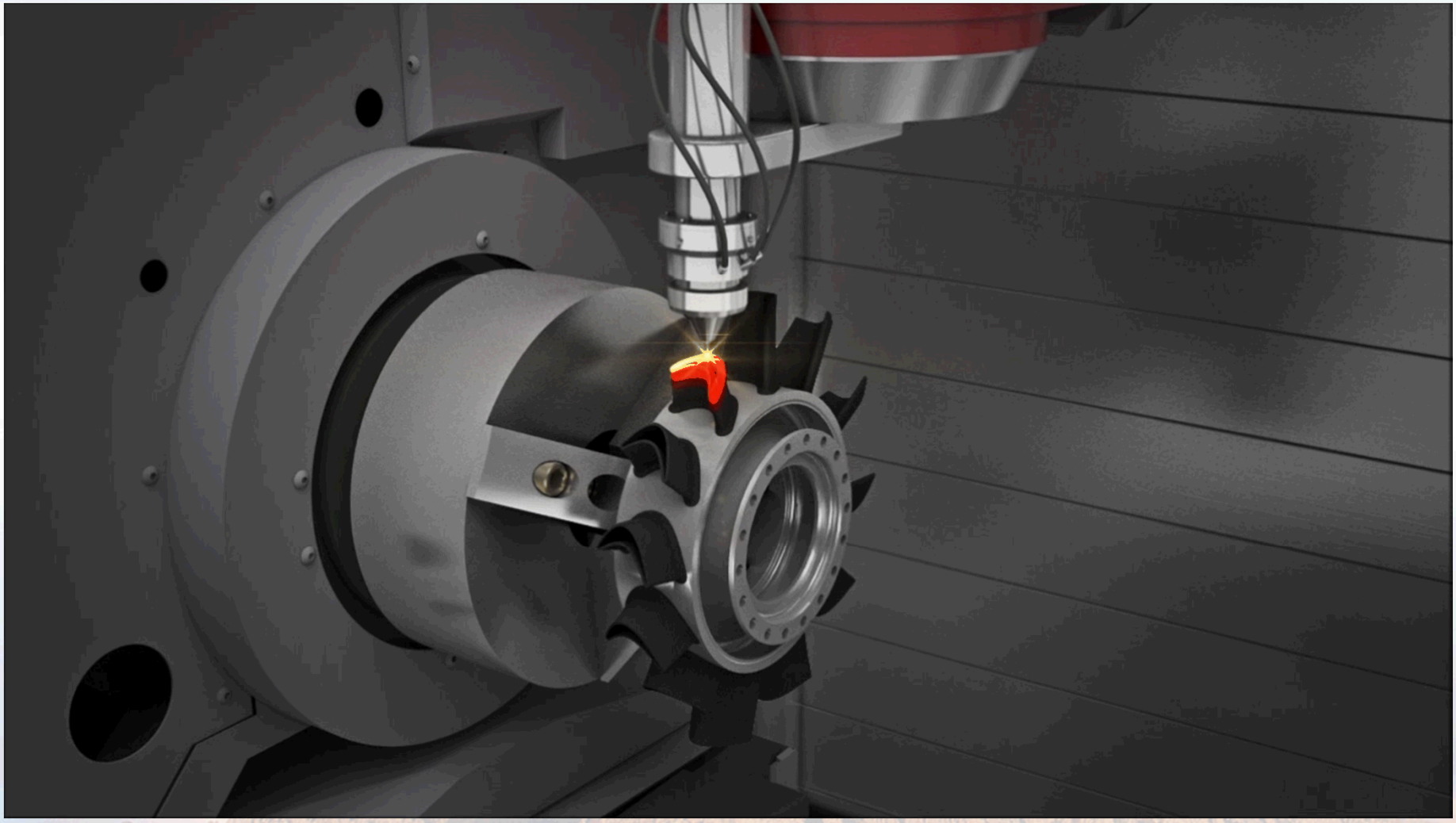
"Selective laser melting", Wikipedia

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



"Ultrasonic consolidation", Wikipedia

"Hybrid" Additive/Subtractive Machine Tools

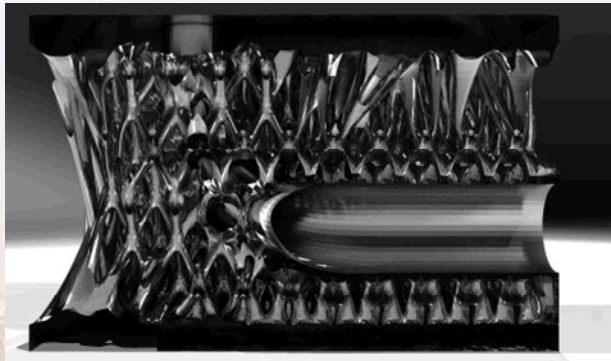


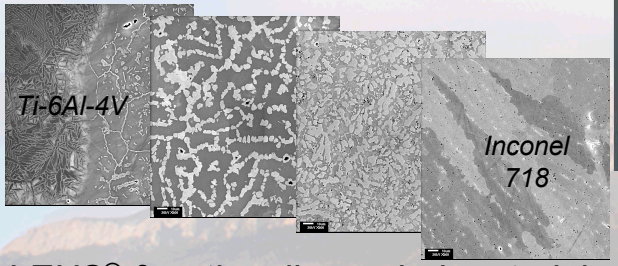
Video Courtesy of DMG Mori

Why Use AM?
Some Potential Advantages

- Design Freedom – shapes previously unachievable/impractical
- Save Weight, Time, Money, Energy
- Print Integrated Assemblies
- Reduce Waste/Materials Cost
- Engineered Materials – special properties
- Rapid/Inexpensive prototypes/jigs/tooling/fixtures

Within Technologies





LENS® functionally graded materials

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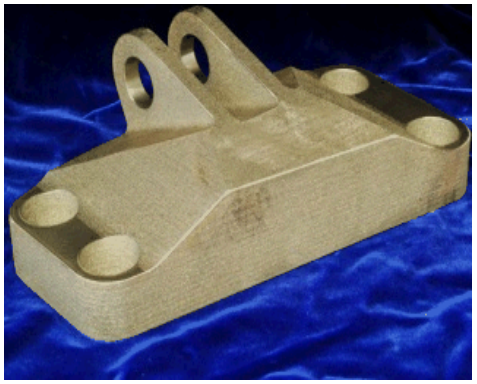
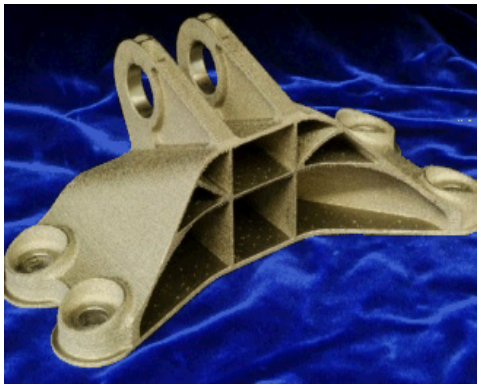
Commercial Aerospace Hardware

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 mfg.***
- ***Replaces 18 parts with 1 – ZERO joining operations***
- ***25% lighter, 5x more durable***
- 19 fuel nozzles per engine
- Plan to build 40,000 nozzles/yr starting in 2017
- 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
"Rally Fighter"

Local Motors
Design Competition
Winner

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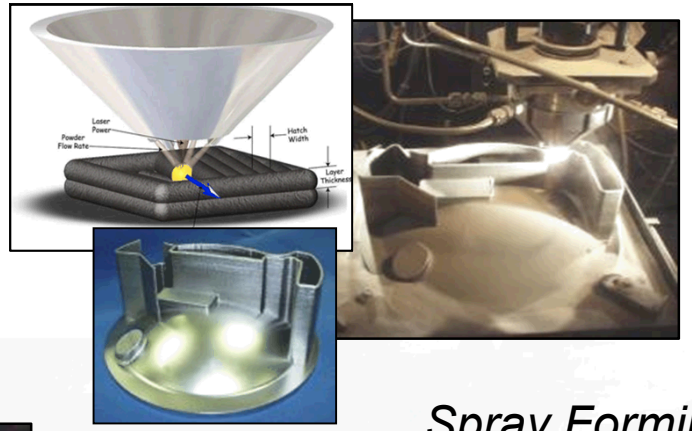
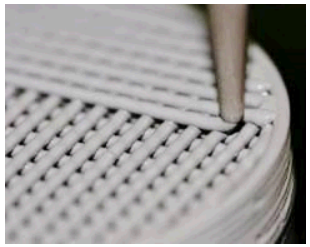
30+ Years of Pioneering Sandia AM Technology Development and Commercialization

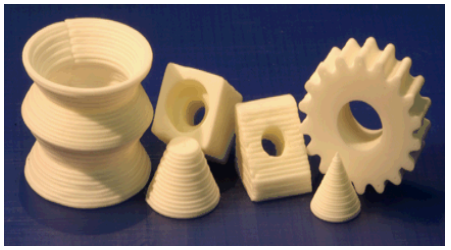
FastCast *
Development Housing

Laser Engineered Net Shaping * LENS®
Stainless Housing

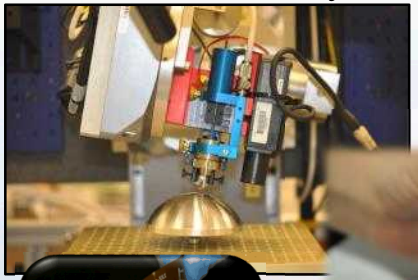


RoboCast *
Ceramic Parts





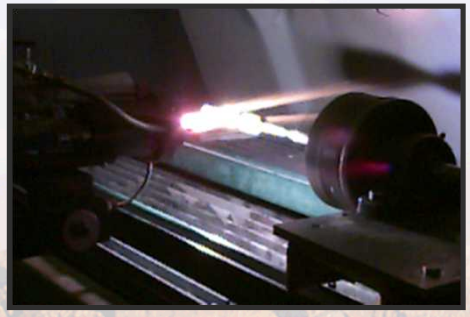
Direct Write
Conformal Circuitry



Printed Battery

Flexible Electronics

Spray Forming
Rocket Nozzle



Energetic Materials

* = Licensed/Commercialized Sandia AM technologies

Underline = *Current Capability/Activity*

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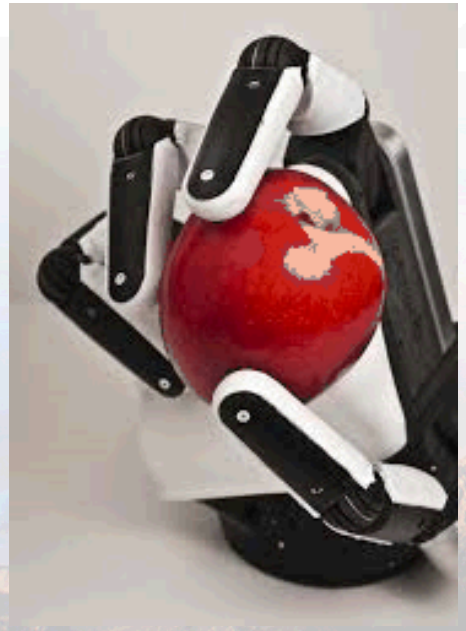
Sandia Hand – AM Enabled Innovative Design and Substantial Cost Reduction

(~*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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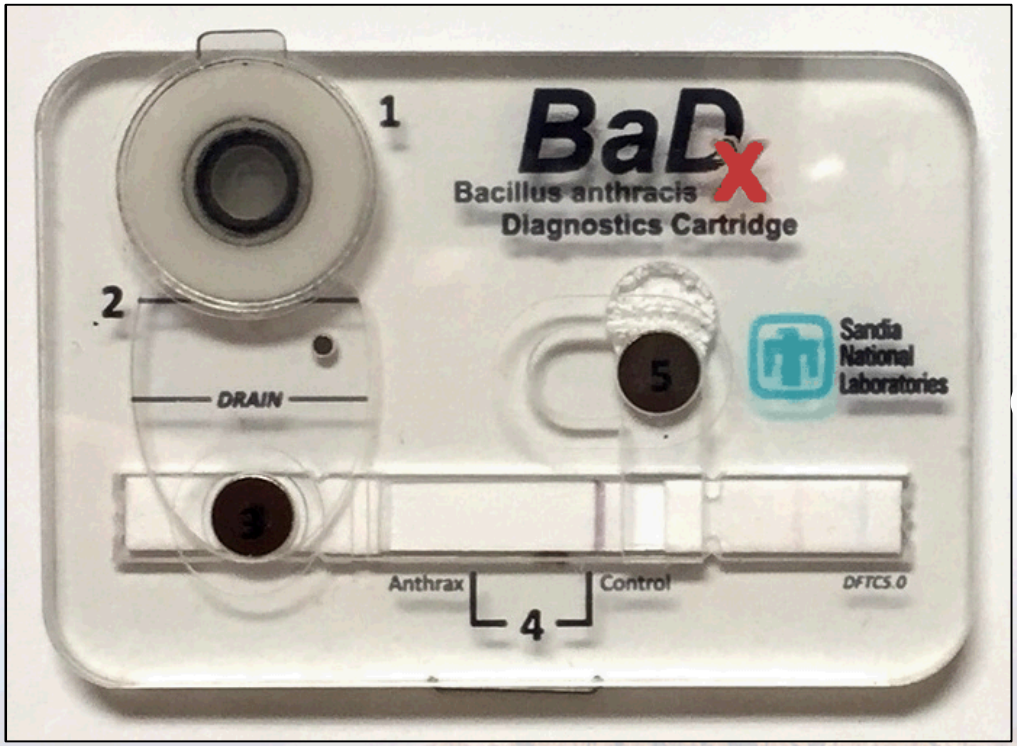
BaDx Anthrax Diagnostics Tool

- 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.

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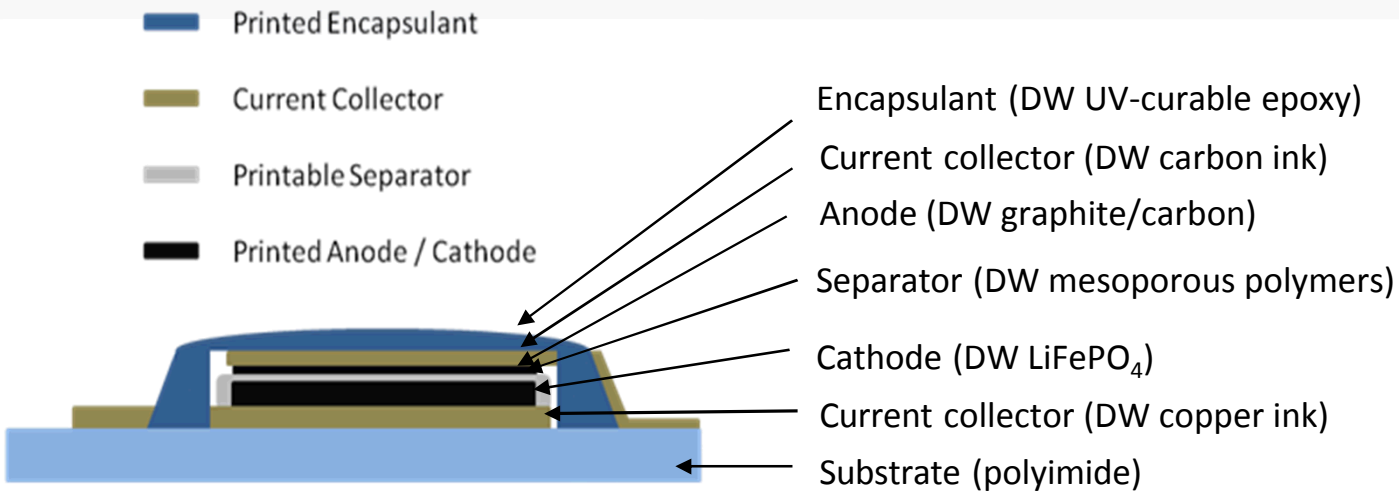
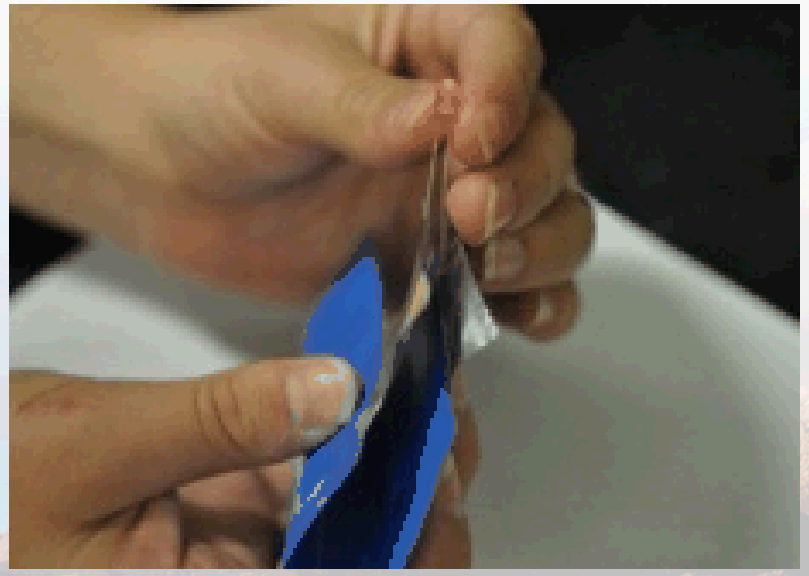
3D Printed Flexible Battery



Roll-to-Roll Printed Electronics



Cleveland Clinic Prosthetics

ALLELES Design Studio, CA

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Analysis-Driven Design Optimization

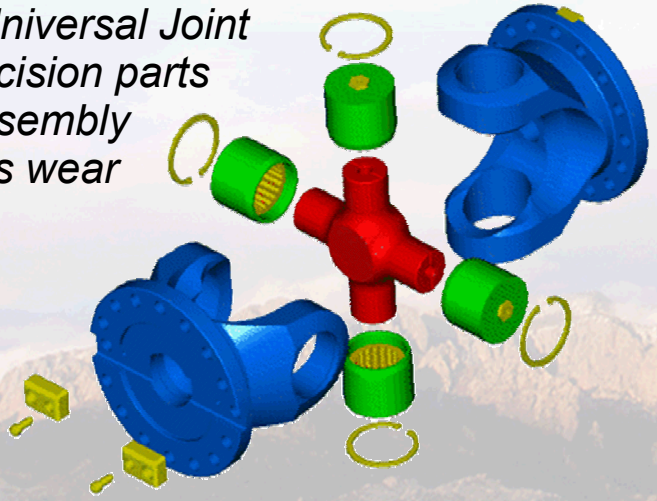
We combined Topological Optimization (TO) with eXtended Finite Element Modeling (X-FEM) & LENS® to optimize selected properties, e.g., strength/weight ratio.

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

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

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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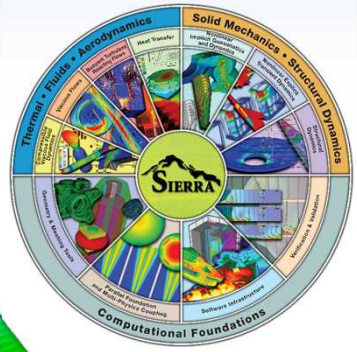
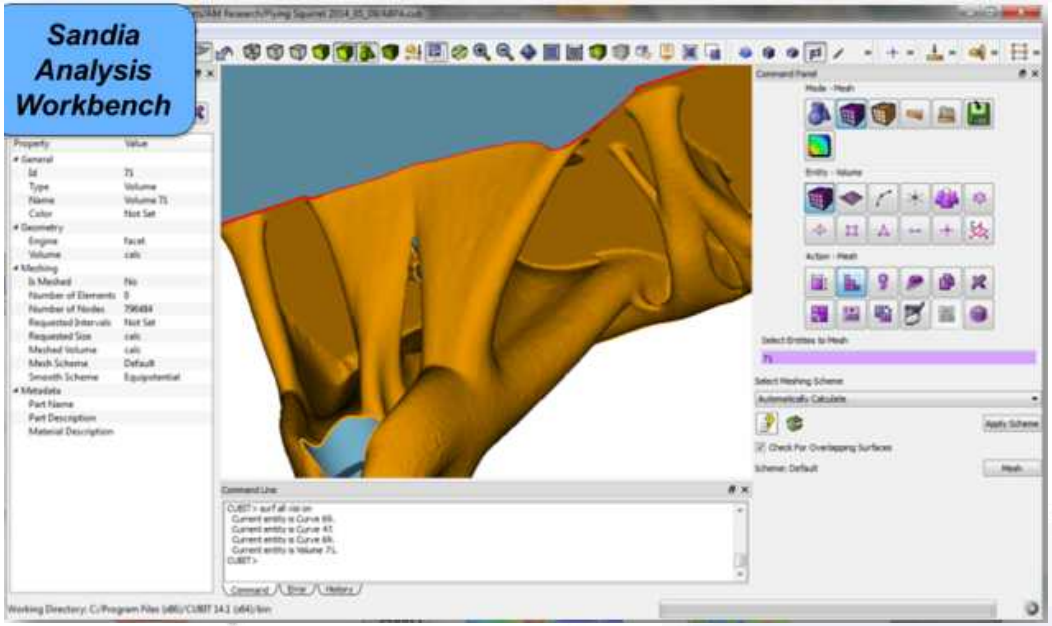
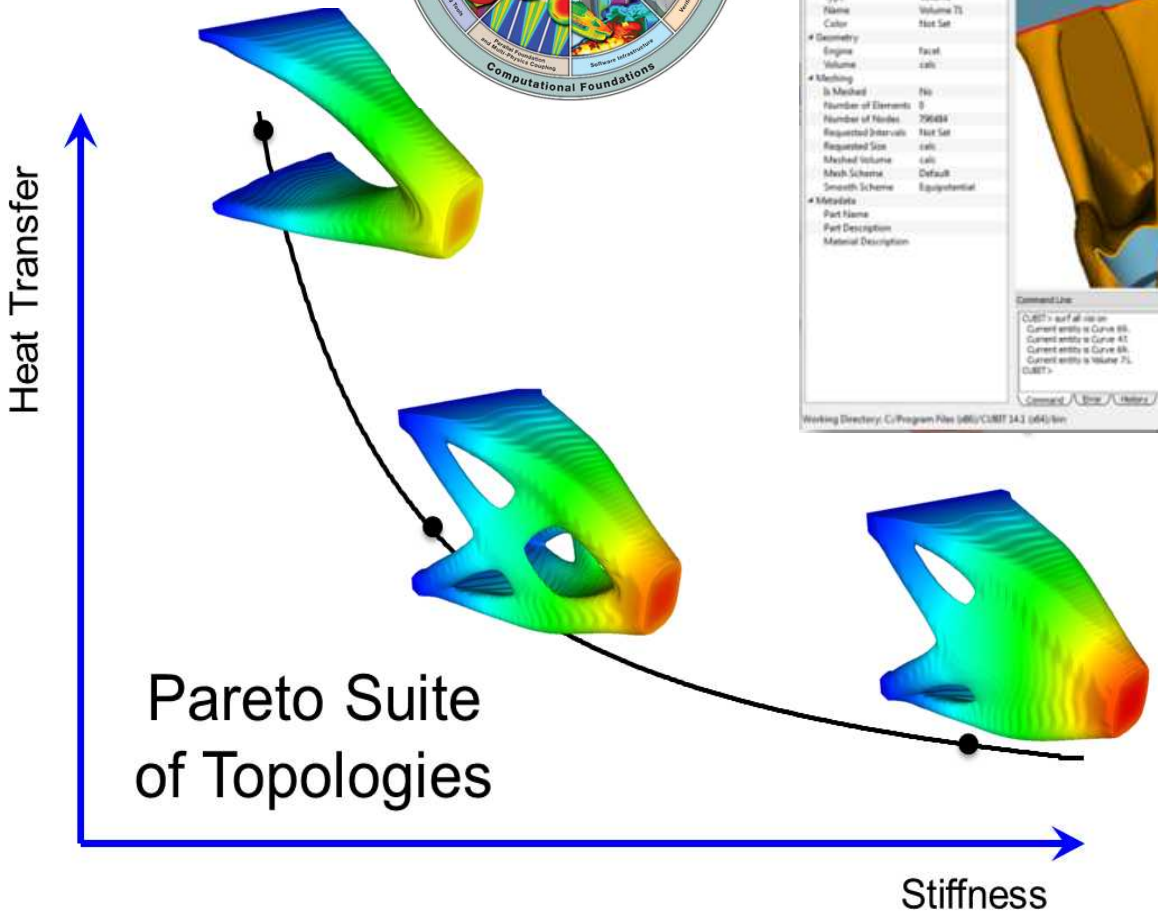
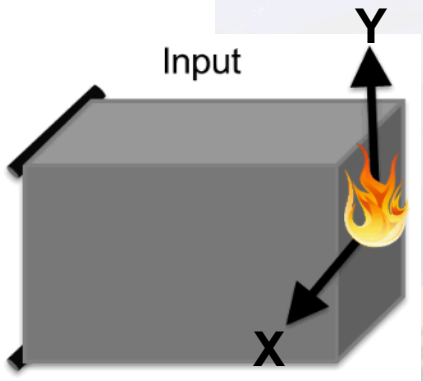
AM Design Via Functional Prioritization



User Friendly Interface







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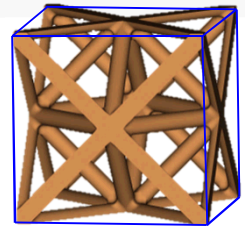
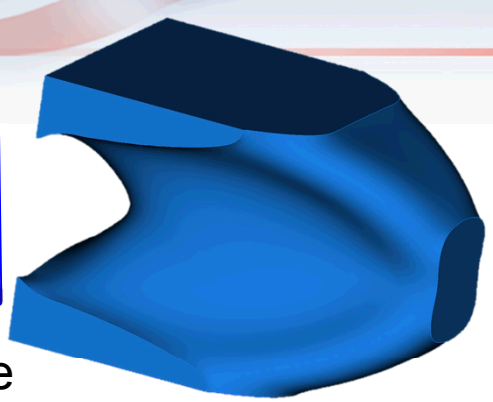
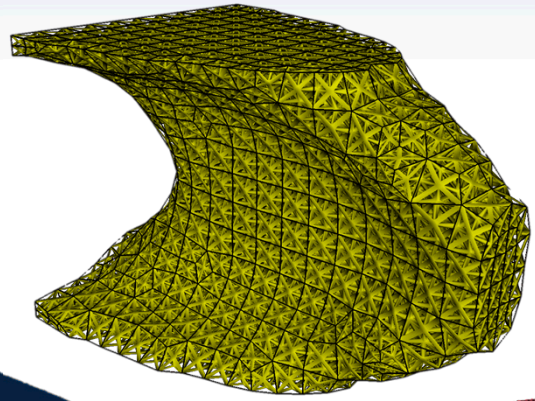
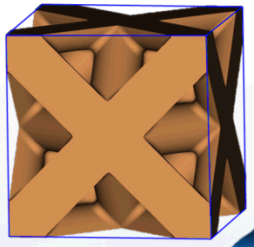
Optimizing Stiffness at Fixed Mass



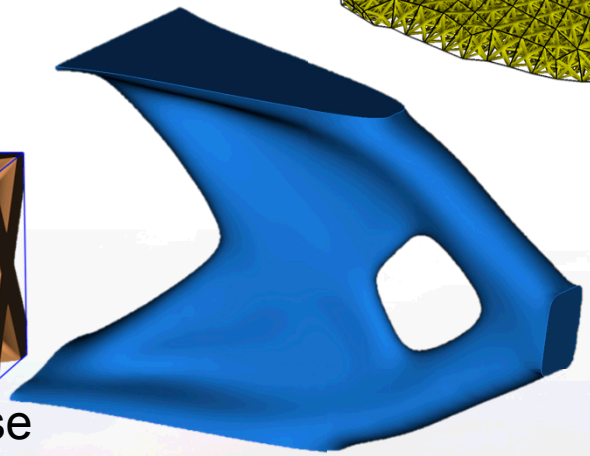
10% Dense

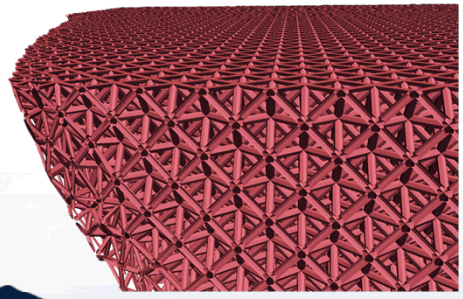


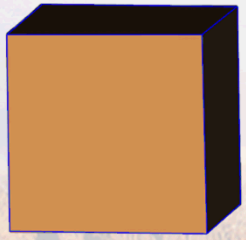




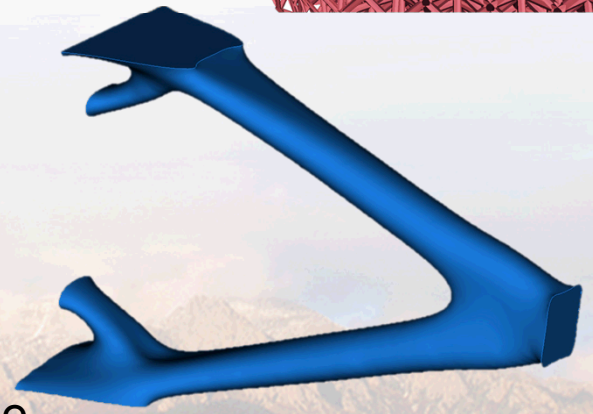
50% Dense

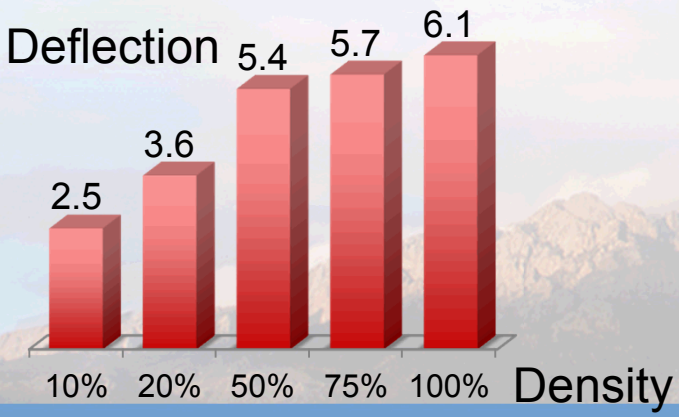






100% Dense





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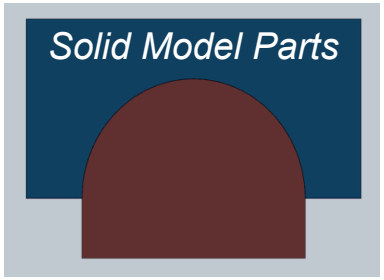
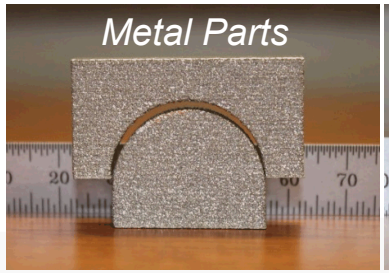
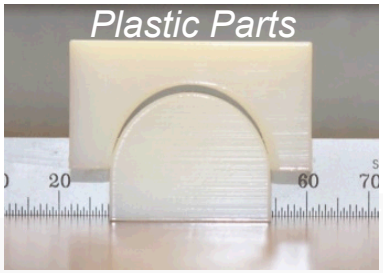
Why Not Additive?
Some Potential Disadvantages/Limitations

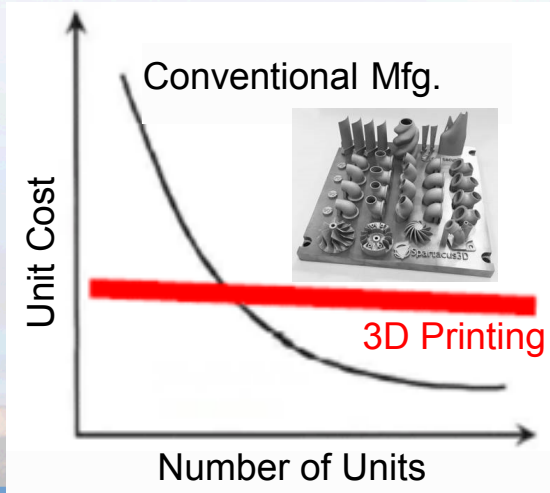
- AM Is Still an Evolving/Emerging Technology
- Many Sources of Variability – Most Machines Run "Open Loop"
- Material is "Built" Along with the Part – Is It Good?
- Lack of Engineering Data/Standards for Designers
- There ARE Design Constraints/Design Software Limitations
- Tolerances, Surface Finish,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

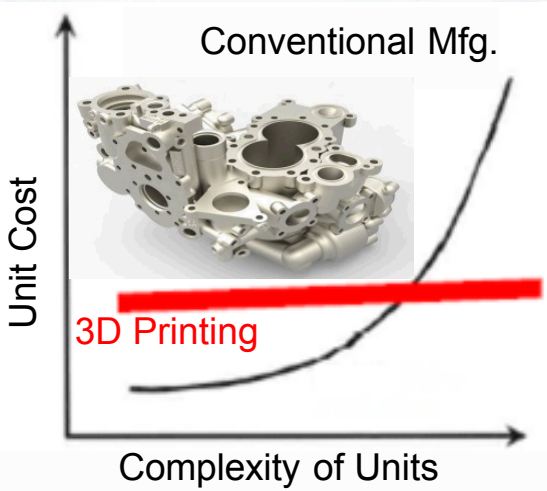






Notional Cost vs. Volume & Cost vs. Complexity Charts





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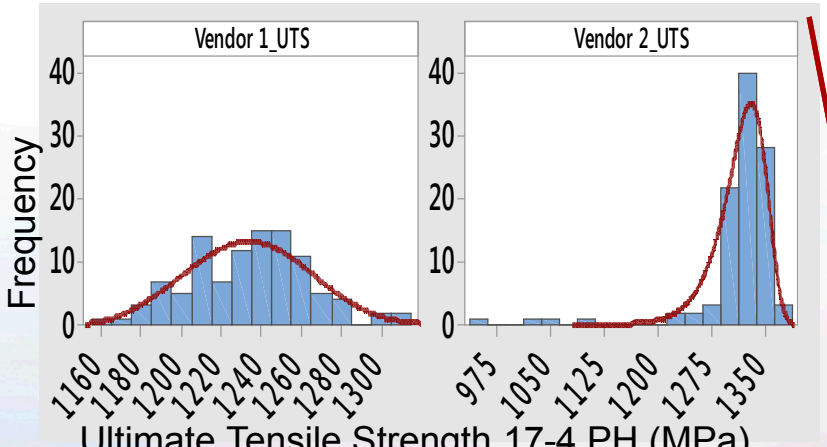
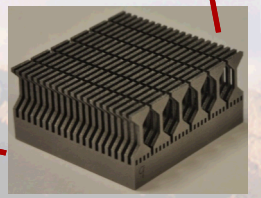
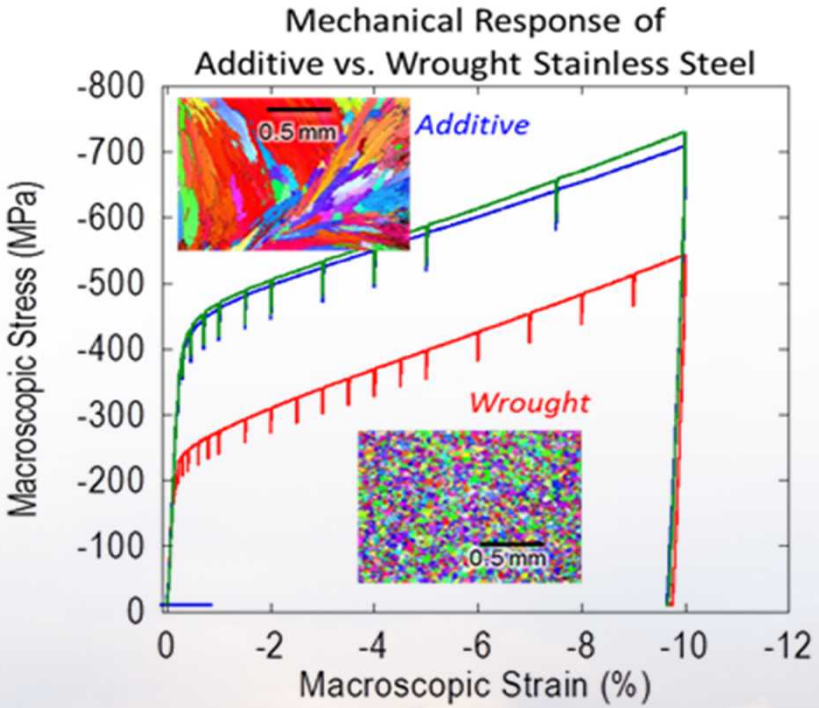
Materials Properties, Residual Stress, and Tolerances are Important Issues

- 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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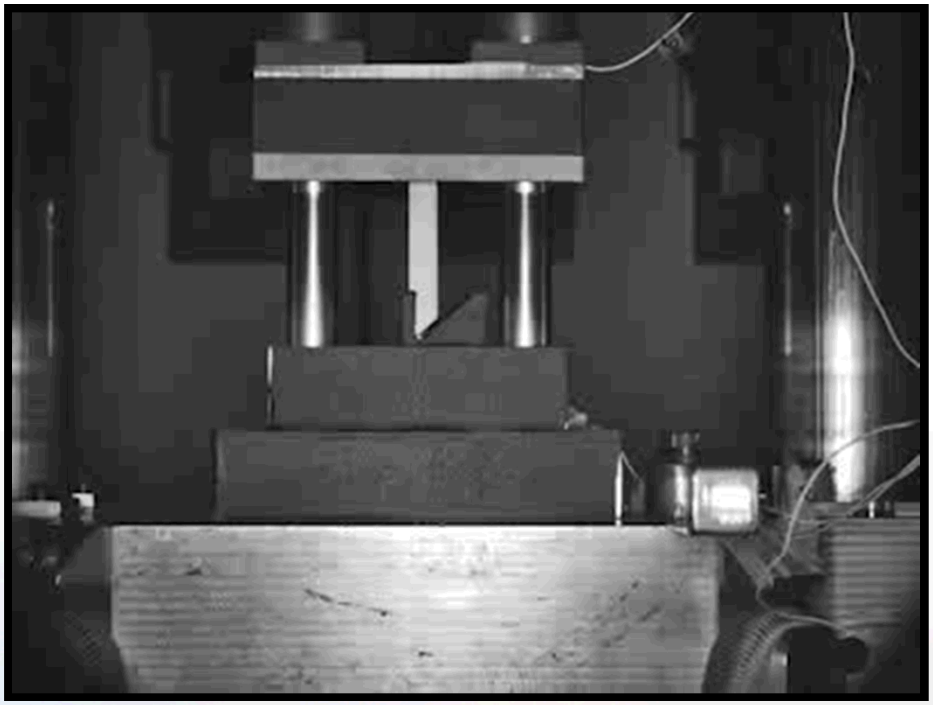
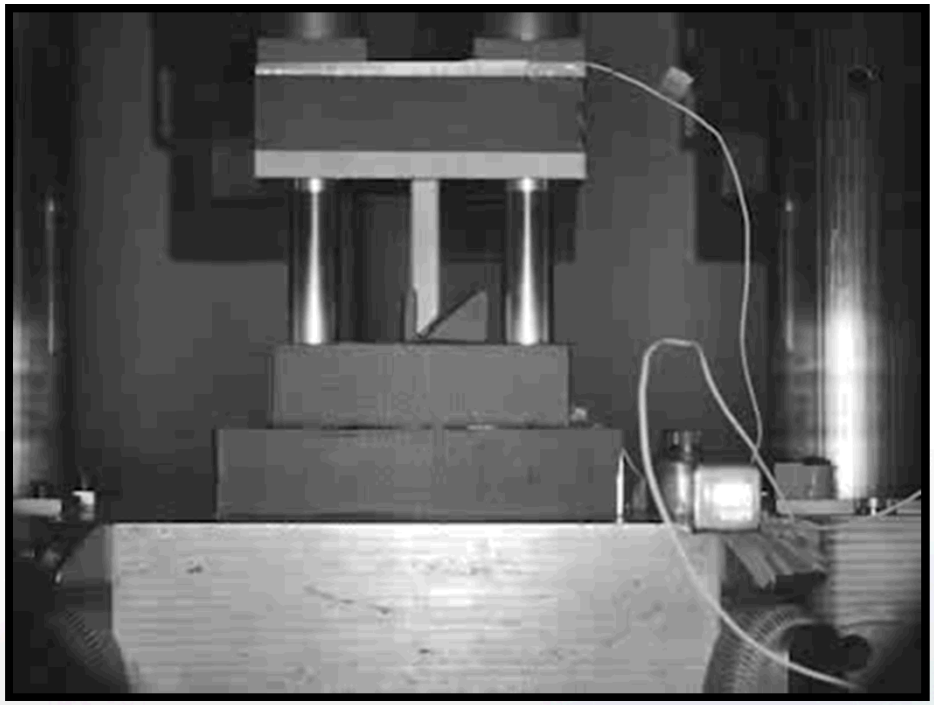
Additive Designs Can Outperform Conventional Designs



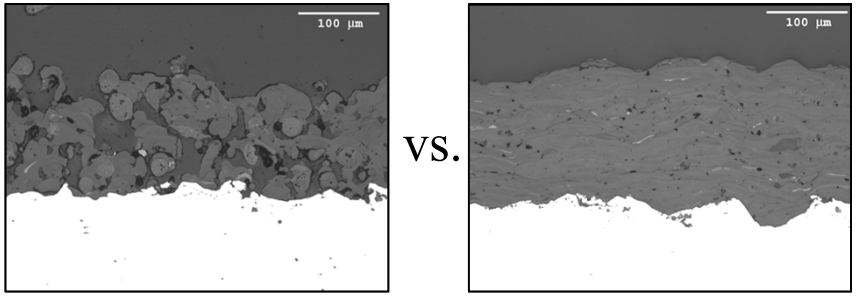
Conventional
Machined/Welded Housing
4047 Al alloy
weight = 45 grams



Additively Manufactured Housing
AlSi10Mg Al alloy
weight = 38 grams

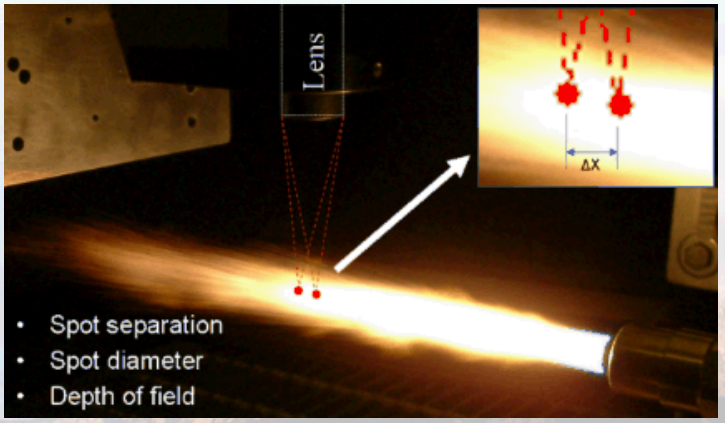
Fundamental Process Understanding is Key to Controlling Variability

Same System, Same Feedstock,



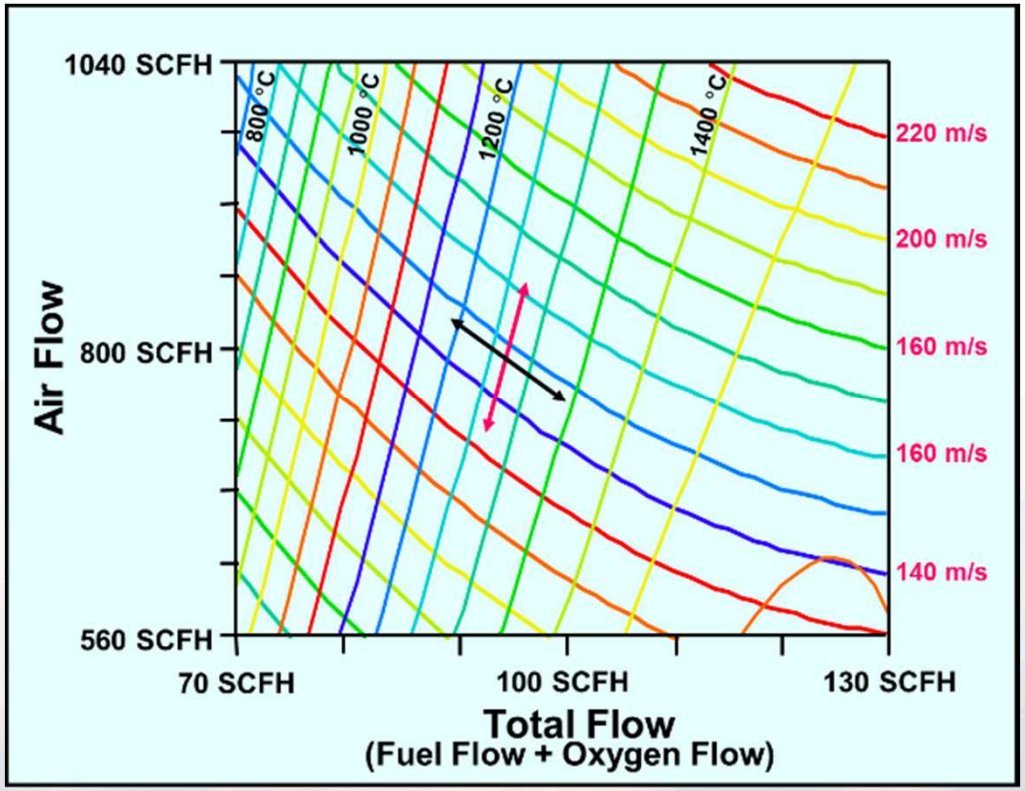
Very Different Results

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



Process Diagnostics/Monitoring

Fundamental process understanding enables closed-loop control based on droplet *temperature* and *velocity* to reduce *variability*



Response surface showing relationships between Process Inputs (Air Flow, Fuel Flow, Oxygen Flow) and Critical Outputs (droplet temperature, droplet velocity)

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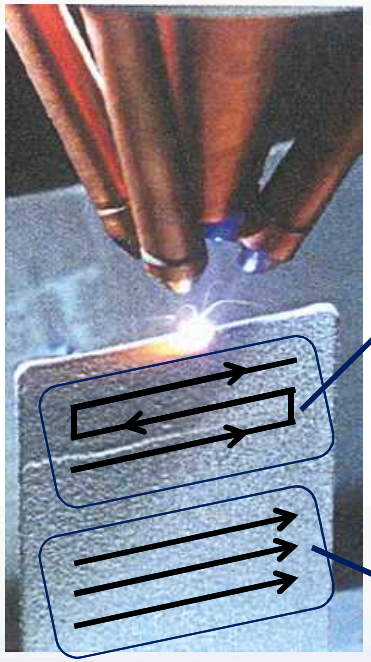
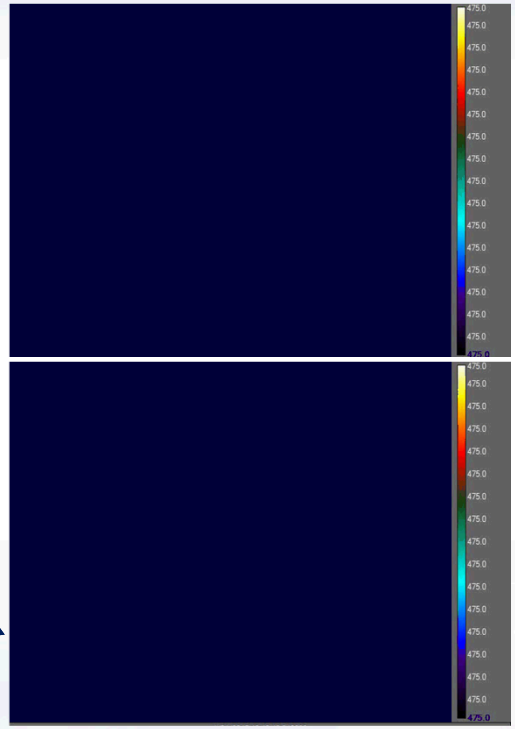
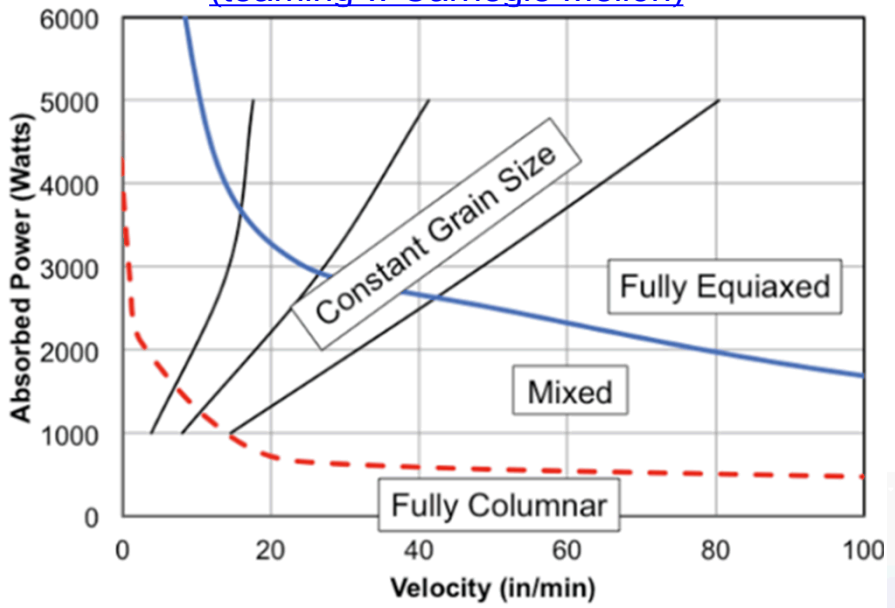
Working to Understand LENS™ Processing-Microstructure Relationships



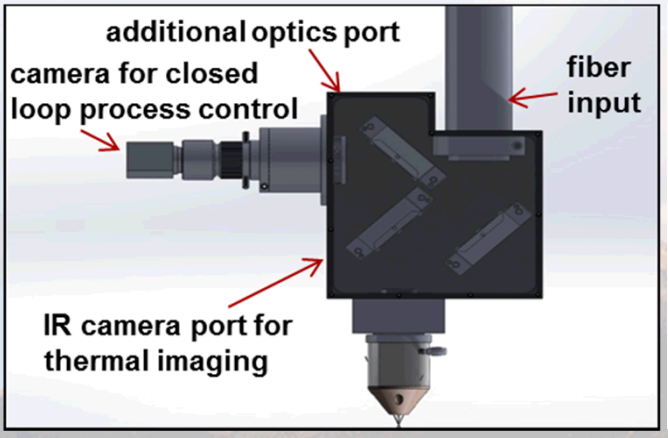


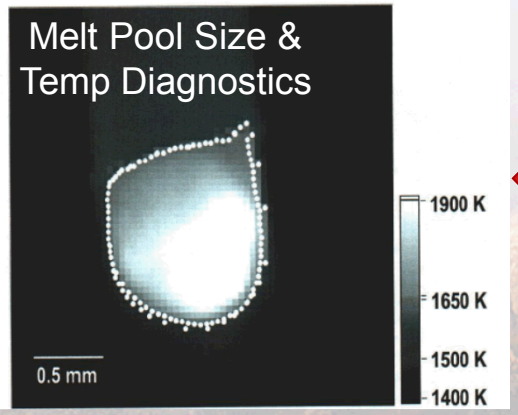
Processing-Microstructure Relationships

(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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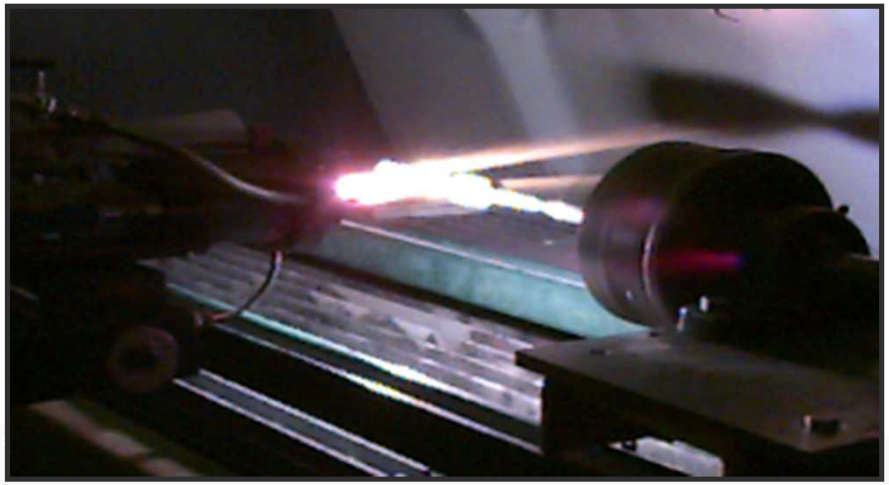
Possible AM Opportunities for Thermal Spray?

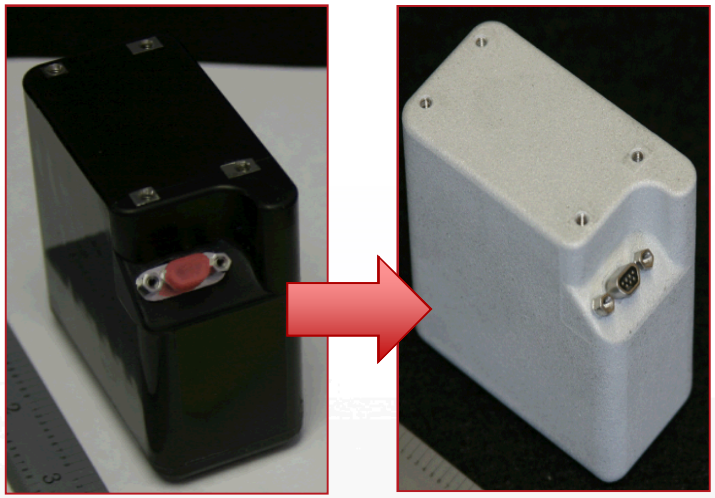
Spray Forming

Rocket Nozzle



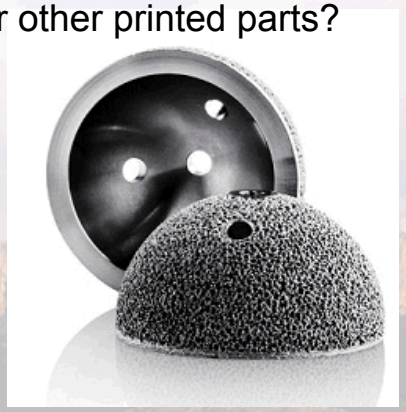
Metallizing

Metallize Plastic AM Parts for Electromagnetic Shielding, Wear, Conductivity, etc.

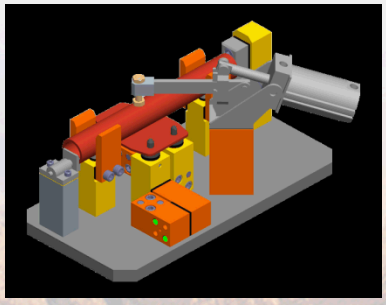


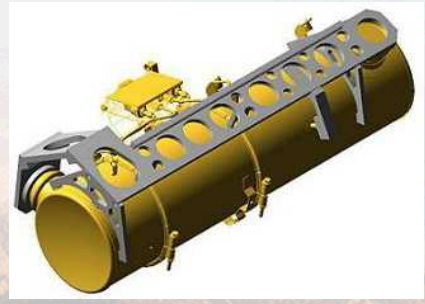
Custom Printed Implants

Coating of printed implants or other printed parts?



Printed Jigs, Tooling, Masking, …





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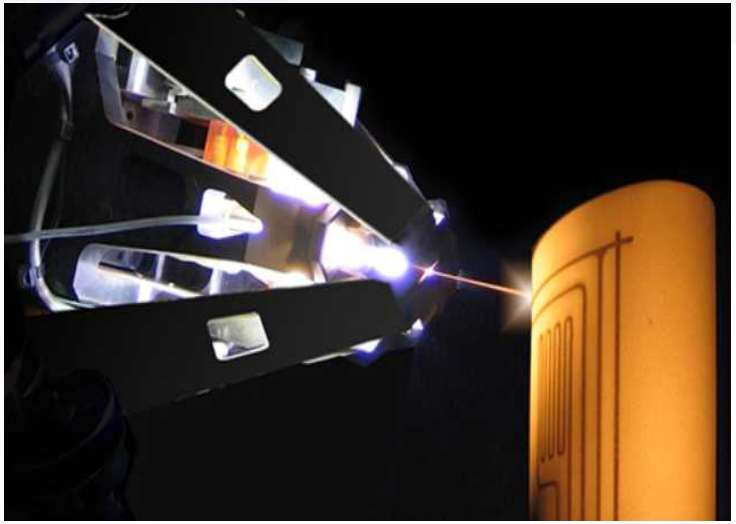
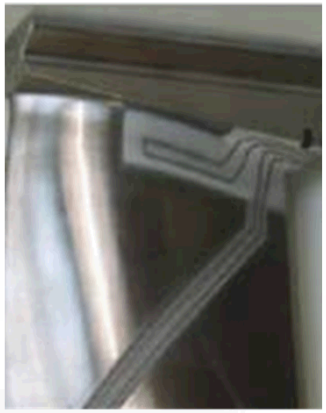
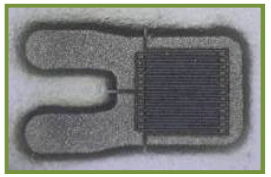
Direct Write Thermal Spray Offers Interesting Possibilities*



Component Health Monitoring

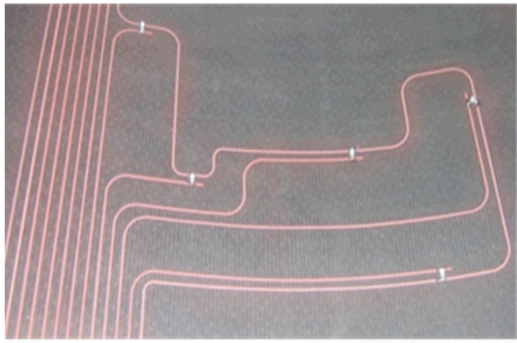


Thermocouples

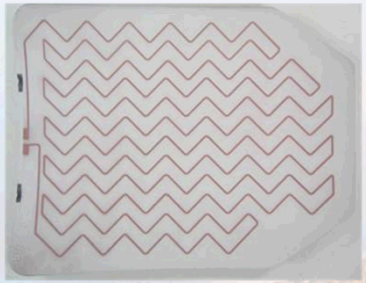


Strain Gauges

Integrated Wiring

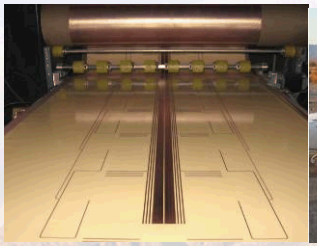


Damage Detection



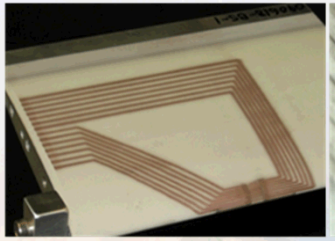
Crack Sensing

Signals Intelligence & Communication



Integrated Antennas

Flight Control



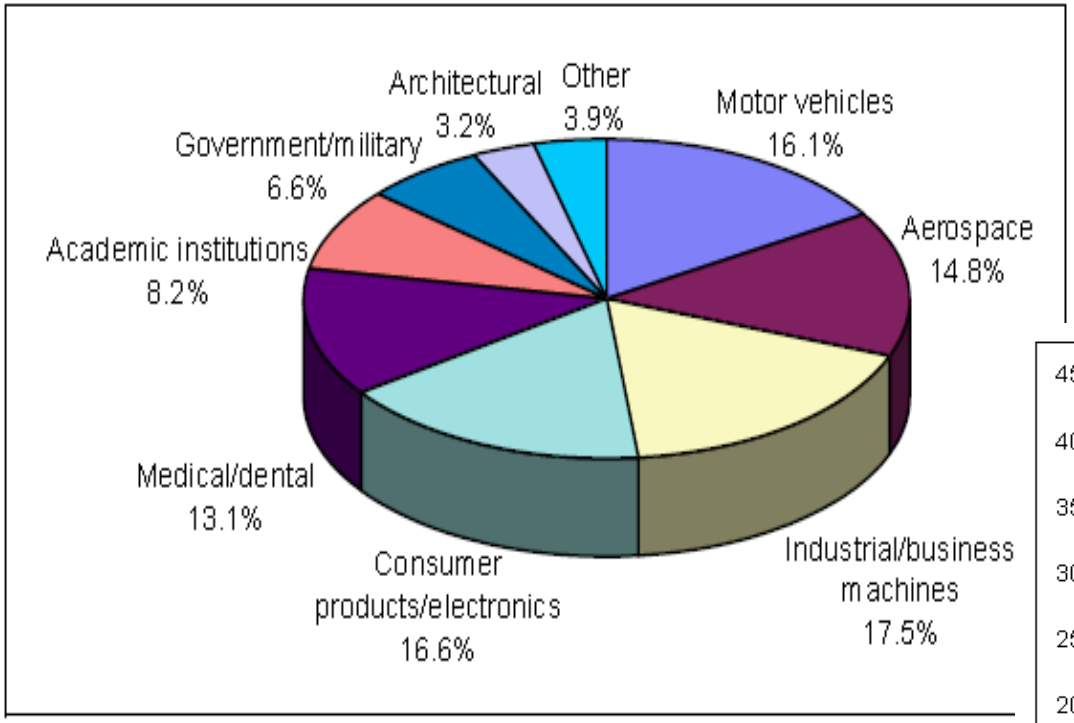
Stagnation Sensors

* Courtesy of MesoScribe Technologies

MESOSCRIBE TECHNOLOGIES

The Market for AM is Broad & Growing

AM Has A Highly Diversified Market Base

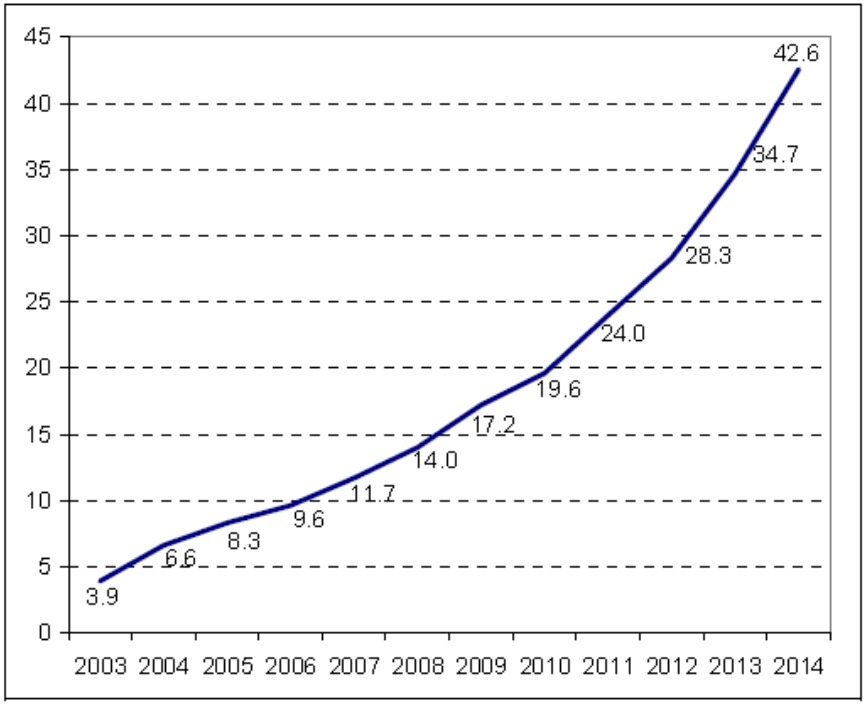


Source: Wohlers Associates, Inc.

Taken from *Wohlers Report 2015* with permission

Use of AM for Part Production More Than10 Fold From 2003 to 2014

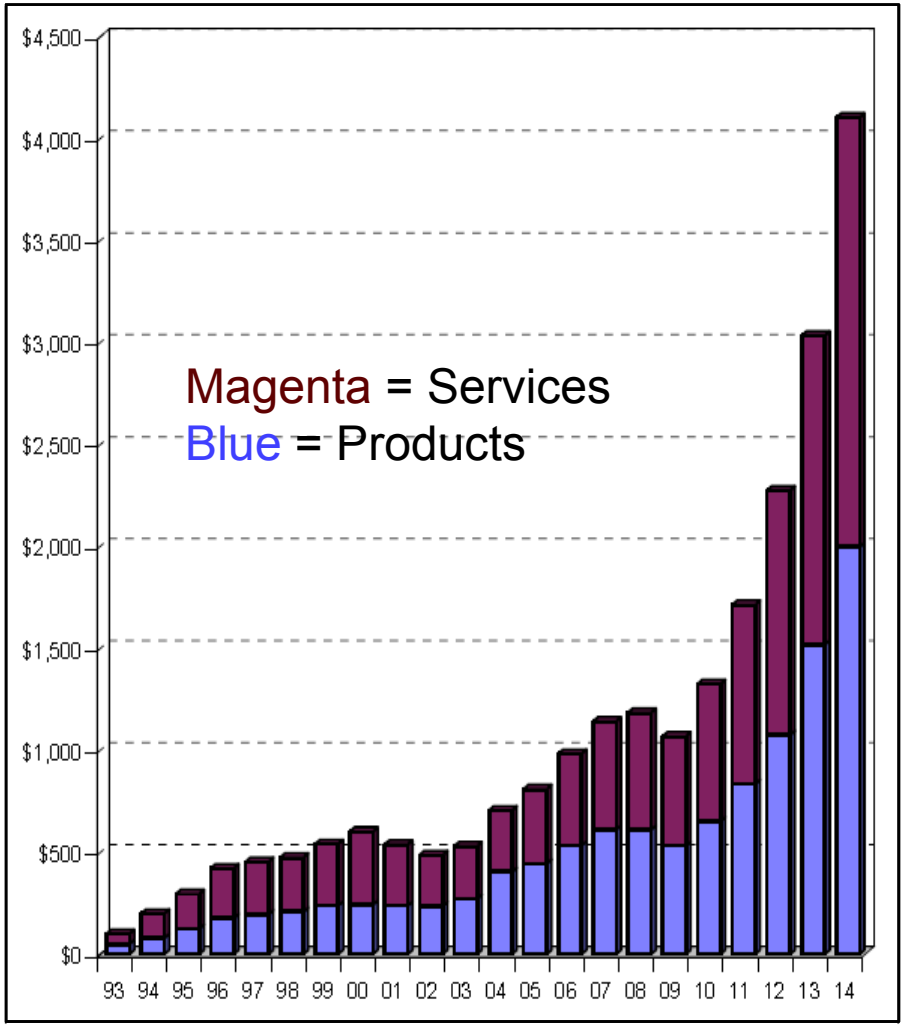
(% of total product/service revenue)



Source: Wohlers Associates, Inc.

Total Revenues & Metal AM Are Growing Rapidly

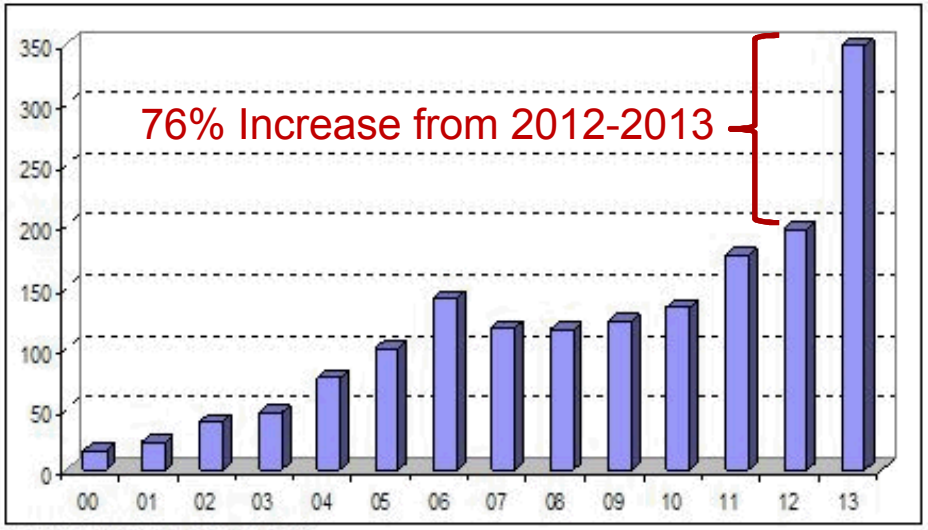
Total Worldwide AM Revenues ($M)



Source: Wohlers Report 2014

The US, Europe, and Far East are all major players in the world market with the US having the largest installed base of AM machines

Annual Sales of Metal AM Machines



Source: Wohlers Report 2014

Taken from *Wohlers Report 2014* with permission

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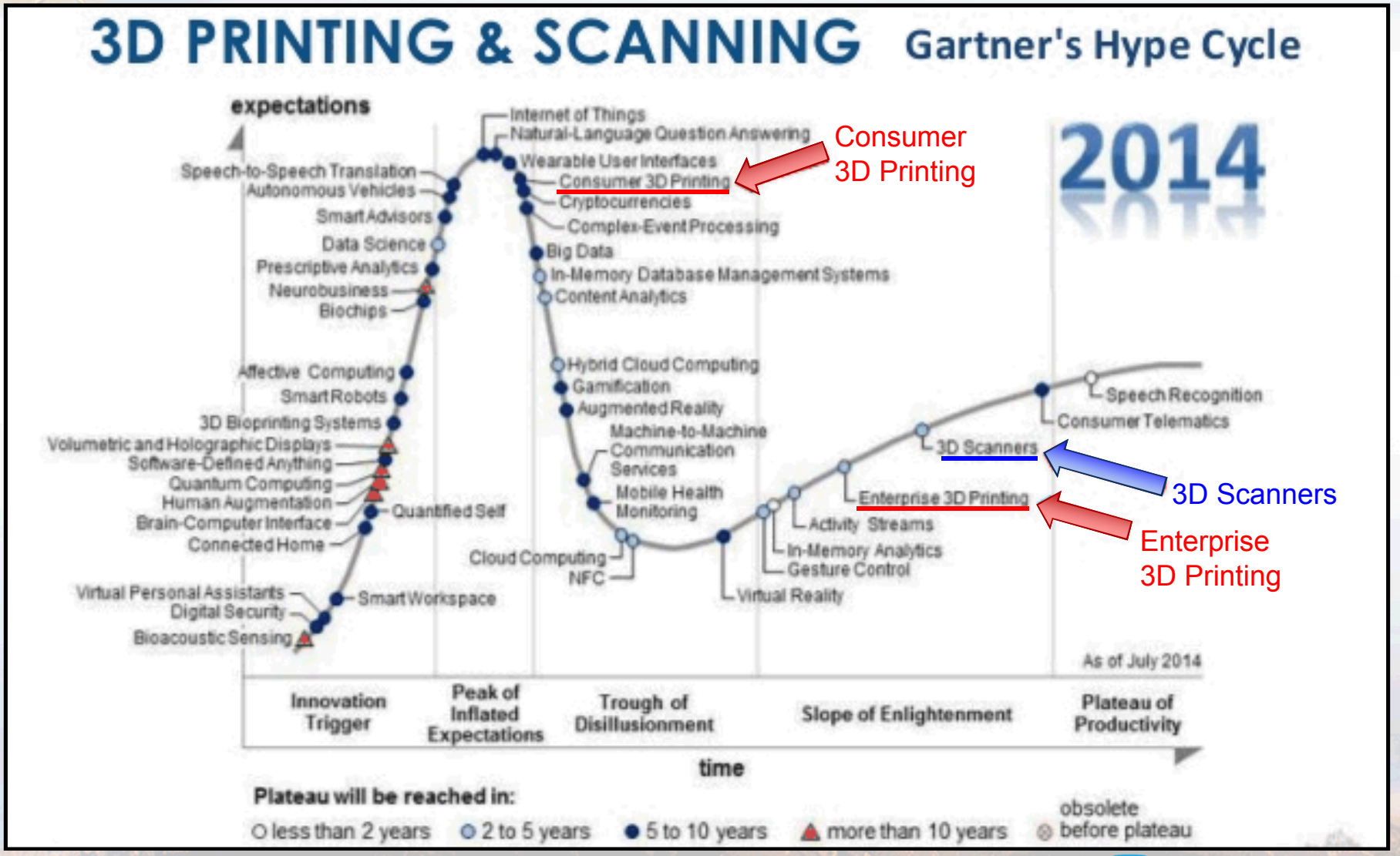
Commercial 3D Printing is Maturing



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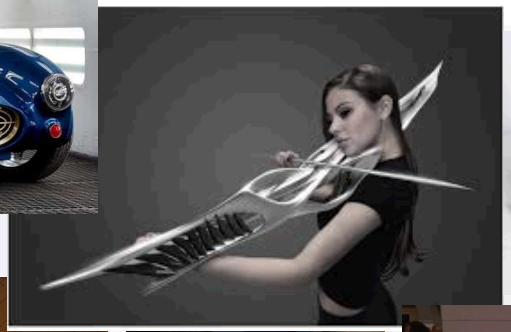
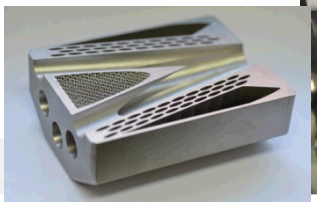
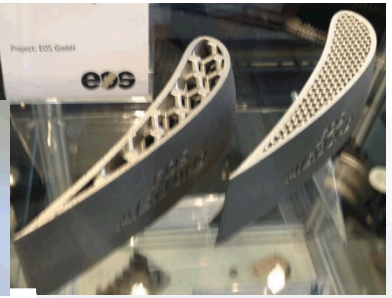
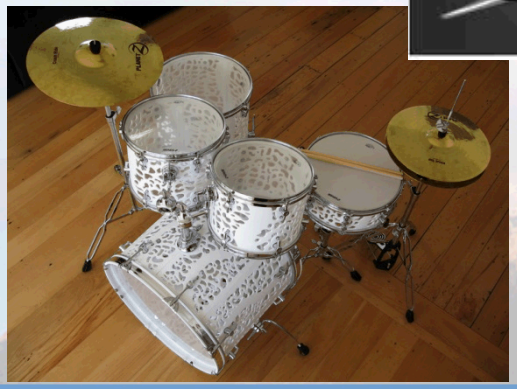
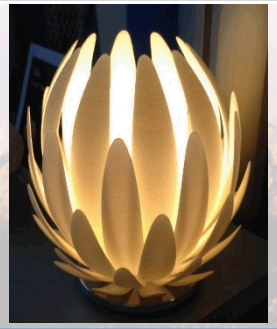
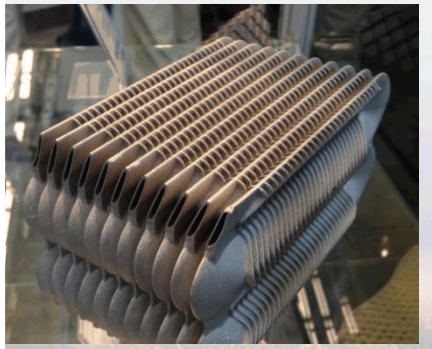
Closing Remarks

- 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
- This may be a good time to consider an initial entry into this rapidly growing market

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