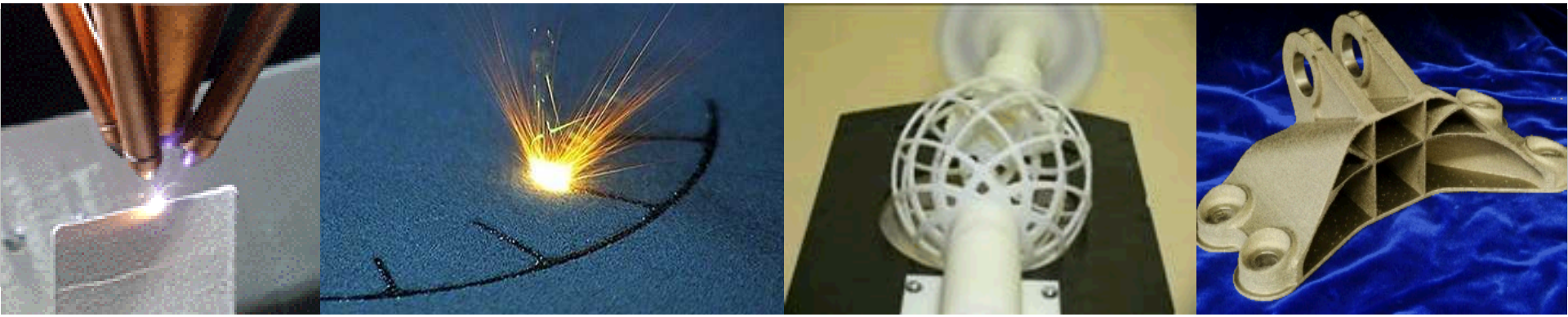
SAND2015-6731C

Exceptional service in the national interest

Sandia National Laboratories



The Wonderful (and not so wonderful) World of Additive Manufacturing

Dr. Mark F. Smith

Materials Science & Engineering Center

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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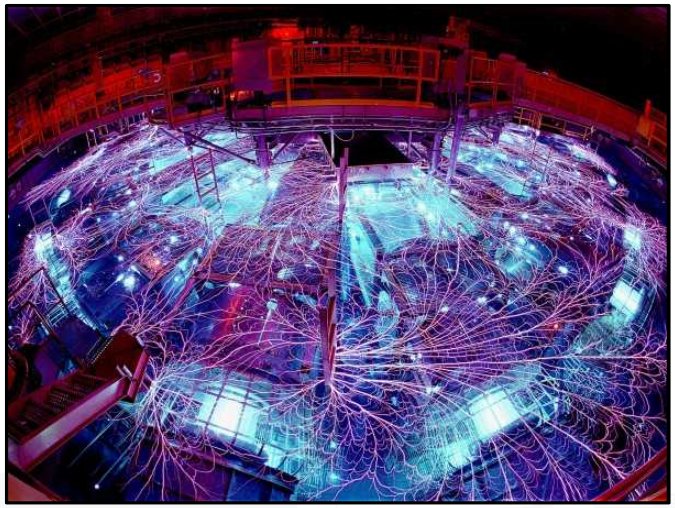
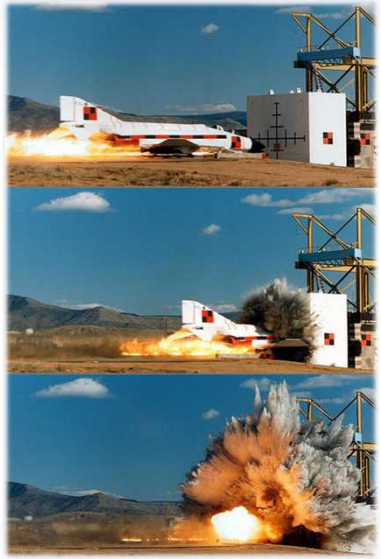
Sandia is a National Security Science and Engineering Laboratory

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

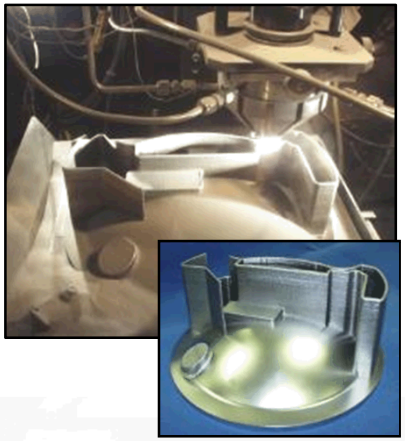
"We work on technologies at a scientific lab, but we must emphasize that science is not an end. The end is solving problems for the nation. Science is perhaps the best tool to achieve that end."

C. Paul Robinson, SNL President 1995-2005

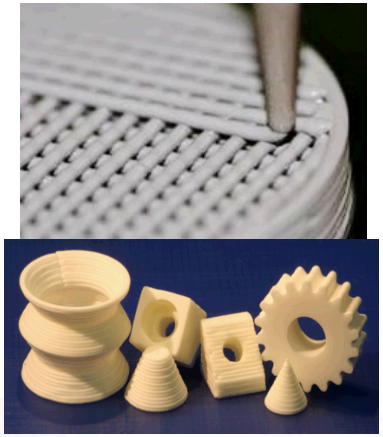
30+ yrs of Sandia AM Tech Development & Commercialization

FastCast*
Development Housing

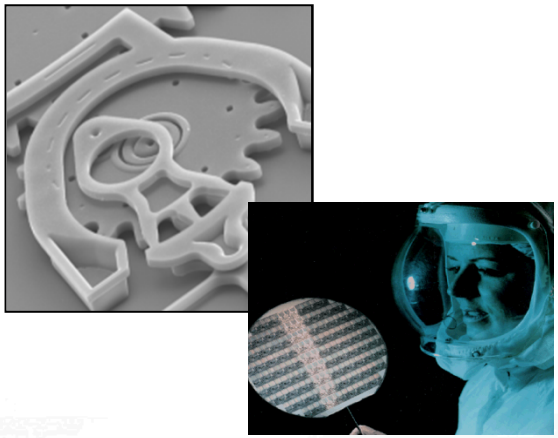
LENS®*
Stainless Housing



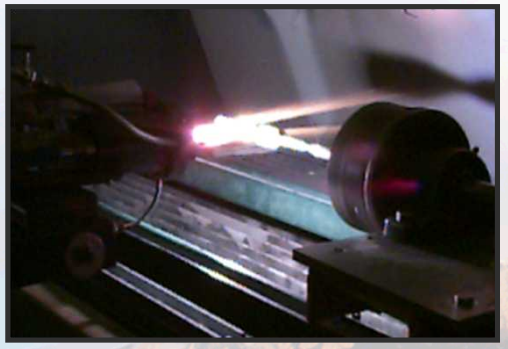
RoboCast *
Ceramic Parts



MEMS SUMMIT™ *
Micro Gear Assembly

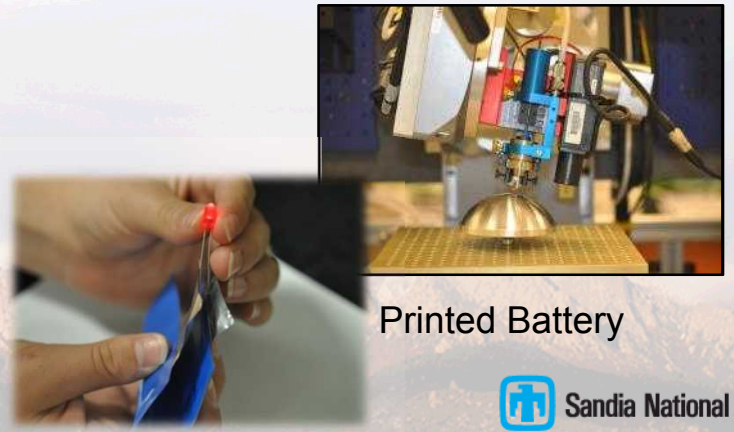


Spray Forming
Rocket Nozzle



LIGA
Miniature Spring

Direct Write
Conformal Electronics



Printed Battery

* Licensed/Commercialized SNL AM technologies

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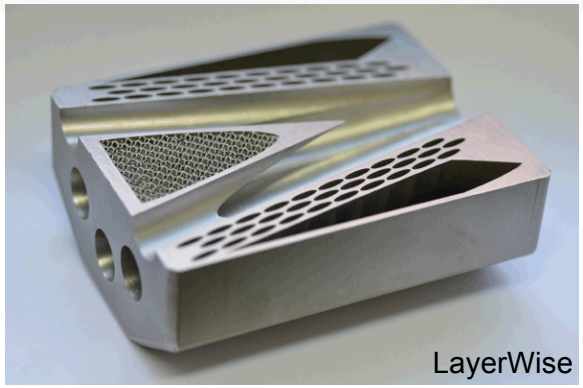
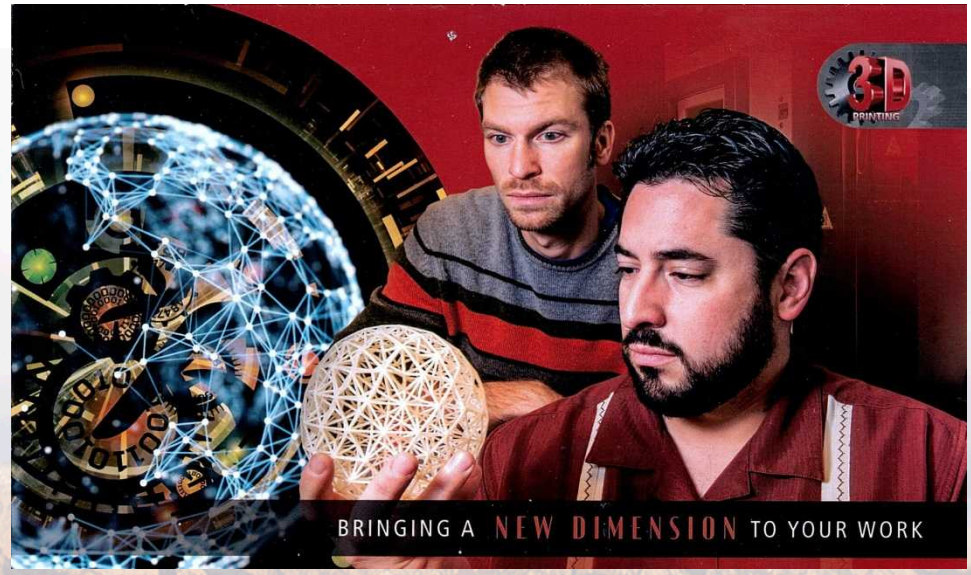
A Balanced Overview of Additive Manufacturing

- *What is Additive Manufacturing?*
- *Potential Advantages -- Examples*
- *Potential Limitations -- Examples*
- *Some Important Trends*
- *Summary*


LayerWise

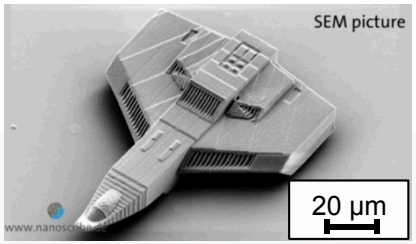

Commercial Metal AM Machine


Sandia Hand

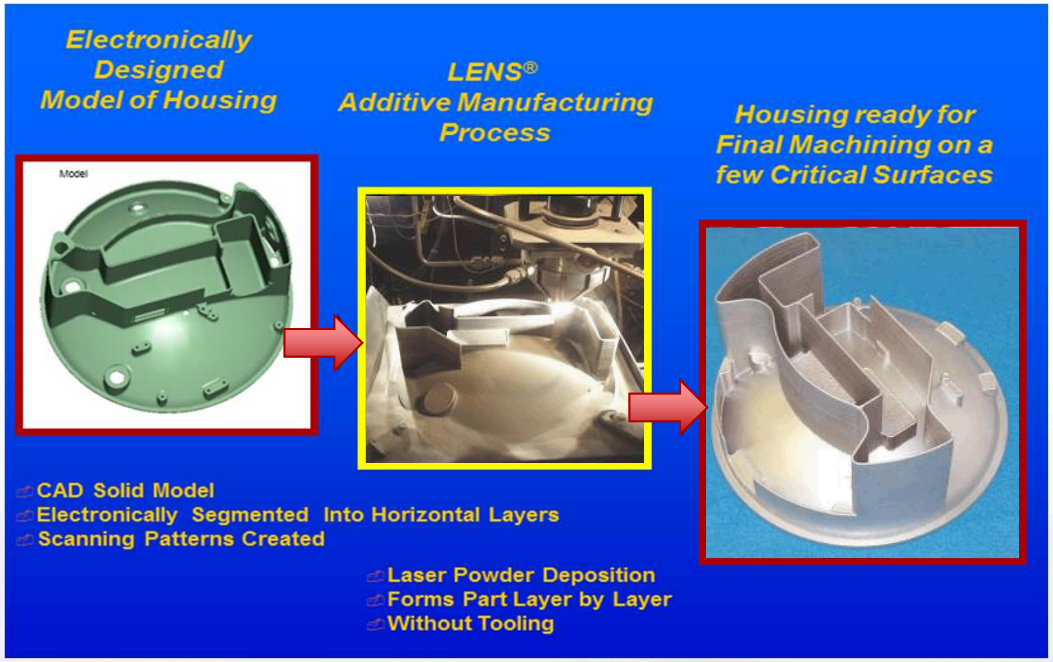


What is Additive Manufacturing (AM)?

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
- *Multi-Material* – Great Potential, Needs Further Development

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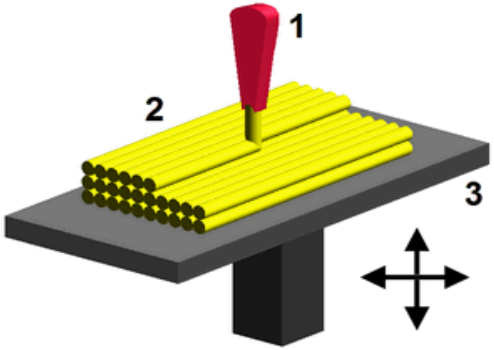
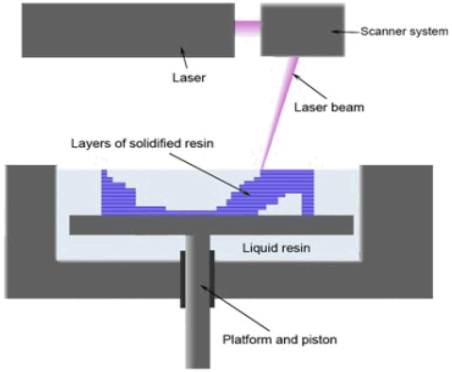
7 ASTM Additive Manufacturing "Process Categories"

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



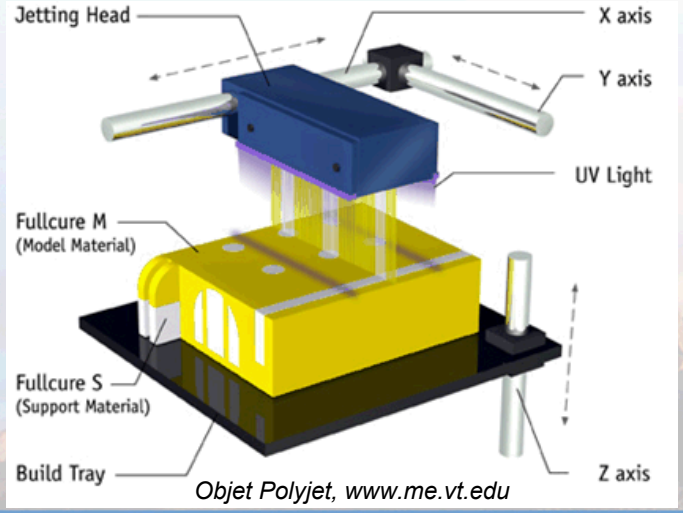
"Fused Deposition Modelling", Wikipedia

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



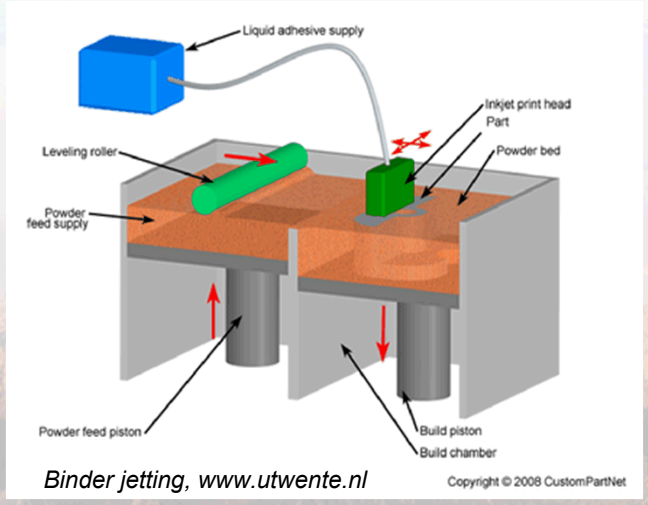
"Stereolithography", Wikipedia

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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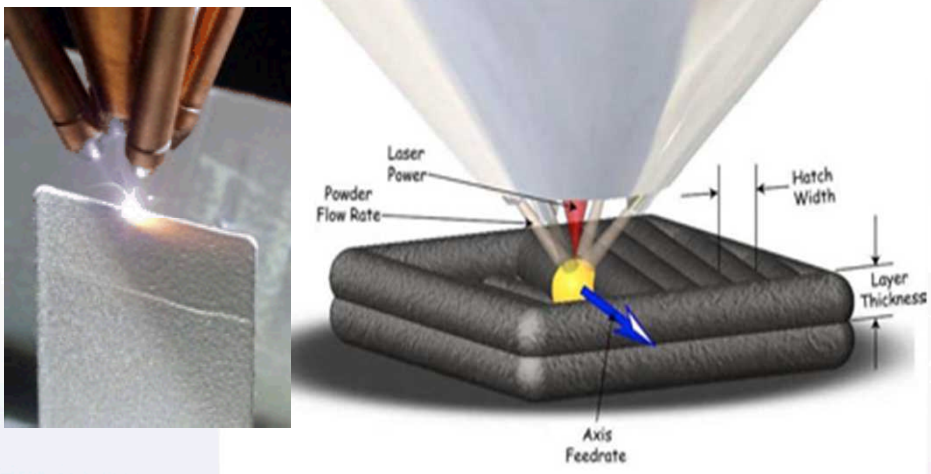
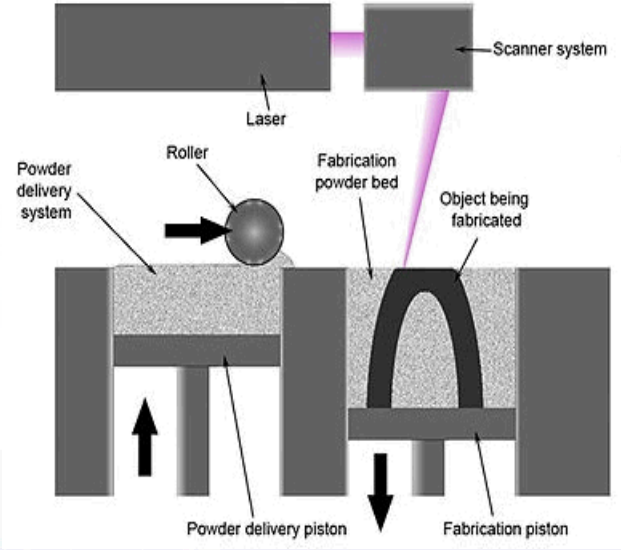
7 ASTM Additive Mfg. "Process Categories"

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

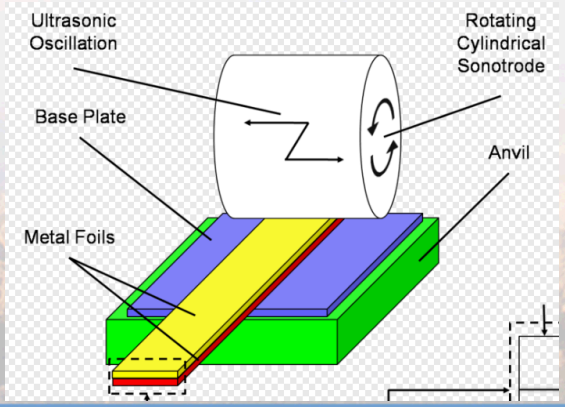


Powder Bed Fusion (Laser or e-Beam)
Thermoplastics, Metals, Ceramics



"Selective laser melting", Wikipedia

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



"Ultrasonic consolidation", Wikipedia

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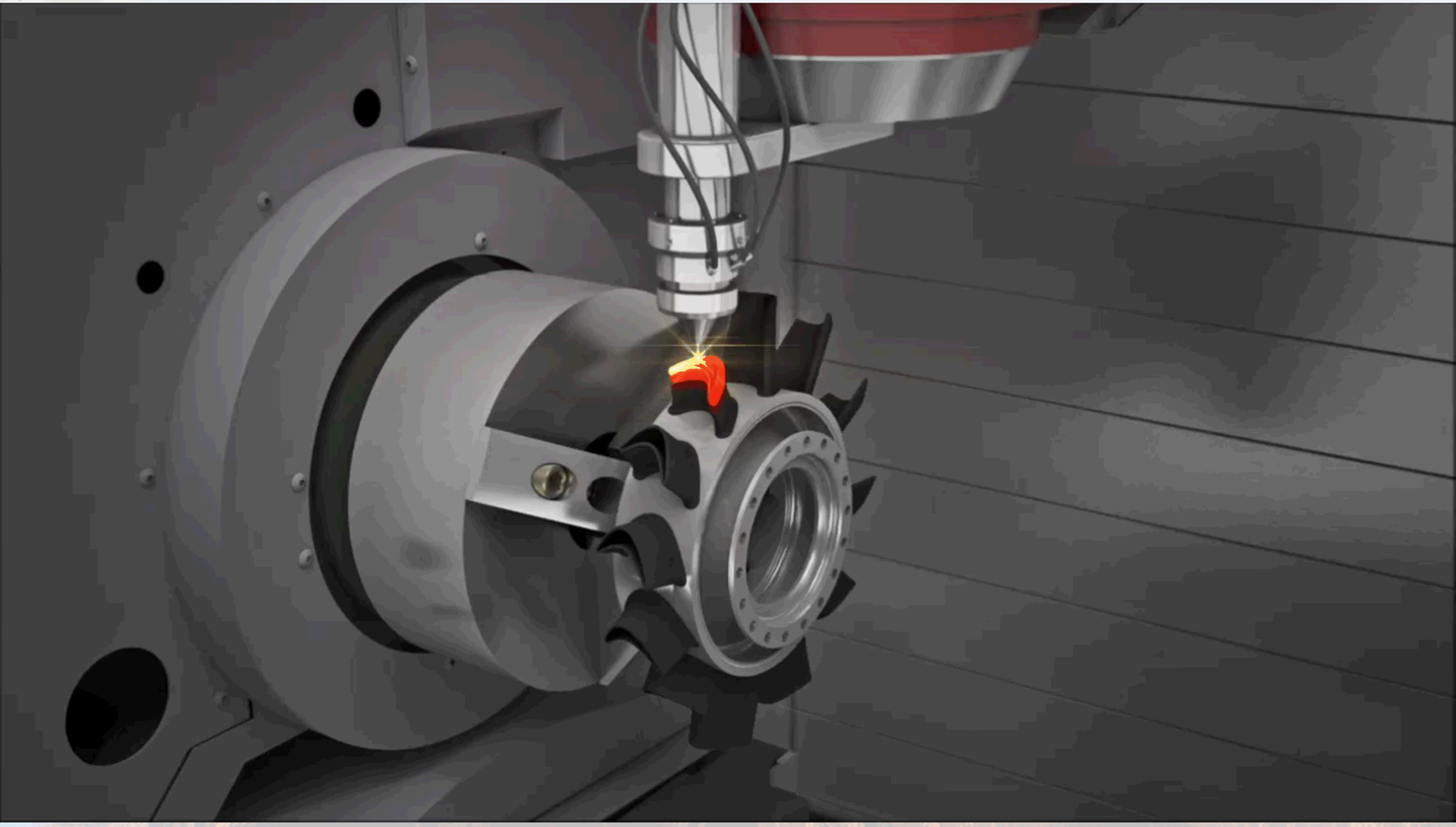
"Hybrid" Additive/Subtractive Machine Tools

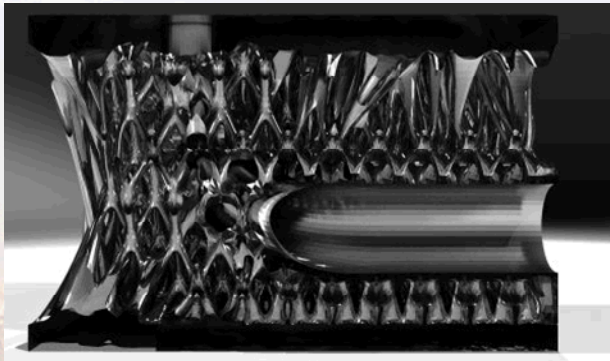


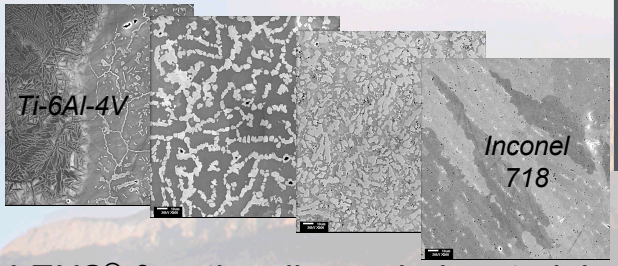
Video Courtesy of DMG Mori

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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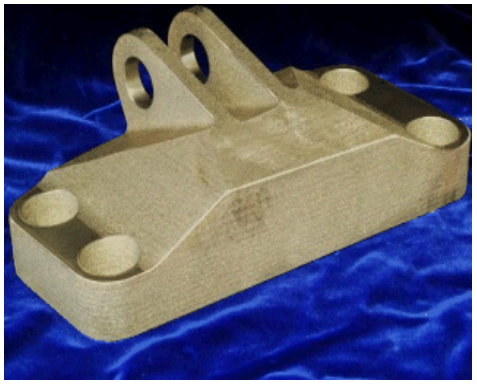
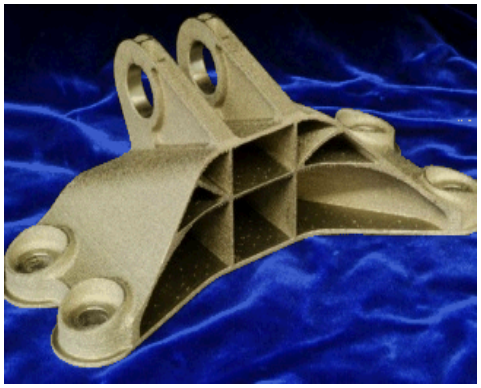
Commercial Aerospace Hardware

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 technology
- Replaces 18 parts with 1 -- eliminates joining operations
- 25% lighter, 5x more durable
- 19 fuel nozzles per engine
- New $50M Mfg. Plant, Auburn, AL, to build 40,000 nozzles/yr

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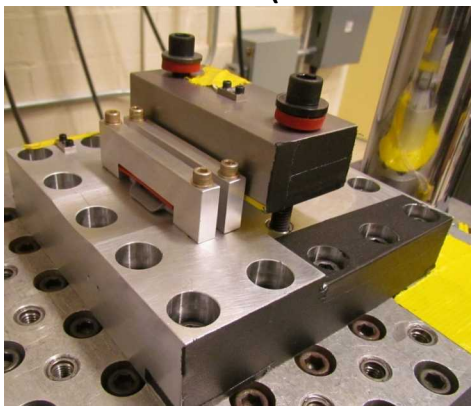
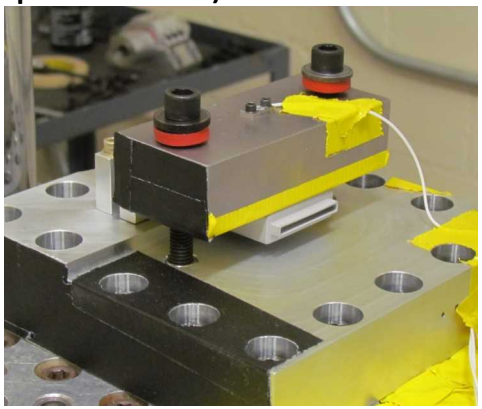
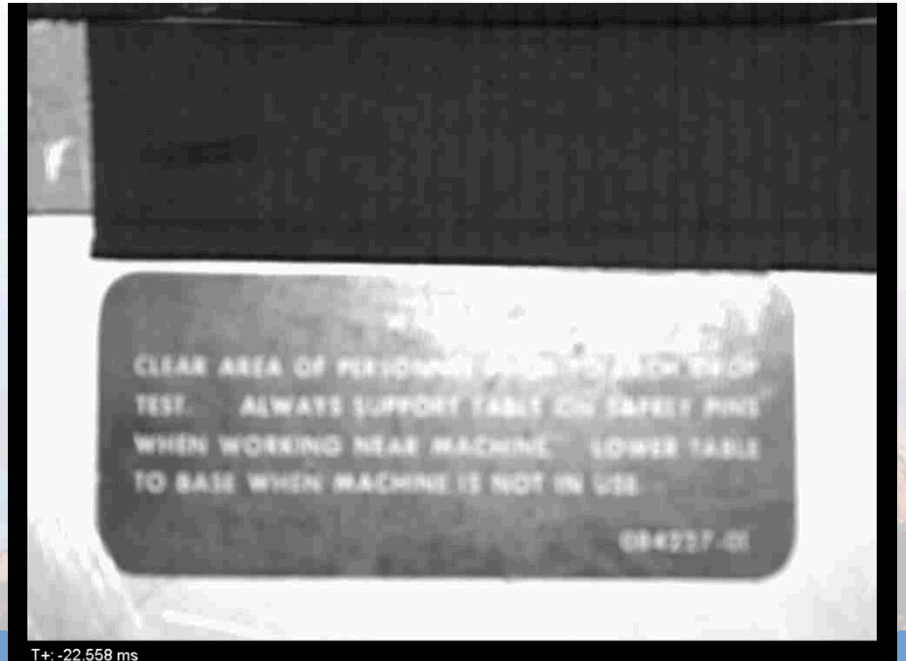
*CFM is a 50/50 Snecma/GE Company

Superior Impact Performance

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







Cast, A380
1 pc, 38 g

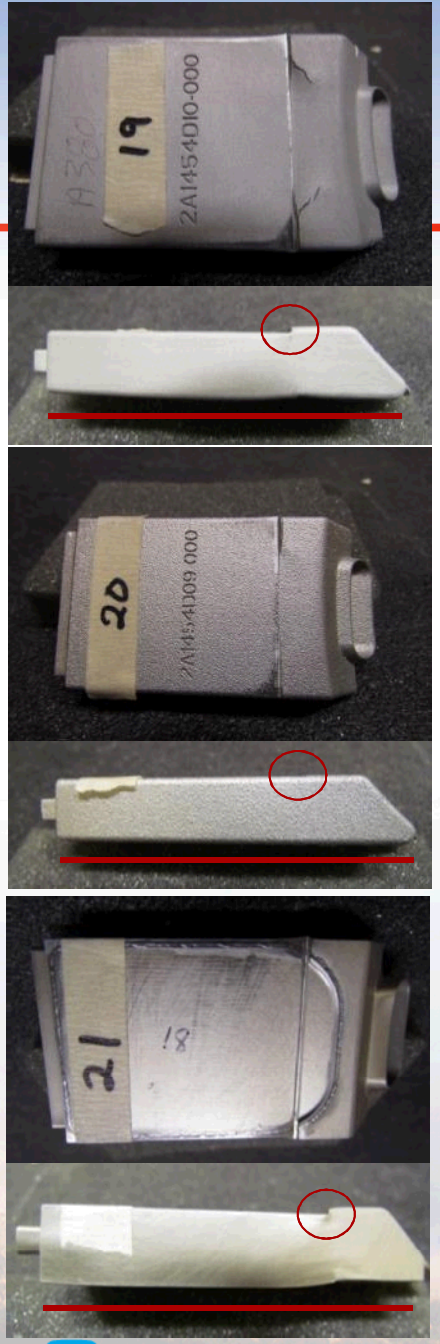
- cracked
- buckled

AM, AlSi10Mg
1 pc, 38 g

- slight indent
- still straight
- 156% higher ultimate failure point

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

- weld cracks?
- buckled



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ORNL “3D Printed” Cobra

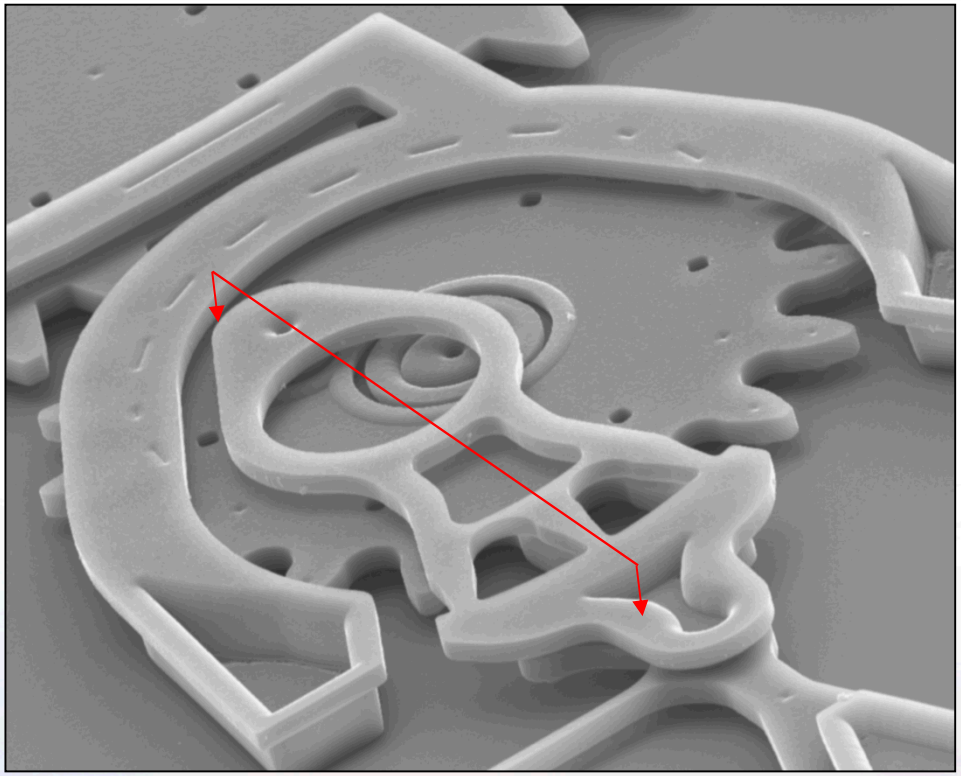
Oak Ridge National Lab/Cincinnati Inc.
50th Anniversary “BAAM” Shelby Cobra

Local Motors
“Rally Fighter”

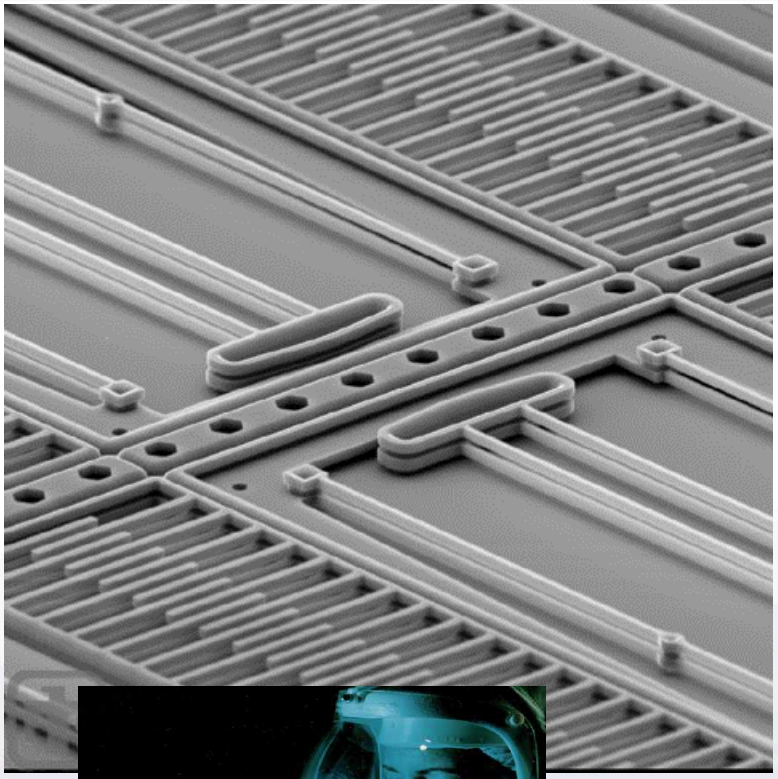
Sandia National Laboratories

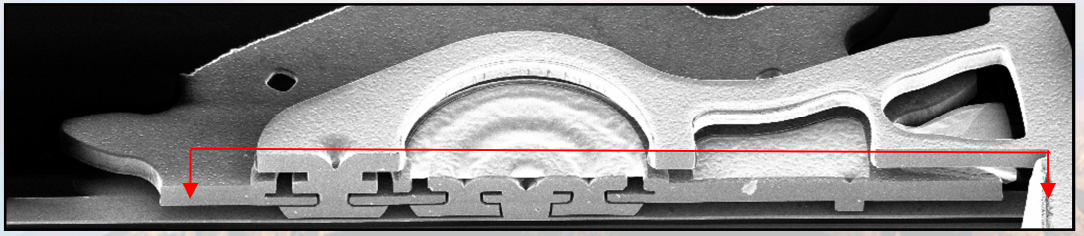
SUMMiT™ Process
(Sandia Ultra-planar Multi-level MEMS Technology)

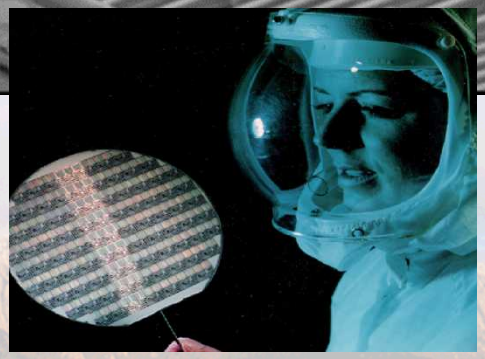
Gear Assembly



Comb Drive







There is no piece part assembly!

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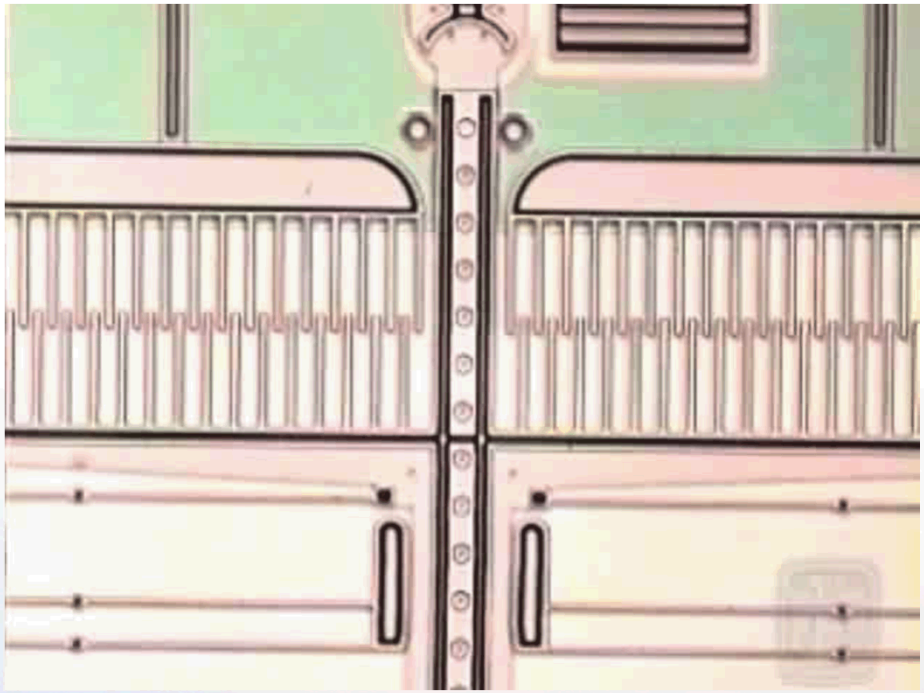
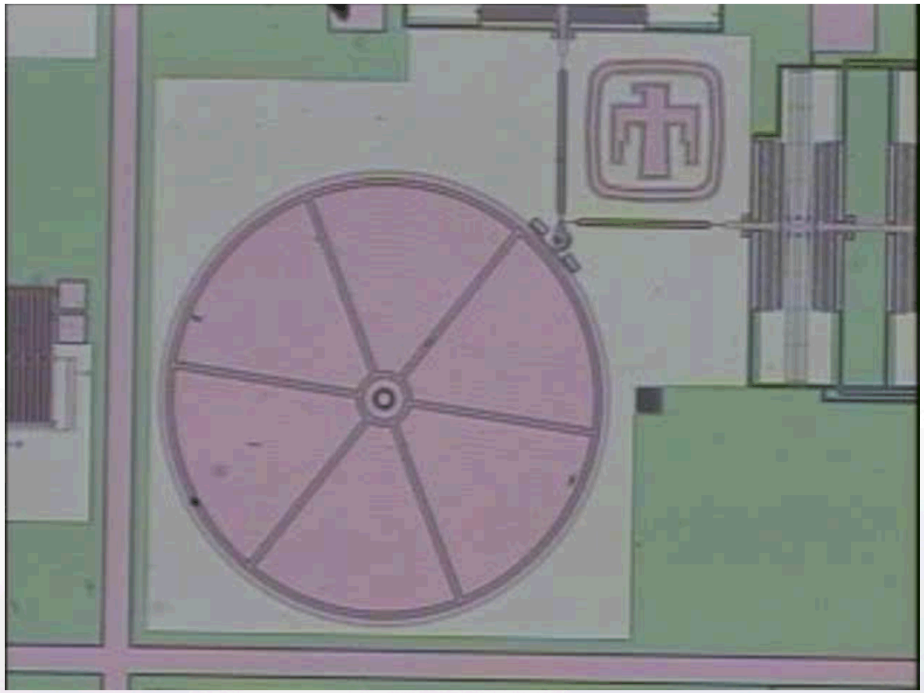
MEMS Drives in Action





Sandia μChemLab™

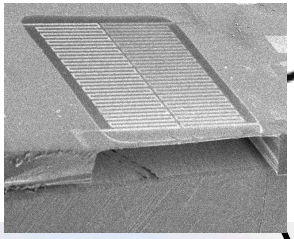
Need:

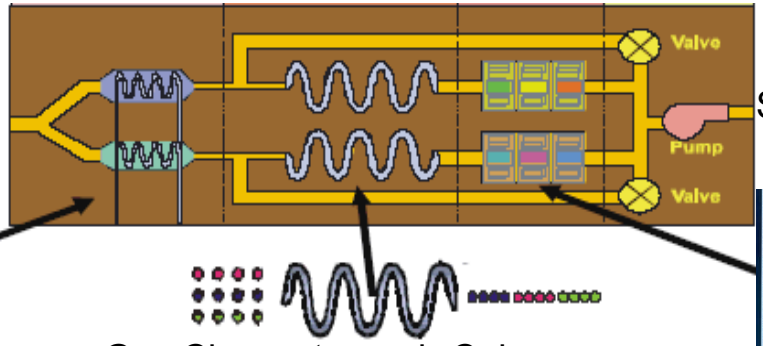
- Small, inexpensive, handheld analyzer for military, first responders, and other applications

Technical Approach:

- Use MEMS to create functional components
- Use Gas Chromatography (GC) column together with selective-surface sensors for analysis.

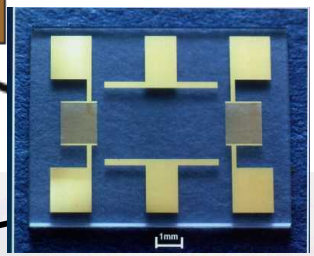
Pre-Concentrator Collects Species of Interest



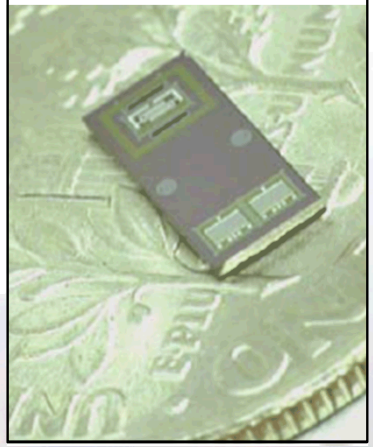


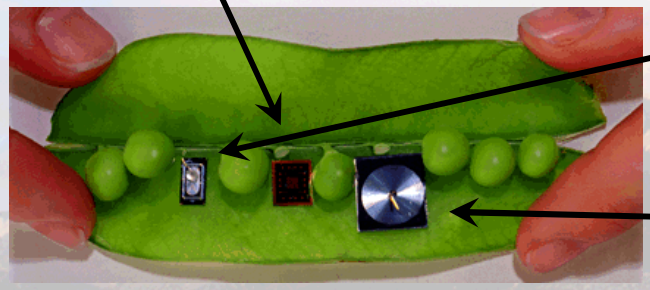
Gas Chromatograph Column Separates Species in Time

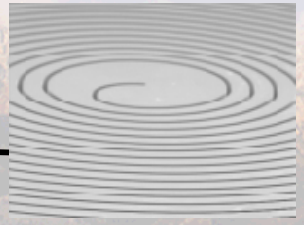
Chemically Selective Surface Acoustic Wave (SAW) Sensors

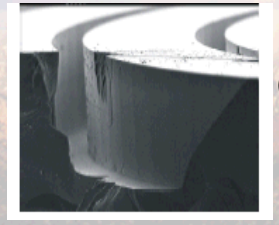


Current all-silicon unit on a dime







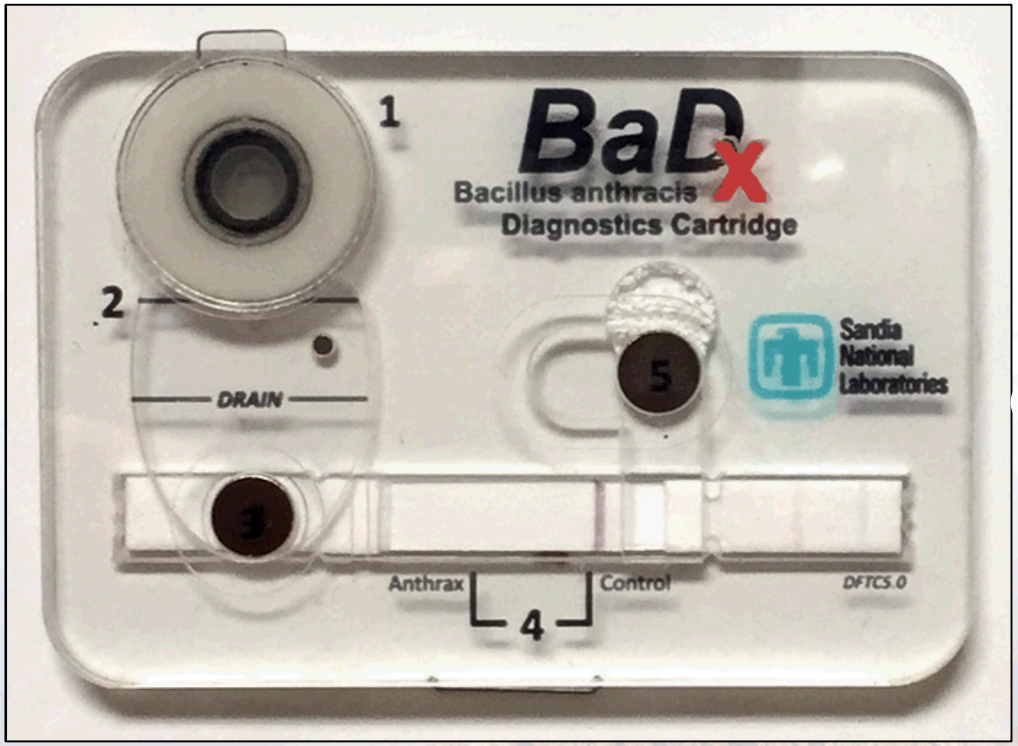


~1 Meter Gas Chromatograph Column

Sandia National Laboratories

BaDx Anthrax Diagnostics Tool

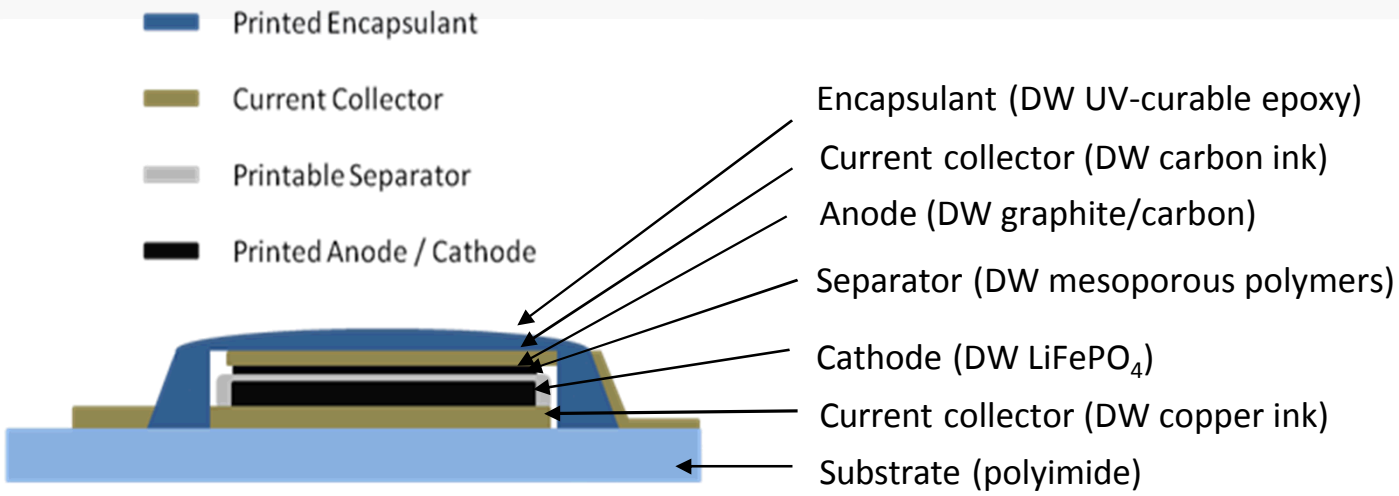
- Microfluidic platform for bacterial detection
- Rapid/inexpensive prototyping & design revisions
- Self-contained, credit card-sized “Lab in a Pocket”



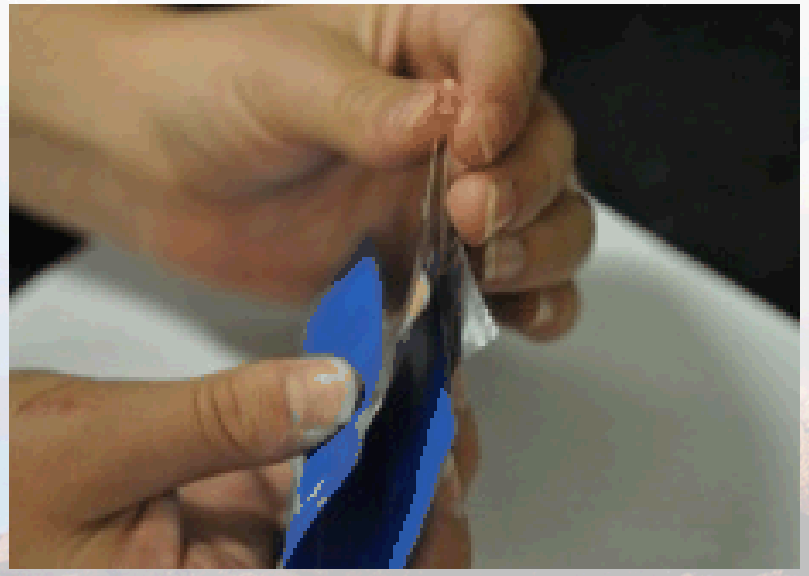
SNL Scientists Jason Harper, Melissa Finley, and Thayne Edwards

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

3D Printed Flexible Battery



Roll-to-Roll Printed Electronics



Cleveland Clinic Prosthetics

ALLELES Design Studio, CA

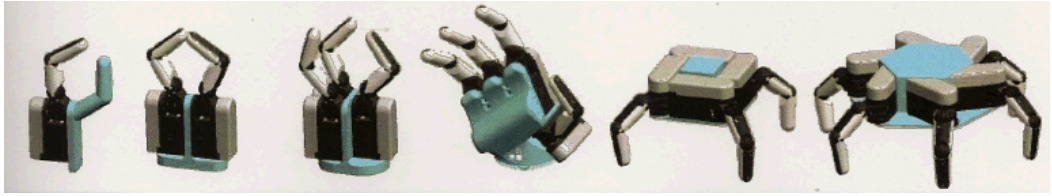
Sandia National Laboratories

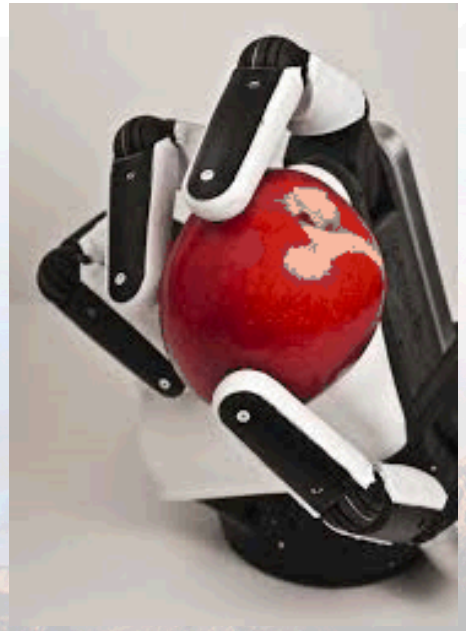
Sandia Hand – AM Enabled Innovative Design and Substantial Cost Reduction

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

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

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





Sandia National Laboratories

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 AM be used to design/build more complex integrated components?

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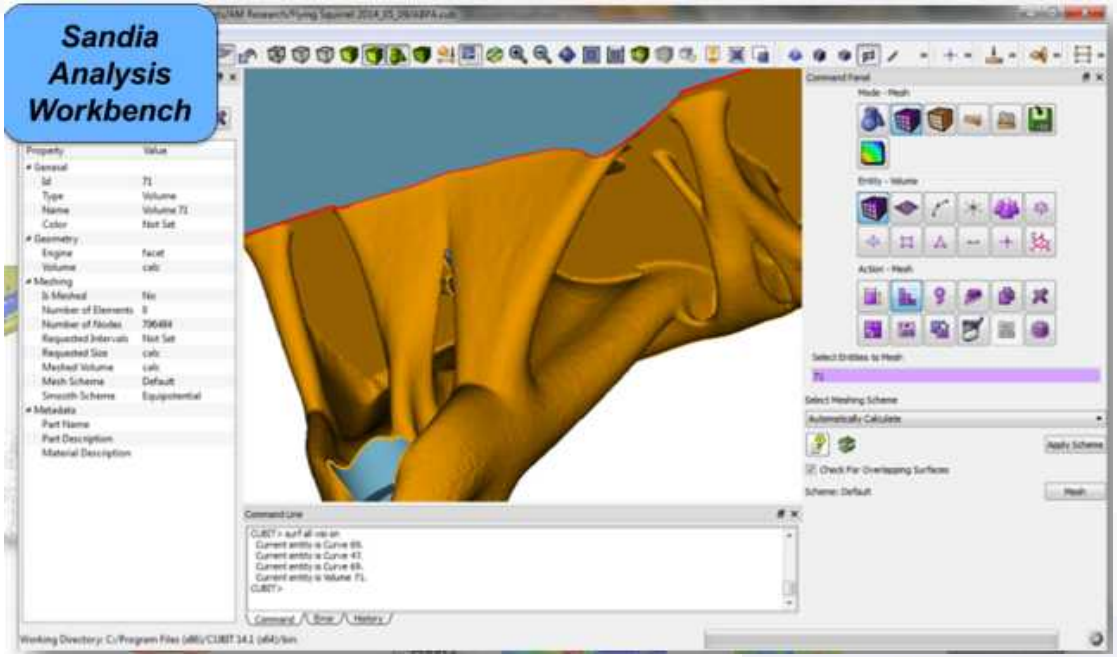
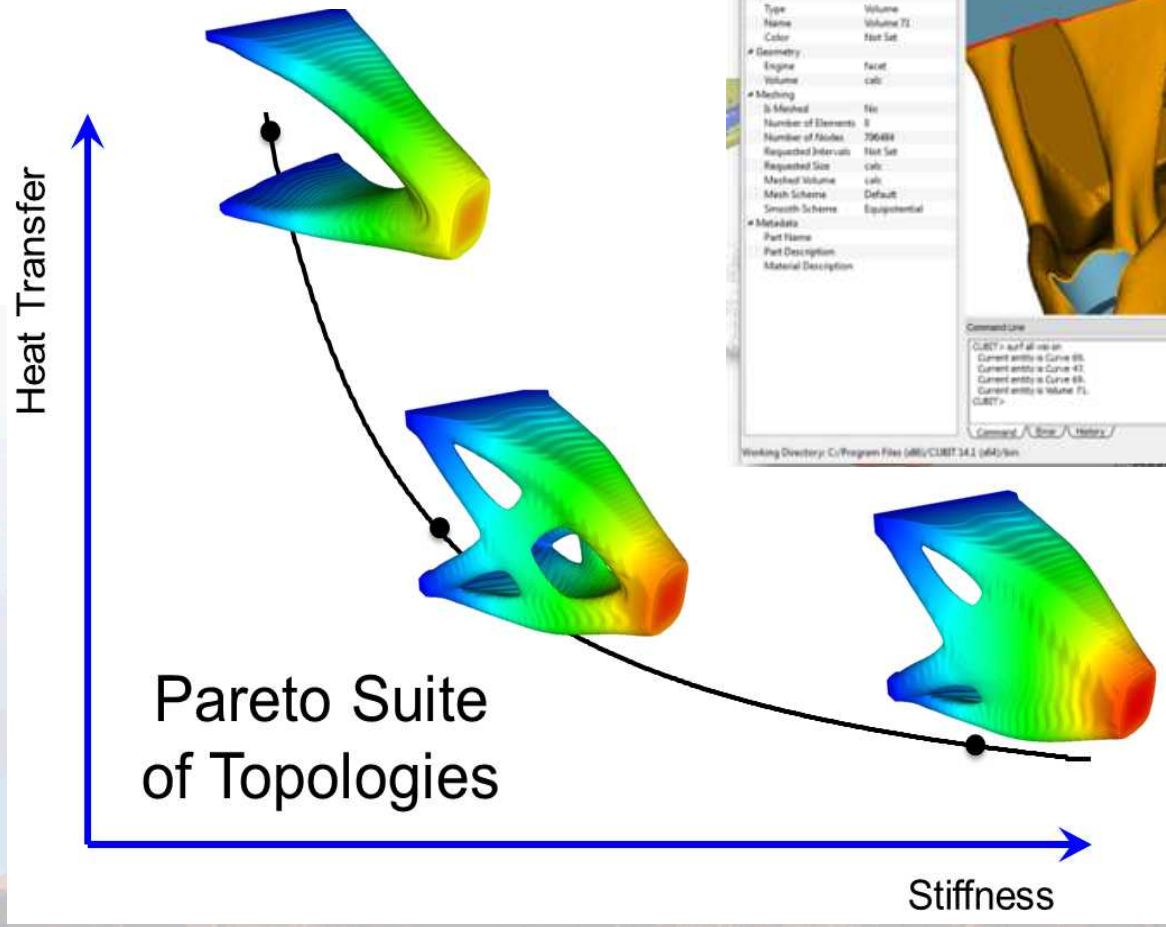
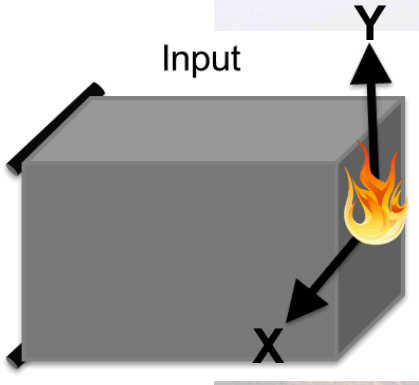
AM Design Via Functionality Prioritization

User Friendly Interface







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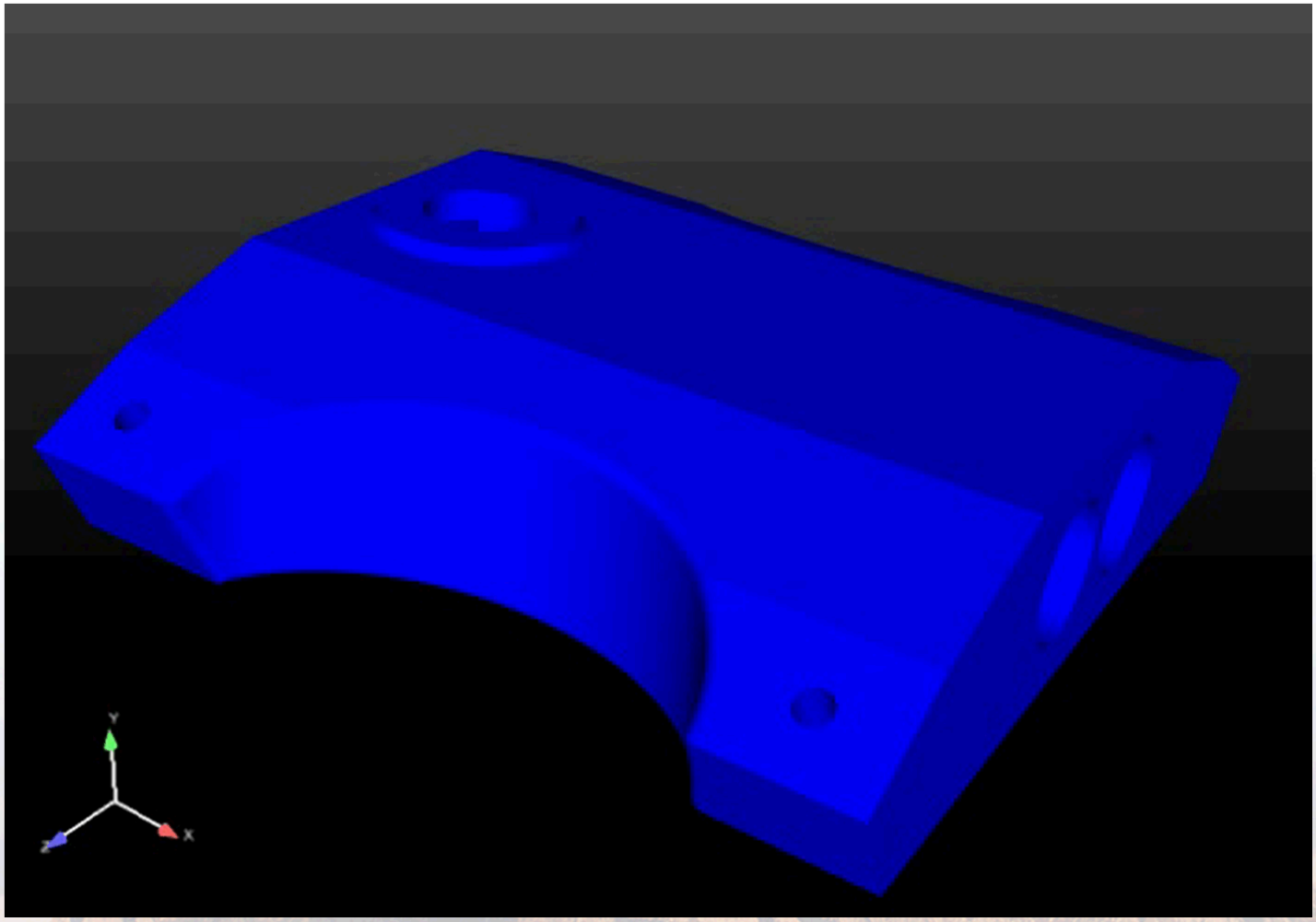
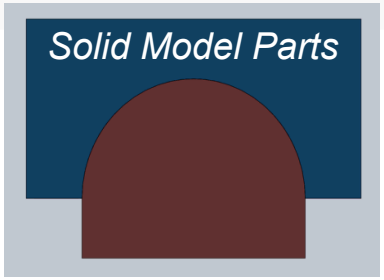
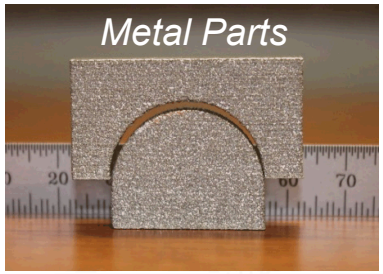
Early Topology Optimization Design

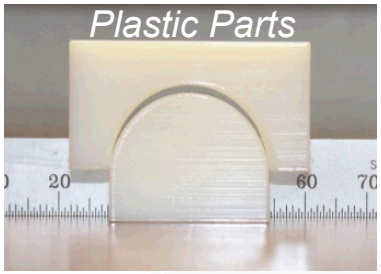


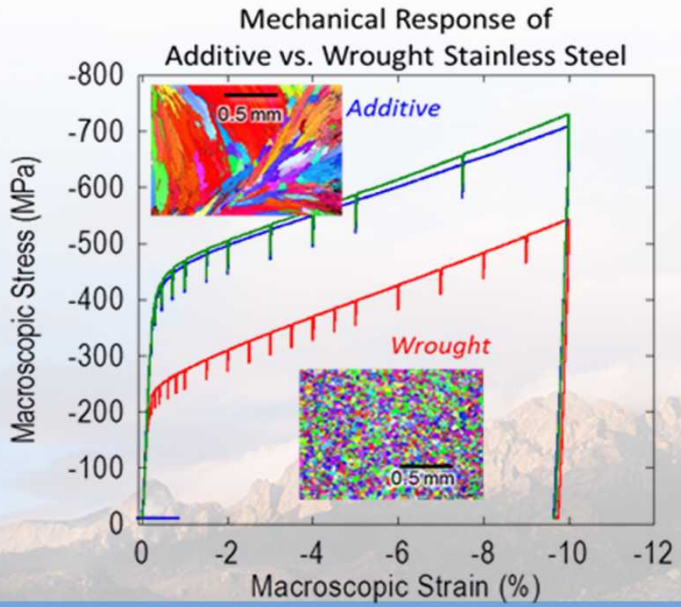
Why Not Additive?
Some Potential Disadvantages/Limitations

- AM Is Still an Evolving/Emerging Technology
- Many Sources of Variability – Still a Fair Amount of "Art"
- 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
- AM Isn't Always Faster/Cheaper
- Inspection/Metrology Challenges
- Additional Support Equipment

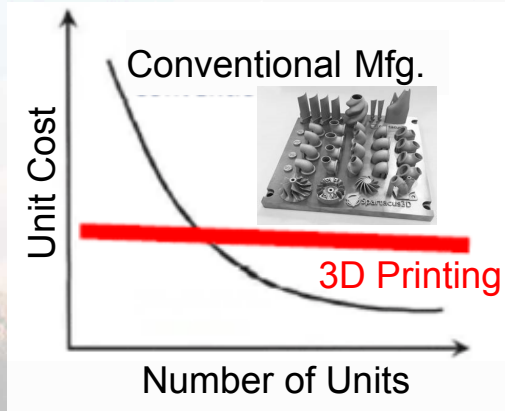


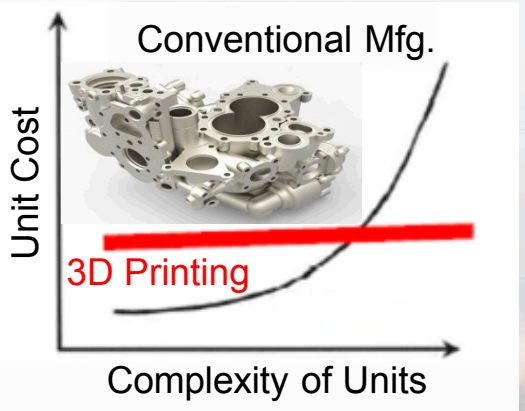






Notional Cost vs. Volume & Cost vs. Complexity Charts





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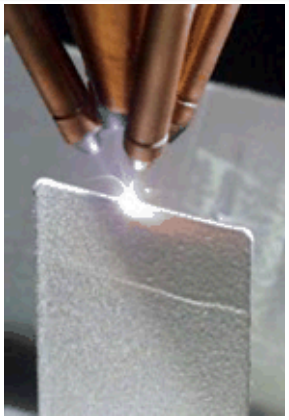
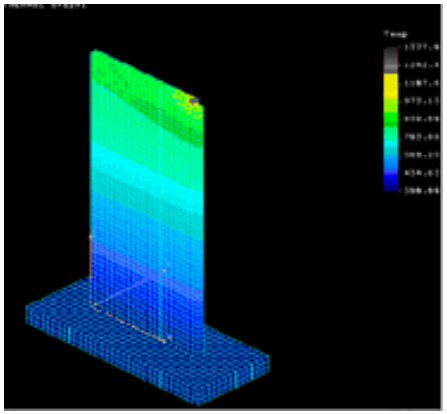
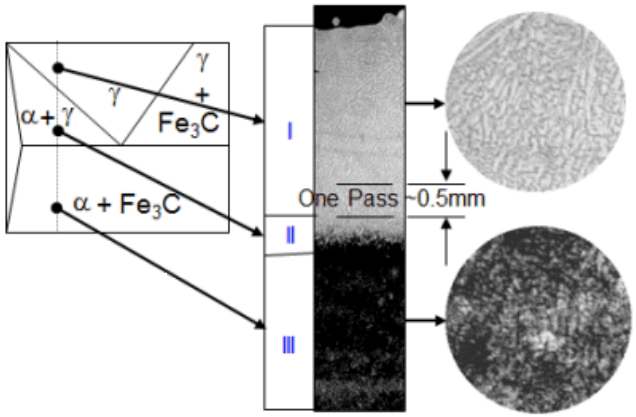
LENS® Process & Materials R&D

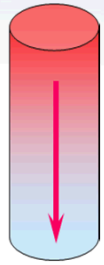
Process characterization/modeling





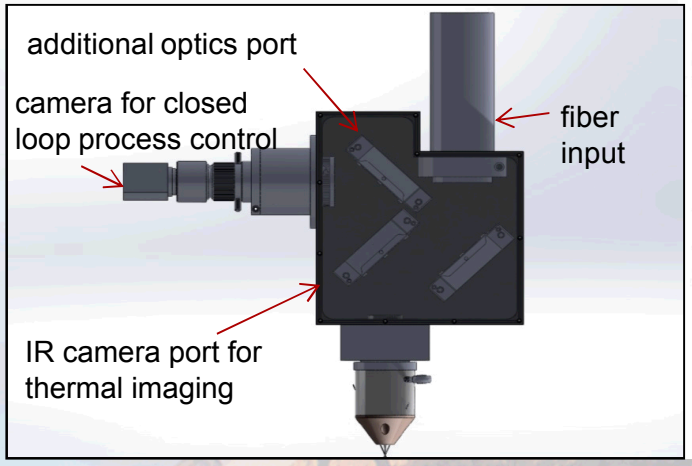


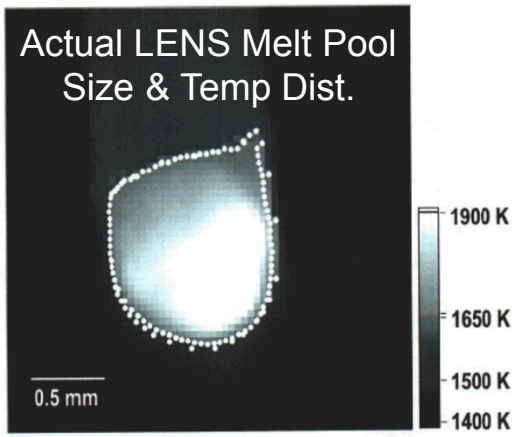
Part heats up during the build & heat flow changes -- so microstructure & properties in the top (I), middle (II), & base (III) may differ

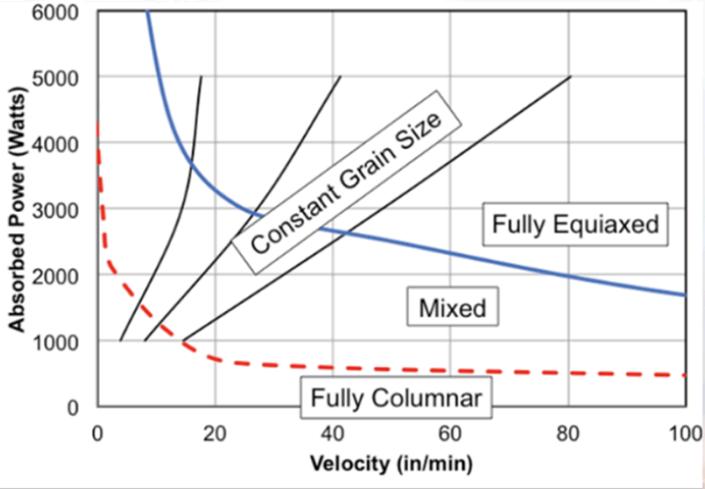


Uni-directional Solidification

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







Sandia has successfully demonstrated active control of melt pool size & temperature to control microstructure and reduce variability

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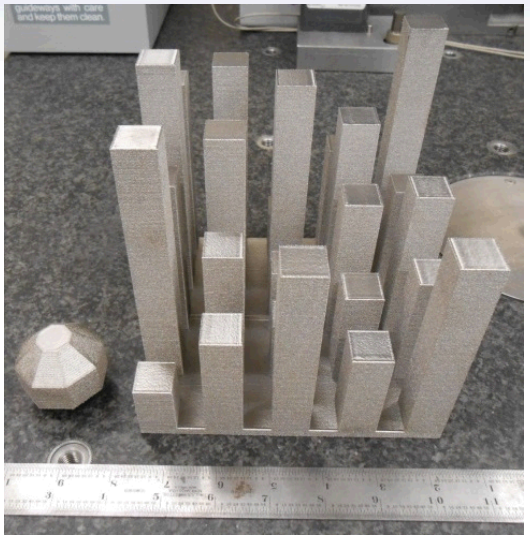
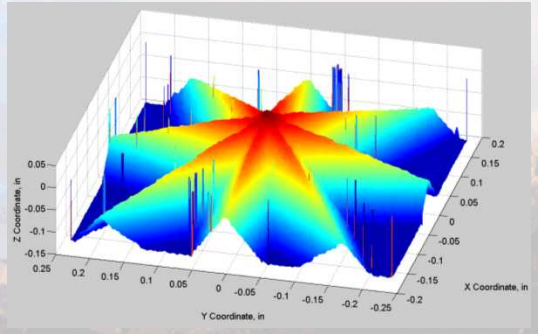
Metrology Is A Key Challenge

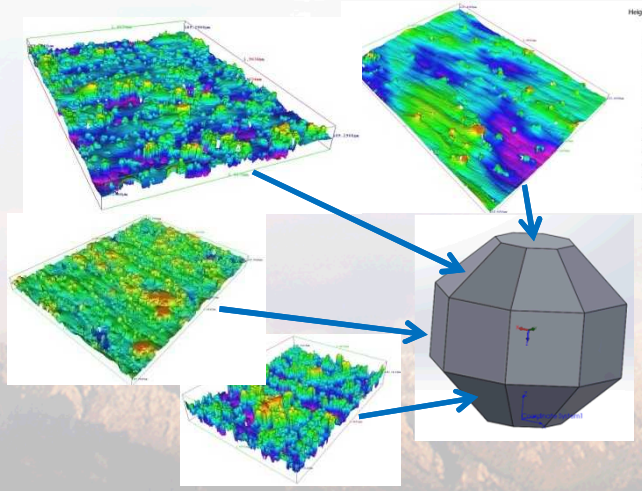
- Family of artifacts designed, printed, & measured
  - Fabrication has been easier than metrology
  - Working to develop optimum measurement techniques
- Unique challenges for process/equip. characterization
  - Tolerances/Surface Finish/Properties vary with machine, material, print orientation, support structures, post-processing,…
  - Sandia working with NIST to develop better metrology artifacts



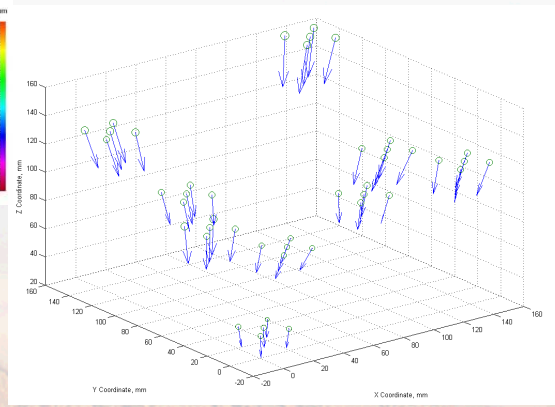
Ti-6Al-4V polyhedron & "Manhattan" artifacts for MPE (maximum permissible error)

Siemens star geometries for resolution evaluation





17-4PH polyhedron texture anisotropy map



"Manhattan" Error Map

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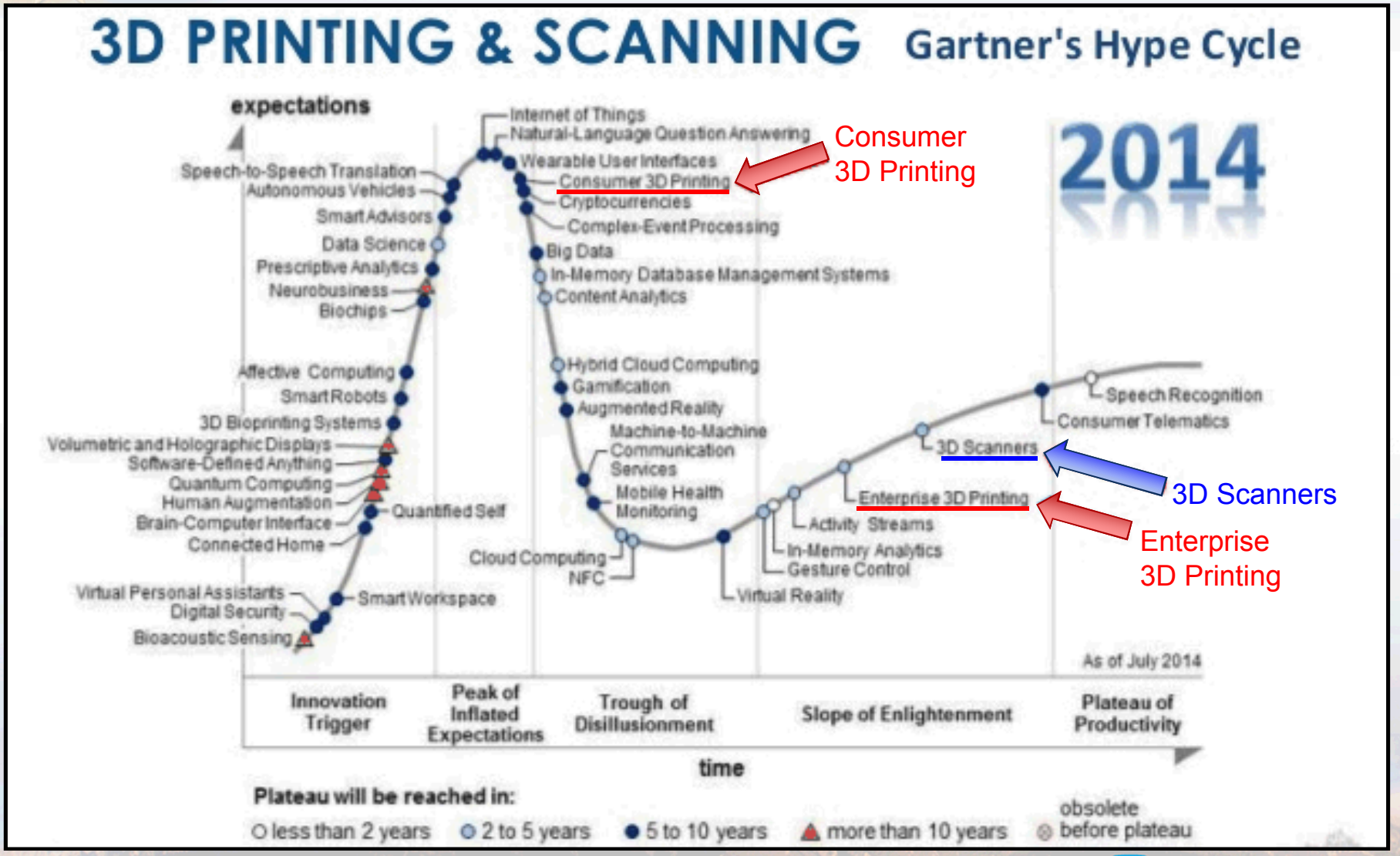
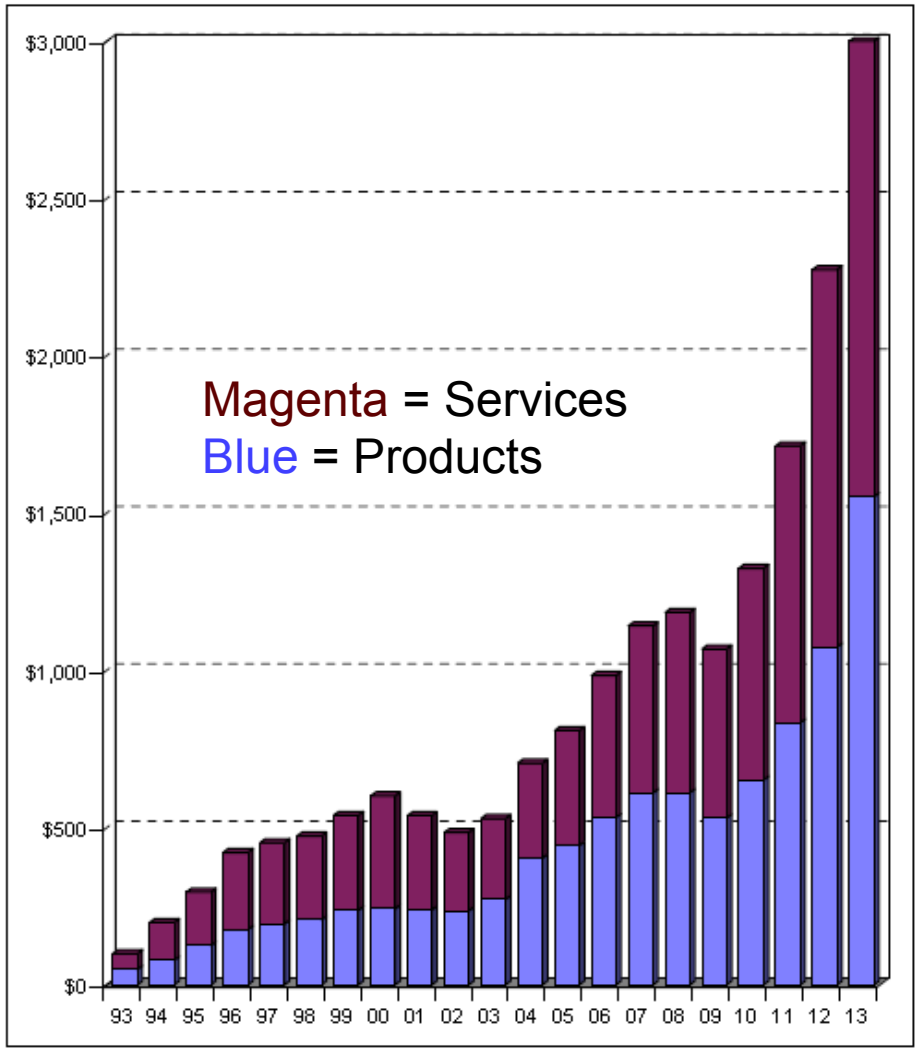
Commercial 3D Printing is Maturing



Total Revenues & Metal AM Are Growing Rapidly

Total Worldwide AM Revenues ($M)

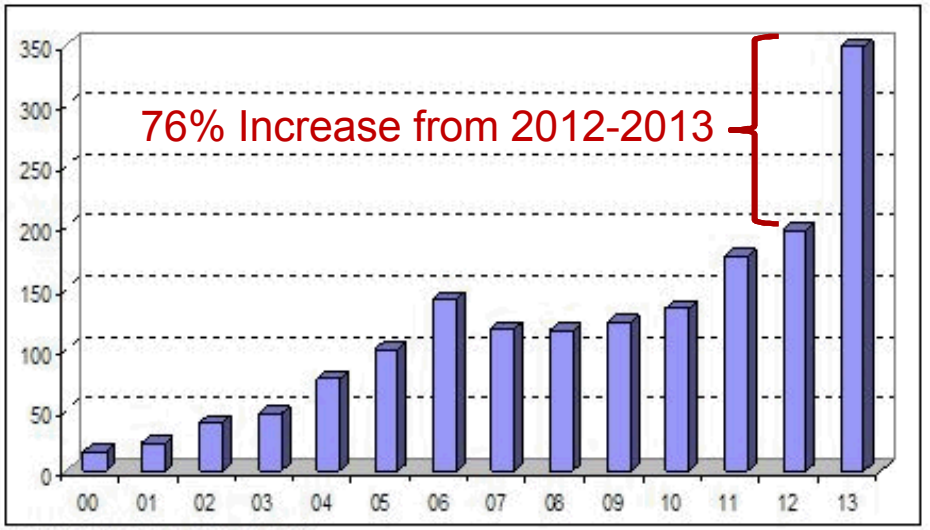


Source: Wohlers Report 2014

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

The cost of commercial AM machines is comparable to commercial machine tools

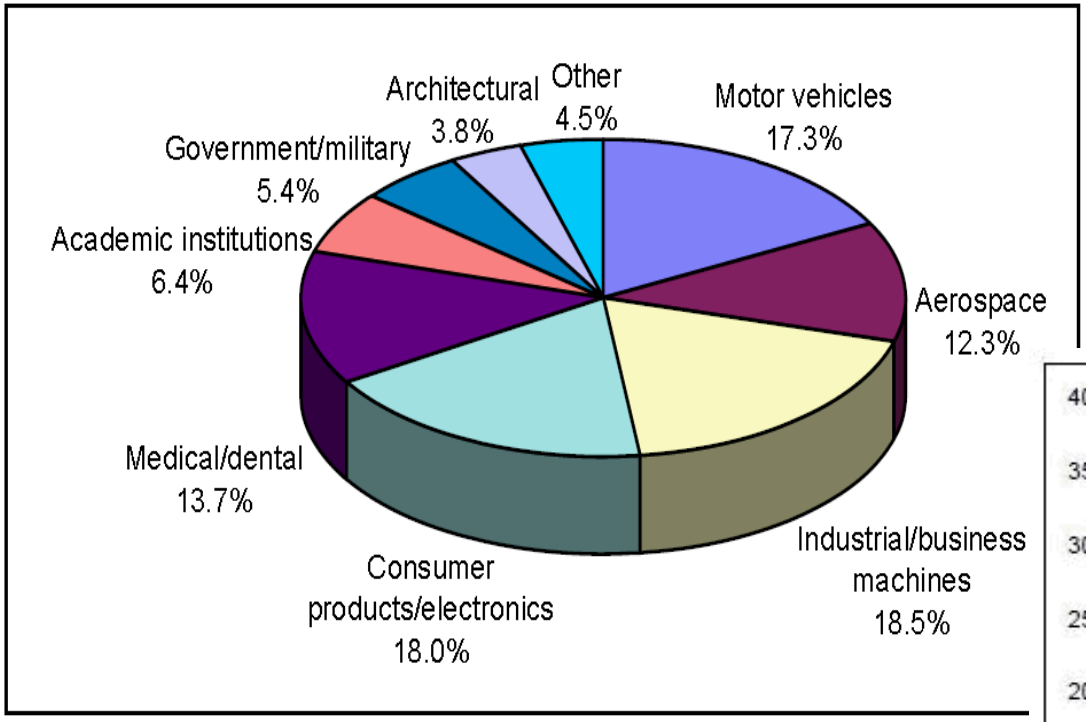
Annual Sales of Metal AM Machines



Source: Wohlers Report 2014

The Market for AM Is Broad & Growing

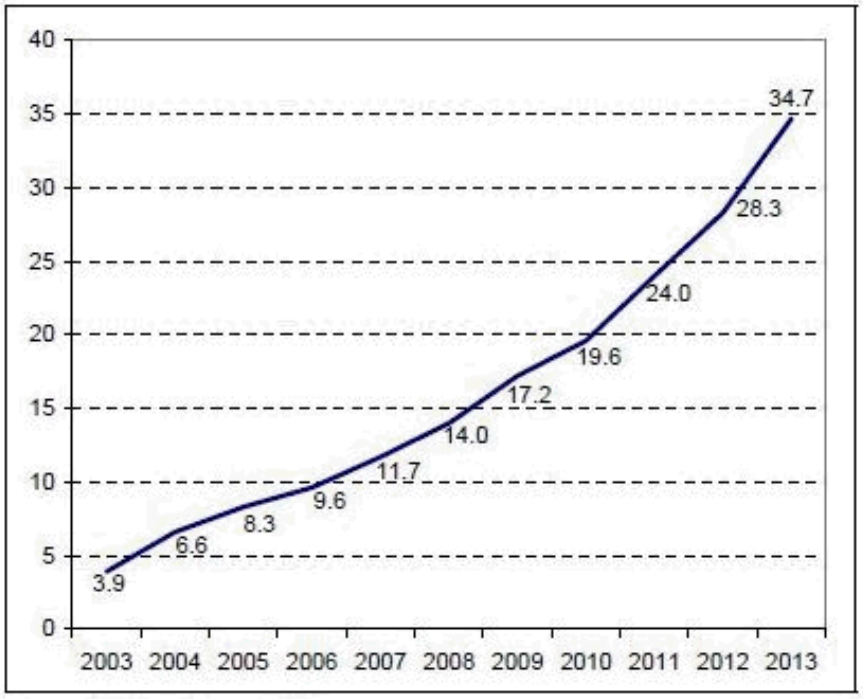
AM Has A Highly Diversified Market Base



Source: Wohlers Associates, Inc.

Use of AM for Part Production Grew Nearly 10 Fold From 2003 to 2013

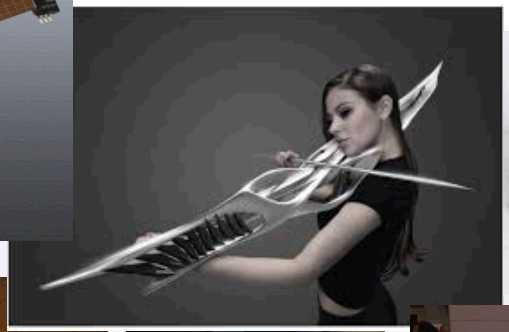
(% of total product/service revenue)



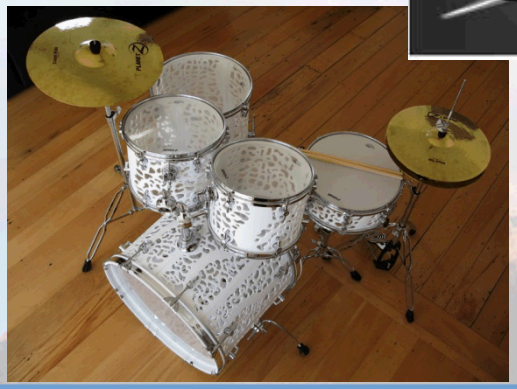
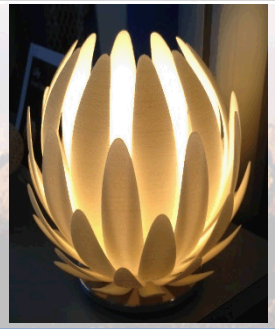
Source: Wohlers Report 2014

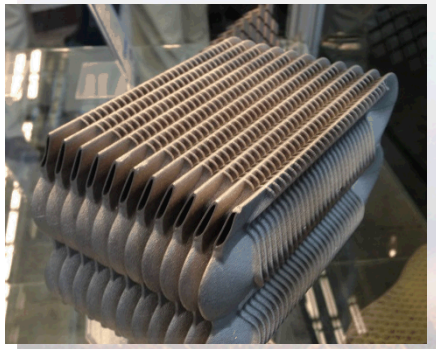
Closing Remarks

- 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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