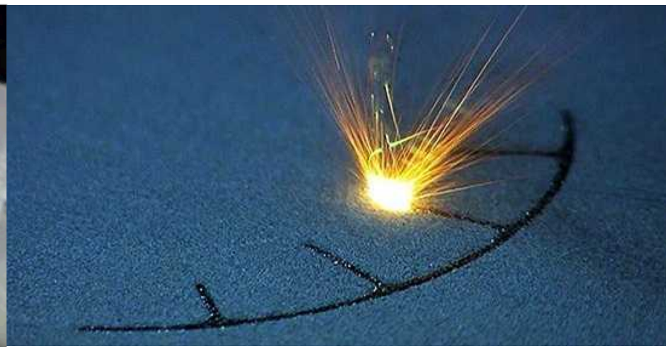
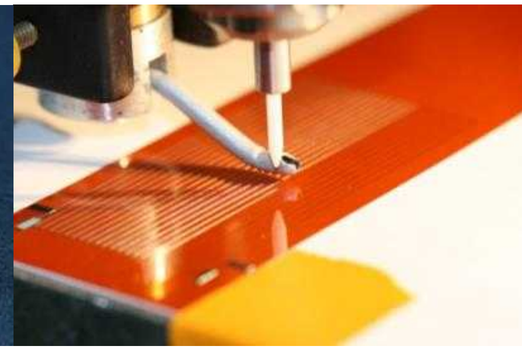
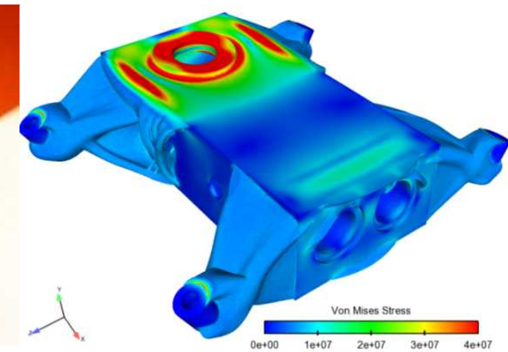
SAND2015-1929PE

Exceptional service in the national interest

Sandia National Laboratories

Additive Manufacturing at Sandia

Mark F. Smith

Materials Science & Engineering Center

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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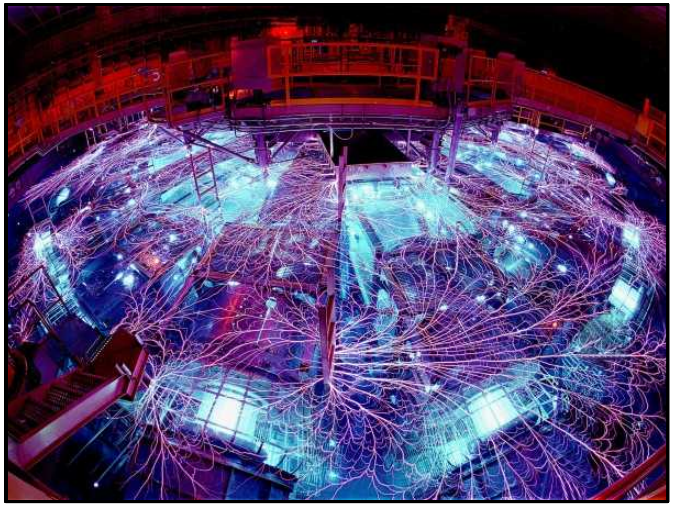
Sandia is a National Security Science and Engineering Laboratory

Weapon Drop Test



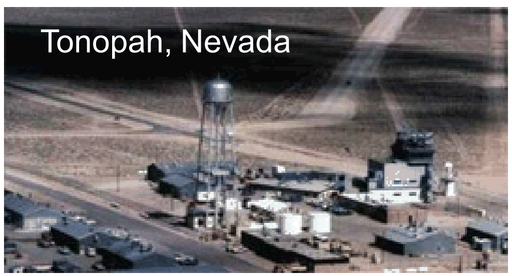
Energy R&D

Threat Test

- Historical mission -- non-nuclear components in nuclear weapons and nuclear weapon security
- Today, broader mission in science & engineering for U.S. national security

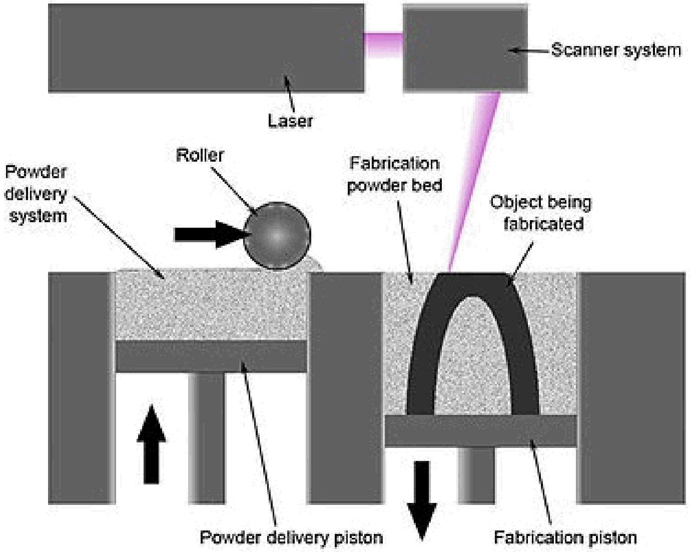
> *"We work on technologies at a scientific lab, but we must emphasize that science is not an end. The end is solving problems for the nation. Science is perhaps the best tool to achieve that end."*
> C. Paul Robinson, SNL President 1995-2005

Sandia National Laboratories Sites



What is Additive Manufacturing?

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

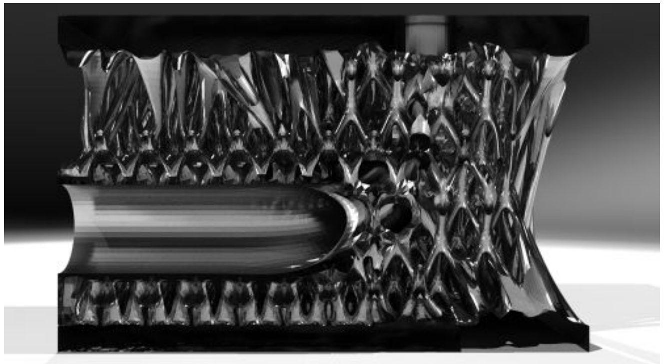


from Wikipedia, "Selective laser sintering"

Many Different AM Process Technologies:

- Plastics – Relatively Mature
- Metals – Less Mature, but Rapidly Evolving
- Ceramics – Relatively Limited at Present
- Multi-Material – Needs Further Development

Within Technologies



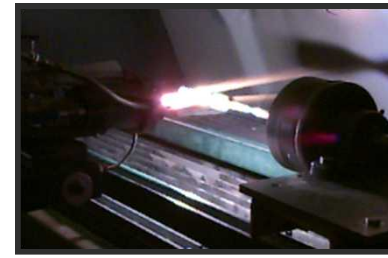
30+ yrs of Sandia Additive Mfg. Tech Development & Commercialization

*FastCast**
Development housing

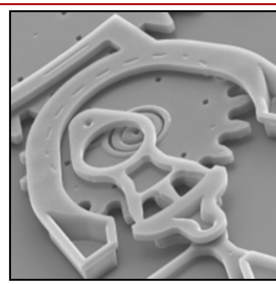
Sandia Hand
50% AM built

LIGA
“Hurricane” spring

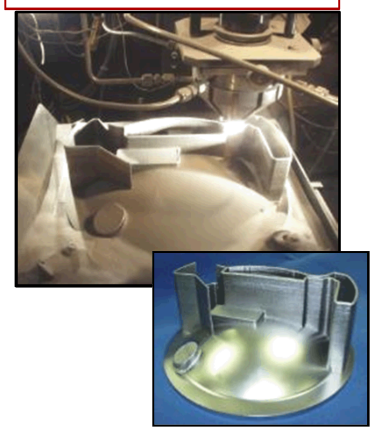
Spray Forming
Rocket nozzle



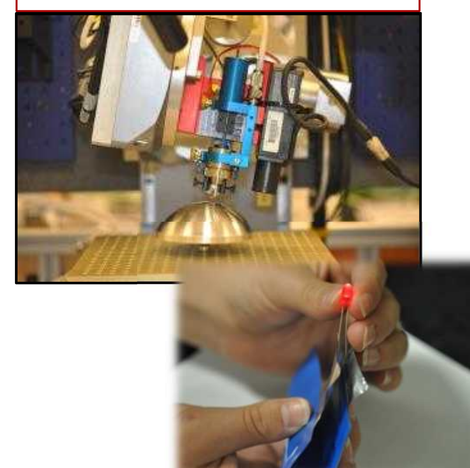
*MEMS SUMMIT™ **
Micro gear assembly



*LENS®**
Stainless housing



Direct Write
Conformal electronics



Printed battery

*RoboCast**

Ceramic parts

Energetic Materials

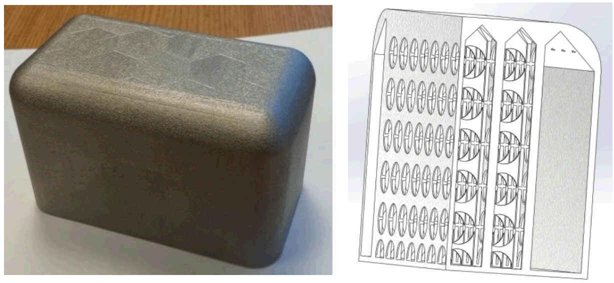
* Licensed/Commercialized Sandia AM technologies

Current Capability/Activity

Current Drivers for AM at Sandia

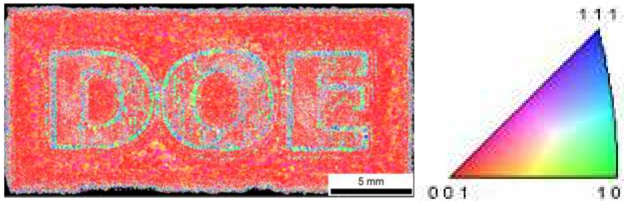
- Potential Cost/Schedule/Design/Risk Benefits
- Optimize for Performance, Not Machinability
  - Engineering analysis drives design
  - Revolutionary new design possibilities
- Potential Materials Advantages
  - Superior material properties (microstructure optimization)
  - Multi-material and graded material parts
    ("print everything inside the box, not just the box")

Complex Mass Mock



Easily customize weight, center of gravity, moment of inertia

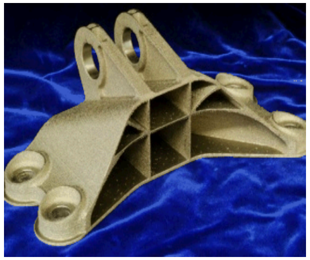
AM Inconel 718 texture control demo'd at ORNL MDF



"We can now control local material properties, which will change the future of how we engineer metallic components," R. Dehoff

GE Additive Manufacturing Design Competition

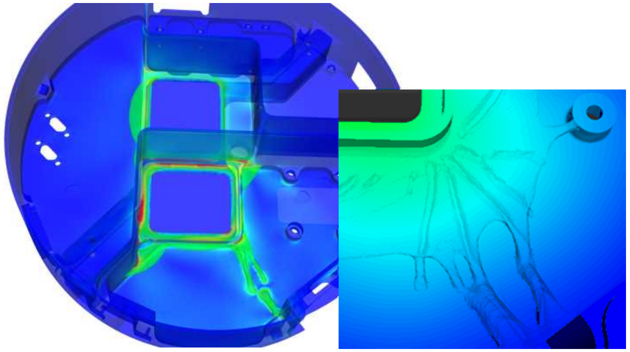
Original Design 4.5 lb.



Winning AM Design 0.7 lb.

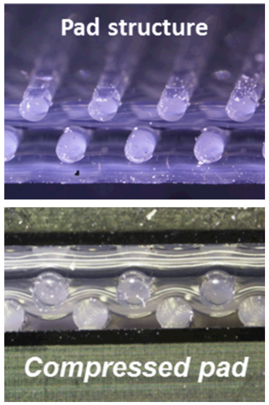
- 84% wt. reduction
- Performed well in load tests

TO/X-FEM Strengthened Housing



- 0.5% Weight Gain
- 52% Less Deflection Under Load!

DW Pad vs. Blown Foam



Potential $2M cost savings

Sandia Additive Manufacturing Strategy

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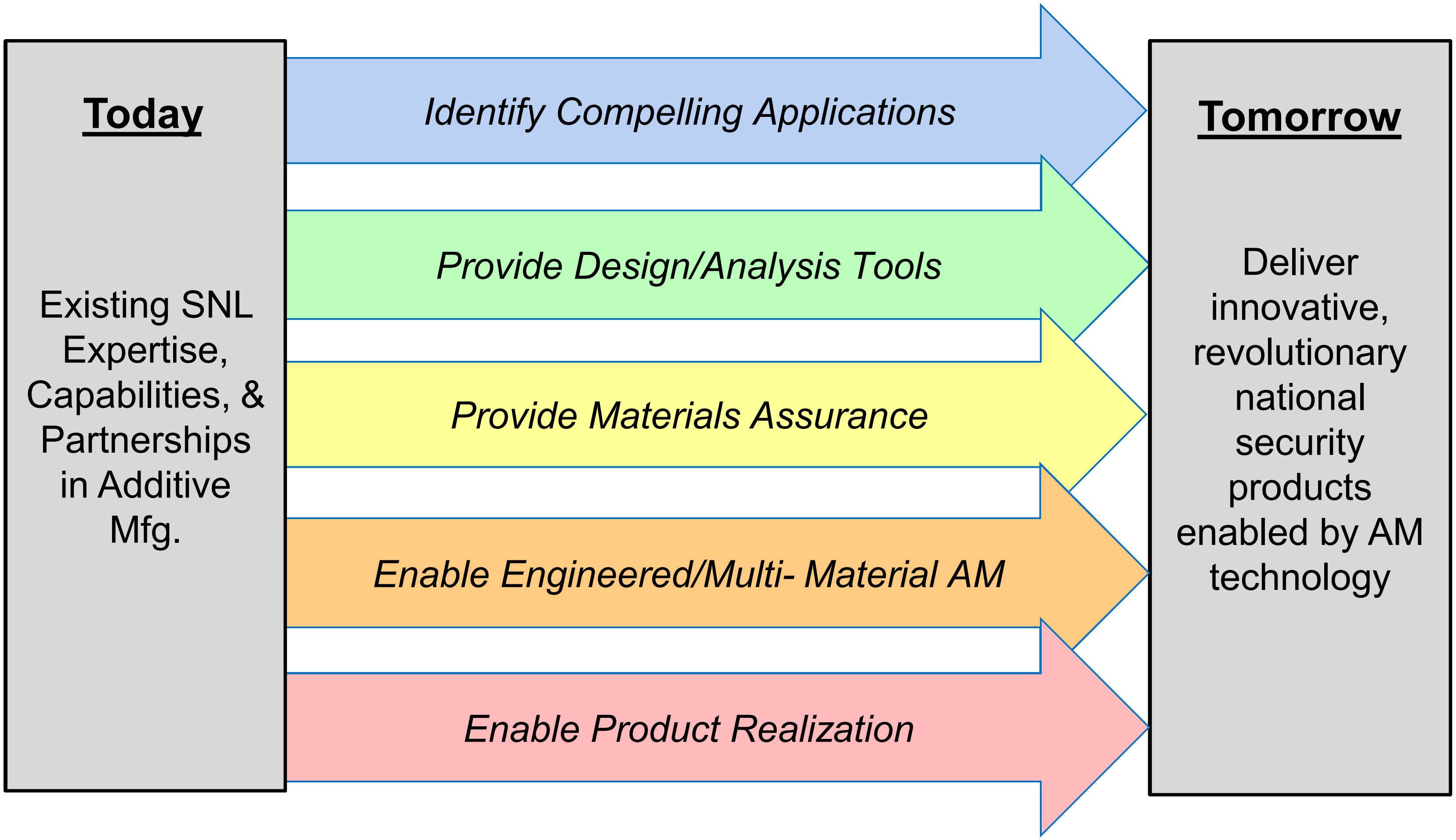
5 Strategic Thrust Areas



Example Applications

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 includes "touch" sensors

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

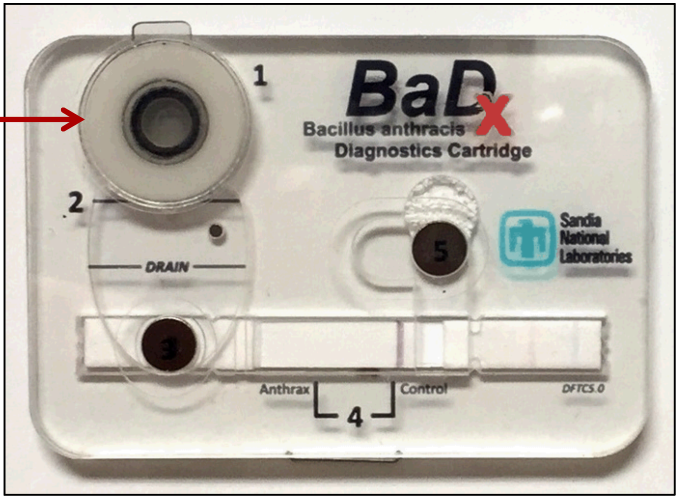
BaDx Diagnostics Tool

Sandia National Laboratories

- Microfluidic platform for bacterial detection prepared from laser ablated plastic laminates
- Allows for rapid and inexpensive prototyping and design revisions
- Self-contained, credit card-sized "Laboratory in a Pocket"
- 3D printed cap
    - Specialized geometry
    - Low cost, quick turnaround

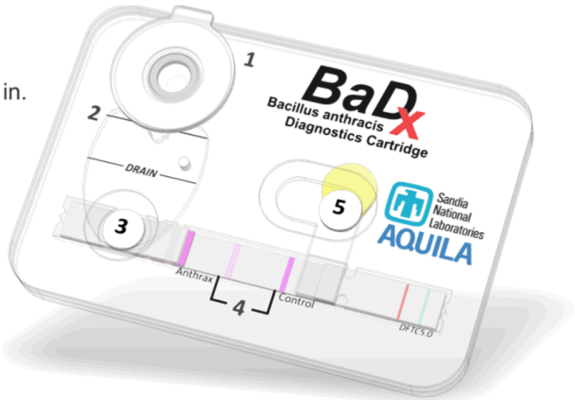
SNL Scientists Jason Harper, Melissa Finley, and Thayne Edwards

3D Printed Cap/Seal



Dimensions
0.20in x 1.88 in. x 2.75 in.

Materials
Plexiglas Acrylic
Acrylic Adhesives
NdFeB Magnets
3D Printed Cap
Paper-based LFA
Disinfectant



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

Design/Analysis Tools

Analysis-Driven Design Optimization

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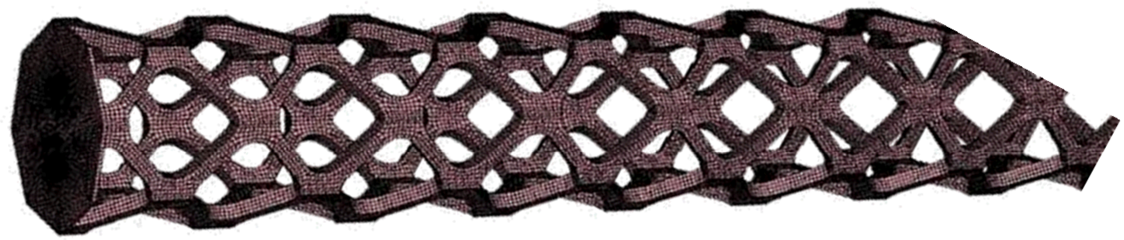
We combined Topological Optimization (TO) with eXtended Finite Element Modeling (X-FEM) & LENS® to optimize selected properties, e.g., strength/weight ratio.

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

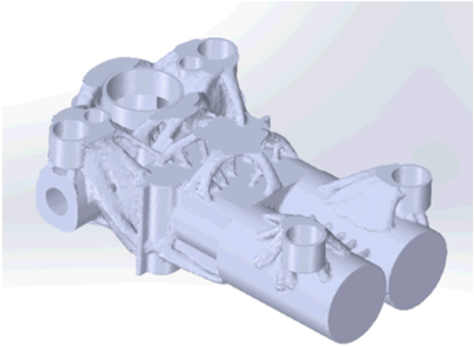


With AM it is faster and cheaper to build this optimized shaft than a solid shaft!

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

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

How can we use AM to design/build more complex integrated components?



complex housing design

AM Design Via Functionality Prioritization

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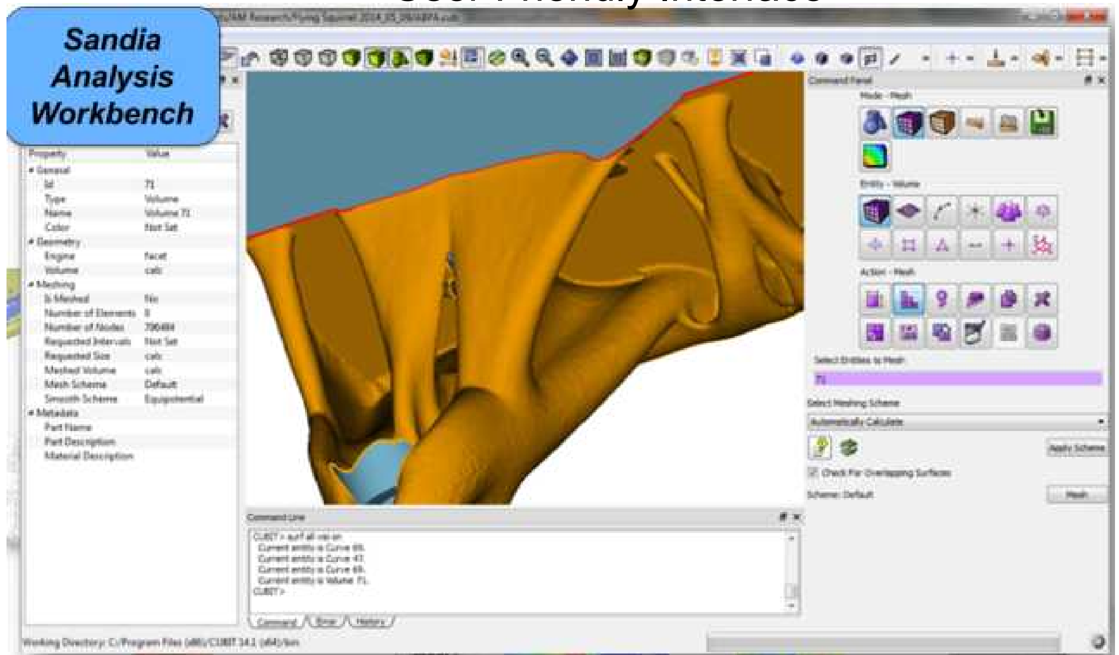
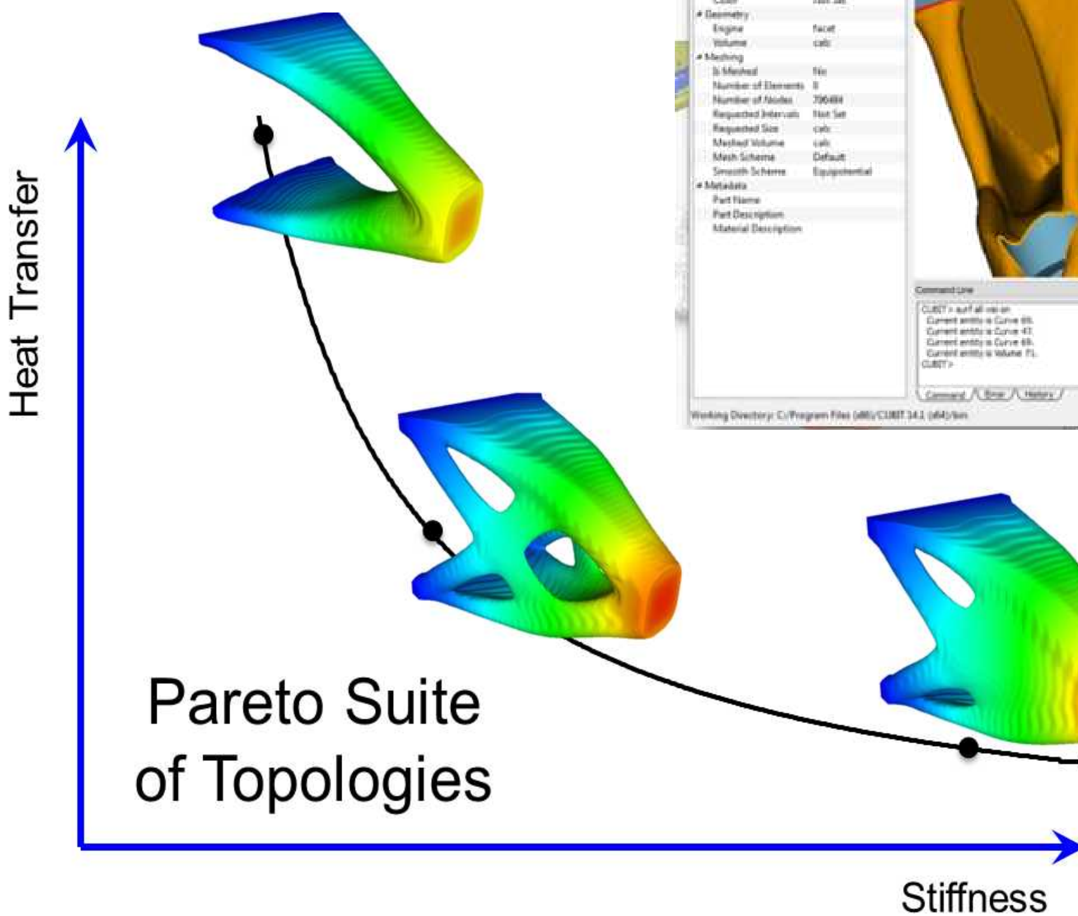
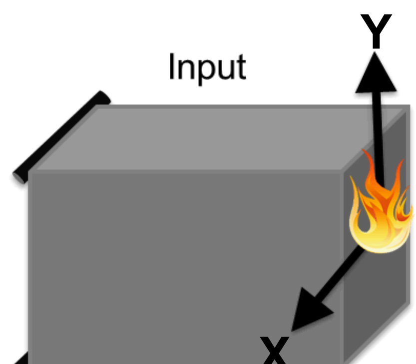
User Friendly Interface







TO/X-FEM Greatly Improved Stiffness

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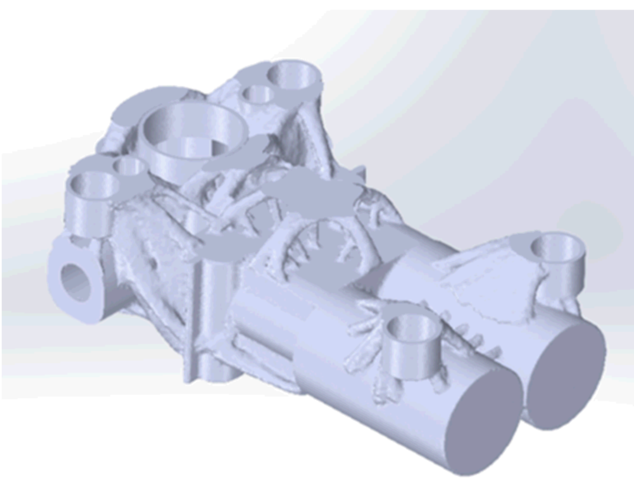
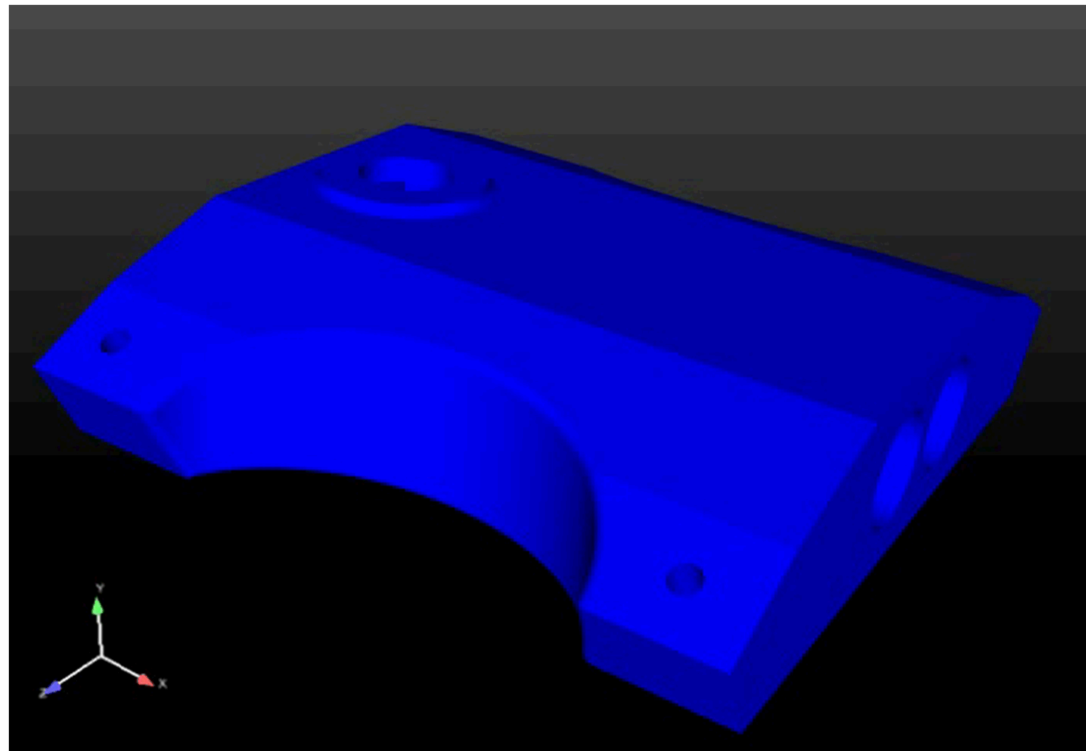
Original Design



Highly Optimized Design

Topology Optimization / eXtended Finite Element Modeling

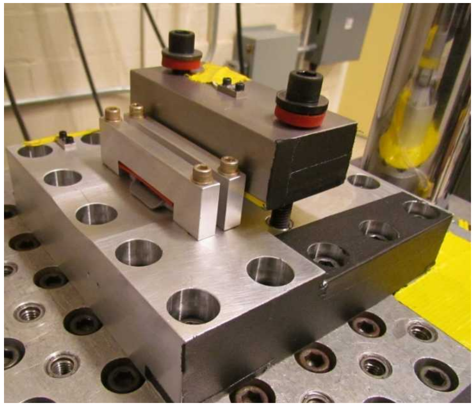


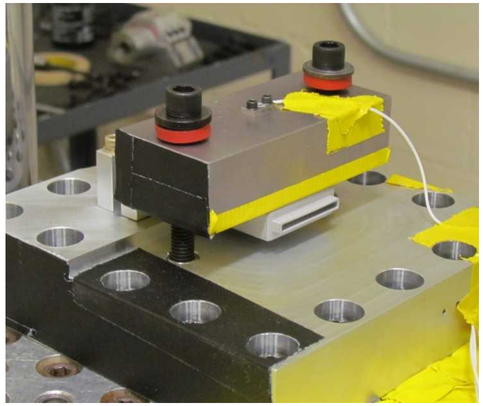
Josh Robbins, Tom Voth

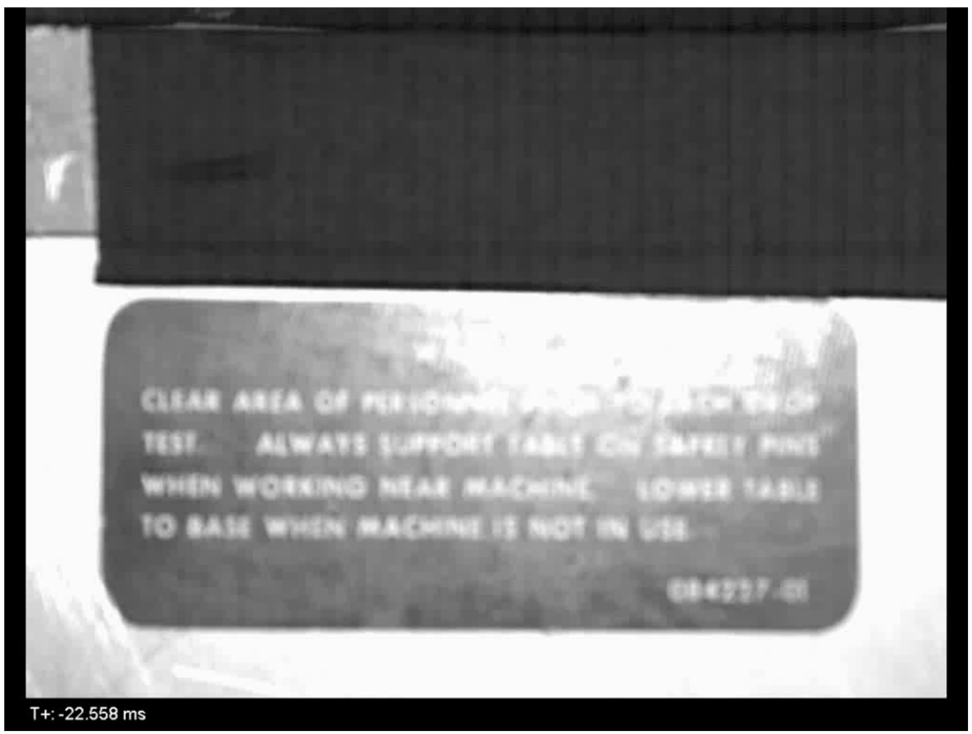
Materials Assurance

Superior Impact Performance

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

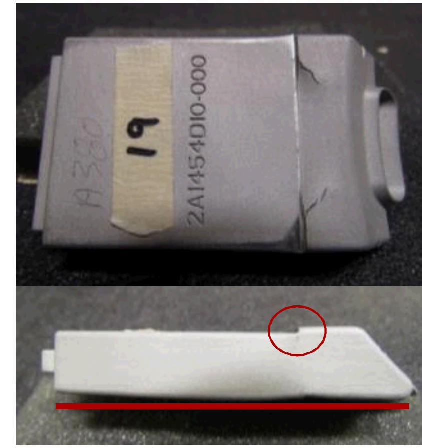






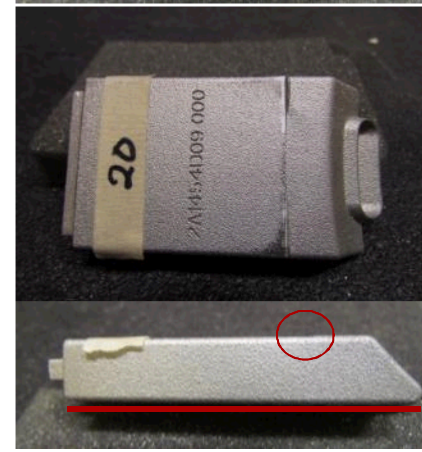
Cast, A380
1 pc, 38 g →

- cracked
- buckled



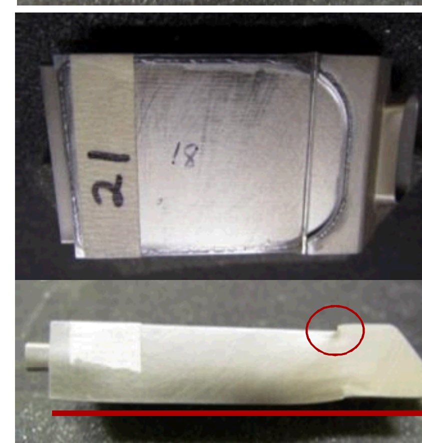
AM, AlSi10Mg
1 pc, 38 g →

- slight indent
- still straight
- best result

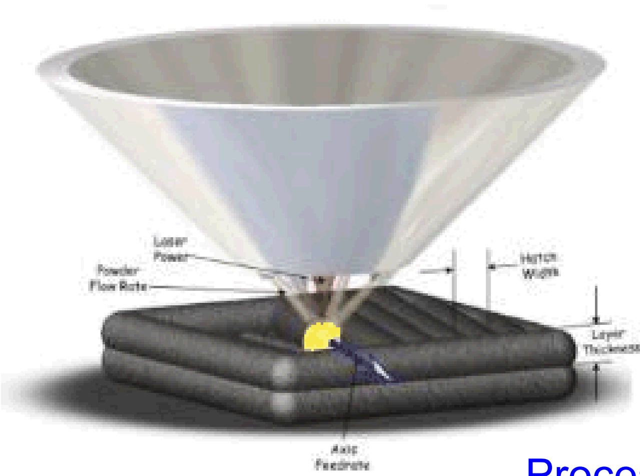


Machined 4047
2 pc assy, 45 g
(Baseline Design) →

- weld cracks?
- buckled

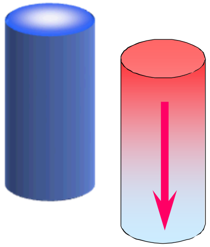


Prior LENS® Process & Materials R&D



Potential LENS® Advantages

- Fully dense metal
- Good mechanical properties
- Graded materials
- Add to exiting parts



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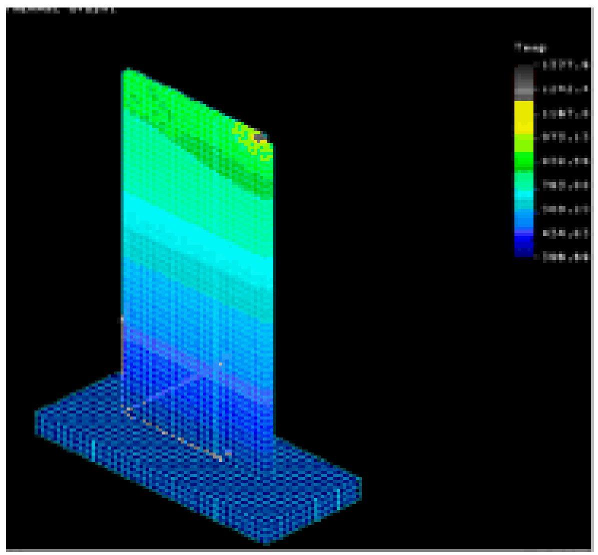
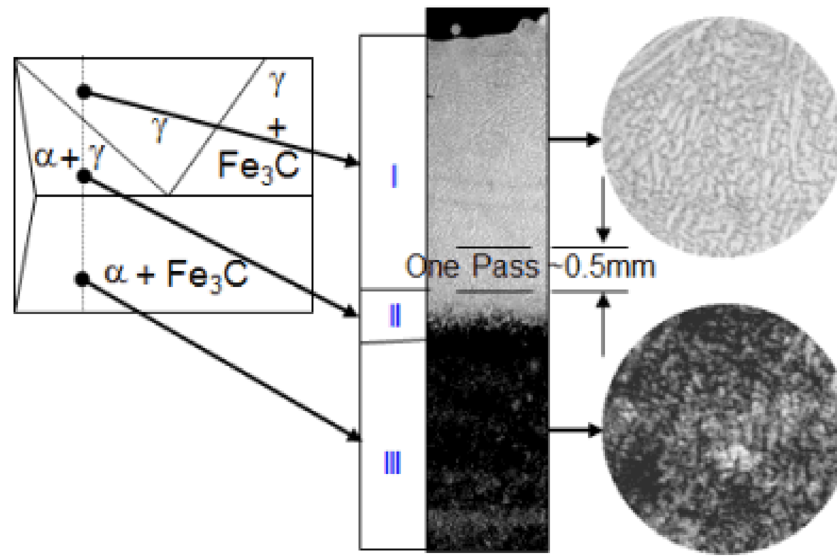
Uni-directional Solidification

- Built narrow "wires" to achieve 1-D heat flow to simplify & understand solidification front
- Simplified comparison with model predictions

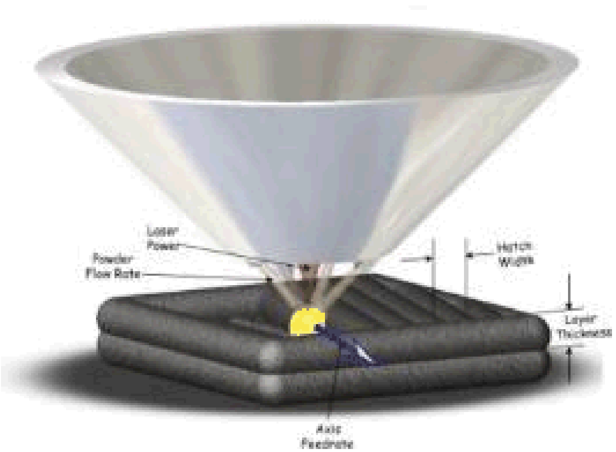
Process characterization/modeling





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

Closed Loop Process Control

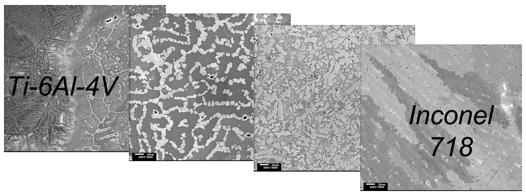


Z - height self-stabilization

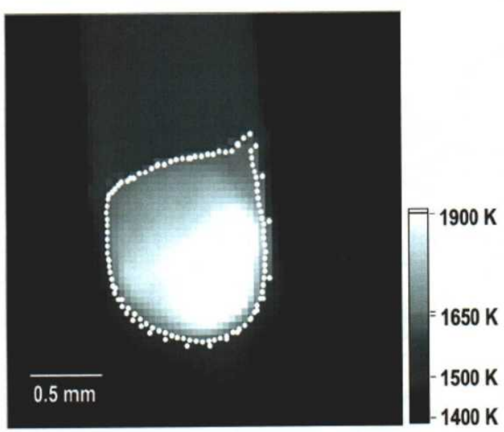
- Understand "magic spot"
- Developed Z-height sensor using reflected NdYAG with position-sensitive detector

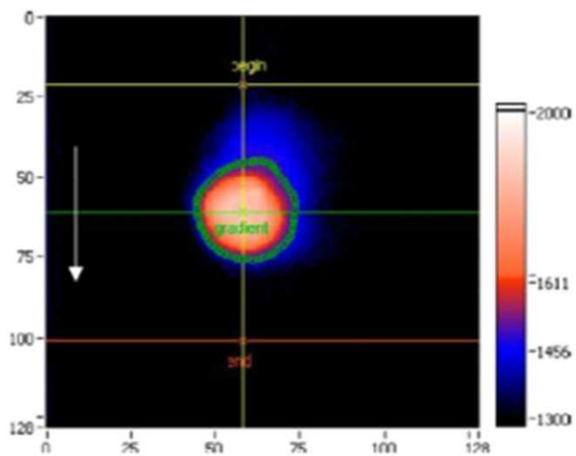
Variety of LENS® Metals

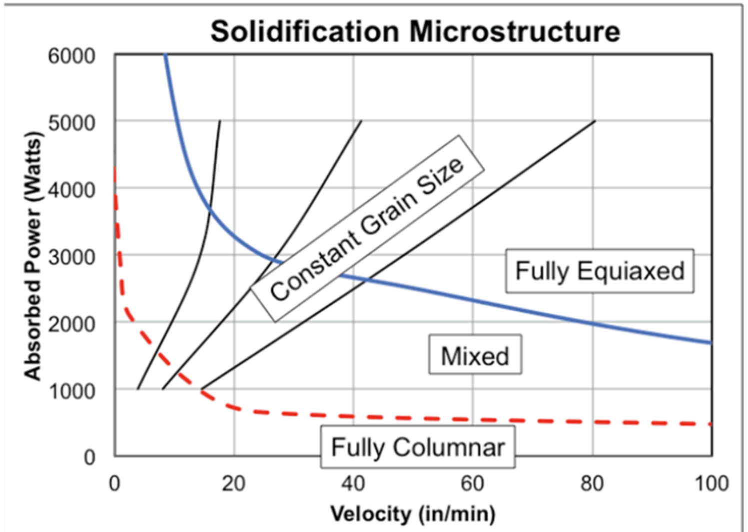
Ti-6Al-4V
Aermet 100
Stainless 304L, 316L
Tool steels
Inconels
Graded Metals



LENS functionally graded materials







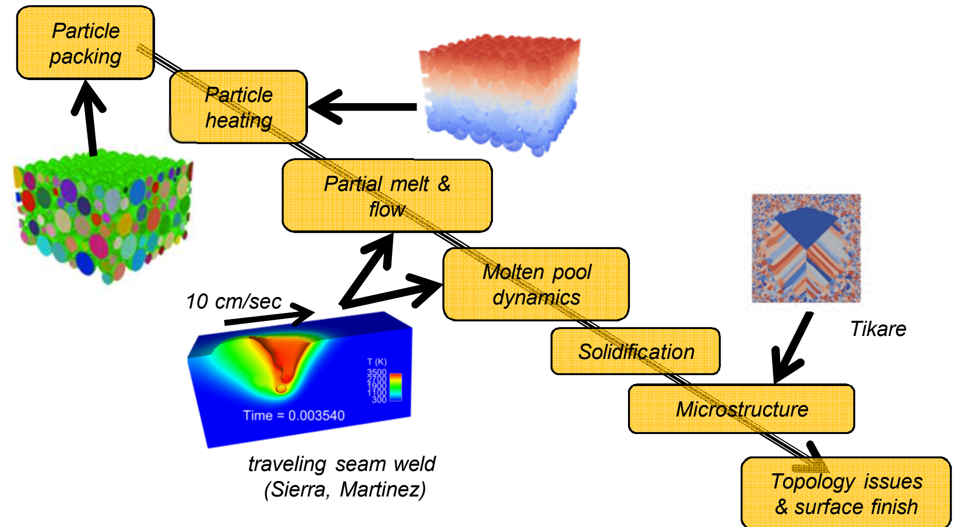
Controlling the Melt Pool Provides Microstructural Control

Working to Model Process → Microstructure → Properties → Performance Relationships

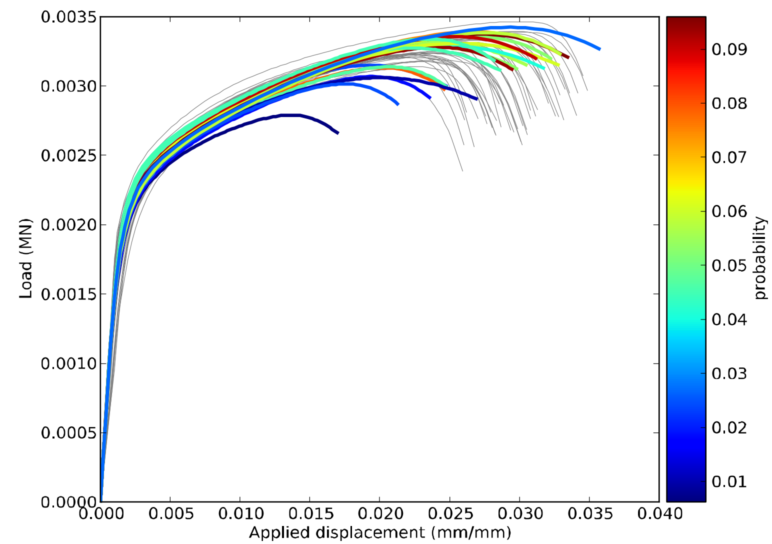
Sandia National Laboratories

- Process
  - Leverage laser welding expertise to model melting/solidification
  - Draw on prior LENS experience to support process model development

- Defect sensitivity
  - Leverage Sandia *Predicting Performance Margins (PPM)* inititative to investigate flaw sensitivity
  - Predict response from stochastic process knowledge leading to quantified performance uncertainty



SNL simulation tools

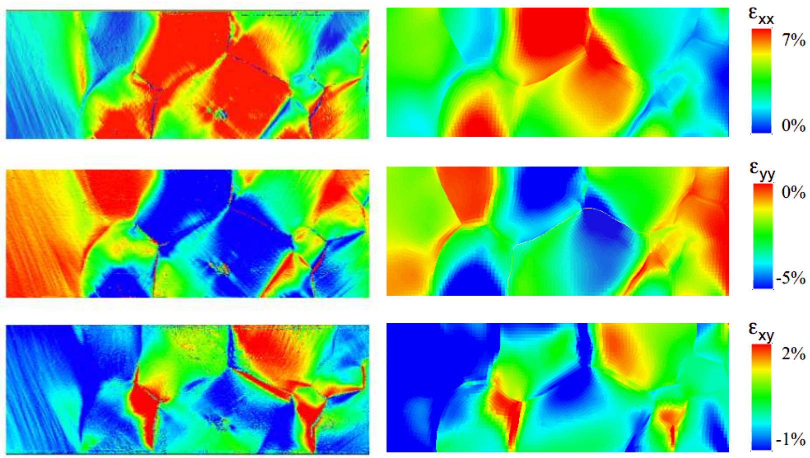


Predicted (color) vs. measured (grey) response for welds (PPM)

Modeling Microstructure & Behavior

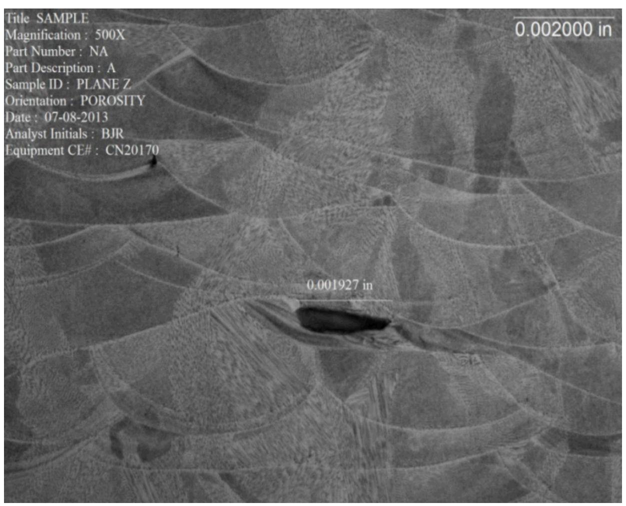
Sandia National Laboratories

Oligocrystal experiments vs. crystal plasticity models (tensile loading)



DIC measurements

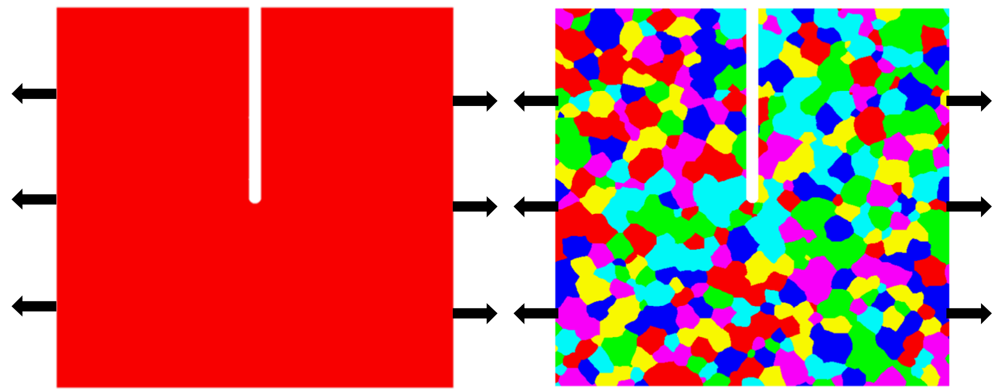
Simulations

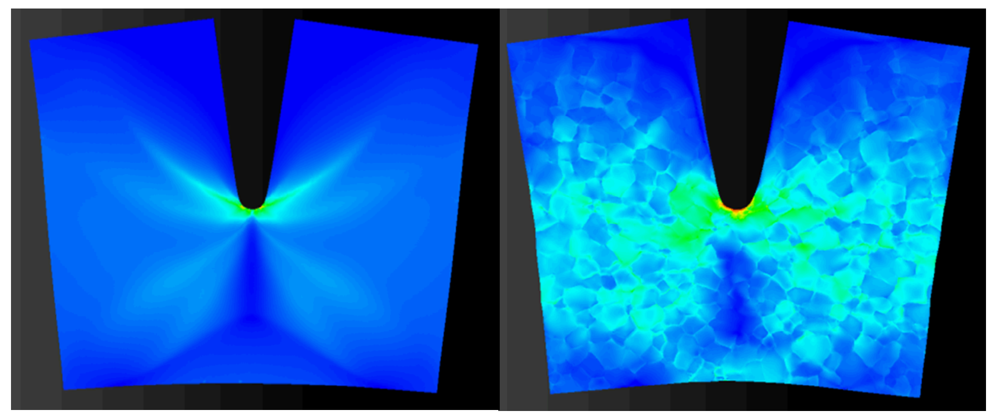


PH17-4 microstructure (Everhart, Honeywell KC)

Ta single crystal [100] orientation

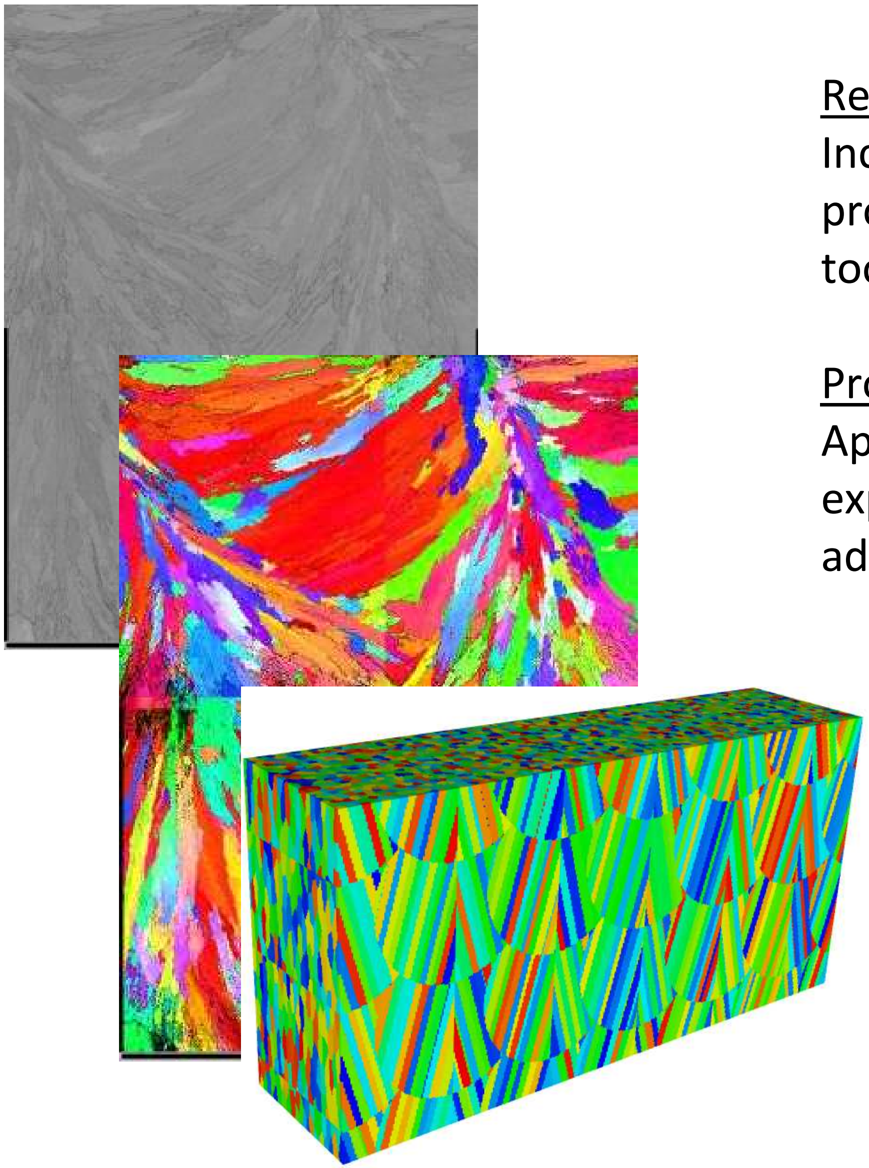
Ta polycrystal 482 grains





(a) Von Mises stress distributions: single crystal vs. polycrystal

Engineering of Materials Reliability Research Challenge



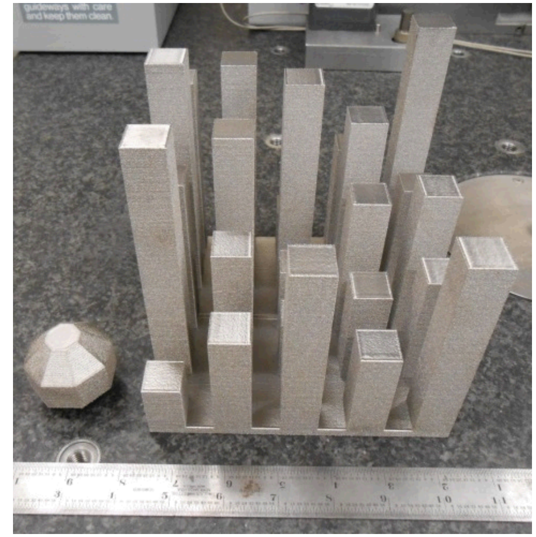
Research Challenge Goal:
Incorporate *material variability* in predictive, probabilistic, performance and optimization tools with appropriate physics.

Progress:
Application of Direct Numerical Simulation to explore the effects of grain orientation for additively manufactured stainless steel

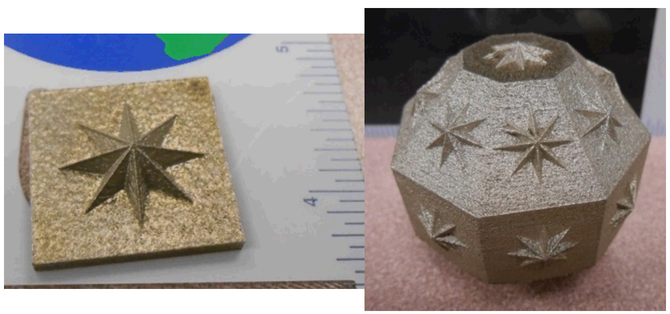
LENS® microstructure with orientation information + Direct Numerical Simulation (DNS) models will enable anisotropic deformation models

Metrology Is Also A Key Challenge

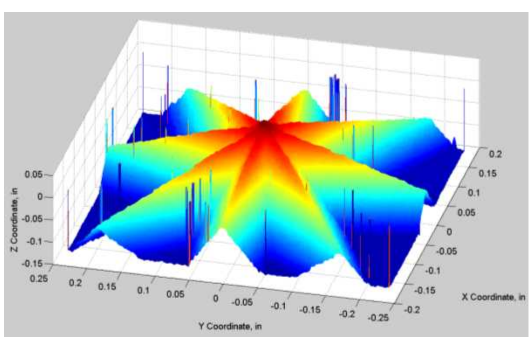
- Family of artifacts designed, printed, & measured
  - Fabrication has been easier than metrology
  - Working to enable predictive process inputs
- Unique challenges for process/equip. characterization
  - Tolerance/Surface Finish/Properties vary with machine, material, print orientation, support structures, post-processing,…)
  - SNL Primary Standards Lab working w NIST to develop better AM metrology artifacts

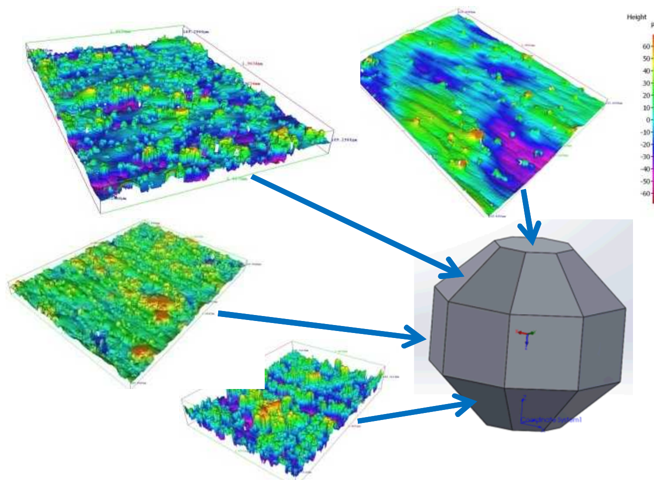


Ti-6Al-4V polyhedron & "Manhattan" artifacts for MPE (maximum permissible error)

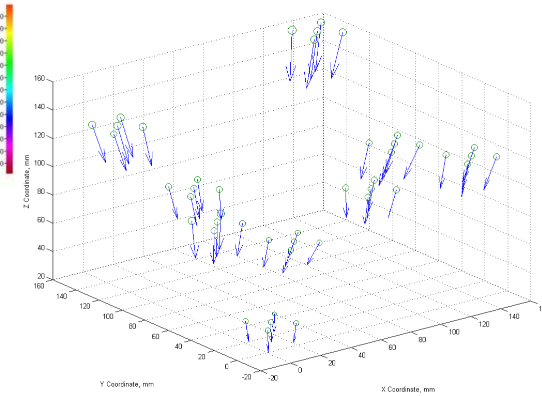


Siemens star geometries for resolution evaluation





17-4PH polyhedron texture anisotropy map



Ti "Manhattan" error map

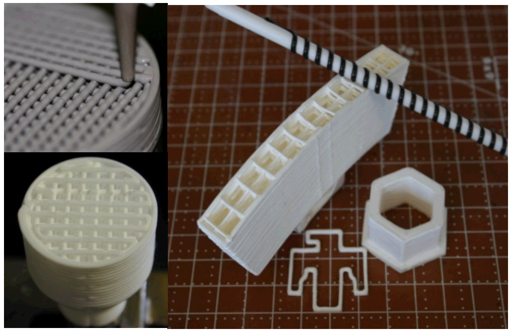
Hy Tran (2523), Bradley Jared (1832)

Multi-Material AM

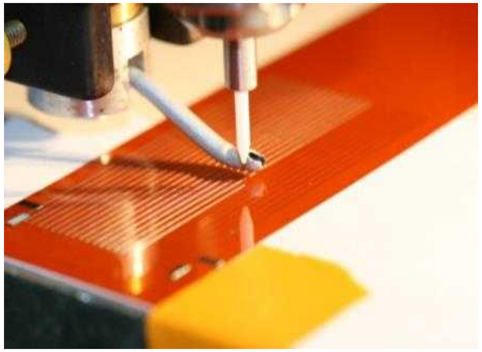
Direct Write, A Versatile, Multi-Material Process

Sandia National Laboratories

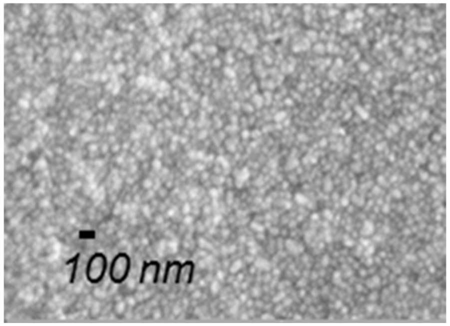
- **Materials**
  - Print: ceramics, metallics, polymerics, energetics, multi-phase
  - Substrates: ceramics, metals, plastics, polyimide, encapsulants, FR4, glass, paper
- **Example Applications**
  - DC & RF interconnects, antennas
  - Flexible electronics
  - Sensor networks / structural health (strain, crack, temperature, …)
  - Electronic package integration (resistors, capacitors, inductors, transistors, batteries)
  - Conformal printing



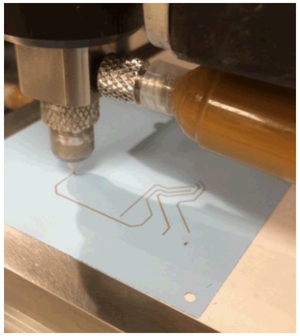
Extrusion casting (Robocasting)



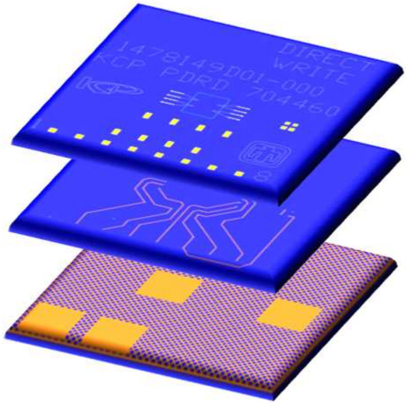
Aerosol jet printing to 10 µm



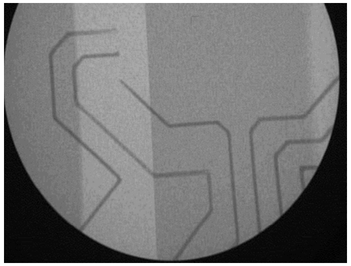
Nano-particle Ag inks for conductive pathways



DW circuit fabrication



Multi-level circuit



X-ray of 4 layer composite system, 200 µm conductors

Direct Write Lithium Iron Phosphate Battery

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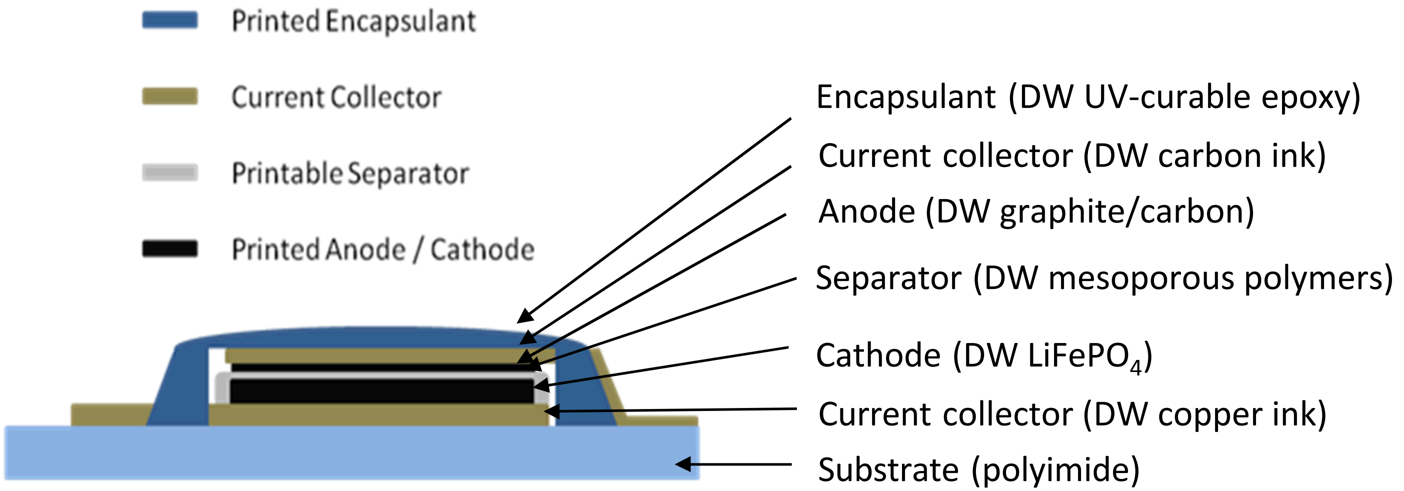

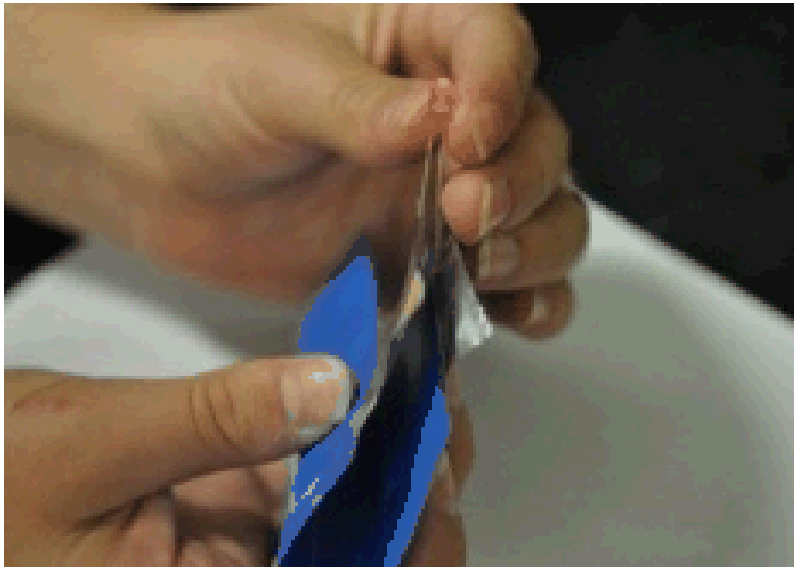

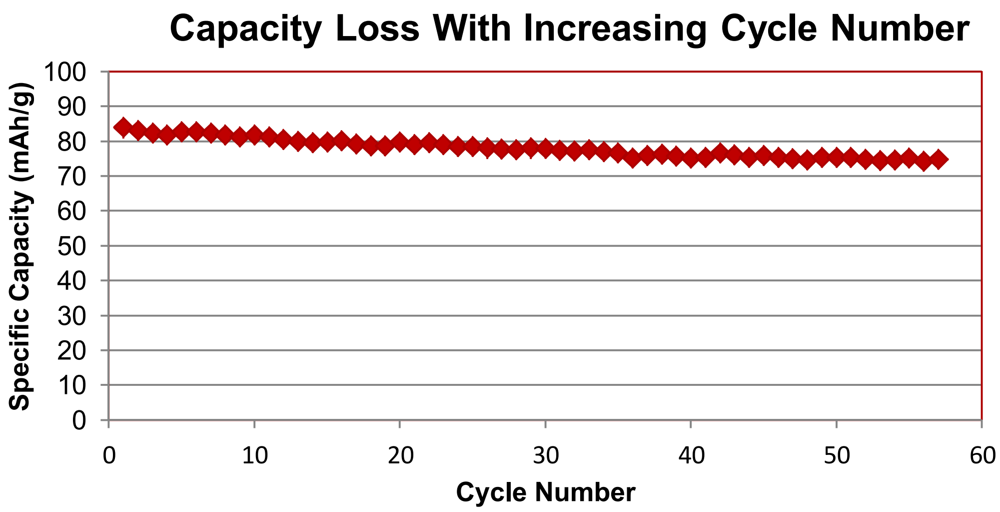

Other Additive Technologies

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

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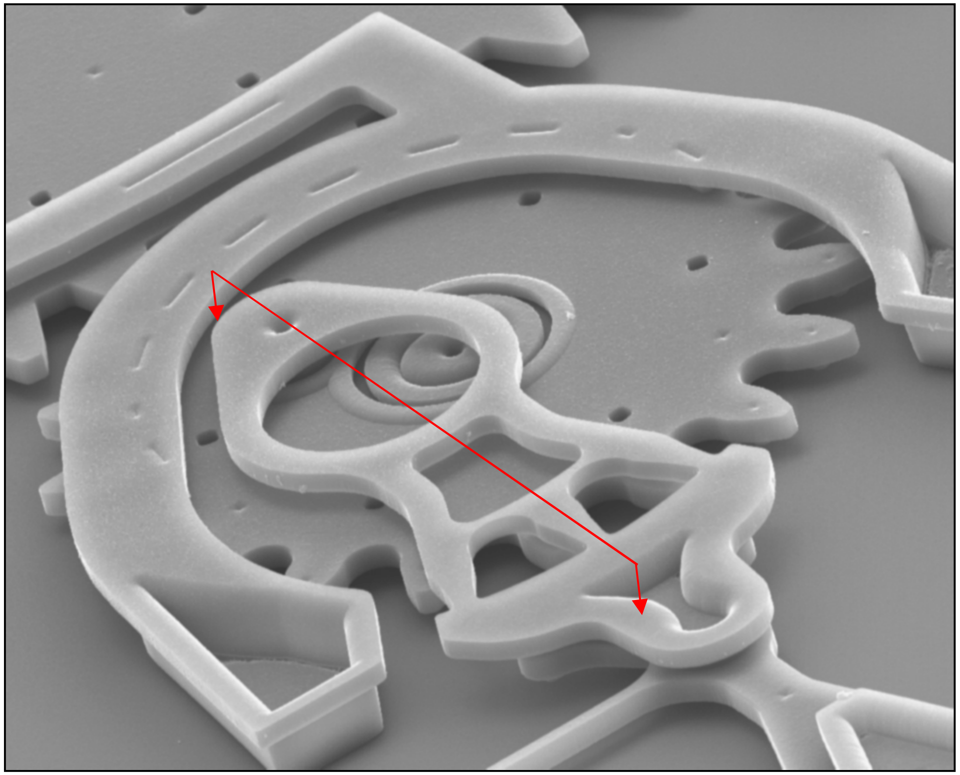
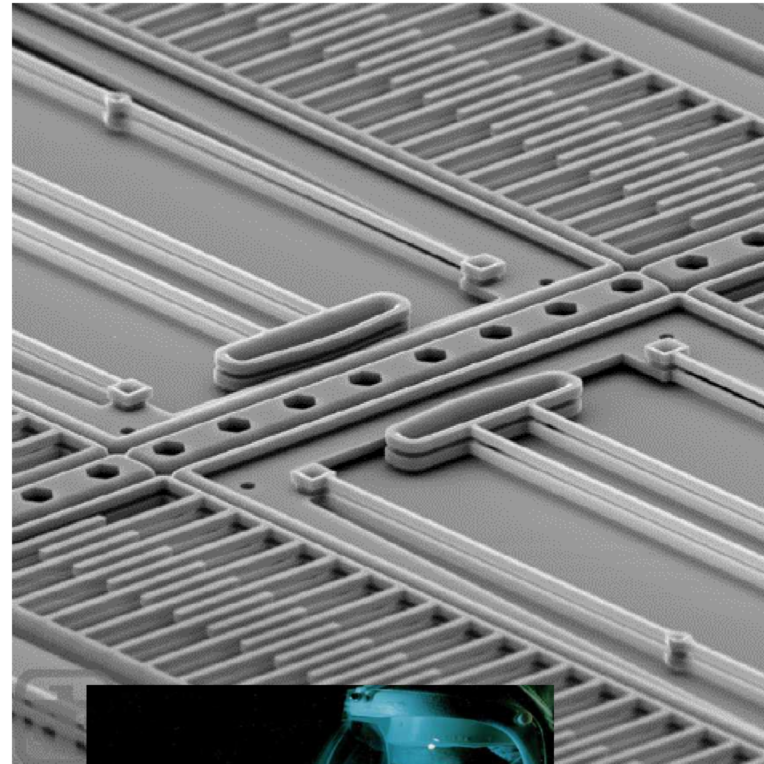
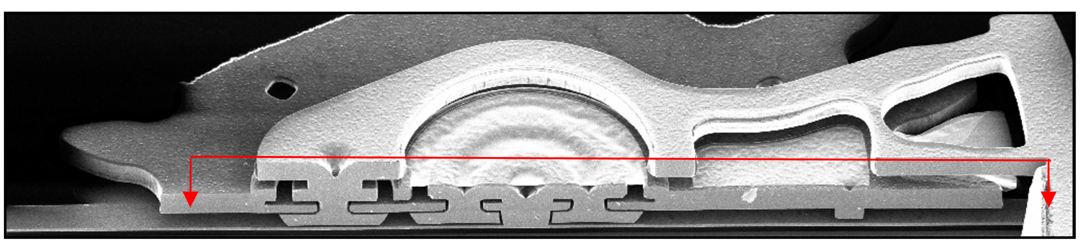
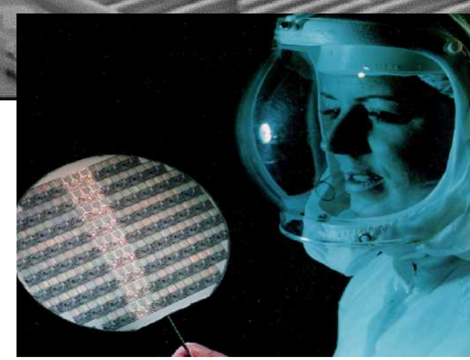
Gear Assembly



Comb Drive

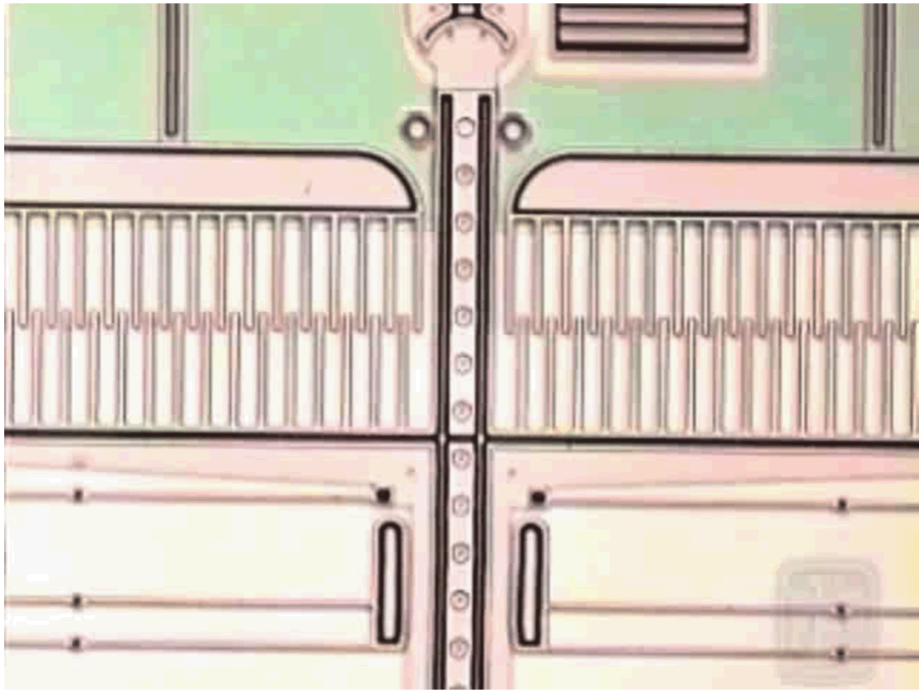


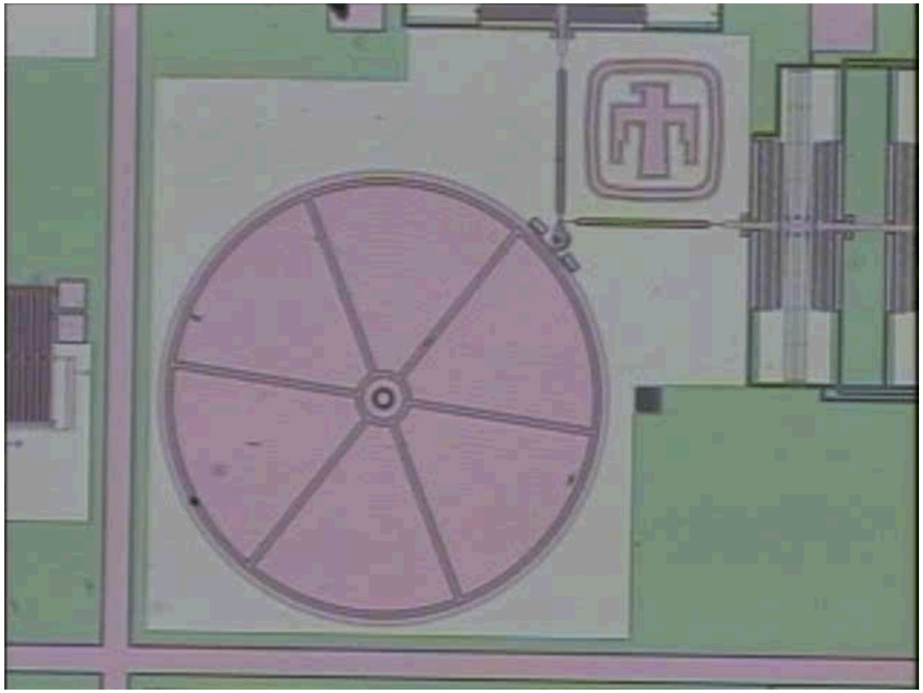




There is no piece part assembly!

MEMS Drives in Action





Sandia μChemLab™

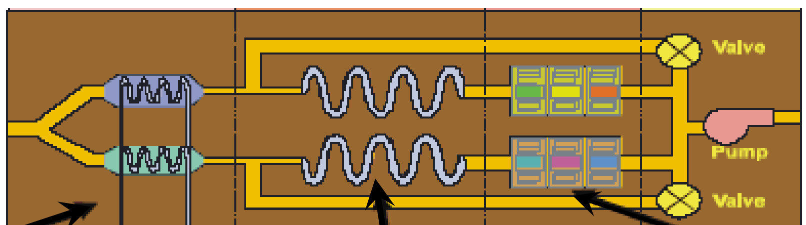
<ins>Need:</ins>

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

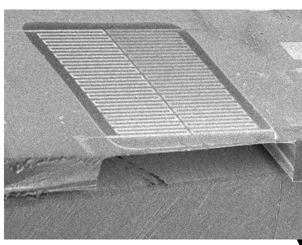
<ins>Technical Approach:</ins>

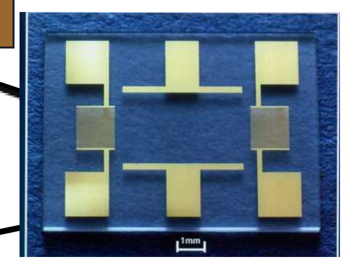
- Use MEMS to create functional components
- Use Gas Chromatography (GC) column together with selective-surface sensors for analysis.

Preconcentrator Collects Species of Interest

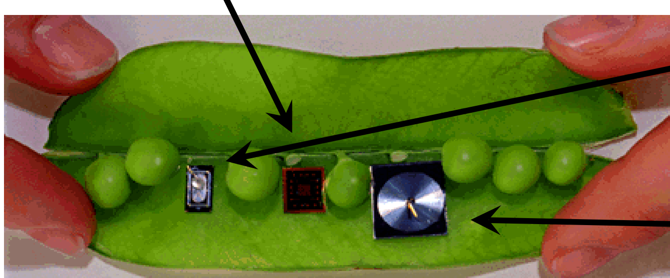


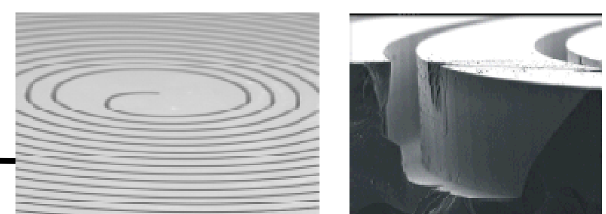
Chemically Selective Surface Acoustic Wave (SAW) Sensors





Gas Chromatograph Column Separates Species in Time





~1 Meter Gas Chromatograph Column

Further μChemLab™ Refinements

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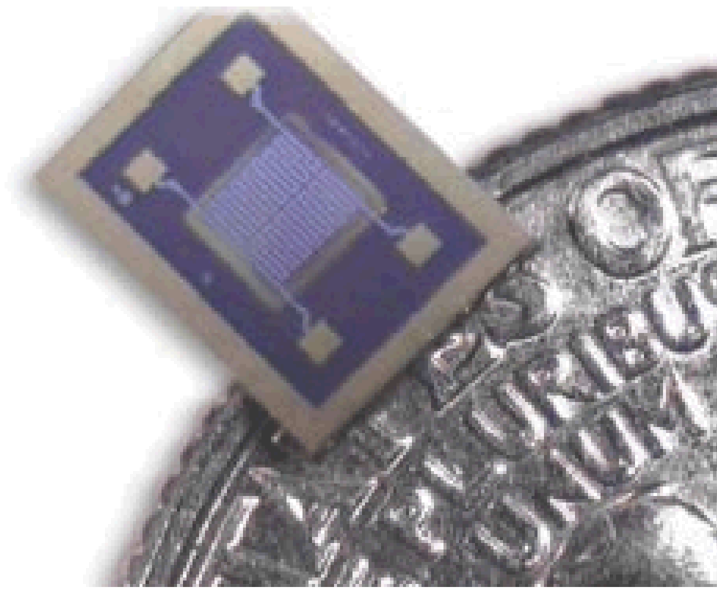
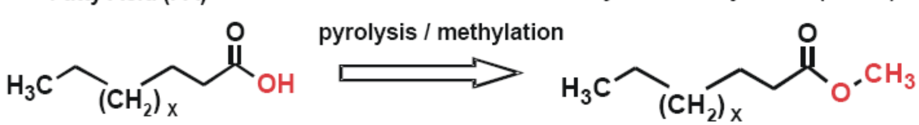
Micropyrolyzer atop a dime



Monolithic all-Si μChemLab™ with Preconcentrator, GC column & Pivot Plate Resonator Detectors on a dime

used for Fatty Acid Methyl Esther (FAME) identification of micro-organisms (bacteria, anthrax, other pathogens

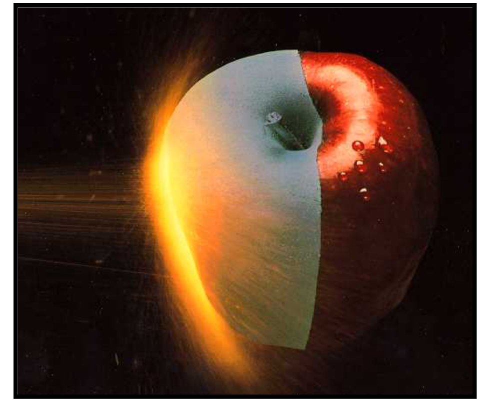


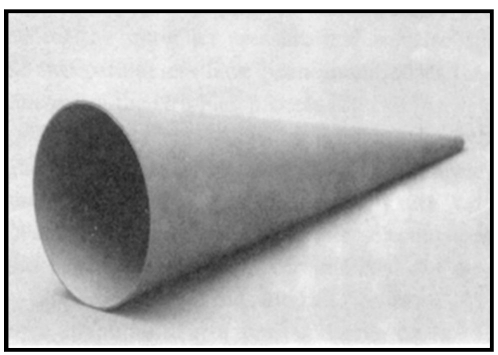
Full-up Monolithic Analysis System on a Sandia Micro-robot

Another Additive Process, Spray Deposition

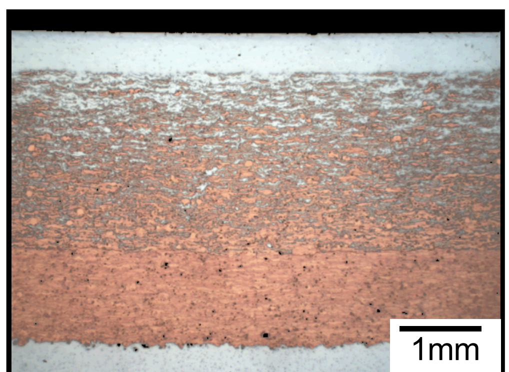
- High Deposition Rates
- Wide Choice of Materials
  "anything that melts"
- Combine Highly Dissimilar Materials
- Unique Microstructures / Properties

*Metallizing an Apple**

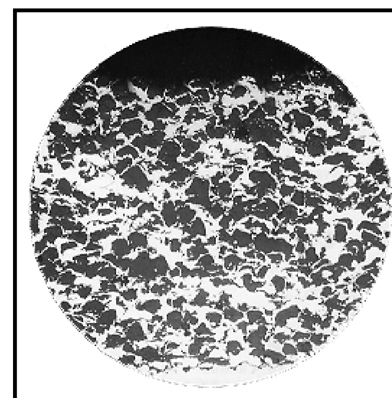




Spray-Formed B_4C Cone†



Graded Density Cu→Al Spray-Formed Flyer Plate



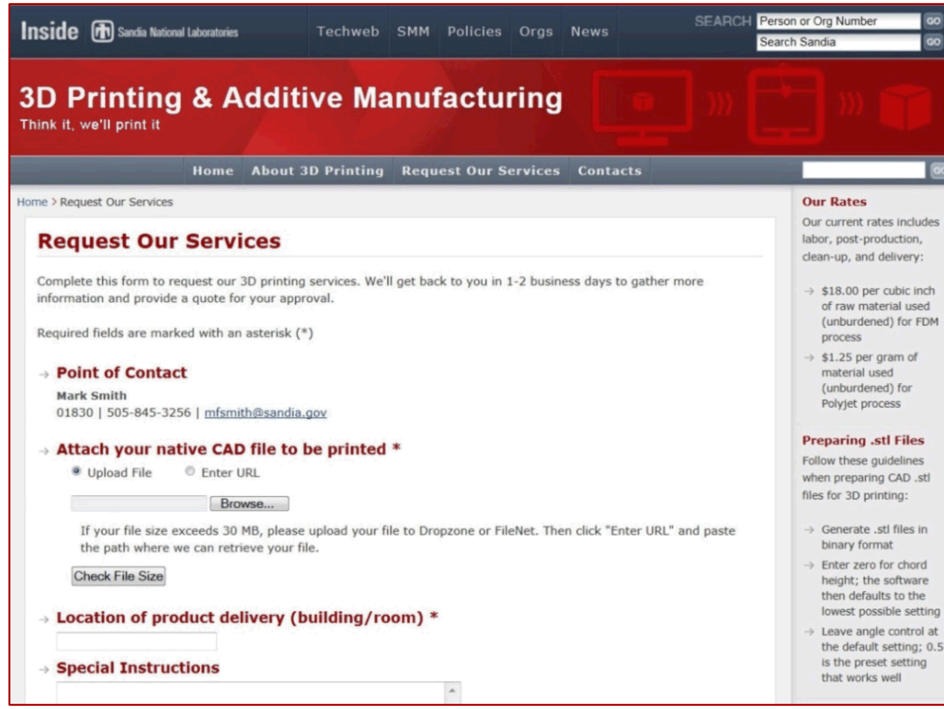
AlSi / Polyester Composite

† From Freslon, Proc. 1995 Intl. Thermal Spray Conf. *Photo provided by TAFA, Inc.

AM Equipment

Plastic AM Machines

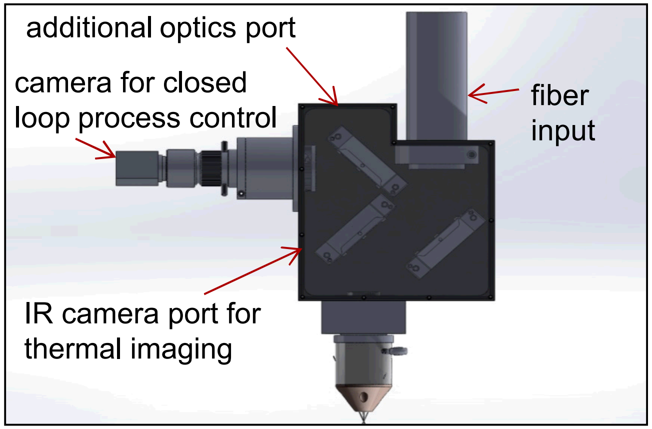
- ~ 100 Plastic AM machines at Sandia
- Web-based Central AM Printing Service

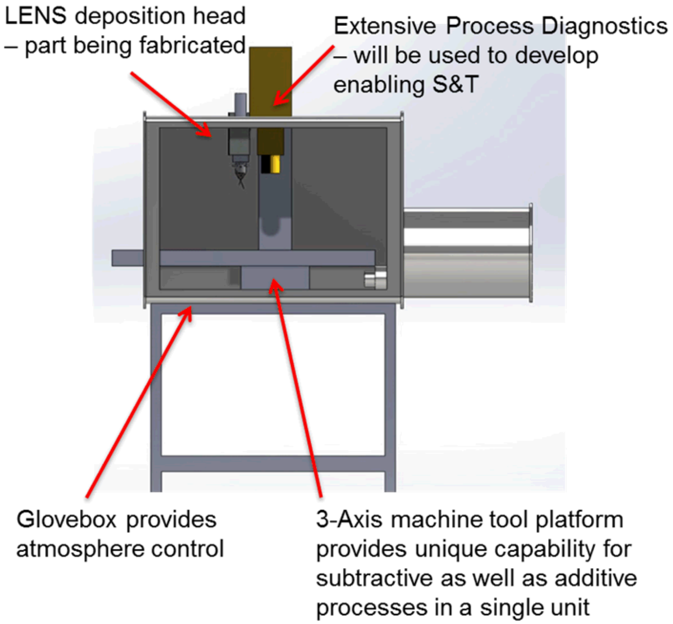


"You Think It, We'll Print It!"

New Metal AM Machines Coming Soon

Custom Built Aditive/Subtractive LENS® System



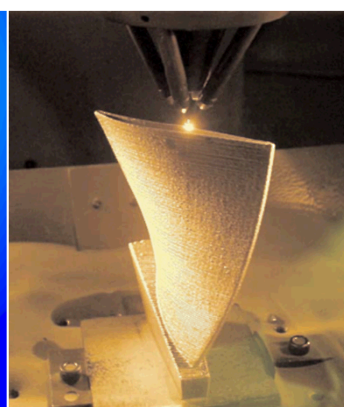
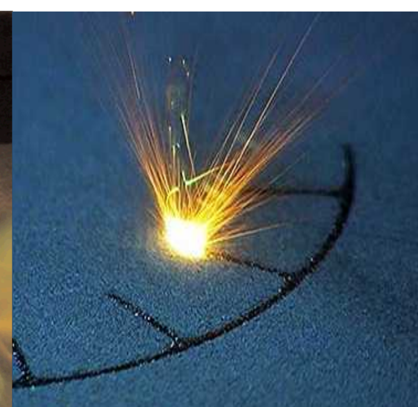
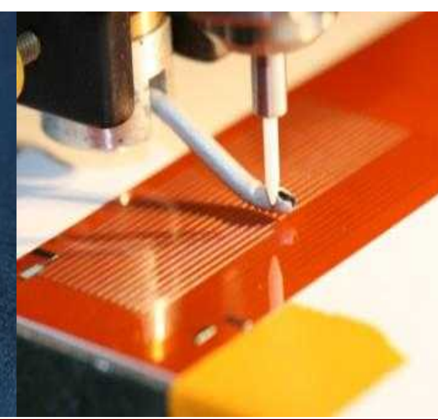
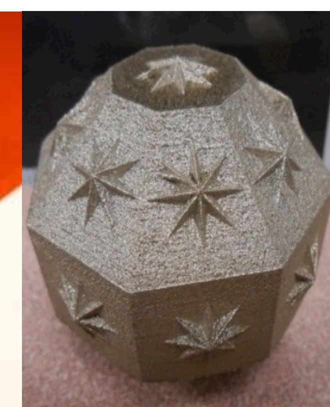


Commercial Powder Bed Laser Systems

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

Summary

- Sandia has a rich history in AM technology development & commercialization
- We are reinvigorating our AM capabilities and activities
- We are especially interested in Design for AM and Materials Assurance
- We have some relatively unique AM and High Performance Computing capabilities
- We are interested in teaming with universities in areas of mutual interest

Backup Slides

Micro Electro-Mechanical Systems (MEMS)

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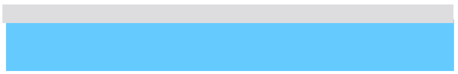
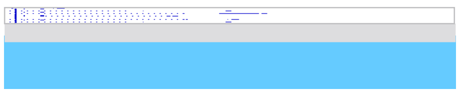
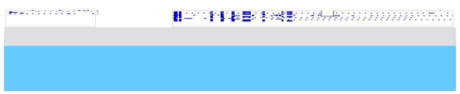
Deposit Ground Plane Layer



Deposit Sacrificial Oxide

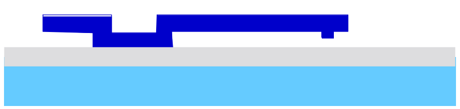


Pattern Sacrificial Oxide

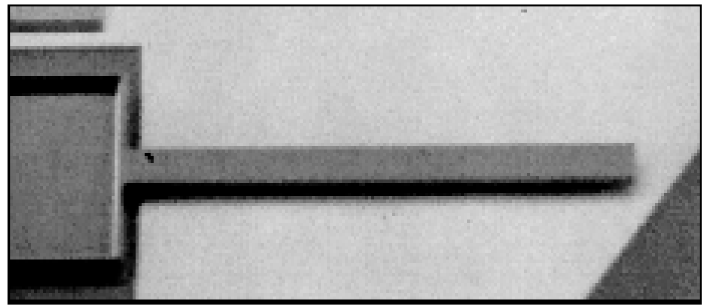


Deposit Poly-Si Layer

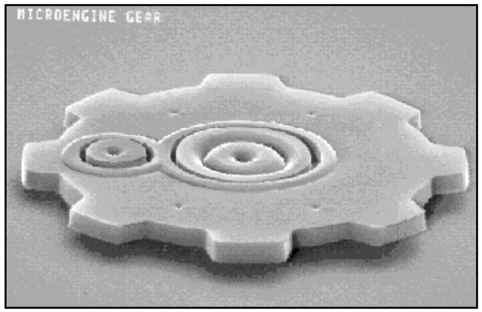
Remove Sacrificial Oxide to Release



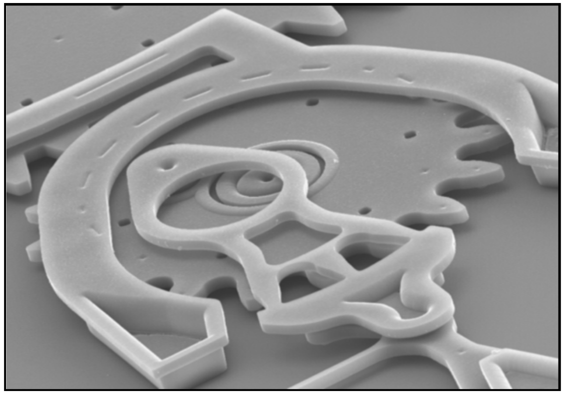
2 levels



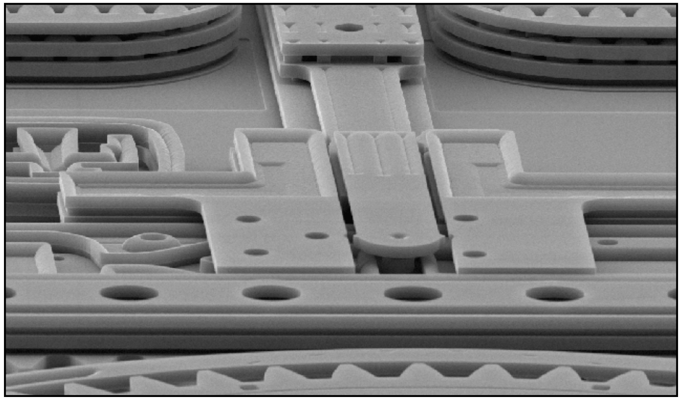
3 levels



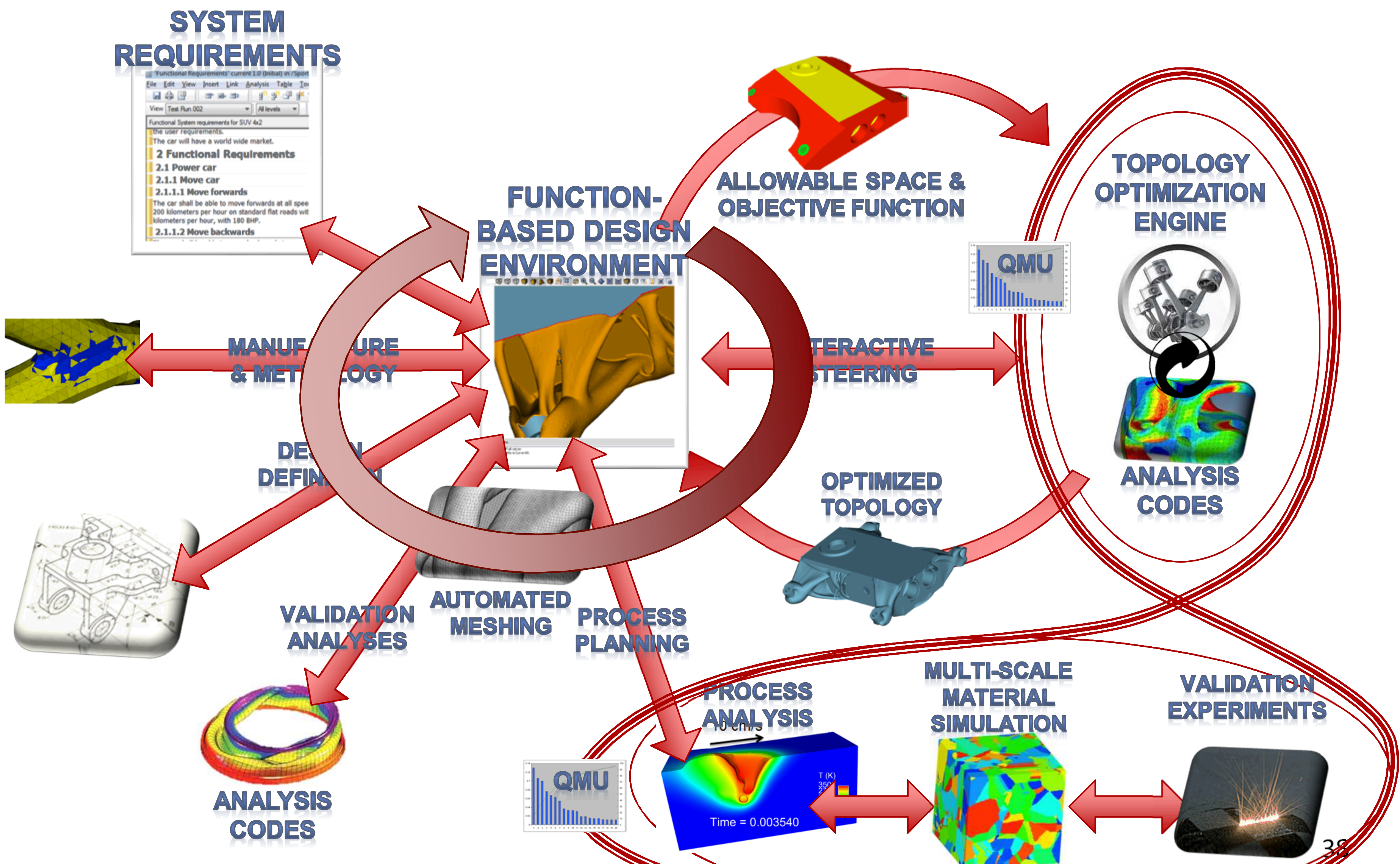
4 levels



5 levels



How Will All of This Work?



Microstructure Influences Variability & Failure

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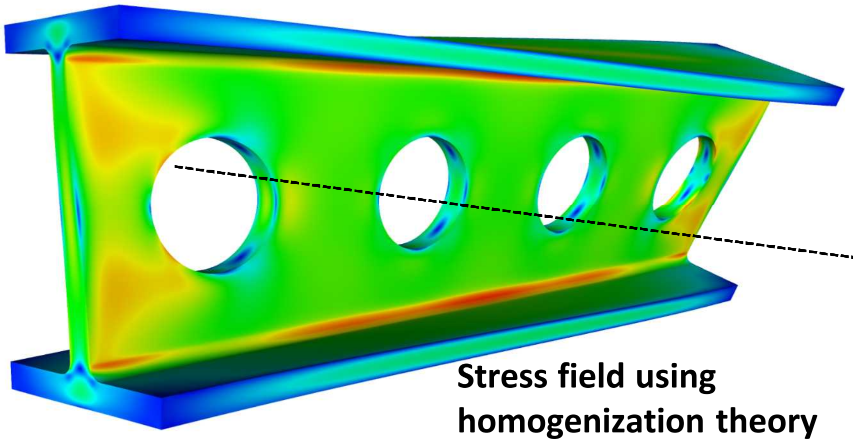
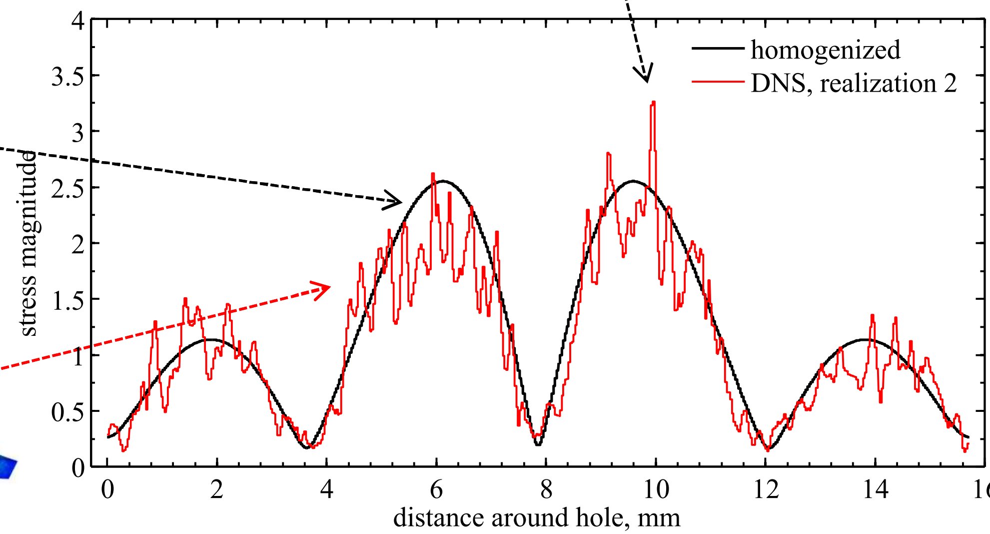
Homogenization theory misses local details - potential fracture initiation

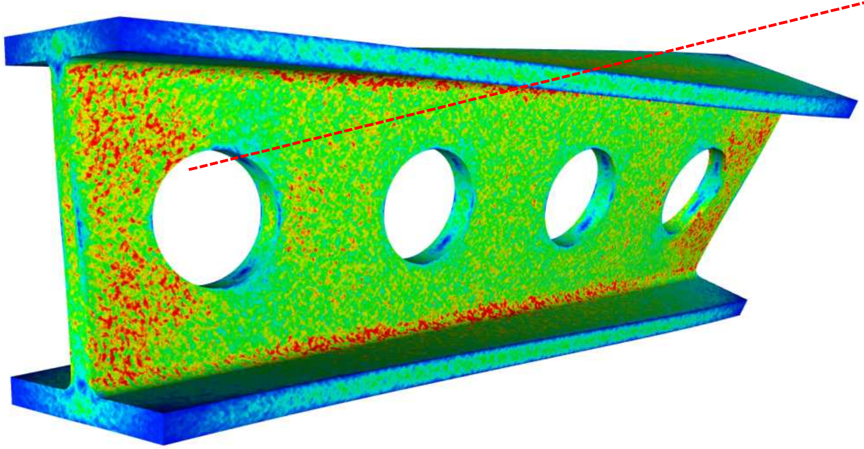
"Enriched physics"



Stress field using homogenization theory



- Homogenization filters physics necessary to predict failure
- Microstructure influences peak stress



Stress field using Direct Numerical Simulation

J. E. Bishop