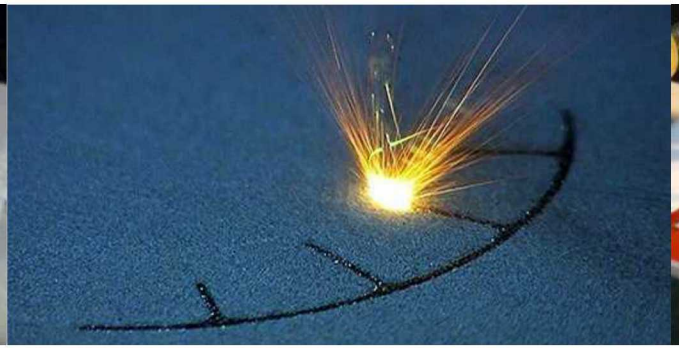
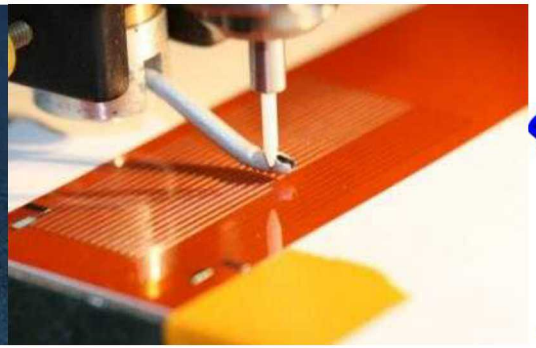
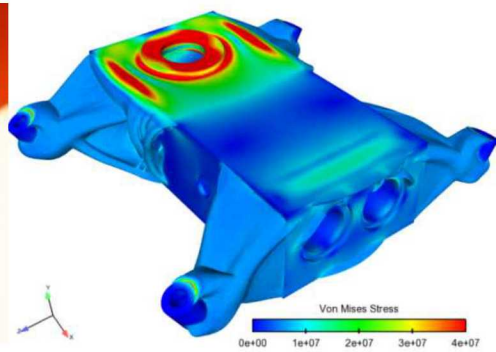
SAND2015-2938PE


# *Additive Manufacturing at Sandia*

Mark F. Smith

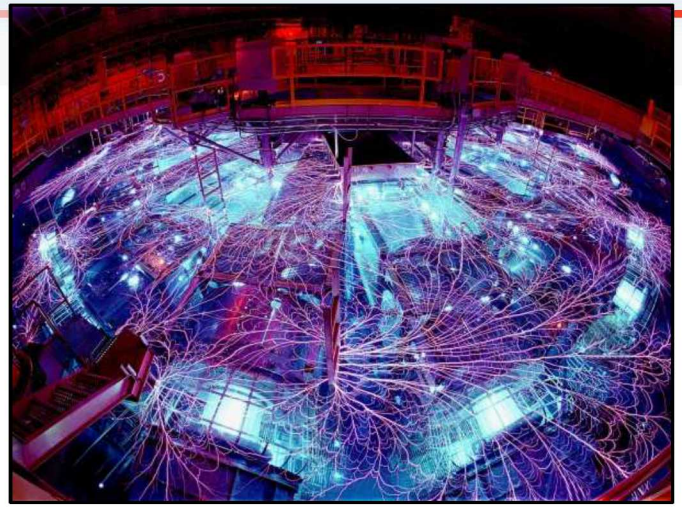
Materials Science & Engineering Center

U.S. DEPARTMENT OF ENERGY | NNSA

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2014-19962PE

# Sandia is a National Security Science and Engineering Laboratory

*Weapon Drop Test*



*Energy R&D*

*Threat Test*

- Historical mission -- non-nuclear component design and total 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

# Sandia National Laboratories Sites

*Albuquerque, New Mexico*

*Livermore, California*

Kauai, Hawaii


*Waste Isolation Pilot Plant, Carlsbad, New Mexico*

*Pantex Plant, Amarillo, Texas*

*Tonopah, Nevada*

All sites: 12,000 employees, $2.8B annual budget

Sandia National Laboratories

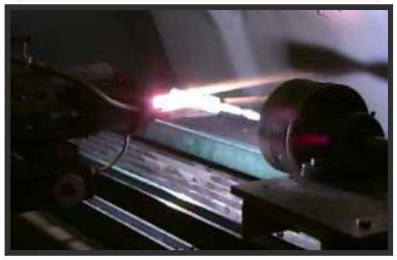
# 30+ yrs of Sandia Additive Mfg. Tech Development & Commercialization

## FastCast*
Development housing

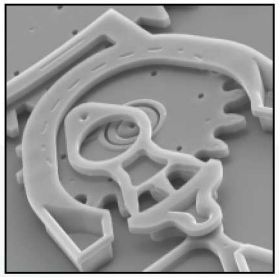
## Sandia Hand
50% AM built

## LIGA
"Hurricane" spring

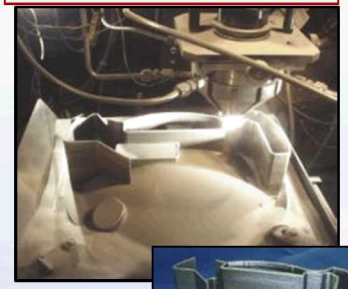
## Spray Forming
Rocket nozzle



## MEMS SUMMIT™ *
Micro gear assembly

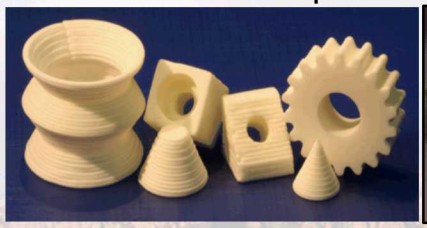


## LENS®*
Stainless housing



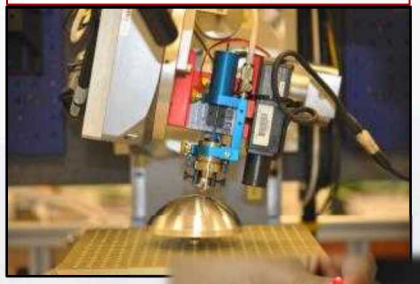
## RoboCast*

Ceramic parts



Energetic Materials

## Direct Write
Conformal electronics



Printed battery

* Licensed/Commercialized Sandia AM technologies

*Current Capability/Activity*

Sandia National Laboratories

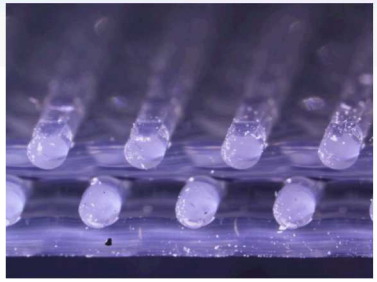
# Mission Drivers for AM at Sandia

- Potential Cost/Schedule/Design/Risk Benefits
- Optimize for Performance, Not Machinability
  - Revolutionary new design possibilities
  - Engineering analysis driven designs
- Engineered Materials
  - Multi-material and graded material parts
  - Future potential for microstructural control?

*Estimated Mfg. Savings*

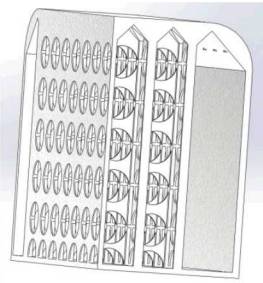
(AM Pads vs. Foam)

- B61-12 ~$6M
- W88 ALT ~$2M



pad side view

*Sandia Mass Mock*



Easily customize weight, center of gravity, moment of inertia

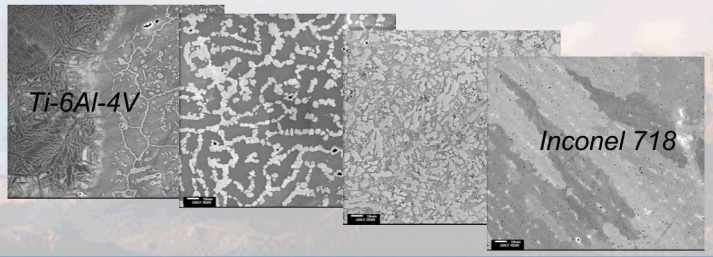
*GE Additive Manufacturing Design Competition*

Original Design 4.5 lb.

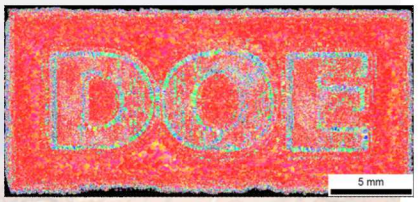
AM Design 0.7 lb.

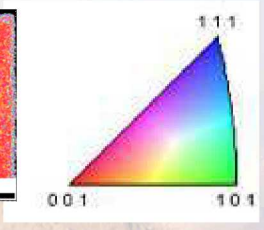
- 84% wt. reduction
- Successful load tests

*Sandia LENS® Functionally Graded Materials*




*AM Inconel 718 Crystallographic Orientation Control Demo'd at ORNL*




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

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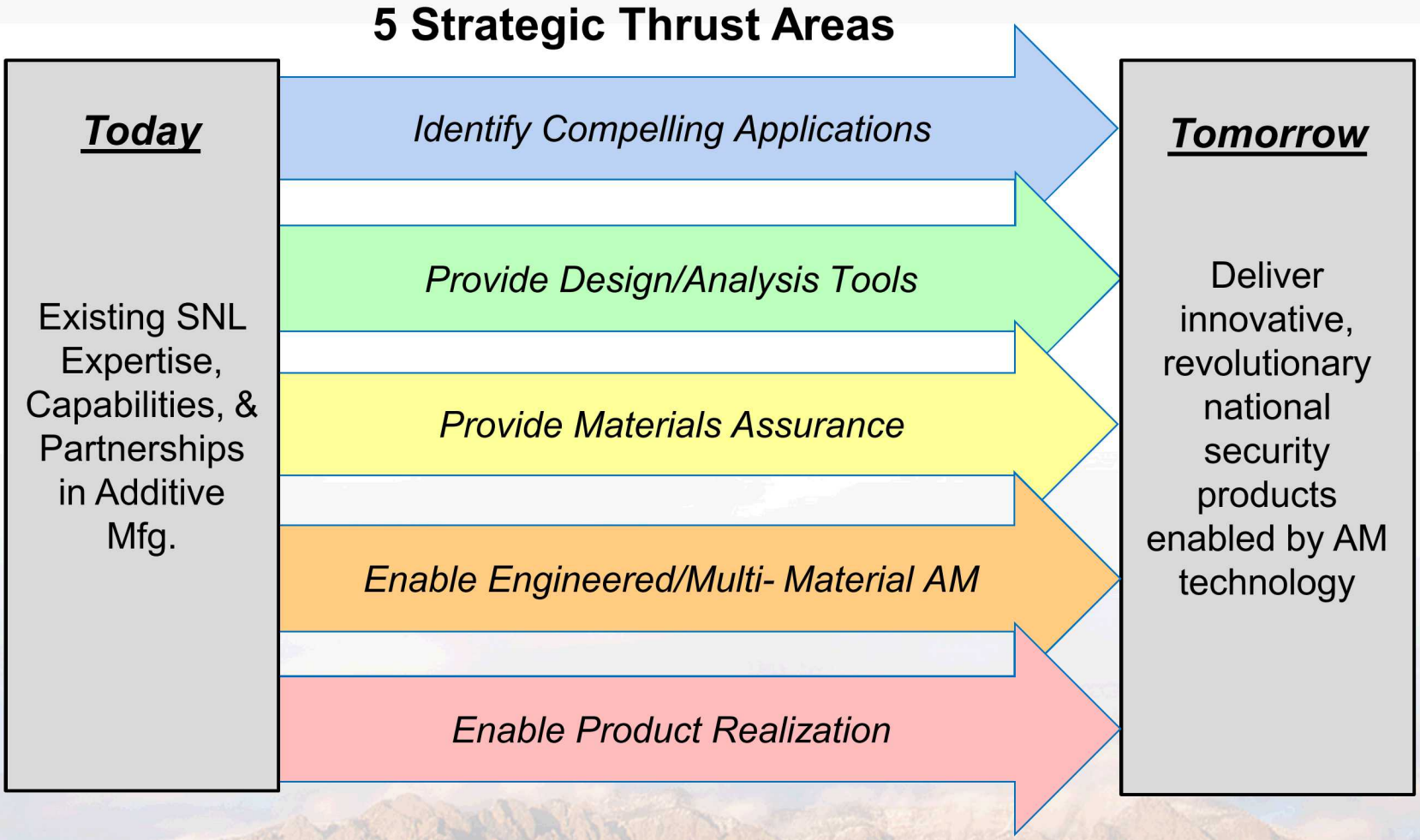
# Sandia Additive Manufacturing Strategy



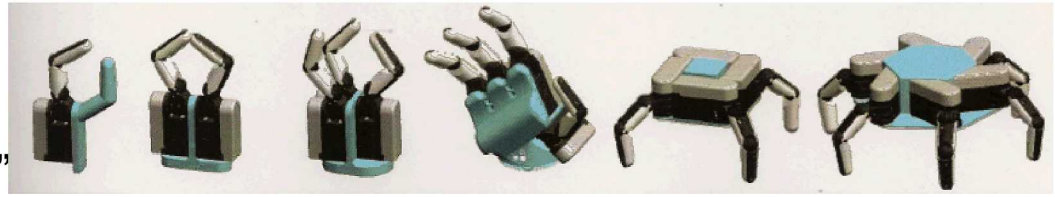
# Example Applications

# Sandia Hand – AM Enabled Innovative Design and Substantial Cost Reduction

(~<u>50% of hand built with AM</u>)

- 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

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# BaDx Anthrax Diagnostics Tool

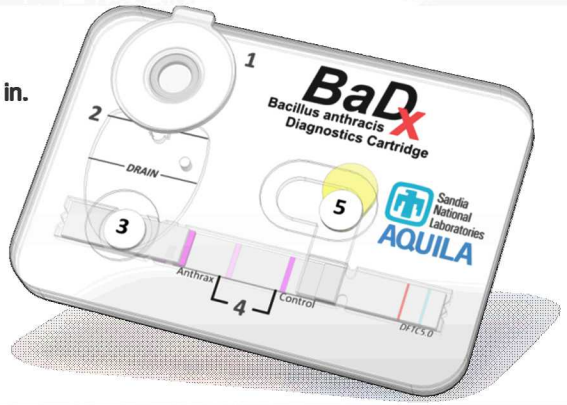
- Microfluidic platform for bacterial detection prepared from laser ablated plastic laminates
- Allows for rapid and inexpensive prototyping and design revisions
- Self-contained, credit card-sized "Laboratory in a Pocket"
- 3D printed cap
  - Specialized geometry
  - Low cost, quick turnaround

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**



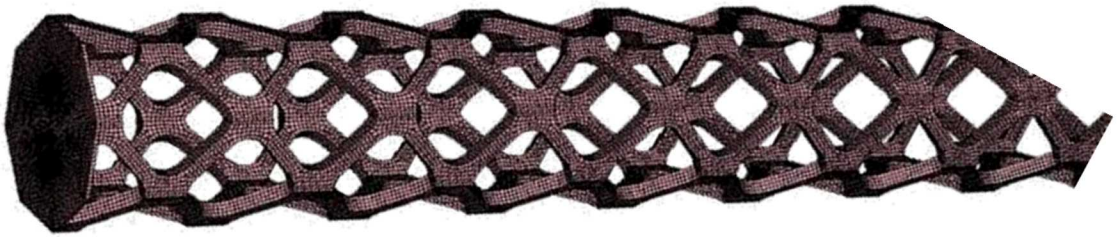

† Edwards *et al*. *Biomicrofluidics* **2011**, *5*, 044115.

# Design/Analysis Tools

# Analysis-Driven Design Optimization

*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?*

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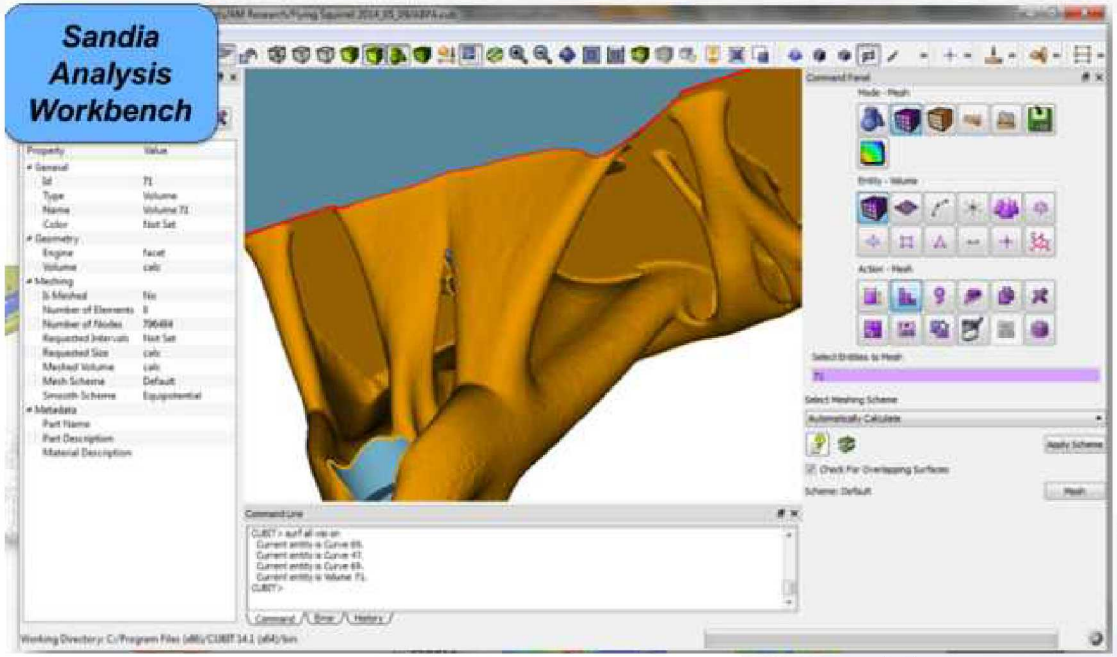
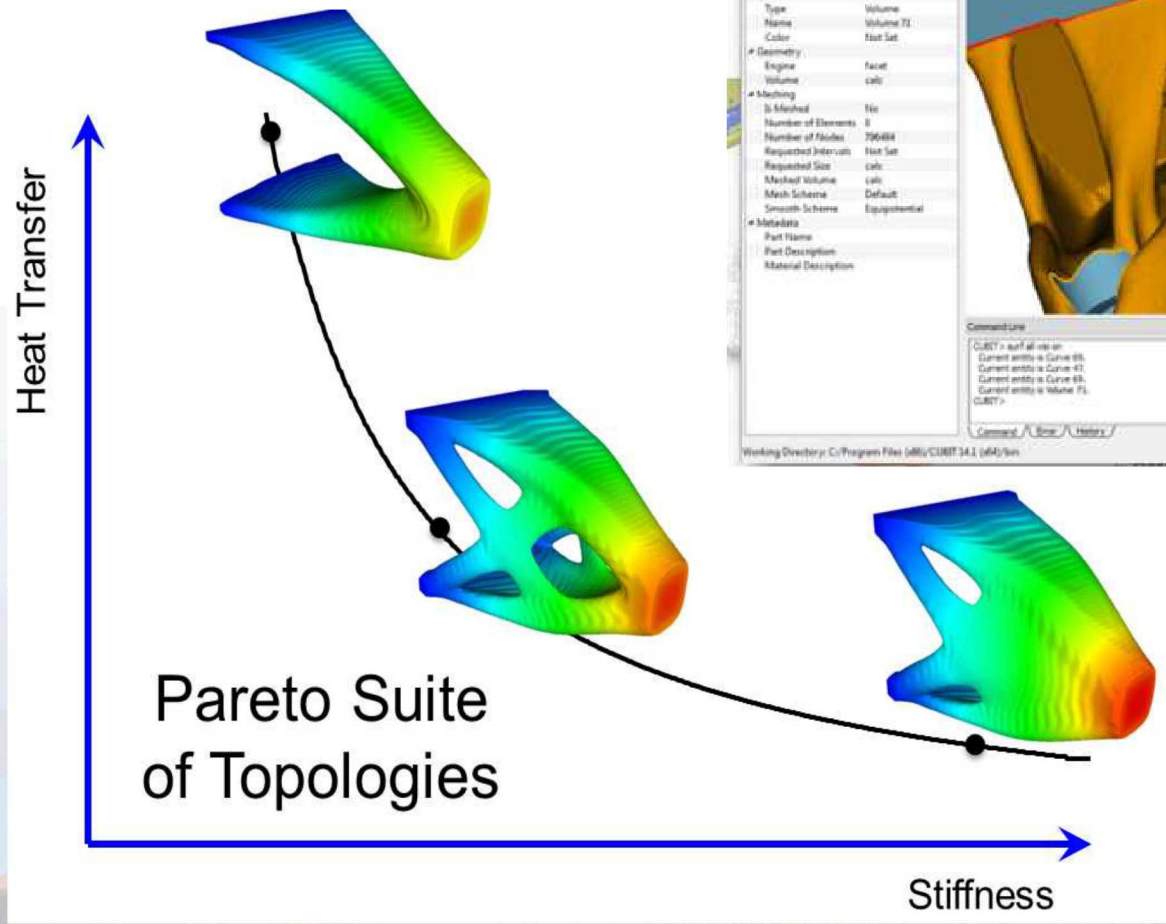
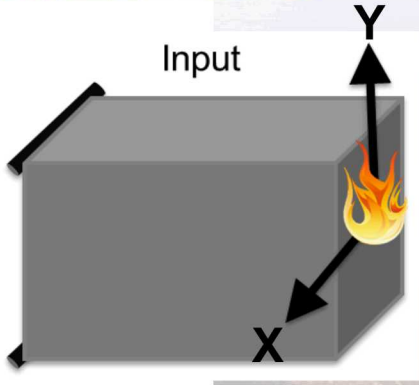
# AM Design Via Functionality Prioritization

User Friendly Interface

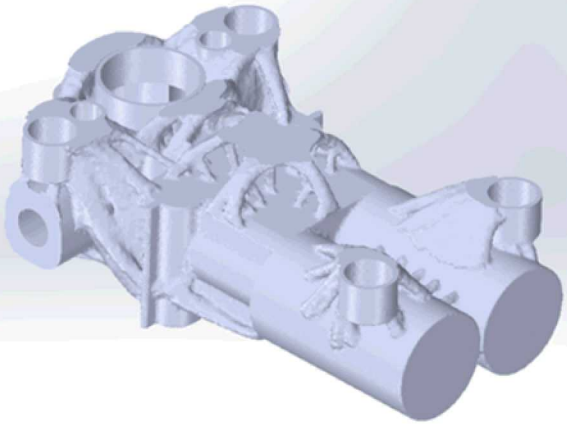


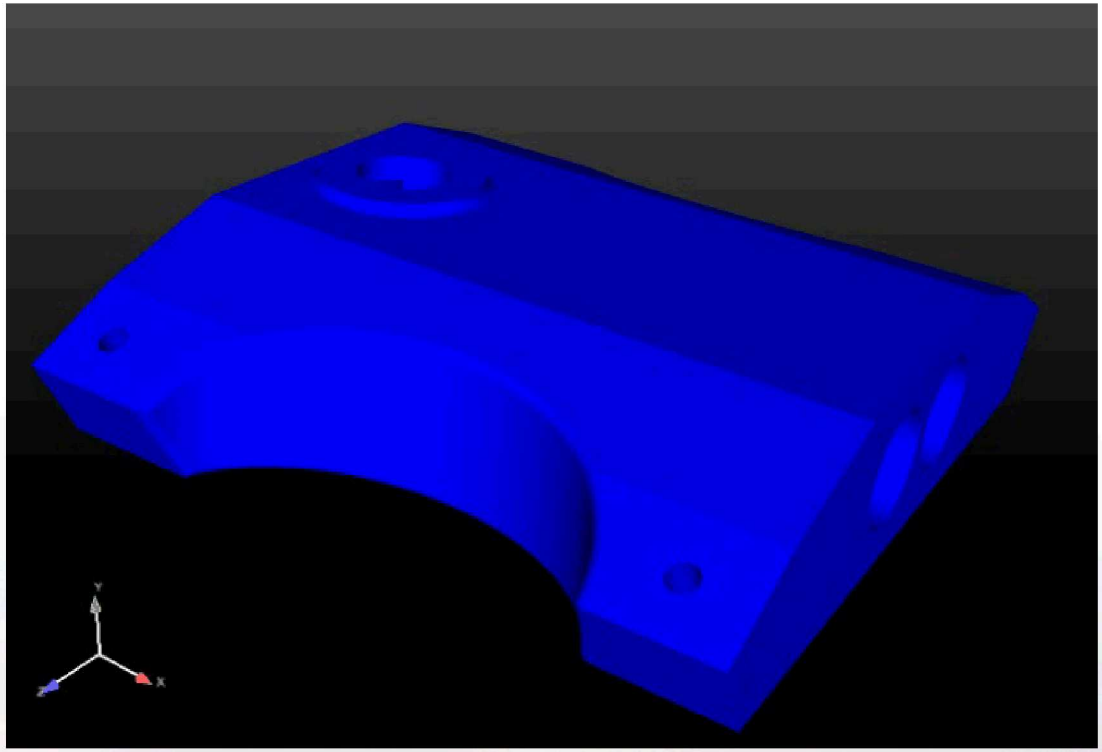
# TO/X-FEM Applied to a Component Housing


*Original Design*



*Highly Optimized Design*

*Topology Optimization / eXtended Finite Element Modeling*



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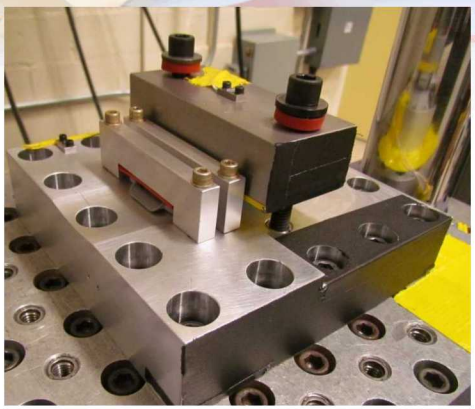
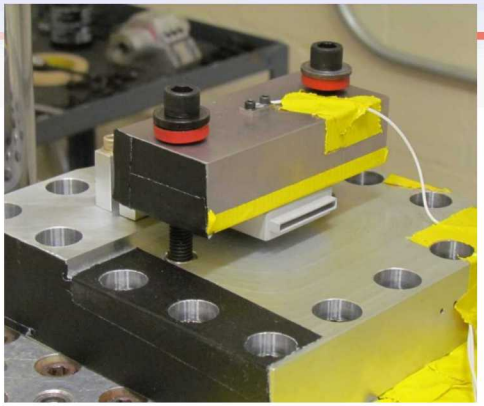
*Josh Robbins, Tom Voth*

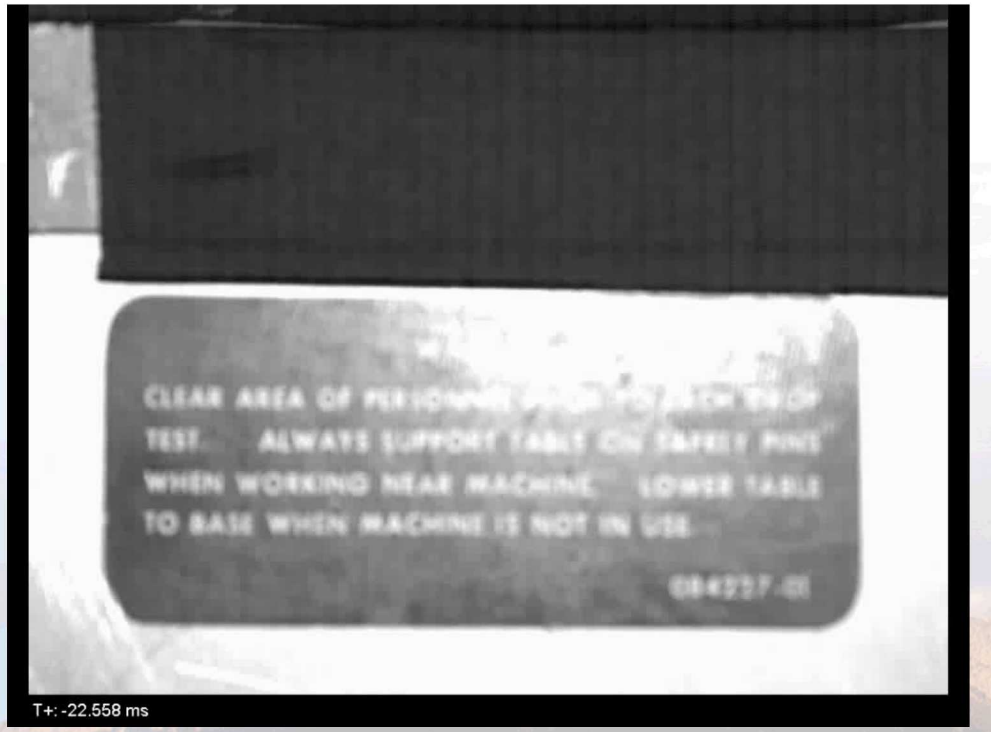
# Materials Assurance

# Superior Impact Performance

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

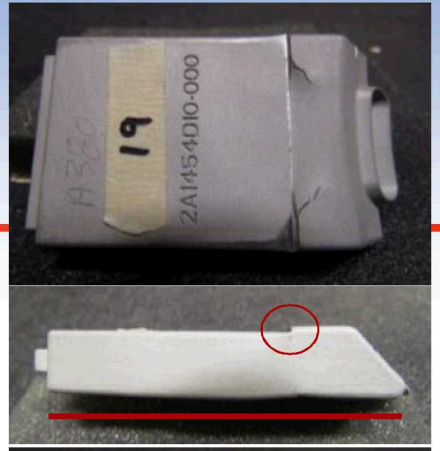






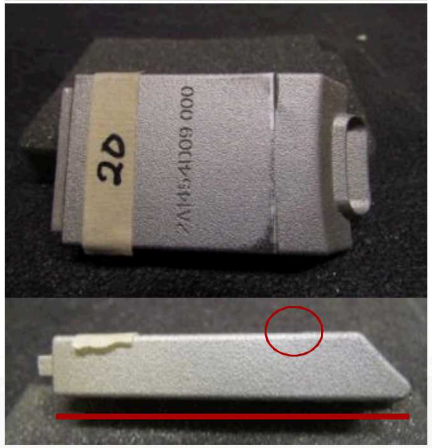

**Cast, A380**
**1 pc, 38 g**

- cracked
- buckled



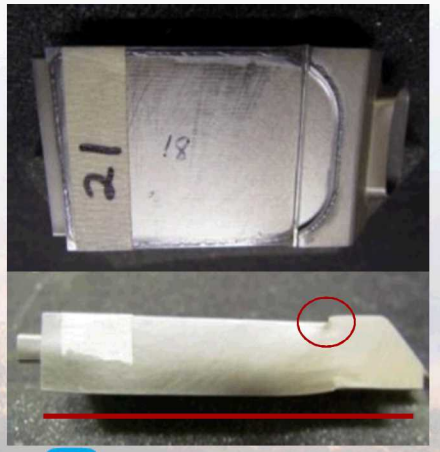

**AM, AlSi10Mg**
**1 pc, 38 g**

- slight indent
- still straight
- best result




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

- weld cracks?
- buckled

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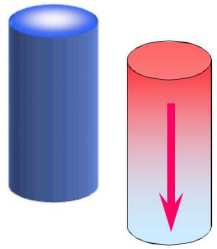
# Prior LENS® Process & Materials R&D


## Potential LENS® Advantages

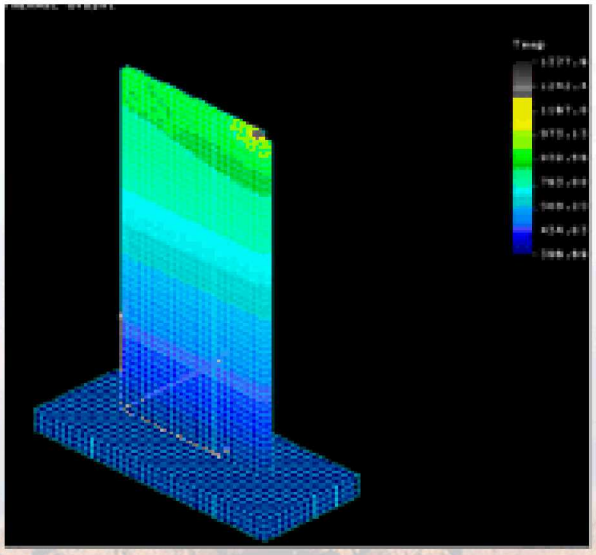
- Fully dense metal
- Good mechanical properties
- Graded materials
- Add to exiting parts

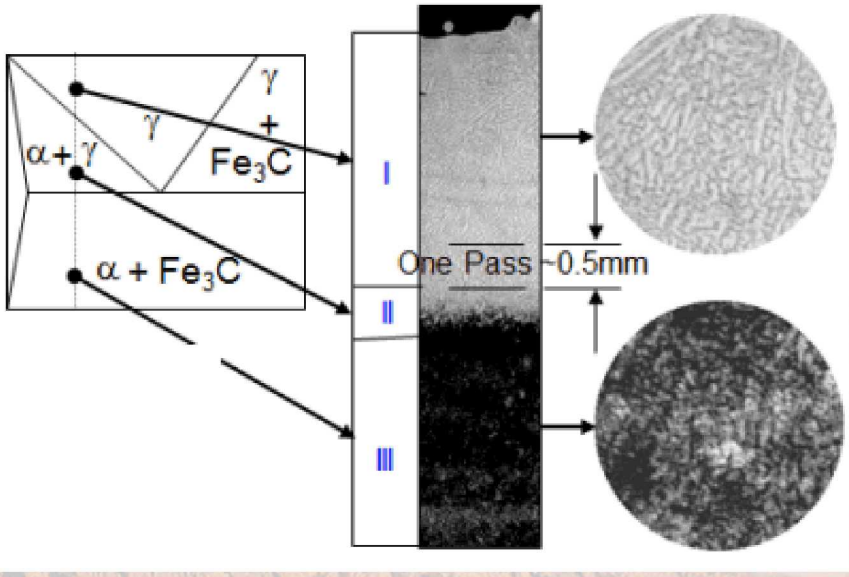
## Uni-directional Solidification

- Built narrow "wires" to achieve 1-D heat flow to simplify & understand solidification front



## Process characterization/modeling






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

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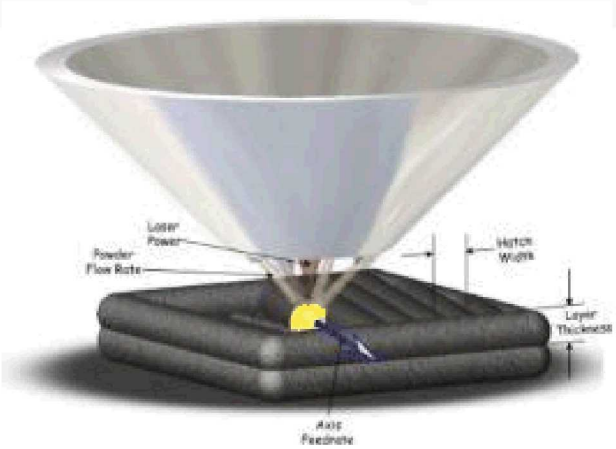
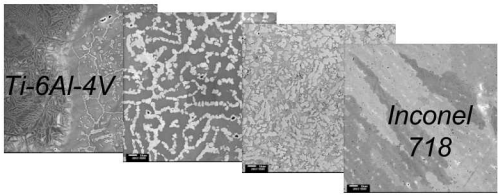
# Closed-Loop Process Control




## Z - height self-stabilization

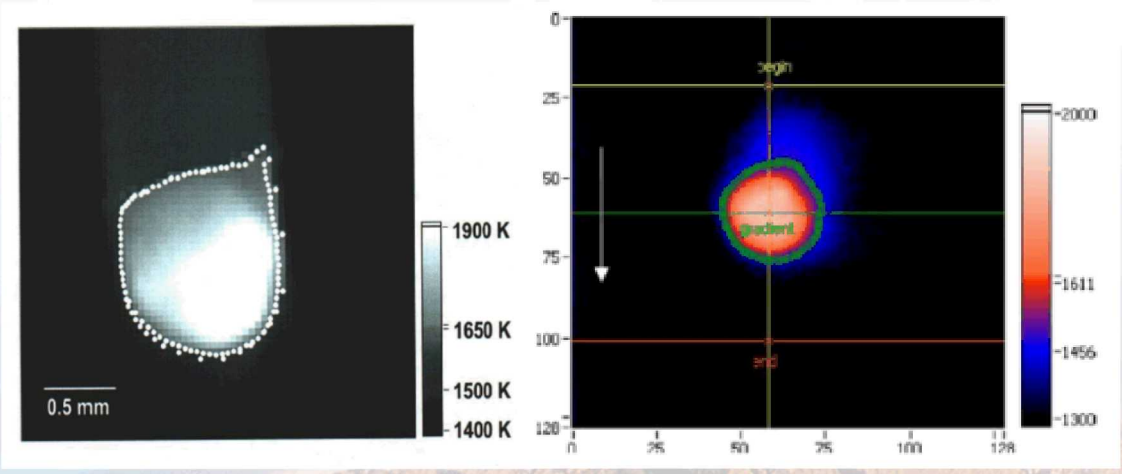
- Understand "magic spot"
- Developed Z-height sensor using reflected NdYAG with position-sensitive detector

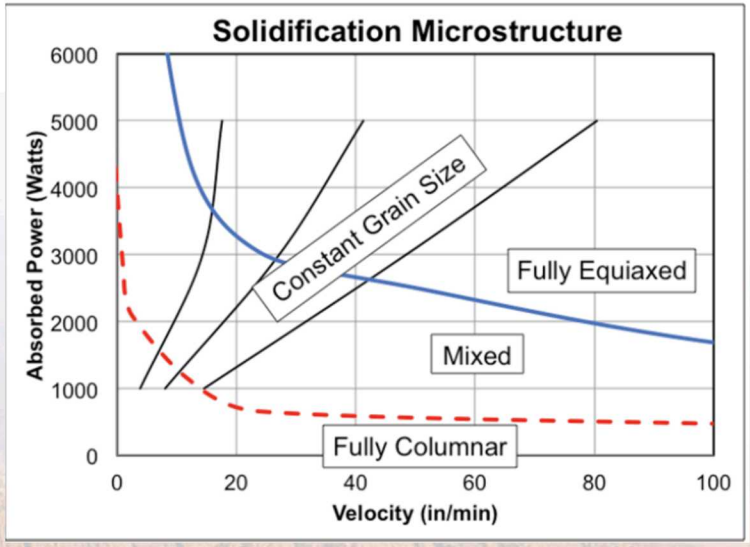



*LENS functionally graded materials*

## Variety of LENS® Metals

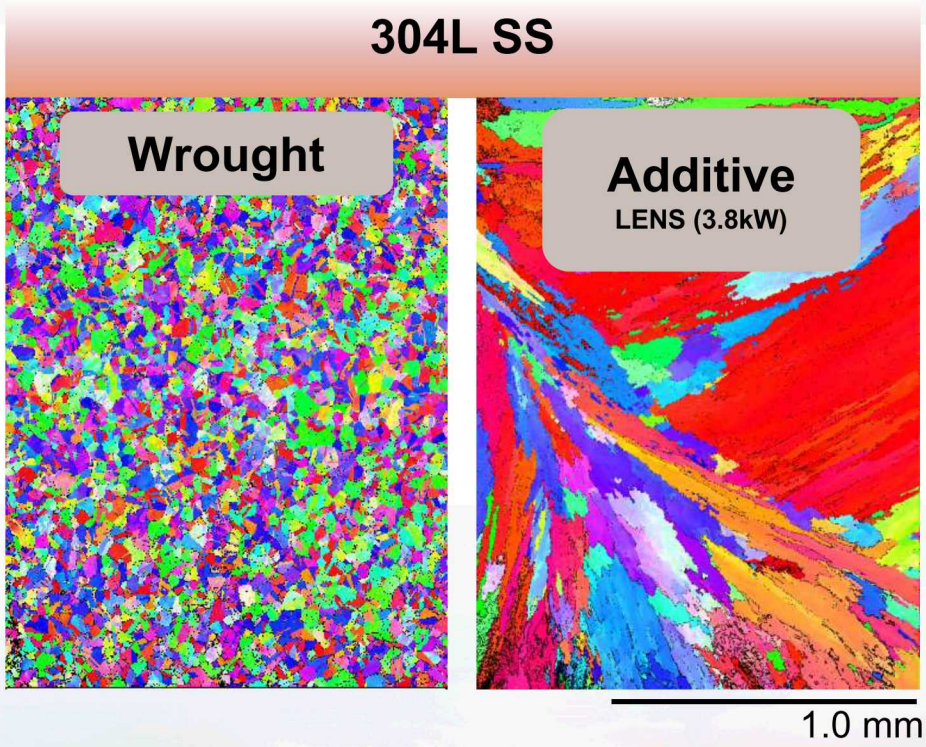
Ti-6Al-4V
Aermet 100
Stainless 304L, 316L
Tool steels
Inconels
Graded Metals




Controlling the Melt Pool Provides Microstructural Control

# AM Materials Are Unlike Conventional Materials




Near Term (traditional approach)

- Property measurements
- Microstructure/defect analyses
- Statistical variability analyses
- Effects of post treatments
- …

Future State (predictive modeling w QMU)

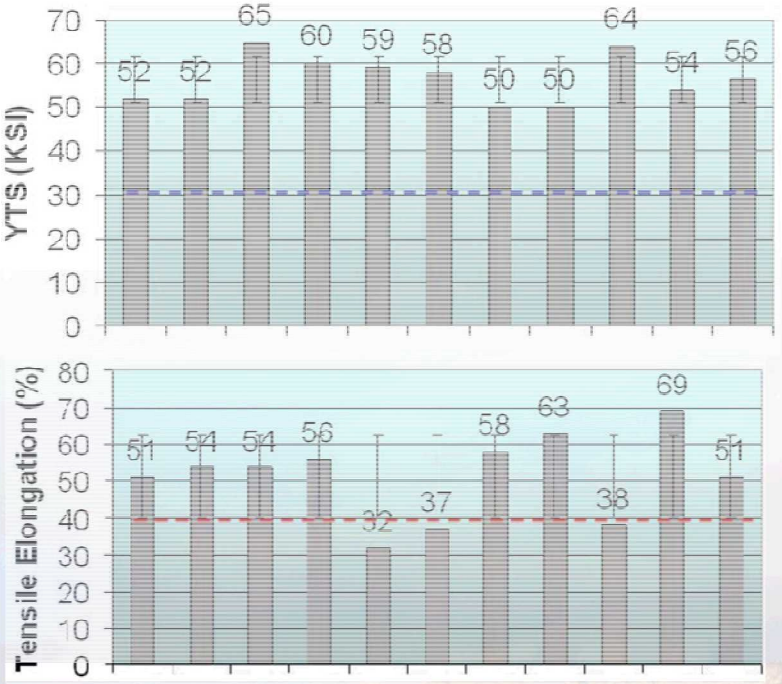
- Establish microstructure-properties-performance relationships
- Multi-scale modeling/validation
  - Poly-crystal plasticity models
  - Direct numerical simulation
  - …

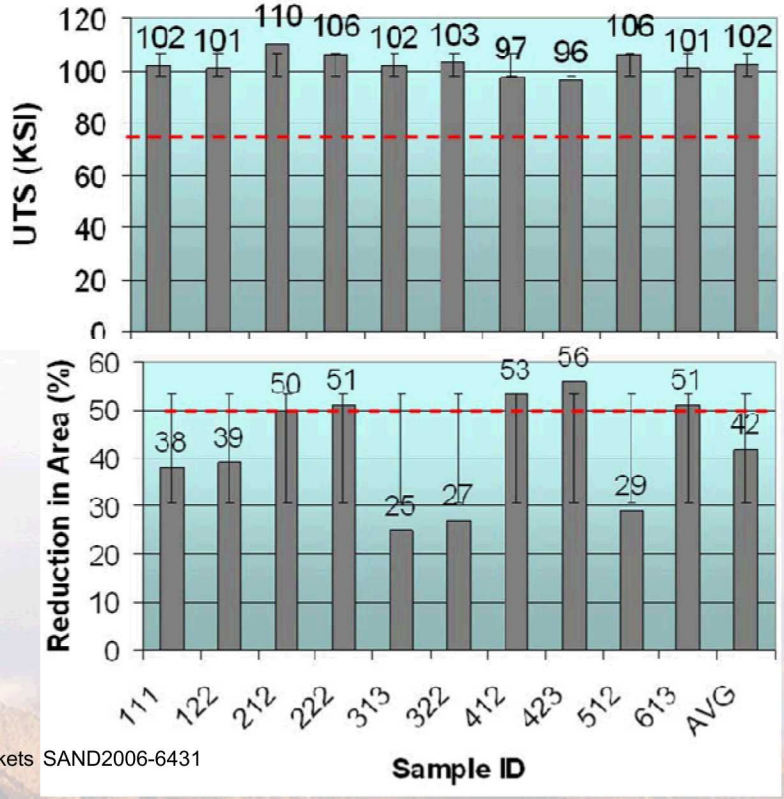
***Engineered Materials Reliability (EMR) Research Challenge***: *Develop a framework for understanding how material variability impacts the reliability of engineering components through the use of multi-scale computational and experimental approaches that account for variability across length scales and provide probabilistic predictions of product performance.*

Key is to understand key *Processing-Microstructure-Property-Performance* relationships!

# We Must Understand Variability in AM Materials

- In 2006 Sandia report ten nominally similar "block" builds – tested along build axis showed significant material variability
- Engineered Materials Reliability Research Challenge is motivated to understand such variability




D. Gill, et al. Process Qualification and Testing of LENS® Deposited AY1E0125 D-Bottle Brackets SAND2006-6431

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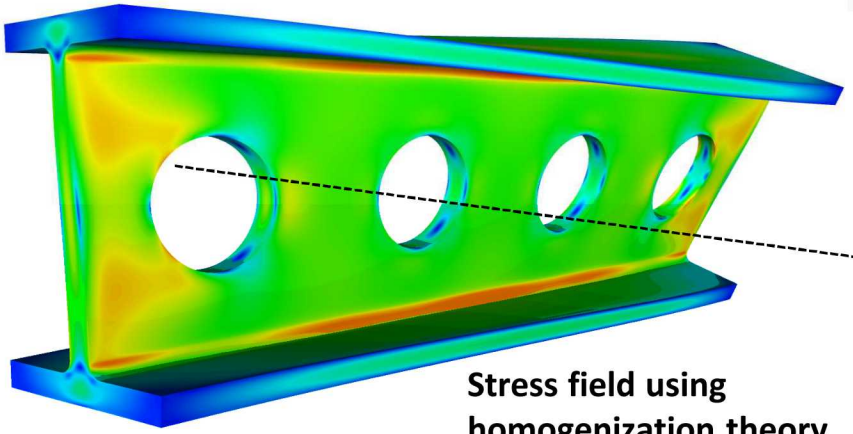
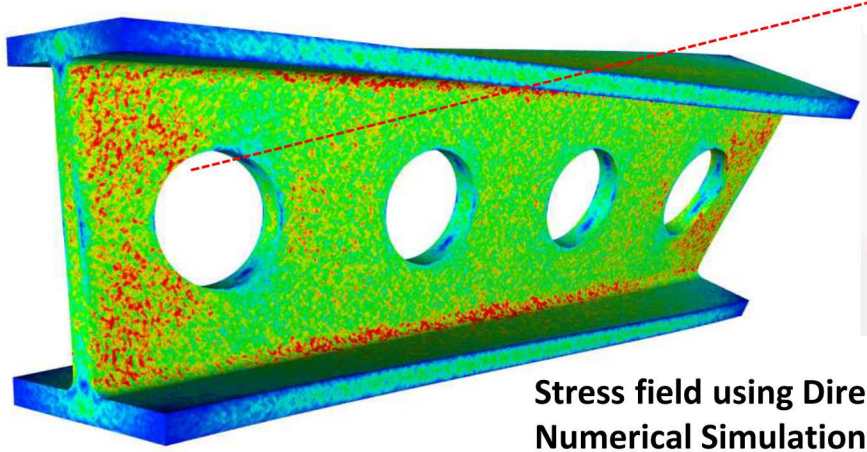
# Microstructure Influences Variability & Failure



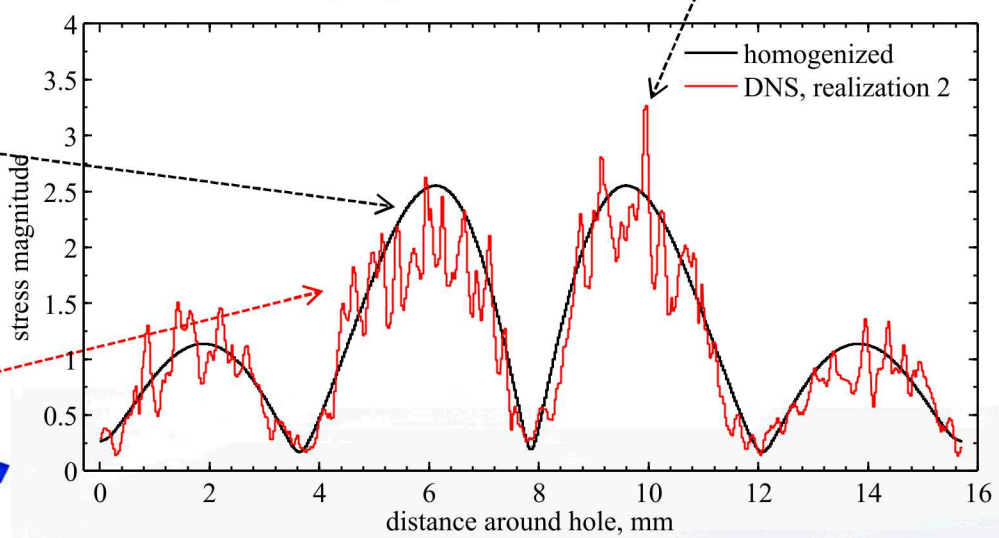
Stress field using homogenization theory



Stress field using Direct Numerical Simulation

Homogenization theory misses local details - potential fracture initiation

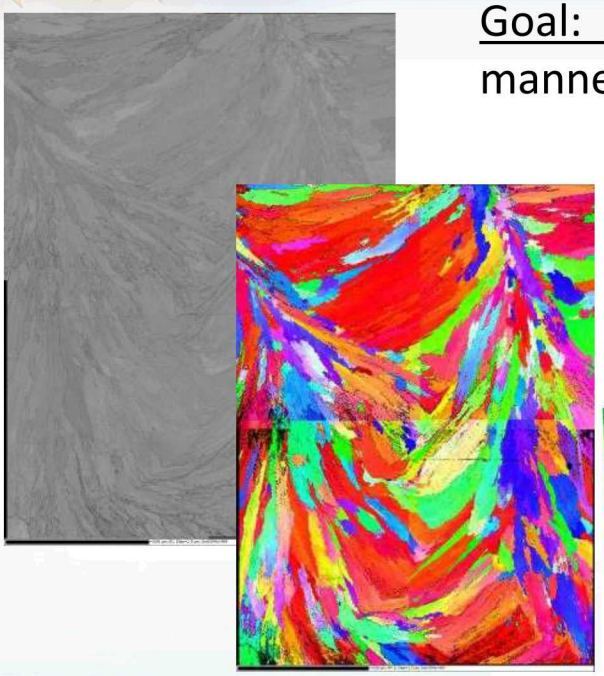
**"Enriched physics"**




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

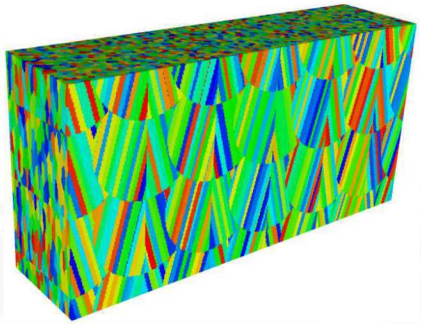
***Enriching local physics and incorporating microstructure is one way to be more predictive***

# Modeling Microstructure & Behavior



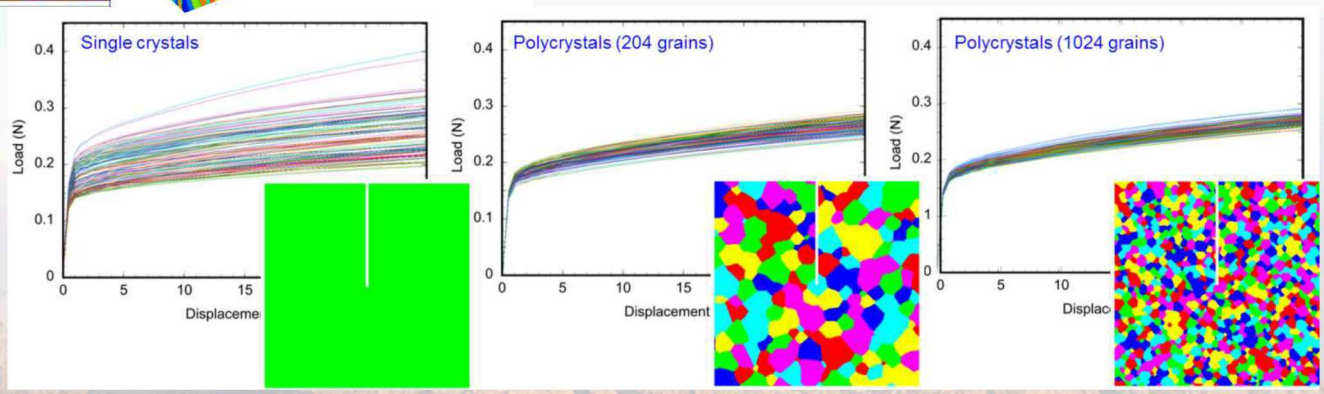
Goal: Incorporate material variability in a probabilistic and predictive manner to optimize performance and determine margins

Systematic sampling of grain structure and orientation via modeling and simulations provides greater confidence of margins when only limited experiments are available.



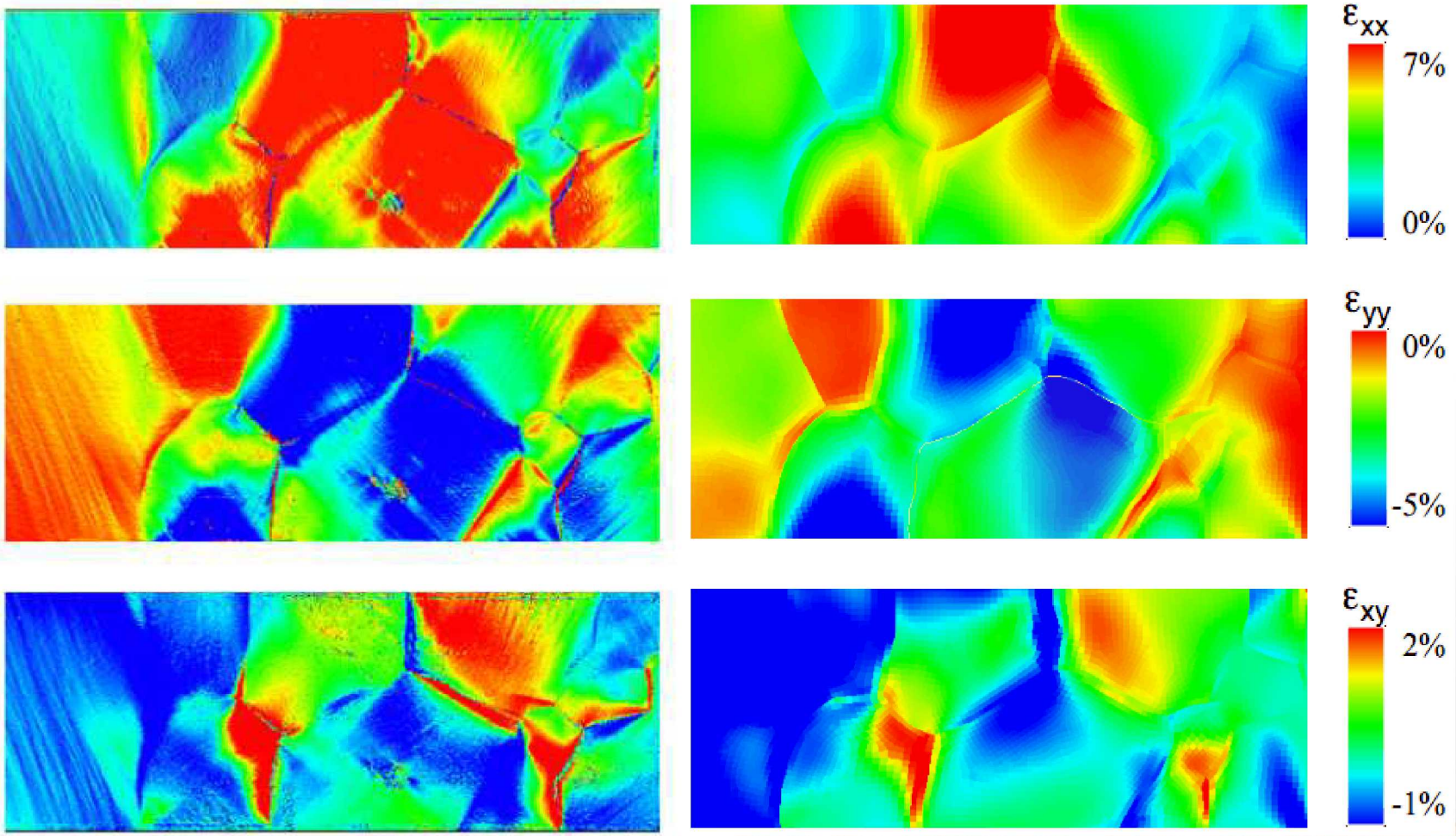
LENS® microstructure with orientation information + Direct Numerical Simulation (DNS) models will enable anisotropic deformation models

Grain size impacts the uncertainty margins of properties and performance.



# Experiments and Models Show Reasonable Agreement

*Oligocrystal experiments vs. crystal plasticity models (tensile loading)*

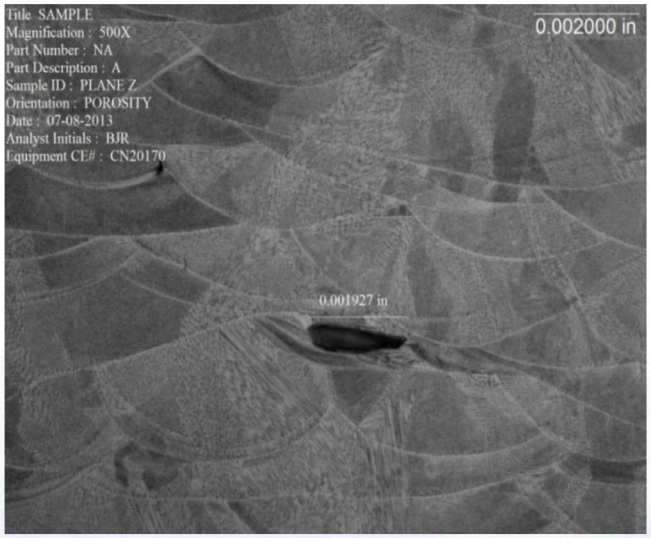



*DIC experimental measurements*

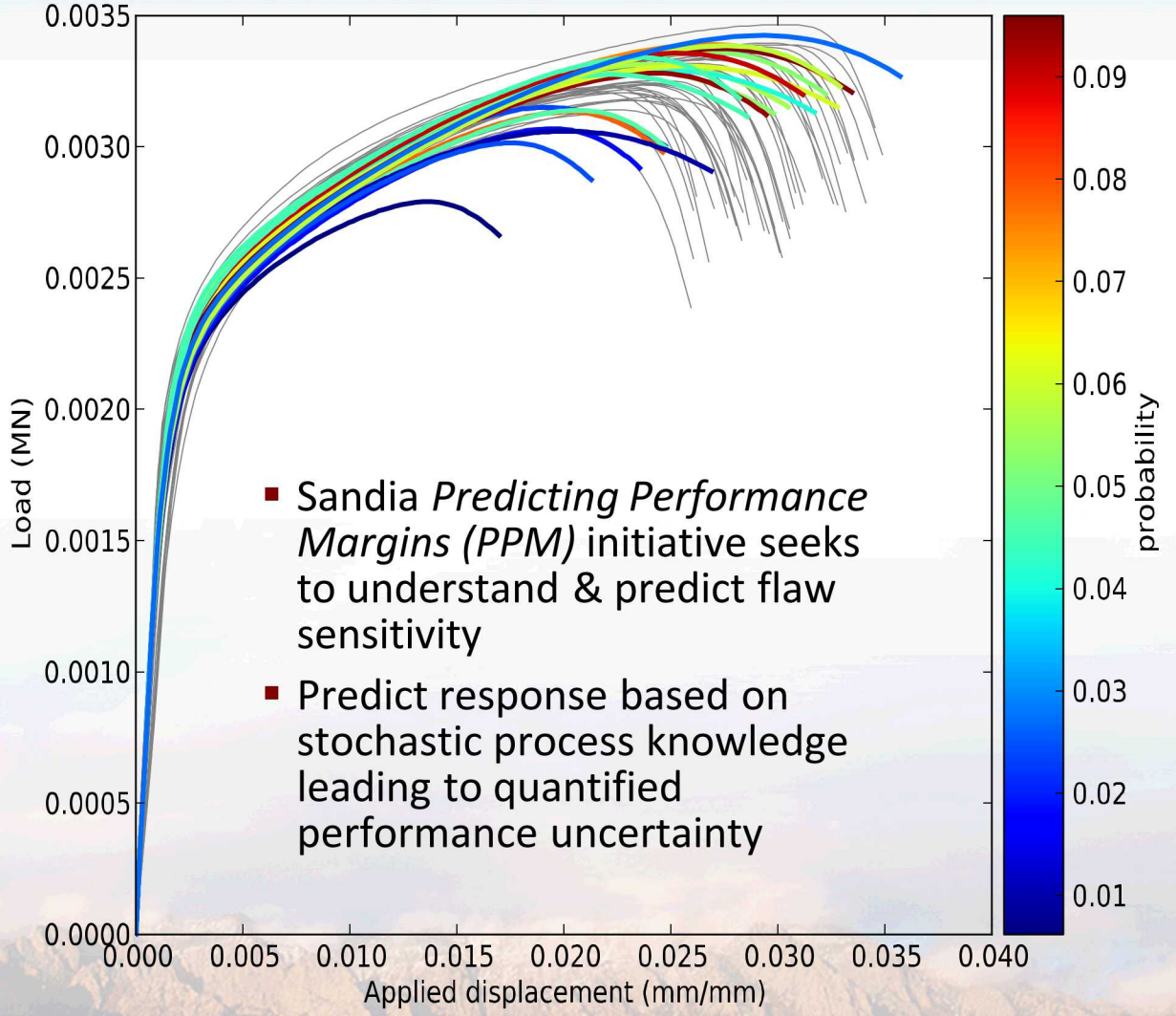
*Simulations*

# Leverage Sandia PPM Study of Flaw Sensitivity

How do flaws affect AM metals?



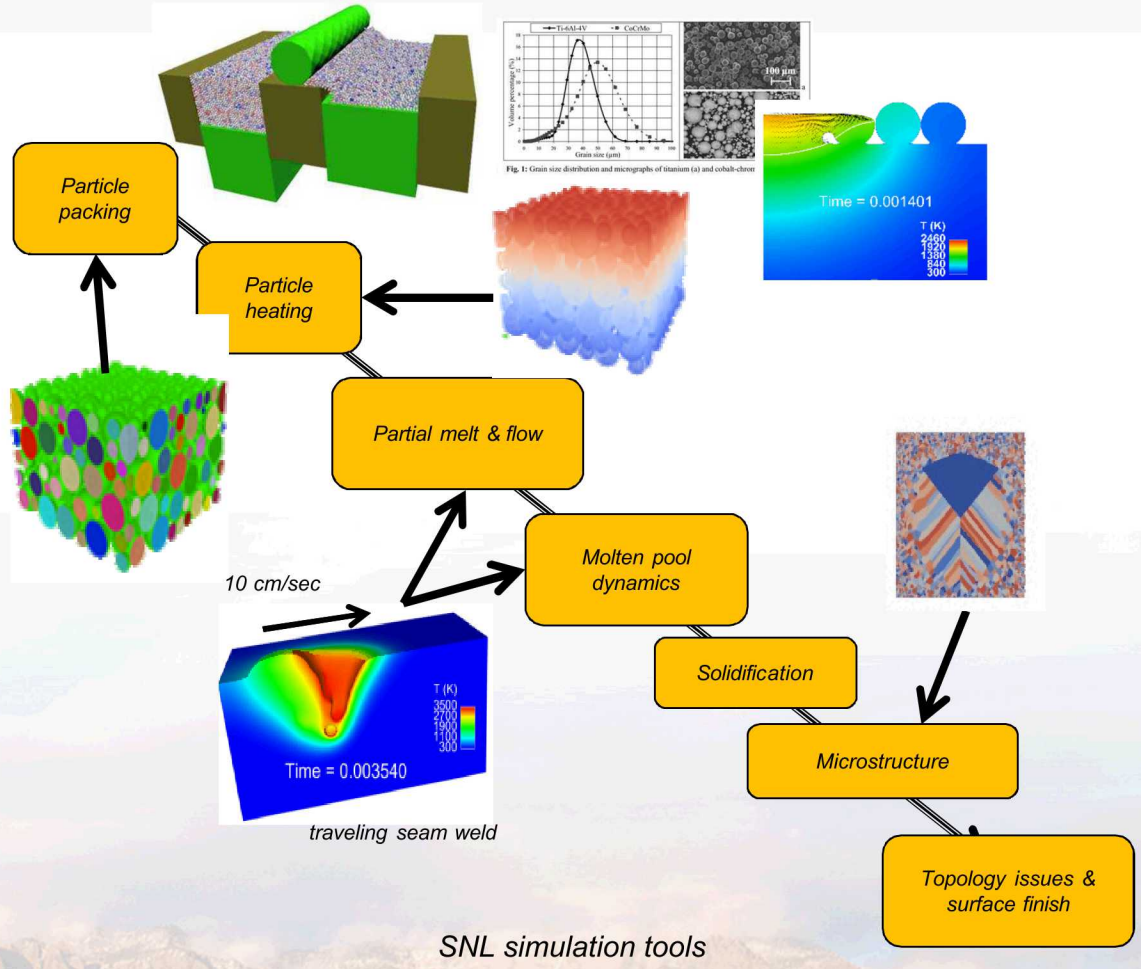

*AM 17-4 PH microstructure (Everhart, Honeywell NSC)*




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

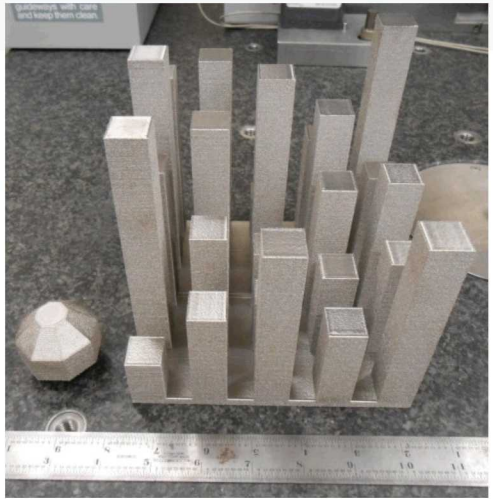
# Working to Model Process → Microstructure

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



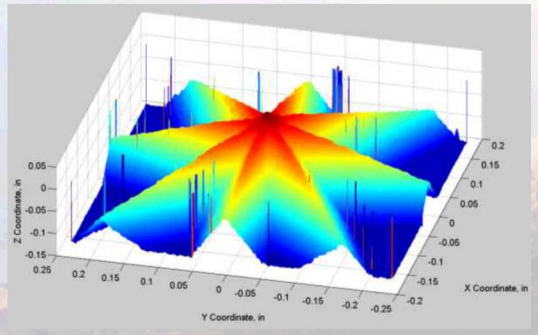
# Metrology for AM Is Also A Key Challenge

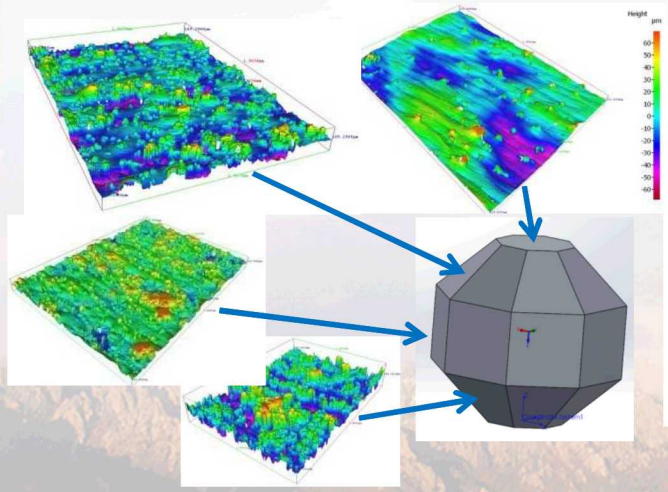
- Family of artifacts designed, 3D printed, & measured
  - Sandia Primary Standards Lab working w NIST to develop better AM metrology artifacts
- Unique challenges for process/equip. characterization
  - Tolerance/Surface Finish/Properties vary with machine, material, print orientation, support structures, post-processing,…)



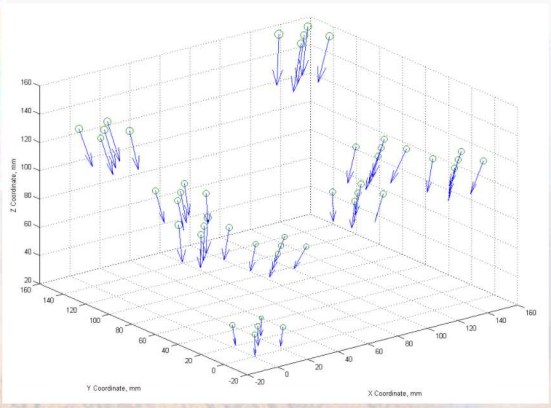
*Ti-6Al-4V polyhedron & "Manhattan" artifacts for MPE (maximum permissible error)*

*Siemens star geometries for resolution evaluation*



*17-4PH polyhedron texture anisotropy map*




*Ti "Manhattan" error map*

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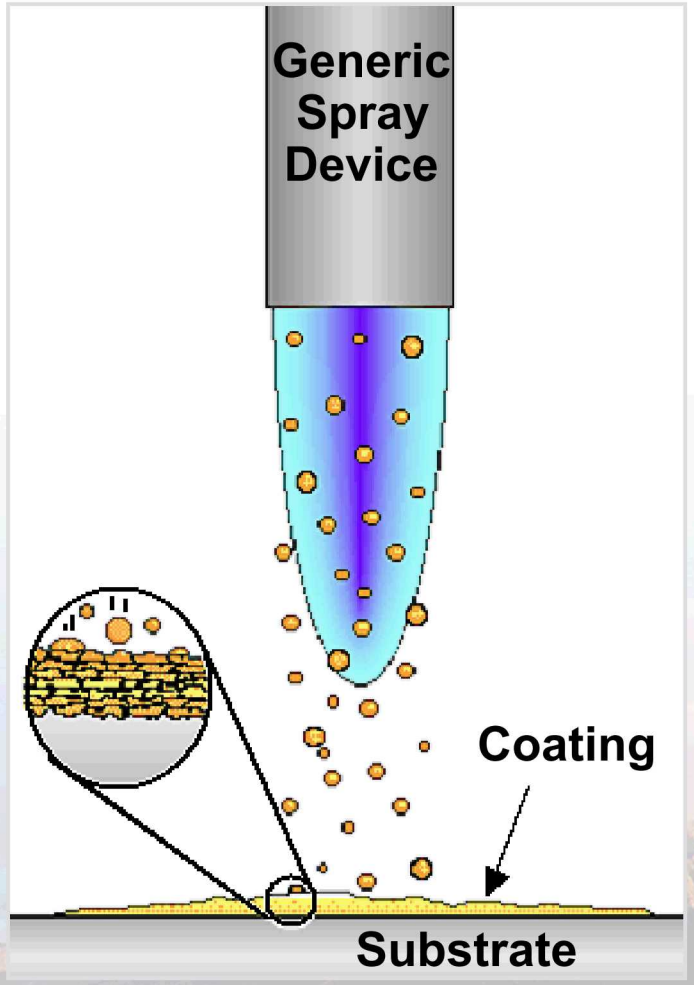
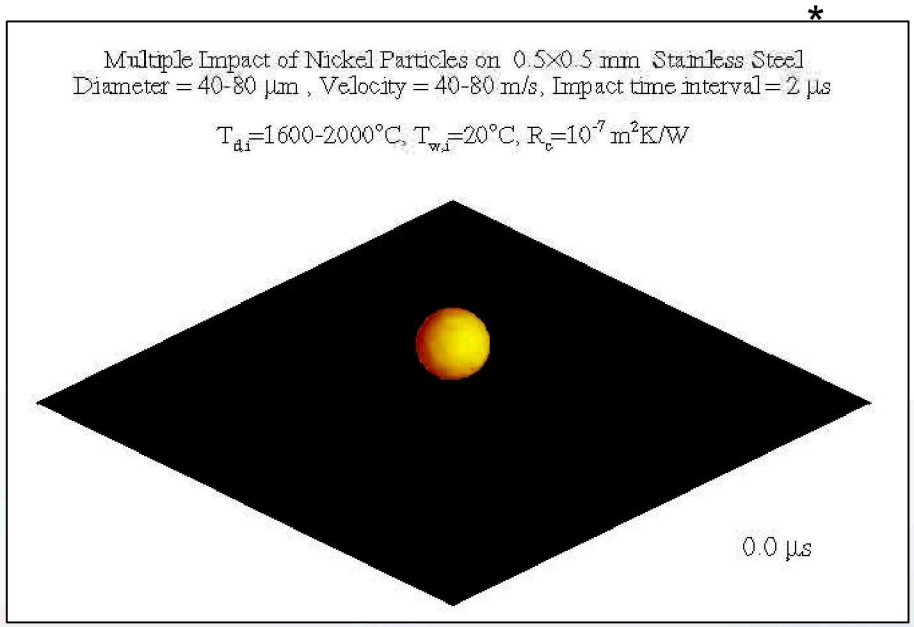
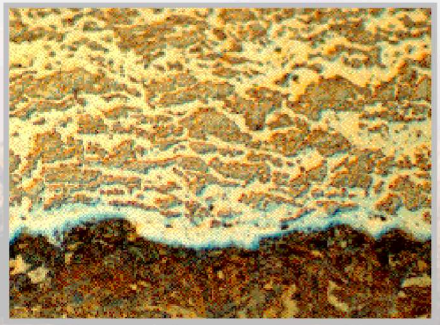
# We Are Building on Prior Success with Another AM Process, Thermal Spray

- Spray ~ 10 - 100 µm Molten or Semi-Molten Droplets
- Cool at $10^4$ - $10^8$ K/sec Forming a Lamellar Microstructure




*



← Cemented Carbide On Steel

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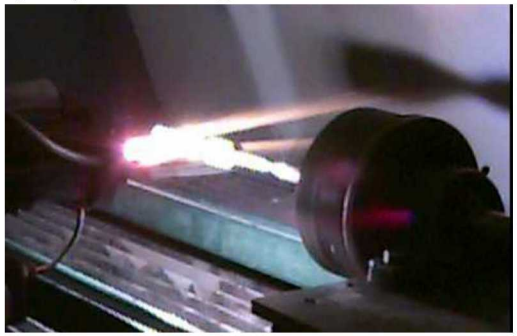
*Droplet Impact Simulation by Prof. J. Mostaghimi, et al, Univ. of Toronto

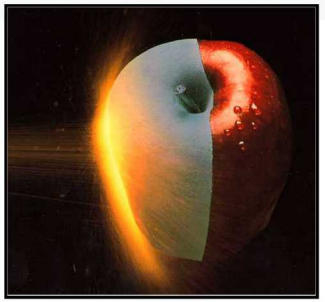
# Extensive Experience with Spray Deposition

*Sandia Thermal Spray Research Laboratory*

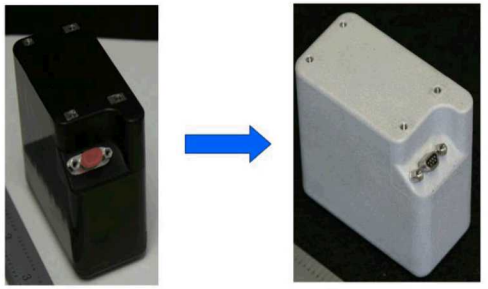
*Spray Forming a Rocket Nozzle*



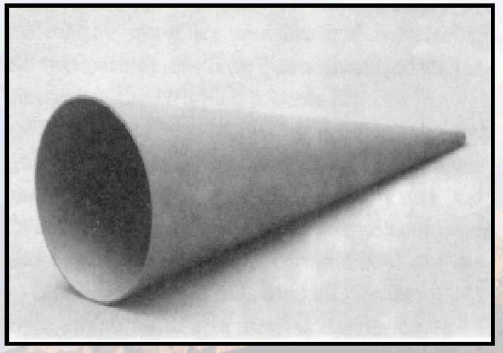
*Metallizing an Apple**



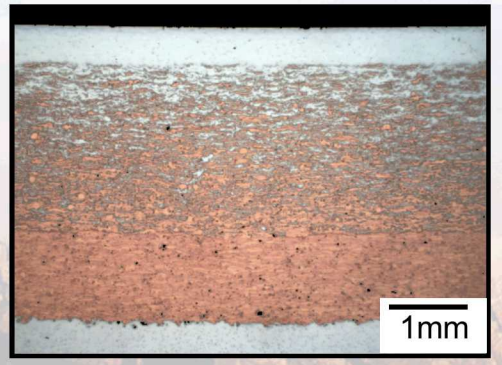
*Metal Coated Plastic Housing*



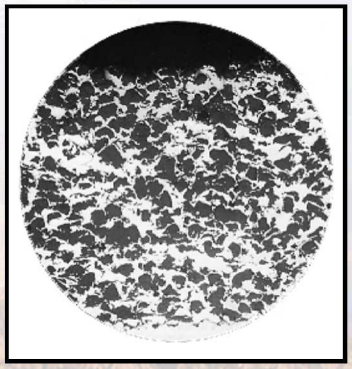
- High Deposition Rates
- Wide Choice of Materials
  *"anything that melts"*
- Combine Highly Dissimilar Materials
- Unique Microstructures / Properties



*Spray-Formed $B_4C$ Cone†*




Graded Density Cu→Al Spray-Formed Flyer Plate



*AlSi / Polyester Composite*

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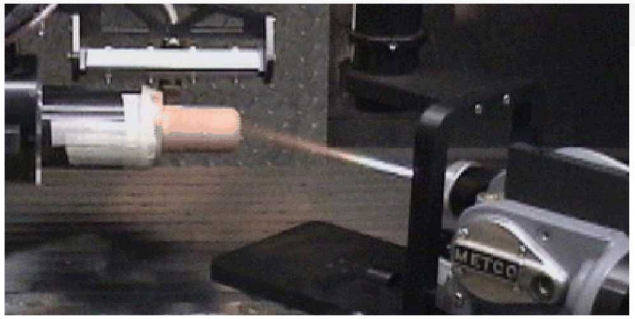
† From Freslon, Proc. 1995 Intl. Thermal Spray Conf.

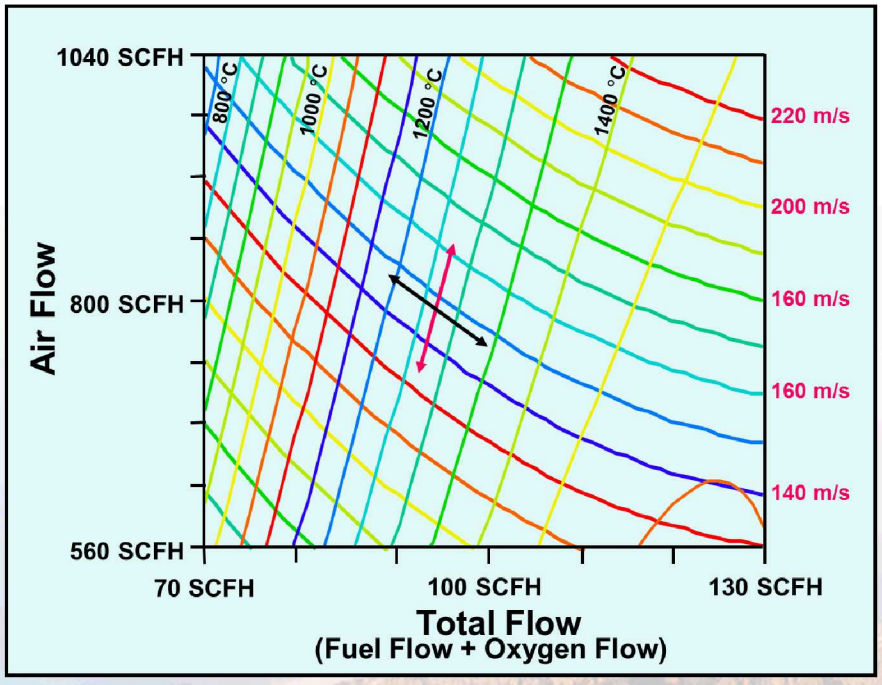
*Photo provided by TAFA, Inc.

# Fundamental Understanding of the Process

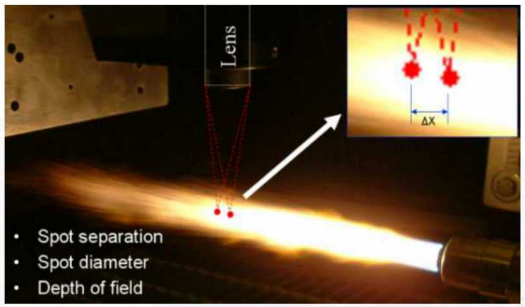
- High-consequence, small-lot production (~$100k/part)
- Decades of R&D work on flame spray coatings have resulted in a science-based process understanding
- Fundamental understanding and modeling used to implement custom closed-loop feedback control



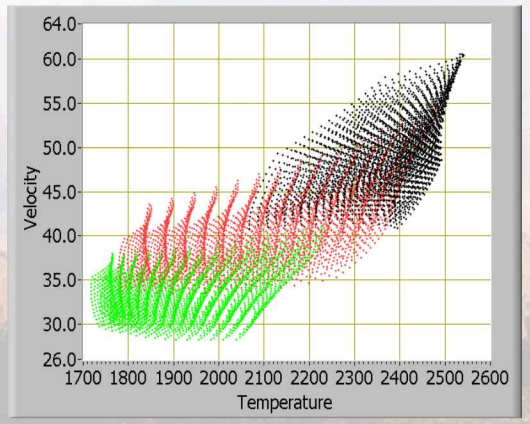
Production Flame Spray




Response surface showing relationship between process inputs (air flow, fuel flow, oxygen flow) and process outputs (particle temperature, particle velocity)

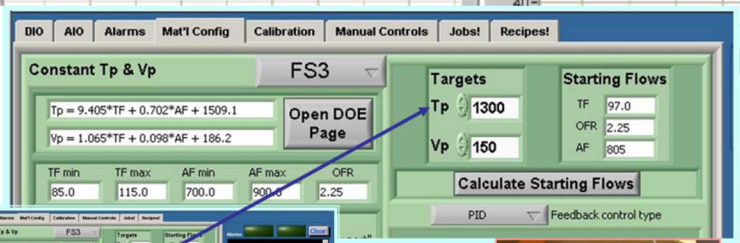


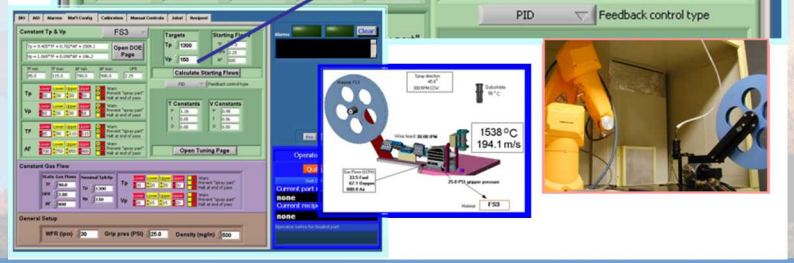

Process Diagnostics/Monitoring




Process Modeling
(All possible vel/temp regimes as a function of torch hardware)

# Custom Built Process Monitoring/Control System for WR Production


*Custom closed-loop feedback provides high-degree of control and reproducibility*

Requested Tp, Vp
Actual Tp, Vp

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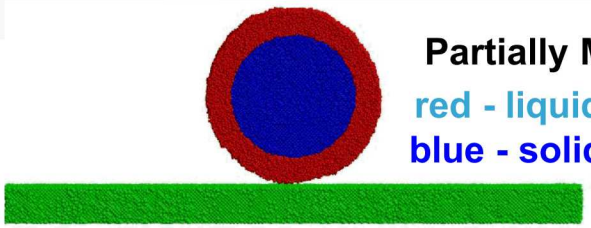
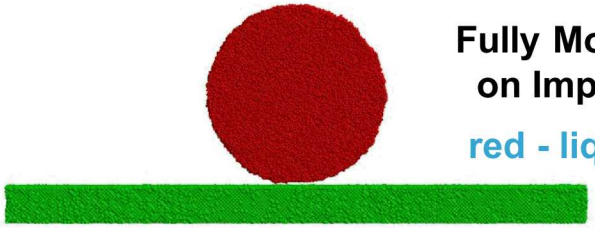
# Various Possible Impact Scenarios



**Partially Melted**

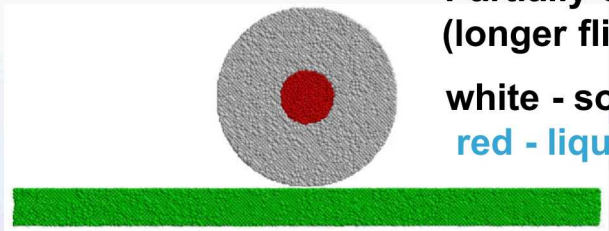
red - liquid 'skin'

blue - solid 'core'



**Fully Molten on Impact**

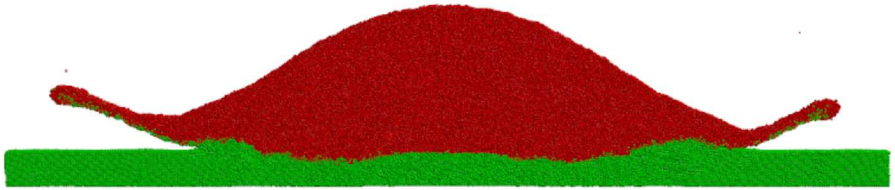
red - liquid



**Partially Solidified (longer flight time)**

white - solid 'skin'

red - liquid 'core'



Complex chemical/physical effects naturally captured in this scale of simulation: fragmentation for appropriate combinations of size, velocity, and wettability

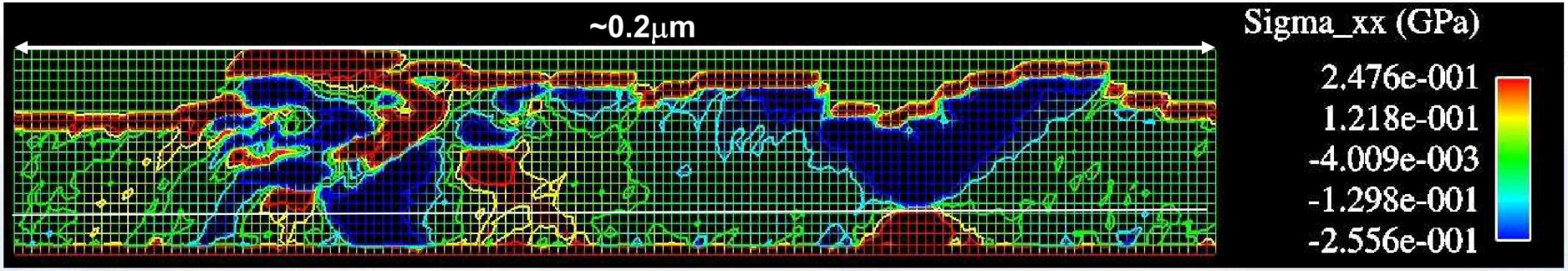
Atomic scale deposition simulations guide development of larger scale structure generation models, connecting flame-spray processing conditions to resulting microstructures.

# Computing Residual Stress in Spray Deposited Metal

- Grid system into volume elements
- Self-consistent method for computing stress in each element

Visualize in *Ensight*

Cross-section image of film and stress distribution between -250 and +250 Mpa.

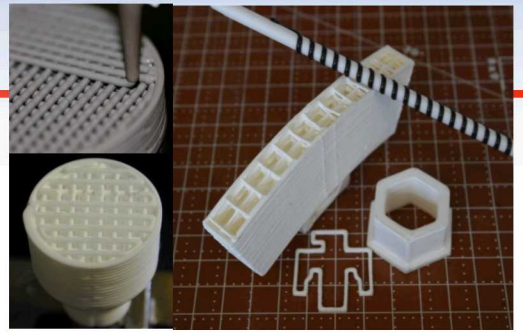



This reveals how processing parameters affect residual stress, providing valuable information for deterministic engineering of stress in flame spray deposited films.

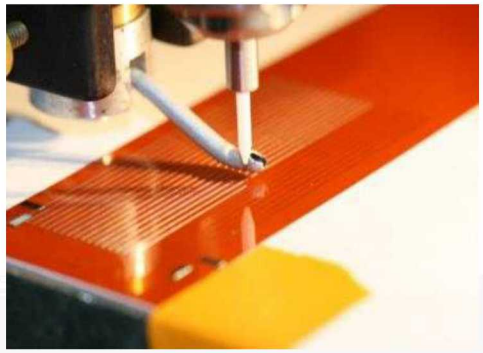
# Multi-Material AM

# Direct Write, A Versatile, Multi-Material Process

- **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

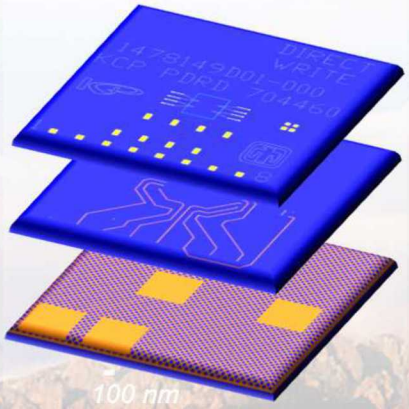


*Extrusion casting (Robocasting)*

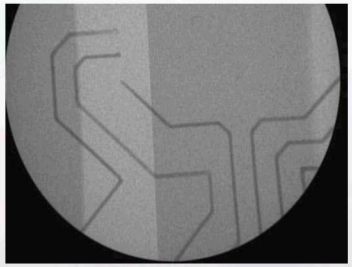


*Aerosol jet printing to 10 μm*

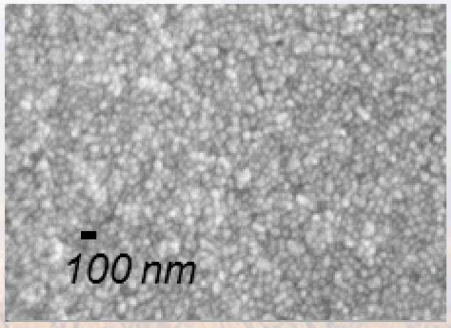
*DW circuit fabrication*




*Multi-level circuit*



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




*Nano-particle Ag inks for conductive pathways*

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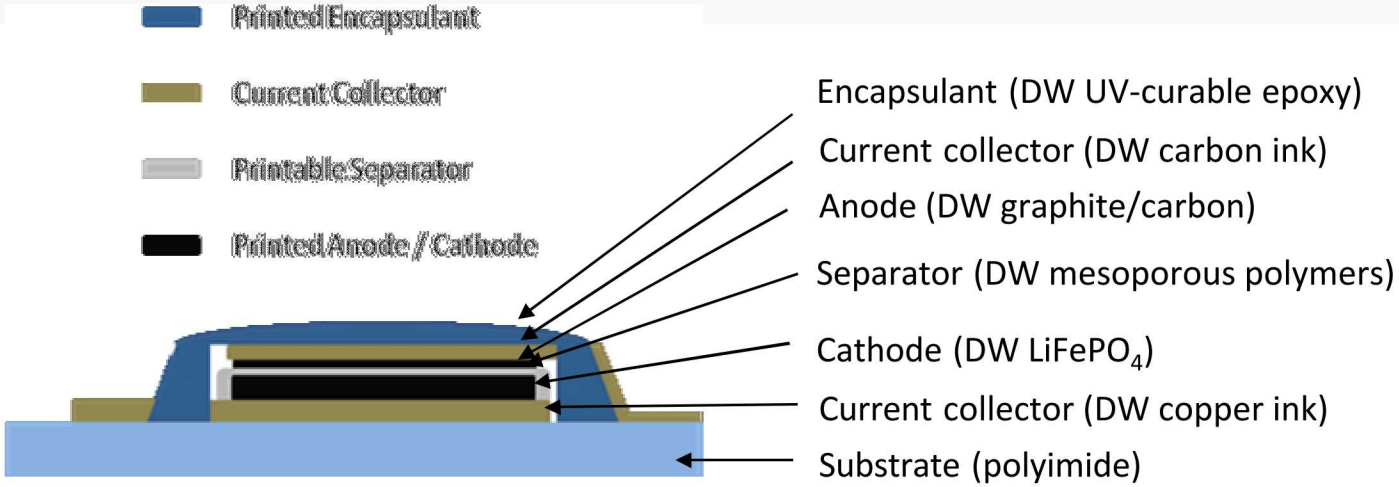
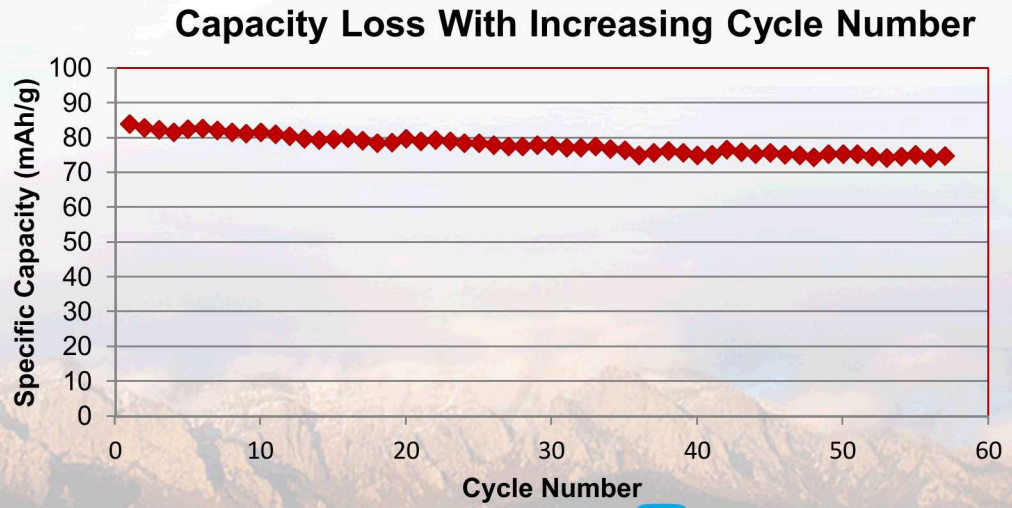
# Direct Write Lithium Iron Phosphate Battery

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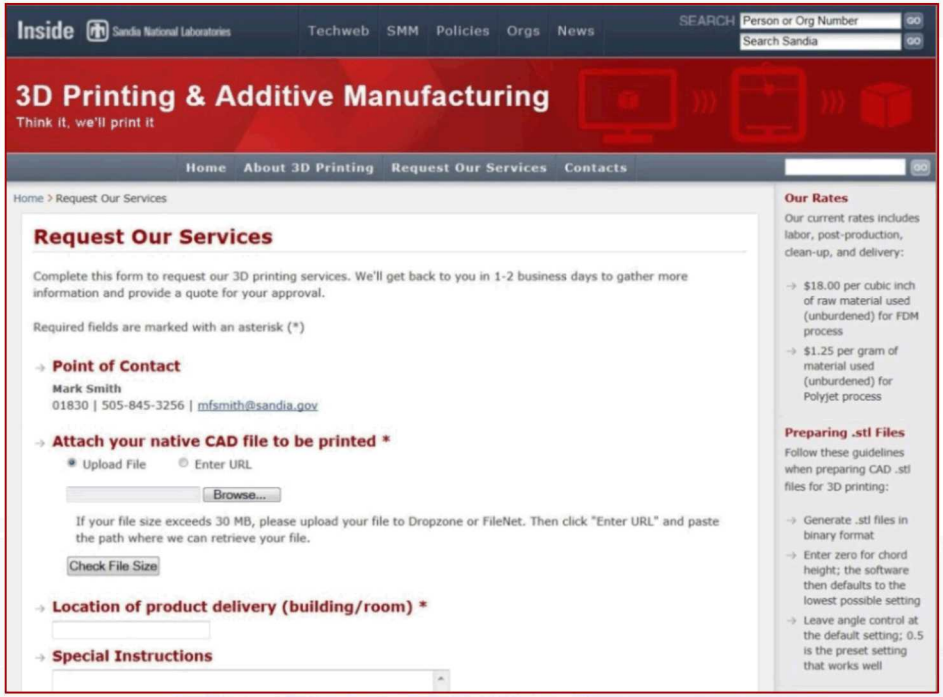
# AM Equipment

# Plastic AM Machines

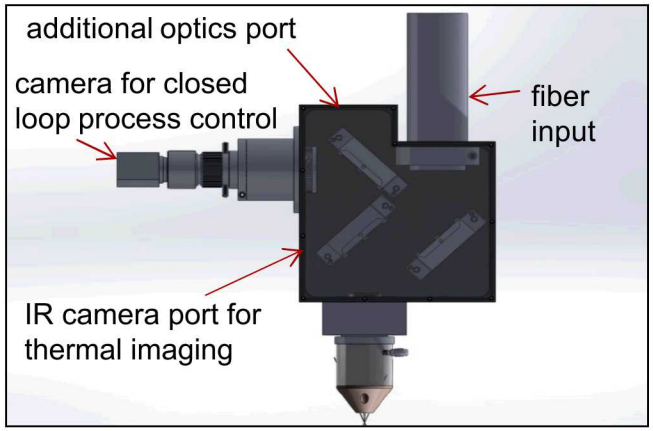
- ~ 100 Plastic AM machines at Sandia
- Web-based Central AM Printing Service

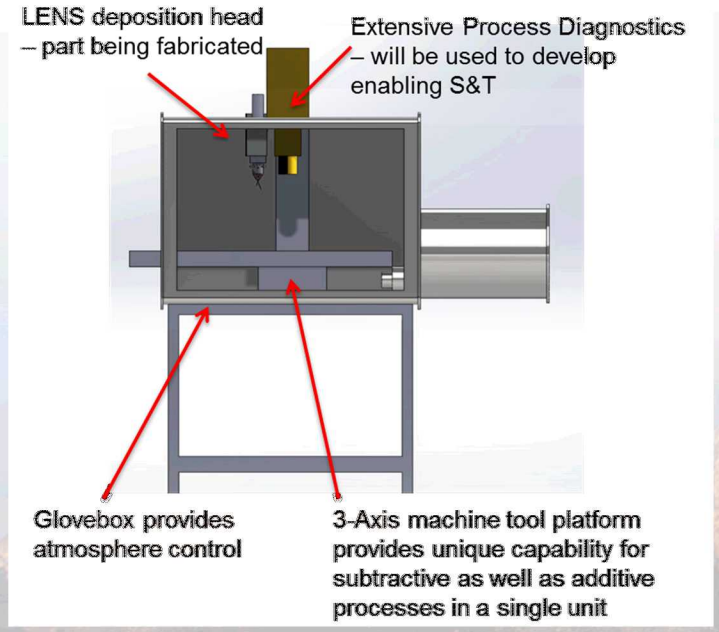



*"You Think It, We'll Print It!"*

# 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?

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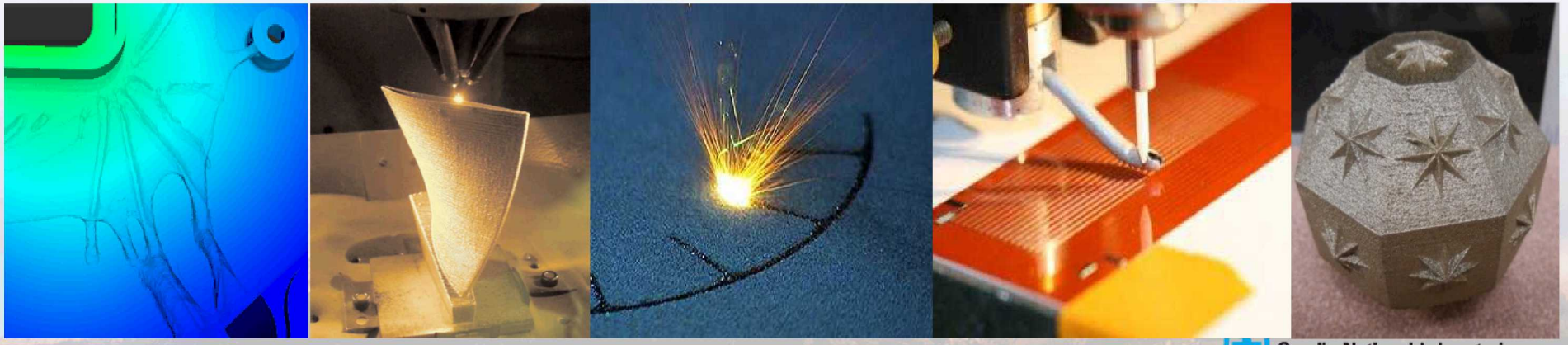
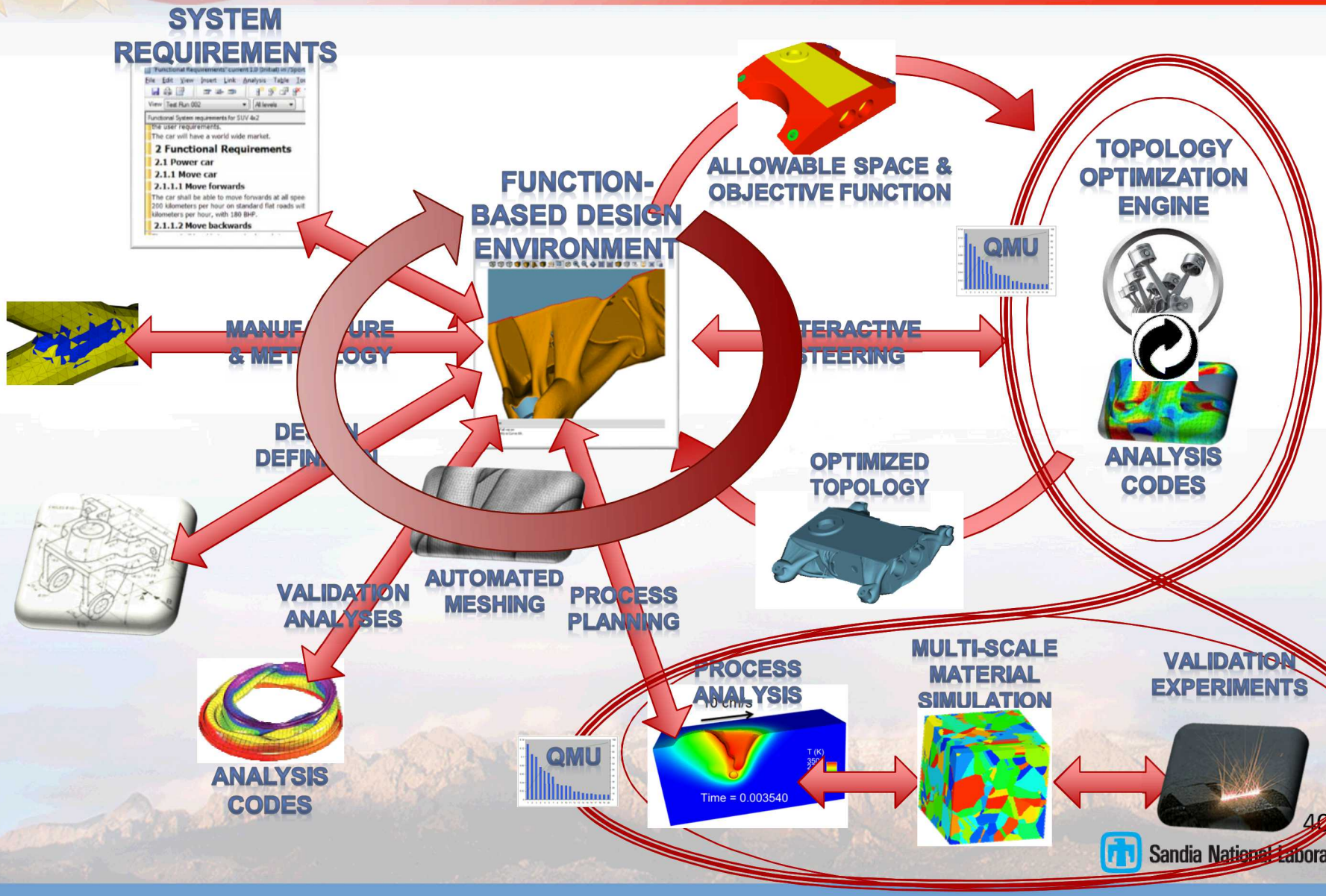
# Summary

- 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 other in areas of mutual interest



# Backup Slides

# How Will All of This Work?



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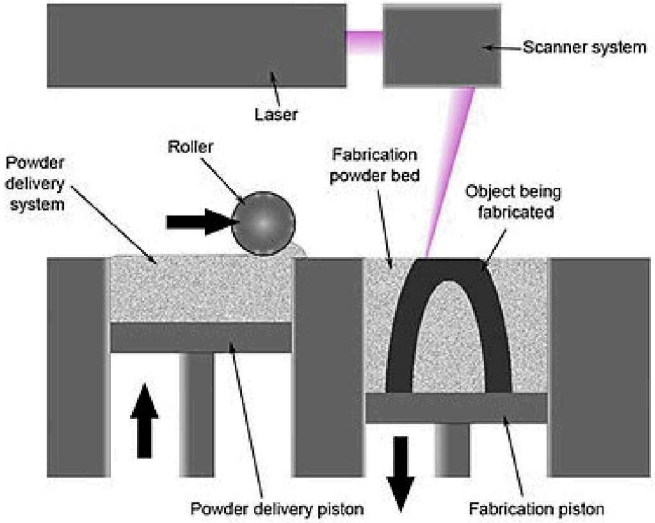
# What is Additive Manufacturing?

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

Many Different AM Process Technologies:

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



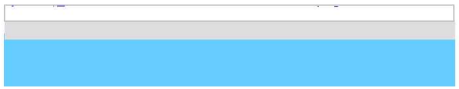

*from Wikipedia, "Selective laser sintering"*

*Within Technologies*

# Micro Electro-Mechanical Systems (MEMS)

Deposit Ground Plane Layer

Deposit Sacrificial Oxide

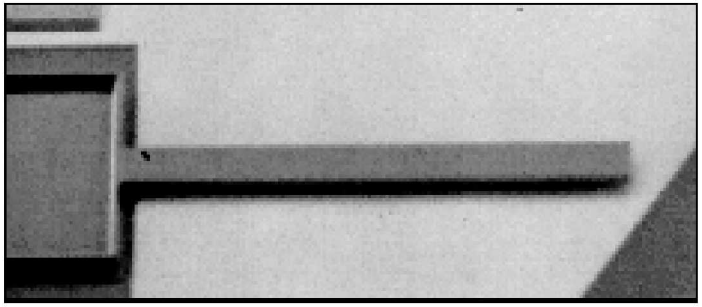


Pattern Sacrificial Oxide

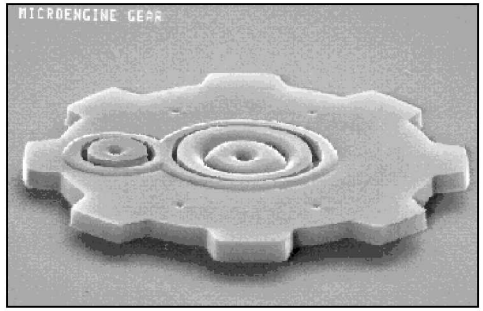
Deposit Poly-Si Layer

Remove Sacrificial Oxide to Release

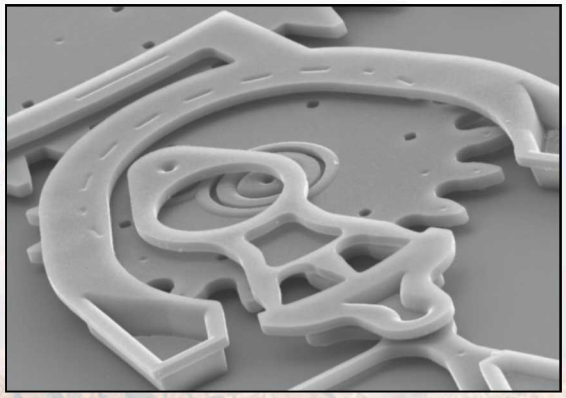
2 levels



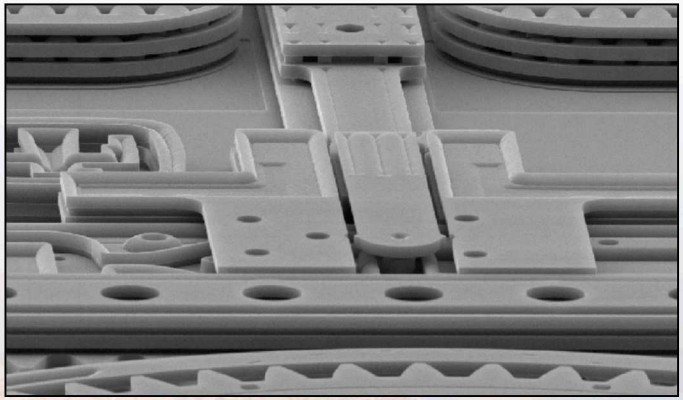
3 levels




4 levels

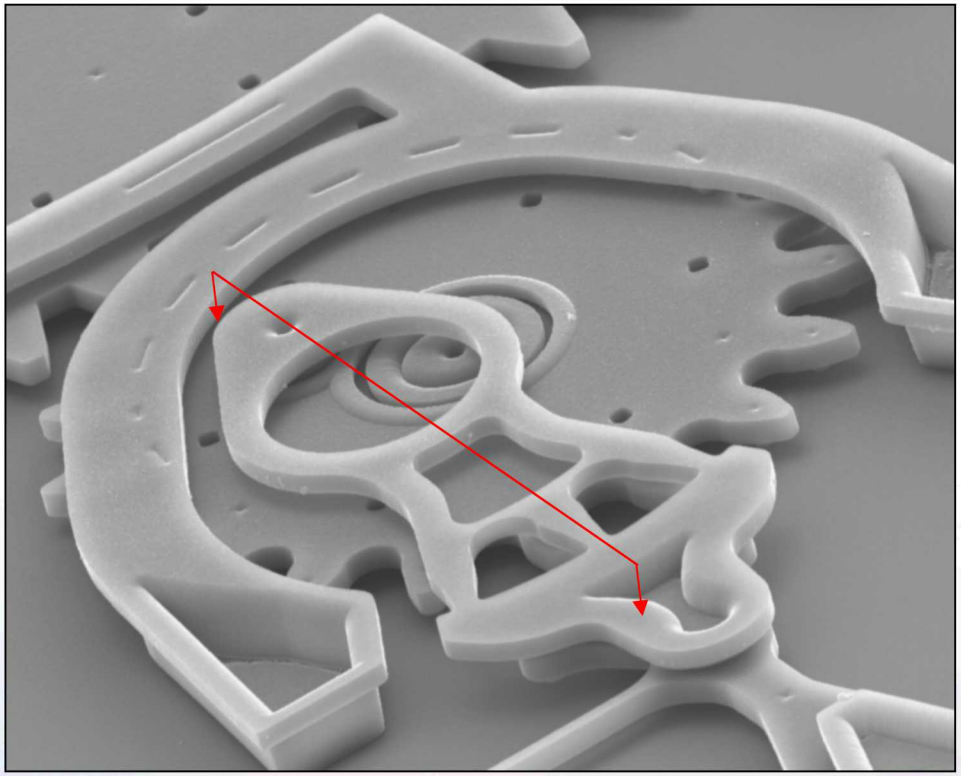


5 levels

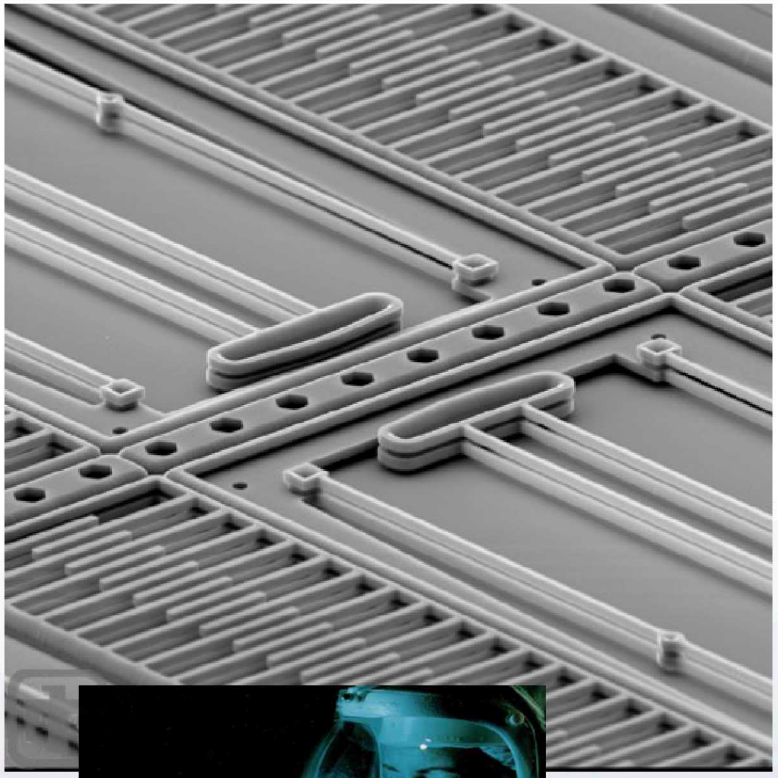


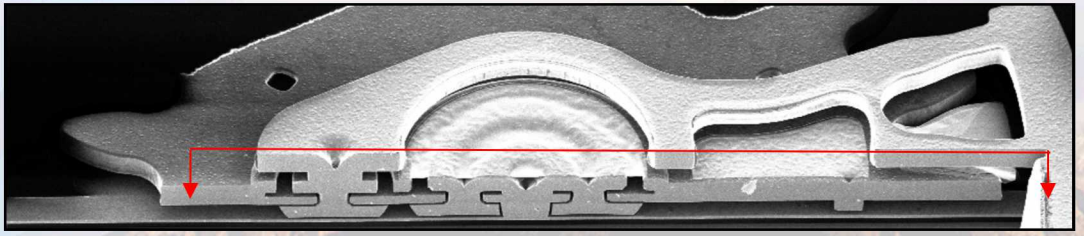
# SUMMiT™ Process
## (Sandia Ultra-planar Multi-level MEMS Technology)

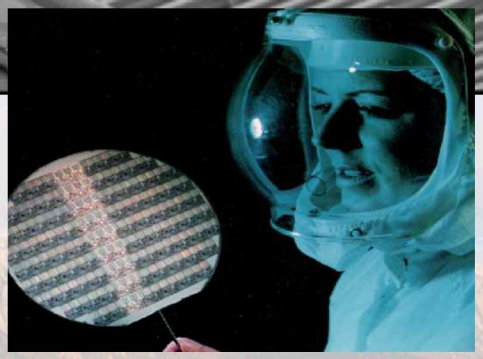
Gear Assembly



Comb Drive







There is no piece part assembly!

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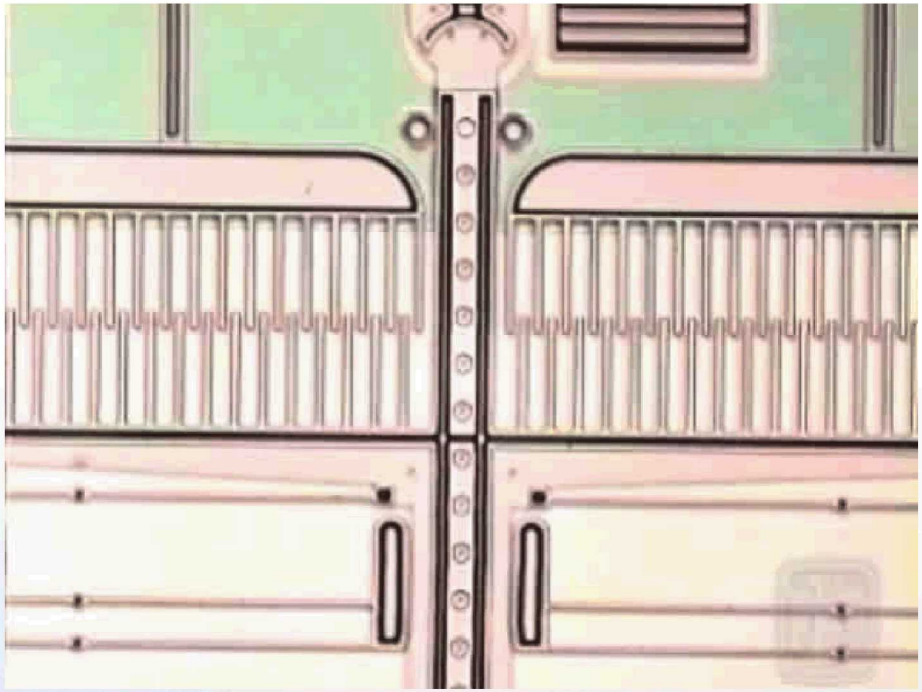
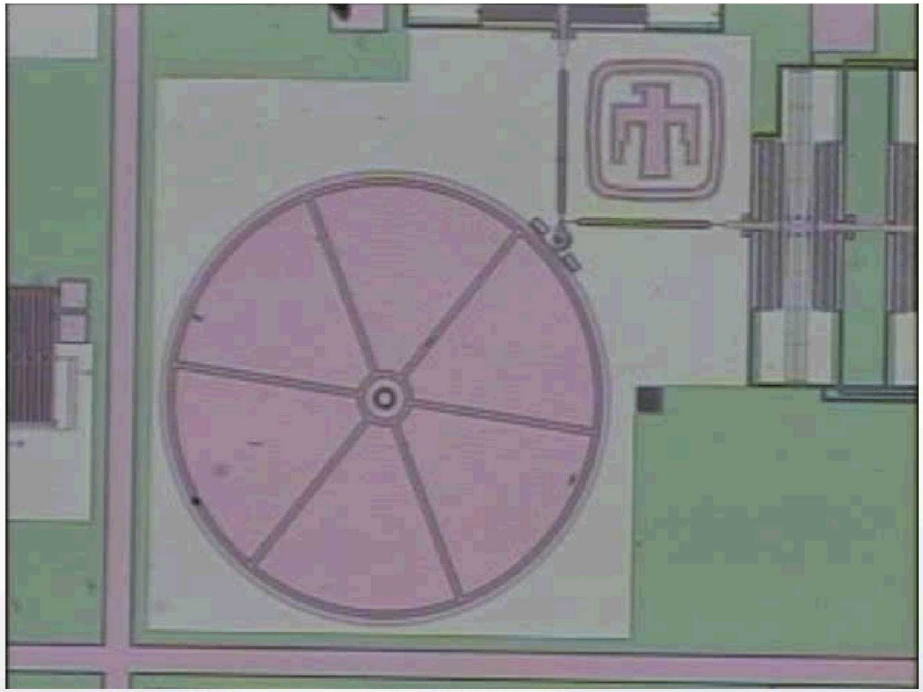
# MEMS Drives in Action





# Sandia μChemLab™

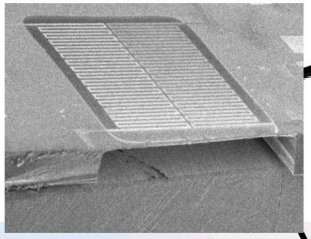
## Need:

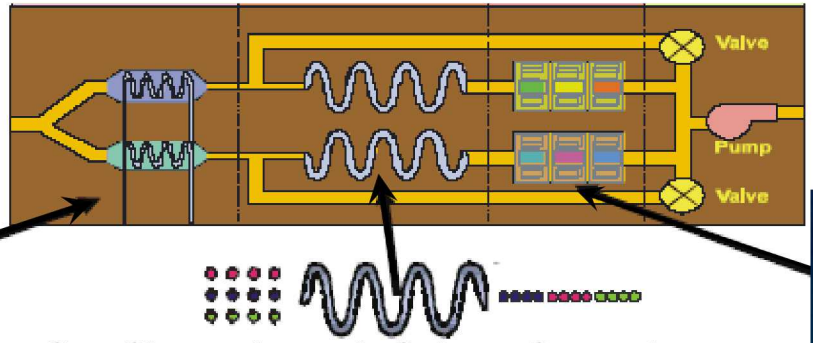
- Small, inexpensive, handheld analyzer for military, first responders, and other applications

## Technical Approach:

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

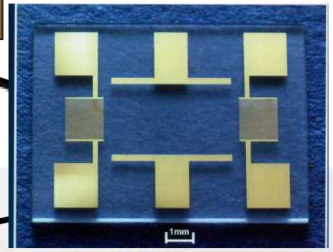
Preconcentrator Collects Species of Interest

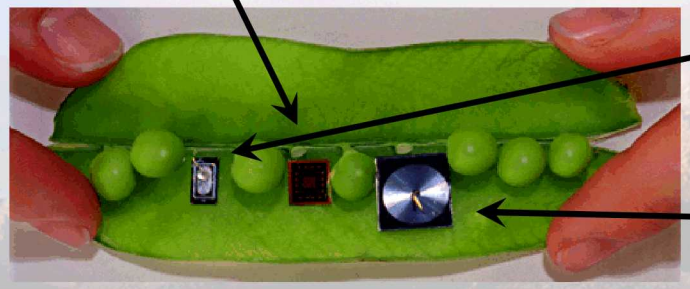


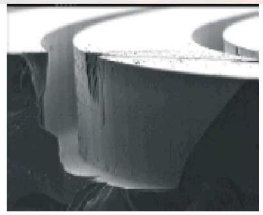



Gas Chromatograph Column Separates Species in Time

Chemically Selective Surface Acoustic Wave (SAW) Sensors







~1 Meter Gas Chromatograph Column

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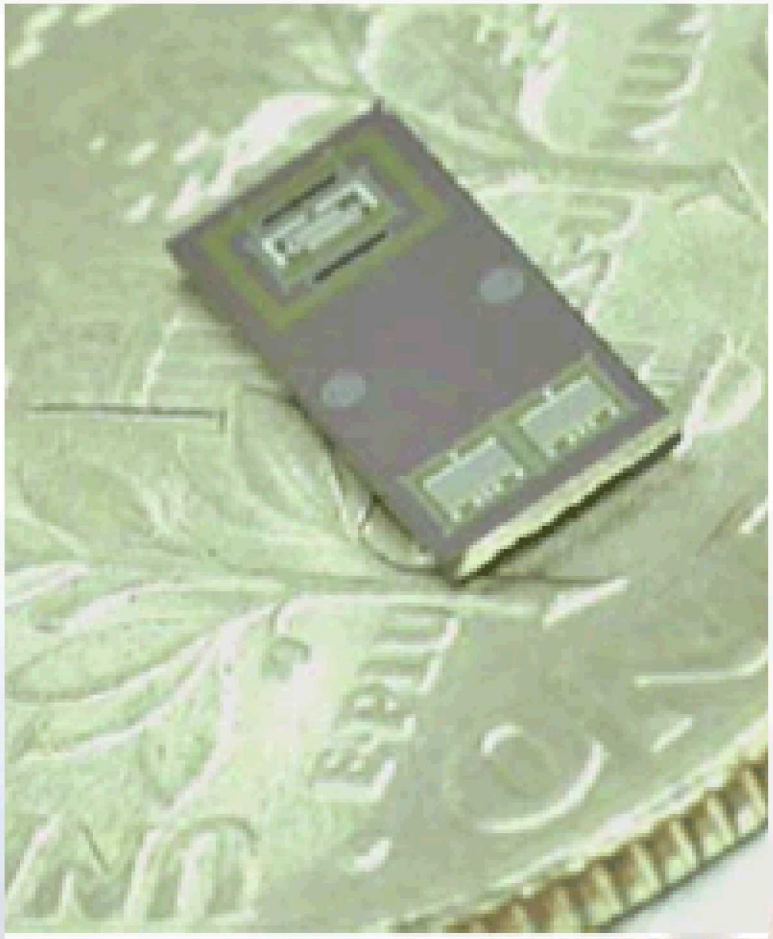
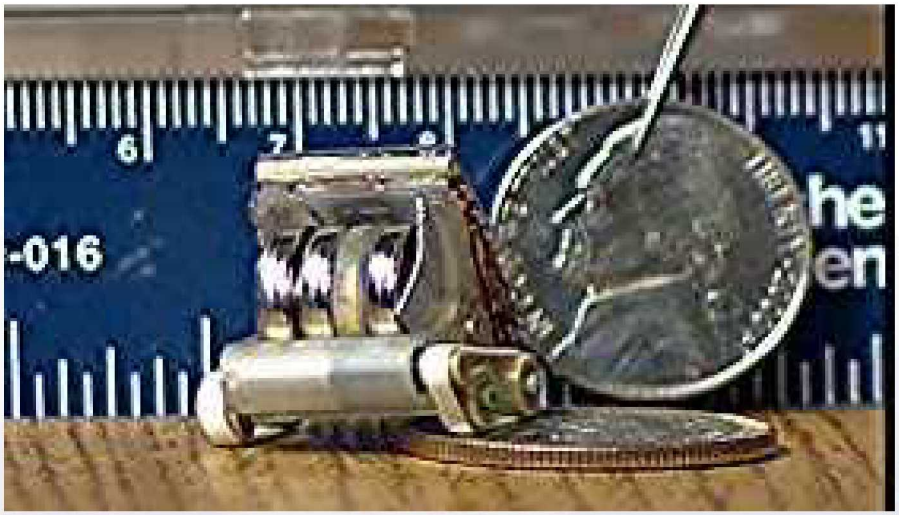
# Further μChemLab™ Refinements



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




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

# Fundamental Modeling of Flame Spray Droplet Deposition

- **Significant continuum modeling exists for droplet deposition**

- **Solution: use atomic scale simulation to study (with very high physical fidelity) molten droplet deposition onto a solid substrate**

- **Specify deposition conditions precisely (droplet size, velocity, temperature, phase, impurities)**

*Droplet velocity & temperature can be directly measured in production.*