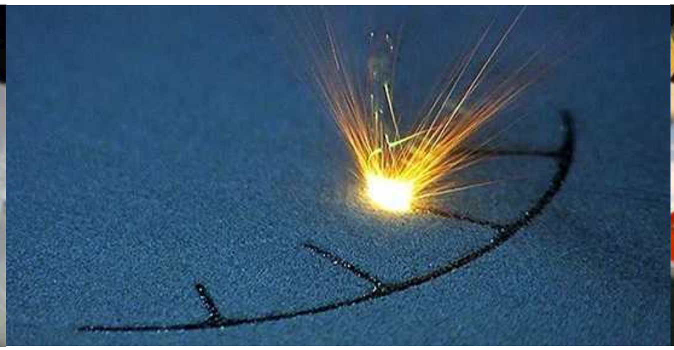
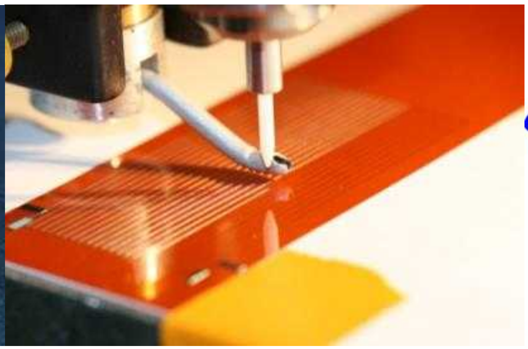
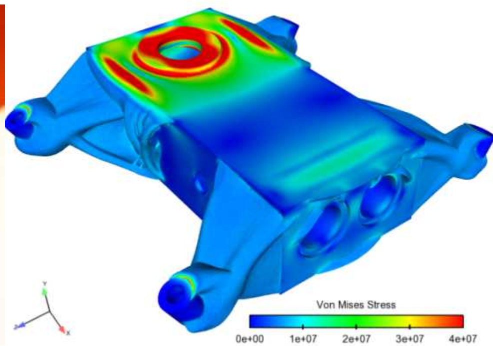
*Exceptional service in the national interest*

SAND2015-6356C


# An Overview of AM Activities & Capabilities at Sandia

Bradley Jared

Materials Science & Engineering Center

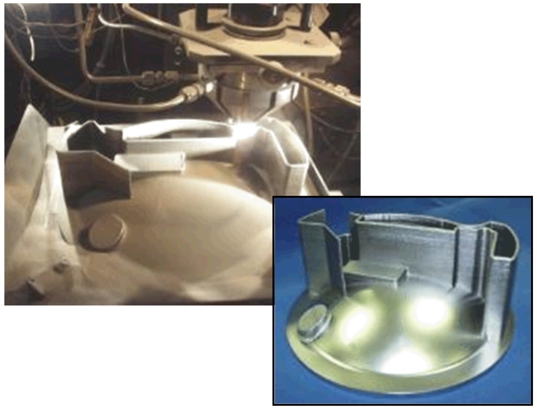
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2015-xxxx

# Sandia Has a Long History in AM

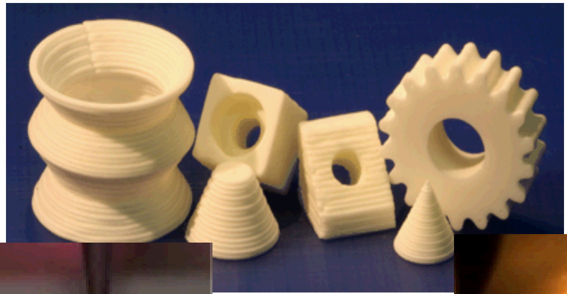
- 30+ yrs of pioneering AM tech development & commercialization

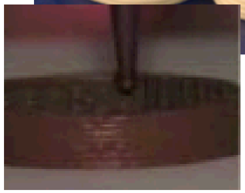
FastCast*
prototype test unit

LENS®*
fireset housing



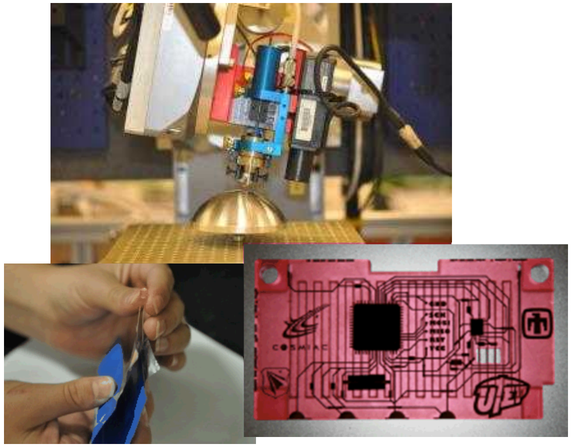
RoboCast*
ceramic parts



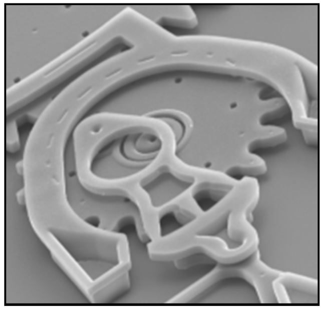


energetic materials

Direct Write
conformal electronics

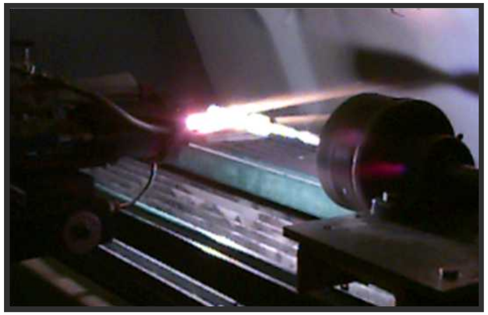


MEMS SUMMIT™ *
micro gear assembly



LIGA
“Hurricane” spring

Spray Forming
rocket nozzle



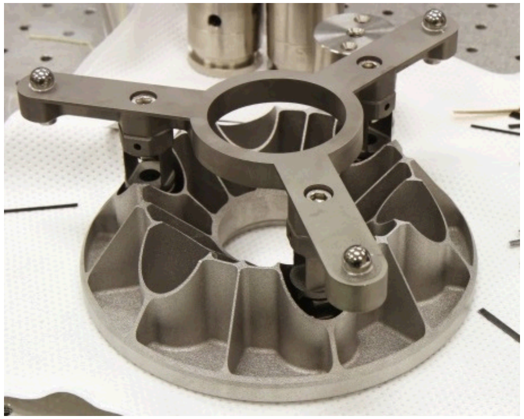
* licensed/commercialized technology

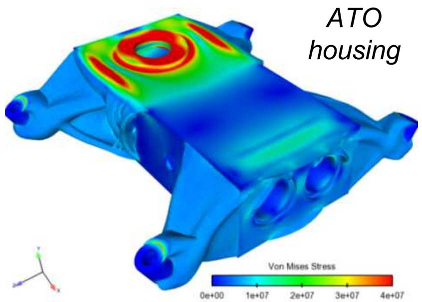
# SNL's Additive Interest

- Reduce risk, accelerate development
  - simplify assembly & processing
  - prototypes, test hardware, tooling & fixturing
    - > 75-100 plastic machines
    - cost reductions often 2-10x
- Add value
  - design & optimize for performance, not mfg
    - complex freeforms, internal structures, integration
  - engineered materials
    - gradient compositions
    - microstructure optimization & control
    - multi-material integration
      - "print everything inside the box, not just the box"

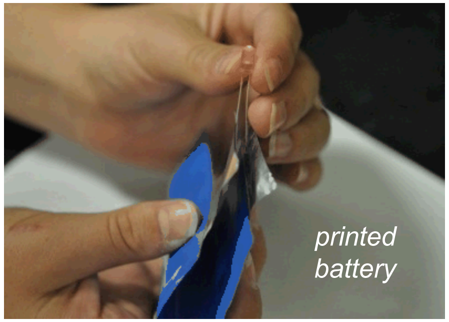
*Sandia Hand, 50% built w/AM, cost ~$10k*

*prototype Al AM mirror & structure*

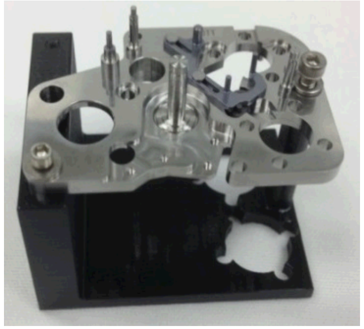





*ATO housing*



*printed battery*

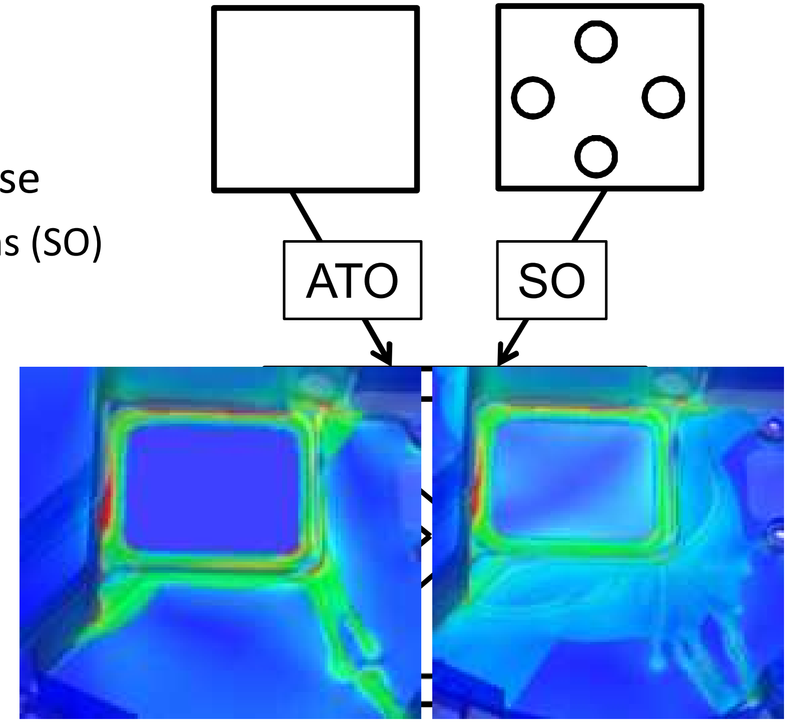


*fixture generated in 1 day*

# New Design Freedom

Sandia National Laboratories

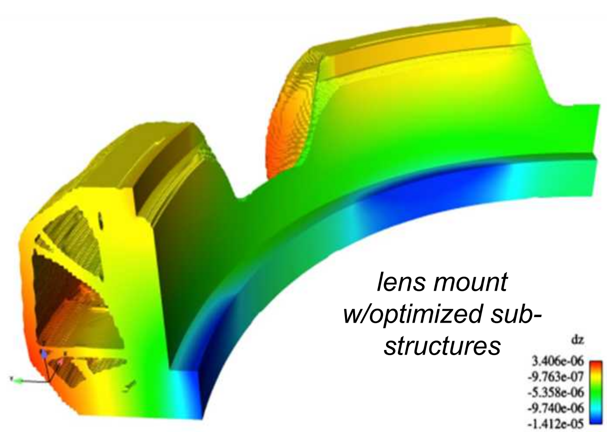
- Computational synthesis for optimal material use
  - adaptive topological (ATO) & shape optimizations (SO)
  - leverages “complexity is preferred”
  - constrained by performance requirements
  - bio-mimicry requires AM
  - design occurs concurrent w/simulation



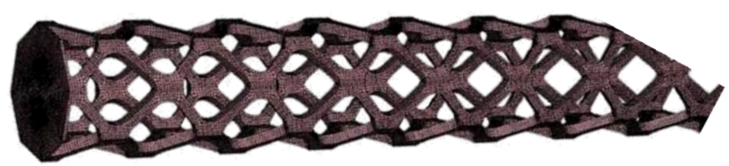

+ 0.55% volume
- 52% deflection

+ 3.3% volume
- 64% deflection

*elasto-static stiffness optimization*



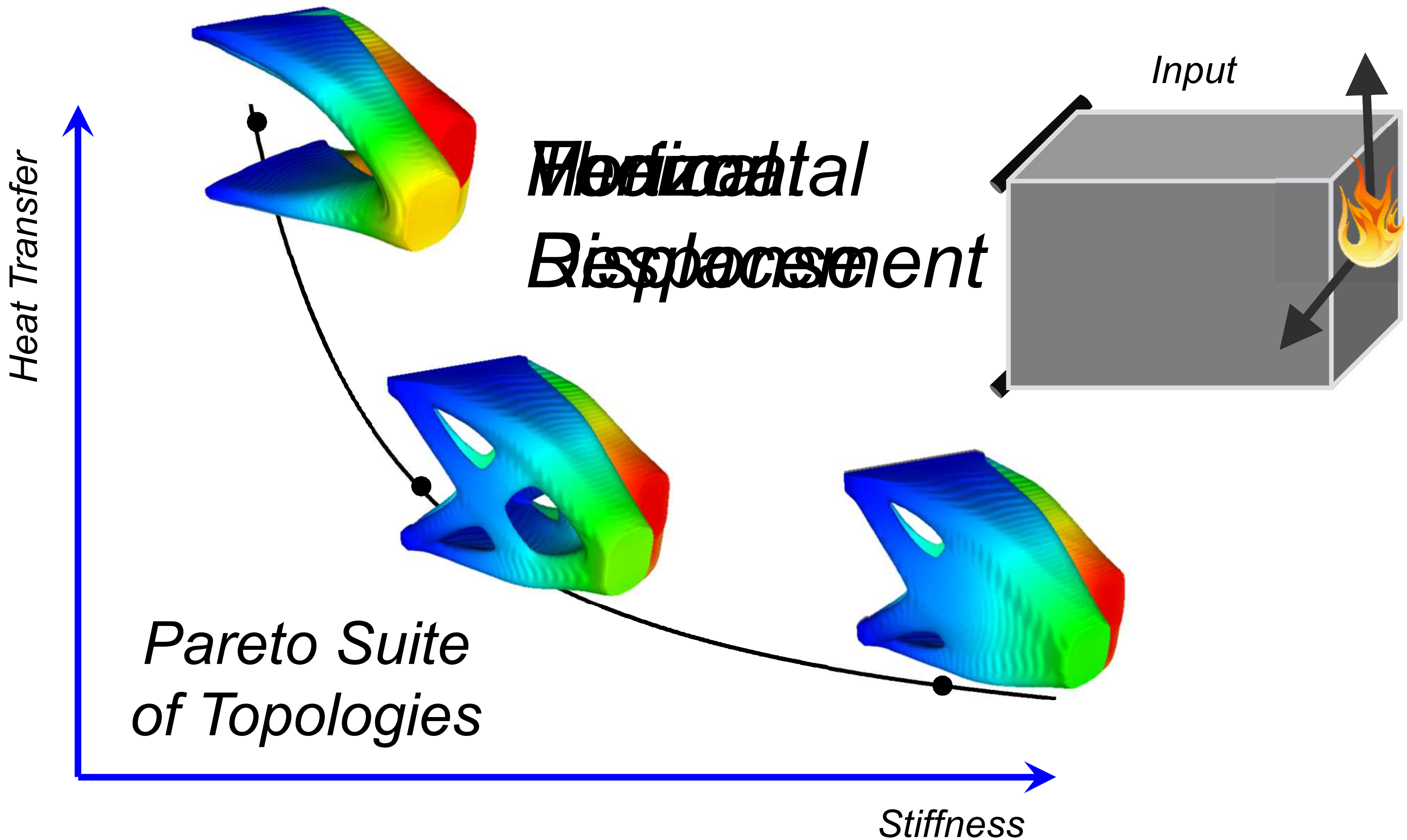

*lens mount w/optimized sub-structures*



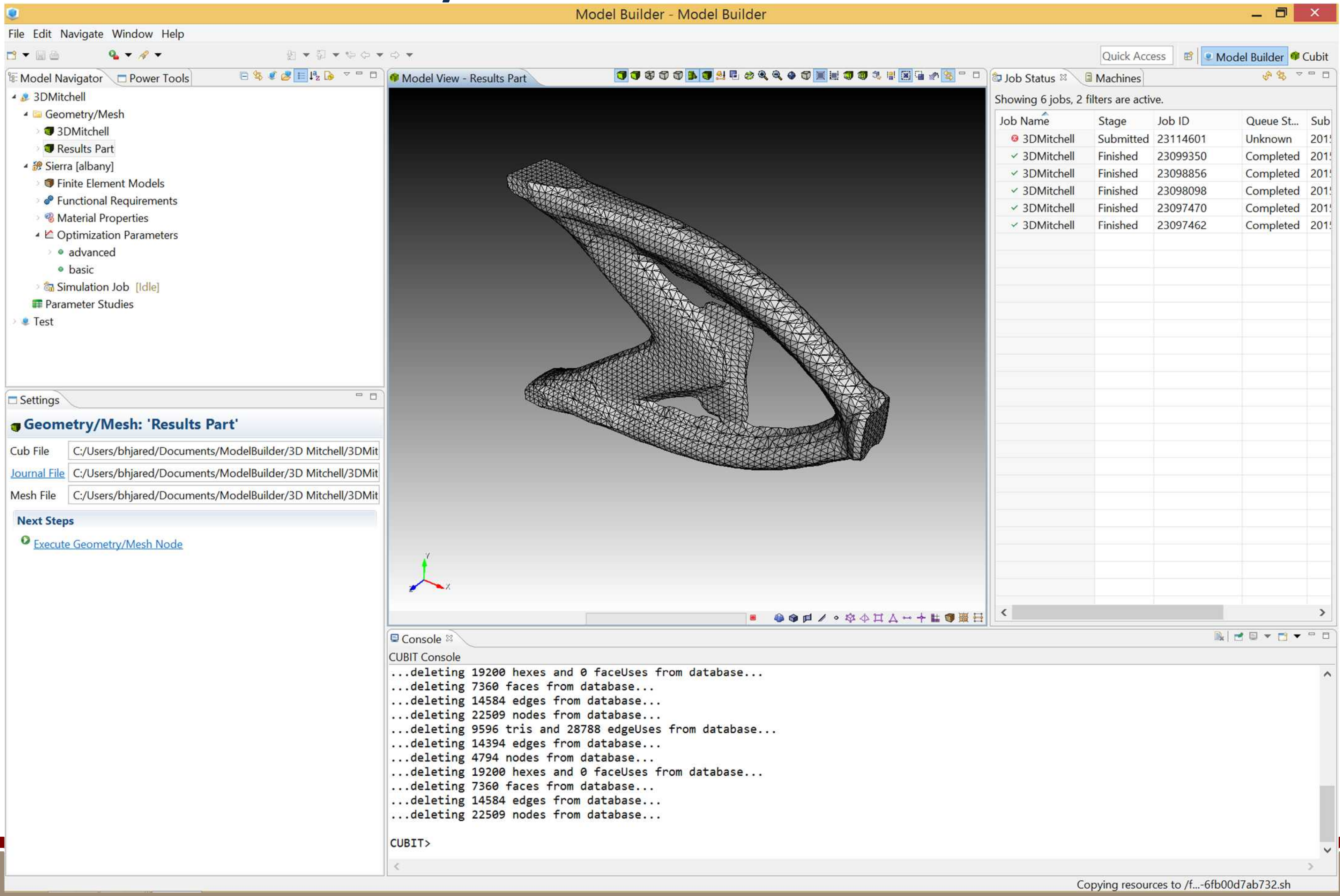
*solution for a bar in pure torsion resembles a cholla cactus*

*Joshua Robbins, Tom Voth, Brett Clark, Ted Blacker*

# Design by Simulation

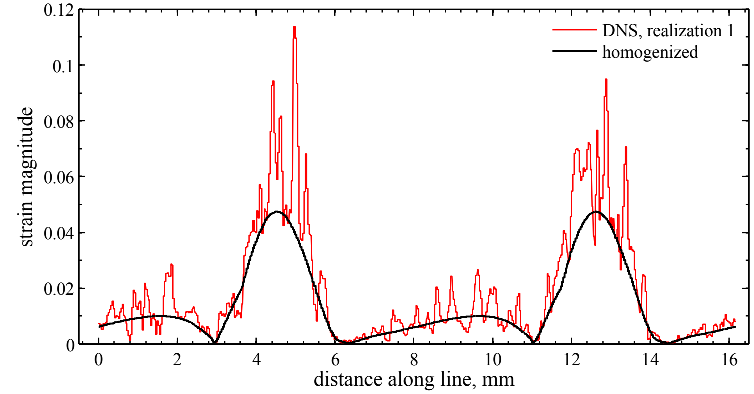


# Sandia Analysis Workbench

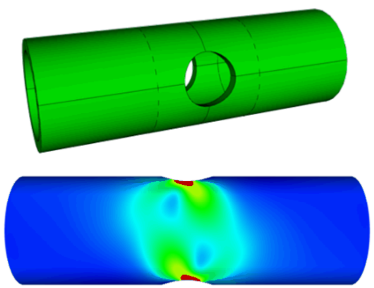


# Engineered Materials

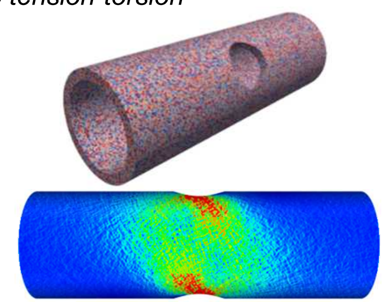
- Integrated Computational Materials Engineering (ICME)
  - materials analog to mechanical engineering
  - microstructure matters
- Voxel access introduces new opportunities for control & design
  - spanning multi-scales is difficult
  - metallurgical limits exist




*strain field due to tension-torsion*

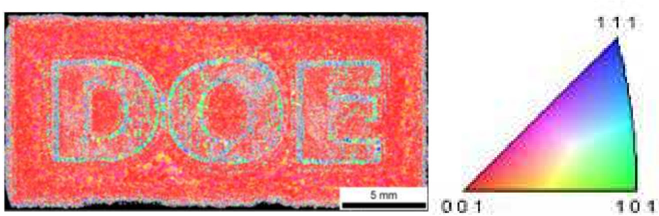


*continuum model*

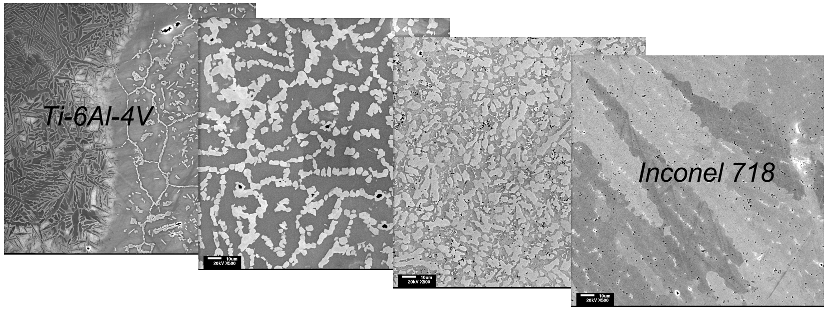


*crystal plasticity model*

*AM Inconel 718 texture control demo by ORNL*




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

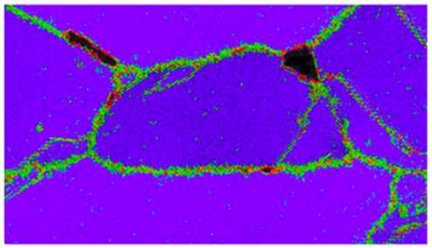


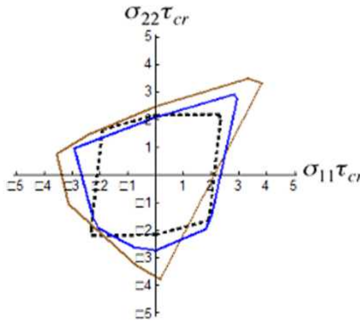

*LENS® functionally graded materials*

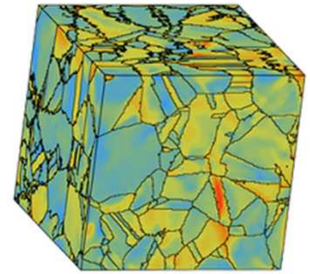
# Predicting Performance Margins (PPM)

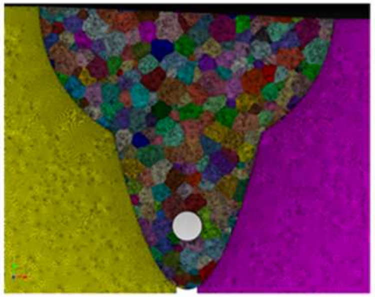
Multi-scale simulation & experiments are necessary to understand & predict material variability

*simulations*

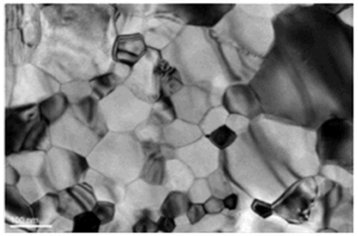


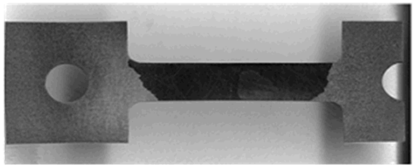


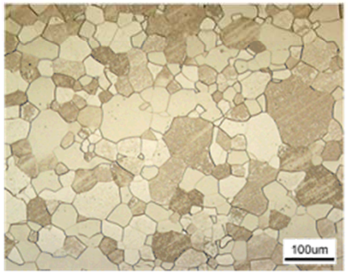



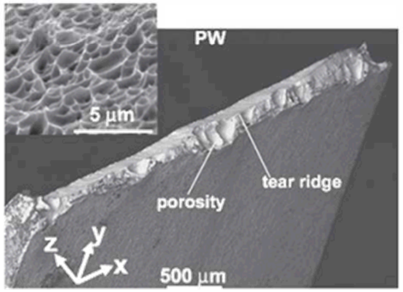


*experiments*








**Atomic scale phenomena**
$10^{-9}$ m $10^{-9}$ s

**Single crystal behavior**
$10^{-6}$ m $10^{0}$ s

**Microstructural effects**
$10^{-3}$ m $10^{3}$ s

**Material performance**
$10^{0}$ m $10^{6}$ s

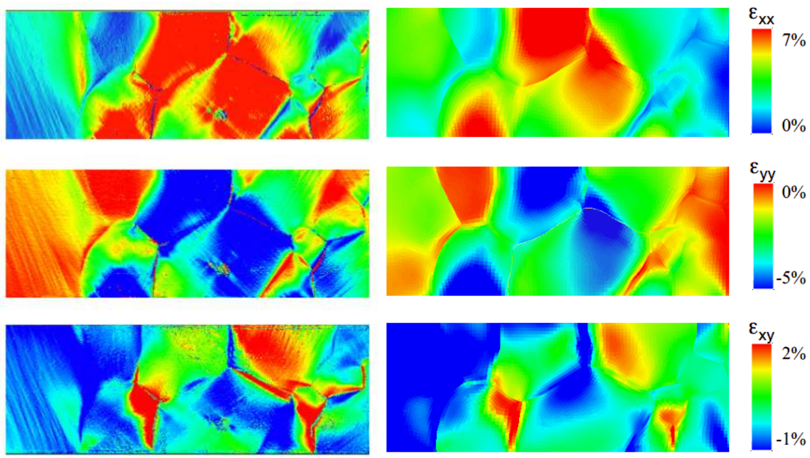
Atoms-up: Develop physics-based models to provide scientific insight

Continuum-down: Augment engineering-scale models to provide improved fidelity

*Brad Boyce, et al*

# Modeling Microstructure & Behavior

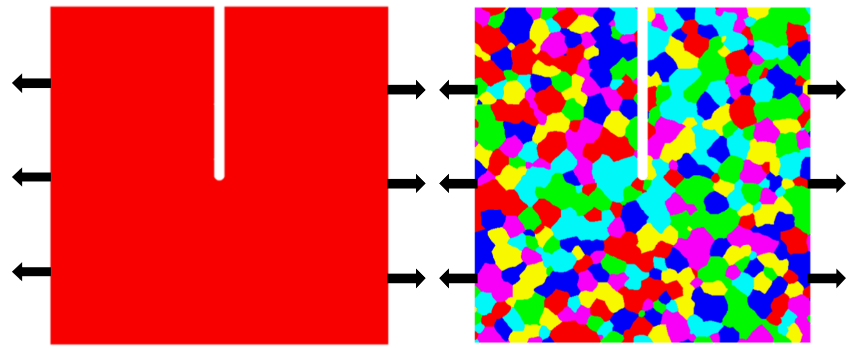
*Oligocrystal experiments vs. crystal plasticity models (tensile loading)*

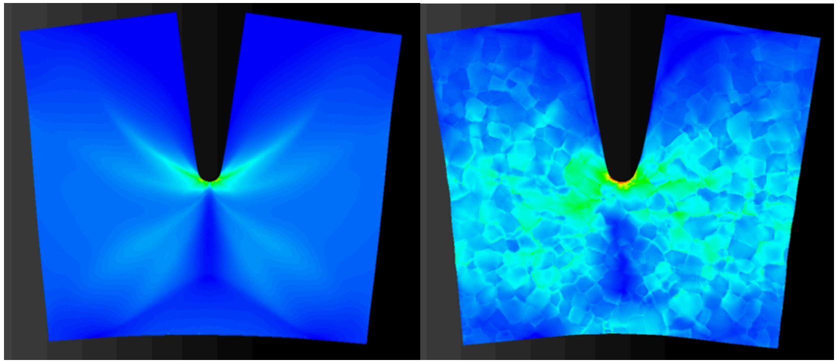



*DIC measurements* *simulations*

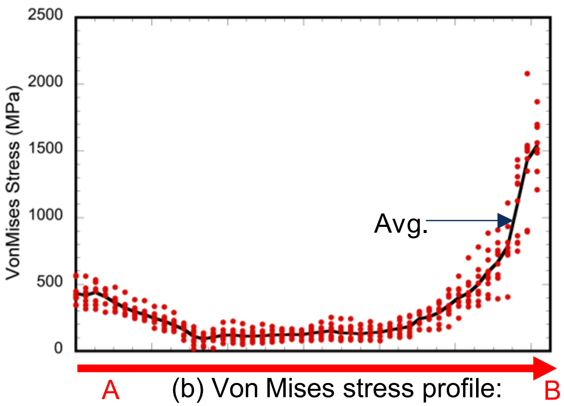
*Ta single crystal [100] orientation*

*Ta polycrystal 482 grains*

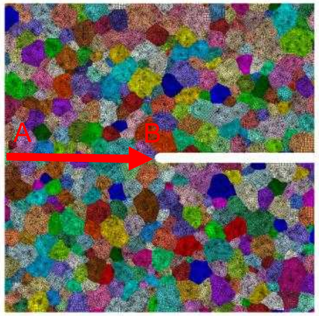




*(a) Von Mises stress distributions: single crystal vs. polycrystal*



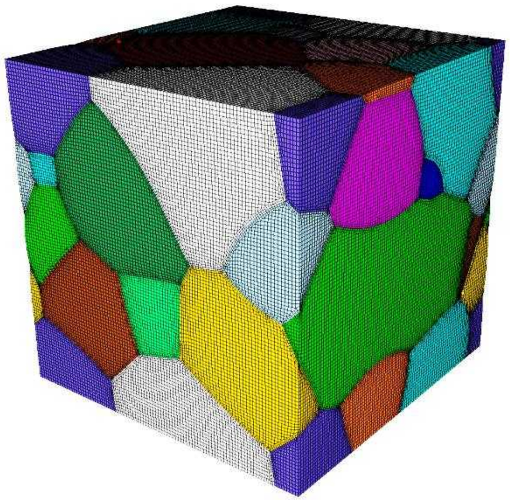

(b) Von Mises stress profile: 10 random polycrystal simulations



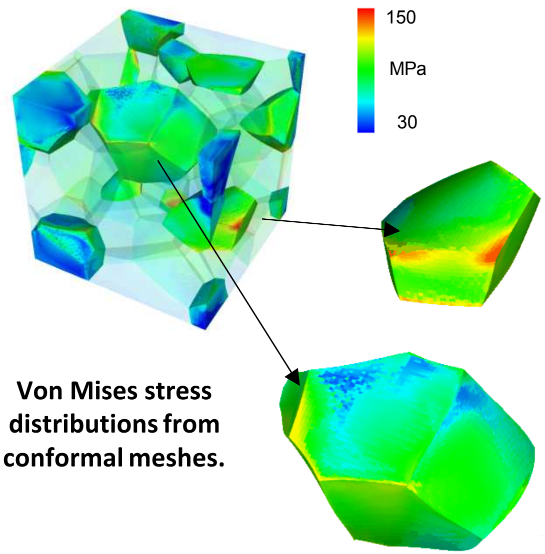

*Brad Boyce, Jay Carroll, Joe Bishop, et al*

# Modeling 3D Microstructures

- Leveraging SNL CUBIT, Sculpt & FEA tools
  - automated tool for large scale 3D hex meshes
  - polyhedra represent grains from phase field simulations
  - all-hex mesh then conforms to crystalline shapes
    - minimizes artifacts from Cartesian meshes
- Bridges phase field & crystal plasticity models
  - physically-based 3D microstructures
  - enables science based understanding of relationships between microstructure inhomogeneity & property statistics
  - potential for scale-up for microstructures, interfaces & engineering-scale applications

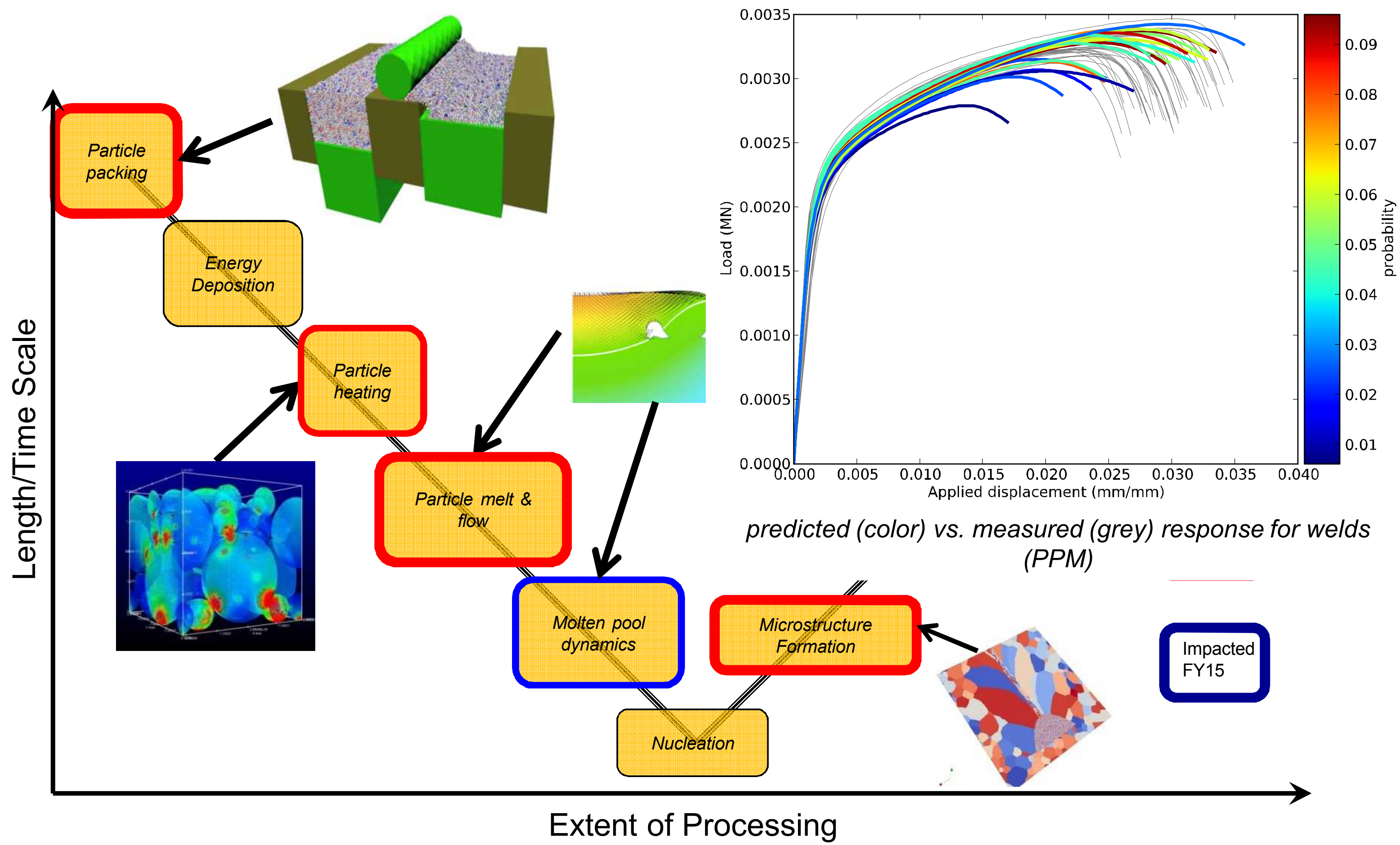


**Sculpt all hex mesh from phase field simulation. 53 grains, 1.35M hexes.**




**Von Mises stress distributions from conformal meshes.**

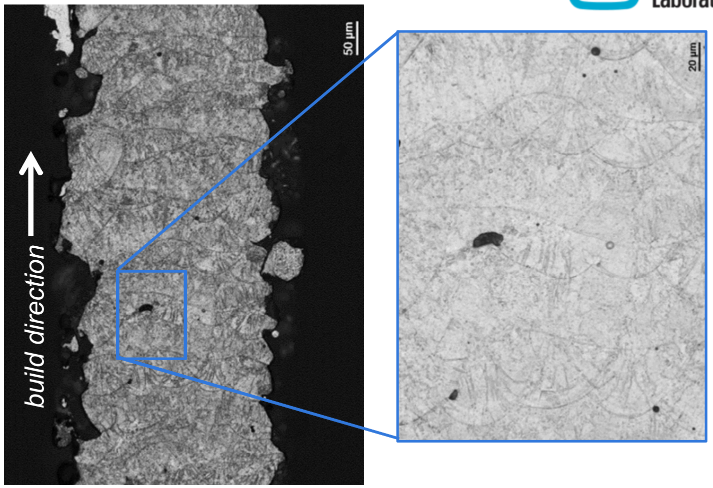
# Process Modelling



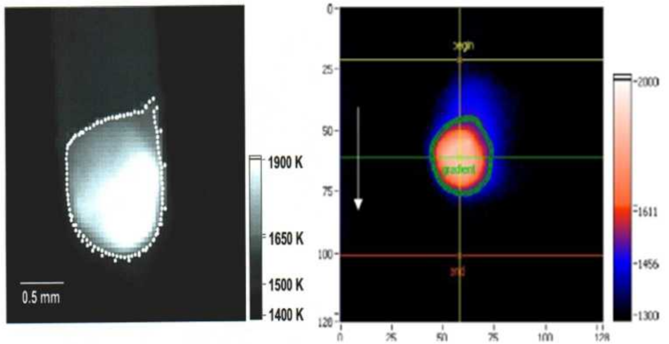

*predicted (color) vs. measured (grey) response for welds (PPM)*

# Materials Assurance

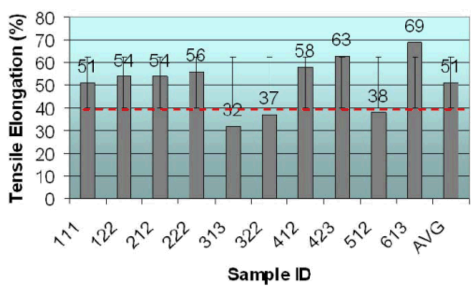
- Material formation concurrent w/geometry
  - opportunity = engineered materials
  - risks abound
    - properties, microstructure, defects, composition…
    - feedstock certs inadequate to quantify performance
    - traditionally just measured surface
  - how do we ID a bad part / material?
    - ex-situ evaluation can be too slow, expensive, inaccurate &/or late
    - complexity isn't "free"
    - must understand the behavior & formation of *critical* defects
- Processes
  - currently open loop
    - only accommodates large material margins
  - new paradigm required for qualification
    - process-structure-property relationships
    - understand behavior & formation of critical defects
    - need monitoring to detect defects
    - leverage mod-sim, predictive process control, …




*defects in 17-4 PH w/ 0.015" nominal wall thickness*



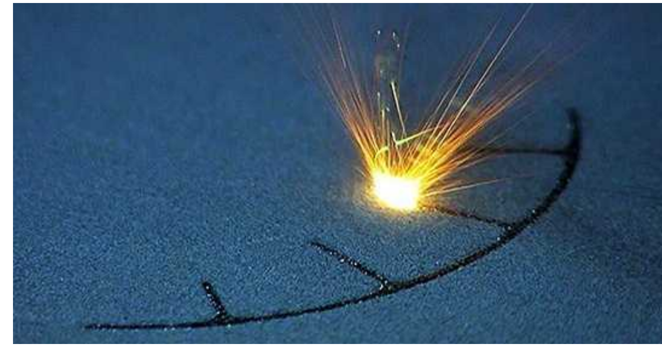

*LENS® control of melt pool & microstructure*

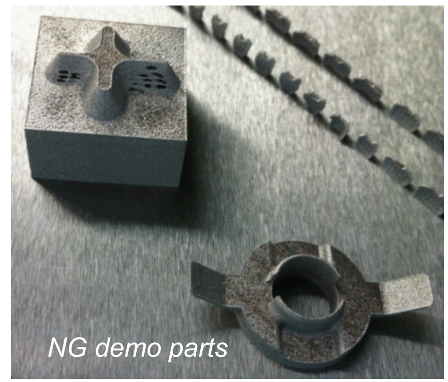


# Powder Bed Fusion

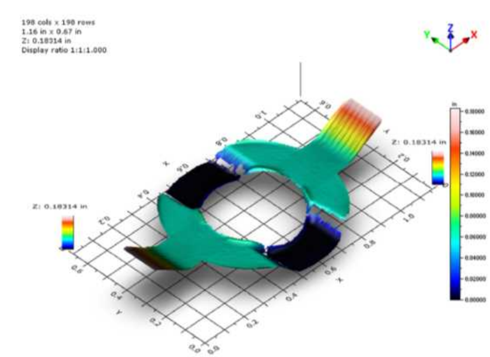
Sandia National Laboratories

- Powder melts @ focal point, then re-solidifies
  - electron beam melting (Arcam)
  - laser based (term varies w/vendor)
  - growing activity exploring metal parts
- 3D System (Phenix) machines purchased
  - process characterization & materials science
  - open architecture controller
- Performance
  - dimensional accuracy
    - best ~ 0.001-0.002”, but scales w/part
  - surface finish
    - >5 µm Sa (~ casting), worse for downward surfaces
  - geometry limits
    - wall thickness > 100 µm, overhangs < 45˚
  - single material parts
    - Ti6Al4V, AlSi10Mg, 6061-T6, 316L SS, 17-4, 15-5, maraging steel, CoCr, Inconel 625 & 718, Au, Ag, W
      - > 99% density
    - ceramics: alumina, WC, cermet
      - 90% dense, 10 µm finish





*NG demo parts*



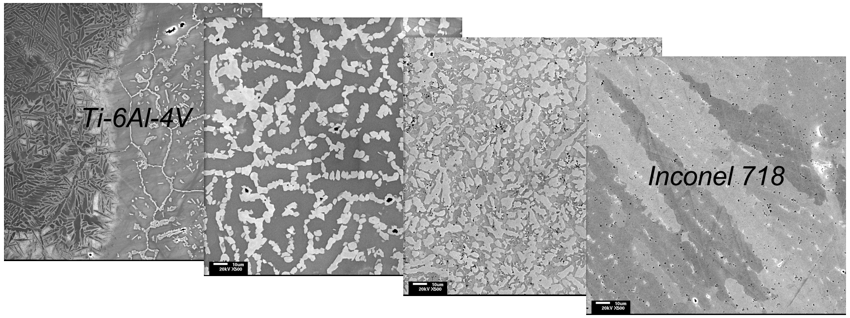
*surface finish ~ 5µm Ra*

*Bradley Jared, Dan Kammler, Larry Carrillo*

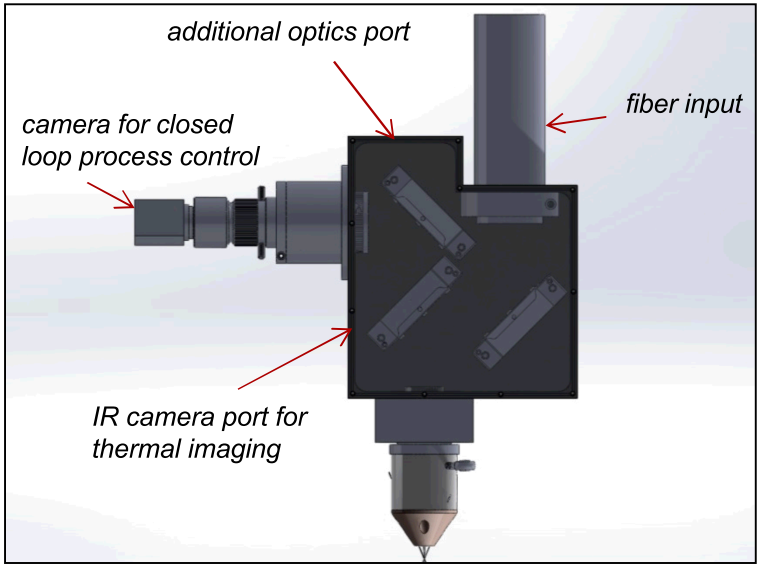
# Laser Engineered Net Shaping (LENS®)

Sandia National Laboratories

- Historical
  - extensive SNL development efforts & investments
  - licensed to Optomec
  - foundation for metal additive research
- Custom research machine
  - re-establishing & expanding capability
    - additive & subtractive
    - deposition head designed for process diagnostics & feedback
  - leveraging existing hardware




*LENS functionally graded materials*

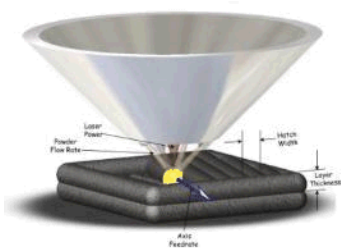




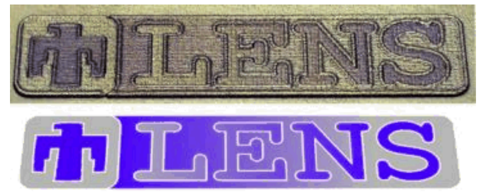
*thermal history during bi-directional metal deposition*

David Keicher, John Smugeresky

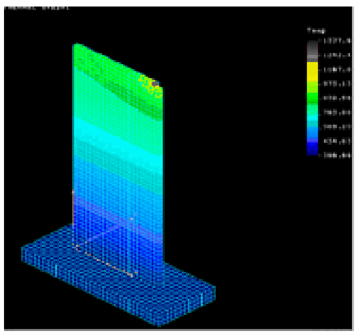
# Prior LENS® Research

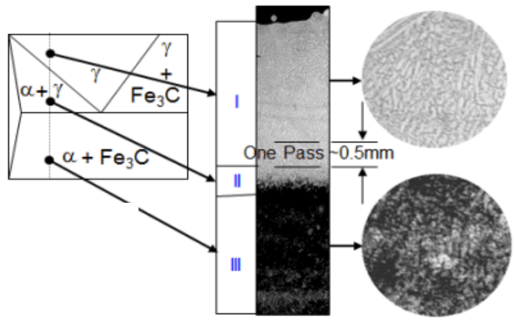


## Graded composition demonstration

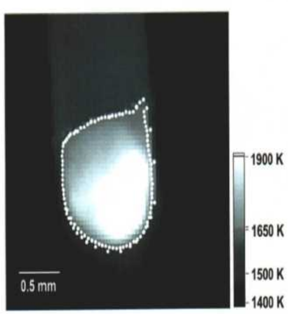


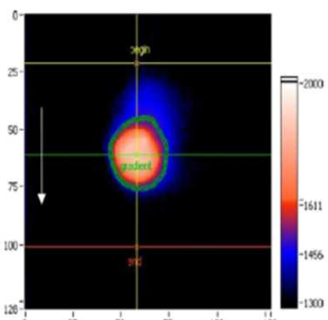

## Process characterization/modeling






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



## Closed-loop process control

melt pool -> microstructure

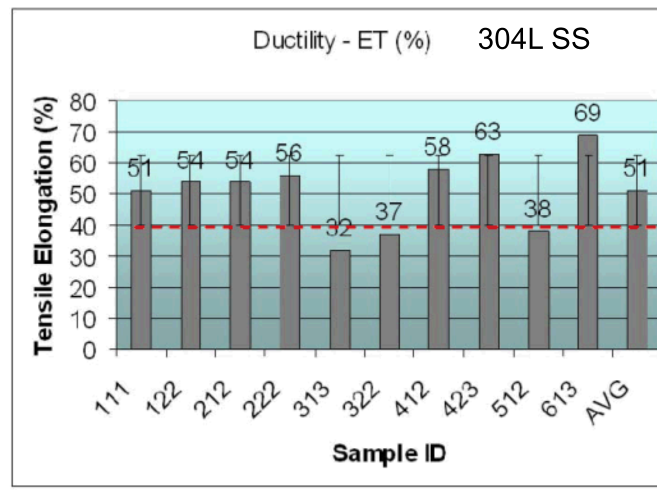
## Variety of LENS® metals

Ti-6Al-4V
Aermet 100
Stainless 304L, 316L
tool steels
Inconel
graded NiTi

## Potential advantages

- fully dense material
- strength up to 1.5x wrought material
- no loss of ductility
- graded materials
- add to exiting parts
- U.S. based supplier

## LENS® materials properties

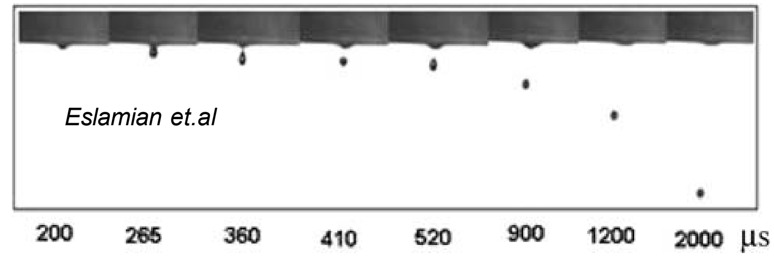


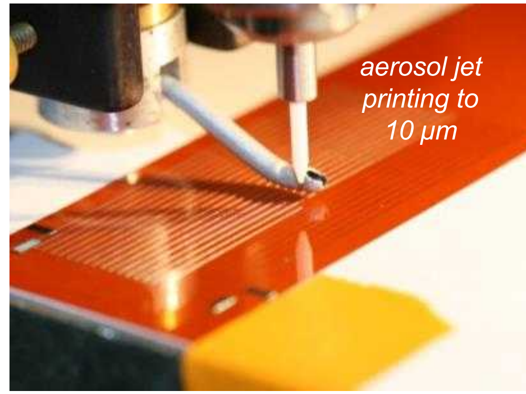

## Potential for process based quality

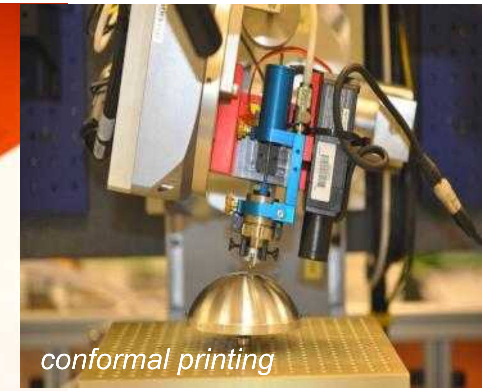
- process monitors ID'd build flaws

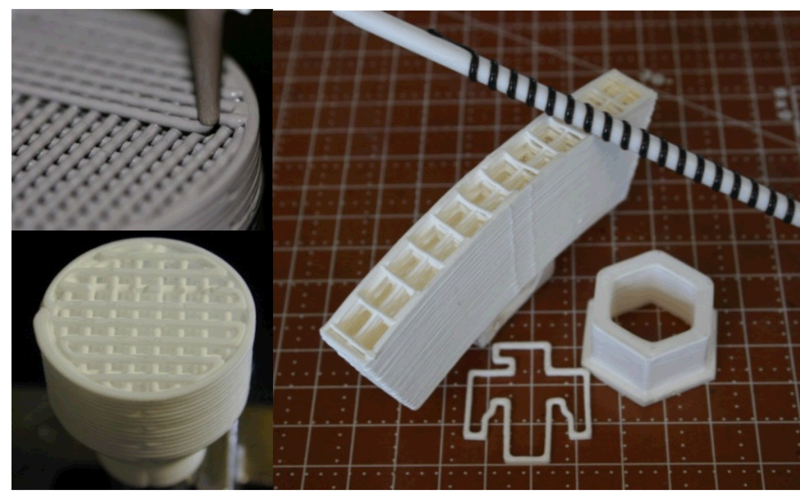
# Direct Write

- Ink jet
  - discrete droplets produce continuous line segments
  - line width a function of droplet size
    - diameter: 18-635 µm
  - material viscosity: 1-1x10$^6$ cPs
- Aerosol jet
  - ink atomized to produce dense aerosol mist
  - aerosol focused w/inert gas streams & small nozzle
  - Ag: 10 µm line width, 0.5-3 µm height
- Extrusion casting
  - volume deposition: 20 pl minimum
  - material viscosity: 1-1x10$^6$ cPs



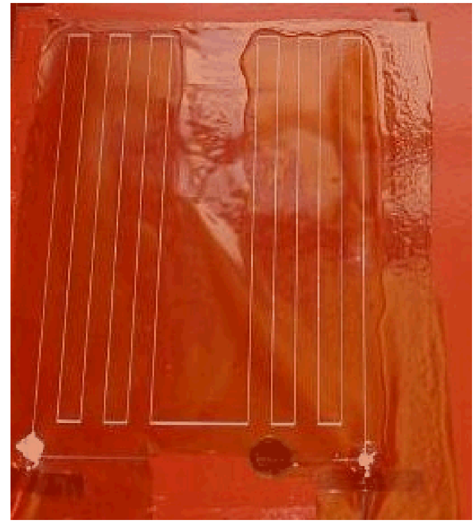
extrusion casting (Robocasting)

# Direct Write

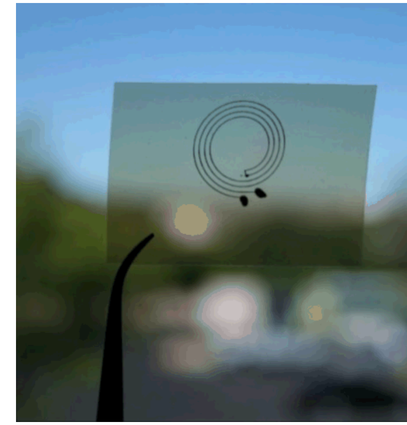
- Materials
  - epoxies, silicones, dielectrics, ceramics, energetics
  - nano-inks: metallic, polymeric, multi-phase
  - material formulation, synthesis & characterization
  - substrates: plastics, ceramics, polyimide, encapsulants, metals, FR4, glass, paper

- Sintering / curing
  - thermal, joule heating, UV, plasma, laser, microwave, room temperature

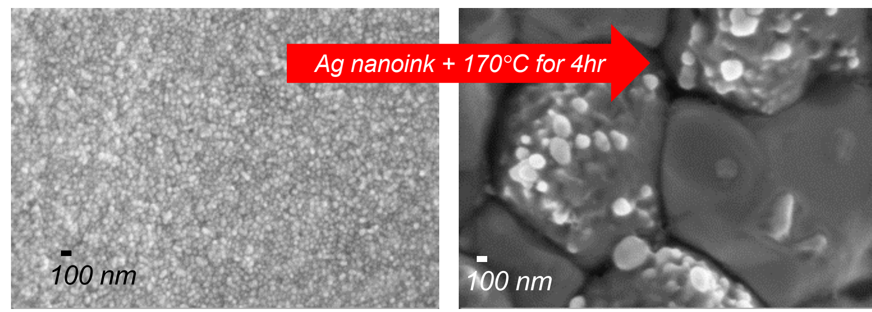
- Applications
  - DC & RF interconnects, antenna
  - sensor networks / structural health (strain, crack, temperature…)
  - package integration (resistors, capacitors, inductors, transistors, batteries)
  - conformal geometries



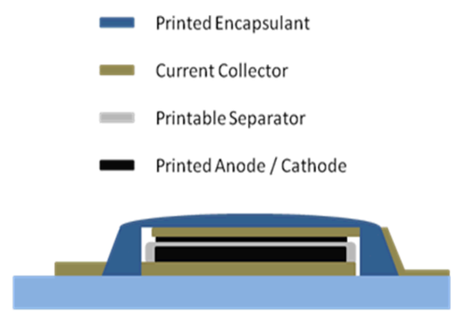
*Ag traces on powdercoat w/overcoat*



*room temp. cure of traces on polymer film*




*sintering of Ag nanoinks for conductive pathways*




*printed battery*

*Adam Cook, Dave Keicher*

# Energetic Materials

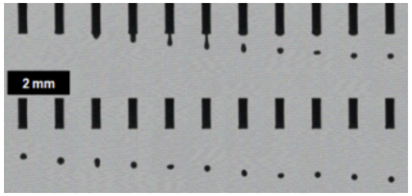
Sandia National Laboratories

## Robocasting

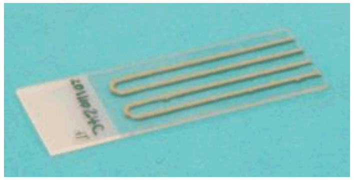
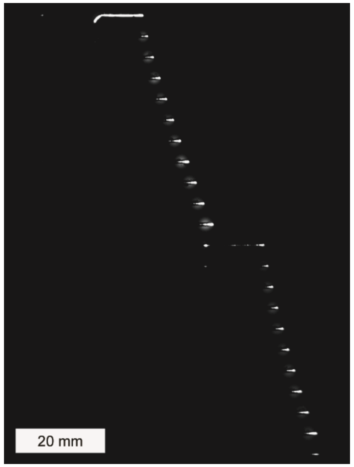

Aluminum/Nickel reactive material

Tappan, A.S., Groven, L.J., Ball, J.P., Miller, J.C., Colovos, J.W., Joseph Cesarano, I., Stuecker, J.N., and Clem, P., "LDRD Final Report: Free-Form Fabrication and Precision Deposition of Energetic Materials," SAND2008-0965, February, 2008.

## Inkjet printing

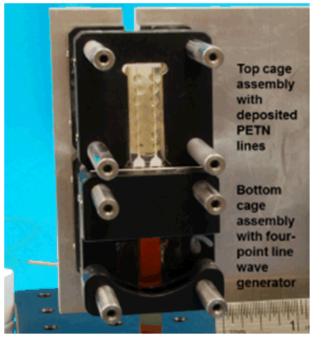


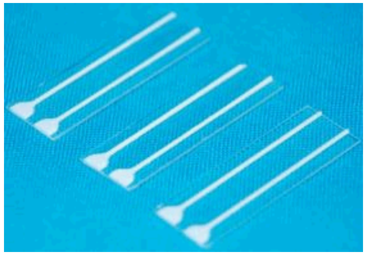

Aluminum/bismuth trioxide thermite

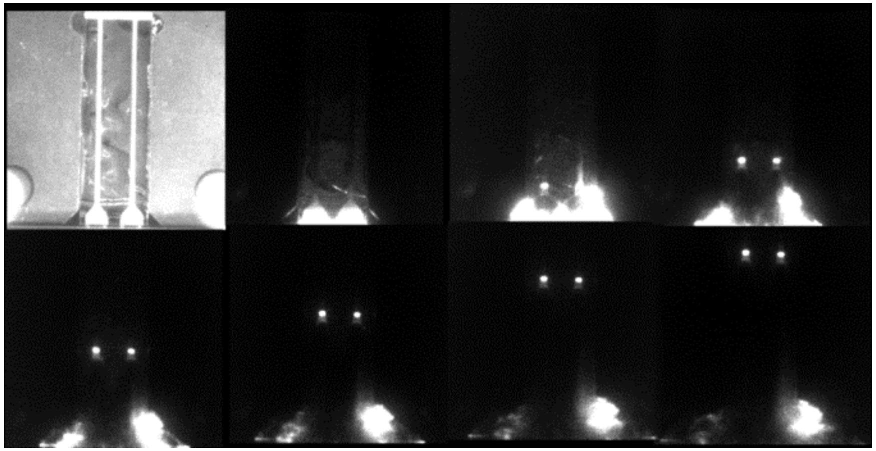

Tappan, A.S., Ball, J.P., and Colovos, J.W., "Inkjet Printing of Energetic Materials: Al/MoO3 and Al/Bi2O3 Thermite," *The 38th International Pyrotechnics Seminar*, Denver, CO, June 10–15, 2012.

## Physical vapor deposition





Pentaerythritol tetranitrate high explosive

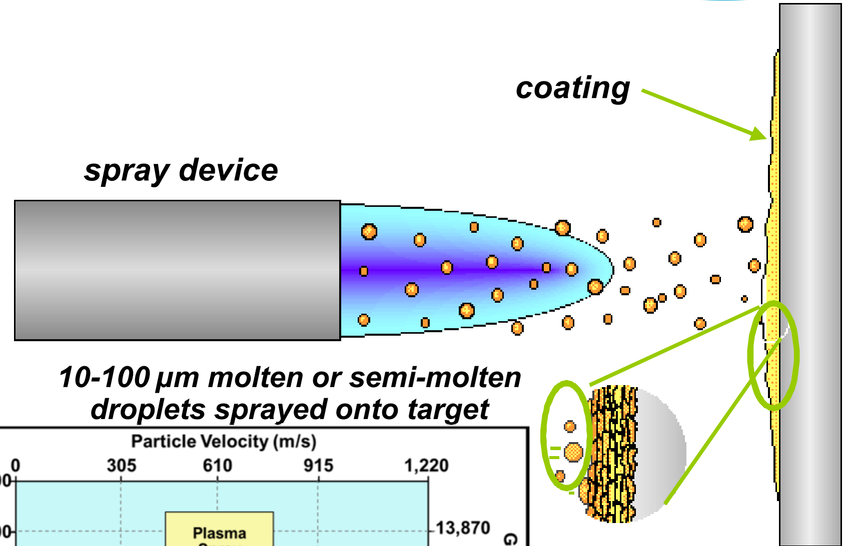


Tappan, A.S., Knepper, R., Wixom, R.R., Marquez, M.P., Miller, J.C., and Ball, J.P., "Critical Thickness Measurements in Vapor-Deposited Pentaerythritol Tetranitrate (PETN) Films," *14th International Detonation Symposium*, Coeur d'Alene, ID, April 11-16, 2010.

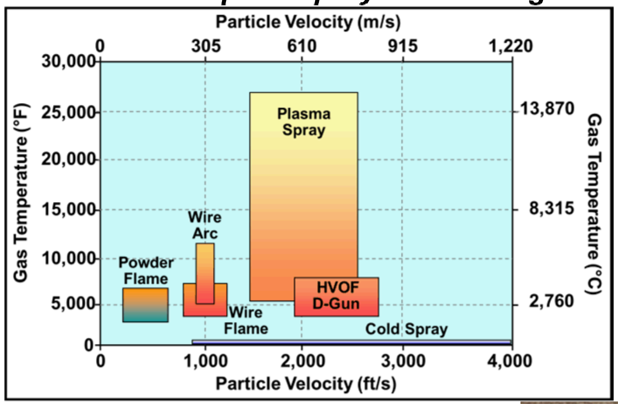
- Different materials and applications require different techniques

# Thermal Spray

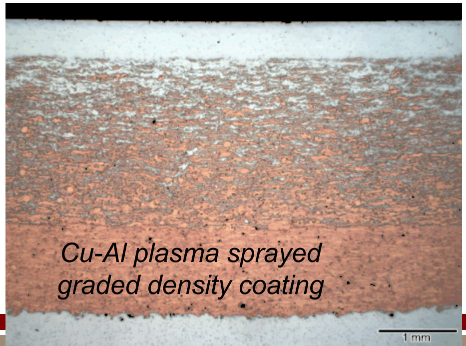
- SNL has all 7 major technologies
  - plasma spray (atmosphere, vacuum), twin wire arc spray, powder flame spray, wire flame spray, cold spray, high velocity oxy-fuel
- Advantages
  - large material set (anything that melts)
    - pure metals, most alloys, traditional ceramics, cermet, carbides, polymer, composites, MMC
    - graded materials
    - able to deposit on lower-melting substrates
  - surface properties differ from bulk
  - high build rates  over large areas (10 - 100 lb/hr)
    - thick deposits (mm to cm)
  - cold spray
    - solid state deposition, no composition changes or solidification stresses
    - near wrought properties w/heat treat

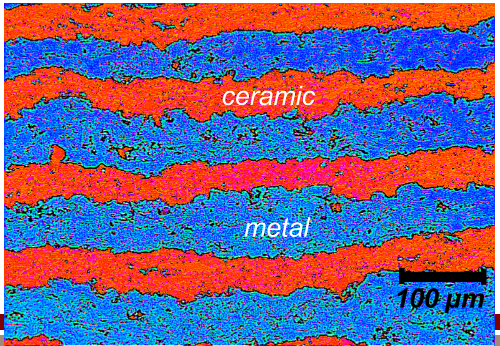


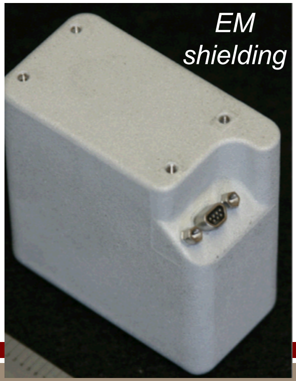

**10-100 µm molten or semi-molten droplets sprayed onto target**

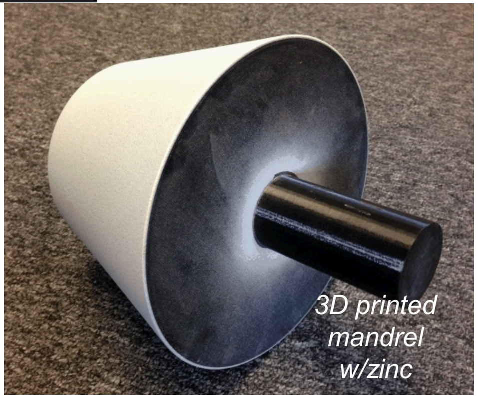



***Adapted from plots by R.C. McCune, Ford Motor Co. & A. Papyrin, Ktech Corp.**



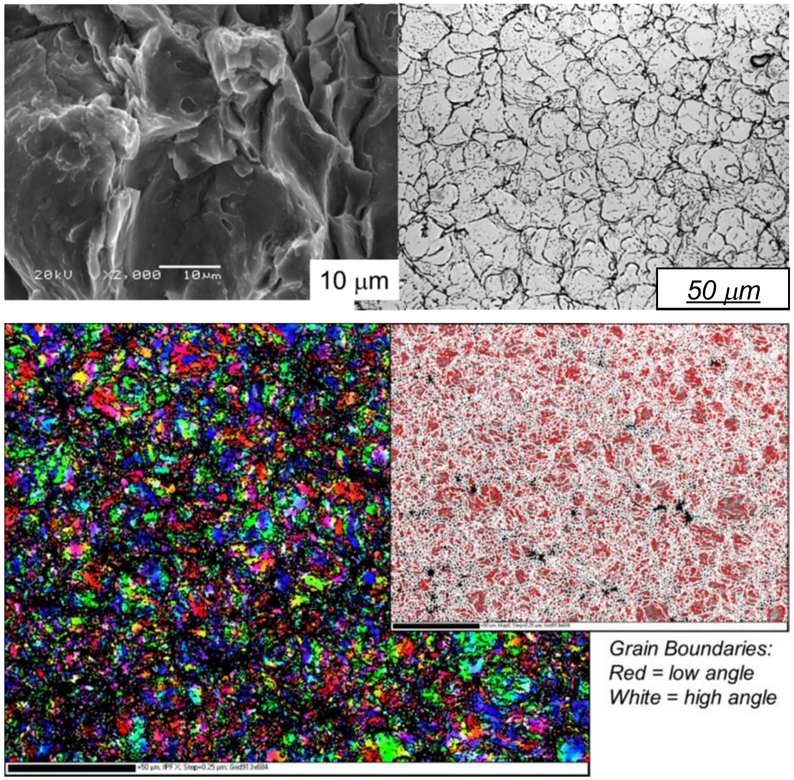



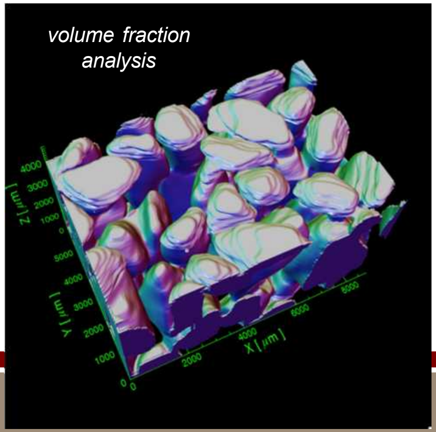



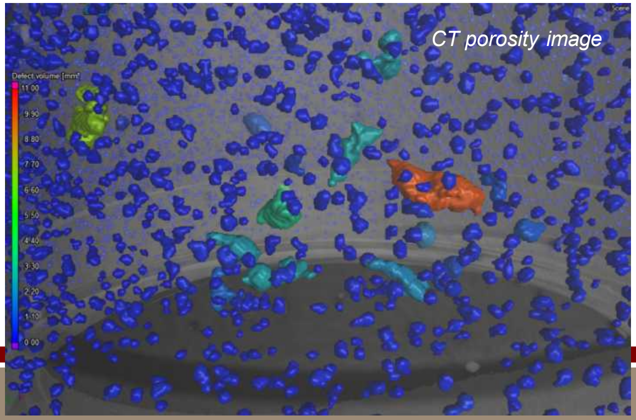
# Material Characterization

- Wide material tools available
  - SEM, FIB, TEM, AFM, EBSD
  - X-ray, neutron diffraction
  - spectroscopy
  - thermal & mechanical testing
  - digital image correlation (DIC) strain field mapping
  - metallography
- Defect detection / metrology
  - automated serial-sectioning
  - computed tomography
  - phase contrast x-ray imaging
- Primary challenges
  - large data sets
  - low throughput



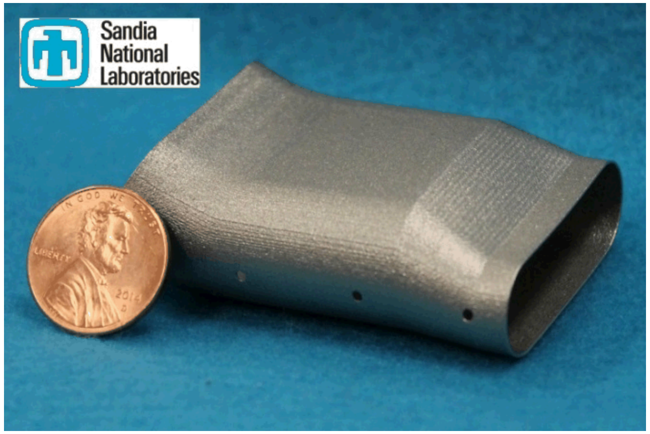

*pure Al cold spray coating*



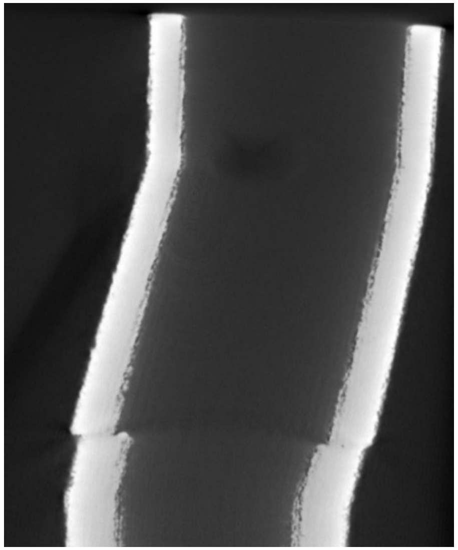



# Computed Tomography

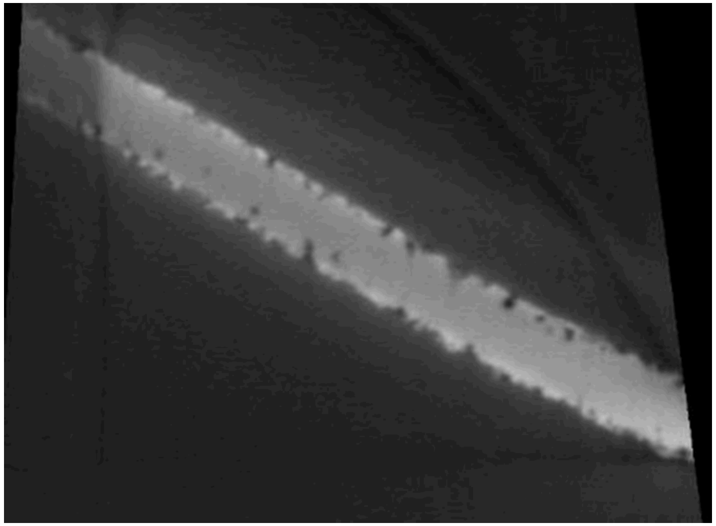
- Industry shift
  - 5 years ago – inspection, not metrology
  - now – necessary for AM complexity
- Interests
  - standards & verification
  - material characterization
  - dimensional metrology
  - big data (throughput, handling)
  - SNL capabilities in CT systems, data, metrology



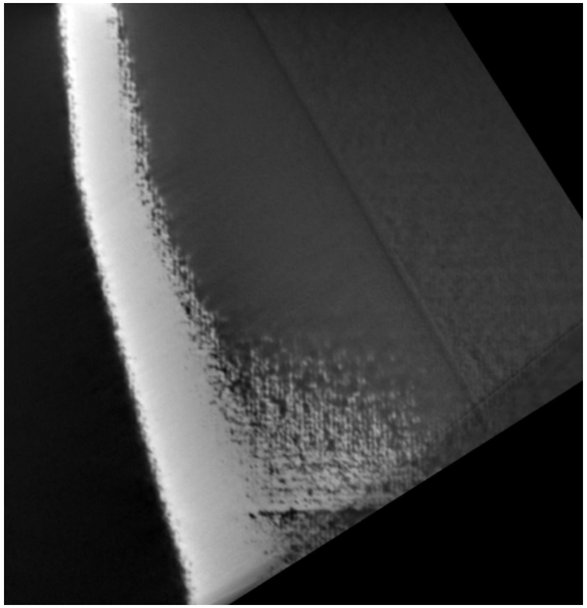

*AM housing prototyped in 17-4PH stainless steel*



*defects – material or measurement?*



*detecting material voids & defects*

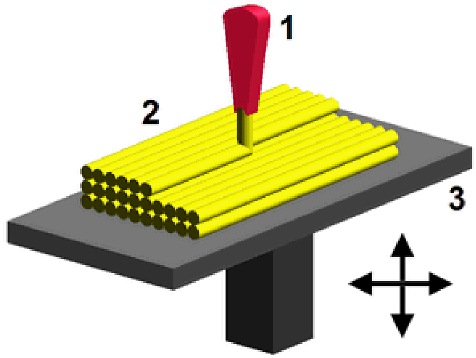


*able to see build layers*

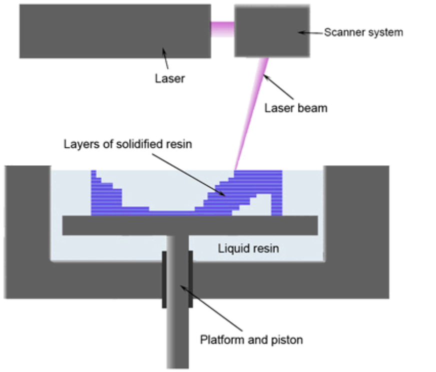
# ASTM “Process Categories”

Sandia National Laboratories

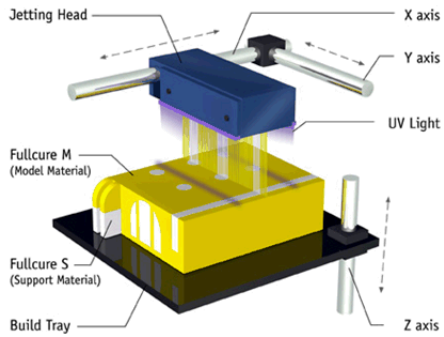
- Material extrusion
  - fused deposition modeling
  - direct write
  - viscous inks, thermoplastics
- Vat photopolymerization
  - stereolithography
  - photopolymers, epoxies
- Material jetting
  - Objet
  - photopolymers
- Binder jet
  - ZCorp, ExOne
  - binder printed into powder, infused w/filler



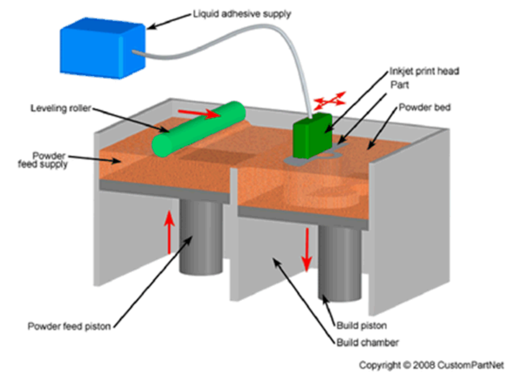

*“Fused deposition modelling”, Wikipedia*




*“Stereolithography”, Wikipedia*




*Objet Polyjet, www.me.vt.edu*




*Binder jetting, www.utwente.nl*

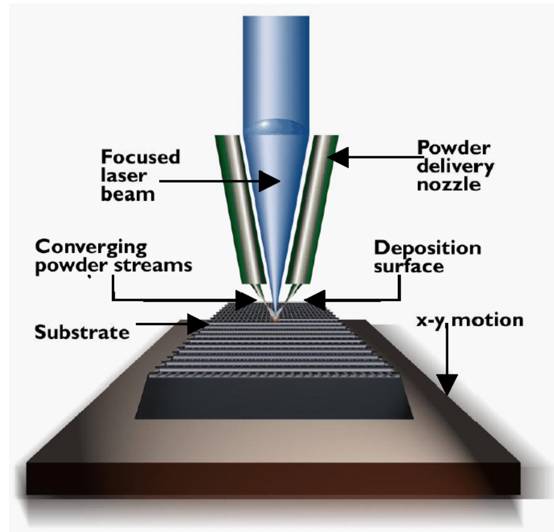




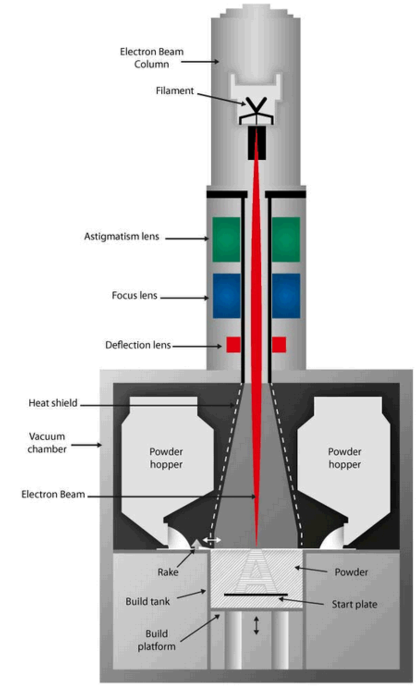
# ASTM "Process Categories"

Sandia National Laboratories

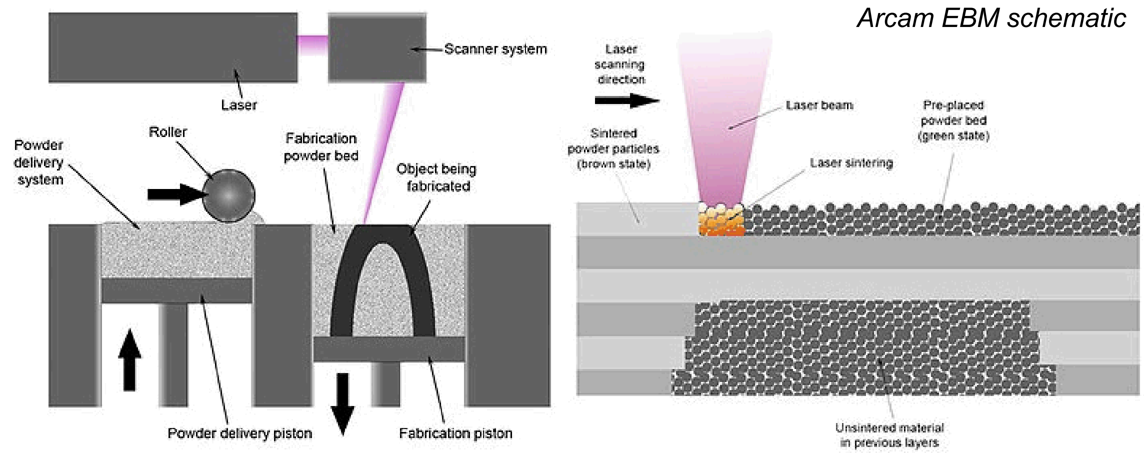
- Directed energy deposition
  - LENS®
  - metals, ceramics
- Powder bed fusion
  - selective laser sintering (SLS)
    - thermoplastics
  - selective laser melting (SLM)
    - metals, ceramics
  - electron beam melting (EBM)
    - metals, Ti-6Al-4V dominates
- Sheet lamination
  - Fabrisonic (ultrasonics)
  - Mcor (paper)
  - multi-material composites




*LENS®*




*Arcam EBM schematic*



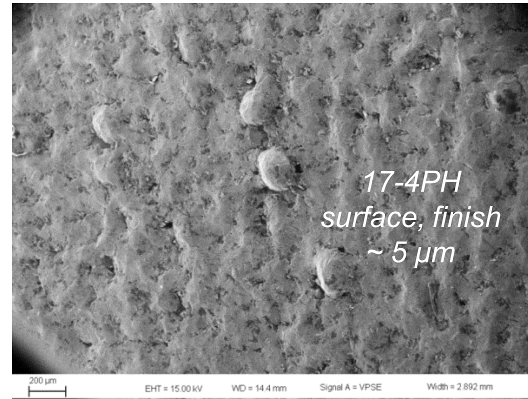

*"Selective laser sintering", Wikipedia*

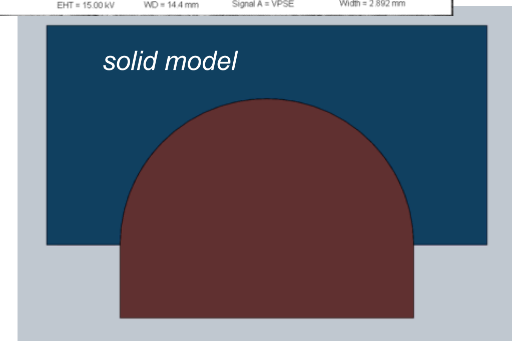
# Process Limits

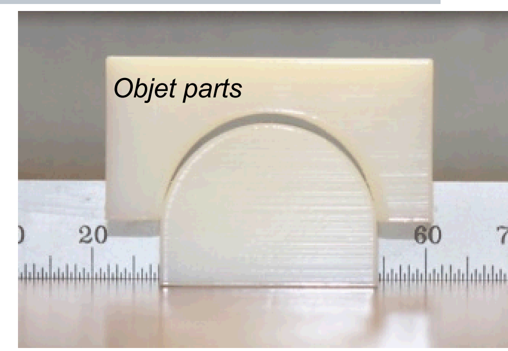
- Metal additive is predominantly a near net process
  - "competition" is casting, not machining
    - similar accuracy & finish
  - complexity isn't arbitrary
    - support structures, powder removal, overhangs
  - what are the physical limits?
    - finish ~ laser wavelength, melt & solidification dynamics
    - accuracy ~ optics, feedstock (safety), rapid phase changes (residual stress / deformation)
  - fundamentally a thermal problem
    - need better thermal constraints / controls
    - equipment uncertainties (~5-10$^{O}$ C in polymer SLS)
    - influenced by part & feature geometry

- Additional costs
  - post processing
    - heat treat, HIP, powder / support removal, finish machining…
  - maximum size, available materials, throughput

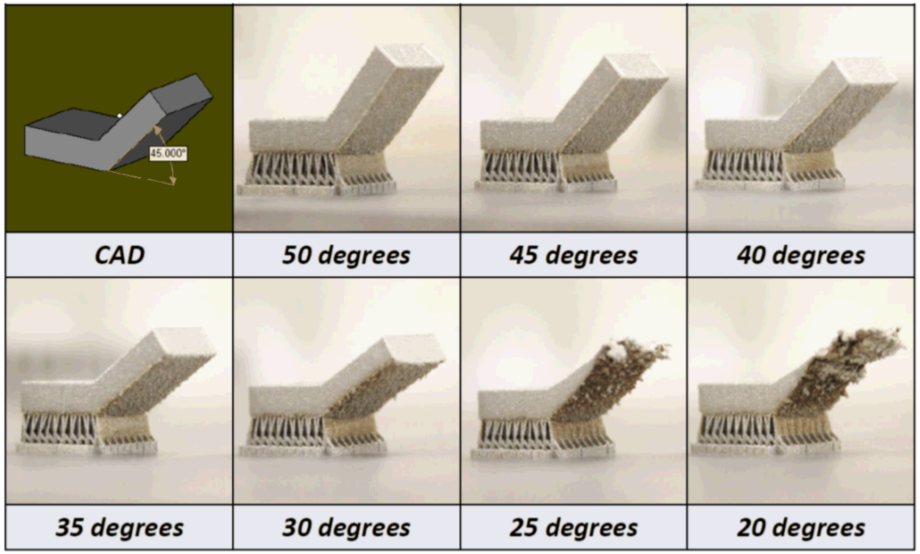
- Dynamic industry, improvements will continue…



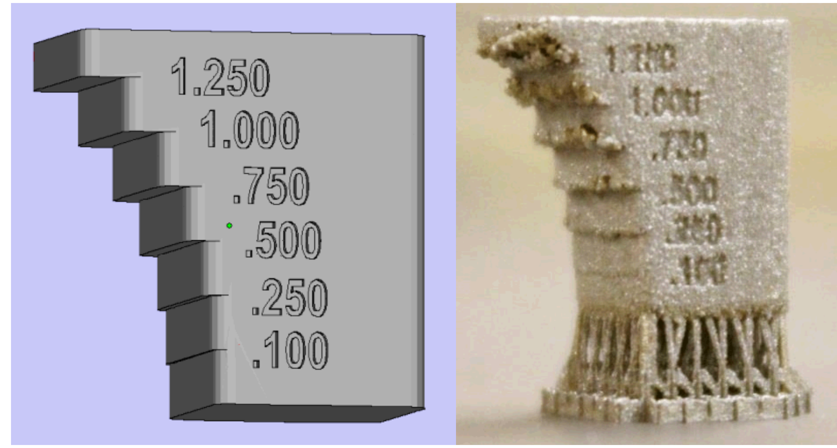




# Fineline Examples

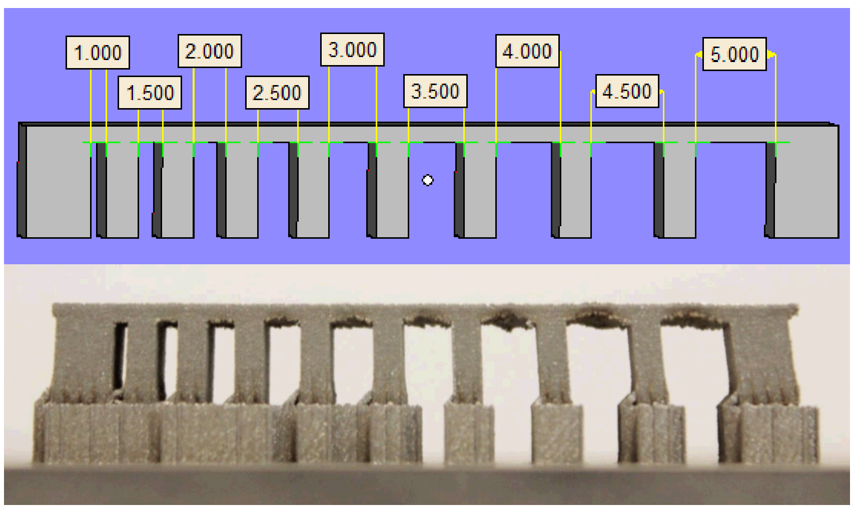



316L, 30 micron layers

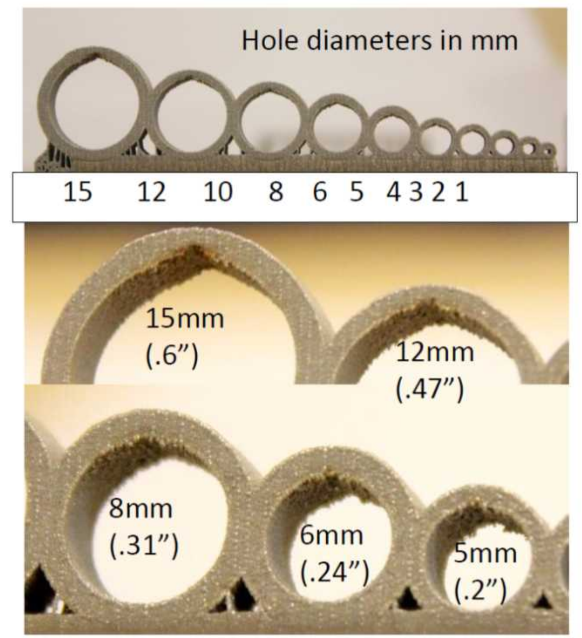
*self-supporting angles*




*overhangs*



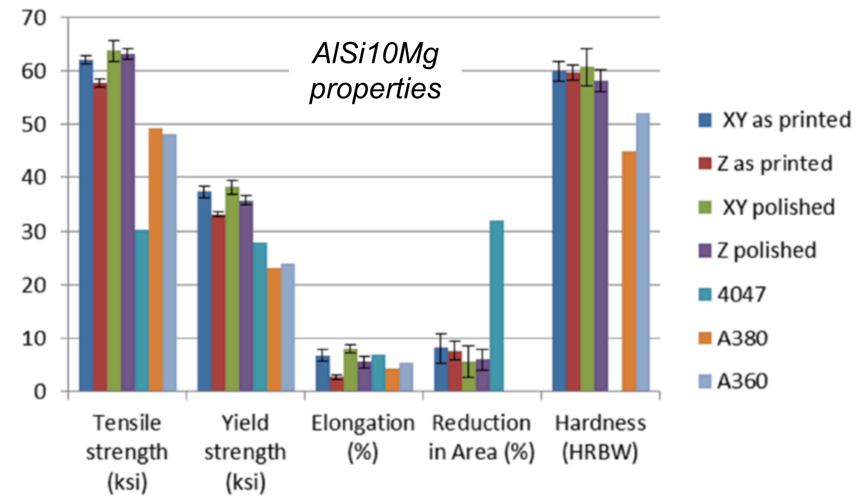

*bridges*

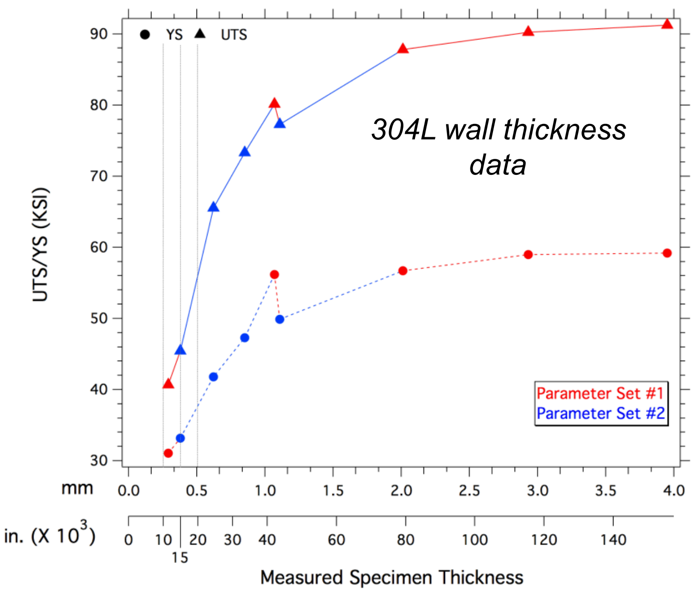



*channels & holes*

# Material Properties

- Unfamiliar & different, but foundations exist
- Properties
  - thermal / electrical / bulk aging
    - limited data consistent w/traditional materials
  - surfaces
    - finish: 5-25 µm
    - impacts corrosion, strength, fatigue
    - influenced by powder, process & orientation
  - bulk structural
    - strength, modulus, ductility, toughness, creep, …
    - microstructure matters
      - rapid phase transformations
      - varying thermal constraints
      - defects can dominate behavior
    - influenced by powder, process & geometry



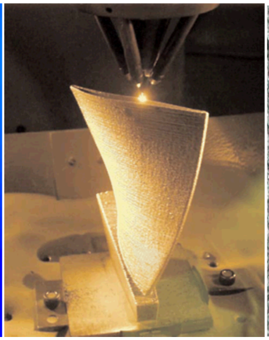
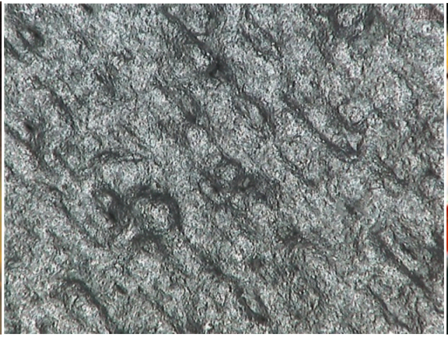
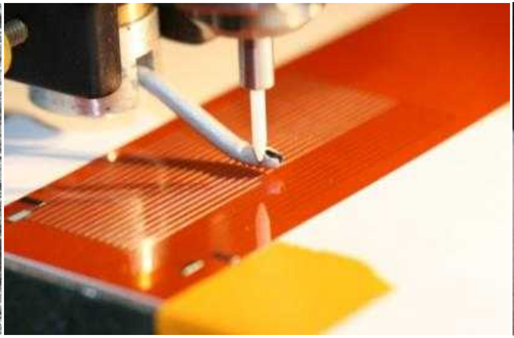
# QUESTIONS?


Bradley Jared, PhD

bhjared@sandia.gov

505-284-5890

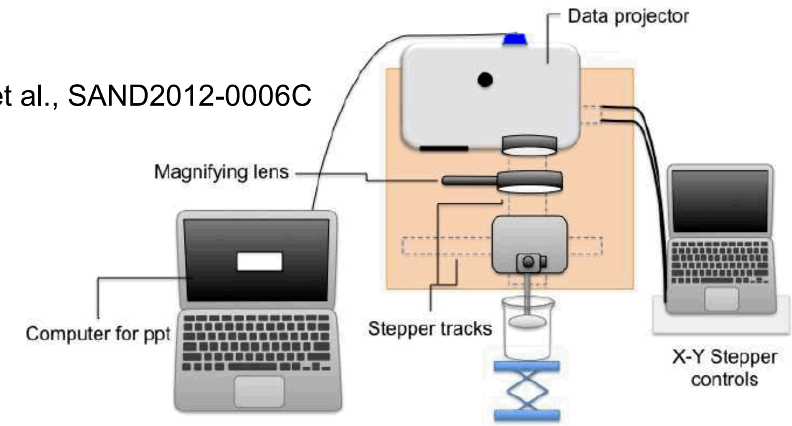


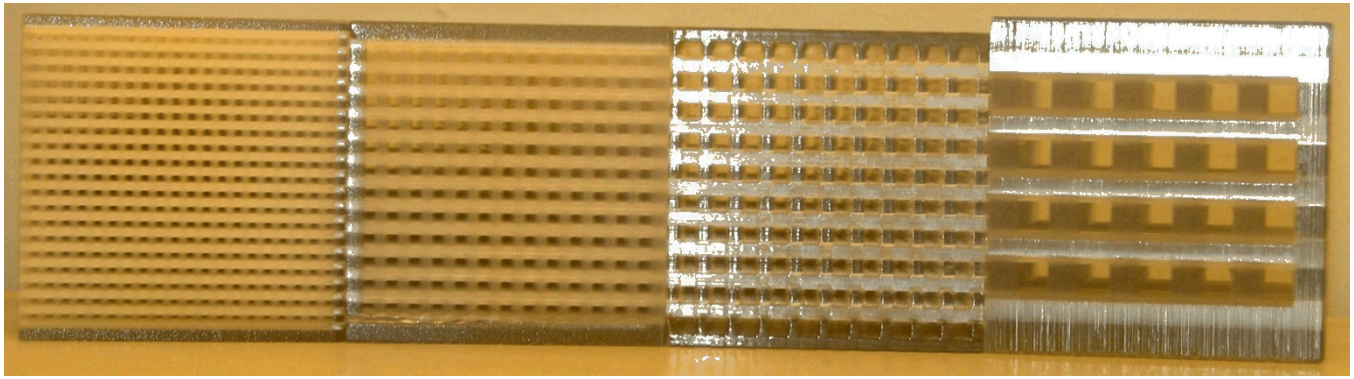





# Porous Structures

- Challenge
  - macroscale parts
  - ~100µm features
  - pore:part ratio limits?
  - fabrication
  - subsequent support/internal material removal
- Exploring
  - sterolithography
  - holography
  - 3D weaving

Dirk et al., SAND2012-0006C



*54mm Objet porous polymer cubes, 5 pores across*