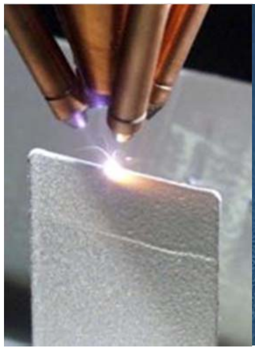
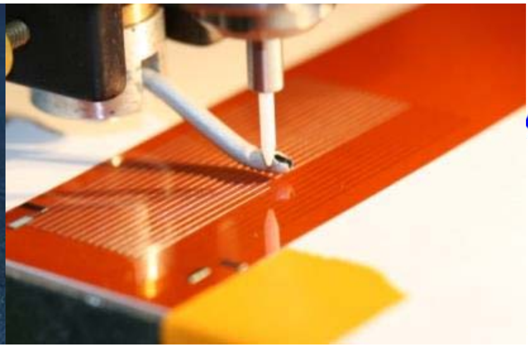
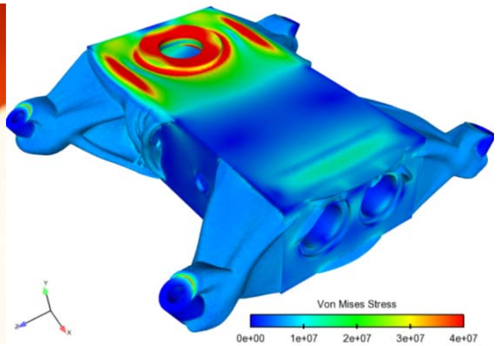
SAND2015-8832PE

Exceptional service in the national interest

Sandia National Laboratories







An Overview of AM Activities & Capabilities at Sandia

Aaron Hall, Bradley Jared

Materials Science & Engineering Center

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

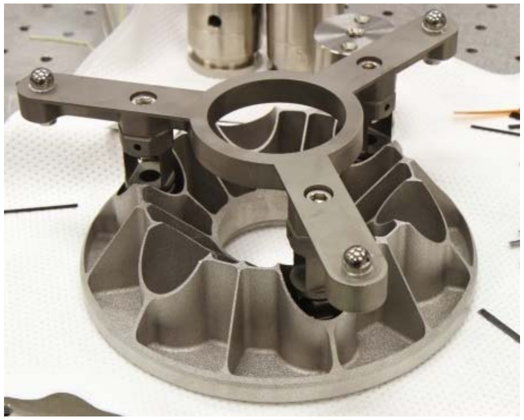
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SNL's Additive Interest

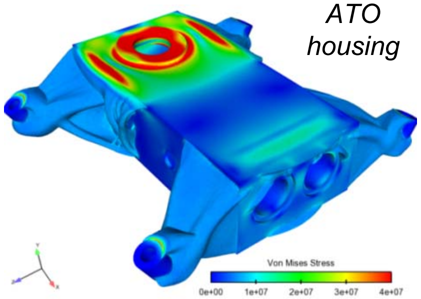
- Reduce risk, accelerate development
  - simplify assembly & processing
  - prototypes, test hardware, tooling & fixturing
    - > 75-100 plastic machines
    - cost reductions often 2-10x

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

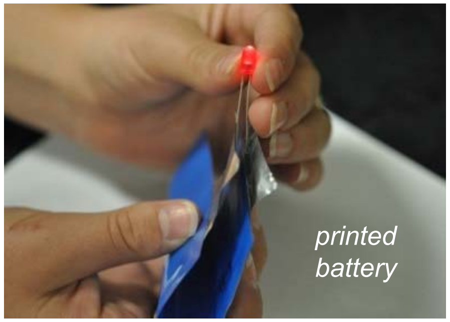
- Add value
  - design & optimize for performance, not mfg
    - complex freeforms, internal structures, integration
  - engineered materials
    - gradient compositions
    - microstructure optimization & control
    - multi-material integration



prototype Al AM mirror & structure



ATO housing



printed battery

fixture generated in 1 day

SNL’s Additive Strategy

Sandia National Laboratories

Vision: *We will deliver innovative national security products – impossible to create with traditional technologies – by exploiting the revolutionary potential of Additive Manufacturing.*

Today

Existing SNL expertise, capabilities, & partnerships in AM.

Identify Compelling Applications

Provide Design/Analysis Tools

Provide Materials Assurance

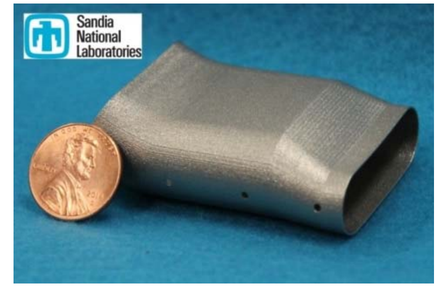
Enable Engineered/Multi-Material AM

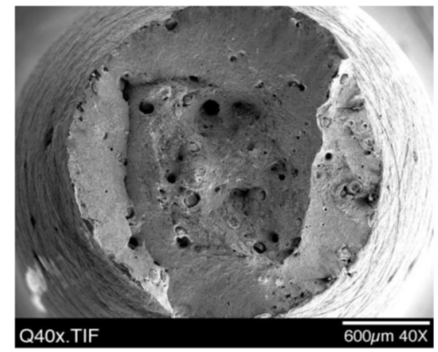
Enable Product Realization

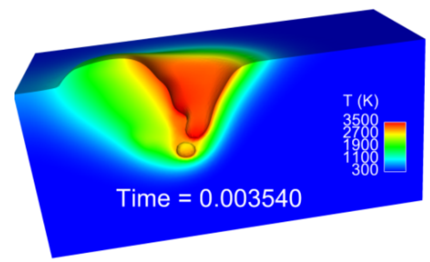
Tomorrow

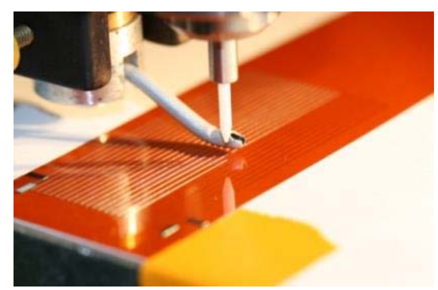
Deliver innovative, revolutionary national security products enabled by AM technology .

5 Strategic Thrust Areas



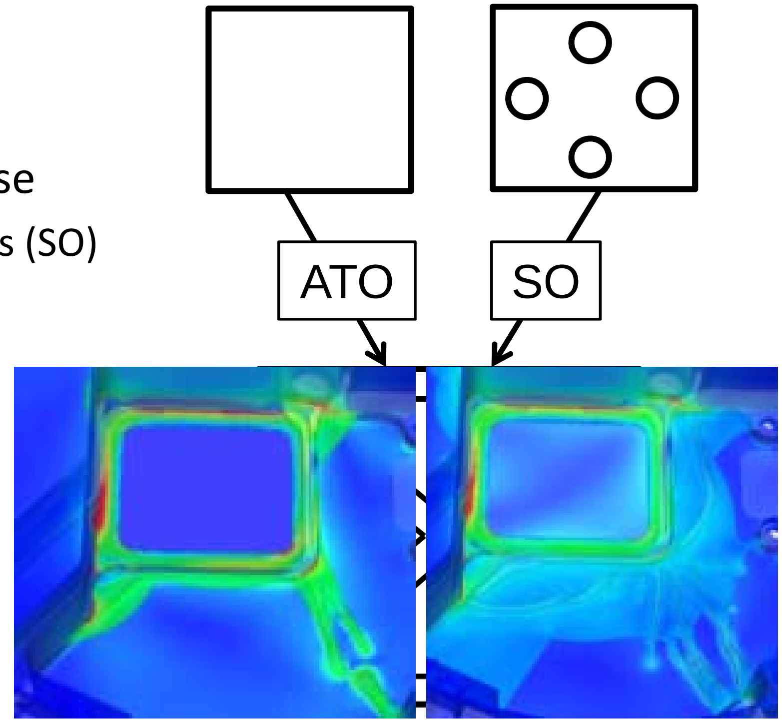






New Design Freedom

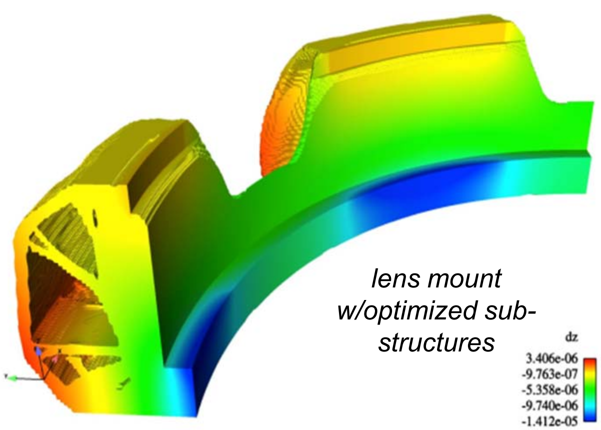
- Computational synthesis for optimal material use
  - adaptive topological (ATO) & shape optimizations (SO)
  - leverages “complexity is preferred”
  - constrained by performance requirements
  - bio-mimicry requires AM
  - design occurs concurrent w/simulation



\+ 0.55% volume
\- 52% deflection

\+ 3.3% volume
\- 64% deflection

elasto-static stiffness optimization

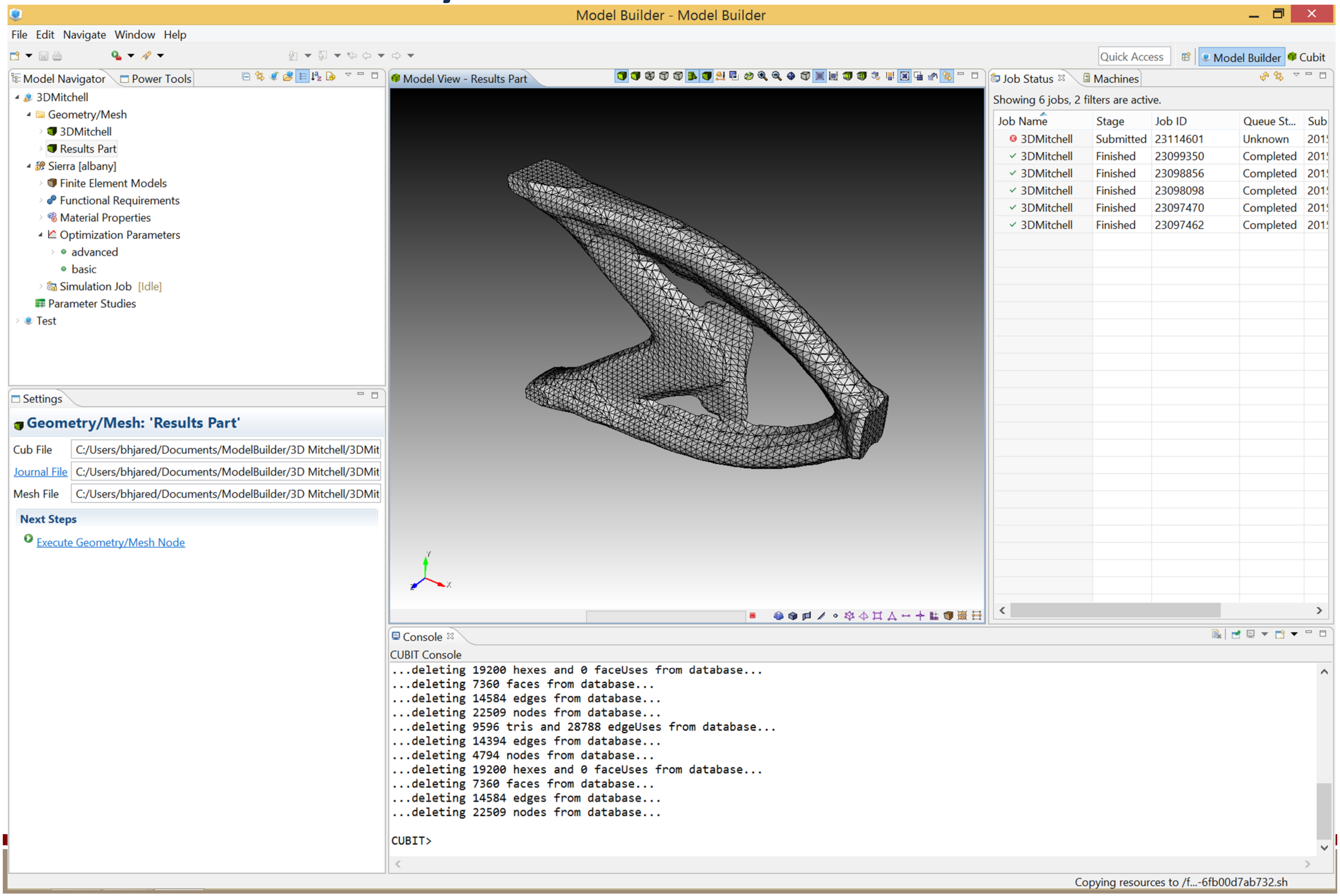


lens mount w/optimized sub-structures

solution for a bar in pure torsion resembles a cholla cactus

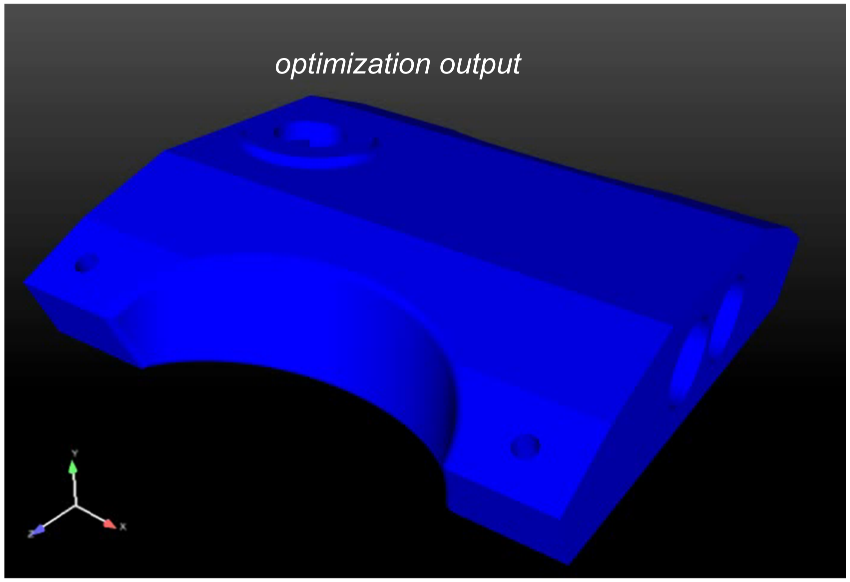
Joshua Robbins (1444), Tom Voth (1443), Brett Clark (1543), Ted Blacker (1543)

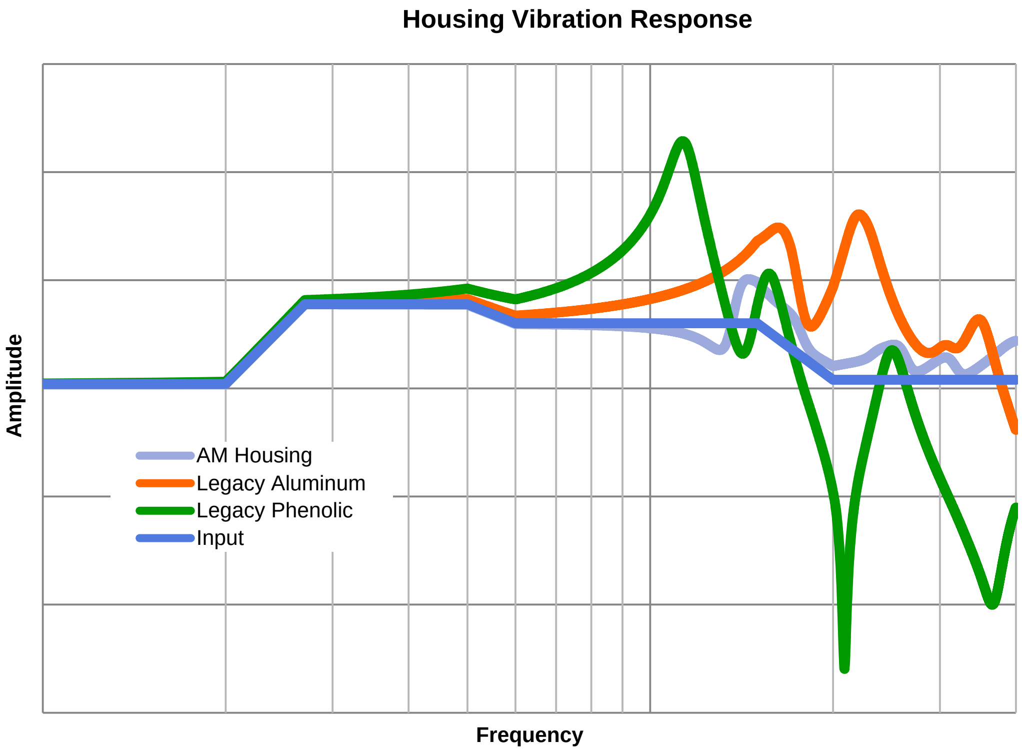
Sandia Analysis Workbench



Optimization Impact

Optimized design (using same mass and material, i.e., carbon phenolic) achieves 39% average increase in modes of interest, compared to 23% increase achieved by printing original design in aluminum.





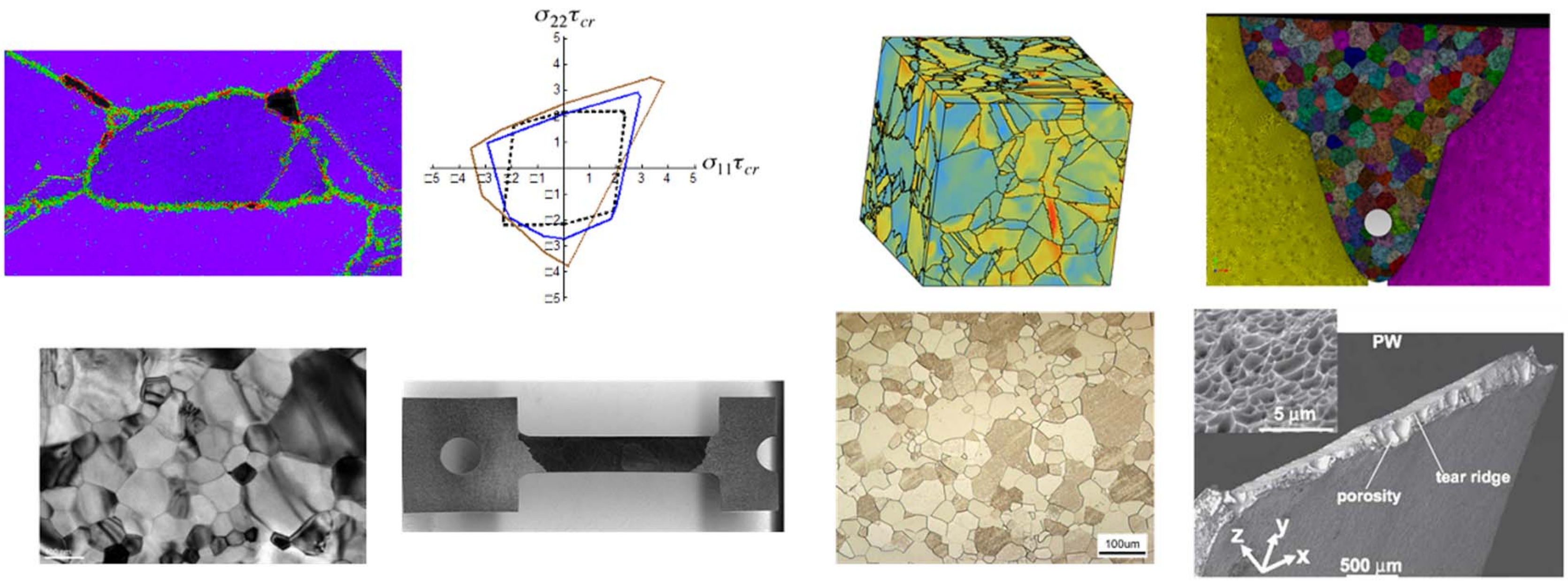
Design optimization provides performance improvements unachievable with materials alone

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

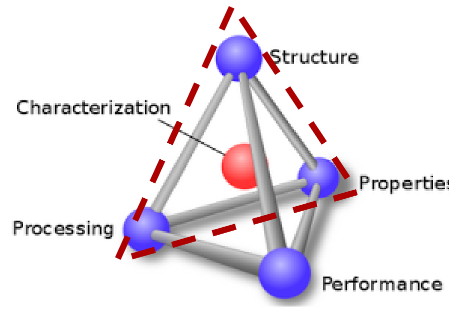
Atoms-up: Develop physics-based models to provide scientific insight

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

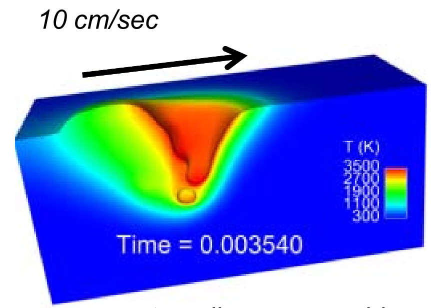
New Material Assurance Paradigm

Sandia National Laboratories

- Quantify process-structure-property relationships
  - process maps, constitutive models & HPC simulations
  - *understand behavior & formation of <u>critical</u> defects*

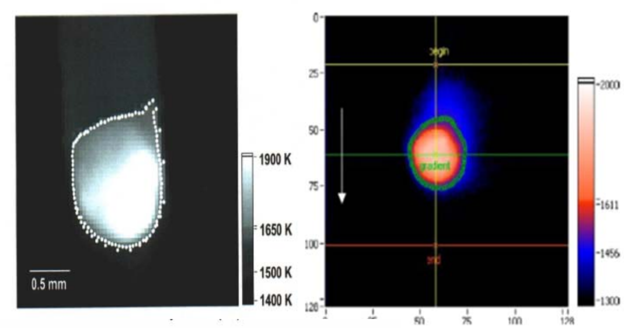


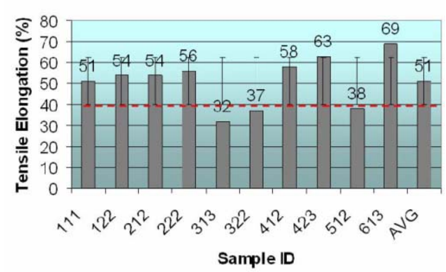
materials tetrahedron



traveling seam weld (Sierra, Martinez)

- Implement process control
  - start w/in-situ monitoring
    - establish property bounds & control needs
  - predictive process control
    - defect prevention (and correction?)
    - material optimization





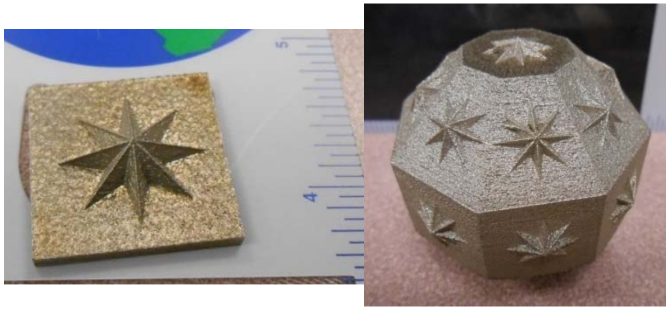
LENS® control of melt pool & microstructure

- Leverage experience in LENS®, laser welding , thermal spray, casting

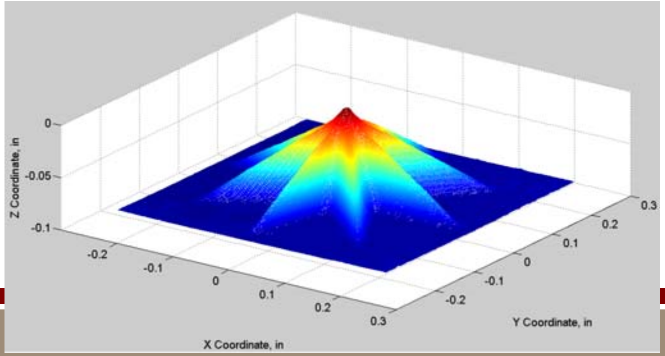
Metrology Artifacts

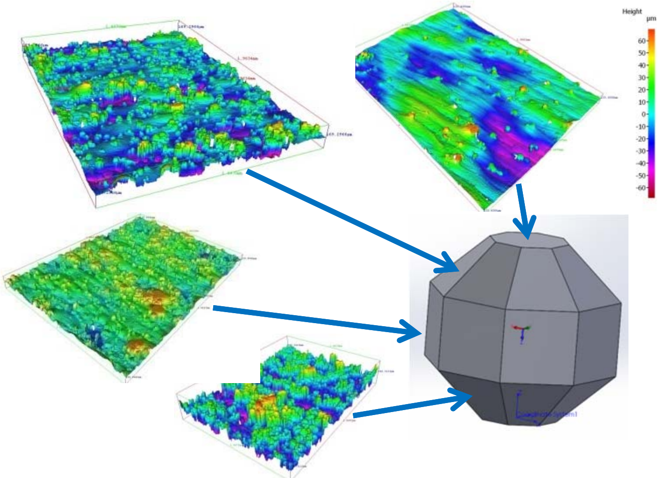
- Unique challenges for process & equipment characterization
  - part geometry = function (material, print orientation, support structures, post-processing,…)
  - equipment generally exceeds process
- Family of artifacts designed, printed & measured
  - fabrication has been easier than metrology
  - working to show utility for predictive process inputs
  - interest for process feedback

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

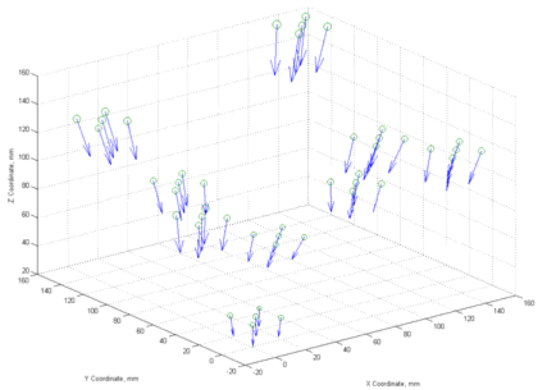


Siemens star geometries for resolution evaluation





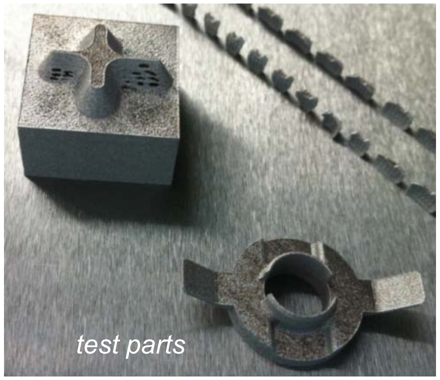
17-4PH polyhedron texture anisotropy map

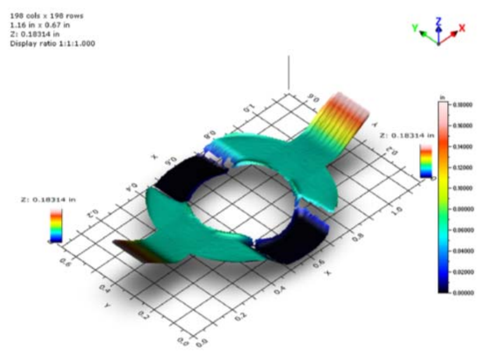


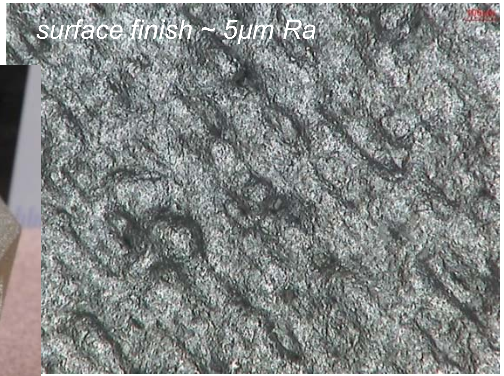
Ti "Manhattan" error map

Powder Bed Fusion

- Powder melts @ focal point, then re-solidifies
  - electron beam melting (Arcam)
  - laser based (term varies w/vendor)
  - growing activity exploring metal parts
- 3D System machines purchased
  - process characterization & materials science
  - open architecture controller
  - three machines (2 in NM, 1 in CA)
- 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


test parts



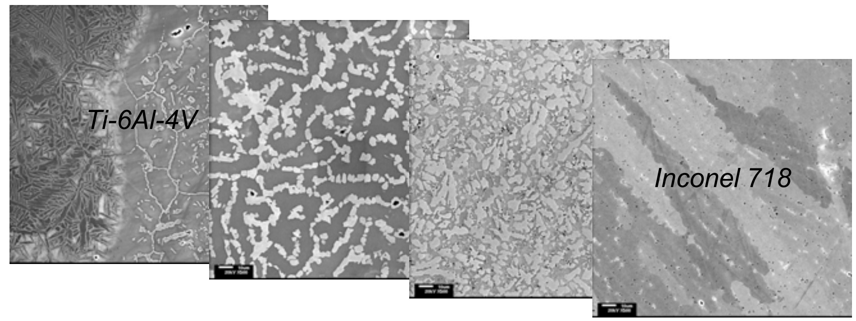

surface finish ~ 5µm Ra

Bradley Jared (1832), Dan Kammler (2735), Larry Carrillo (8247)

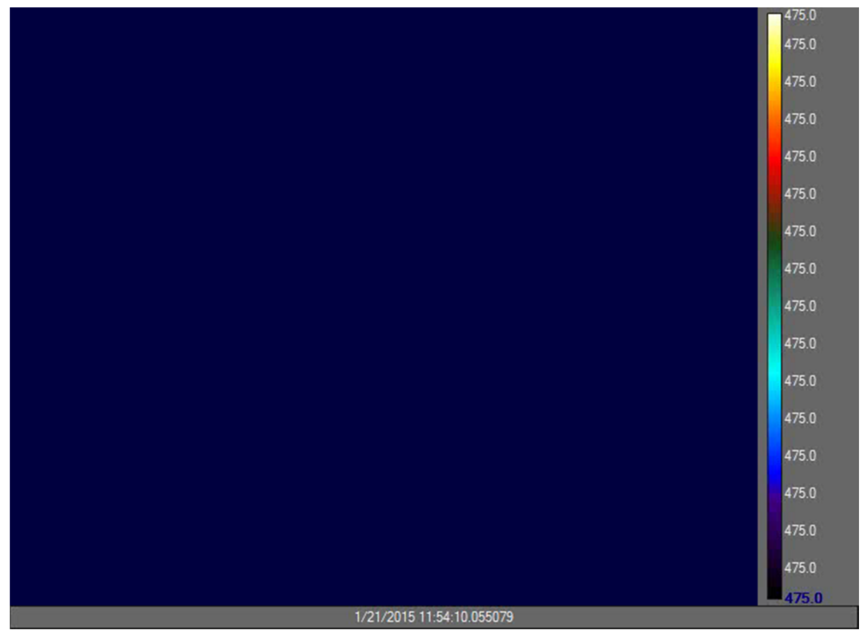
Laser Engineered Net Shaping (LENS®)

- Historical
  - extensive SNL development efforts & investments
  - licensed to Optomec
  - foundation for metal additive research

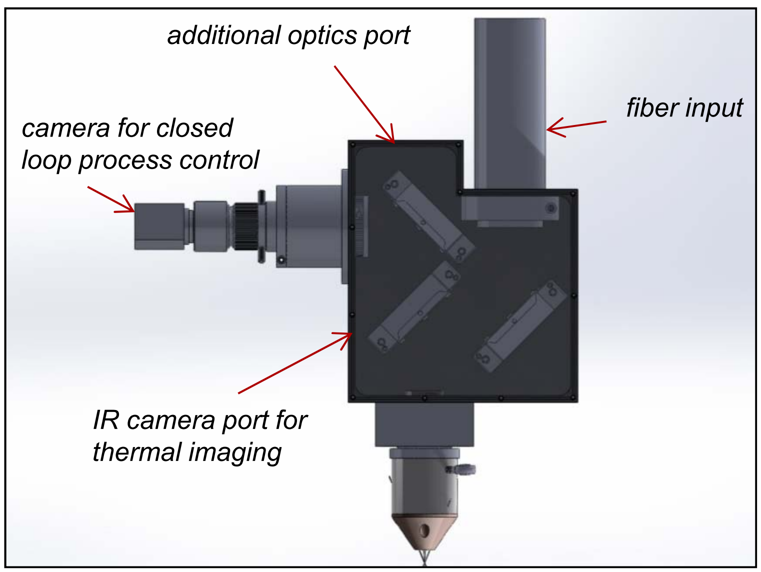
- Custom research machine
  - re-establishing & expanding capability
    - additive & subtractive
    - deposition head designed for process diagnostics & feedback
  - leveraging existing hardware



LENS functionally graded materials



thermal history during bi-directional metal deposition



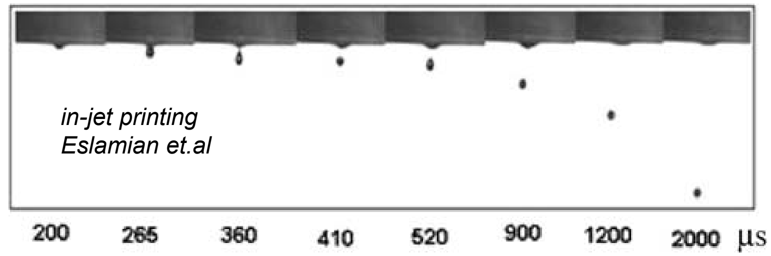
David Keicher (1832), John Smugeresky (8247), Josh Sugar (8342)

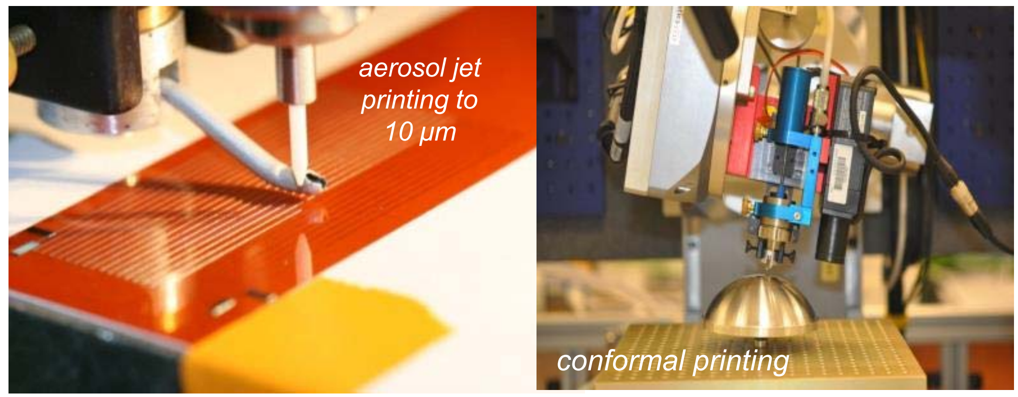
Direct Write

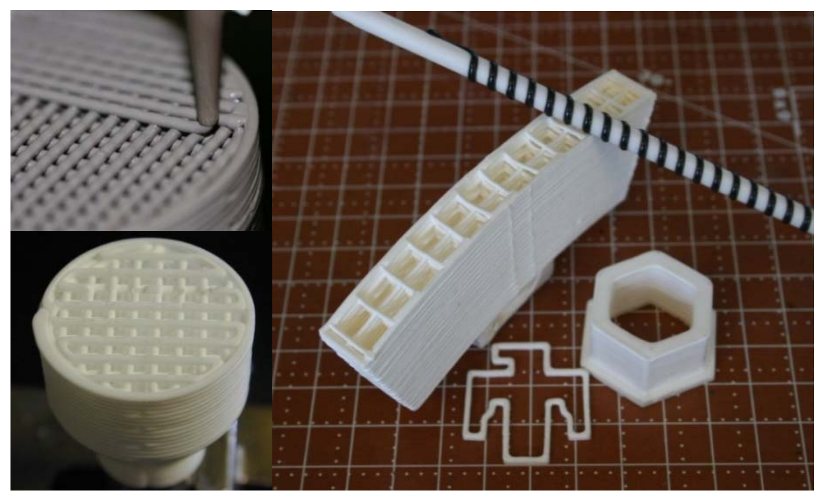
- Ink jet
  - discrete droplets produce continuous line segments
  - line width a function of droplet size
    - diameter: 18-635 µm
  - material viscosity: 1-1x10^6 cPs

- 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)

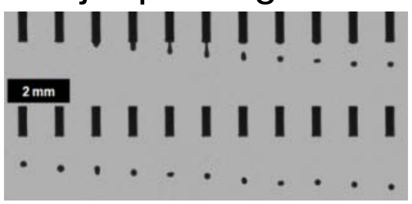
Energetic Materials

Robocasting

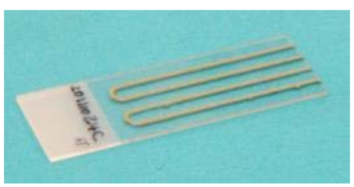
Aluminum/Nickel reactive material

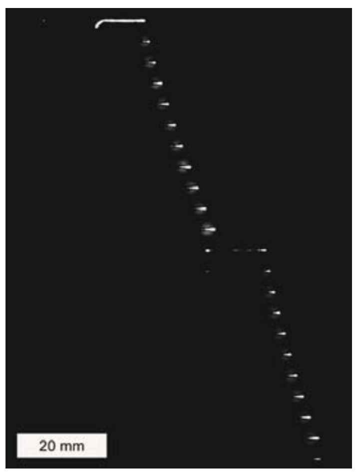
Tappan, A.S., Groven, L.J., Ball, J.P., Miller, J.C., Colovos, J.W., Joseph Cesarano, I., Stuecker, J.N., and Clem, P., "LDRD Final Report: Free-Form Fabrication and Precision Deposition of Energetic Materials," SAND2008-0965, February, 2008.

Inkjet printing



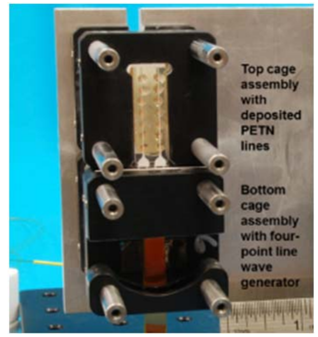
Aluminum/bismuth trioxide thermite

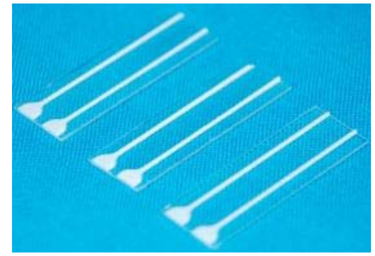




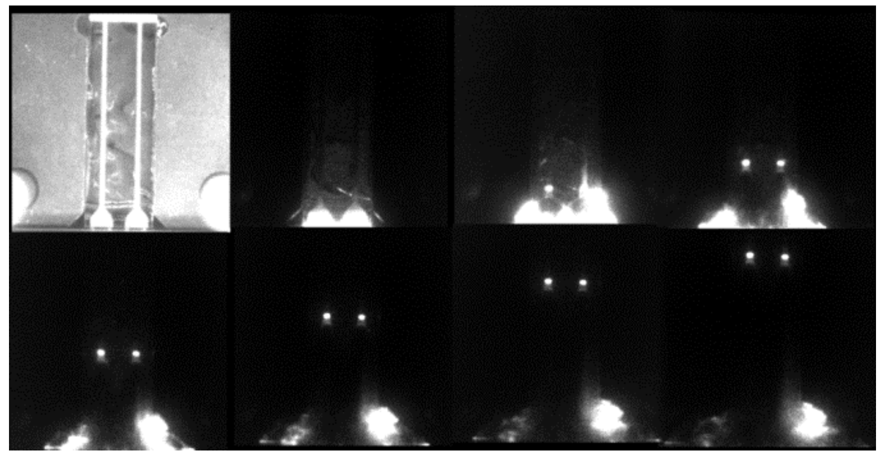
Tappan, A.S., Ball, J.P., and Colovos, J.W., "Inkjet Printing of Energetic Materials: Al/MoO3 and Al/Bi2O3 Thermite," *The 38th International Pyrotechnics Seminar*, Denver, CO, June 10–15, 2012.

Physical vapor deposition





Pentaerythritol tetranitrate high explosive

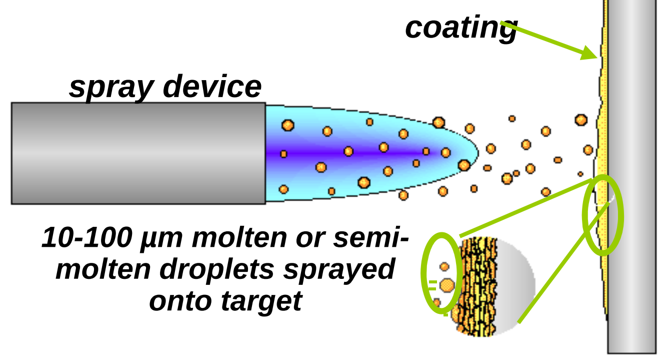


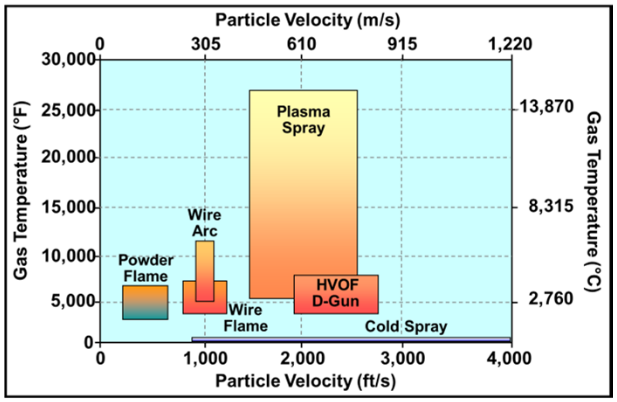
Tappan, A.S., Knepper, R., Wixom, R.R., Marquez, M.P., Miller, J.C., and Ball, J.P., "Critical Thickness Measurements in Vapor-Deposited Pentaerythritol Tetranitrate (PETN) Films," *14th International Detonation Symposium*, Coeur d'Alene, ID, April 11-16, 2010.

- Different materials and applications require different techniques

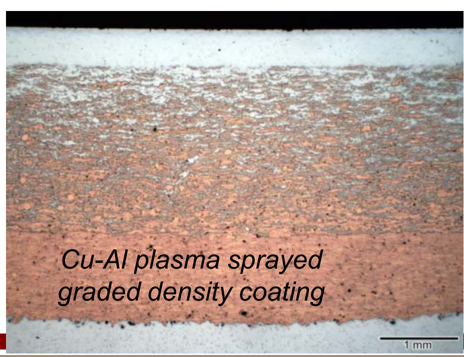
Thermal Spray

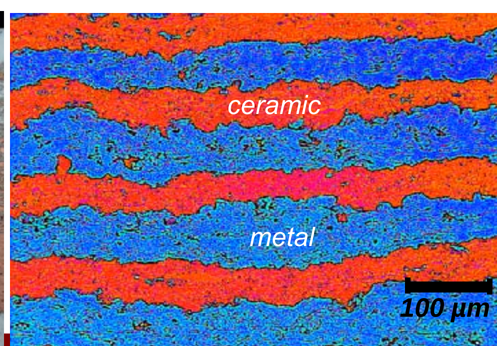
- SNL has all major thermal spray processes
  - plasma spray (atmosphere, vacuum), twin wire arc spray, powder flame spray, wire flame spray, cold spray, high velocity oxy-fuel
- Advantages
  - large material set (anything that melts)
    - pure metals, most alloys, traditional ceramics, cermet, carbides, 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

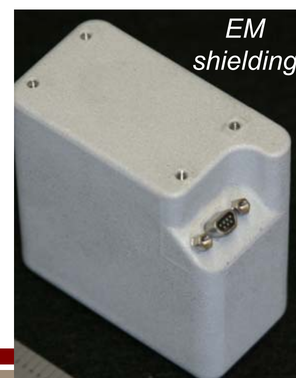


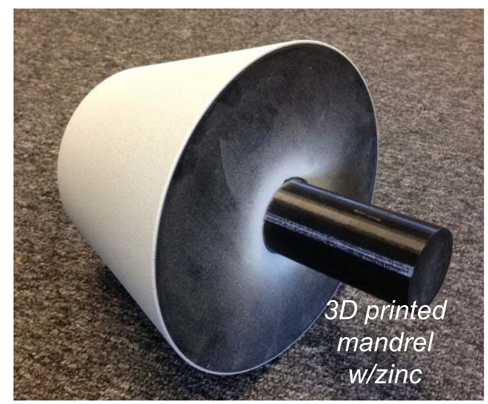


**Adapted from plots by R.C. McCune, Ford Motor Co. & A. Papyrin, Ktech Corp.*

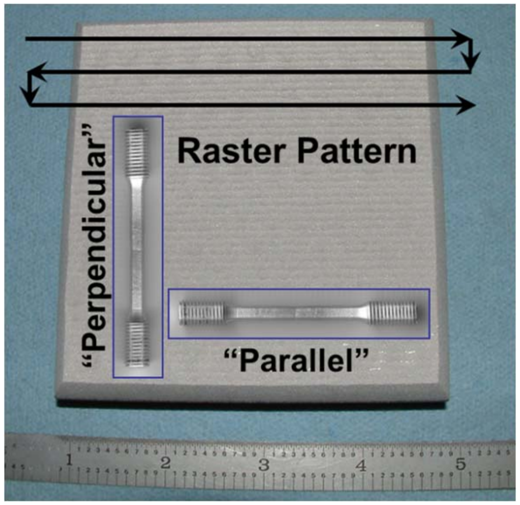




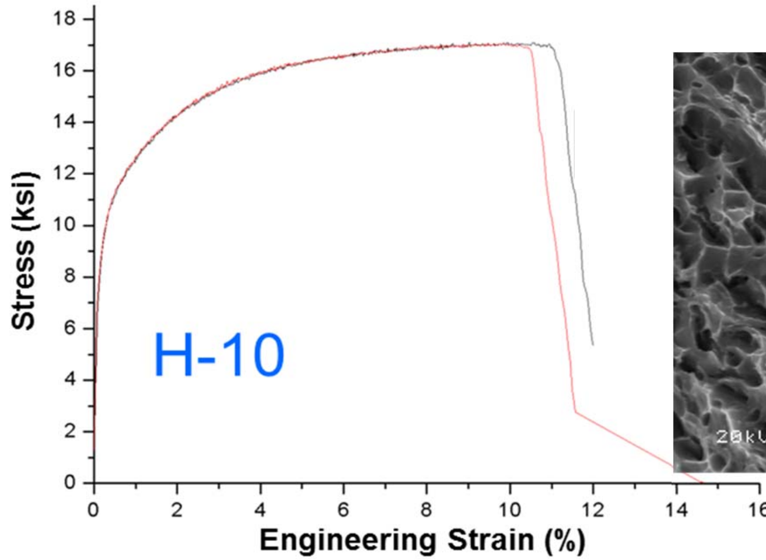


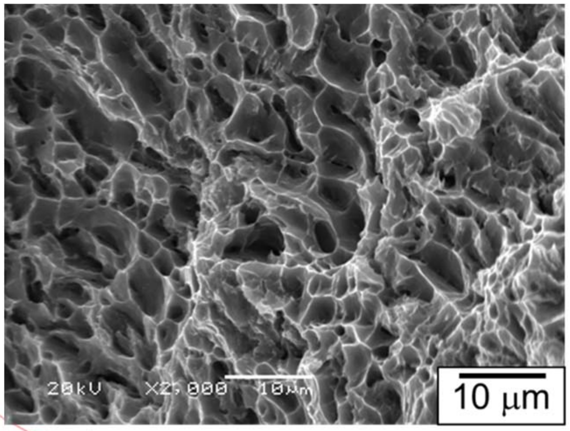


Cold spray Aluminum deposits exhibit near-wrought properties after annealing.



ASTM E8 tensile bars machined from ½" thick aluminum deposits



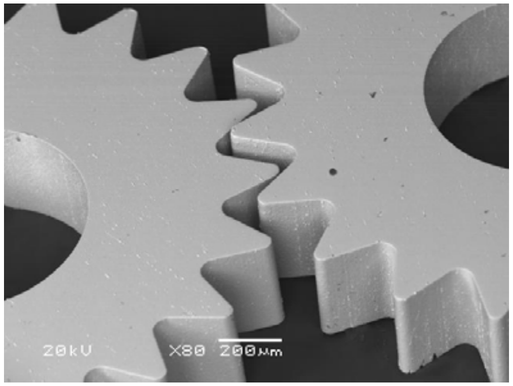


Spray deposits exhibit wrought properties (11% strain to failure and classic cup-and-cone ductile fracture surfaces) after 300ºC anneal!

- **Aluminum deposit 4"x4"x1/2" thick prepared at Sandia National Laboratories using cold spray.**
- ***Total build time was less than 20 minutes! Aluminum was not melted in this process!***
- **Solid state deposition proven for: Al, Ti, SS, Cu, Ni, and Ta alloys**

Cold spray offers an important alternative to melt-based deposition techniques currently used for 3-D printing.

Nanocrystalline 6061 Aluminum Prepared Using Cold Spray

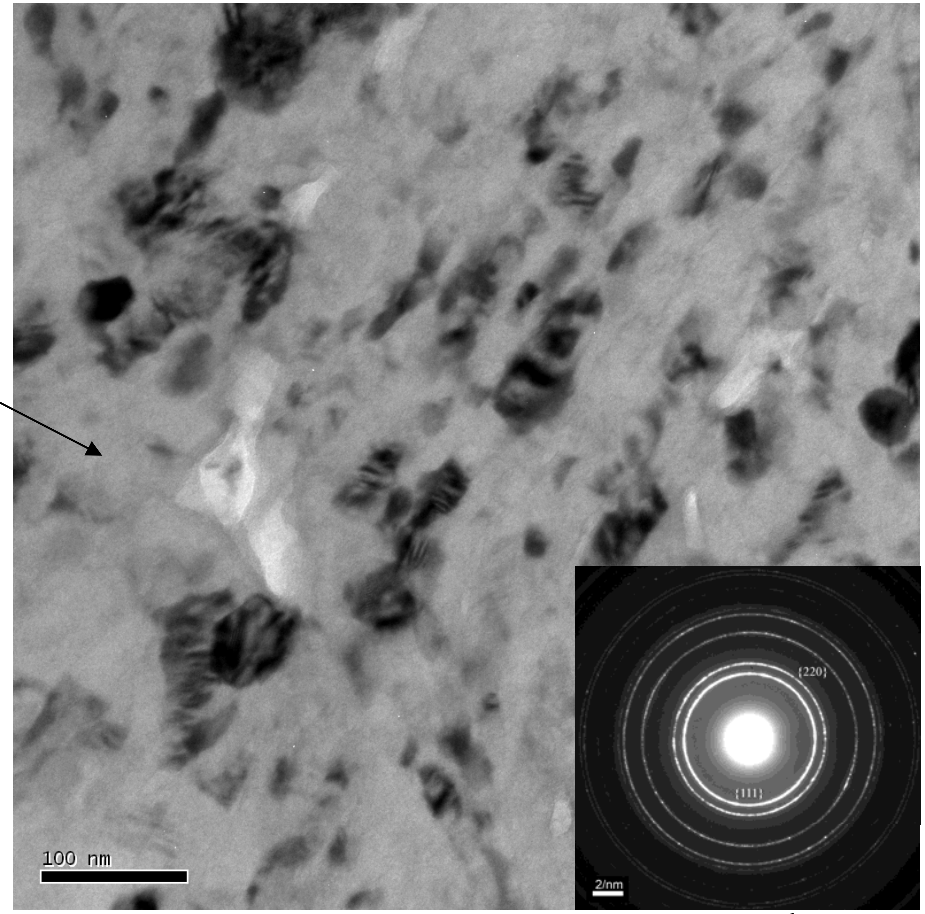


Fine grained material needed to manufacture meso-scale mechanical components

- Minimum grain size for Aluminum is ~ 20 nm
- Dislocations are unstable in Aluminum grains smaller than 18nm
- Plastic deformation is responsible for grain refinement in LN_2 ball milled and cold sprayed aluminum

Sample ID	Depth (nm)	Avg.'d CSM results (100-200nm) E (GPa)	Avg.'d CSM results (100-200nm) H (GPa)	Results using Unloading Curve E (GPa)	Results using Unloading Curve H (GPa)
6061 T6 Bulk Wrought	1000	87.5±3.6	1.464±0.132	85.7±2.0	1.411±0.028
6061 T6 Bulk Wrought	250	86.7±1.6	1.450±0.054	89.3±8.2	1.385±0.044
6061 coating as-received powder	1000	87.9±3.3	1.322±0.278	90.8±5.5	1.349±0.169
6061 coating as-received powder	250	86.7±3.4	1.363±0.458	92.4±10.1	1.347±0.325
6061coating LN2 milled powder	1000	84.4±1.6	2.621±0.309	86.0±2.6	2.306±0.275
6061 coating LN2 milled powder	250	83.9±1.7	2.715±0.198	90.4±5.9	2.416±0.172

30- 50 nm grains



No discernable texture!

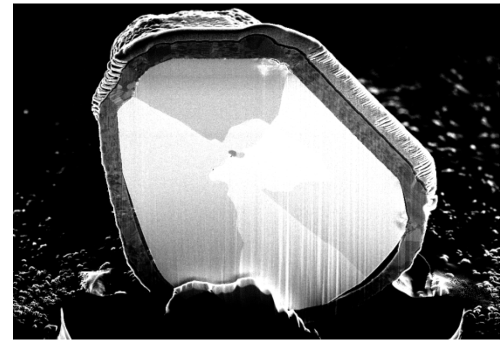
The nanocrystalline coating has ~ double the hardness of conventional cold sprayed 6061 Al.

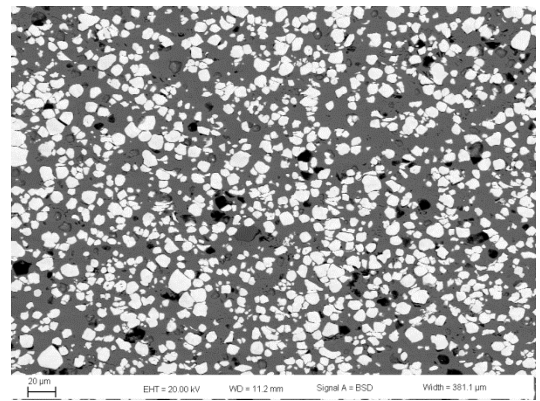
Cold Spray Copper-Tungsten MMC

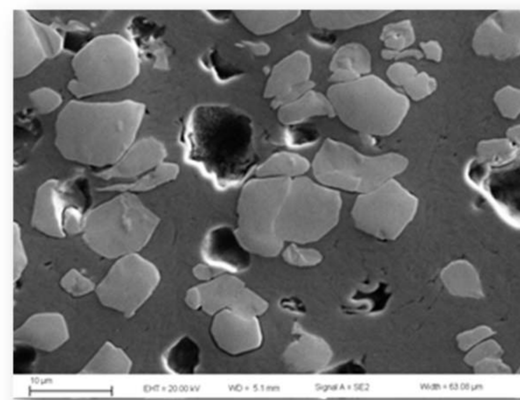
Sandia National Laboratories

- Cu coated W powder deposits readily
- Cu-W critical velocity is significantly lower than Cu, as predicted by particle density increase
- W loss occurs during deposition
- Cu coating separates from the W particles
- W fracture occurs during deposition at high W loadings (>85%)
- Reducing particle velocity did not reduce tungsten loss
- Coating adhesion and interfaces matter in Cu-W feedstock.

Cu-W metal coated powders deposit beautifully; but are changed by the cold spray process!





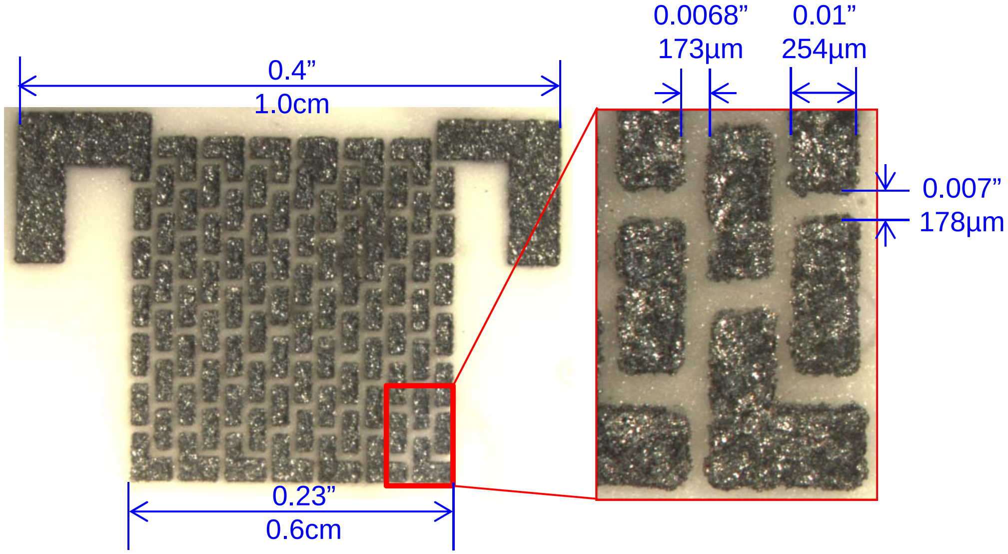


Moly Thermoelectric Module Interconnect

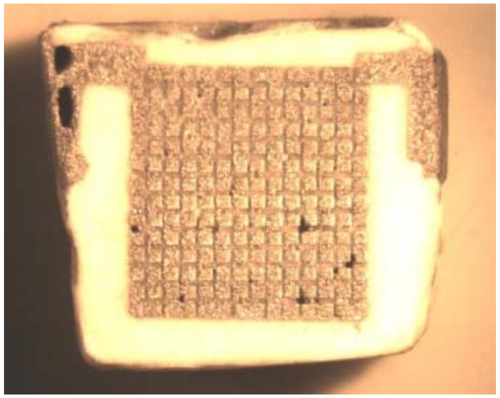
Feasibility of Air Plasma Sprayed (APS) Mo interconnects

- Laser-cut high temp polymer (400°C) mask
- Results show great potential:
  - Feature size ~250 µm
  - ~170 µm spacing
  - Dense & low porosity coating
  - High electrical conductivity
- APS is a fast, efficient, and inexpensive method for Mo coatings as interconnects.

Mo plasma sprayed coating through Laser-patterned Polymer Mask



Coated thermoelectric module



Plasma spray processes can be used to create surprisingly small features using straightforward masking techniques!

QUESTIONS?

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