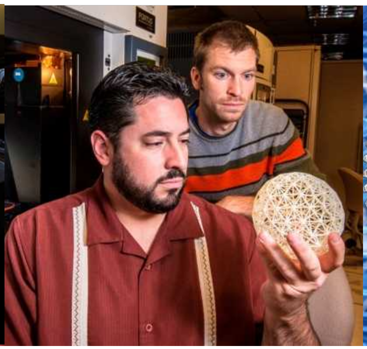

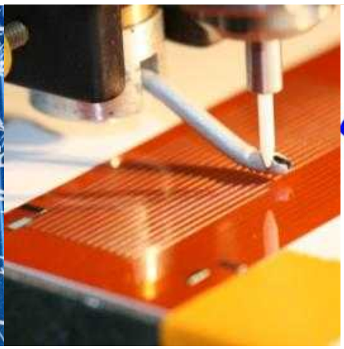

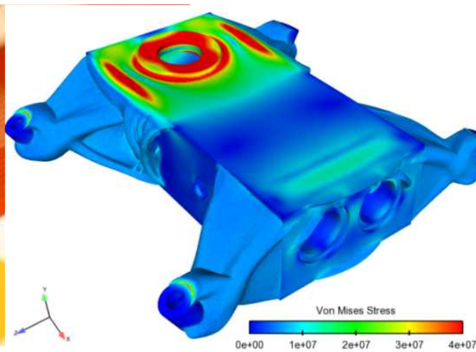

Additive Manufacturing Initiatives at Sandia National Laboratories

Bradley Jared, Materials Engineering R&D

Abraham Sego, R&D Manager, Mechanical Design

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Sandia National Laboratories

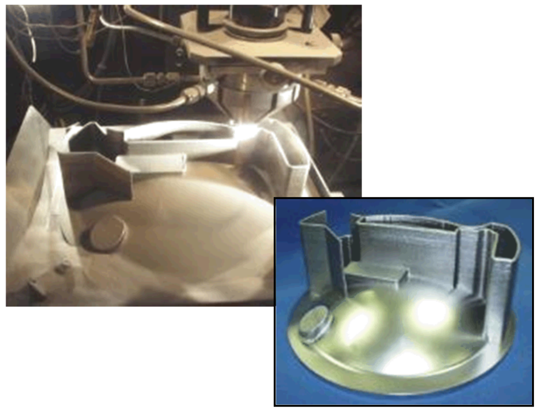
- A National Security Science & Engineering Laboratory
  - “Exceptional service in the national interest”
- Nuclear Weapons
- Defense Systems & Assessments
- Energy & Climate
- International, Homeland, & Nuclear Security

Sandia Has a Long, Rich History in AM

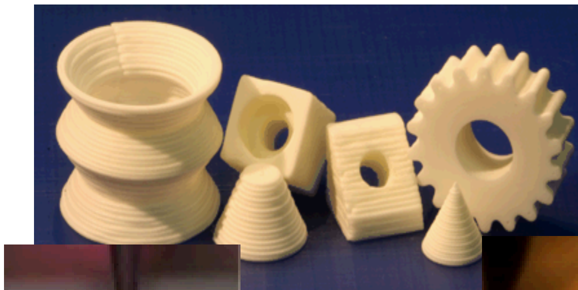
- 30+ yrs of pioneering AM tech development & commercialization

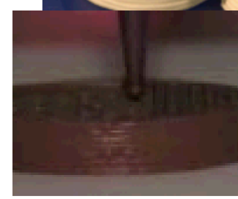
FastCast*
prototype test unit

LENS®*
fireset housing

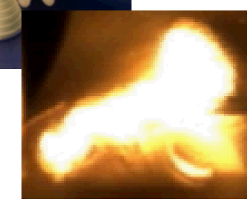


RoboCast*
ceramic parts

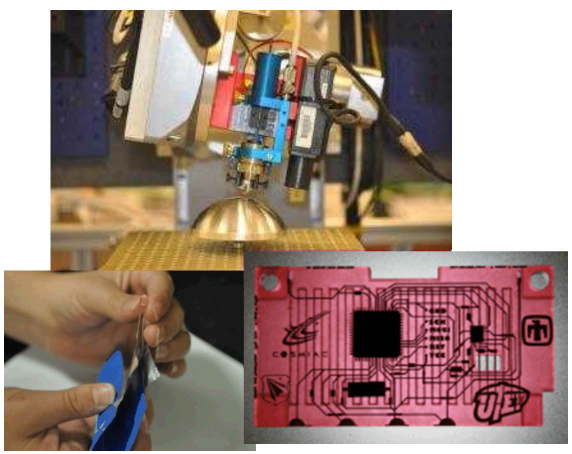




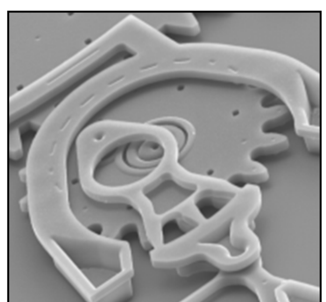
energetic materials



Direct Write
conformal electronics

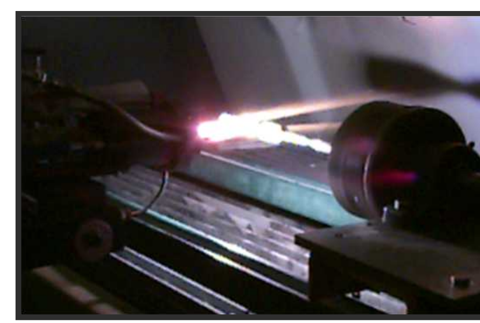


MEMS SUMMIT™*
micro gear assembly



LIGA
"Hurricane" spring

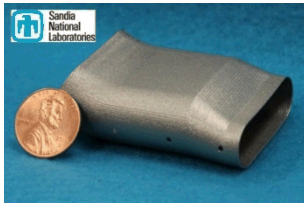
Spray Forming
rocket nozzle



* licensed/commercialized technology

SNL Additive Manufacturing Strategy

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

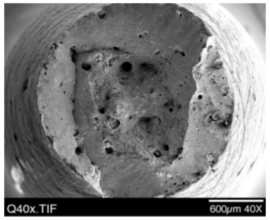


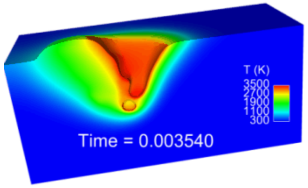
5 Strategic Thrust Areas

Existing SNL Expertise, Capabilities, & Partnerships in Additive Mfg.

- *Identify Compelling Applications*
- *Provide Design/Analysis Tools*
- *Provide Materials Assurance*
- *Enable Engineered/Multi- Material AM*
- *Enable Product Realization*

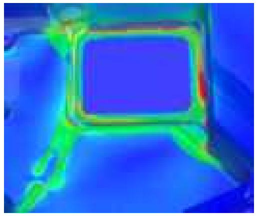
Deliver innovative, revolutionary national security products enabled by AM technology



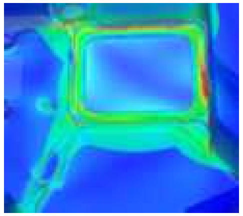


SNL’s Additive Interest

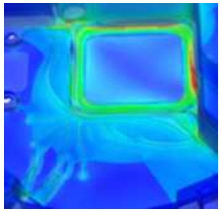
- Reduce risk & accelerate development
  - simplify assembly & processing
  - produce multiple designs simultaneously
  - prototypes, test hardware, tooling & fixturing
    - > 100 plastic machines
    - cost reductions often 2-10x
- Add value
  - non-traditional geometries (ex. internal)
  - design & optimize for performance, not mfg
  - engineered materials
    - gradient compositions
    - microstructure optimization & control
    - multi-material integration
  - topologically optimize for performance & constraints



+ 0.55% volume
- 52% deflection

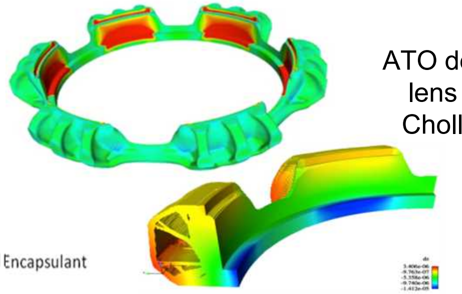


+ 1.1% volume
- 56% deflection

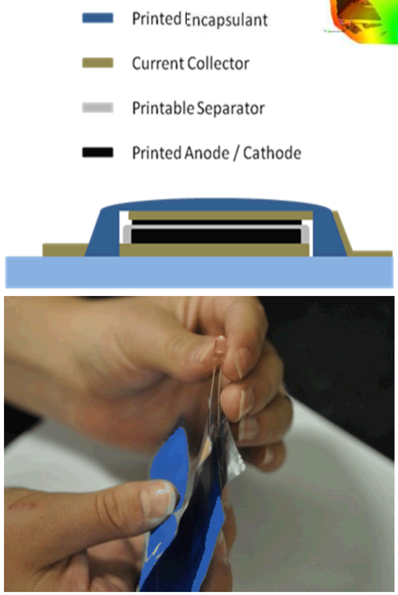


+ 3.3% volume
- 64% deflection

design optimization



ATO designed and built lens mount, SNL Ti Cholla LDRD (2005-2008)

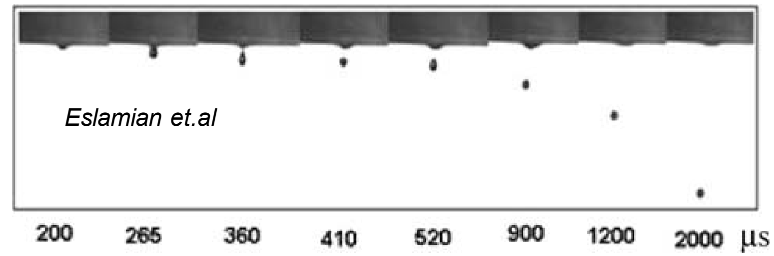


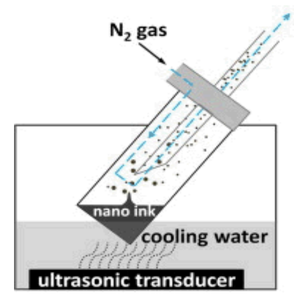
printed battery

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

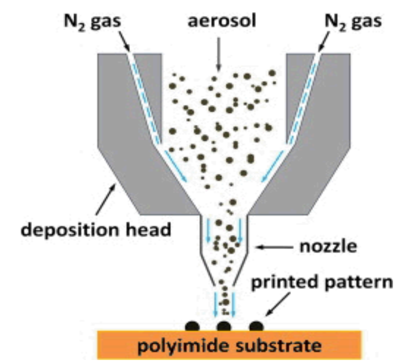
Direct Write

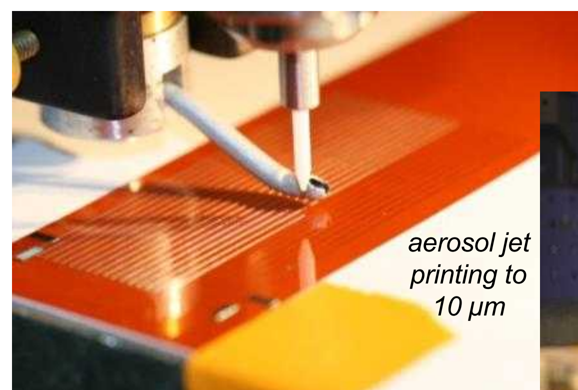
- Ink jet
  - discrete droplets produce continuous line segments
  - line width a function of droplet size
    - diameter: 18-635 µm
  - material viscosity: 1-1x10^6 cPs
- Aerosol jet
  - ink atomized to produce dense aerosol mist
  - aerosol focused w/inert gas streams & small nozzle
  - Ag: 10 µm line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

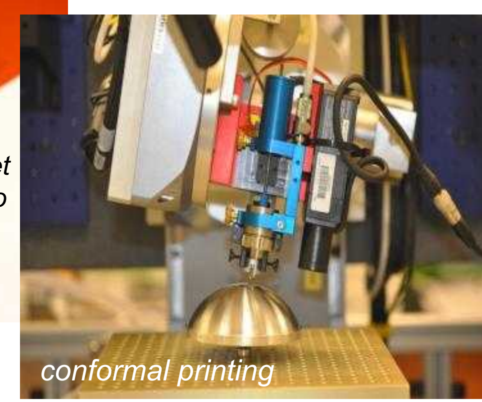




Zhao et. at

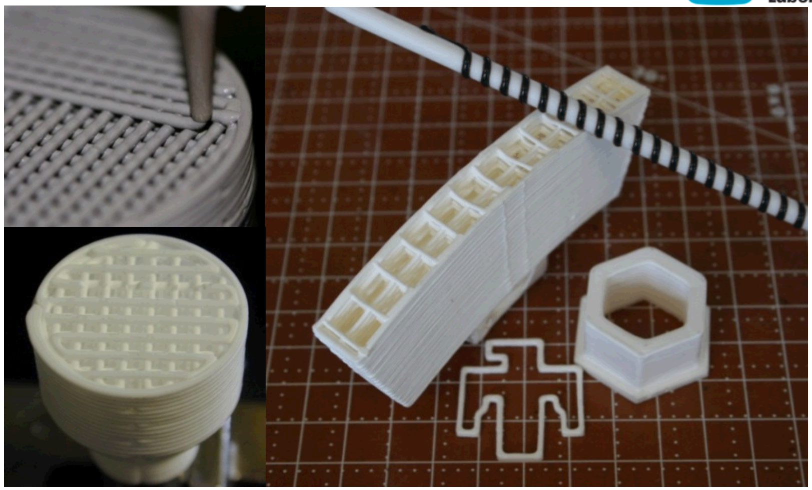




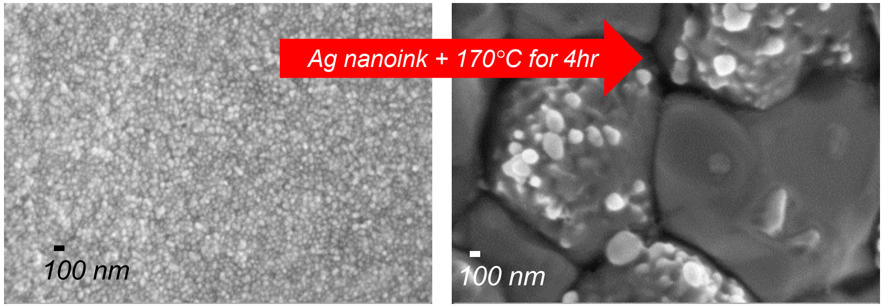


Direct Write

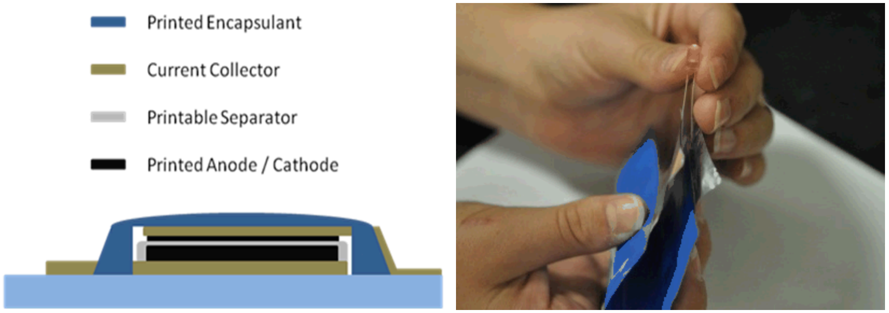
- Materials
  - epoxies, silicones, dielectrics, ceramics, energetics
  - nano-inks: metallic, polymeric, multi-phase
  - material formulation, synthesis & characterization
  - substrates: plastics, ceramics, polyimide, encapsulants, metals, FR4, glass, paper
- Sintering / curing
  - thermal, joule heating,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



extrusion casting (Robocasting)



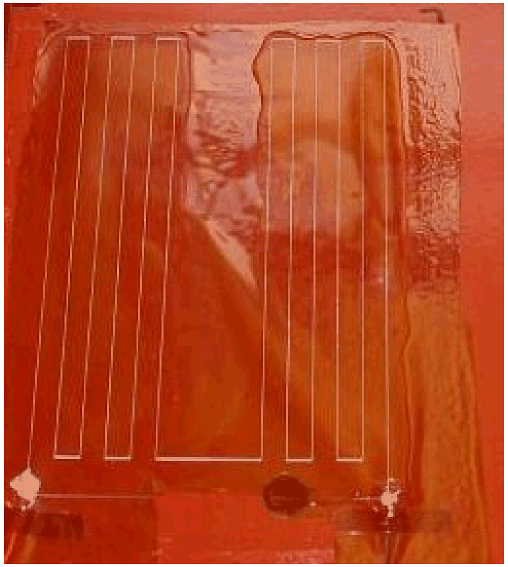
sintering of Ag nanoinks for conductive pathways



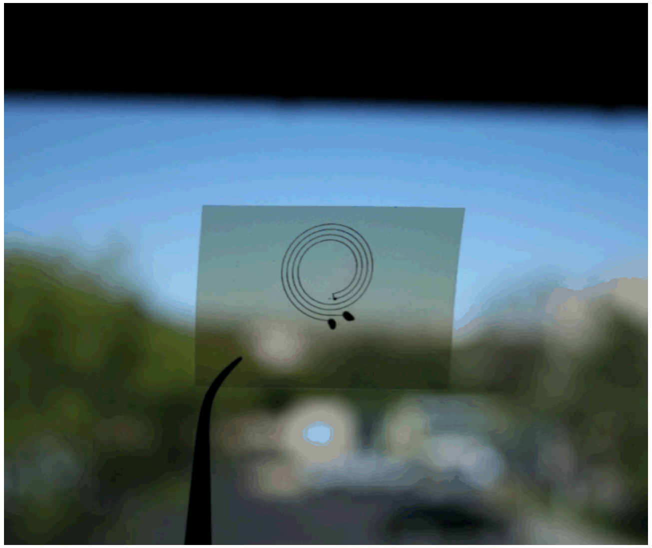
printed battery

Recent Activities

Sandia National Laboratories

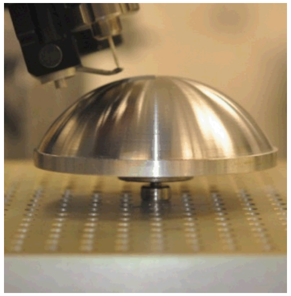


Ag traces on powdercoat with overcoat

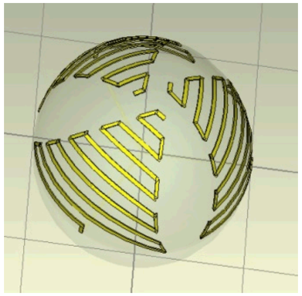


room temperature cure of conductive traces on polymer film

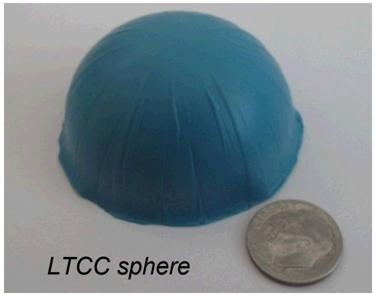
DW circuit fabrication



6-axis platform

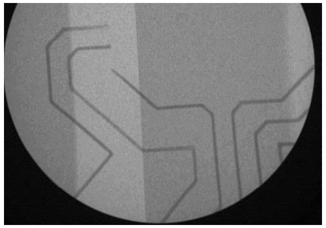


path planning

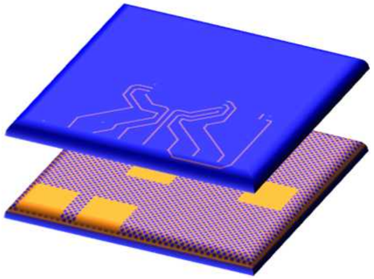


LTCC sphere

conformal printing



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



multi level circuit concept

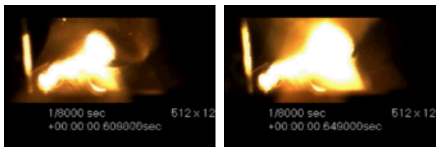
thick film low temperature co-fired ceramic

Energetic Materials

Sandia National Laboratories

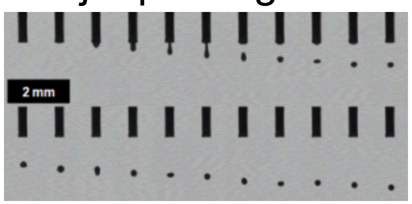
Robocasting

Aluminum/Nickel reactive material

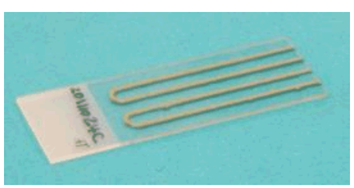


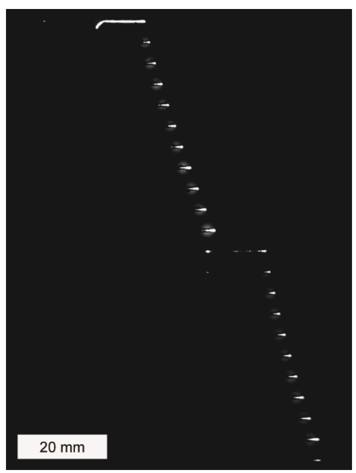
Tappan, A.S., Groven, L.J., Ball, J.P., Miller, J.C., Colovos, J.W., Joseph Cesarano, I., Stuecker, J.N., and Clem, P., "LDRD Final Report: Free-Form Fabrication and Precision Deposition of Energetic Materials," SAND2008-0965, February, 2008.

Inkjet printing



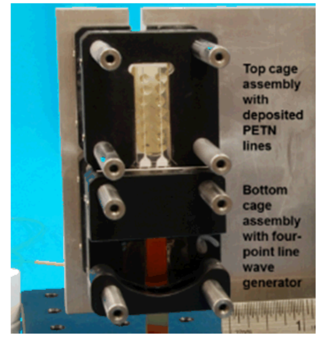
Aluminum/bismuth trioxide thermite

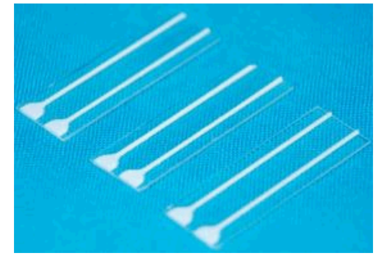




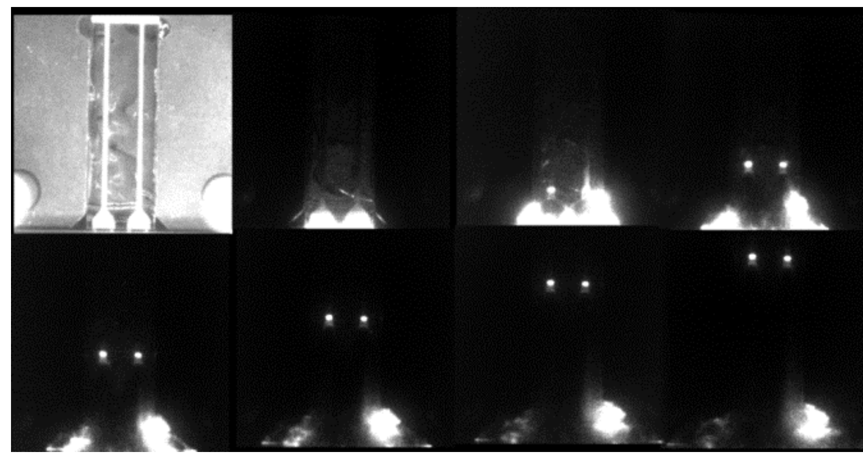
Tappan, A.S., Ball, J.P., and Colovos, J.W., "Inkjet Printing of Energetic Materials: Al/MoO3 and Al/Bi2O3 Thermite," *The 38th International Pyrotechnics Seminar*, Denver, CO, June 10–15, 2012.

Physical vapor deposition





Pentaerythritol tetranitrate high explosive

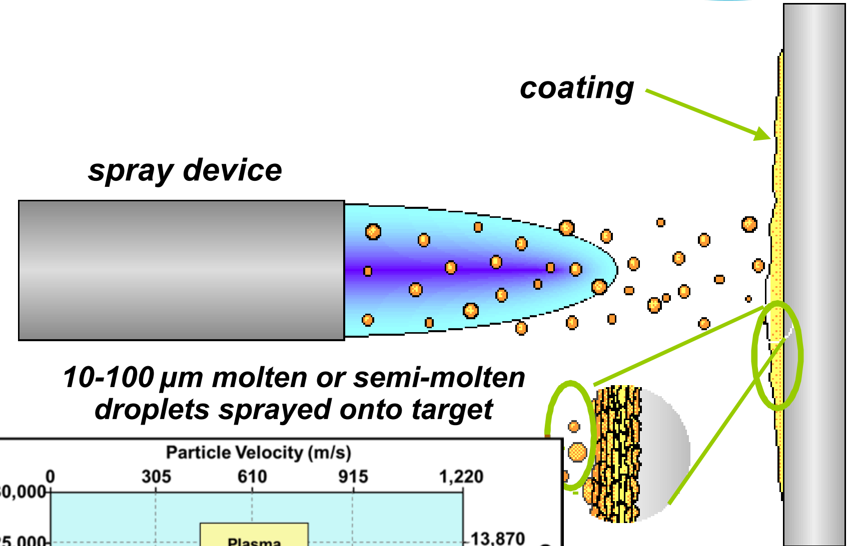


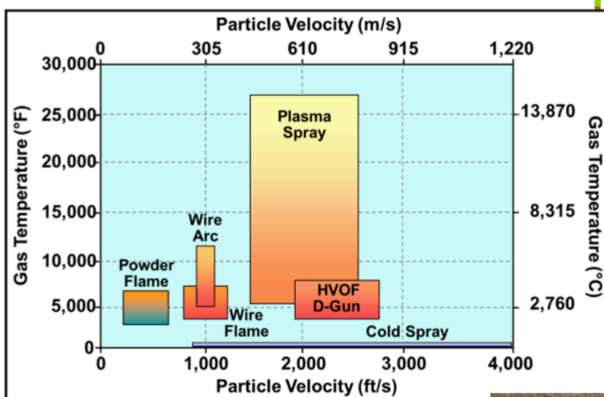
Tappan, A.S., Knepper, R., Wixom, R.R., Marquez, M.P., Miller, J.C., and Ball, J.P., "Critical Thickness Measurements in Vapor-Deposited Pentaerythritol Tetranitrate (PETN) Films," *14th International Detonation Symposium*, Coeur d'Alene, ID, April 11-16, 2010.

- Different materials and applications require different techniques

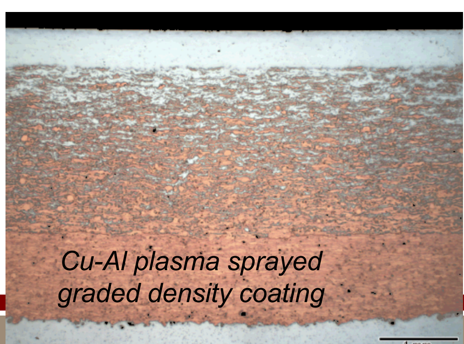
Thermal Spray

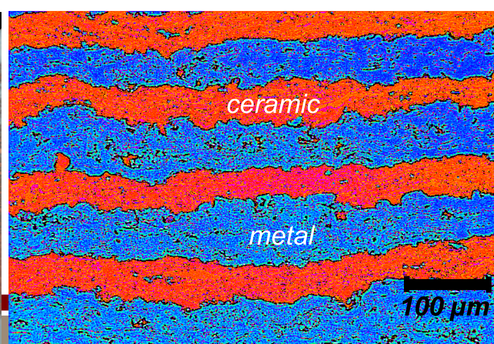
- SNL has all 7 major technologies
  - plasma spray (atmosphere, vacuum), twin wire arc spray, powder flame spray, wire flame spray, cold spray, high velocity oxy-fuel
- Advantages
  - large material set (anything that melts)
    - pure metals, most alloys, traditional ceramics, cermet, carbides, polymer, 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

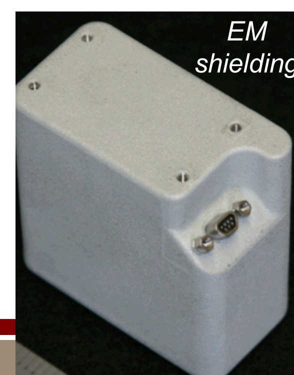


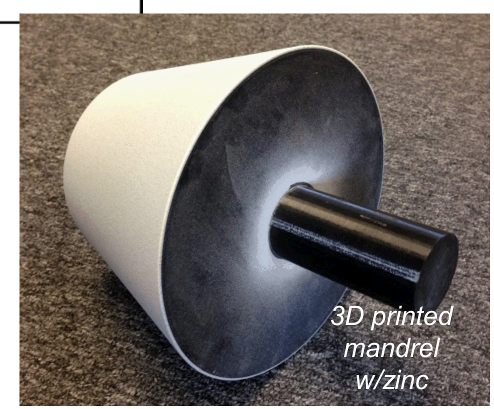


*Adapted from plots by R.C. McCune, Ford Motor Co. & A. Papyrin, Ktech Corp.







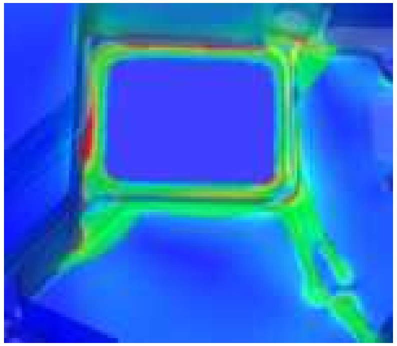


Design Optimization

- Adaptive topological optimization (ATO)
  - computational synthesis for optimized material use
    - leverages that “complexity is free”
    - constrained by performance requirements
    - design occurs concurrent w/performance predictions
  - requires parallel supercomputer processing
- Solutions resemble natural structures (bio-mimicry) & require AM to realize

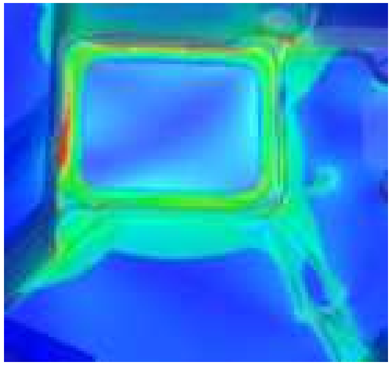
solution for a bar in pure torsion resembles a cholla cactus

from Ti-Cholla LDRD (2005-2008)

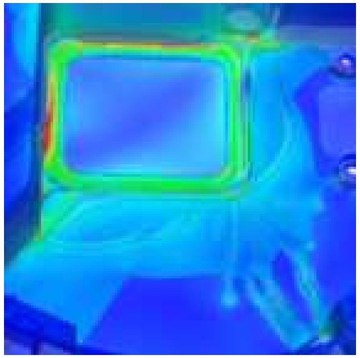


+ 0.55% volume
- 52% deflection

+ 1.1% volume
- 56% deflection



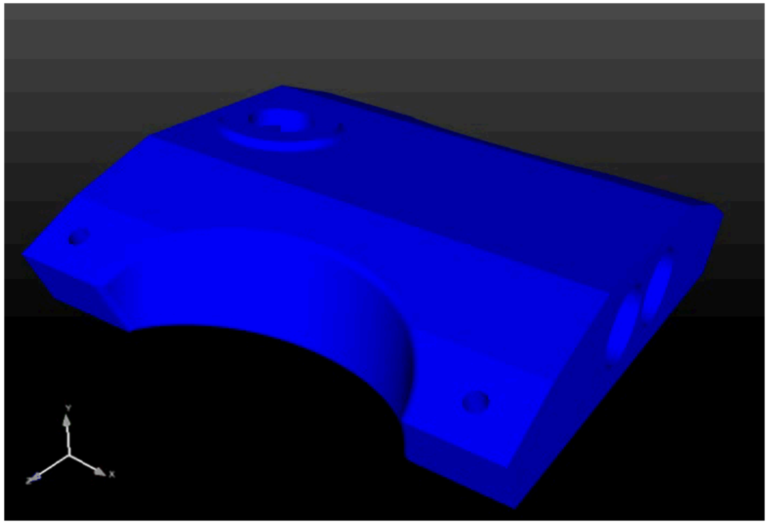
+ 3.3% volume
- 64% deflection

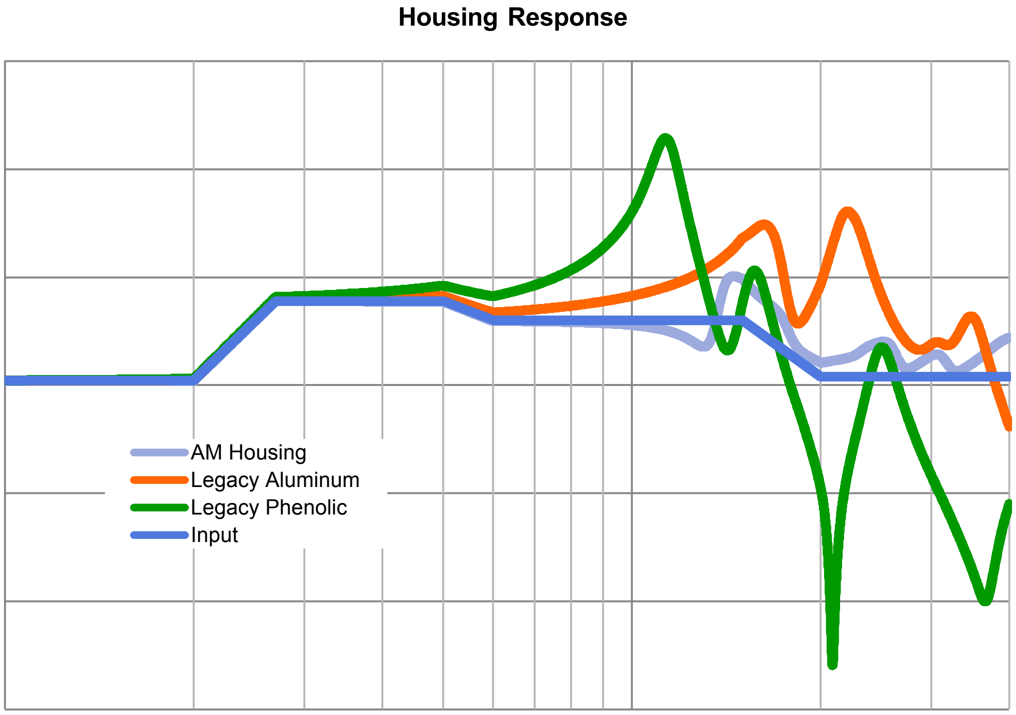


elasto-static stiffness optimization

Optimization Impact

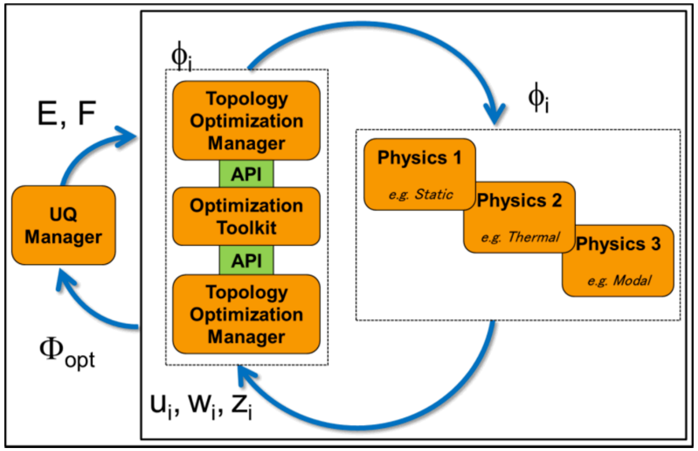
Optimized design (using same mass and material, i.e., carbon phenolic) achieves 39% average increase in modes of interest, compared to 23% increase achieved by printing original design in aluminum.



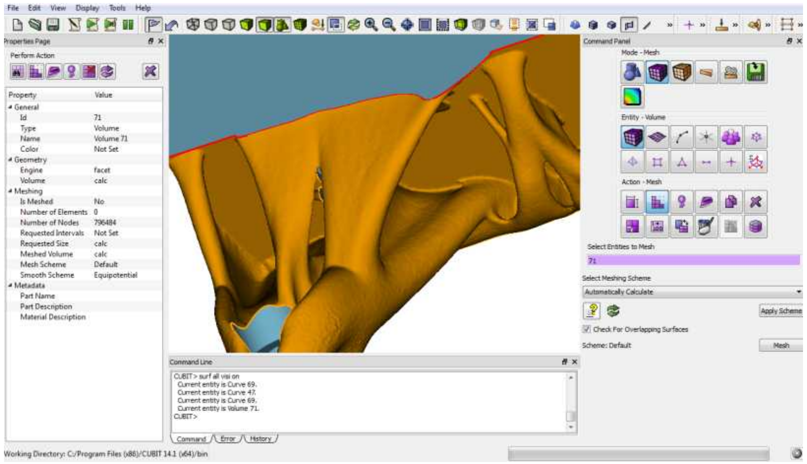


Optimization Design Environment

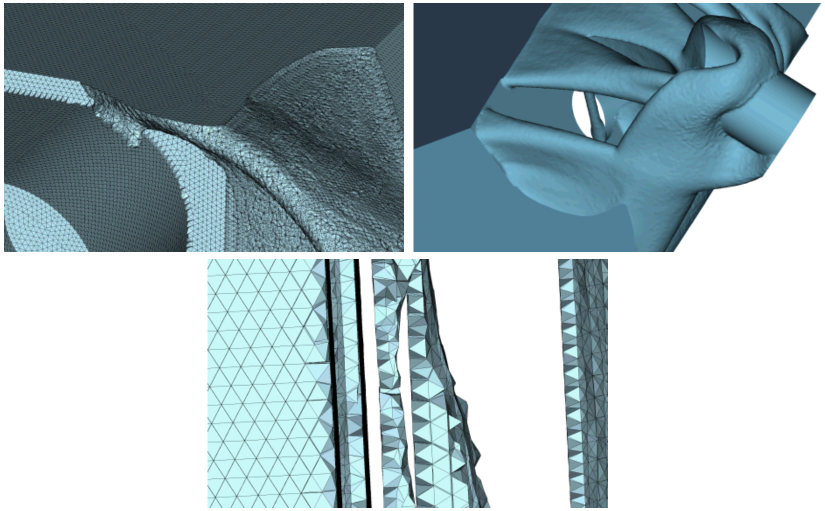
- Algorithms
  - multi-physics
  - integration w/process modeling & process planning
- Usability
  - validation, intervention, data formats, model size, computing power



optimization scheme

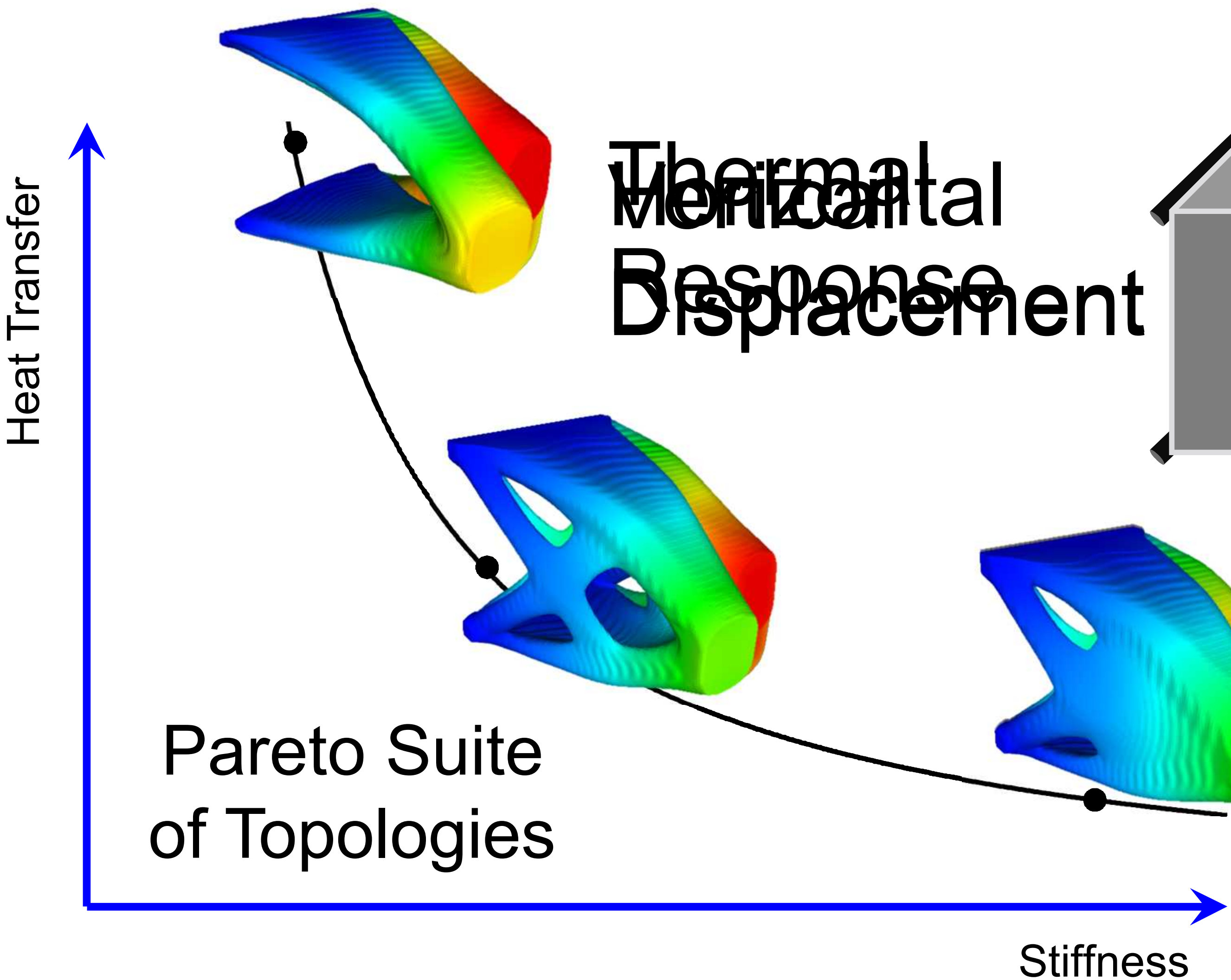


user interface



geometry cleanup & intervention

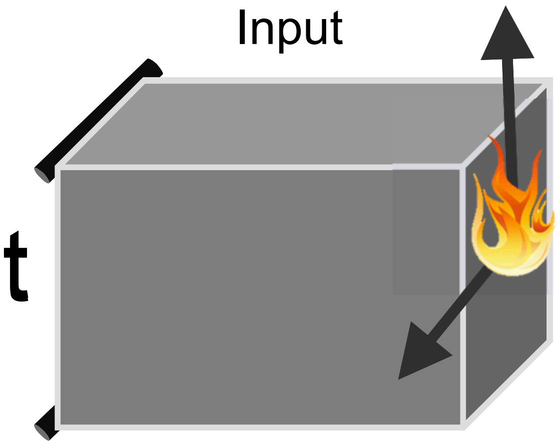
Inversion of Design



Thermal Response

Vertical Displacement

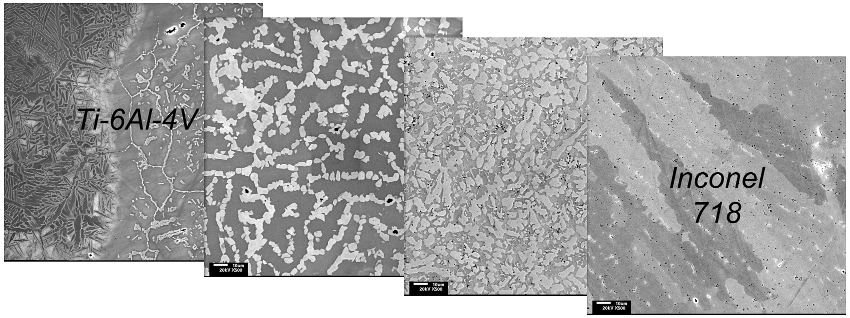
Horizontal Displacement



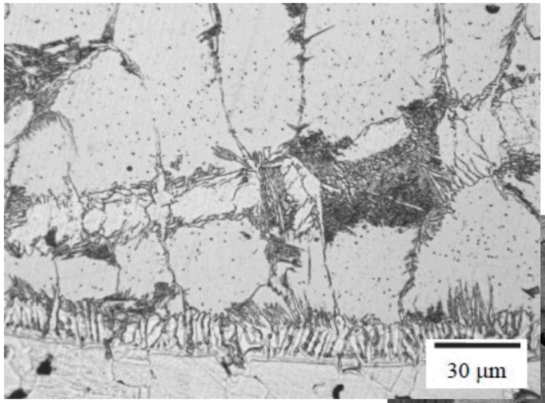
Materials Challenge of Additive

- Material formation concurrent w/geometry
  - opportunity = engineered materials
  - risks abound
    - properties, microstructure, defects, composition…
    - feedstock certs inadequate to quantify material or part performance
    - ex-situ evaluation is too slow, too expensive, too inaccurate & too late
    - must understand the behavior & formation of *critical* defects

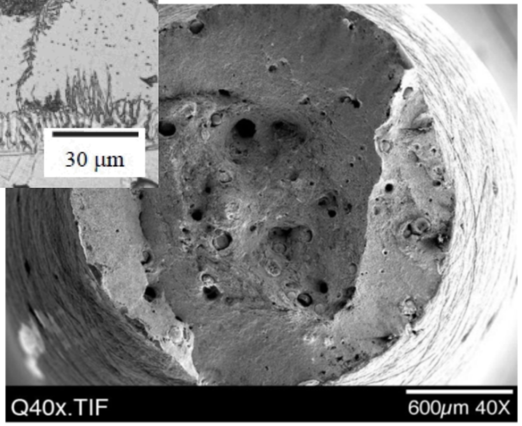
- Processes
  - equipment predominantly open loop
    - acceptable for large material margins
  - in-situ monitoring is becoming available
    - enables some in-situ defect detection
    - moderate margins, but potentially low yields
  - high performance applications
    - current uncertainties are unacceptable
    - industry leaders agree the problem remains



LENS® functionally graded materials



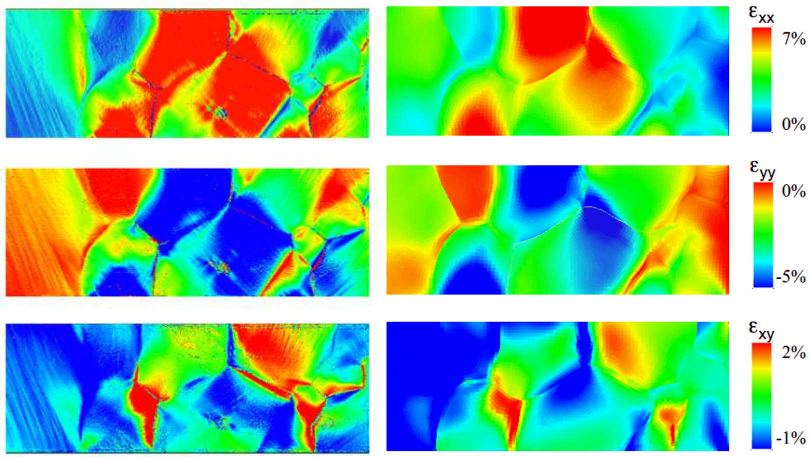
DMLS 316L SS, Brytan



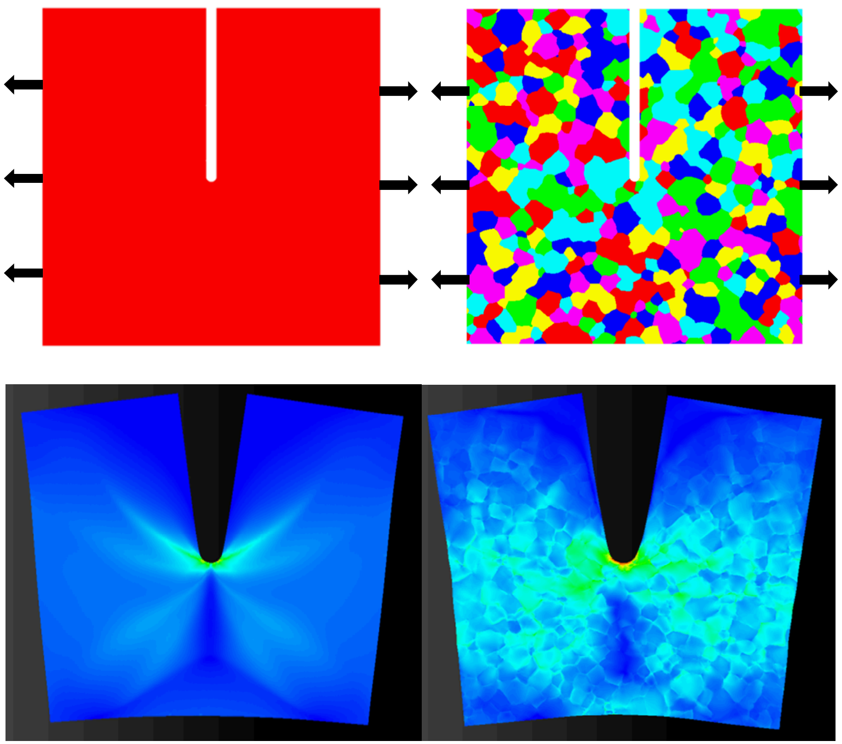
ductile fracture initiated by LENS® defects in PH13-8Mo, Smugeresky

Modeling Microstructure & Behavior

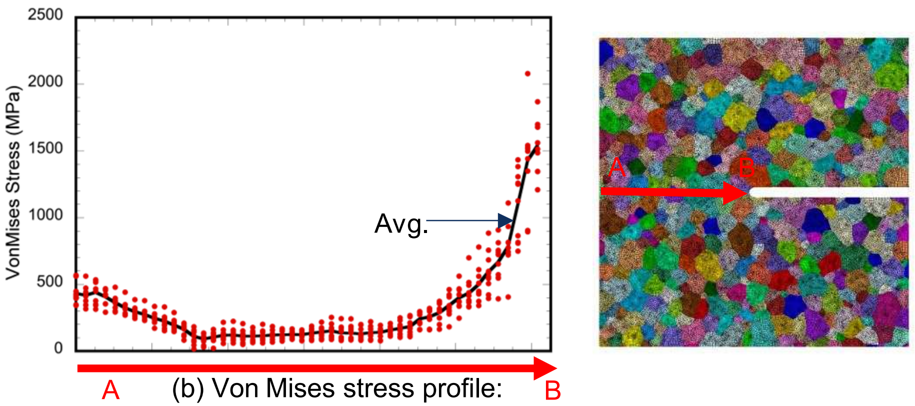
Oligocrystal experiments vs. crystal plasticity models (tensile loading)



DIC measurements *simulations*



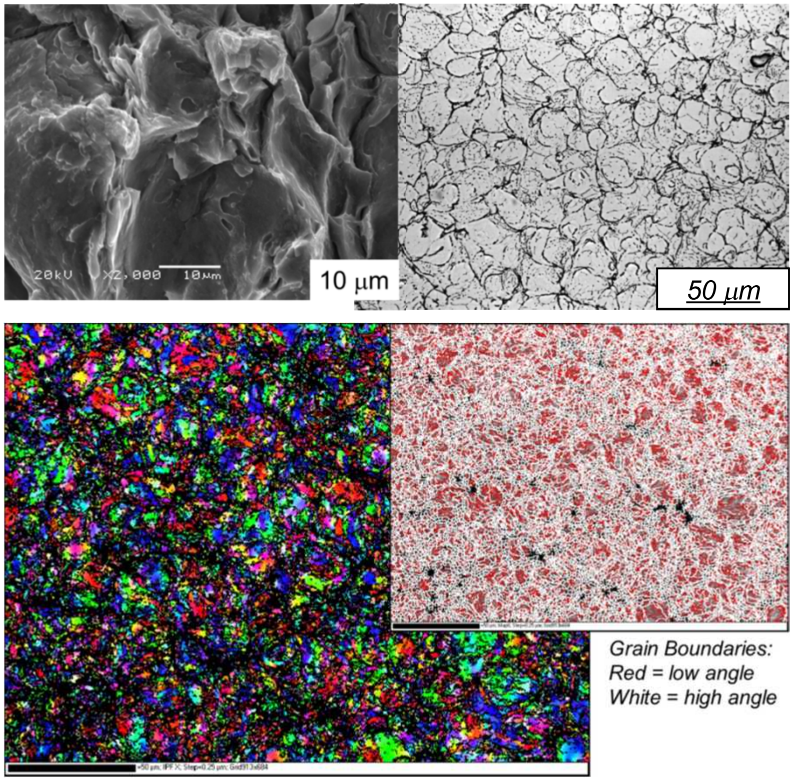
(a) Von Mises stress distributions: single crystal vs. polycrystal



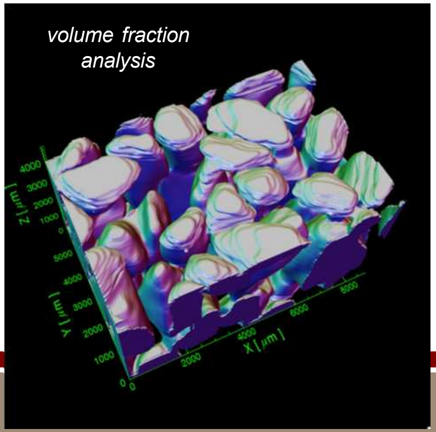
(b) Von Mises stress profile: 10 random polycrystal simulations

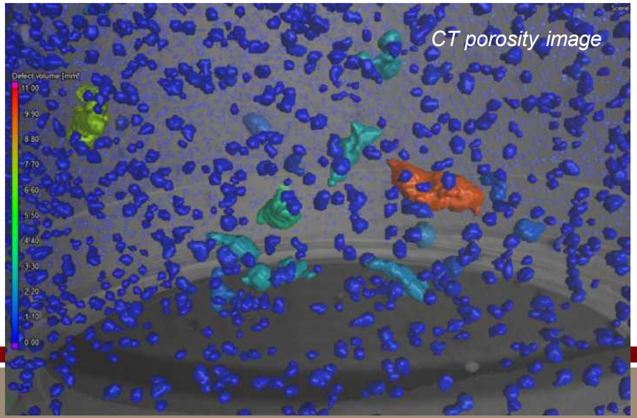
Material Characterization

- 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



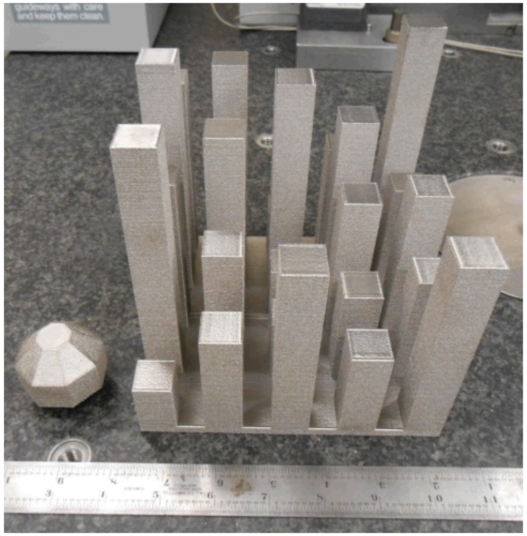
pure Al cold spray coating



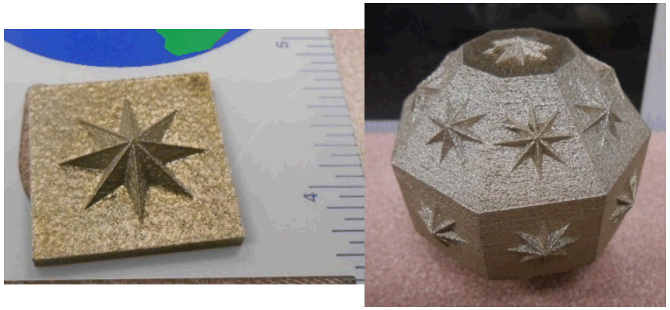


Metrology Artifacts

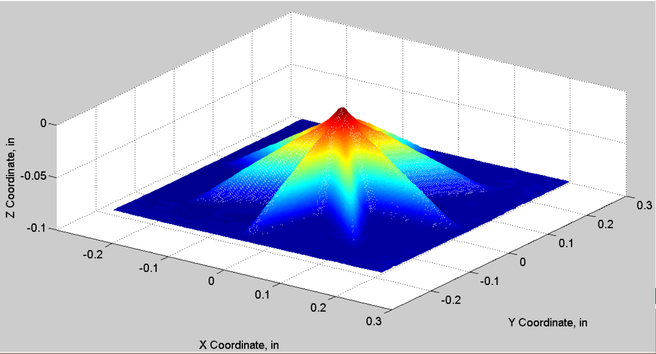
- Unique challenges for process & equipment characterization
  - part geometry = function (material, print orientation, support structures, post-processing,…)
  - equipment generally exceeds process
- Family of artifacts designed, printed & measured
  - fabrication has been easier than metrology
  -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

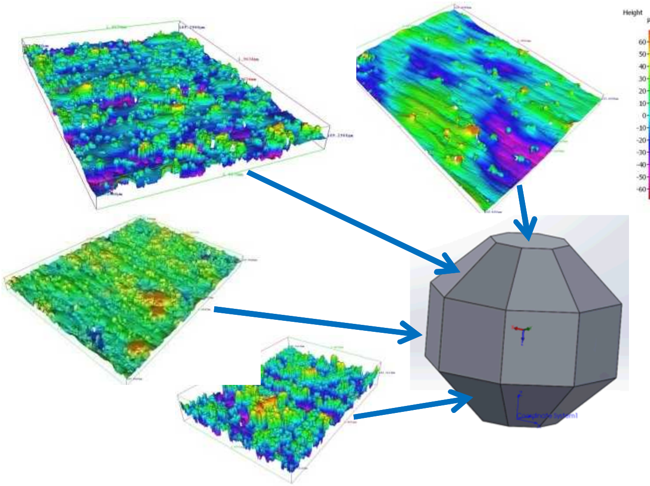


Ti-6Al-4V polyhedron & "Manhattan" artifacts for MPE (maximum permissible error)

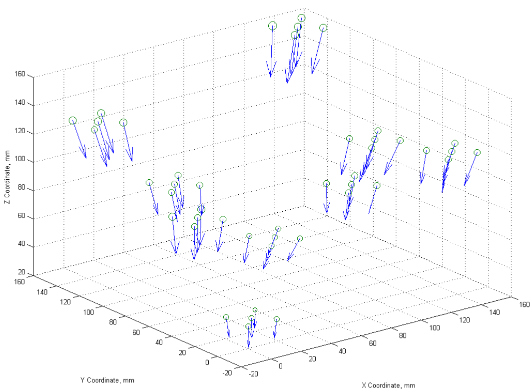


Siemens star geometries for resolution evaluation





17-4PH polyhedron texture anisotropy map

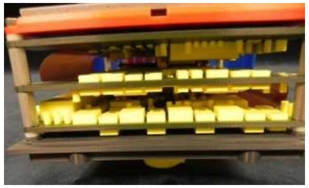


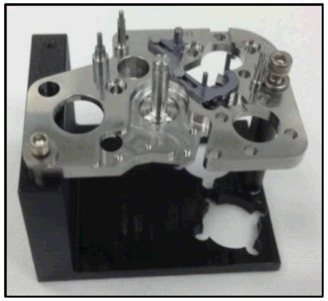
Ti "Manhattan" error map

Product Design & Development

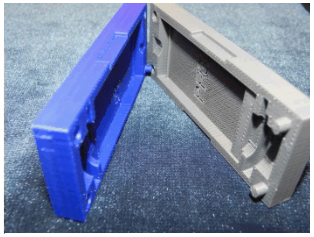
Sandia National Laboratories

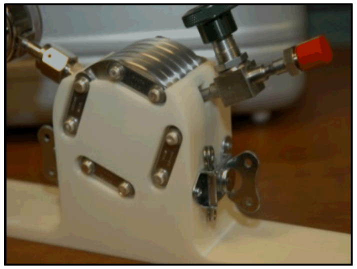
- Enables innovation throughout lifecycle
  - conceptual, communication of intent, fit & form validation, assembly procedures, tooling and fixtures, flight testing, education and training, production
- Over 100 plastic AM machines at SNL
  - saves time & money, adds design freedom
  - 2 plastic machines, estimated >$1M saving in FY13 for development activities
  - >50% cost savings in FY14 tooling

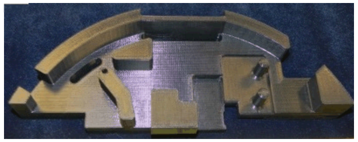

Simulated circuit boards


Fixture generated in 1 day

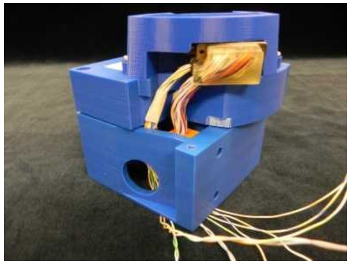

Flexible materials


Shipping container


Printed tooling (white part)


Protective cover


Full-scale systems

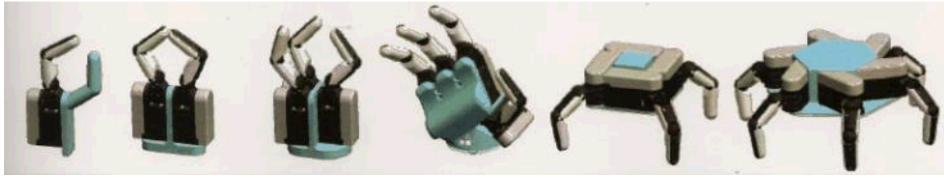

Jig for cable design

Cable routing

Sandia Hand

- Additive
  - helped reduce cost (~$250k vs. $10k)
  - enabled rapid design iterations
  - 50% of hand built with AM
- Potential applications include bomb disablement
- Current version includes "touch" sensors

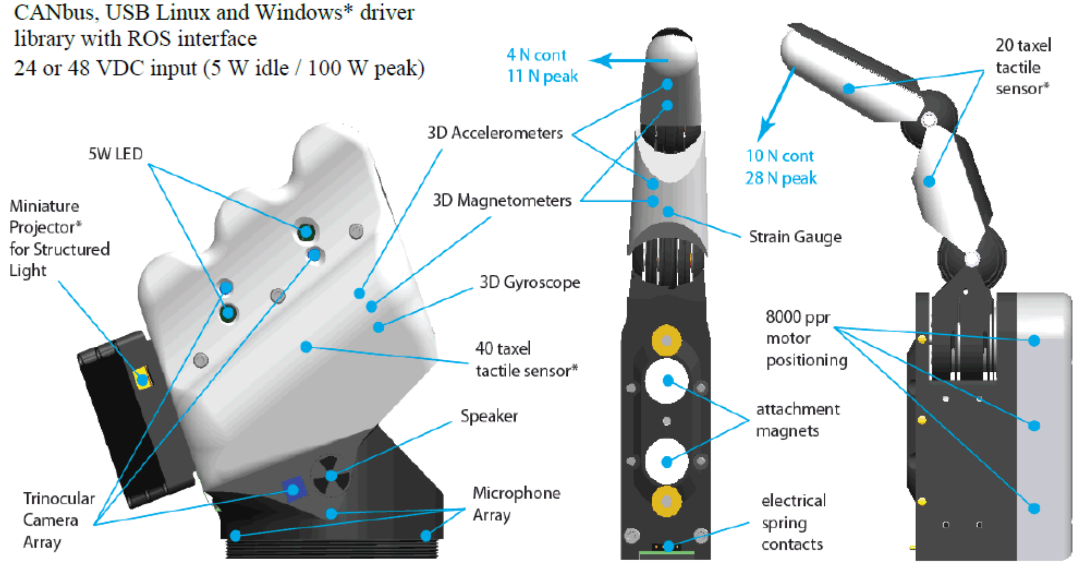
Fingers or other tools (e.g., drills) can be quickly magnetically attached in many configurations



Features and Specifications

*coming soon

- Connectivity: 10/100/1000 Ethernet, CANbus, USB Linux and Windows* driver library with ROS interface
- 24 or 48 VDC input (5 W idle / 100 W peak)



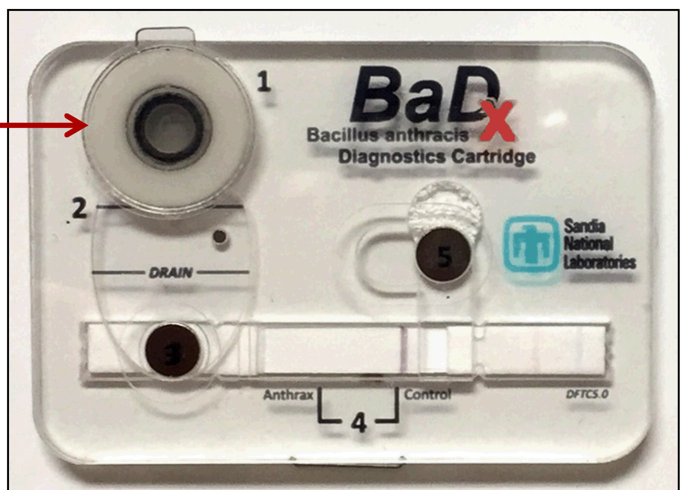
BaDx Diagnostics Tool

Sandia National Laboratories

- Microfluidic platform for bacterial detection preparaed 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

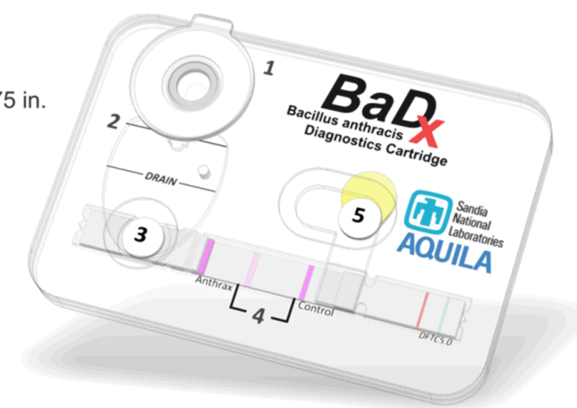
SNL Scientists Jason Harper, Melissa Finley, and Thayne Edwards

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.

Challenges as Opportunities

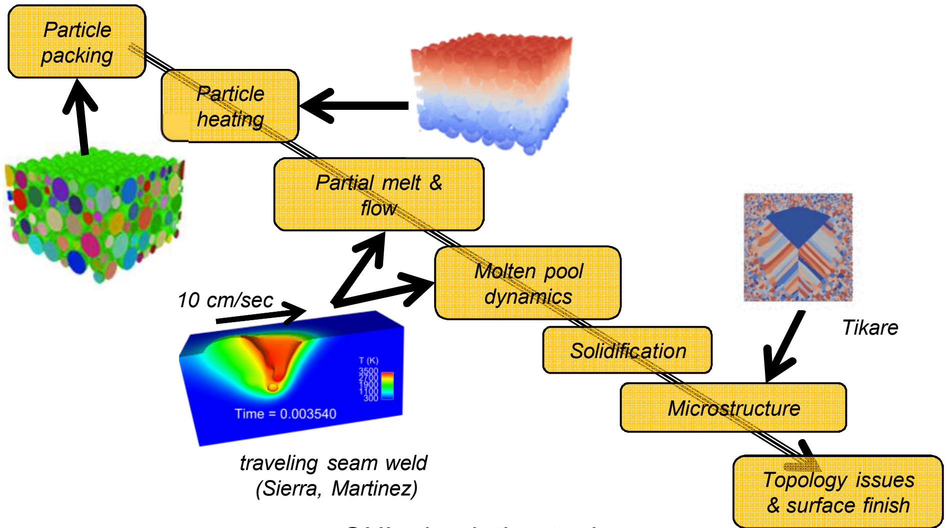
- Train CAD designers & engineers to think about design in new ways
- Overcome current CAD tool constraints which are based on traditional manufacturing methods
- Accommodate legacy processes based on 2D part definition drawings
- Explore & validate model-based definition & qualification
- Confront existing cultural barriers & resistance to new manufacturing processes & methods
- Simplify accessibility to 3D printing technology

Backup Slides

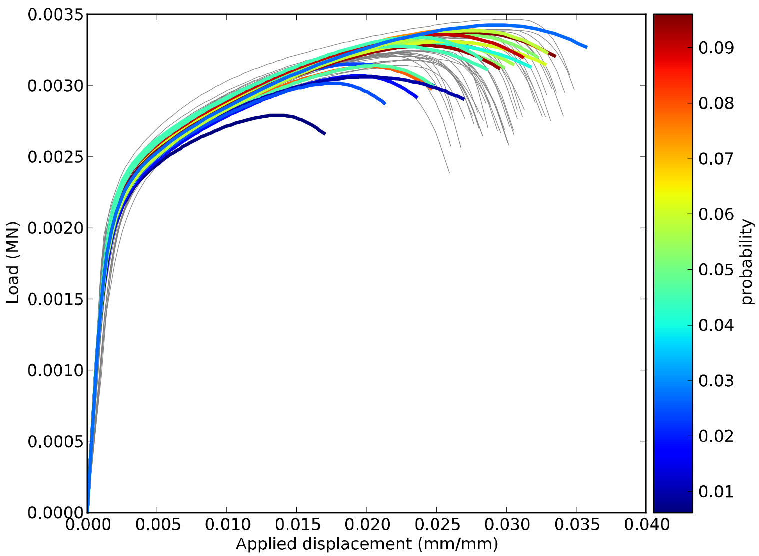
Sandia National Laboratories

Application of Modeling & Simulation

- Process
  - leverage laser welding
    - reduce experimentation
  - defect formation
    - laser-material interaction
    - discrete particle physics
  - industry gaps
    - process -> structure relationships
    - defect formation
    - process limits
- Defect impact
  - utilize DNS to explore uncertainty quantification (UQ)
  - predict response from stochastic process knowledge



SNL simulation tools

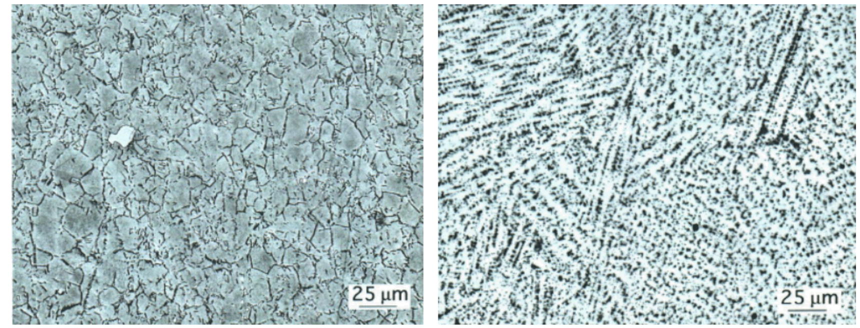


predicted (color) vs. measured (grey) response for welds

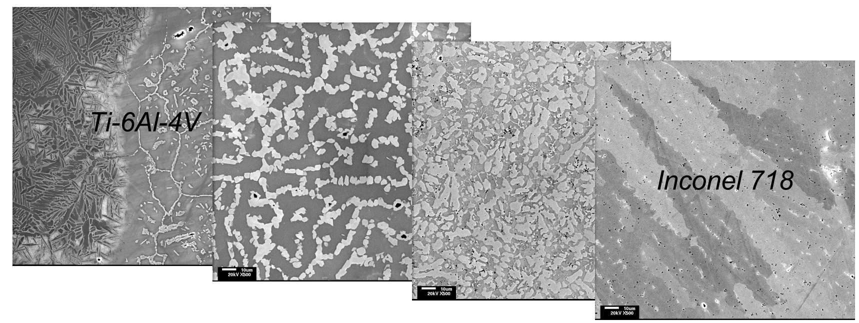
Laser Engineered Net Shaping (LENS®)

Sandia National Laboratories

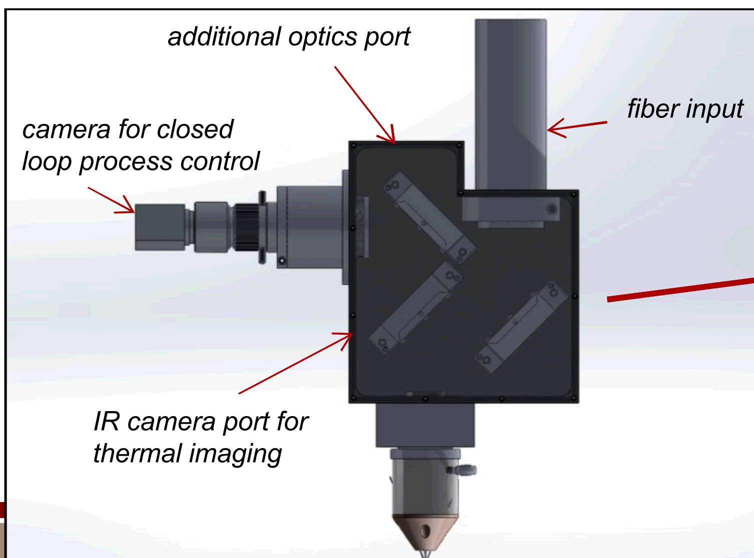
- Historical
  - licensed to Optomec
  - extensive SNL development efforts & investments
  - foundation for metal additive research
- Custom research machine
  - re-establishing & expanding capability
    - additive & subtractive
    - deposition head designed for process diagnostics & feedback
  - leveraging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

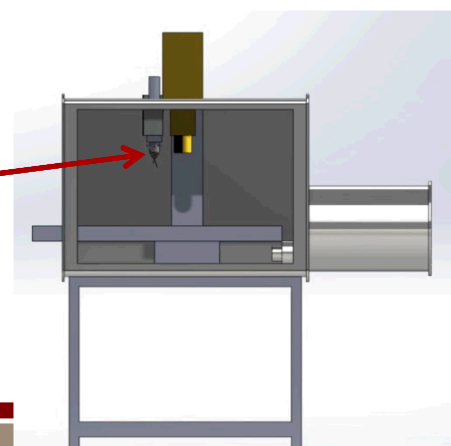


typical *316 stainless steel* *LENS*

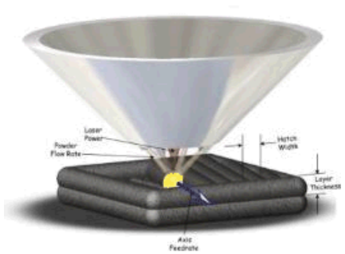


LENS functionally graded materials

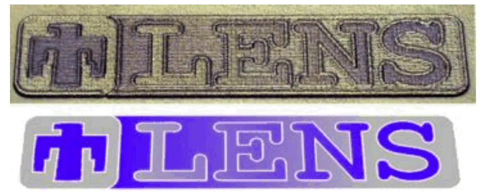




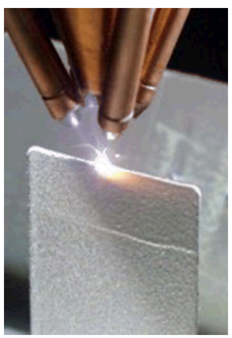
Prior LENS® Research

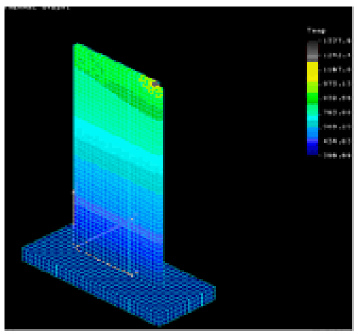


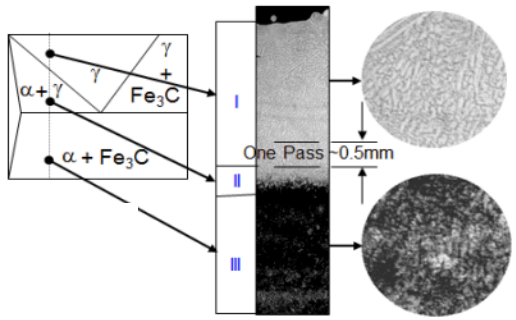
Graded composition demonstration



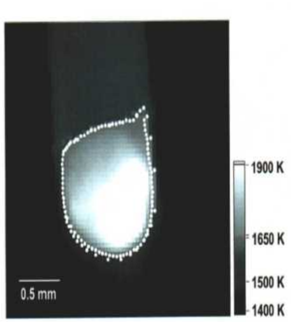
Process characterization/modeling

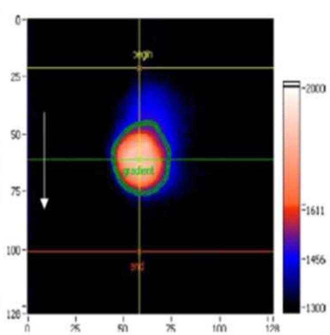






Part heats up during the build & heat flow changes -- so microstructure & properties in the top (I), middle (II), & base (III) of the part differ





Closed-loop process control

melt pool -> microstructure

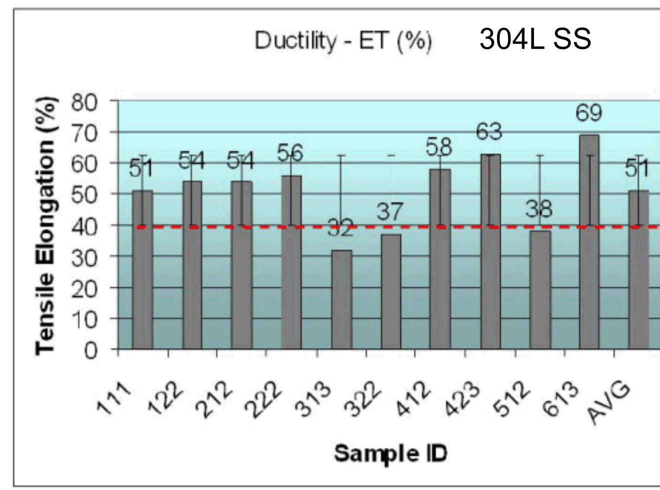
Variety of LENS® metals

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