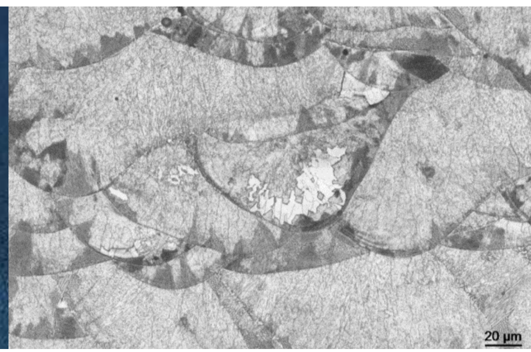
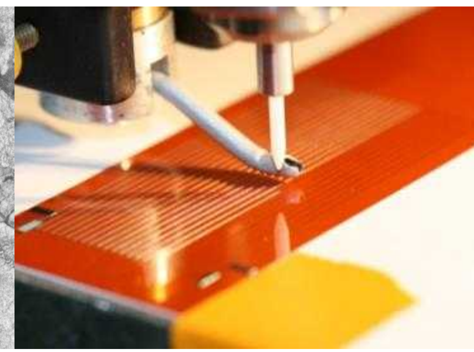
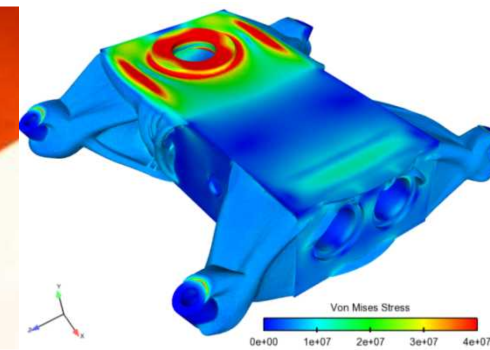
SAND2016-3212PE

Exceptional service in the national interest

Sandia National Laboratories

Additive Manufacturing at Sandia National Laboratories

Bradley Jared, PhD

Materials Science & Engineering Center

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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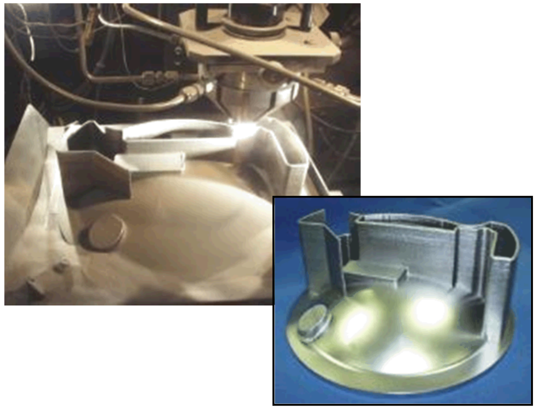
Sandia Has a Long History in AM

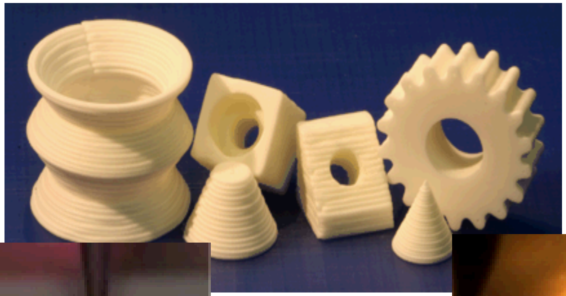
- 30+ yrs of pioneering AM tech development & commercialization

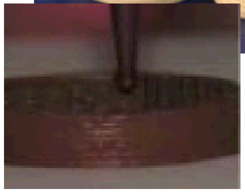
FastCast*
prototype test unit

LENS®*
fireset housing



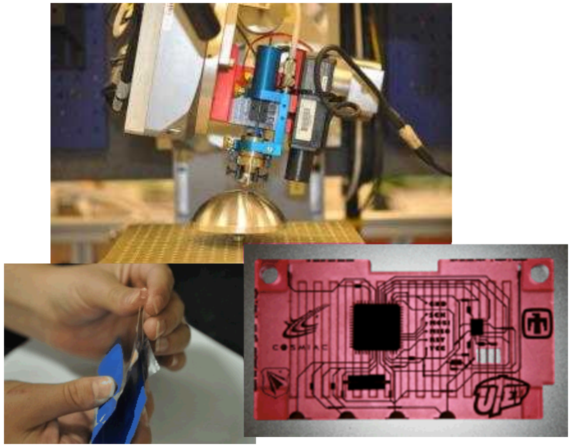
RoboCast*
ceramic parts



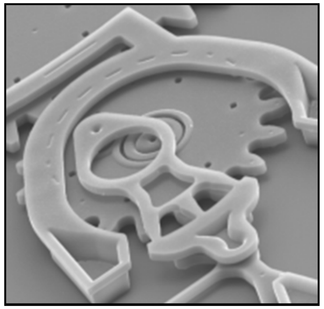


energetic materials

Direct Write
conformal electronics

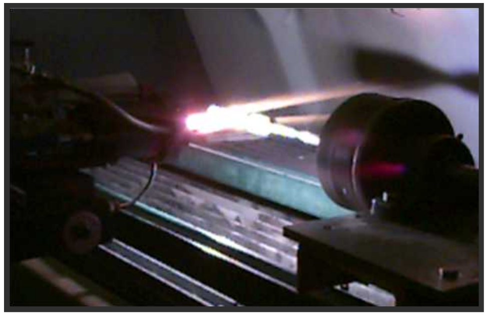


MEMS SUMMIT™*
micro gear assembly



LIGA
“Hurricane” spring

Spray Forming
rocket nozzle

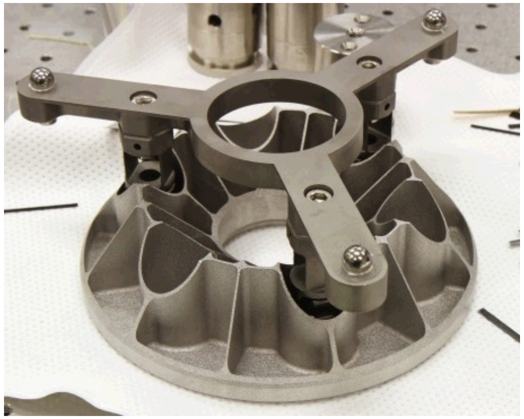


* licensed/commercialized technology

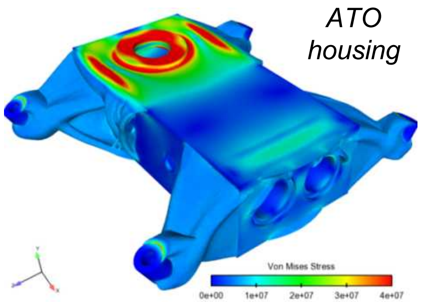
SNL’s Additive Interest

- 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

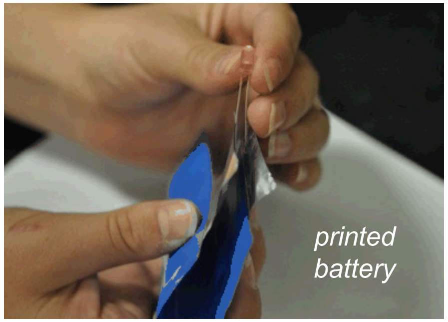
Sandia Hand, 50% built w/AM, cost ~$10k



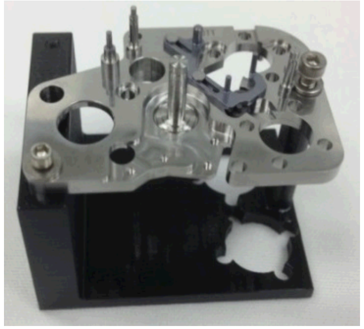
prototype Al AM mirror & structure



ATO housing



printed battery



fixture generated in 1 day

SNL's Additive Strategy

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

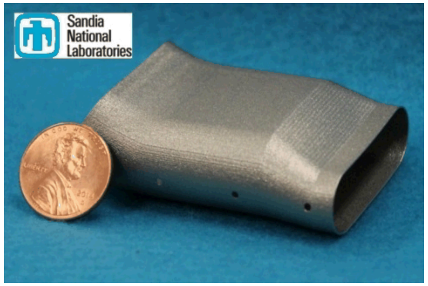
Enable Engineered/Multi-Material AM

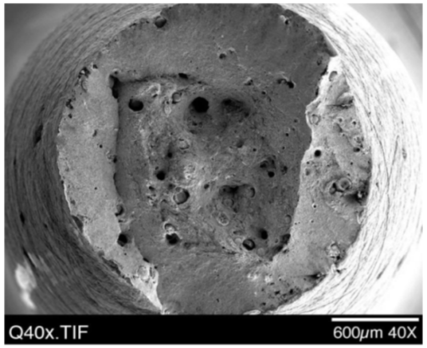
Enable Product Realization

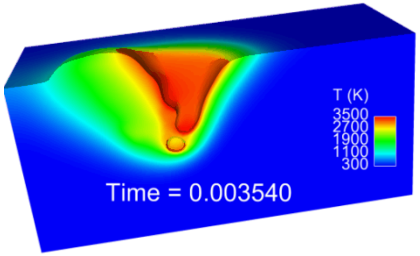
Tomorrow

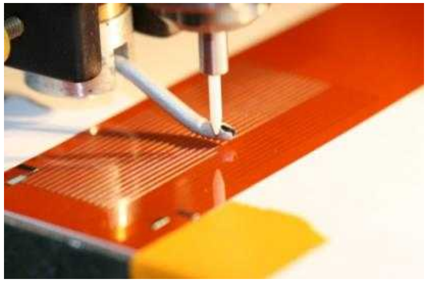
Deliver innovative, revolutionary national security products enabled by AM technology .

5 Strategic Thrust Areas



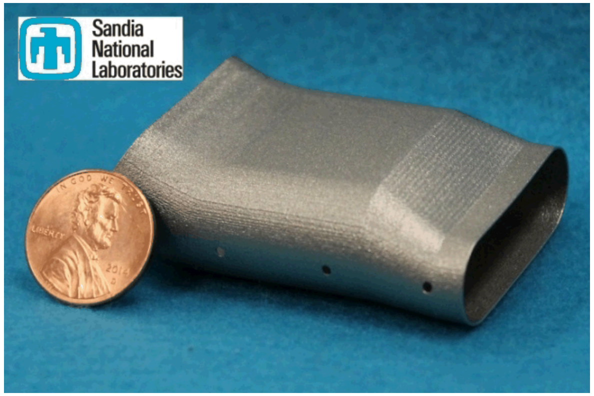


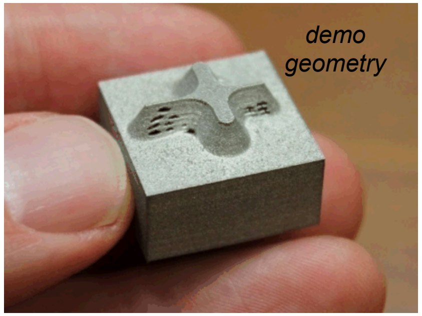




Metal Powder Bed Fusion

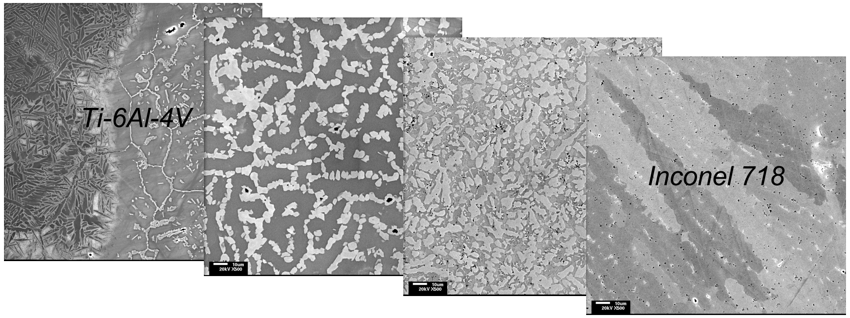
- Growing activity exploring metal parts
  - existing components, future systems
  - process characterization
  - leveraging NSC & external vendors
- 3D Systems (Phenix) machine purchases
  - two ProX 300, one ProX 200
  - motivations
    - roller-wiper powder compression
      - spherical & non-spherical powders, 1 µm minimum
      - 10 µm layer thickness, 100 µm features
      - metal (any with <3% C content), ceramic (alumina, cermet, WC)
      - claim 99.9% dense metals
      - 90% dense ceramics, 10 µm finish
    - process flexibility – open architecture controller, semi-automated clamping & chucking



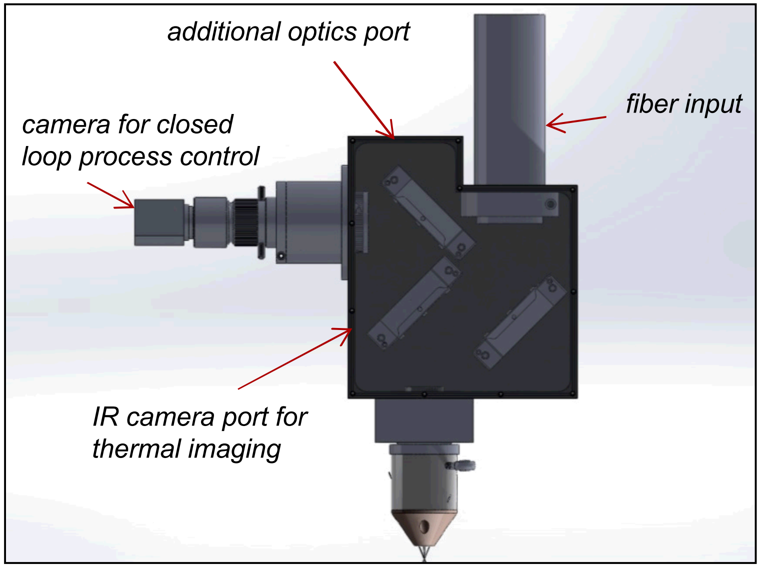


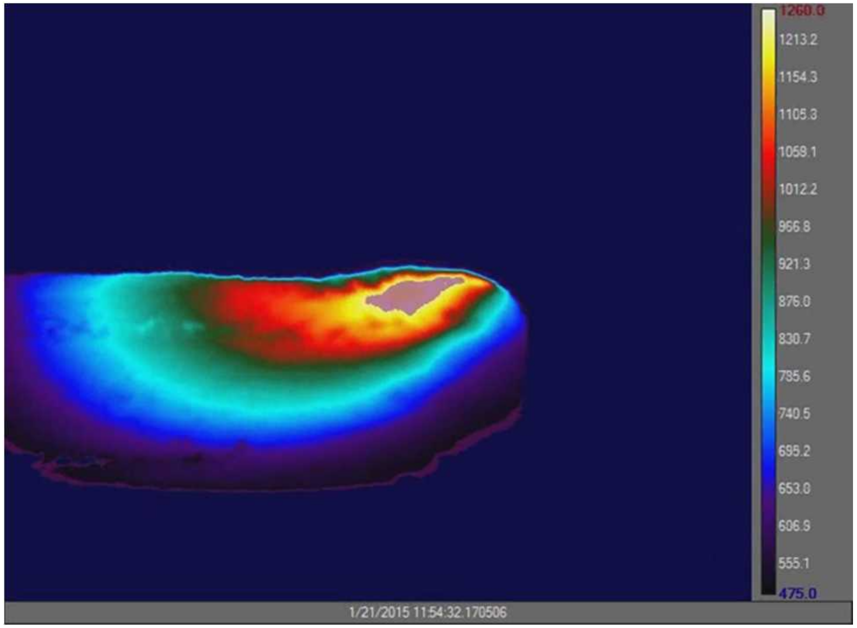
Laser Engineered Net Shaping (LENS®)

- 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



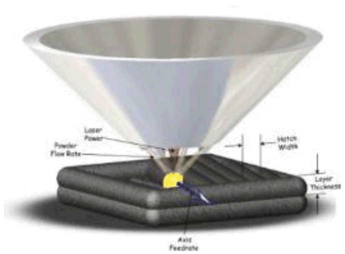
LENS functionally graded materials



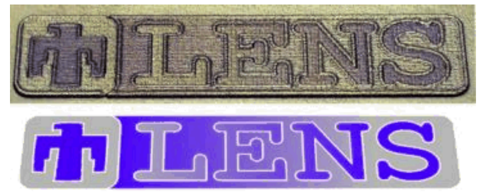


thermal history during bi-directional metal deposition

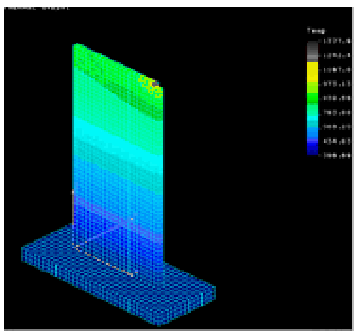
Prior LENS® Research

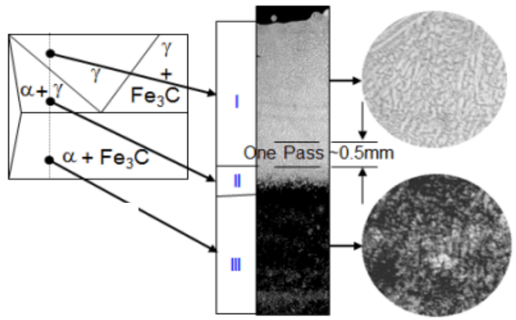


Graded composition demonstration

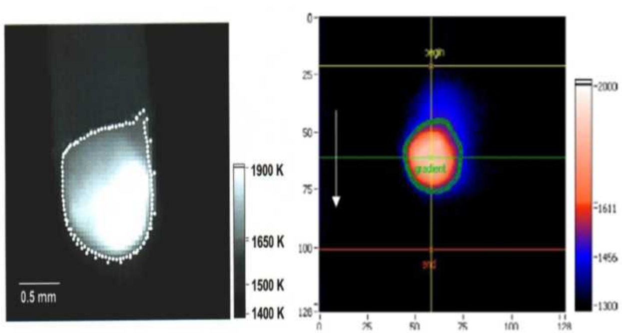


Process characterization/modeling





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

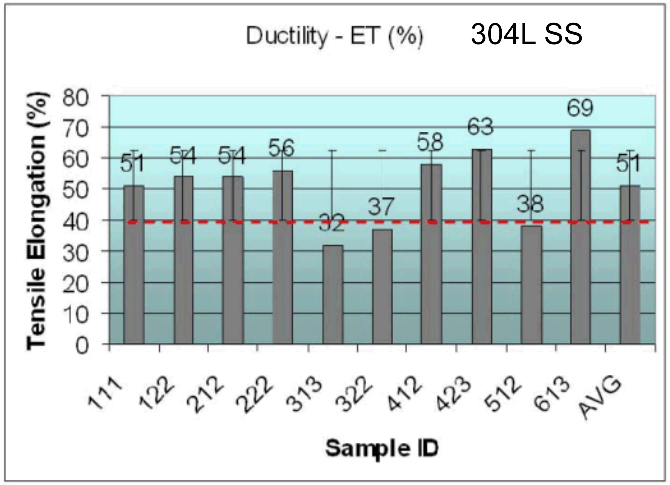
Variety of LENS® metals

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

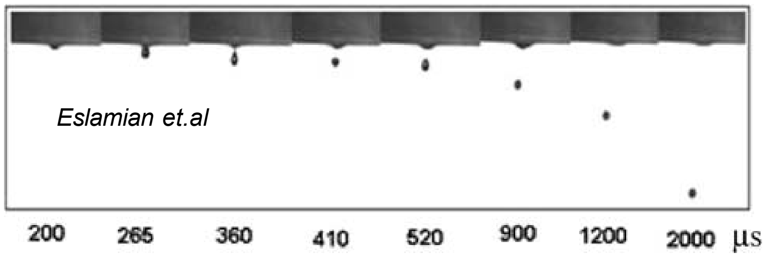
- process monitors ID'd build flaws

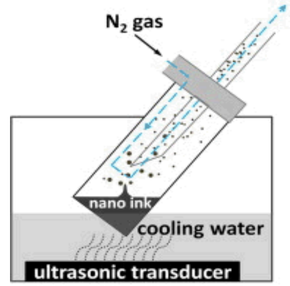
Direct Write

- 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

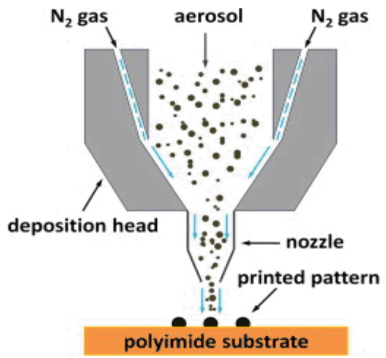
- Aerosol jet
  - ink atomized to produce dense aerosol mist
  - aerosol focused w/inert gas streams & small nozzle
  - Ag: 10 µm line width, 0.5-3 µm height

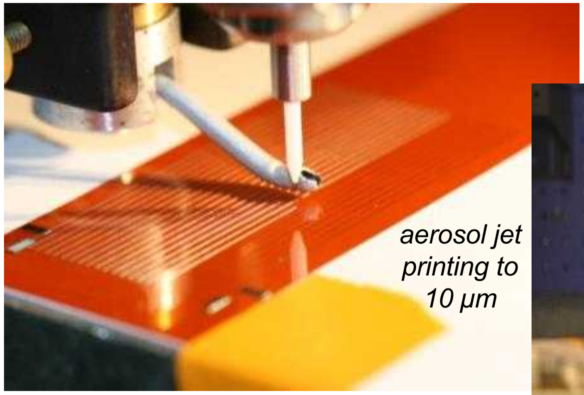
- Extrusion casting
  - volume deposition: 20 pl minimum
  - material viscosity: 1-1x10^6 cPs

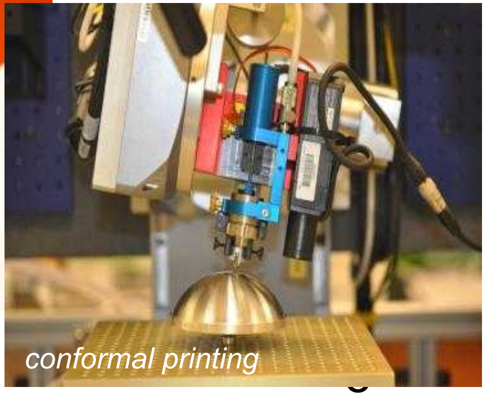




Zhao et. at

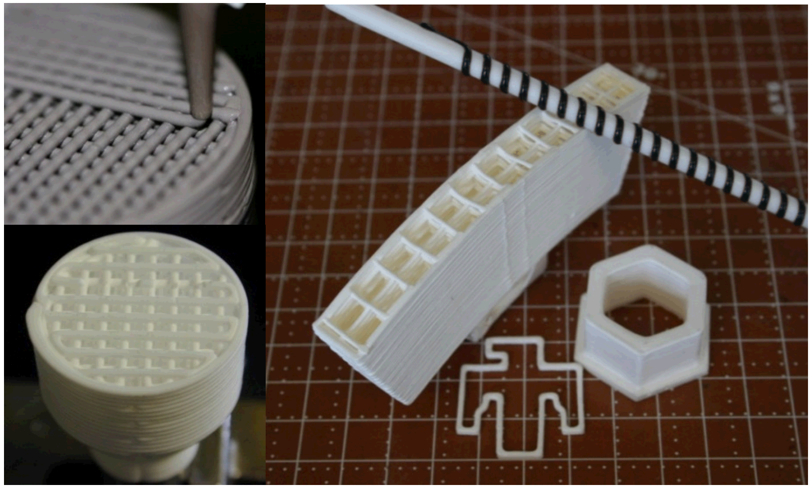




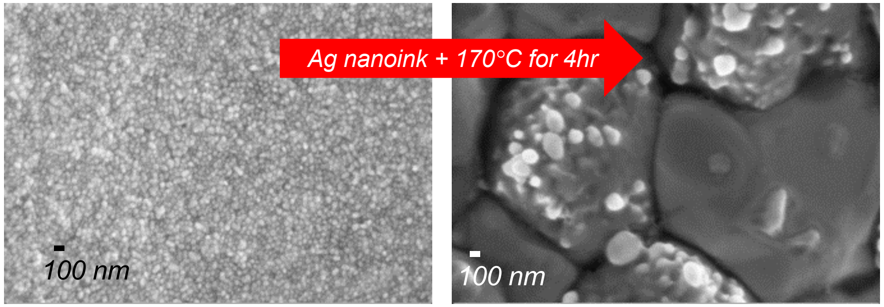


Direct Write

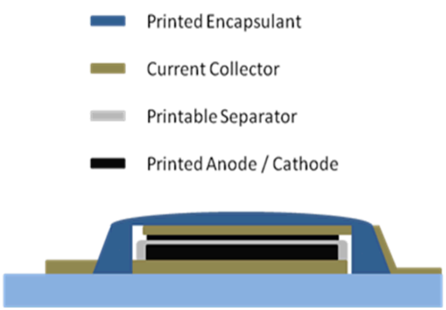
- Materials
  - epoxies, silicones, dielectrics, ceramics, energetics
  - nano-inks: metallic, polymeric, multi-phase
  - material formulation, synthesis & characterization
  - substrates: plastics, ceramics, polyimide, encapsulants, metals, FR4, glass, paper
- Sintering / curing
  - thermal, joule heating,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

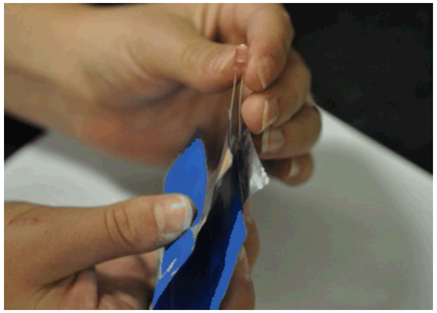


extrusion casting (Robocasting)



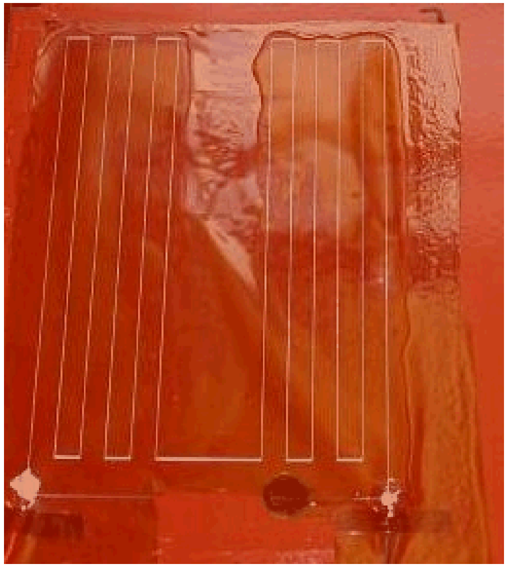
sintering of Ag nanoinks for conductive pathways



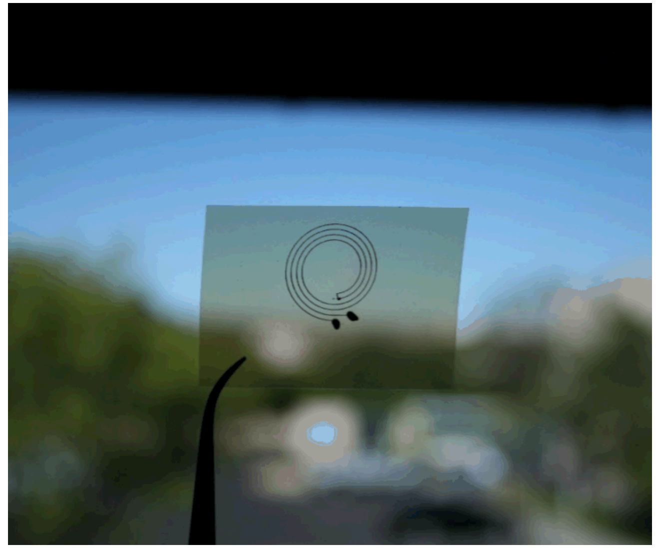


printed battery

Recent Activities

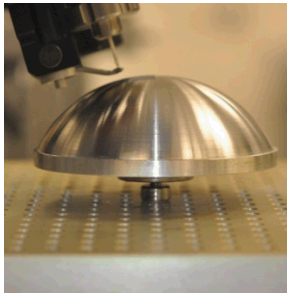


Ag traces on powdercoat with overcoat

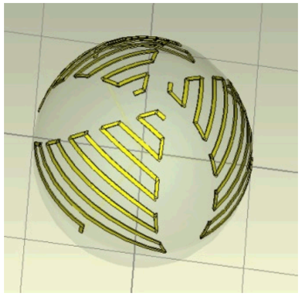


room temperature cure of conductive traces on polymer film

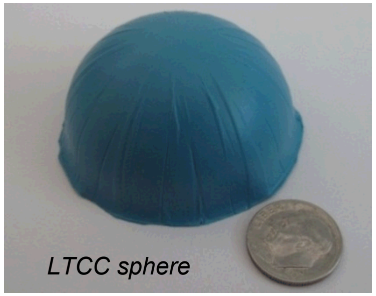
DW circuit fabrication



6-axis platform

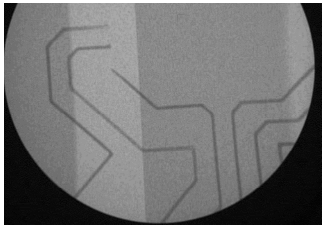


path planning

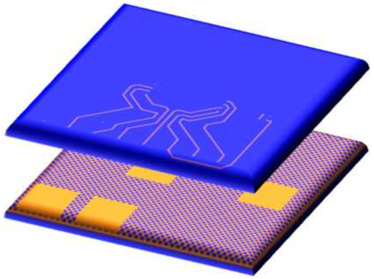


LTCC sphere

conformal printing



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



multi level circuit concept

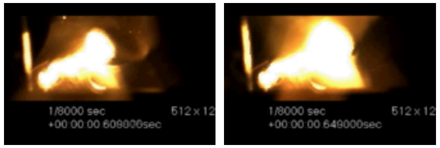
thick film low temperature co-fired ceramic

Adam Cook, David Keicher

Energetic Materials

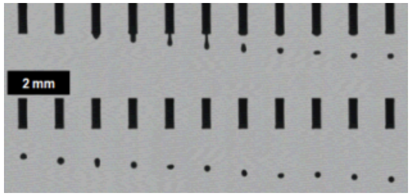
Robocasting

Aluminum/Nickel reactive material

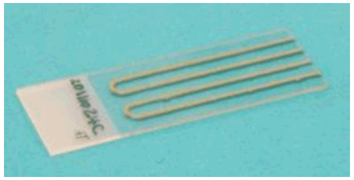


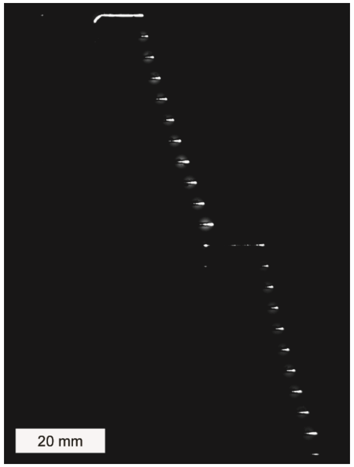
Tappan, A.S., Groven, L.J., Ball, J.P., Miller, J.C., Colovos, J.W., Joseph Cesarano, I., Stuecker, J.N., and Clem, P., "LDRD Final Report: Free-Form Fabrication and Precision Deposition of Energetic Materials," SAND2008-0965, February, 2008.

Inkjet printing



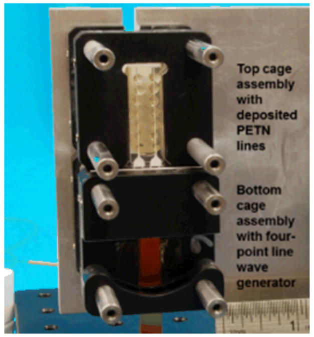
Aluminum/bismuth trioxide thermite

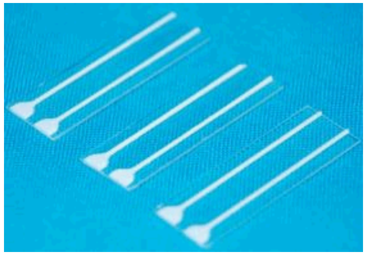




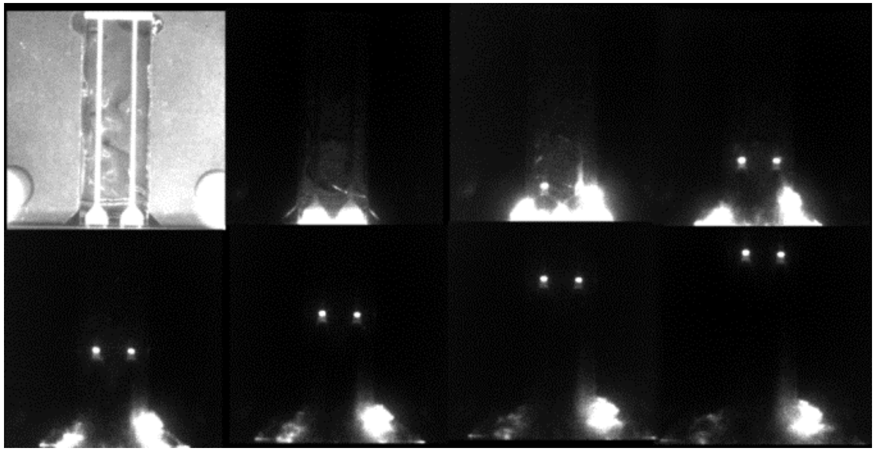
Tappan, A.S., Ball, J.P., and Colovos, J.W., "Inkjet Printing of Energetic Materials: Al/MoO3 and Al/Bi2O3 Thermite," *The 38th International Pyrotechnics Seminar*, Denver, CO, June 10–15, 2012.

Physical vapor deposition





Pentaerythritol tetranitrate high explosive

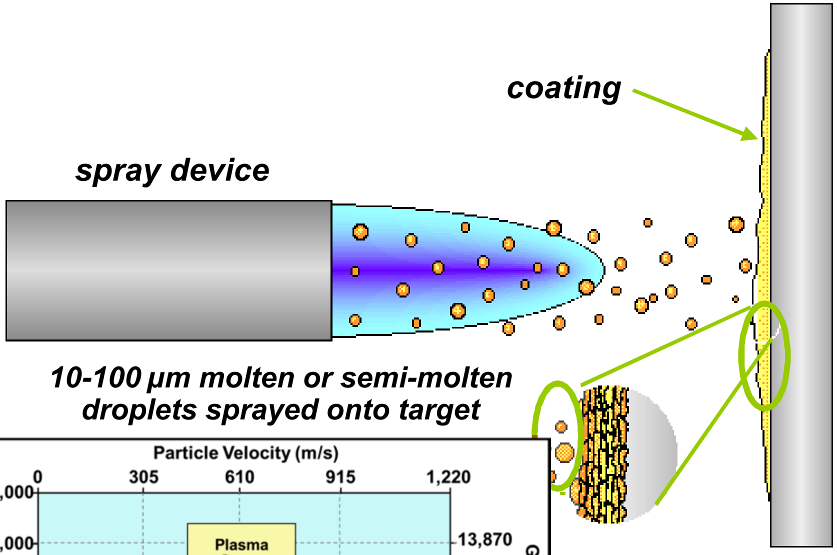


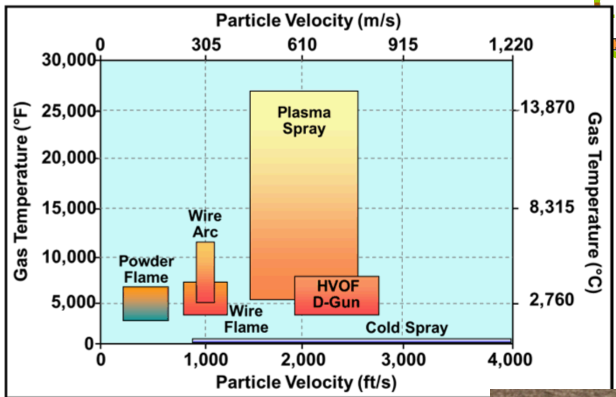
Tappan, A.S., Knepper, R., Wixom, R.R., Marquez, M.P., Miller, J.C., and Ball, J.P., "Critical Thickness Measurements in Vapor-Deposited Pentaerythritol Tetranitrate (PETN) Films," *14th International Detonation Symposium*, Coeur d'Alene, ID, April 11-16, 2010.

- Different materials and applications require different techniques

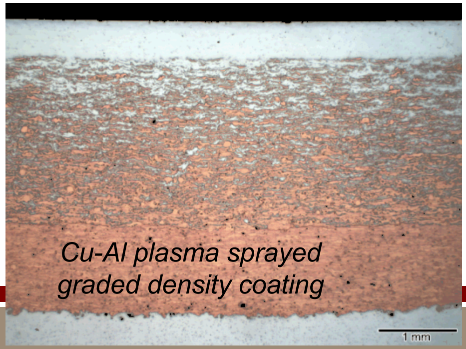
Thermal Spray

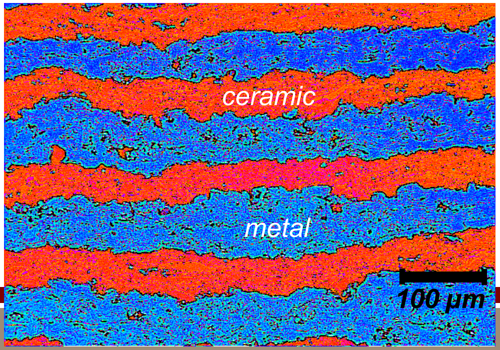
- SNL has all 7 major technologies
  - plasma spray (atmosphere, vacuum), twin wire arc spray, powder flame spray, wire flame spray, cold spray, high velocity oxy-fuel
- Advantages
  - large material set (anything that melts)
    - pure metals, most alloys, traditional ceramics, cermet, carbides, polymer,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

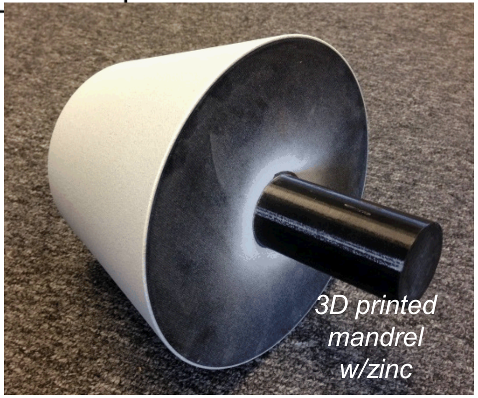




**Adapted from plots by R.C. McCune, Ford Motor Co. & A. Papyrin, Ktech Corp.*



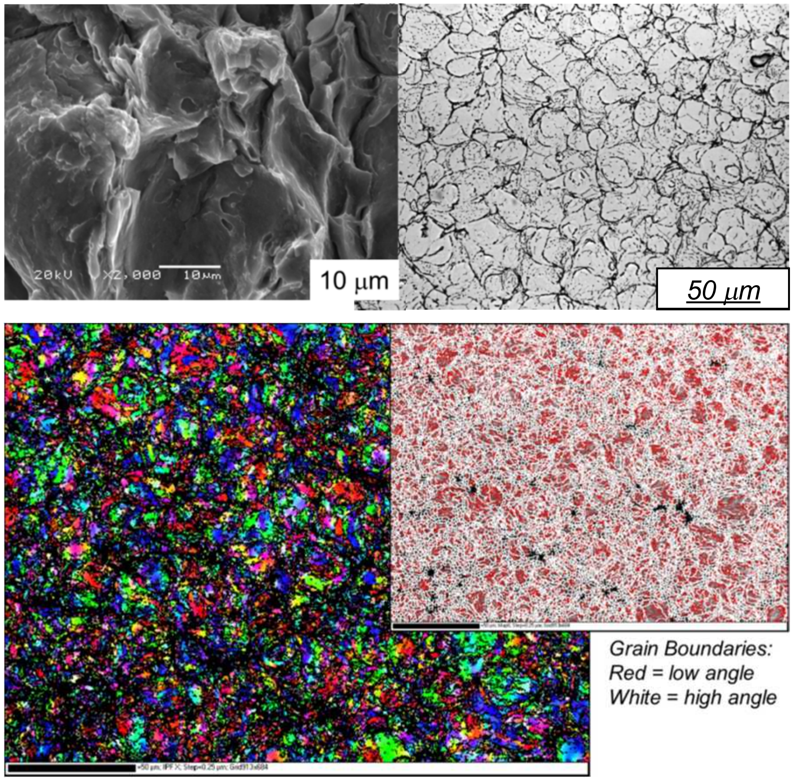




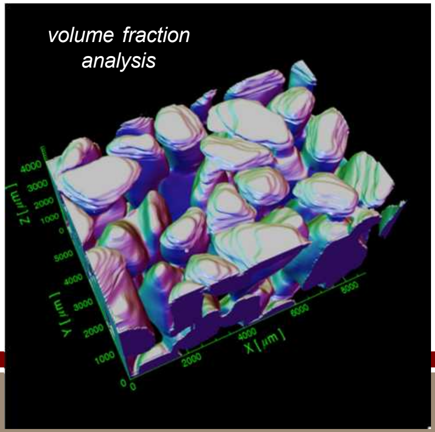
Aaron Hall, Pylin Sarobol

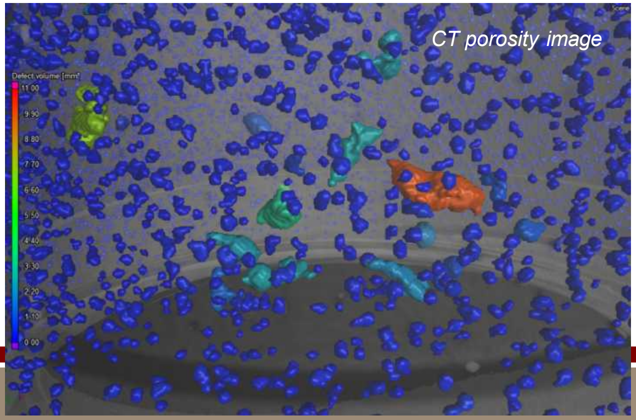
Material Characterization

- 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



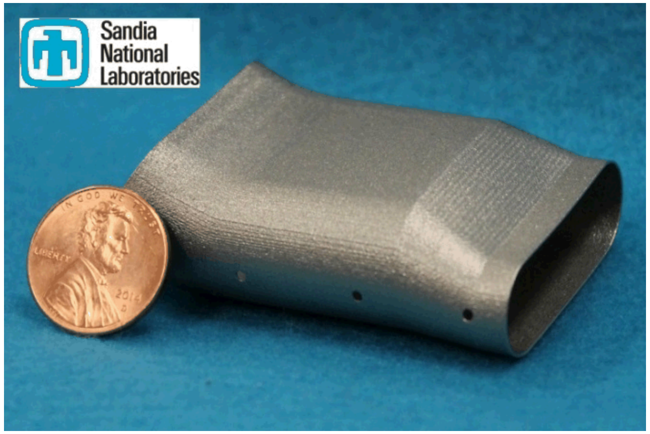
pure Al cold spray coating



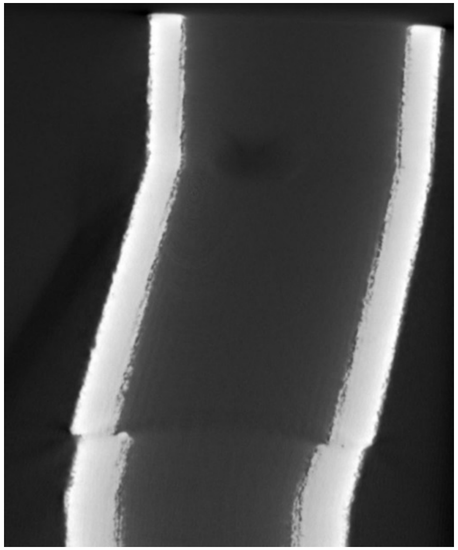


Computed Tomography

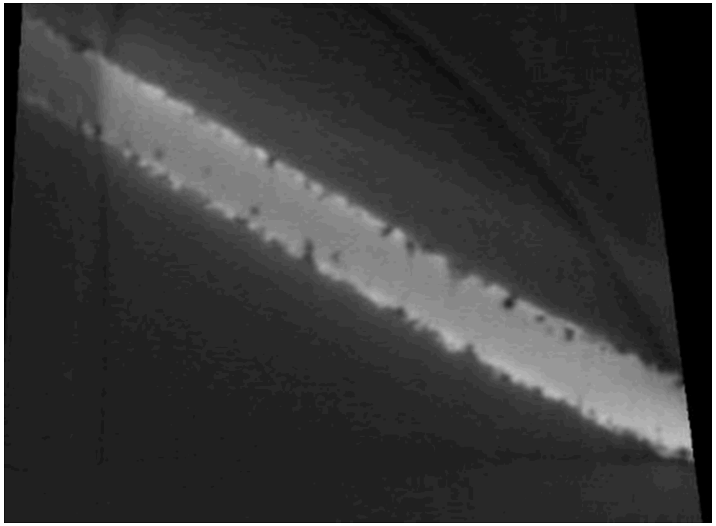
- Industry shift
  - 5 years ago – inspection, not metrology
  - now – necessary for AM complexity
- Interests
  - standards & verification
  - material characterization
  - dimensional metrology
  - big data (throughput, handling)
  - SNL capabilities in CT systems, data, metrology



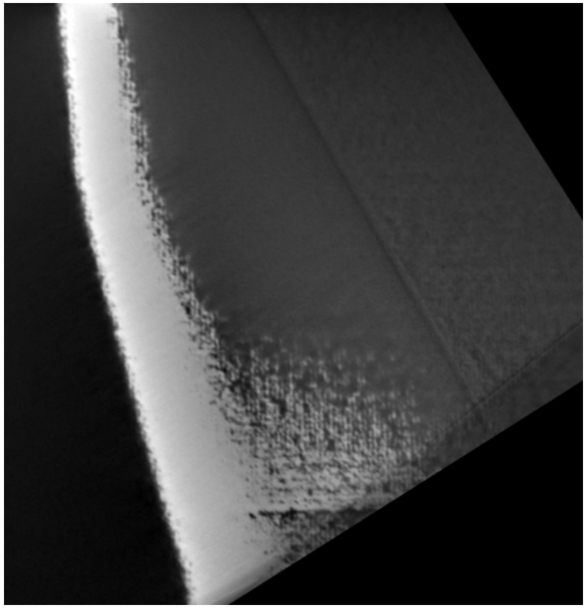
AM housing prototyped in 17-4PH stainless steel



defects – material or measurement?



detecting material voids & defects



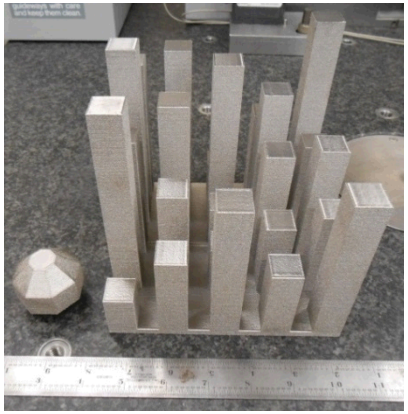
able to see build layers

Kyle Thompson, David Moore

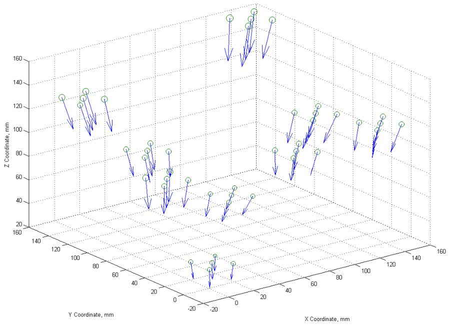
Sandia National Laboratories

Metrology

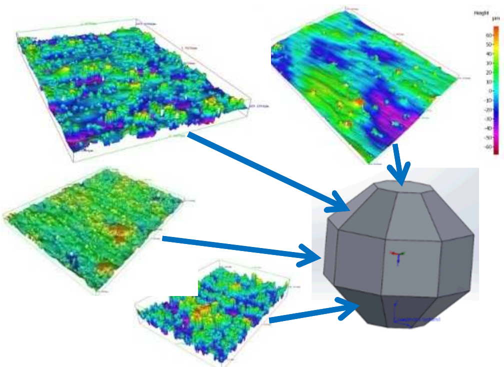
- Unique challenges for processes, equipment & parts
  - geometry depends on material, process, machine, orientation, supports, post-processing…
  - equipment accuracy generally exceeds process
- Challenges
  - metrology can be harder than fabrication
  - inferior surface quality
  - form deviations included in uncertainty analyses
  - GD&T applies, but less “traditional” surfaces
  - internal features
  - now worried about material, not just geometry



Ti-6Al-4V polyhedron & “Manhattan” artifacts

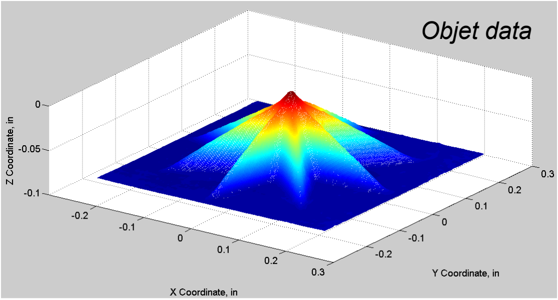


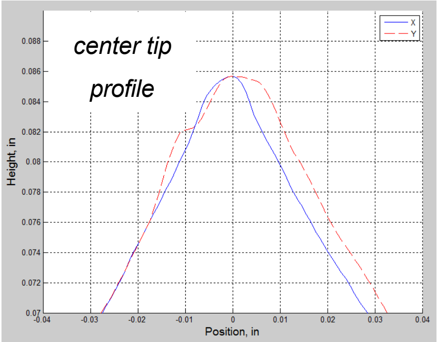
Ti “Manhattan” error map



17-4 PH polyhedron texture anisotropy map

17-4 PH “death” star

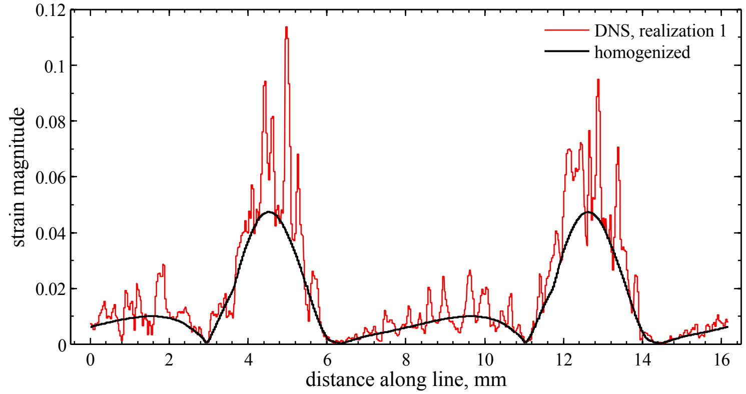




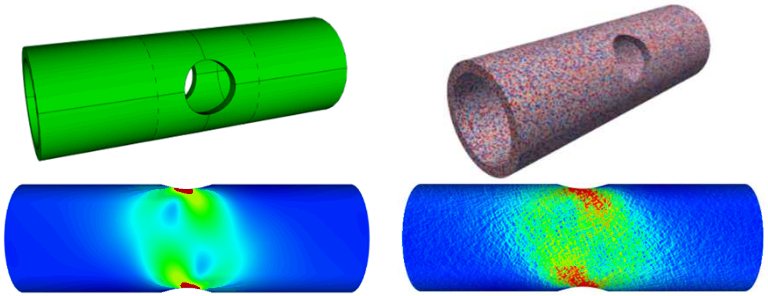
Engineered Materials

- 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



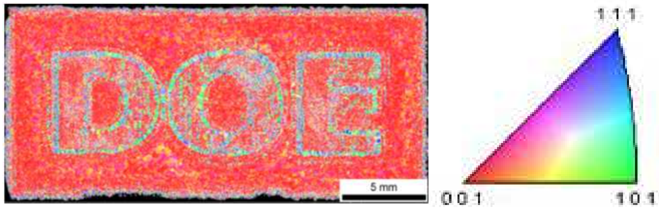
strain field due to tension-torsion



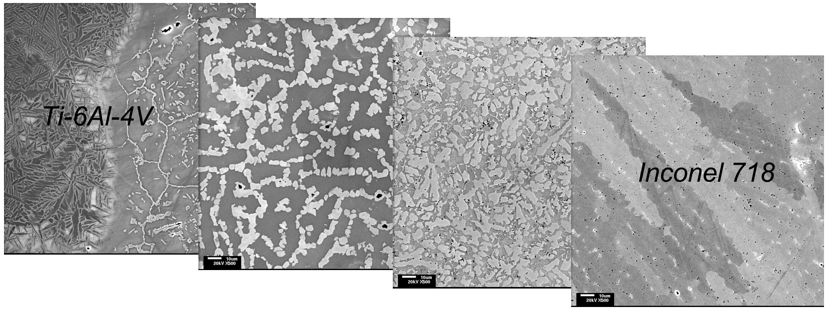
continuum model

crystal plasticity model

<u>*AM Inconel 718 texture control demo by ORNL*</u>

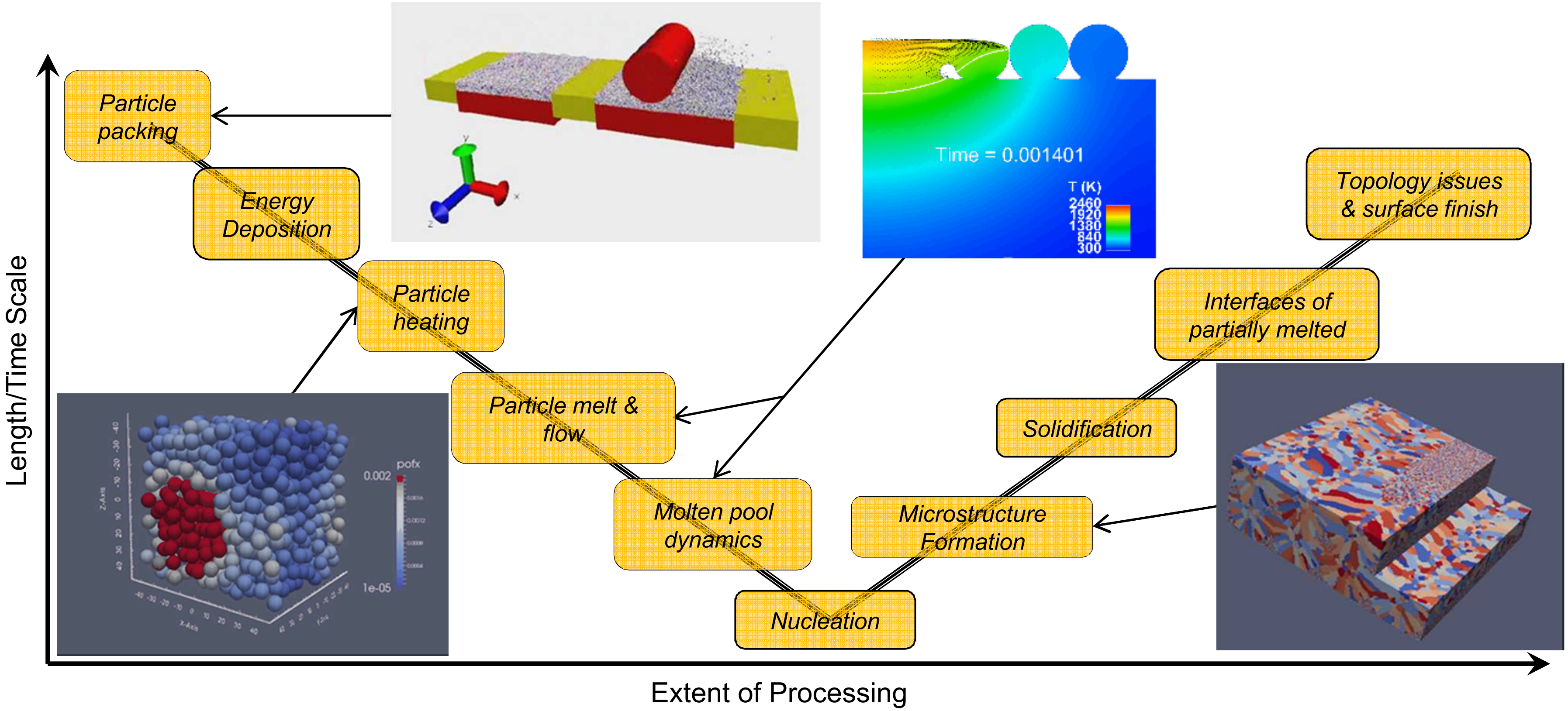


"We can now control local material properties, which will change the future of how we engineer metallic components," R. Dehoff



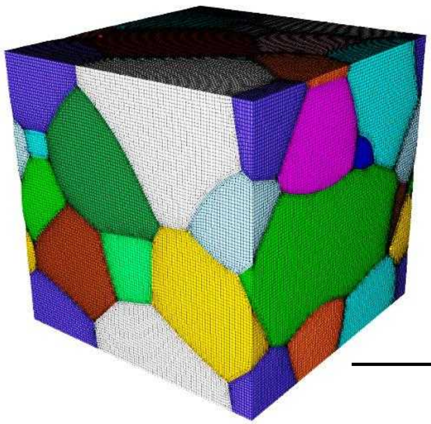
LENS® functionally graded materials

Process Simulations

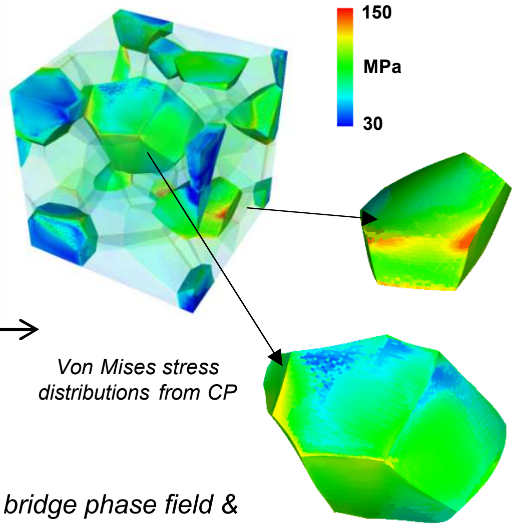


- Process
  - reduce experimentation
    - laser-material interaction
    - discrete particle physics
  - process -> structure relationships
  - process limits
- Defect impact
  - understand formation mechanisms
  - explore uncertainty quantifications
  - predict response from stochastic process knowledge

Predicting Material Performance

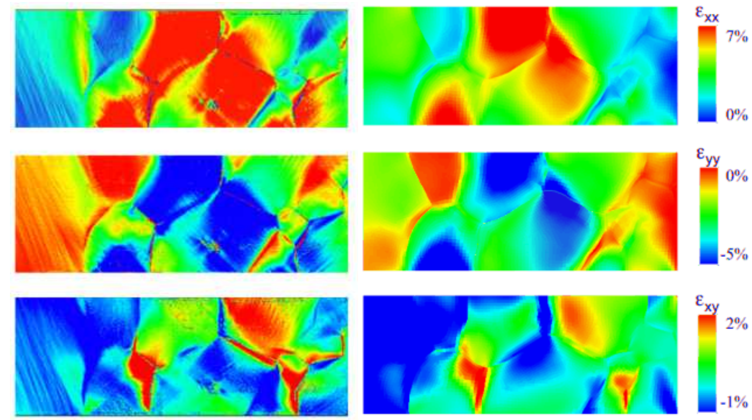


53 grains from phase field, 1.35M element conformal hex mesh



Von Mises stress distributions from CP

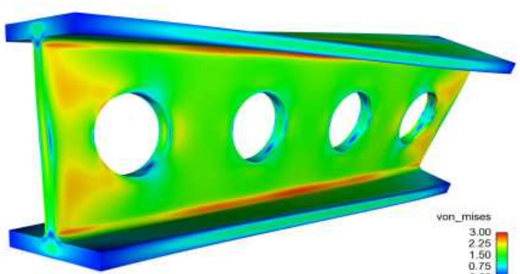
microstructure models bridge phase field & crystal plasticity simulations



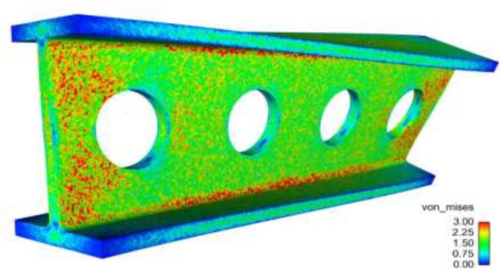
DIC measurements

simulations

oligocrystal tensile load experiment vs. crystal plasticity models

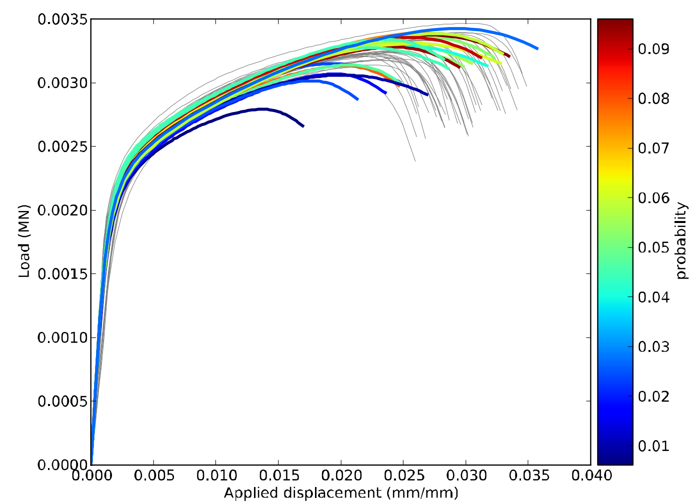


homogenization theory



Direct Numerical Simulation (DNS)

macroscale torsion stress fields

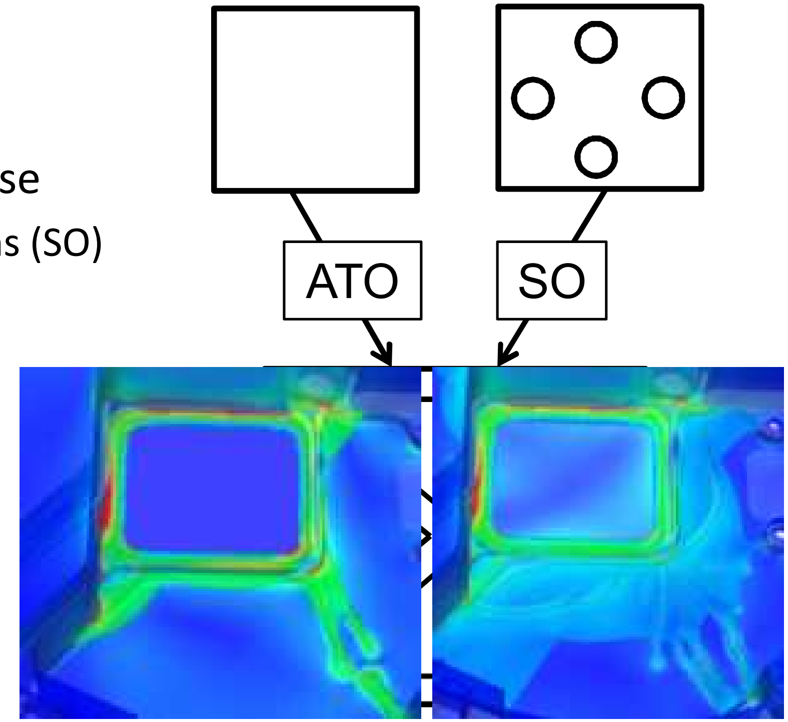


predicted (color) vs. measured (grey) response for welds (PPM)

Brad Boyce, Corbett Battaile, Jay Carroll, Joe Bishop, et al

New Design Freedom

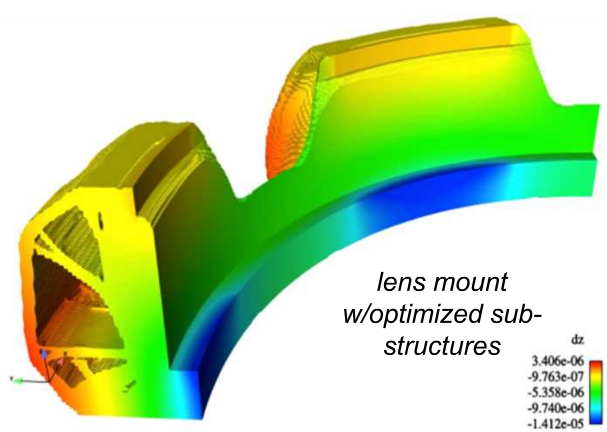
- Computational synthesis for optimal material use
  - adaptive topological (ATO) & shape optimizations (SO)
  - leverages “complexity is preferred”
  - constrained by performance requirements
  - bio-mimicry requires AM
  - design occurs concurrent w/simulation



+ 0.55% volume
- 52% deflection

+ 3.3% volume
- 64% deflection

elasto-static stiffness optimization



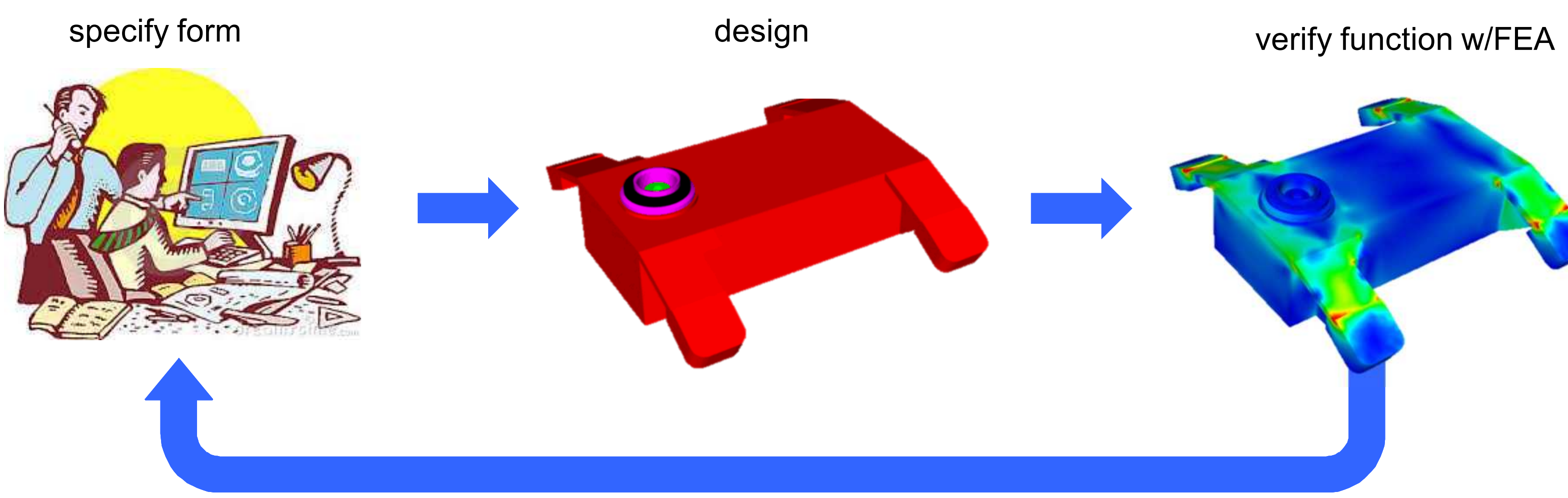
lens mount w/optimized sub-structures

solution for a bar in pure torsion resembles a cholla cactus

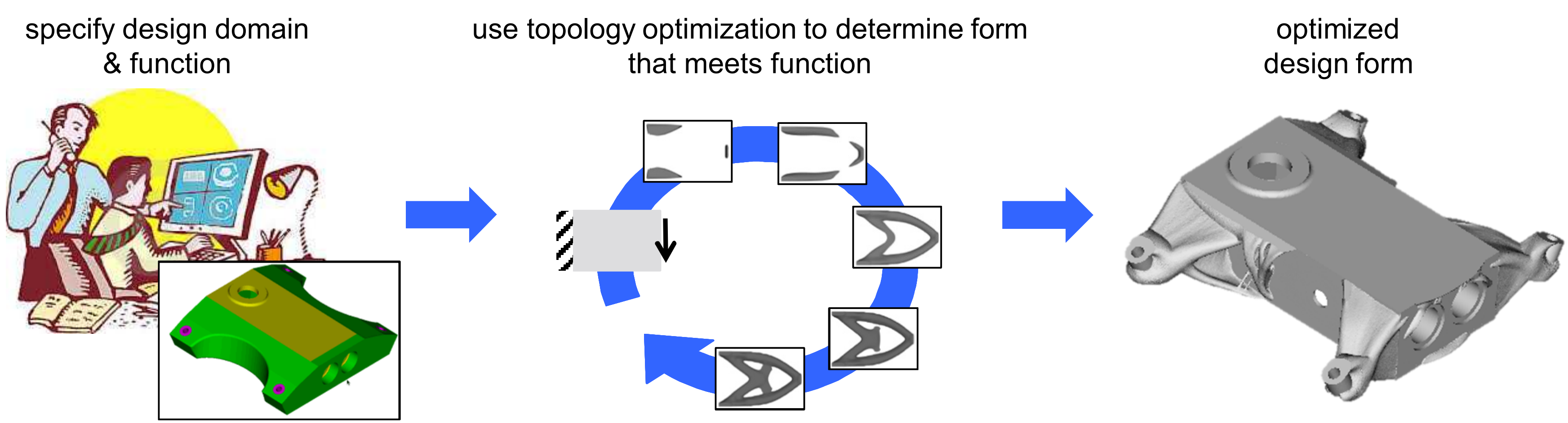
Joshua Robbins, Tom Voth, Brett Clark, Miguel Aguilo, Ted Blacker, et al

Inverting the Design Cycle

CURRENT

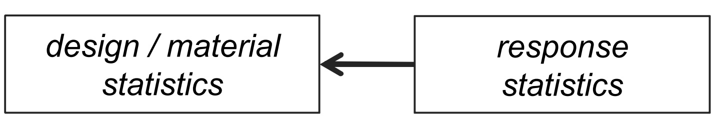


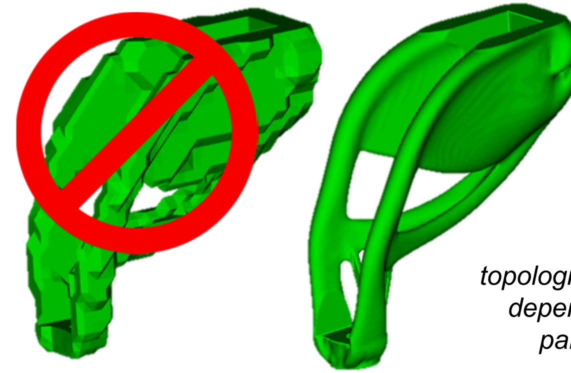
NEW



Design Challenges

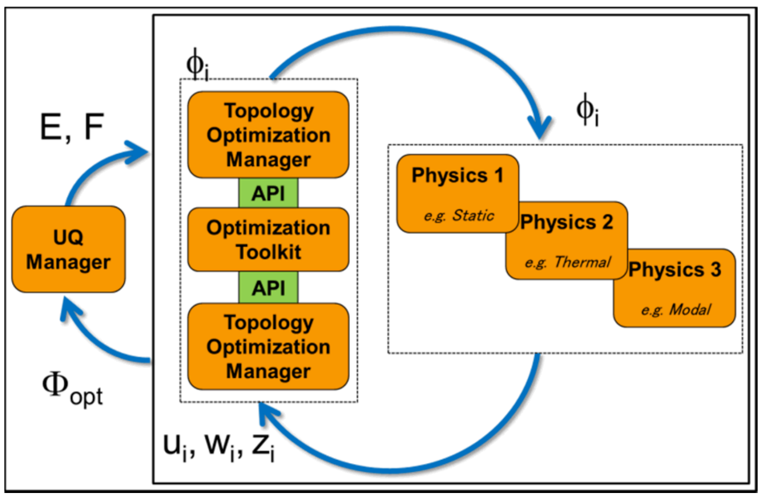
- Ease of use
  - data formats
  - interactive steering
  - smooth, connected geometries
- Efficiency
  - manipulating volume data
  - reduced order models
  - faster converging algorithms
- Physics
  - elasto-statics, modal, thermal exist
  - complex boundary constraints (ex. sliding)
  - multi-physics
  - process constraints & design rules
- Uncertainties
  - computational, requirements, materials
  - solve stochastic inverse problem





topologies & surfaces depend on mesh parameters

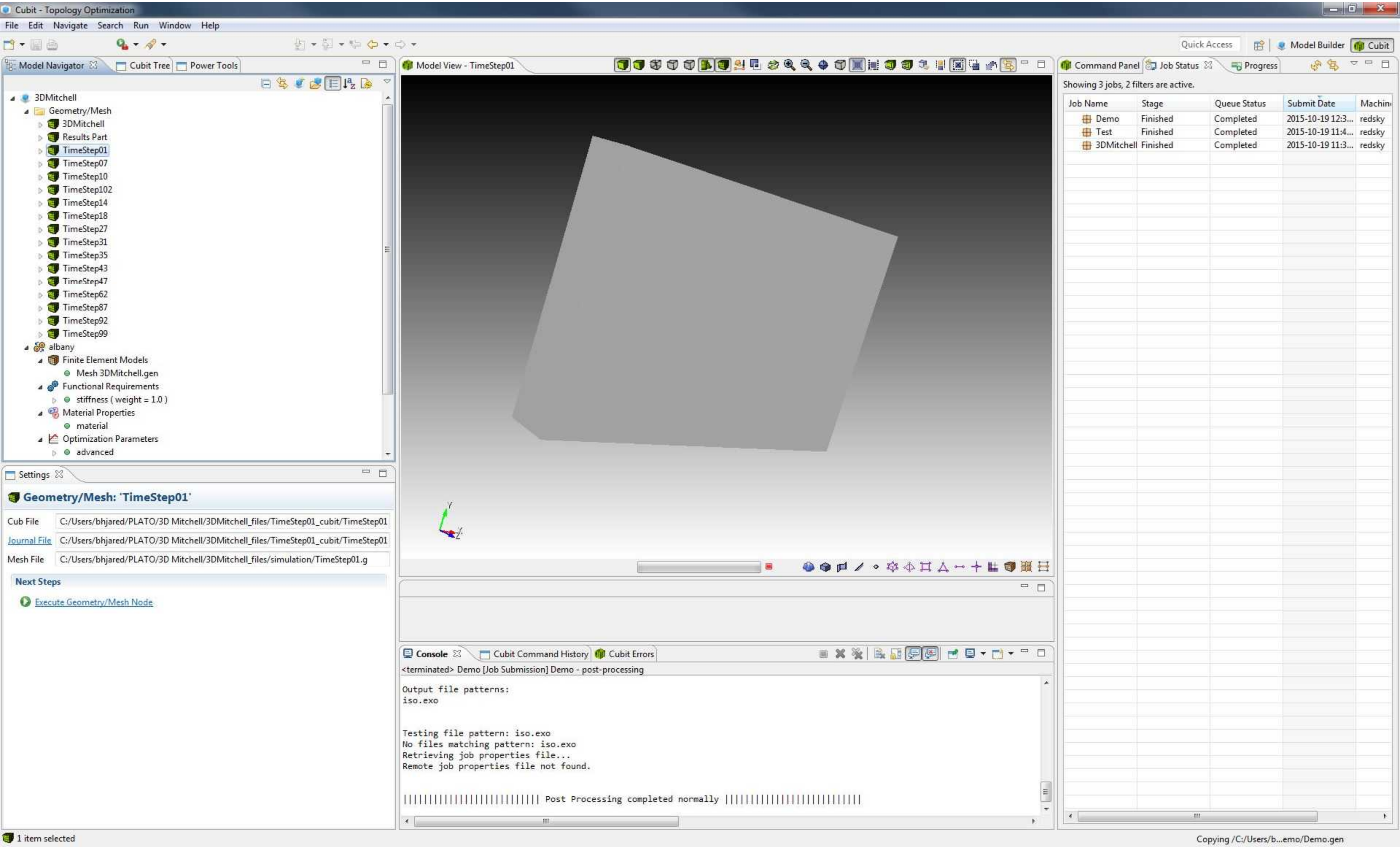
discontinuous topologies are unacceptable



optimization scheme

Joshua Robbins, Tom Voth, Brett Clark, Miguel Aguilo, Ted Blacker, et al

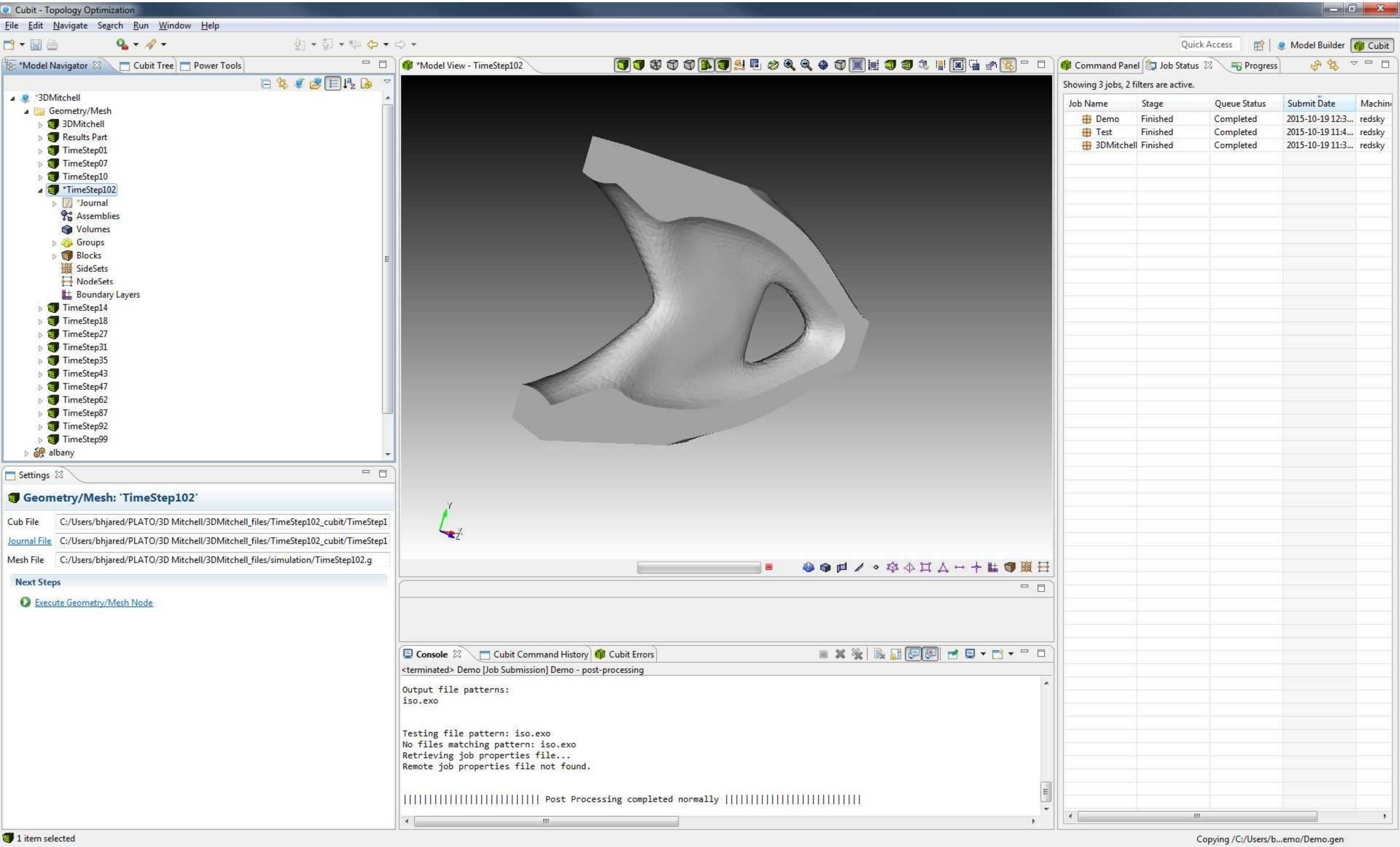
Sandia Analysis Workbench (SAW)



Joshua Robbins, Tom Voth, Brett Clark, Miguel Aguilo, Ted Blacker, et al

Sandia Analysis Workbench (SAW)

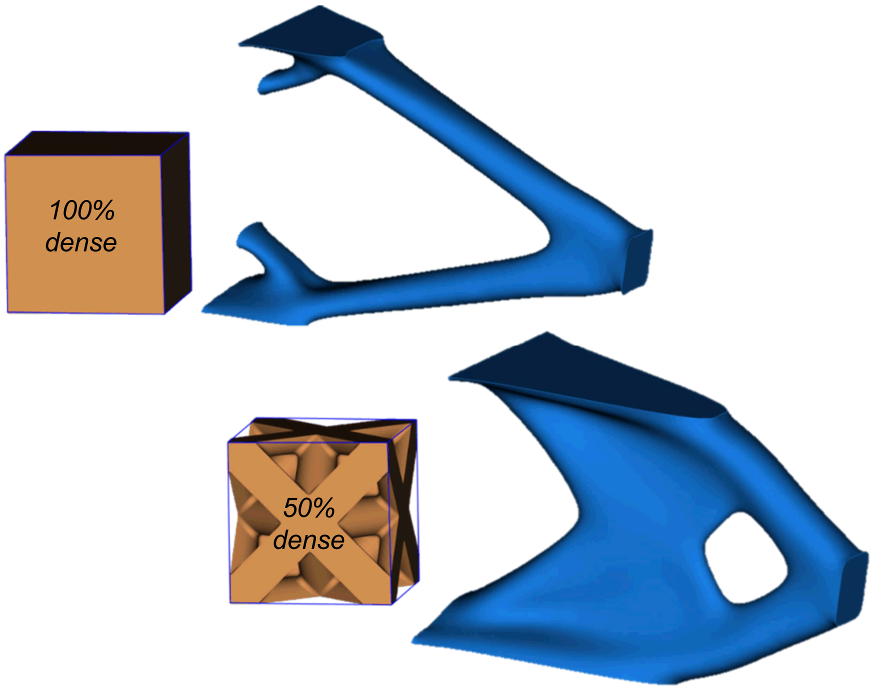
Sandia National Laboratories

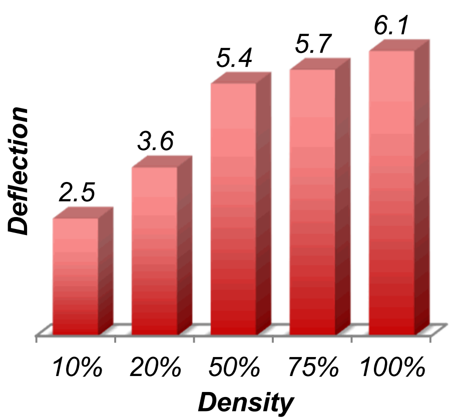


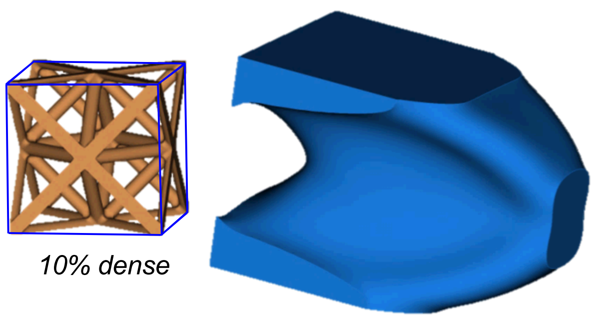
Joshua Robbins, Tom Voth, Brett Clark, Miguel Aguilo, Ted Blacker, et al

TO w/Lattice Structures

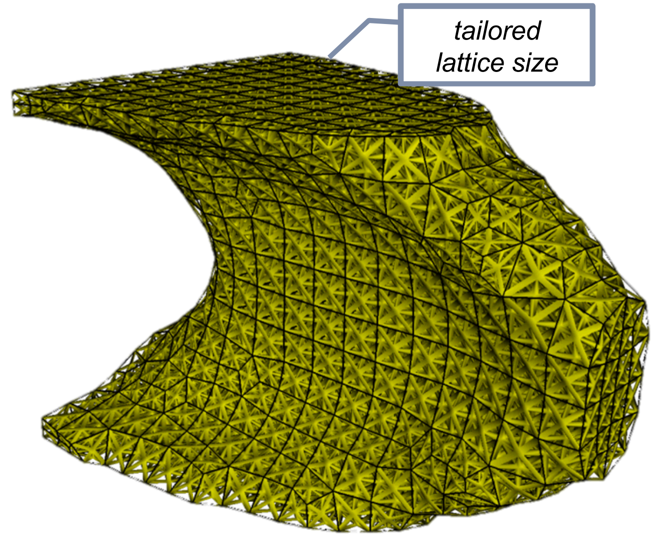
Optimizing stiffness w/fixed mass

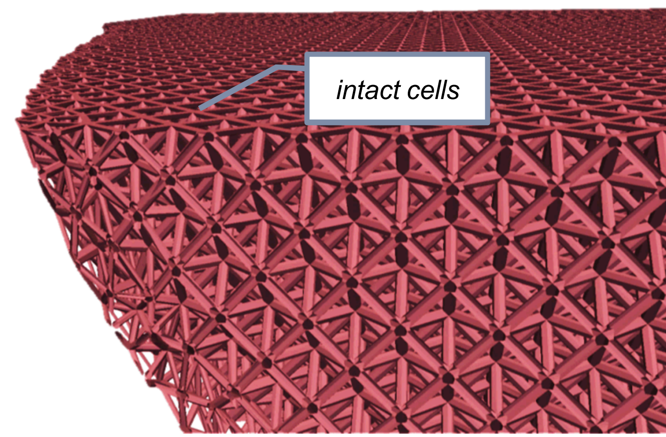






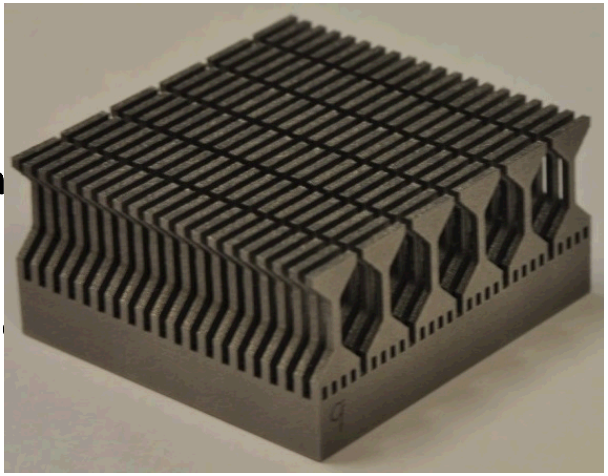
Tailored geometry avoids "loose ends"



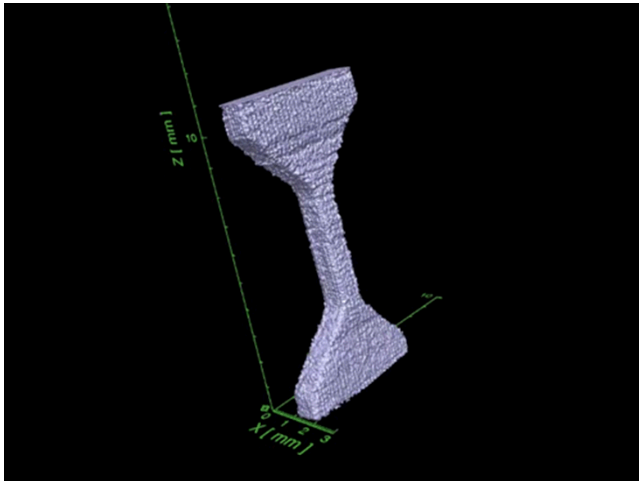


Identifying Defect Signatures

- Examining multiple techniques
  - destructive
    - high throughput testing (HTT), fractography, m
  - non-destructive
    - computed tomography (CT), density, process c (PCRT)
  - AM enables large sample sets
    - desire similar measurement throughput
- Correlation study underway
  - data sets for 110 17-4PH dogbones
    - ~2 Gb/dogbone
  - parts from a single baseplate
    - nominally constant process parameters



high throughput test sample w/120 dogbones, 1x1mm gage x-section

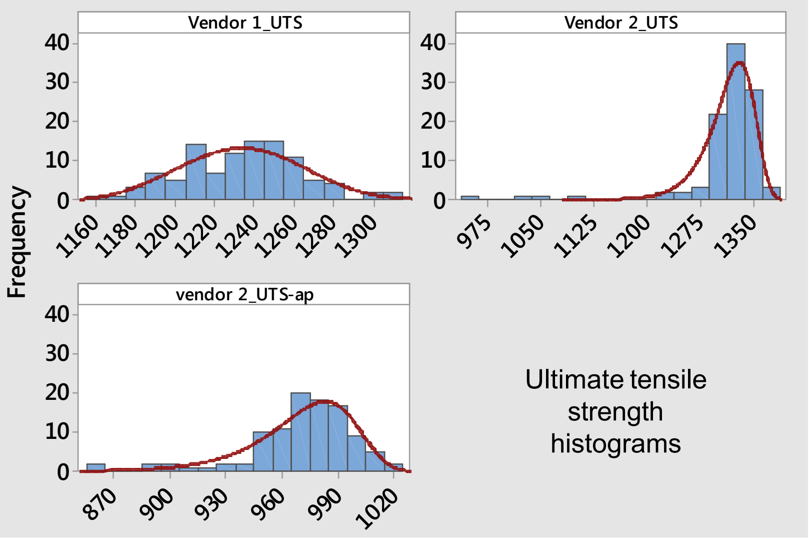


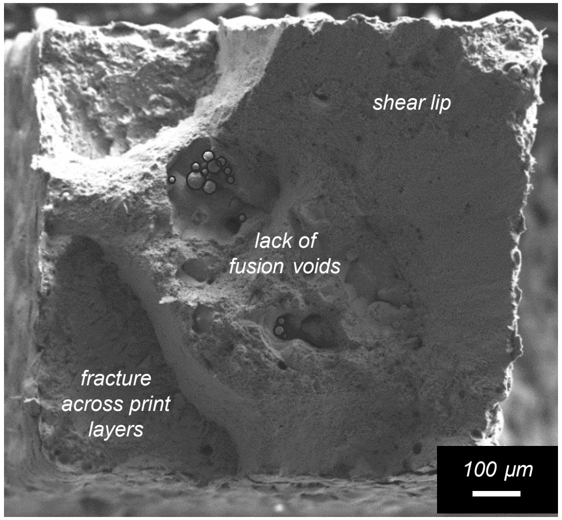
CT model of 1x1 mm test sample

Bradley Jared, Brad Boyce, Jeff Rodelas, Jon Madison

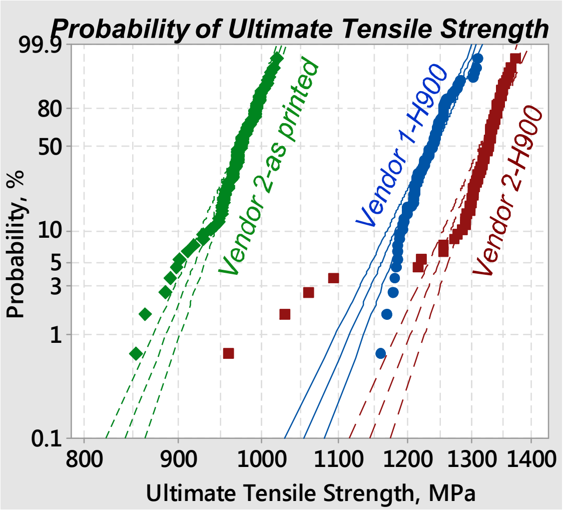
Mechanical Strength Distributions

- Characterizing using HTT tensile
  - quantifying mean, outliers & probabilities
- Current testing
  - 1.0 mm square gage sections
    - >100 samples / test condition
  - external vendor sources
    - limited process specificity
  - defect dominated behavior to-date
    - similar to castings & ceramics
    - Weibull distributions prove appropriate



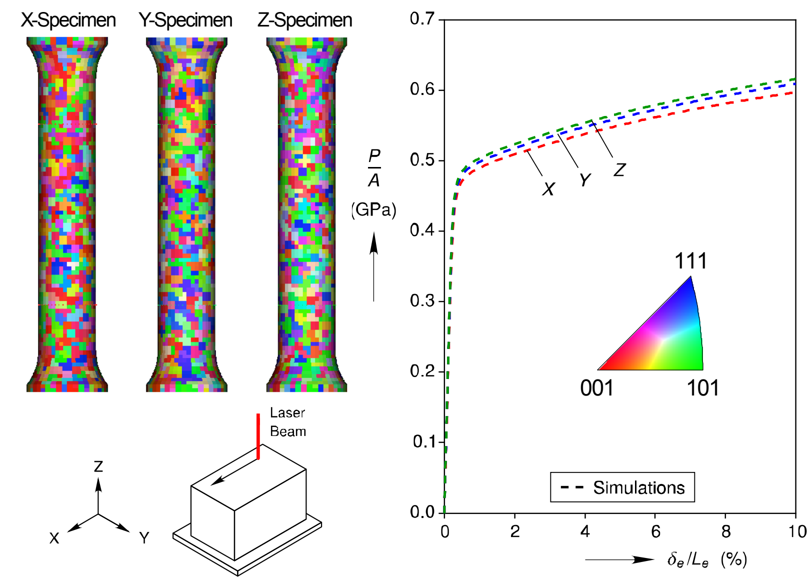


failure at 2% elongation, Vendor #1, H900

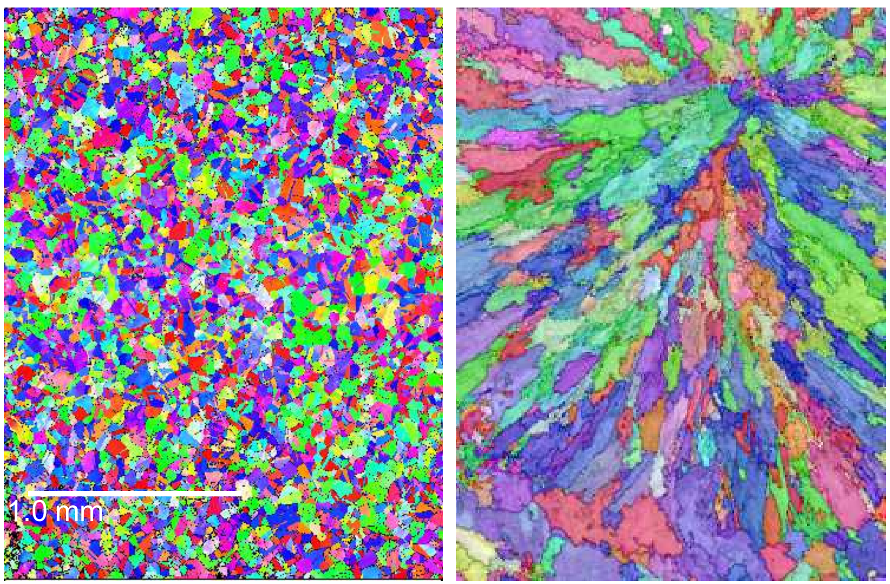


Variable Strain Rate Mechanical Response

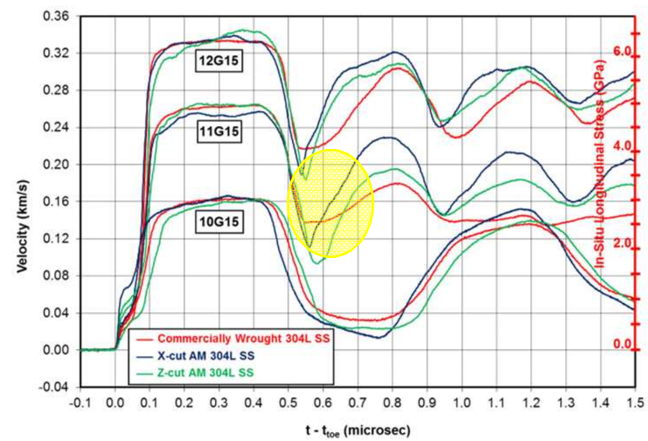
- High power LENS (0.5-3.8 kW, Penn State)
- Exploring strain rates from 10^{-5} to 10^{6} /sec
  - quasi-static to gas gun
- Building crystal plasticity predictive models
- Probing material behavior using neutron diffraction (LANL)



Prediction of material anisotropy



Wrought 304L SS microstructure (left) & AM (right)



Spall strength of LENS 304L SS varies from 3.27 to 3.91 GPa & exceeds wrought material (2.63 – 2.88 GPa)

QUESTIONS?

Bradley Jared, PhD

bhjared@sandia.gov

505-284-5890