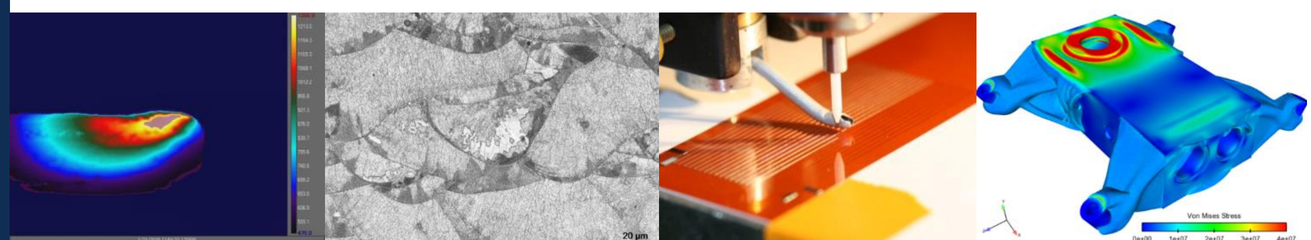
SAND2017-2863C

Additive Manufacturing at Sandia

Bradley Jared, PhD

Materials Science & Engineering

Sandia National Laboratories



U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Outline

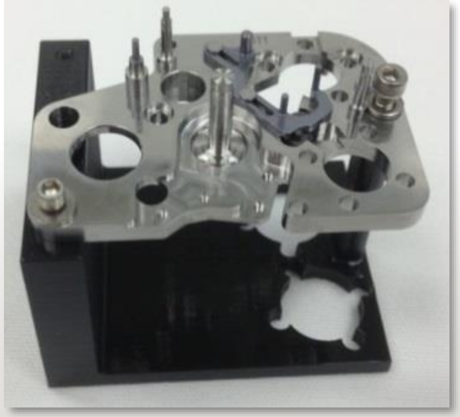
- Sandia's interest in AM
- AM processes
  - metal
  - direct write
- Analysis driven design
  - topology optimization
  - material & process simulation
- Stockpile components
  - B61-12 LEP
  - W88 ALT370
- Material assurance

Sandia National Laboratories

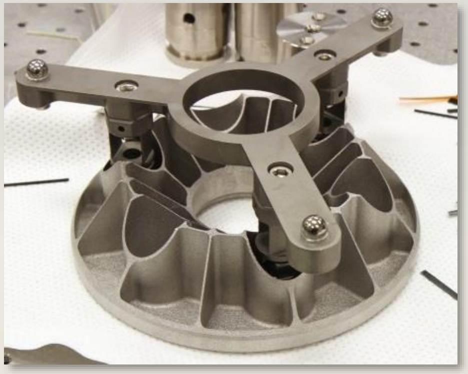
- A National Security Science & Engineering Laboratory
  - “Exceptional service in the national interest”
- Nuclear Weapons
- Defense Systems & Assessments
- Energy & Climate
- International, Homeland, & Nuclear Security

SNL's Additive Interest

- Reduce risk, accelerate development
  - simplify assembly & processing
  - prototypes, test hardware, tooling & fixturing
- 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"



fixture generated in 1 day



prototype AM mirror & structure

full scale additive weapon mock-up

Powder Bed Fusion

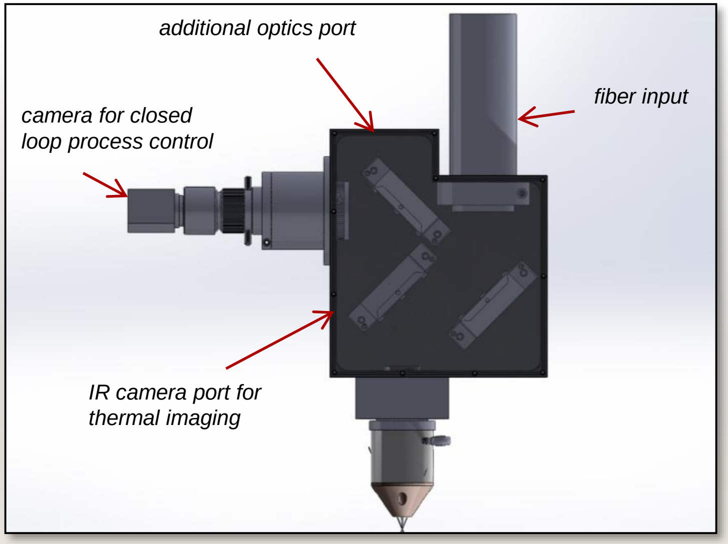
- Growing activity for metal parts
  - supporting wide-ranging SNL missions
  - partnering w/NSC for NW
  - research platforms for process & material characterization
- 3D System machines
  - two ProX 300, one ProX 200
  - motivations
    - roller powder compression
    - process flexibility
    - domestic OEM
  - materials
    - now: 316L
    - future: Kovar, 304L, 17-4Ph, 13-8Mo

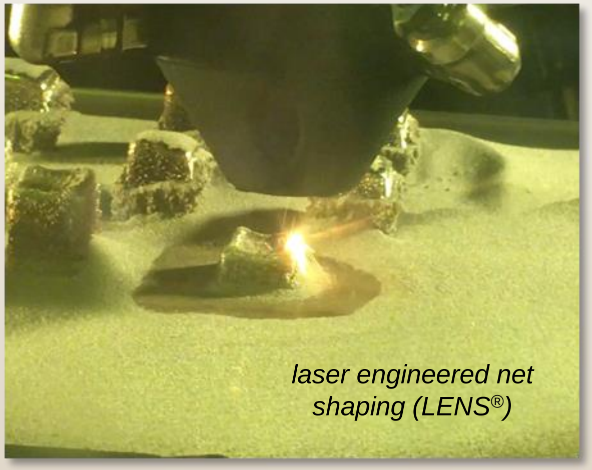
ProX 200, materials science lab

ProX 300, neutron generator vault

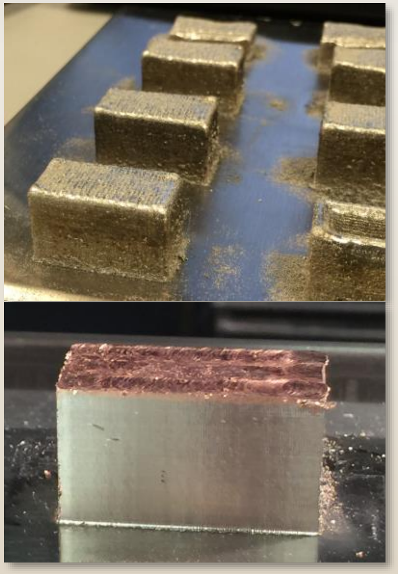
Laser Engineered Net Shaping (LENS®)

- Historical
  - extensive SNL development efforts & investments
  - licensed to Optomec
- Custom research machine
  - 2 kW laser source
  - 10,000 rpm spindle for machining
  - custom deposition head for powder delivery & process diagnostics
- Optomec MR-7 (CA)

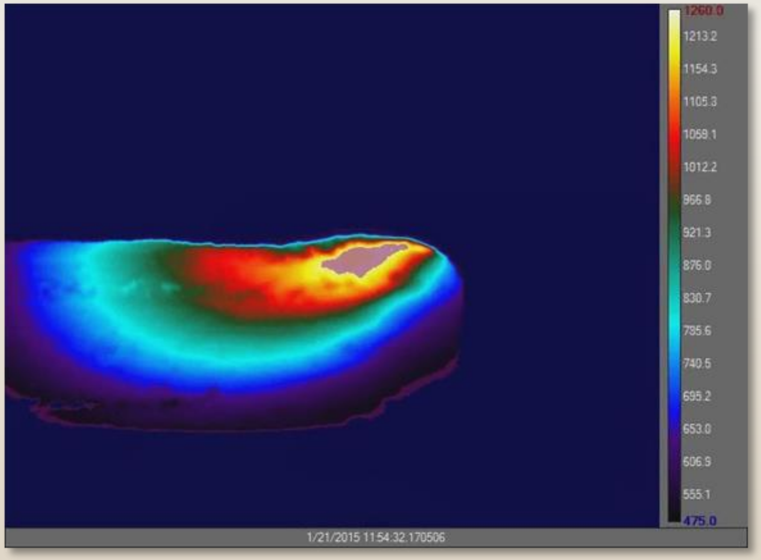




laser engineered net shaping (LENS®)



304L SS – Cu multi-material thermal concentrator

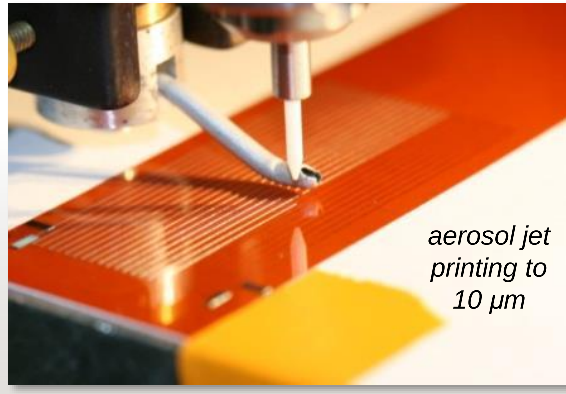


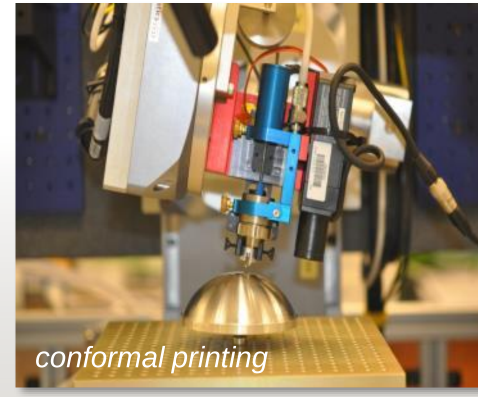
thermal history during bi-directional metal deposition

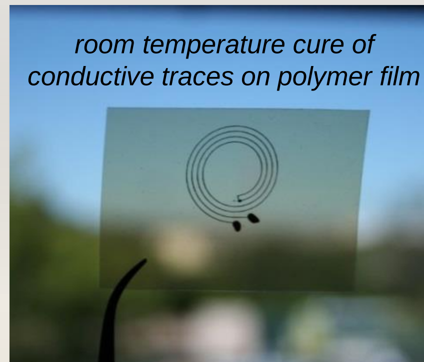
David Keicher, Gary Hux

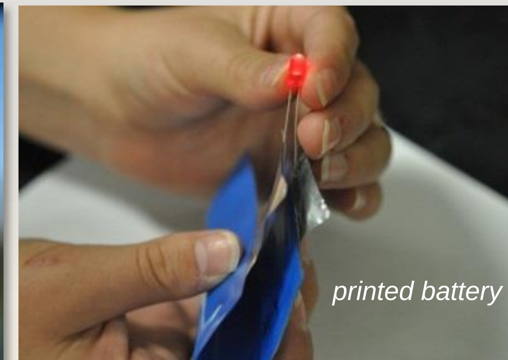
Direct Write

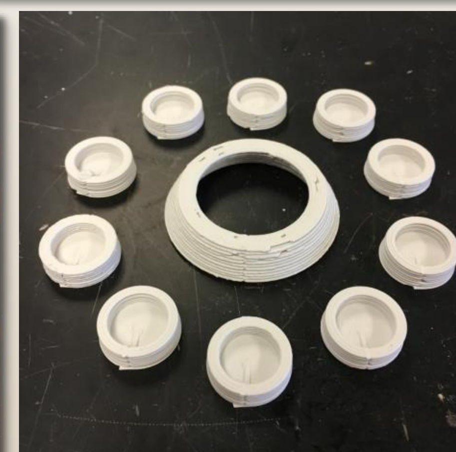
- Processes
  - ink jet, aerosol jet, extrusion casting
- Materials
  - epoxies, silicones, dielectrics, ceramics, nano-inks, energetics
  - substrates: plastics, ceramics, polyimide, encapsulants, metals, FR4, glass, paper
  - formulation, synthesis & characterization
- Sintering / curing
  - thermal, joule heating, UV, plasma, laser, microwave, room temperature
- Applications
  - DC & RF interconnects, antenna, sensor networks, structural health, package integration
  - conformal geometries
  - prototype circuitry in LTCC


aerosol jet printing to 10 μm


conformal printing


room temperature cure of conductive traces on polymer film

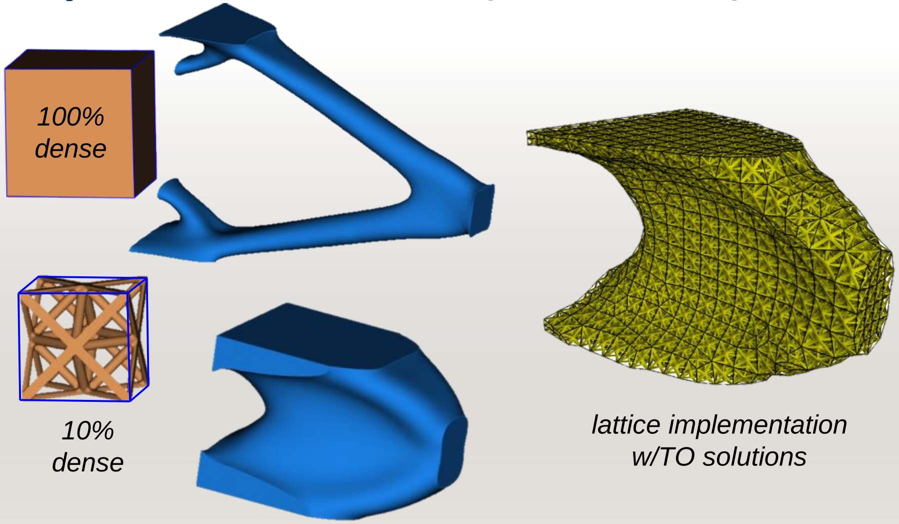

printed battery

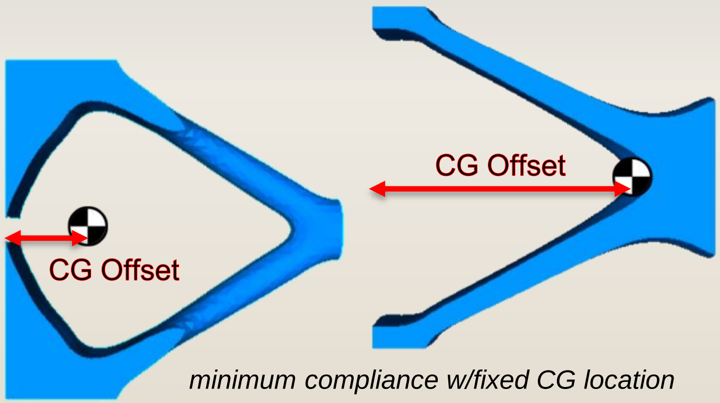


ceramic-thermoplastic 3D (CT3D) printing of alumina

Adam Cook, Chris Diantonio

Plausible Topology Optimization (PLATO)

- SIERRA implementation
  - available for government use
- Current capabilities
  - SAW user interface
  - elasto-static & thermal solutions
  - load cases
    - displacement, surface or body loads, CG, temperature, flux
  - anisotropic, multi-materials
  - lattices
  - parallel HPC processing
- Future work
  - stress optimization, UQ, material distributions, more multi-physics, increase efficiency, process awareness, user intervention

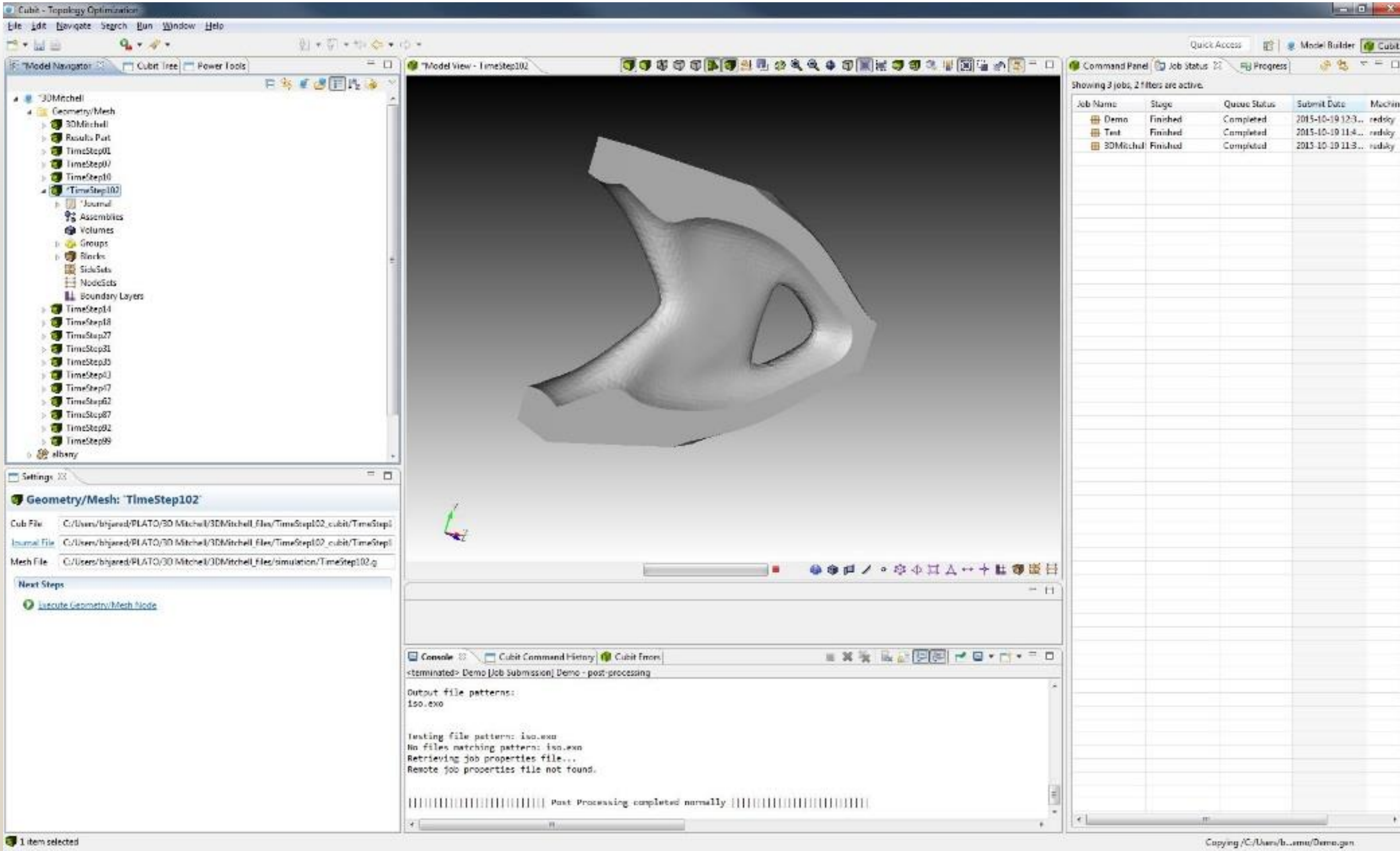




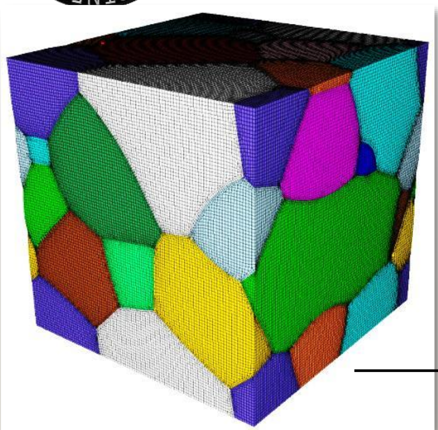
minimum compliance w/fixed CG location

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

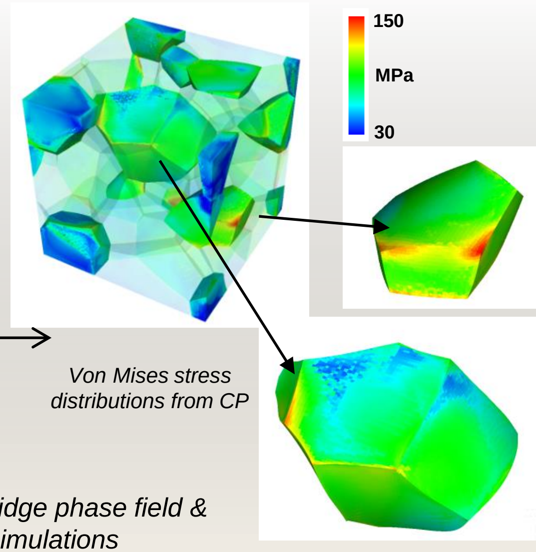
Sandia Analysis Workbench (SAW)



Predicting Material Performance

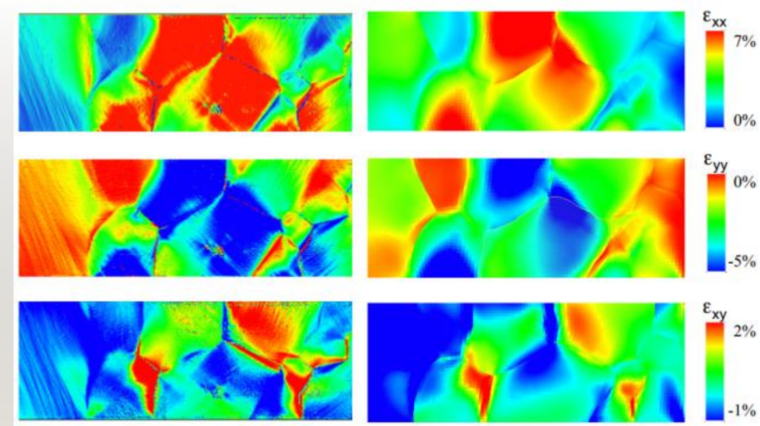


53 grains from phase field, 1.35M element conformal hex mesh



Von Mises stress distributions from CP

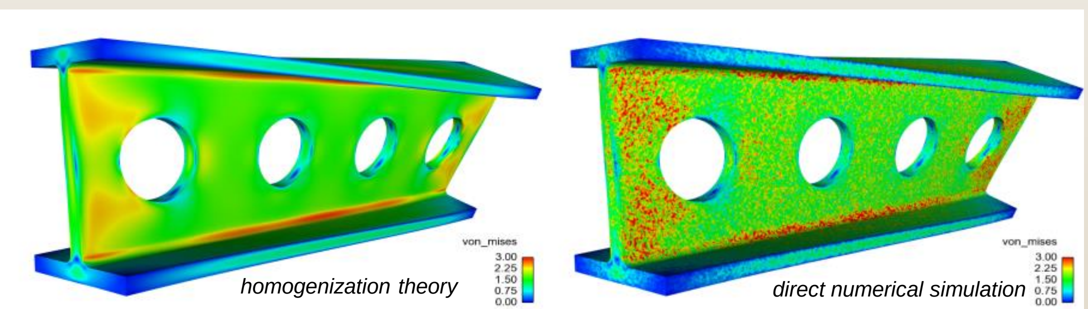
microstructure models bridge phase field & crystal plasticity simulations



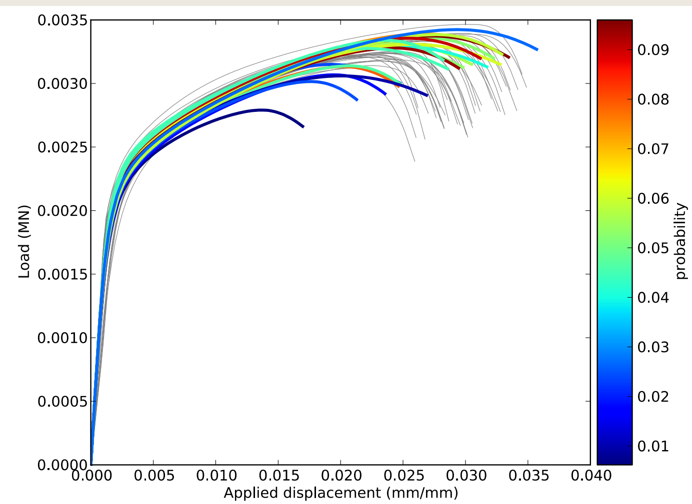
DIC measurements

simulations

oligocrystal tensile load experiment vs. crystal plasticity models



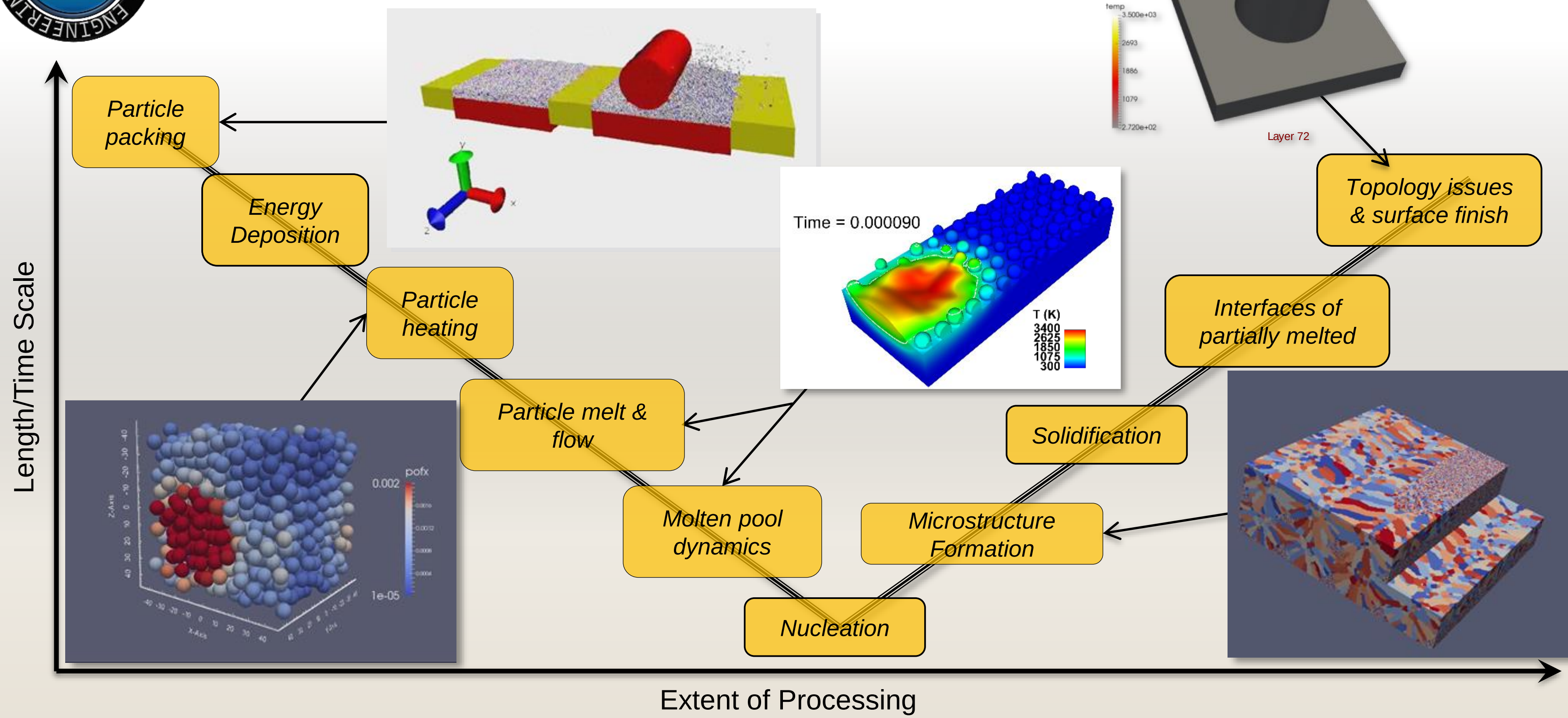
macroscale torsion stress fields



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

Brad Boyce, Corbett Battaile, Jay Carroll, Joe Bishop

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

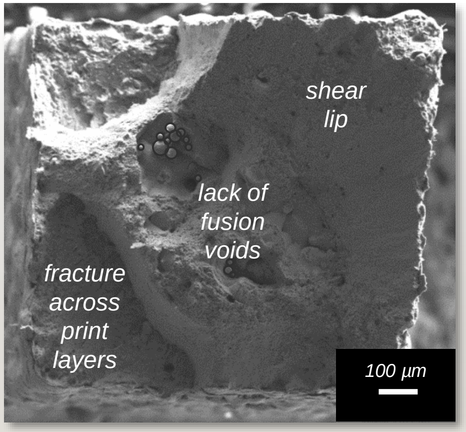
Development Approach

- First opportunities
  - predominantly cost or performance driven
  - simple integration
- Requirements, requirements, requirements
  - function in relevant environments
  - materials & processes
  - specifications & tolerances
- Quality
  - development thru qualification
    - determine process-material-performance relationships
    - specify process requirements for production
    - demonstrate process variation within functional margin
  - production
    - product acceptance of AM builds, part material & part geometry

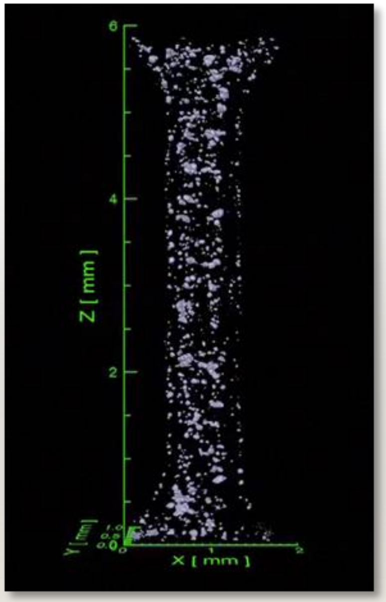
Material Assurance

- Material formation concurrent w/geometry
  - how to ID a bad part?
    - must quantify <u>critical</u> defects & useful “signatures”
    - processes are currently open loop
    - complexity isn’t “free”
  - requires significant design margins **and/or** rigorous post-process inspection / validation

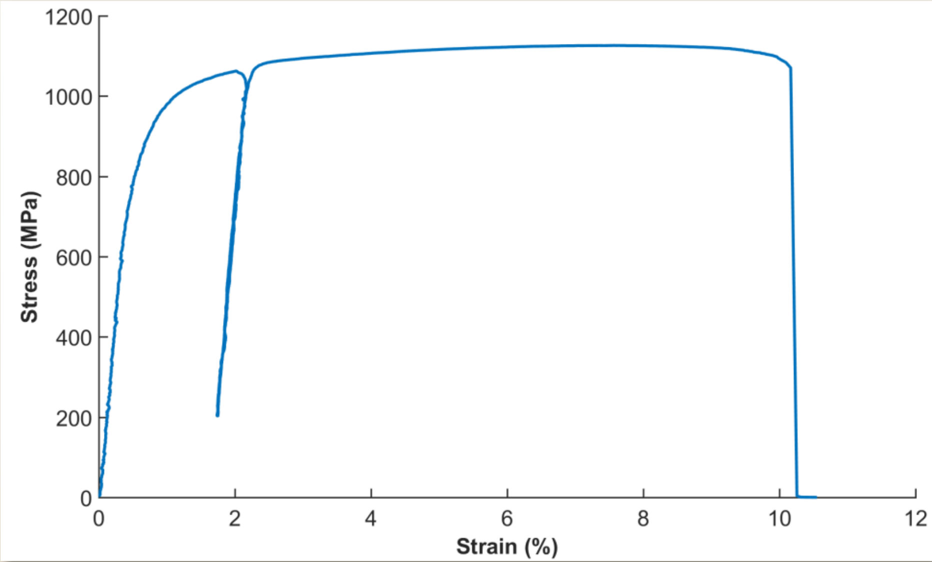
- Understand mechanistic impacts on properties
  - build process-structure-property relationships to predict margins & reliability
  - characterize stochastics
  - design for uncertainties
  - provide scientific basis for qualification of AM metals for high consequence applications



17-4PH dogbone fracture surface



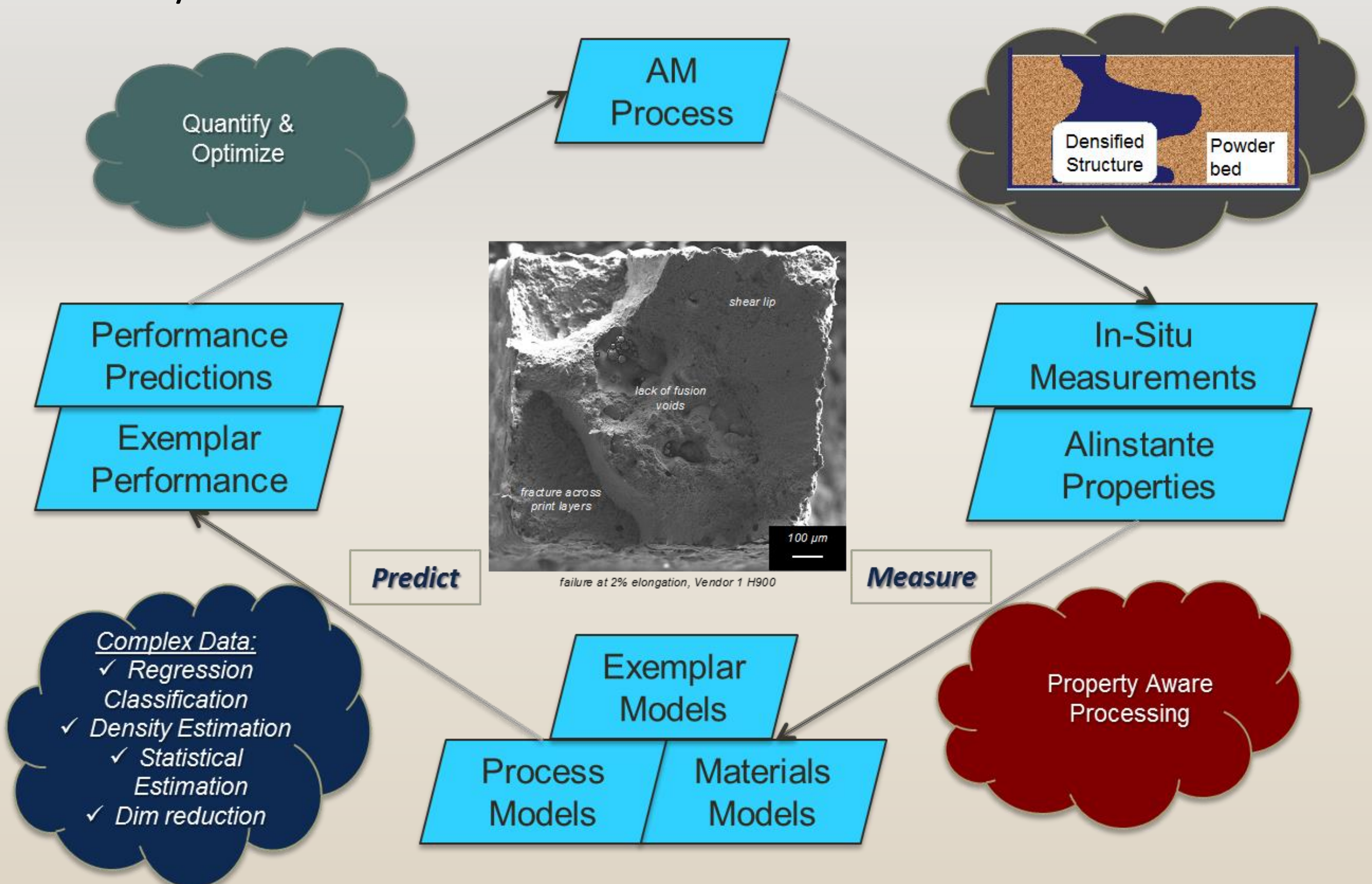
17-4PH dogbone porosity



17-4PH dogbone stress strain response

Born Qualified Grand Challenge LDRD

- "Changing the Engineering Design & Qualification Paradigm"
  - leverage AM, in-process metrology & HPC to revolutionize product realization
  - starts w/foundational materials science



QUESTIONS?

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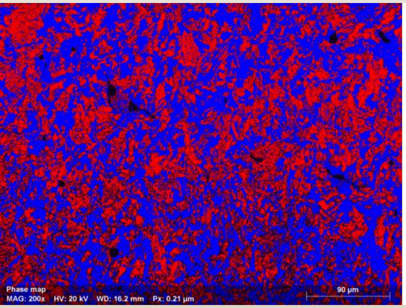
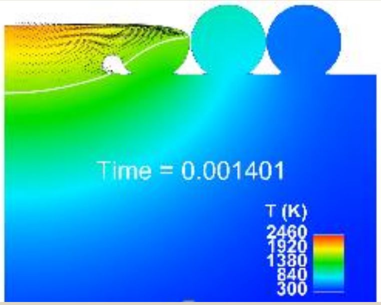
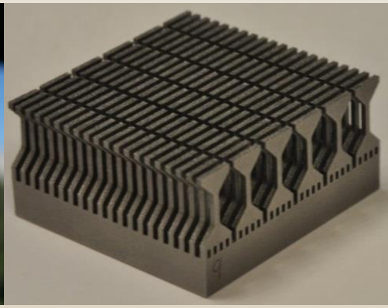
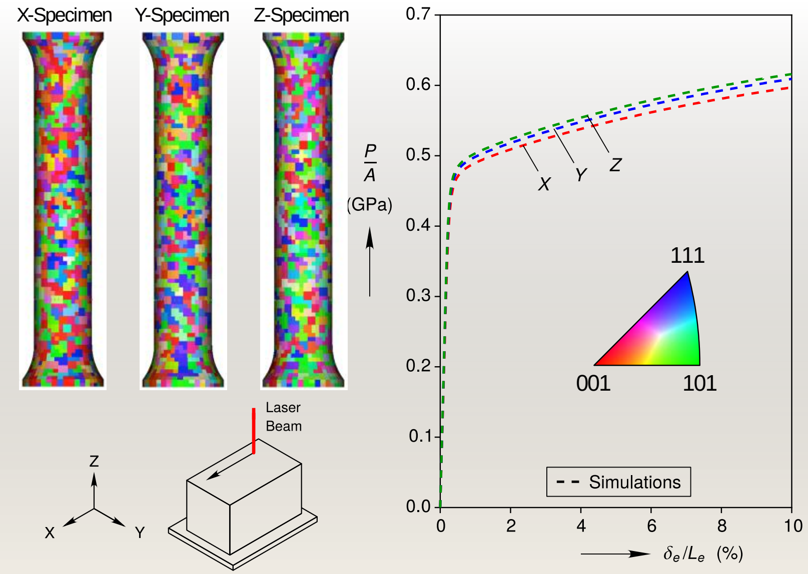




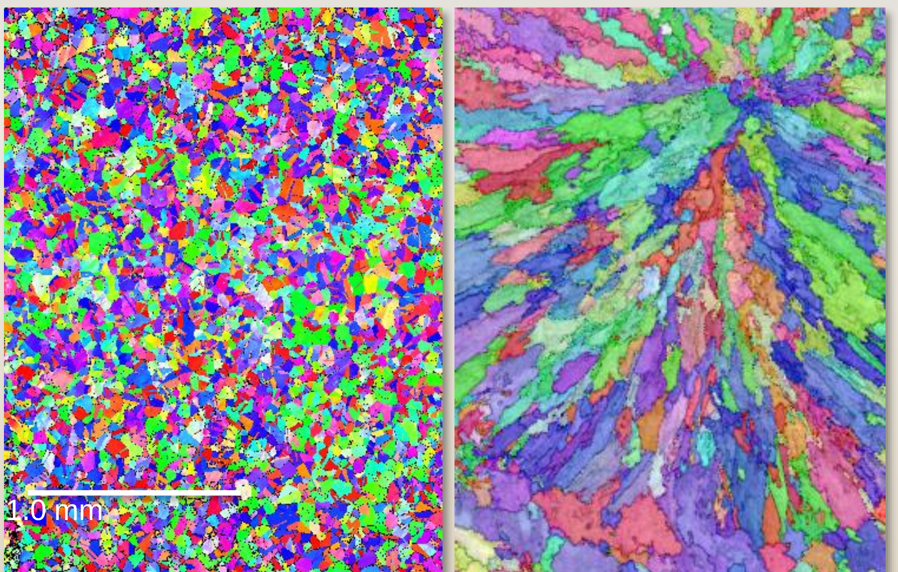


Variable Strain Rate Mechanical Response

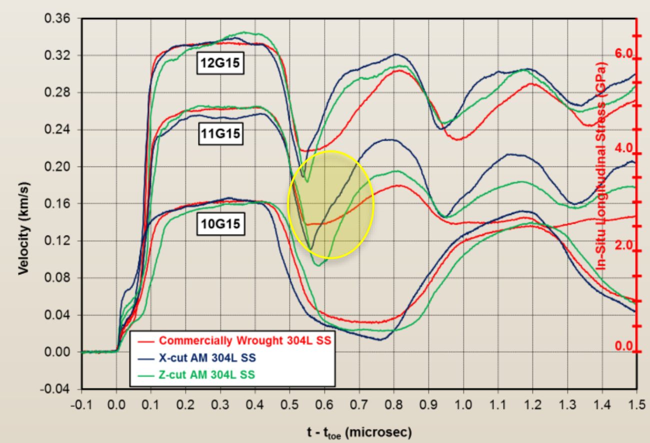
- High power LENS (0.5-3.8 kW, Penn State)
- Exploring strain rates from 10^{-5} to 10^{6} /sec
  - quasi-static to gas gun
- Building crystal plasticity predictive models
- Probing material behavior using neutron diffraction (LANL)



prediction of material anisotropy



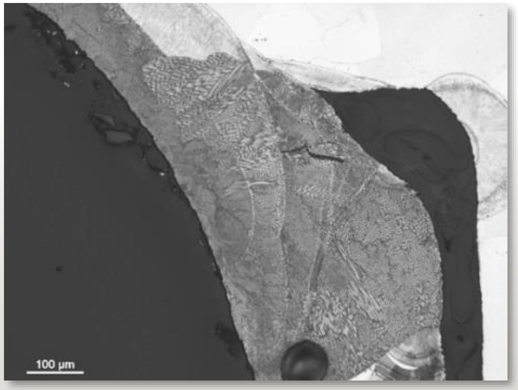
wrought 304L SS microstructure (left) & AM (right)



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

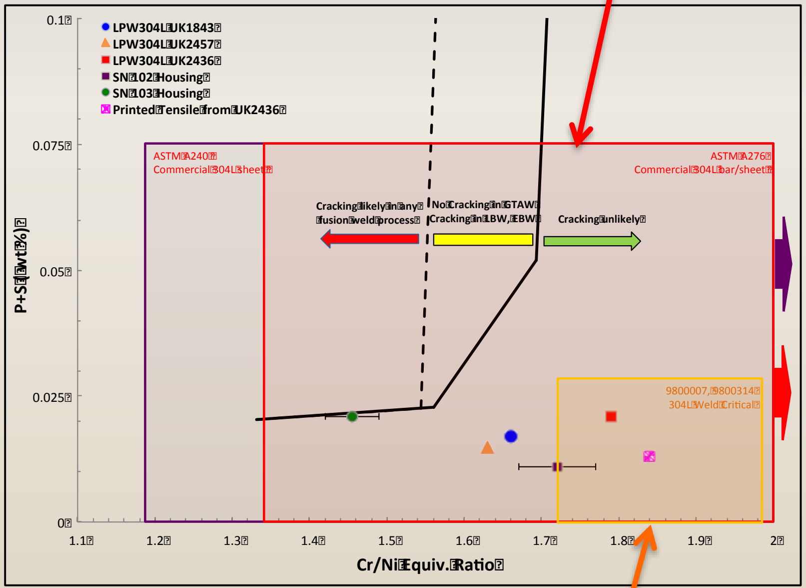
Weld Critical Powder

- Welding studies identified cracking risk from commercial 304L powder
  - draft spec developed & powder heat lot procured mimicking weld critical 304L VAR chemistry
  - stringent composition range to prevent solidification crack susceptible microstructure
- Housing will have reduced weld cracking susceptibility
  - housings & material samples fabricated from weld critical powder for testing



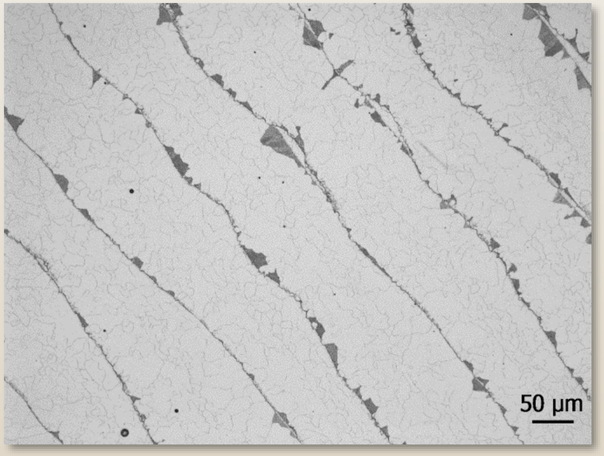
weld cracks on housing made from uncontrolled commercial AM powder

machined 304L housing composition range



Solidification Cracking Susceptibility Diagram

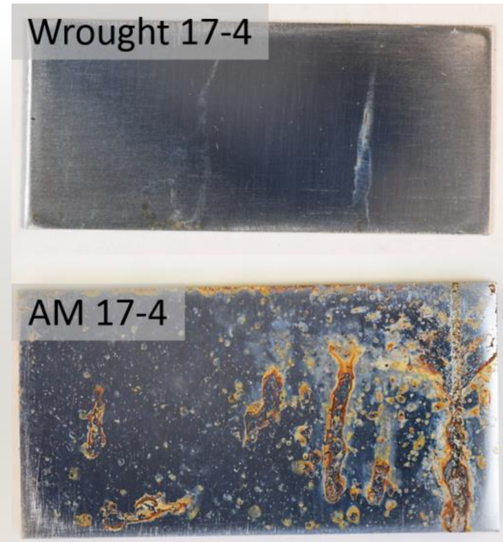
weld-critical AM 304L powder range



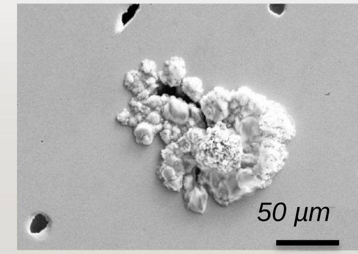
microstructure of AM part produced from weld critical powder shows solidification crack resistant microstructure

Corrosion

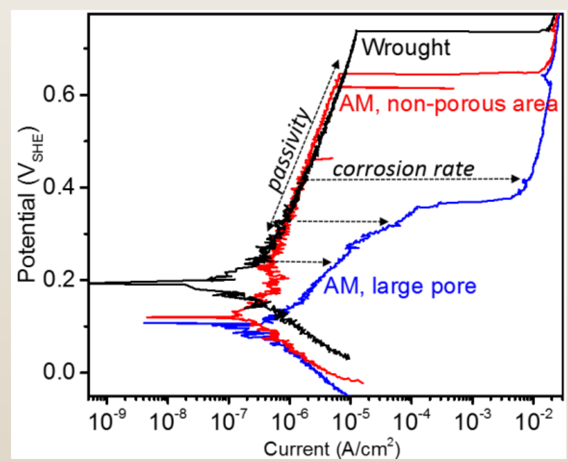
- Exploring
  - performance of PBF stainless steels relative to conventional materials
  - linkages to processing-microstructure
- Case study: commercial PBF 17-4 PH vs. conventional wrought
  - inferior performance of AM material
  - passivity compromised by porosity in material
  - sets up favorable (crevice-like) conditions for pitting corrosion
- Underway
  - performance characterization of 304L and 316L
  - impact of varied process conditions & surface finish on passivity



conventional wrought and AM 17-4PH coupons after B117 salt fog corrosion test



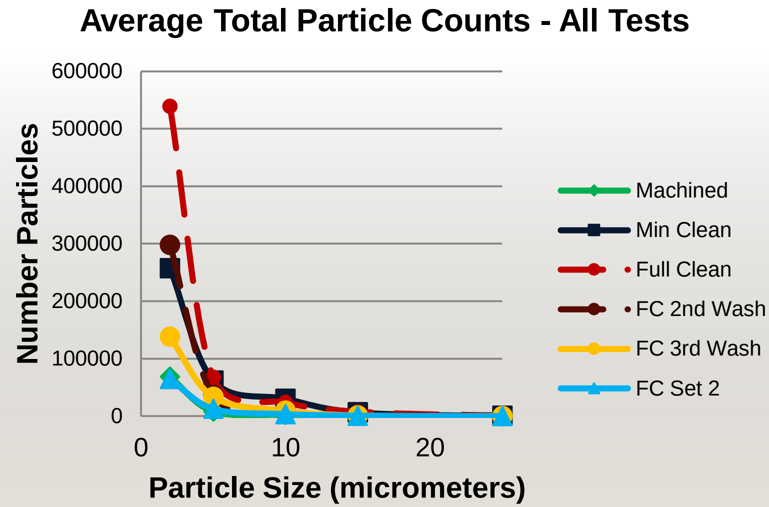
polished AM 17-4PH surface exhibiting corrosion product build-up over pore after 7 day immersion in 0.6 M NaCl



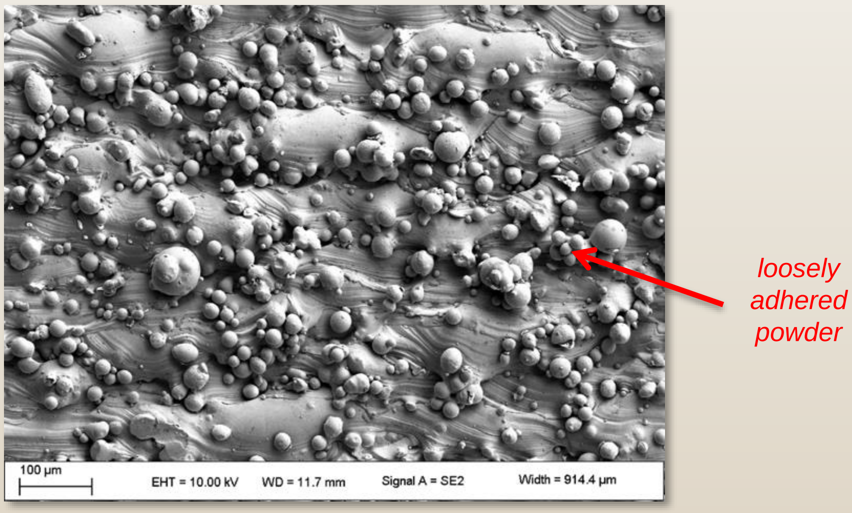
micro-electrochemical measurements in 0.6 M NaCl reveal AM 17-4 porosity compromises stainless nature

Cleaning

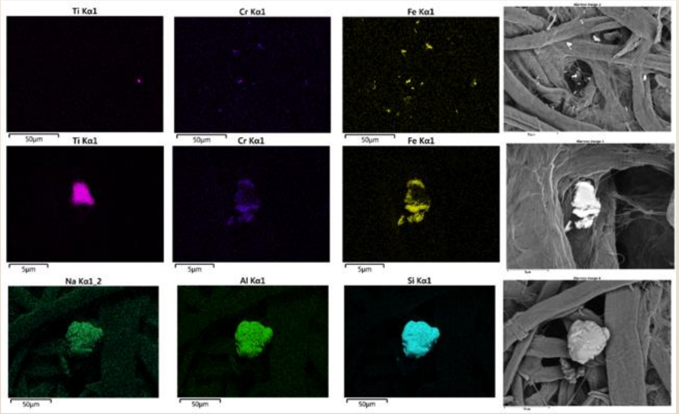
- Concern over loose, conductive “cling-ons”
- Study initiated to examine efficacy of cleaning
  - blasting & vibratory polishing housings
  - cleaning wash & rinse
- Parallel effort to examine cleaning residues potentially trapped in rough AM surfaces



increased cleaning time (light blue) reduces loose particle count to machined housing levels (green)



as-printed AM 304L surface



EDS particle analyses to characterize composition/morphology of particles after cleaning

Kim Archuleta, Jeff Rodelas, Bradley Jared, David Bonner