SAND2019-8756PE

Additive Manufacturing at Sandia National Laboratories

PRESENTED BY

Bradley Jared, PhD, Materials Engineering and Manufacturing S&T

Allen Roach, PhD, Thermal, Fluid and Aero Sciences

Outline

Motivation

Processes
- metal
- non-metal

Computational tools
- PLATO design optimization
- mod-sim

Materials
- properties
- inspection
- design

SNL's Additive Interests

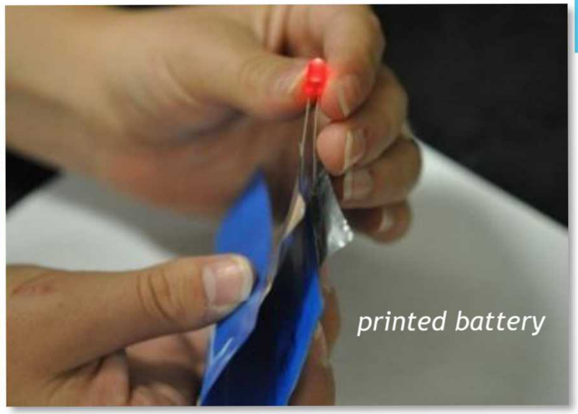
Reduce risk, accelerate development

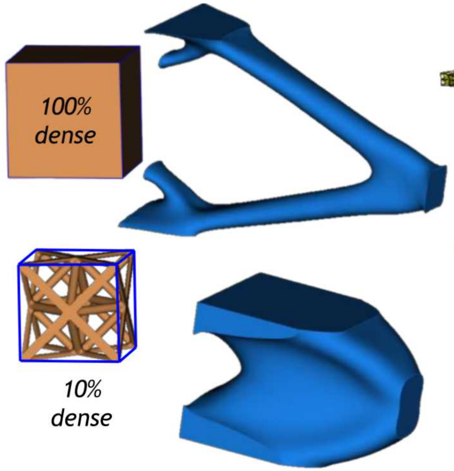
- simplify assembly & processing
- prototypes, test hardware, tooling & fixturing

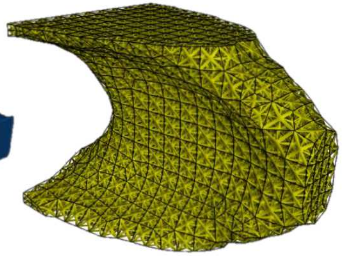
Add value

- 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"

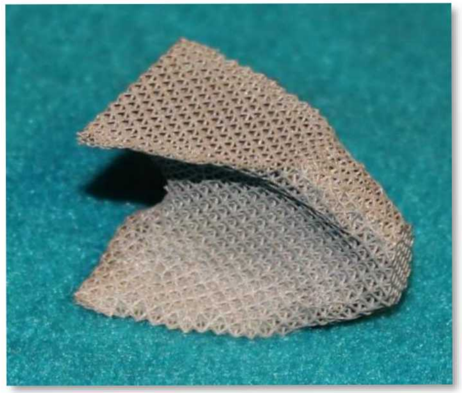
Continually growing interest across Sandia missions







lattice implementation
w/TO solutions from
PLATO,
Robbins, **Add Mfg**, 2016



316L SS lattice part

High Operational Tempo (HOT SHOT)

A sounding rocket designed and launched by Sandia lifts off from the Kauai Test Facility in Hawaii on April 24. (Photo by Mike Bejarano and Mark Olona, Sandia Lab News)

Nicholas Leathe

Laser Powder Bed Fusion

Machines

- supporting research & development
- 3D Systems
  - ProX 200 (NM)
    - 140x140x100mm build volume
  - ProX 300 (NM)
    - 250x250xx330mm build volume
- Two Renishaw AM 400
  - 250x250x300mm build volume
  - 78x78x78mm reduced volume build

Materials

- 316L stainless steel
- 304L stainless steel
- planning for Ti6Al4V, AlSi10Mg
- previously – Fe-3Si

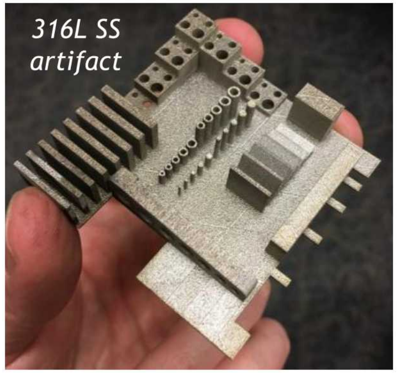

ProX 200, materials science lab


SNL/CA ProX 300


ProX 200 in operation


high throughput dogbone sample

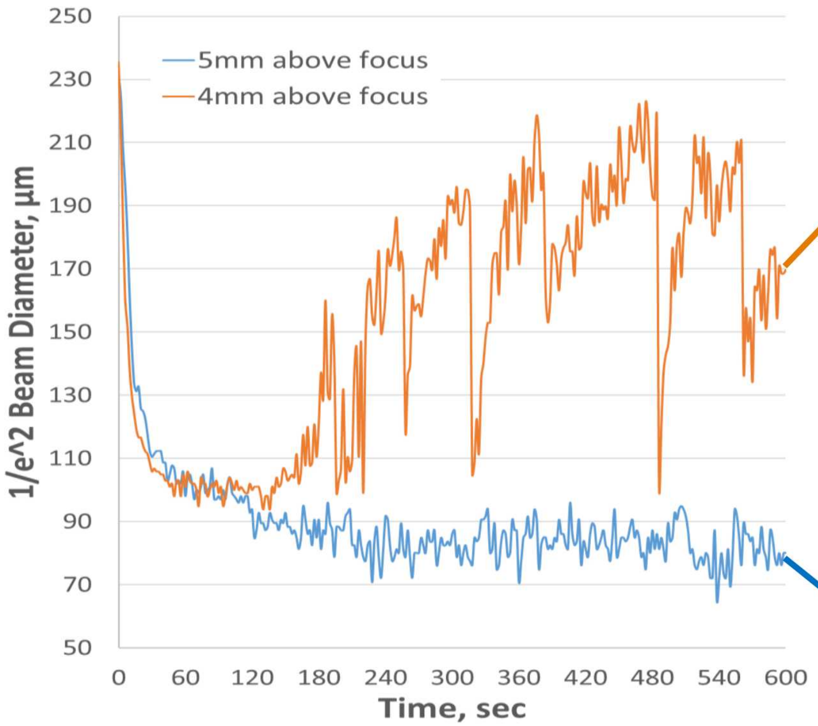

316L SS lattice part


316L SS artifact

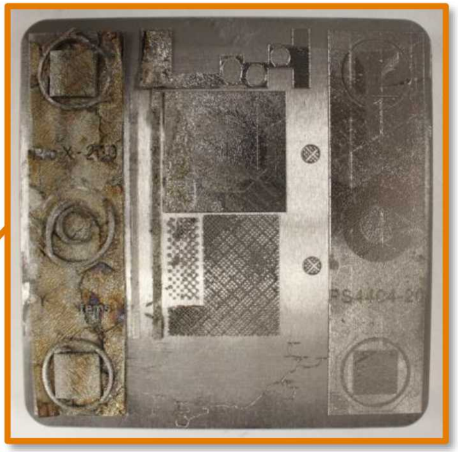

residual stress artifacts

Bradley Jared, Manuel Martinez, Dale Cillessen, David Saiz

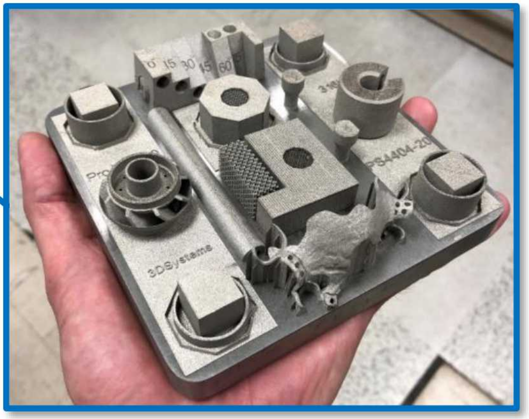
Machine Metrology is Critical to Assure Part Quality



beam diameter variations w/original f-theta lens

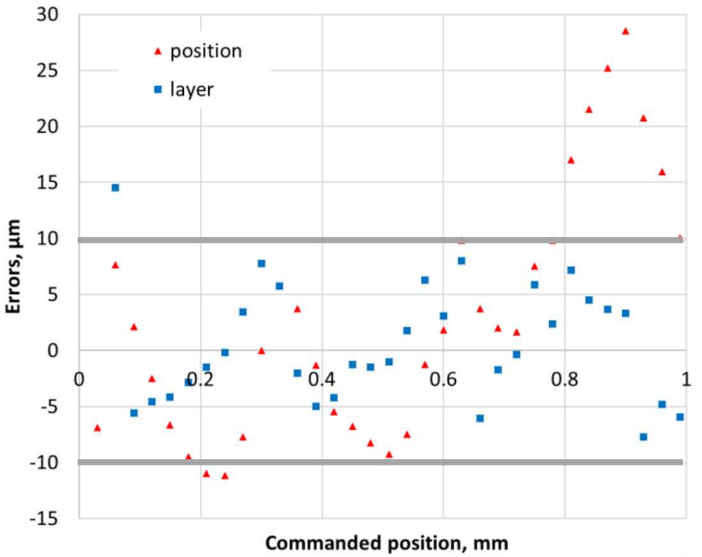


nominal focus offset

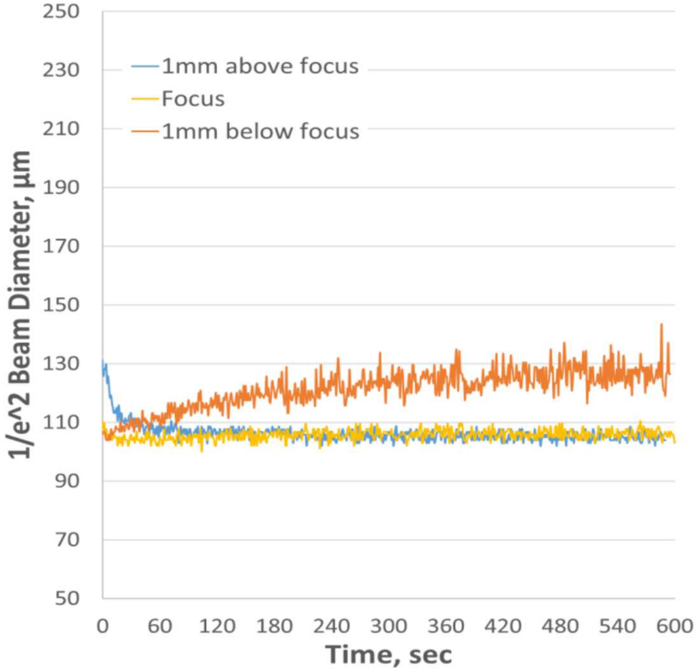


5mm focus offset

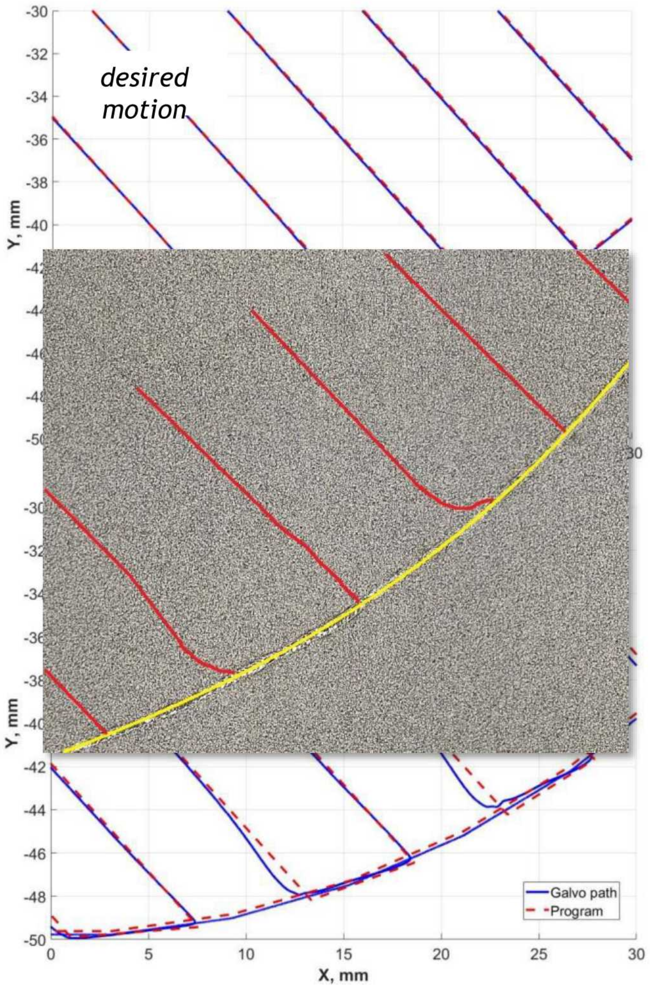
layer thickness errors

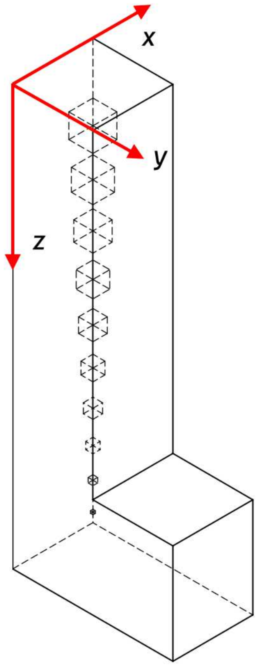


upgraded f-theta lens response

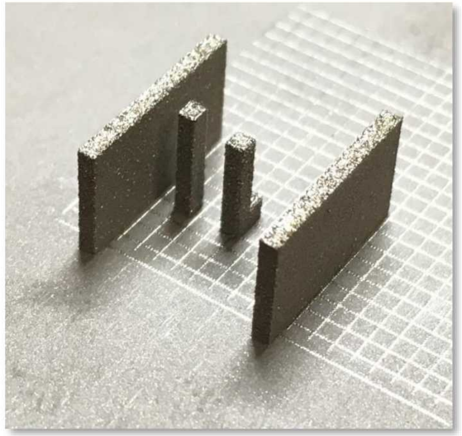


Real-Time Machine Monitoring Reveals Process Perturbations

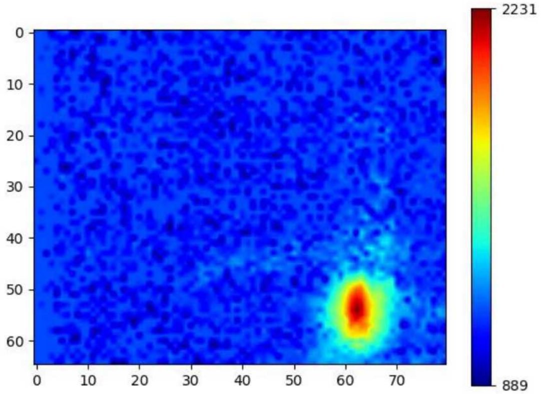




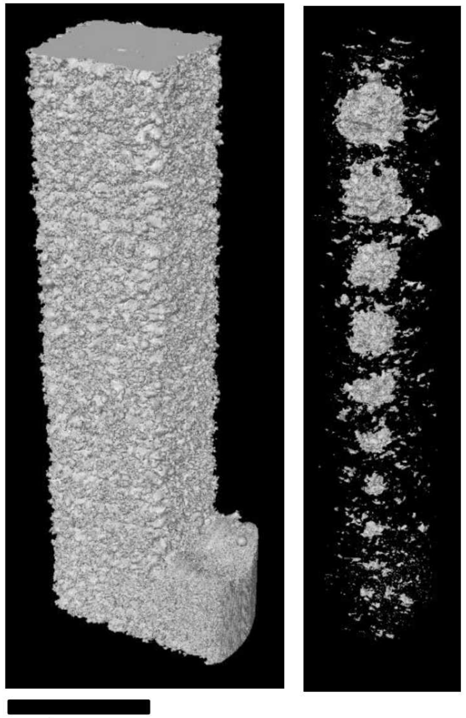
captured hole
structure design



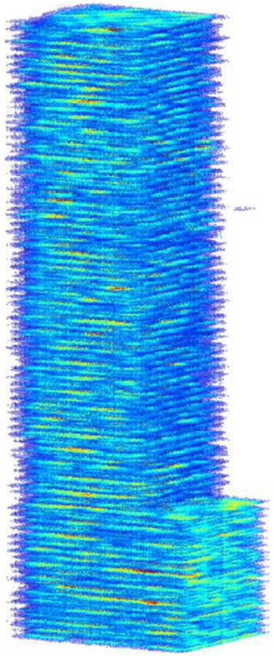
1x1x5mm 316L SS column w/support walls



melt pool motion, nominal settings



µCT reconstruction



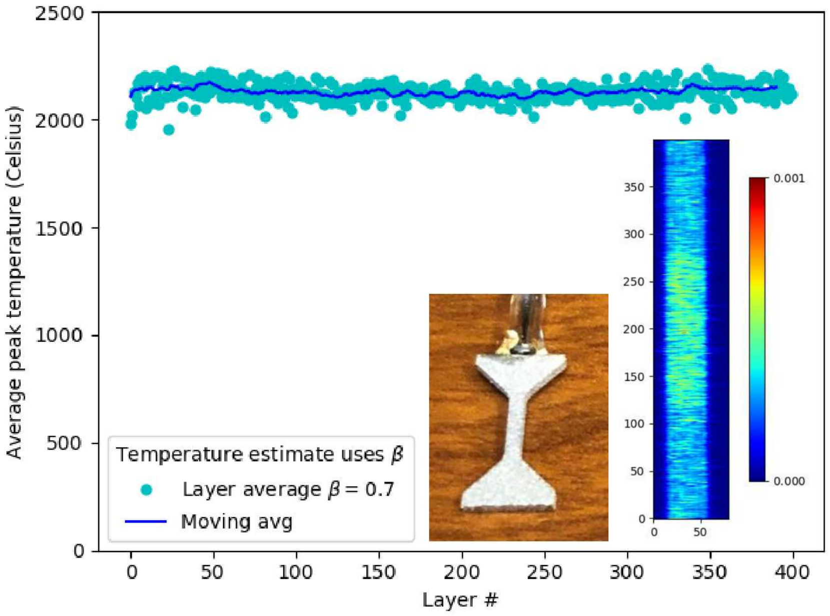
two color pyrometer data reconstruction

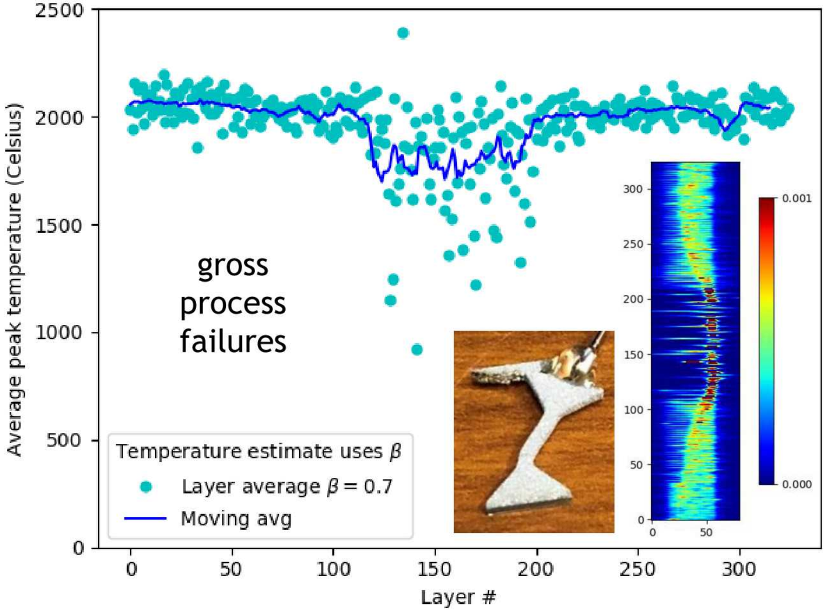
Archive, Research, Control, Synchronization (ARCS)
- Penn State, 3D Systems collaboration

motion @ 100kHz

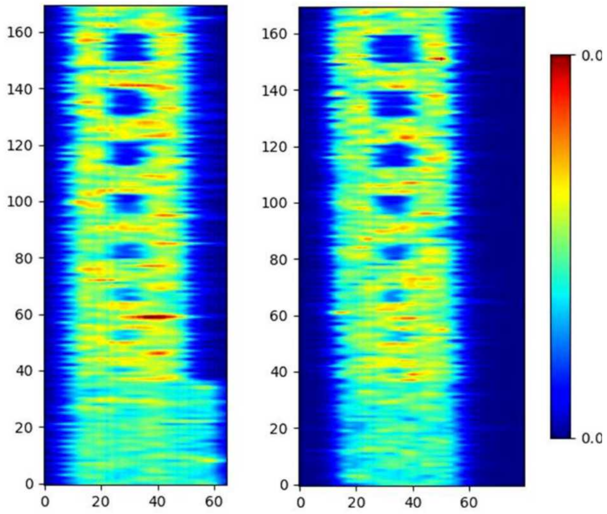
Exploring multiple sensor signatures
- thermal, optical, acoustic
- two-color pyrometry explored here
- data management & analysis is critical

Correlating Process Signatures w/Material Structures



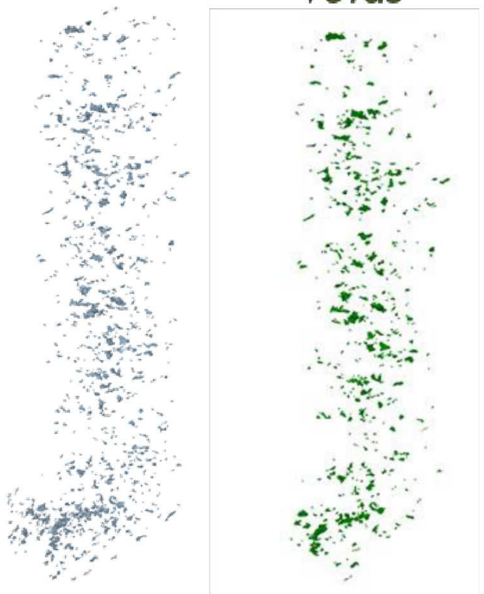


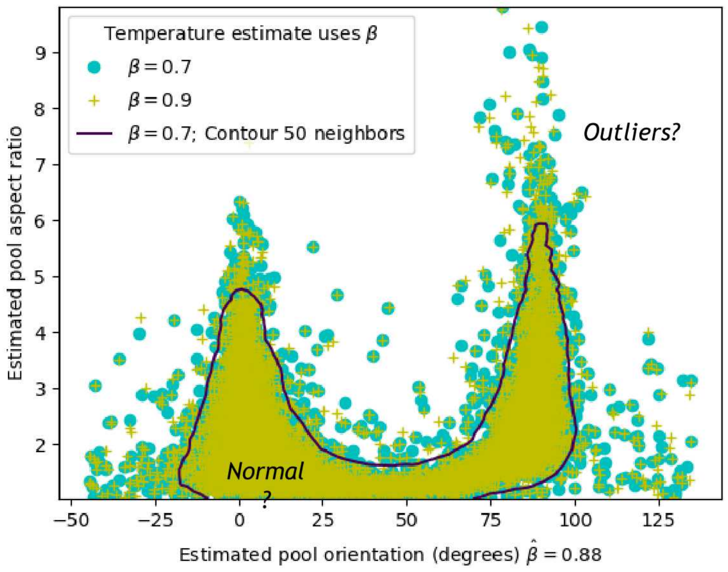
melt pool outliers via ***machine learning*** correlate local void porosity

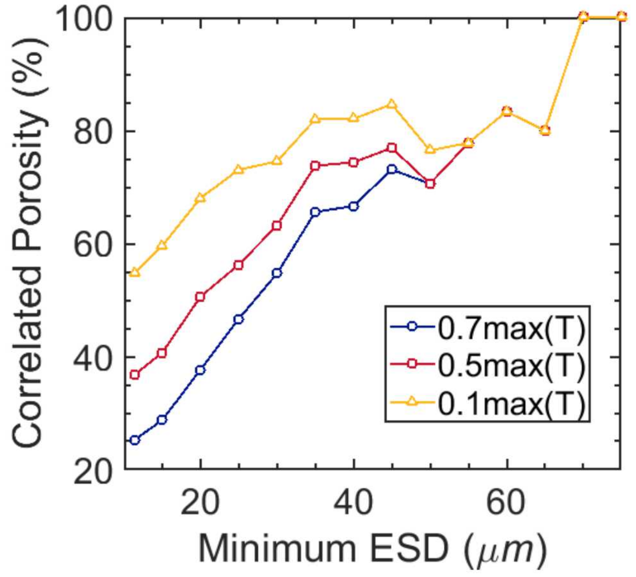


pyrometer data, YZ section (left) & XZ section (right)

All voids *Correlated voids*







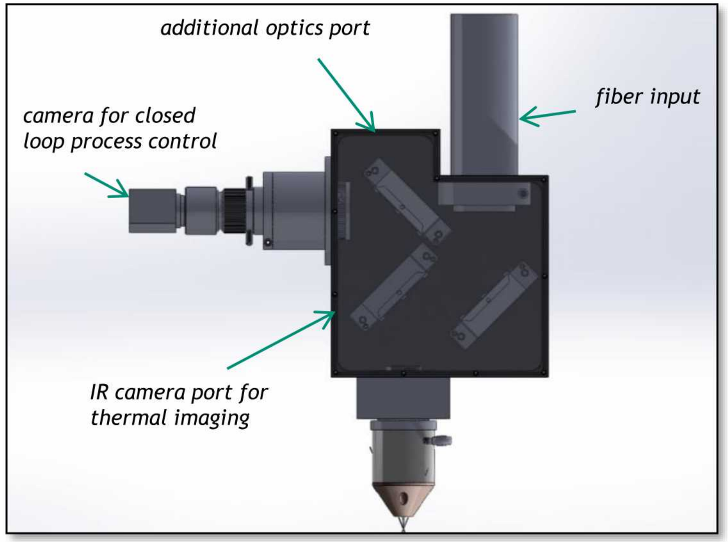
John Mitchell, paper in process

Laser Engineered Net Shaping (LENS®)

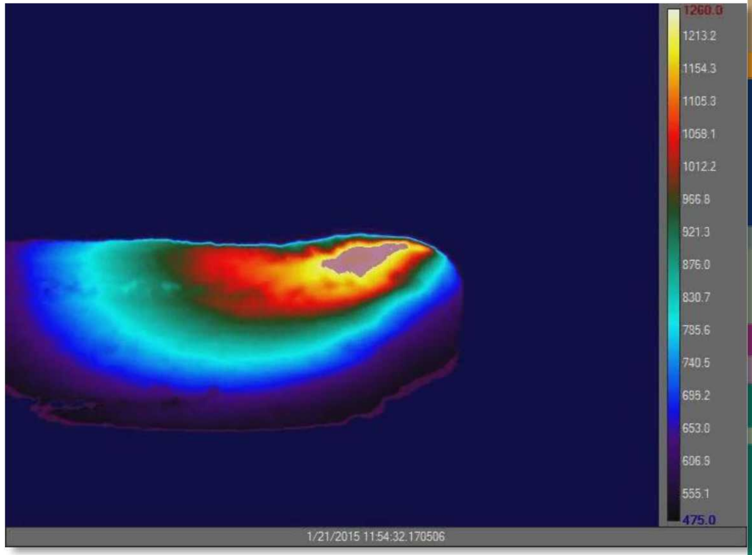
SNL custom research machine

- 2 kW laser source
- 10,000 rpm spindle for machining
- process diagnostics
- 5 powder hoppers for in-situ alloy & multi-material processing
- materials – steel, Ti, Cu, refractories, HEAs, magnetics
- 150x175x150mm build volume

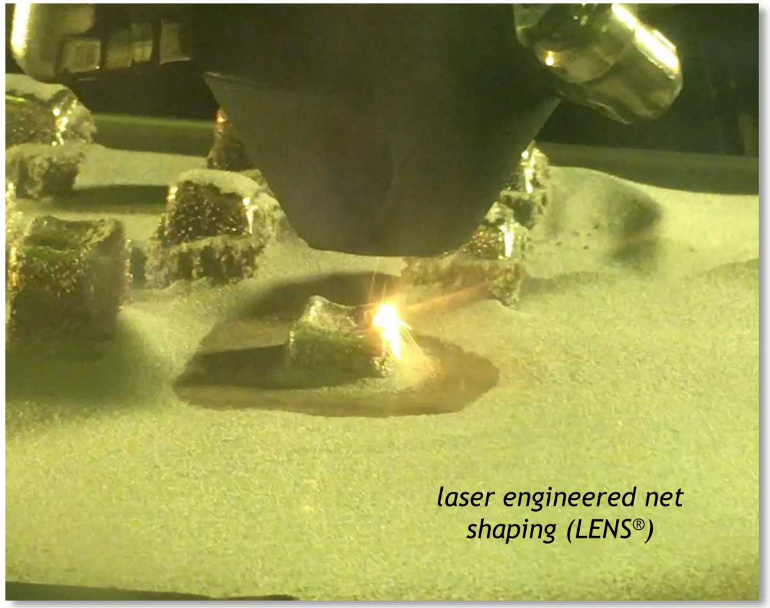
Optomec MR-7 – LANL, SNL/CA



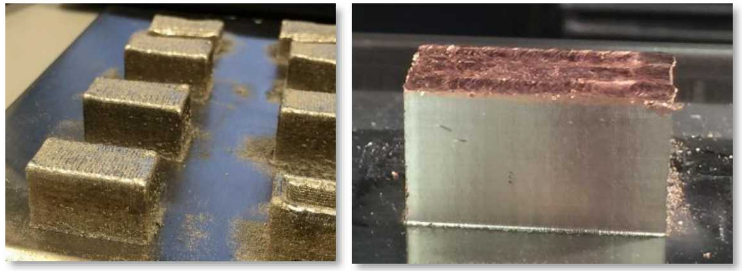
multi-material Hiperco core w/304L exterior



thermal history during bi-directional metal deposition



laser engineered net shaping (LENS®)

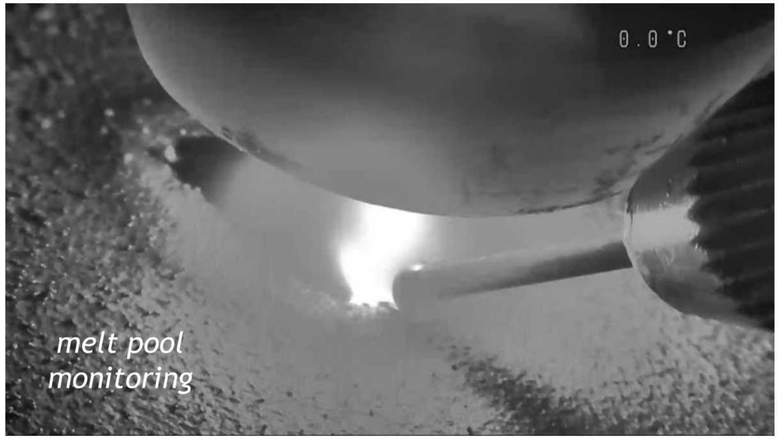


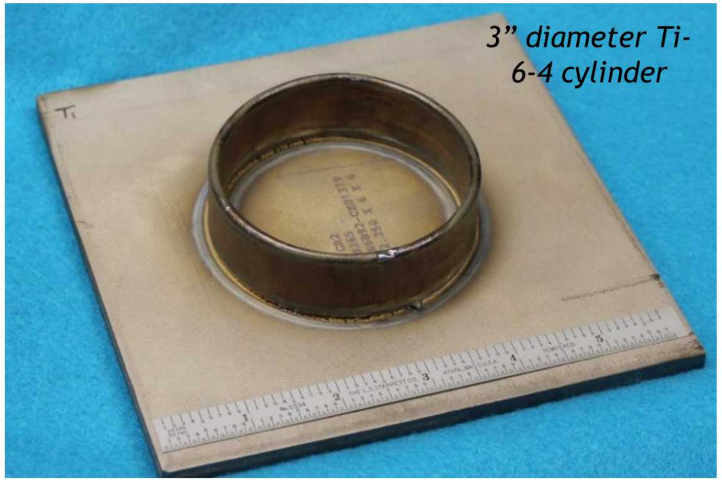
304L SS / Cu multi-material thermal concentrator

Shaun Whetten, Ray Puckett

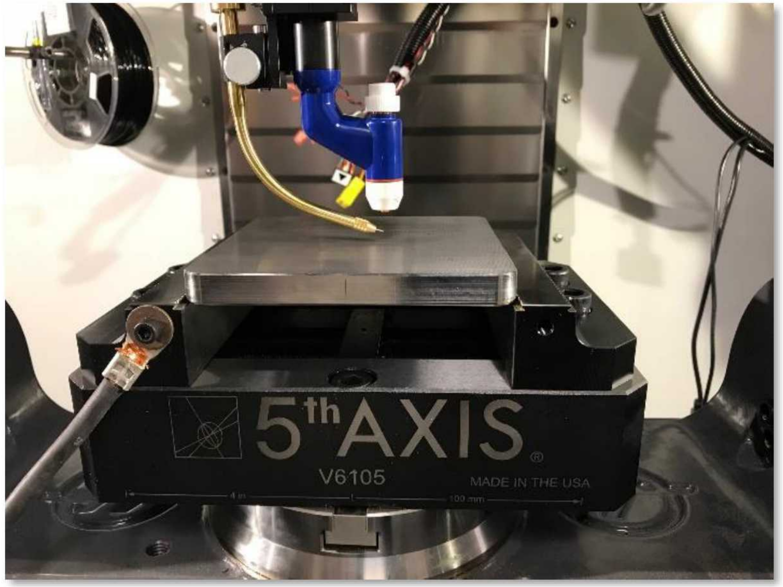
Wire Feed

New capability for SS, Ti & Cu
- plasma arc welding torch (PAW)
  - MIG head ordered
- retro-fit onto HAAS VF2
  - hybrid additive / subtractive capable
- good microstructures observed
- addressing growing needs for ES&H & larger parts
  - 300x300x150mm build volume
  - 2-6mm weld bead size





HAAS VF2 mill-turn



Ti-6Al-4V printing

Shaun Whetten, Ray Puckett

Direct Write

Processes

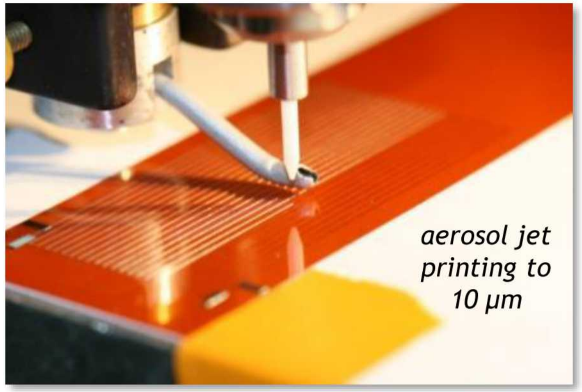
- ink jet, aerosol jet, extrusion casting, laser photo-lithography

Materials

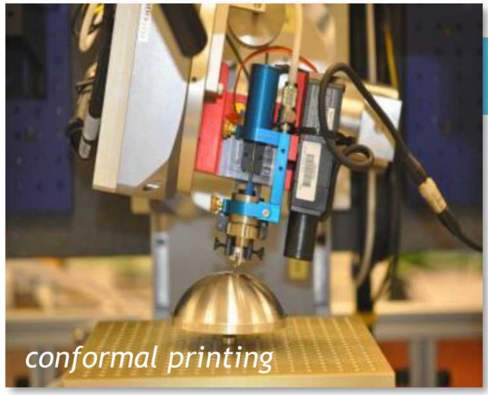
- epoxies, silicones, dielectrics, ceramics, nano-inks, energetics
- substrates: plastics, ceramics, polyimide, encapsulants, metals, FR4, glass, paper
- formulation, synthesis & characterization

Sintering / curing

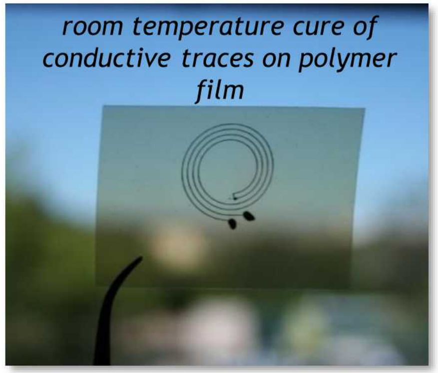
- thermal, joule heating, UV, plasma, laser, microwave, room temperature



aerosol jet printing to 10 µm

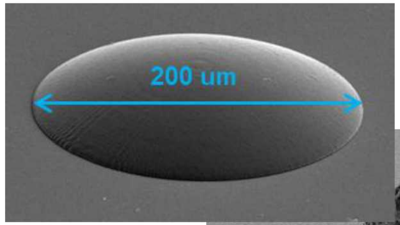


conformal printing

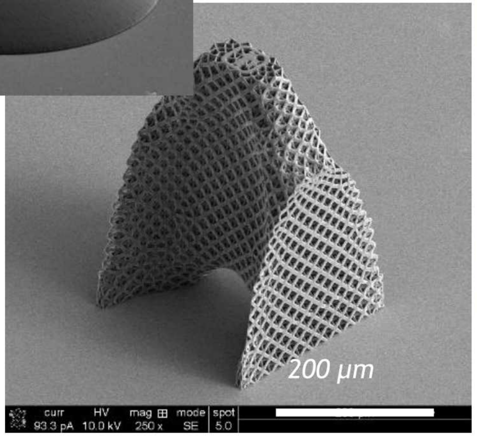


room temperature cure of conductive traces on polymer film

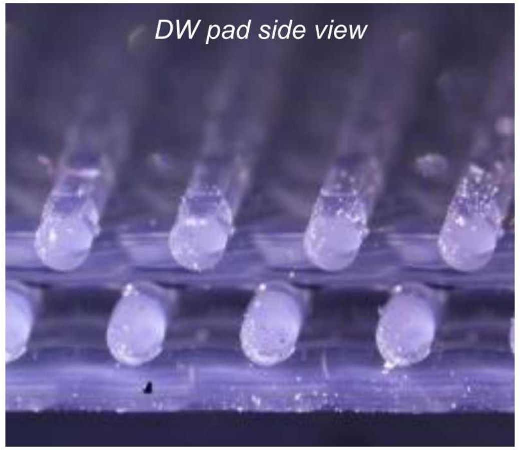
printed battery



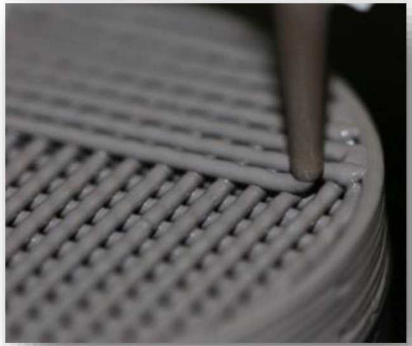
printed micro-optic

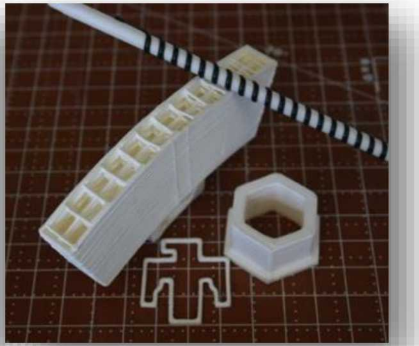


Nanoscribe two-photon lithography



DW pad side view





extrusion casting (Robocasting)

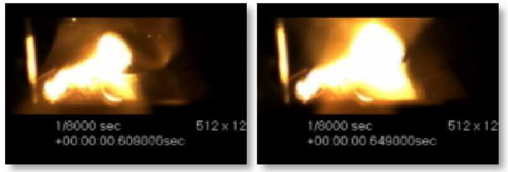
ceramic-thermoplastic 3D (CT3D) printing alumina

Adam Cook, Bryan Kaeher

Energetic Materials

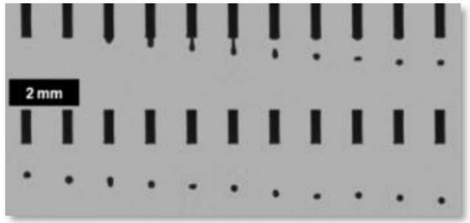
Robocasting

Aluminum/Nickel reactive material

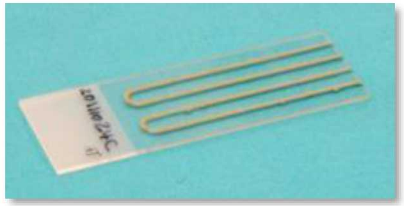


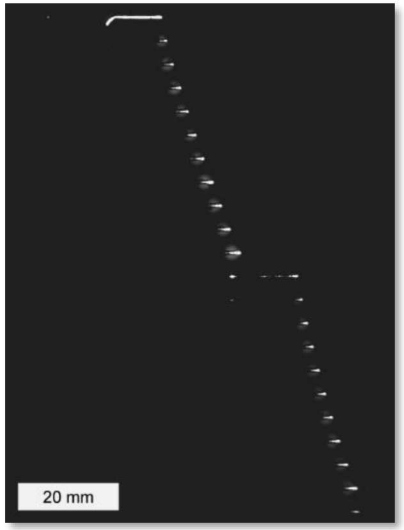
Tappan, A.S., Groven, L.J., Ball, J.P., Miller, J.C., Colovos, J.W., Joseph Cesarano, I., Stuecker, J.N., and Clem, P., "LDRD Final Report: Free-Form Fabrication and Precision Deposition of Energetic Materials,“ SAND2008-0965, February, 2008.

Inkjet printing



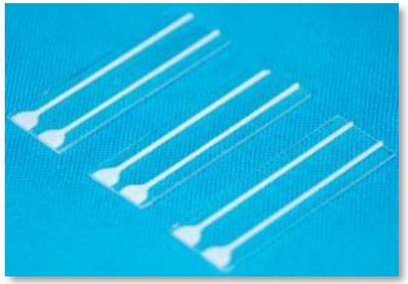
Aluminum/bismuth trioxide thermite



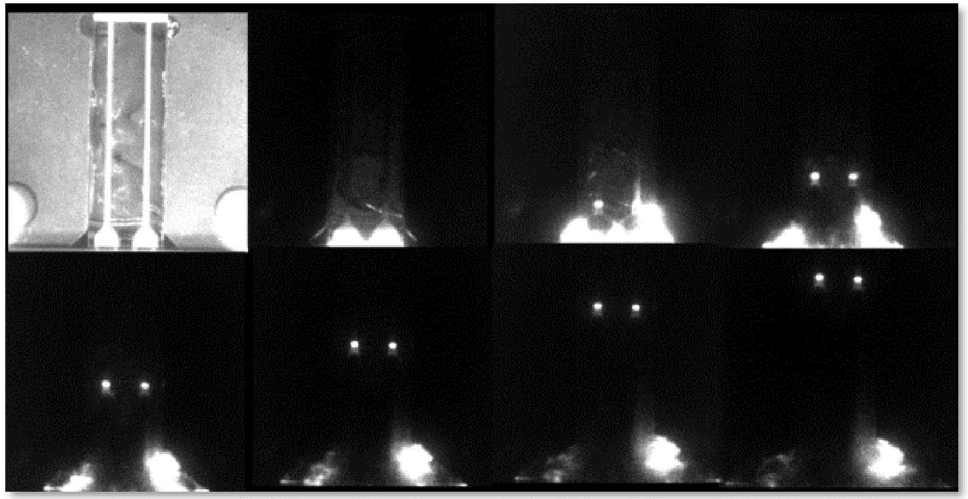


Tappan, A.S., Ball, J.P., and Colovos, J.W., "Inkjet Printing of Energetic Materials: Al/MoO3 and Al/Bi2O3 Thermite," *The 38th International Pyrotechnics Seminar*, Denver, CO, June 10–15, 2012.

Physical vapor deposition



Pentaerythritol tetranitrate high explosive

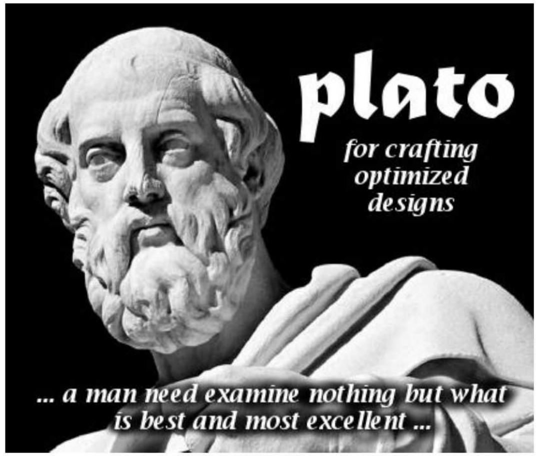


Tappan, A.S., Knepper, R., Wixom, R.R., Marquez, M.P., Miller, J.C., and Ball, J.P., "Critical Thickness Measurements in Vapor-Deposited Pentaerythritol Tetranitrate (PETN) Films," *14th International Detonation Symposium*, Coeur d'Alene, ID, April 11-16, 2010.

Different materials and applications require different techniques

Alex Tappan

PLATO Design Platform



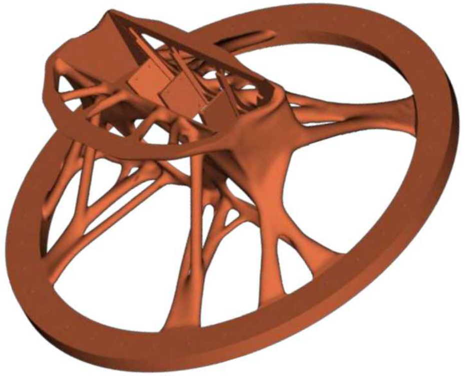
End-user environment for physics-based design using topology optimization

HPC-enabled: physics, optimizers, services, …

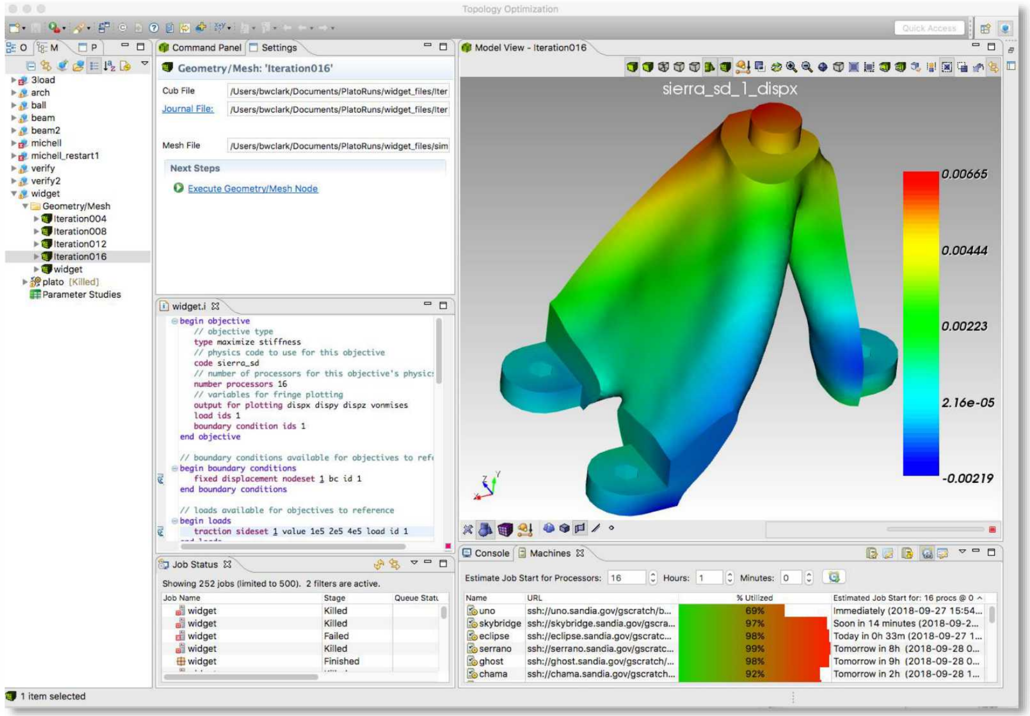
Interactive design feedback and user control

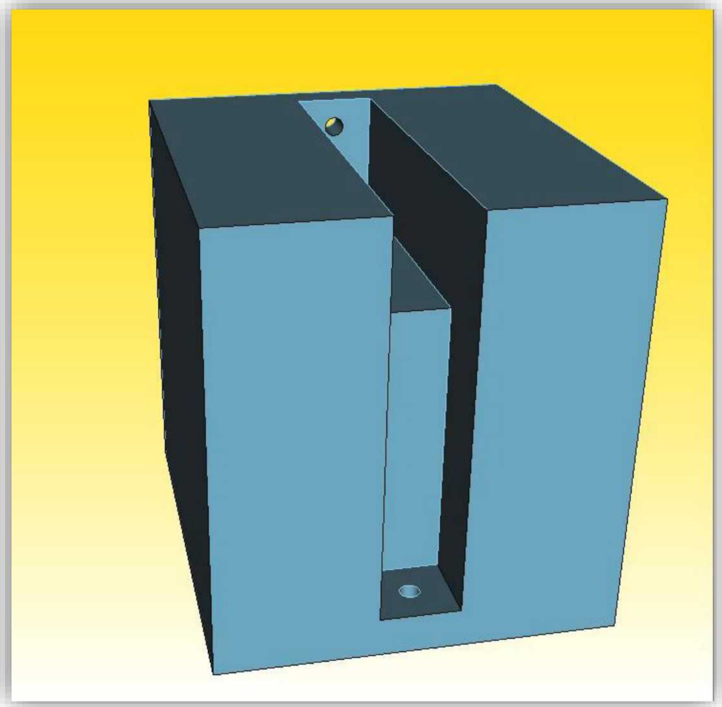
Smooth, print-ready designs

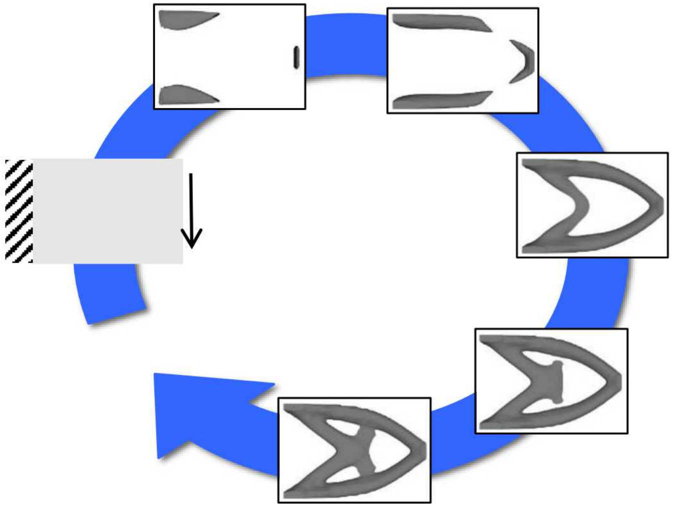
Extensible architecture



Website: www.sandia.gov/plato3D
Github: https://github.com/platoengine/platoengine
email: plato3D-help@sandia.gov







Interactive design feedback and user control

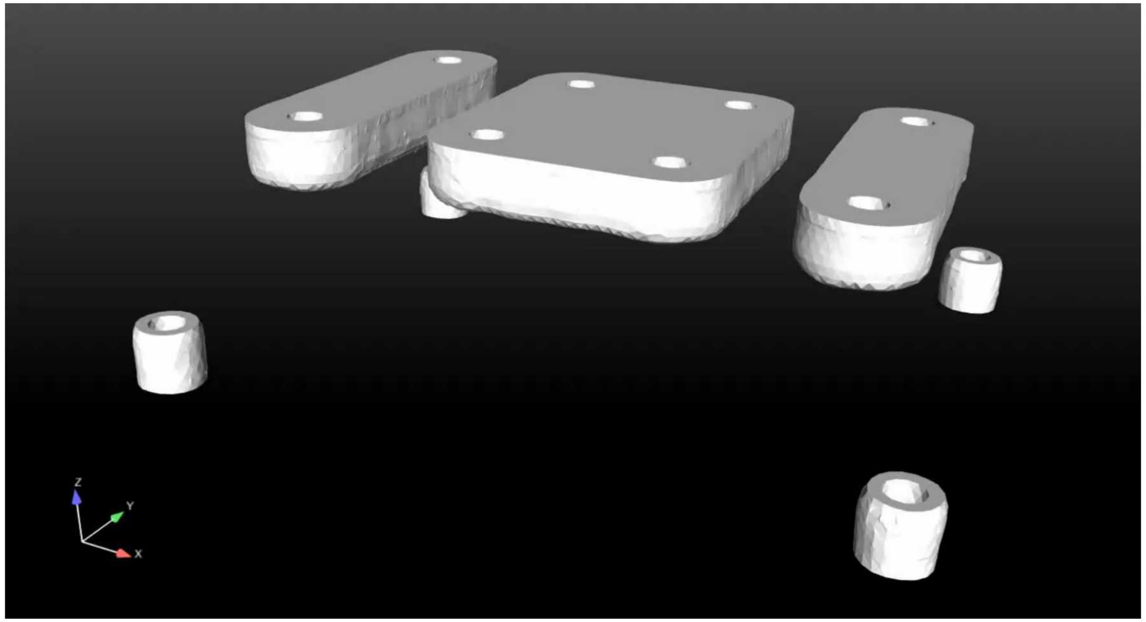
Brett Clark, Josh Robbins, Miguel Aguilo

Optimization-Based Design for Manufacture

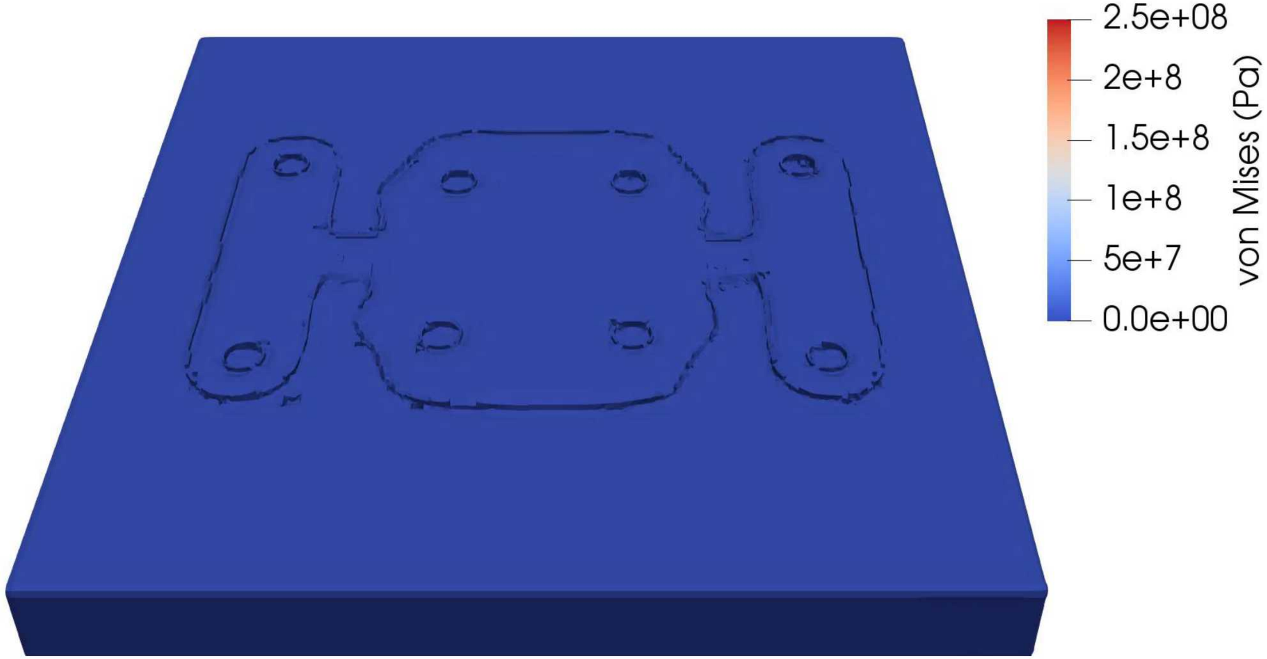
"Manufacturability" objectives: integrate manufacturing process awareness into optimization-based design tools to enable manufacturability and performance

- static loads, stress constraints, thermomechanics, residual stress
- mass, compliance, thermomechanical minimizations

Concurrent shape and topology optimization: deliver an optimization-based concurrent component/system design tool to reduce design iteration cycle time



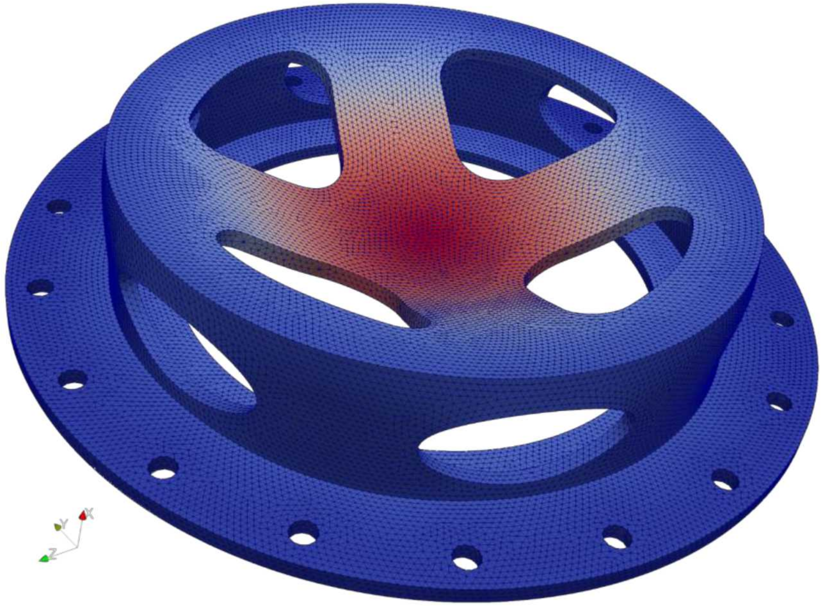
coupled thermo-mechanics TO geometry generation, maximized stiffness & heat conduction



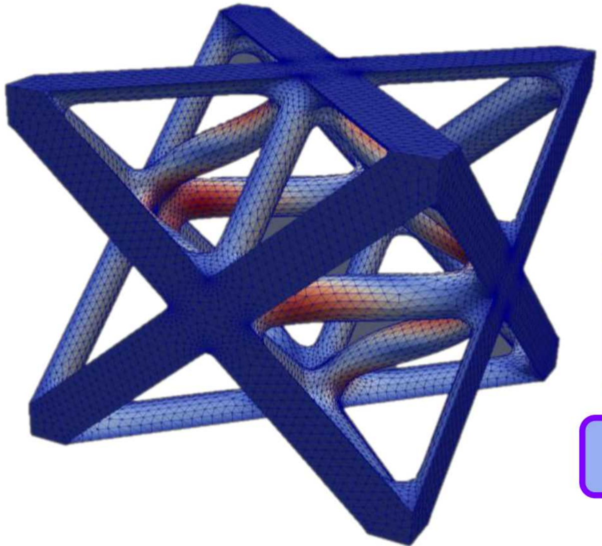
residual stress prediction from high-fidelity process simulation

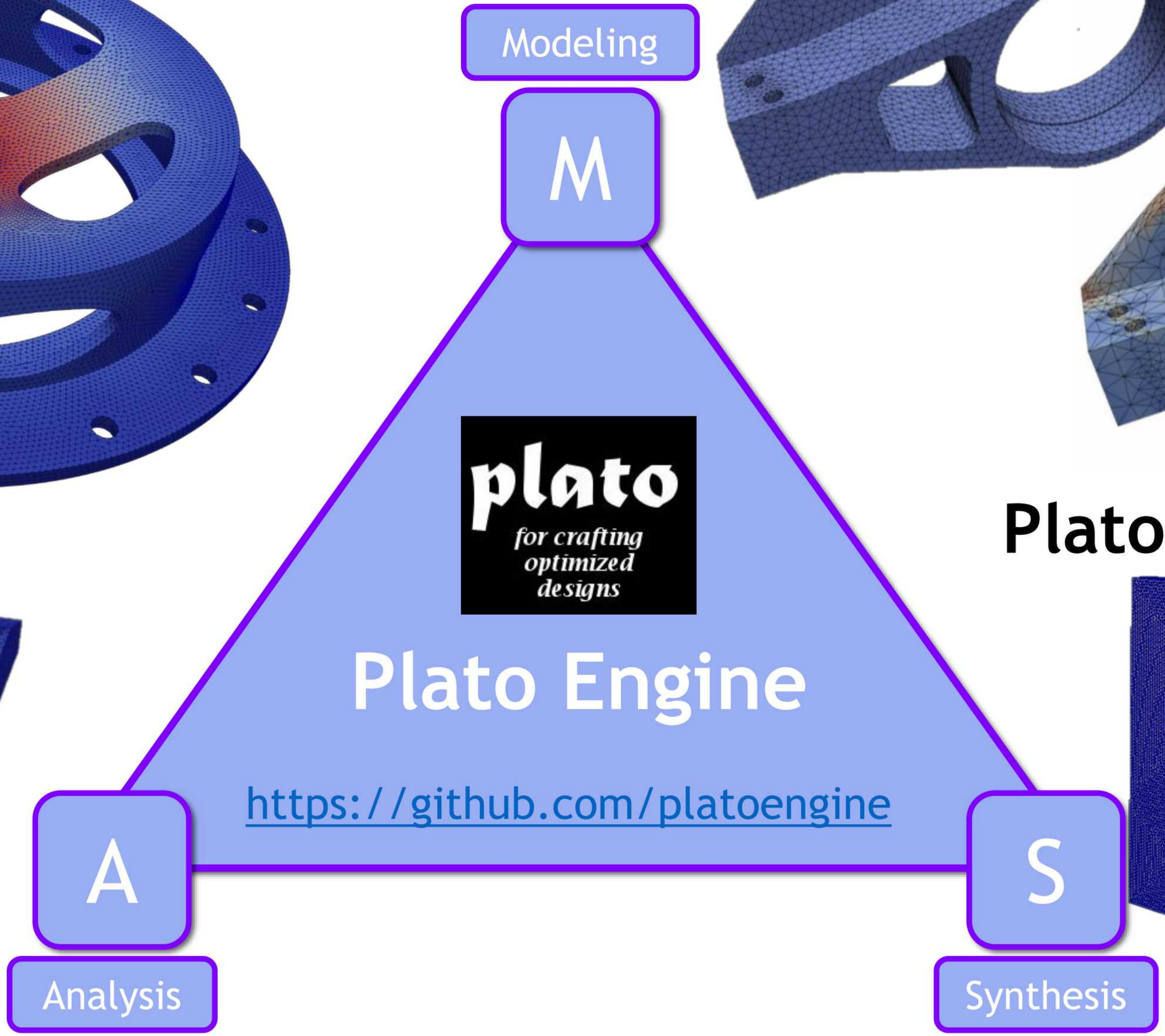
Josh Robbins, Brett Clark, Kyle Johnson

DARPA TRADES Design Ecosystem

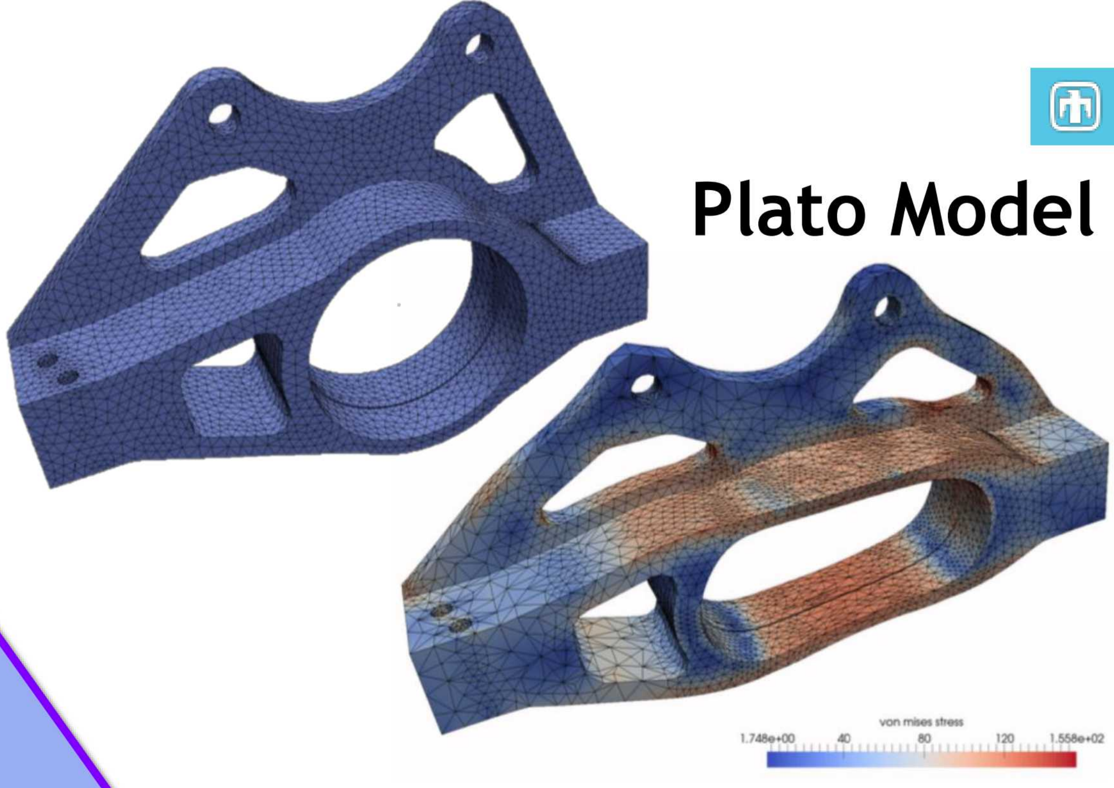


Plato Analyze

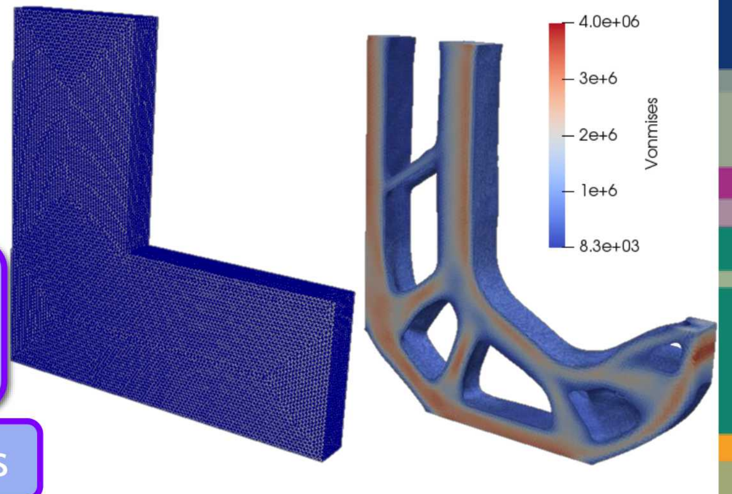




Plato Model



Plato Optimize

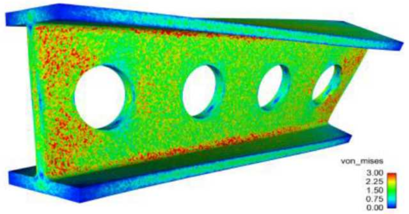


Miguel Aguilo, Brett Clark, Josh Robbins

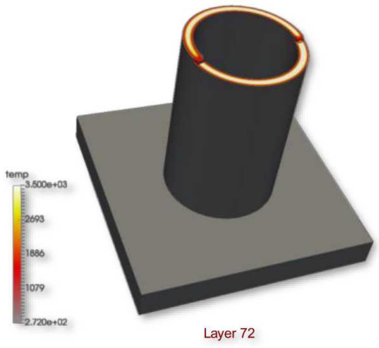
Qualification Tomorrow

"Changing the Engineering Design & Qualification Paradigm"

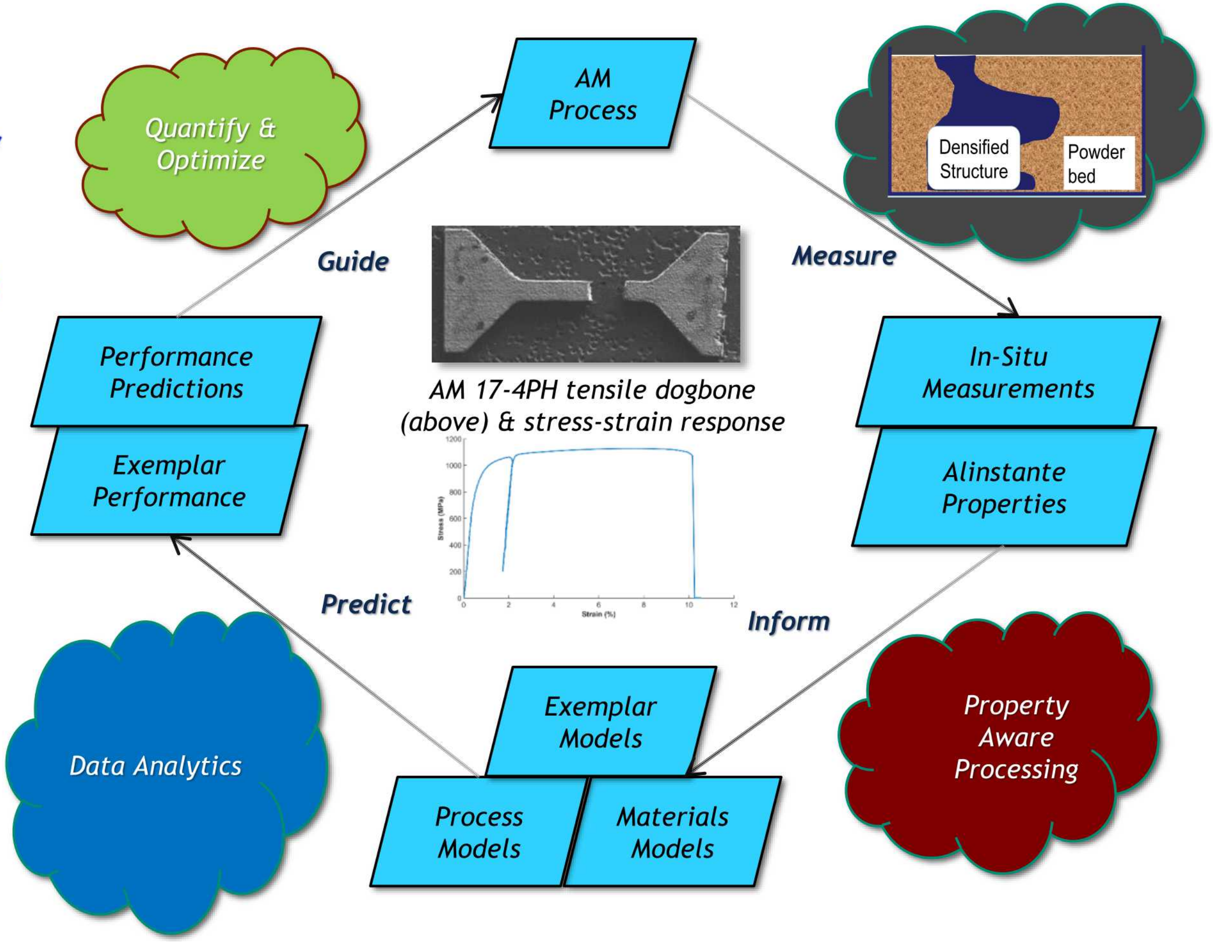
- leverage AM, in-process metrology & HPC to revolutionize product realization
- accelerating design to production

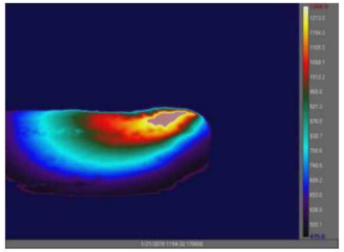


material / part performance simulation

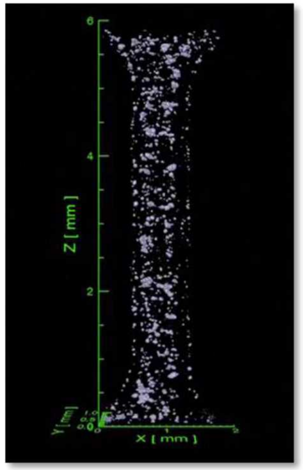


process simulation





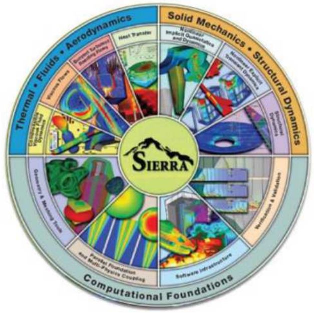
thermal history during bi-directional metal deposition



17-4PH dogbone porosity

Roach, ***SFF Proceed.***, 2018

Models Bridging Length Scales



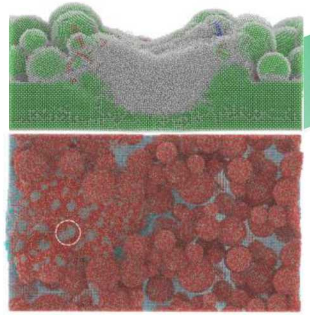
LAMMPS

ARIA

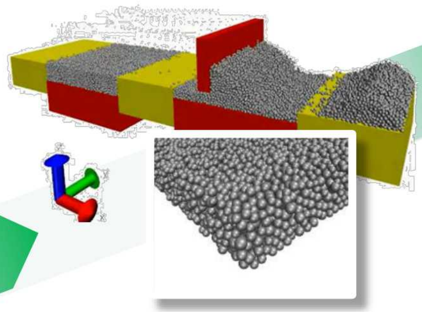
ADAGIO

SPPARKS

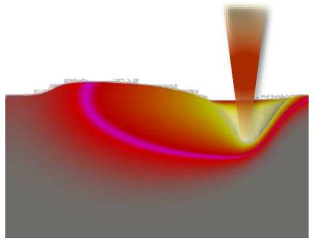
Powder Behavior
M. Wilson

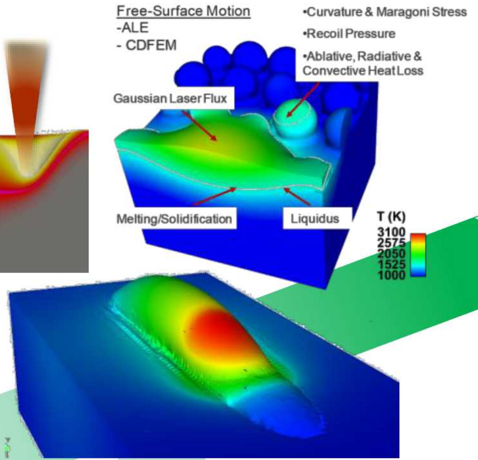


Powder Spreading
D. Bolintineanu

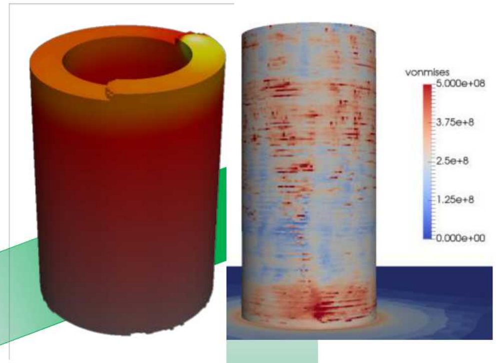


Solidification Scale Thermal
M. Martinez, B. Trembacki, D. Moser

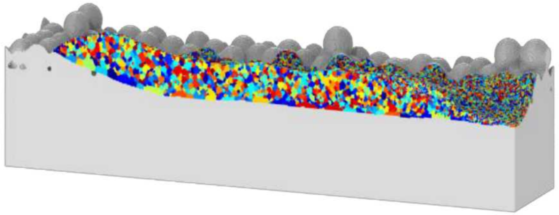




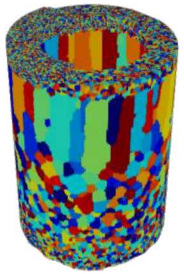
Build Scale Thermal + Mechanics
K. Johnson, K. Ford, L. Beghini, M. Stender & J. Bishop



Mesoscale Texture/Solid Mechanics
T. Rodgers, J. Brown, K. Ford



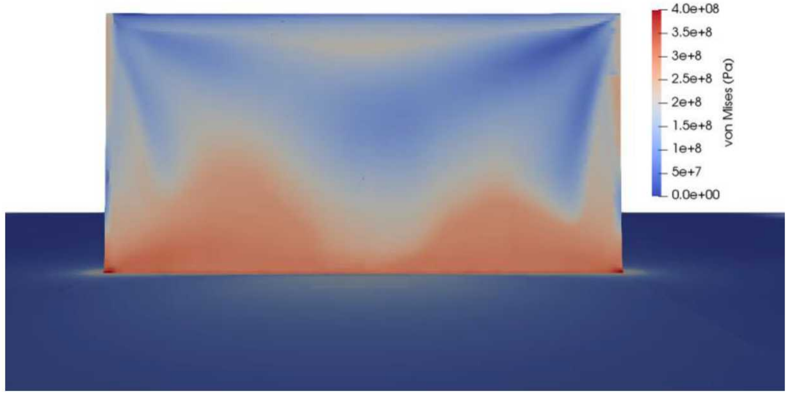
Build Scale Microstructure
T. Rodgers, J. Madison



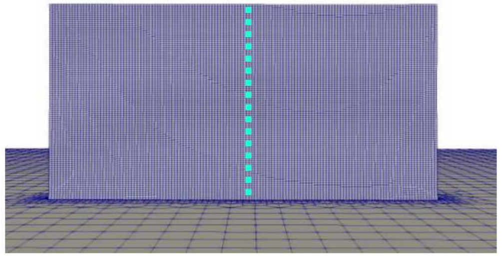
10^{-6} 10^{-3} 1

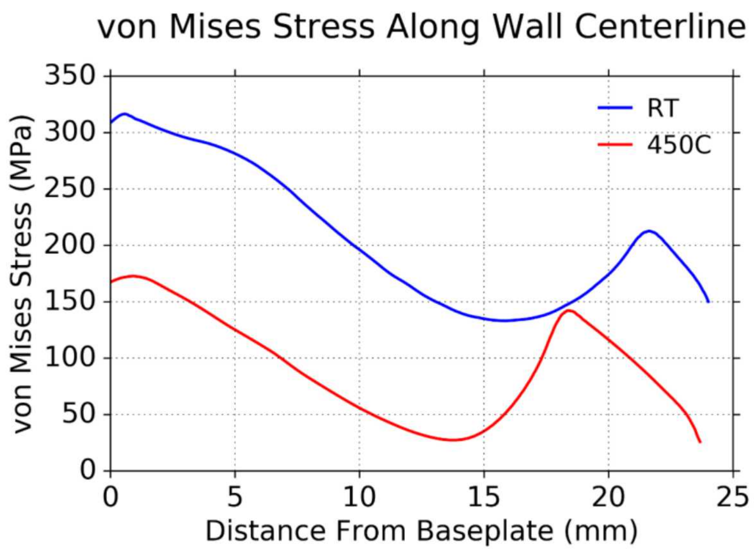
Length Scale (m)

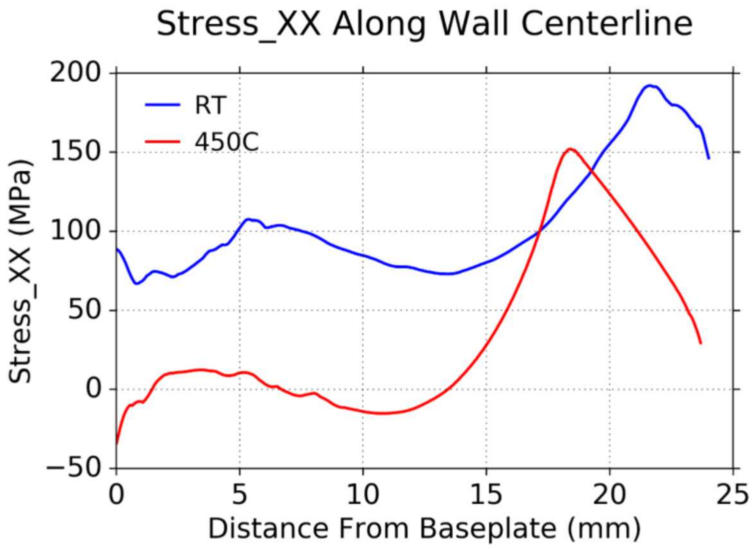
High Fidelity Process Models Capture Each Laser Pass



304L Two Pass LENS Thin Wall Build Study
Examining Baseplate Preheating Effects

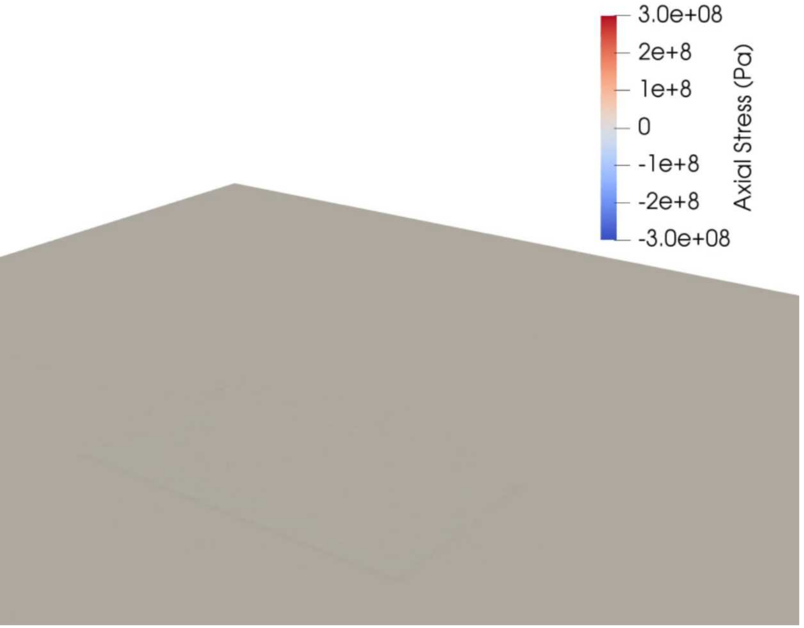




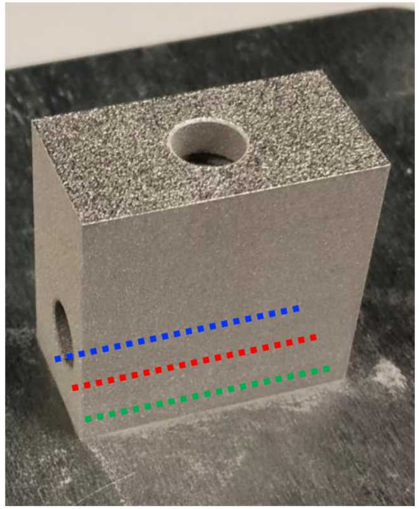


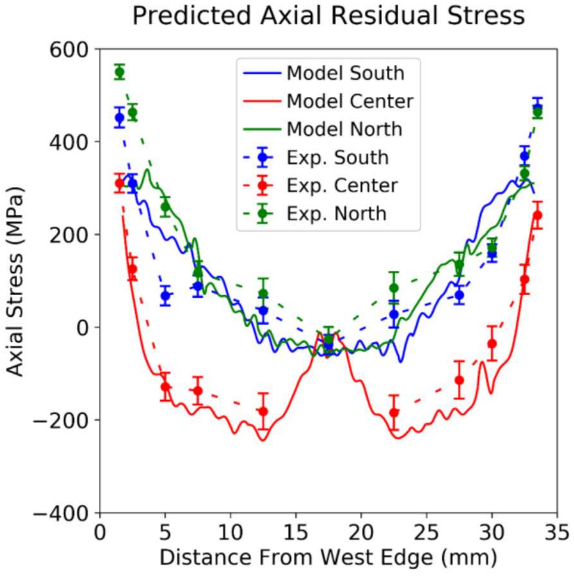
Kyle Johnson

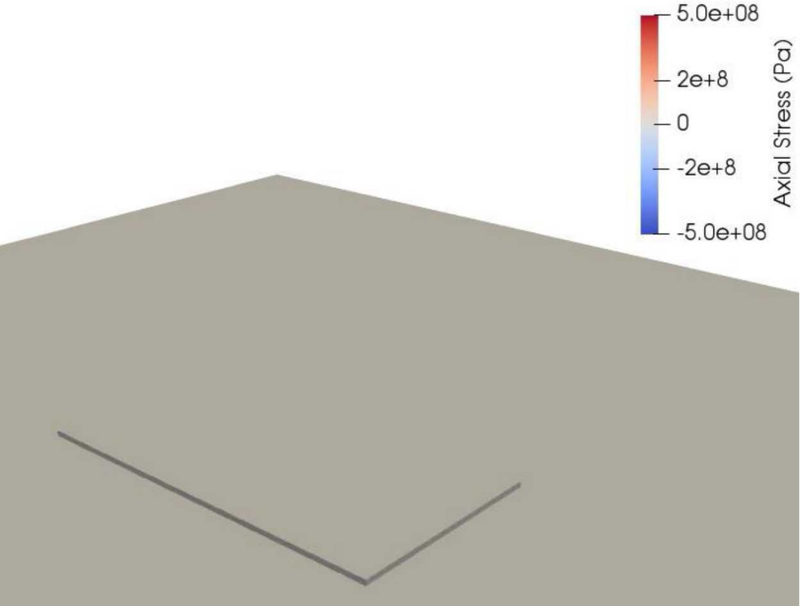
High Fidelity Models Inform Reduced Order Models



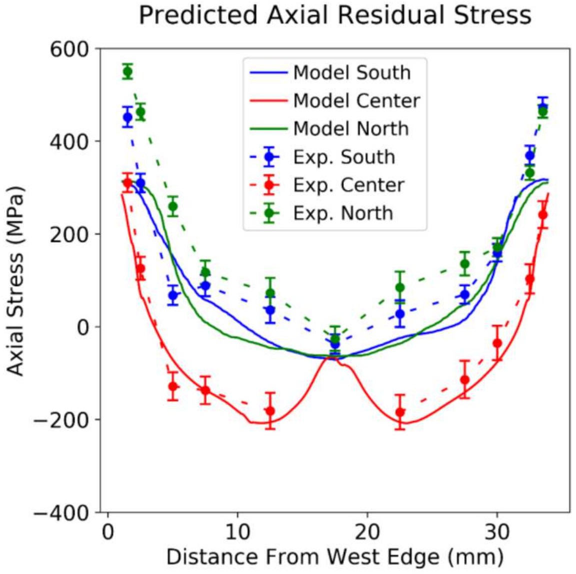
Enlarged Heat Source*
and Layer Thickness
100 cpus
6 hrs (~real time)







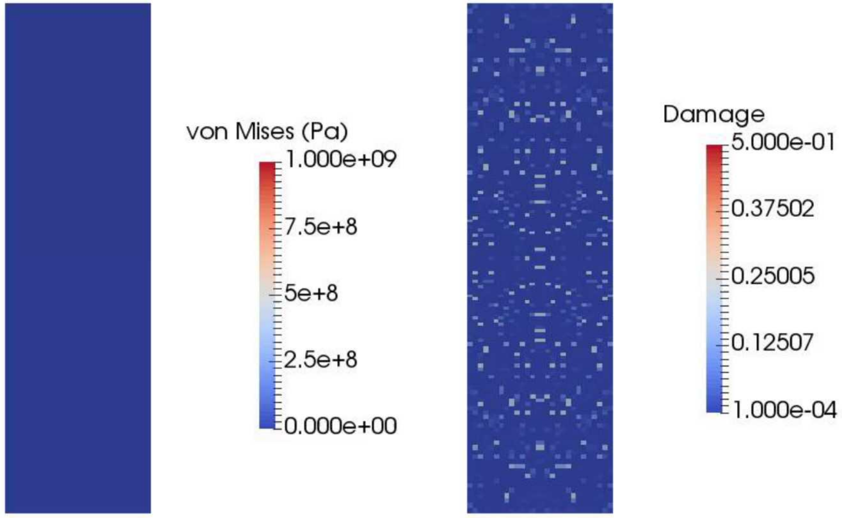
Mechanical Inherent Strain
60 cpus
30 minutes



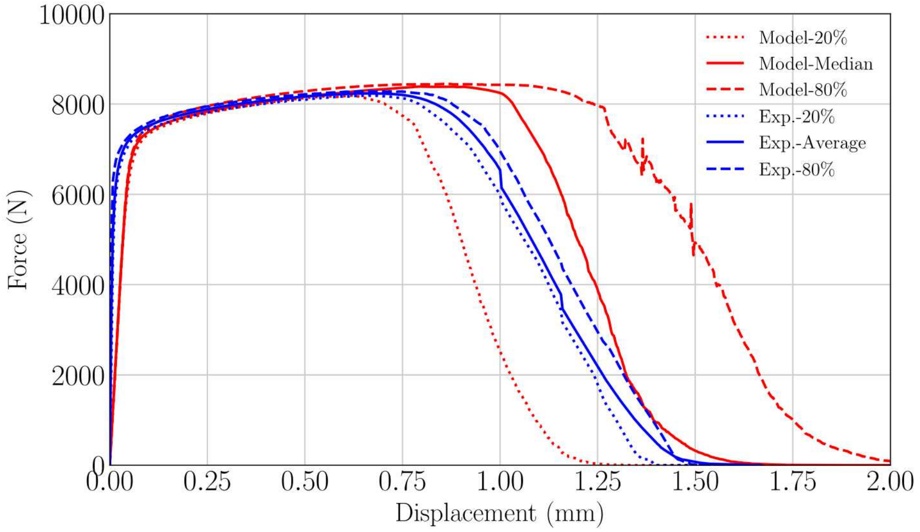
* Similar to Hodge et al. 2014 and 2016, Ganeriwala et al. 2019

Kyle Johnson

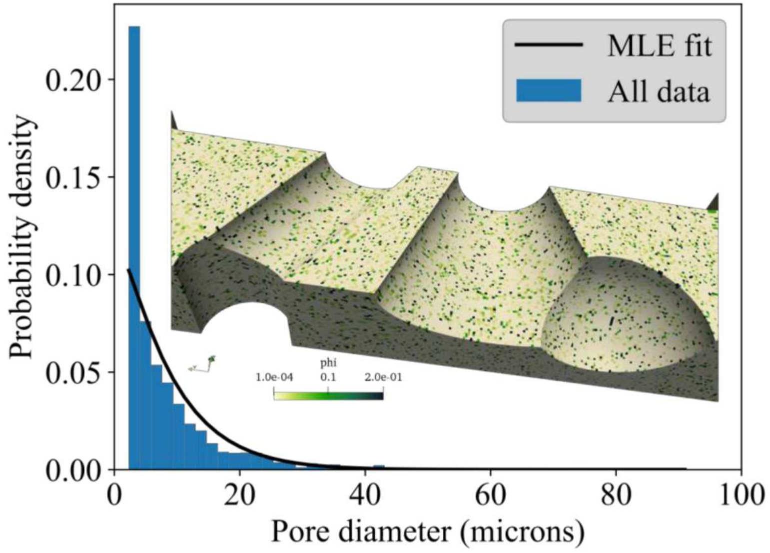
Predicting Part Performance

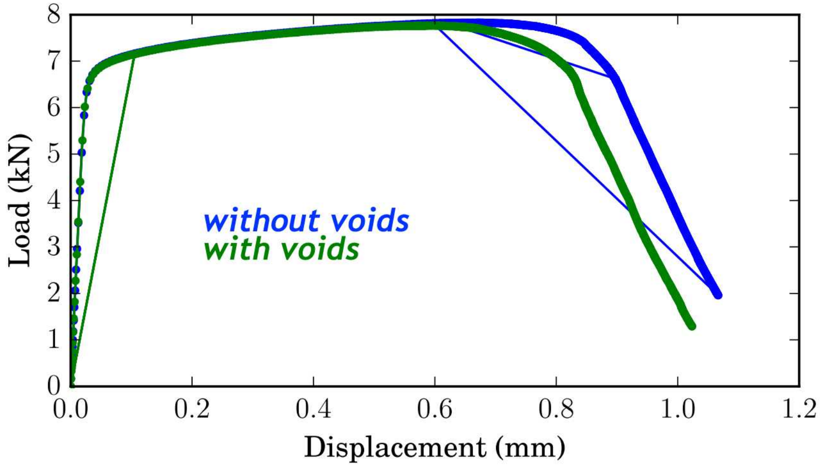


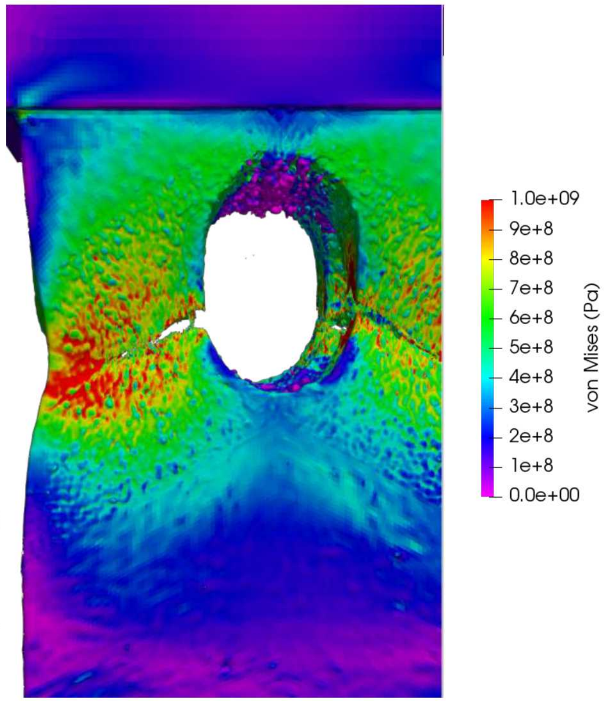
representing porosity as initial damage



SNL/NM prediction for 3rd Sandia Fracture Challenge



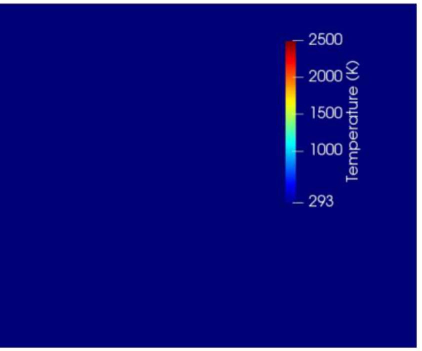




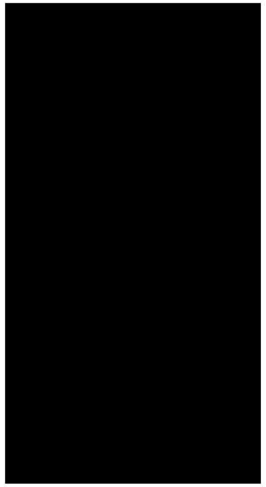
material response changes w/voids & surface roughness

Kyle Johnson, Kyle Karlson, Brad Boyce

Microstructure Prediction in Stochastic Parallel PARticle Kinetic Simulator (SPPARKS)



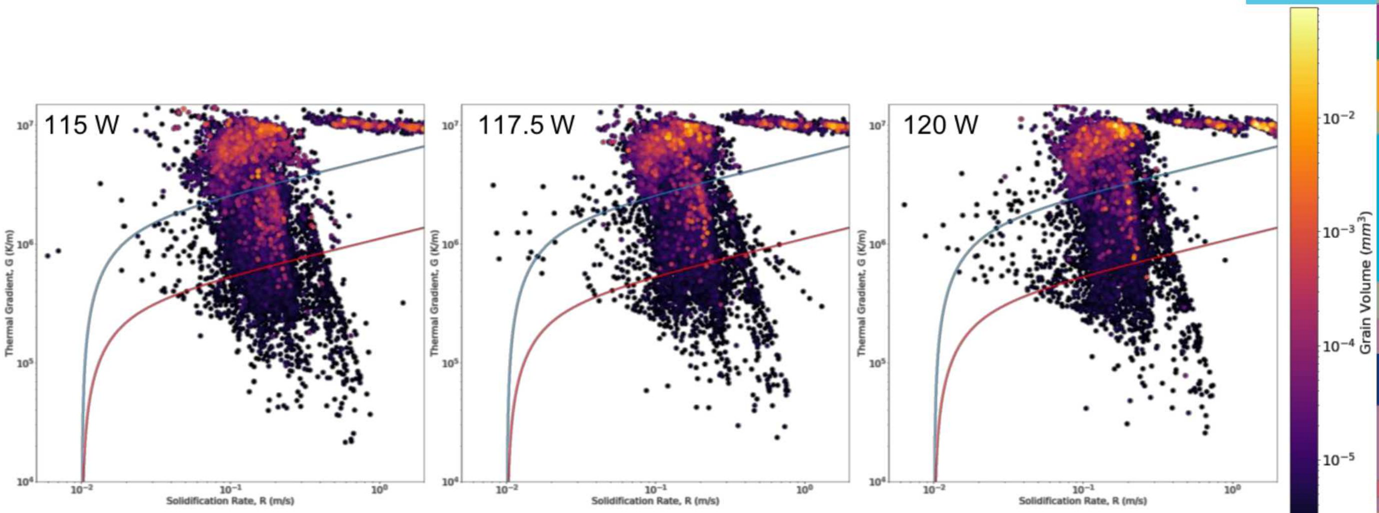
Thermal Simulation from Sierra/Aria (Thermal/Fluid Solver)

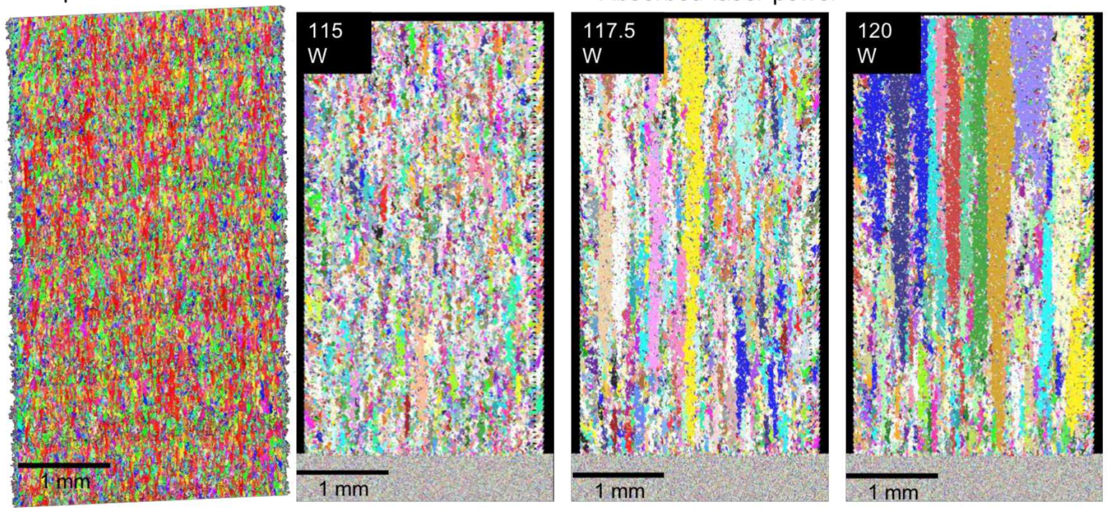


Single Continuous Build

Double Build (8 second delay in between layers)

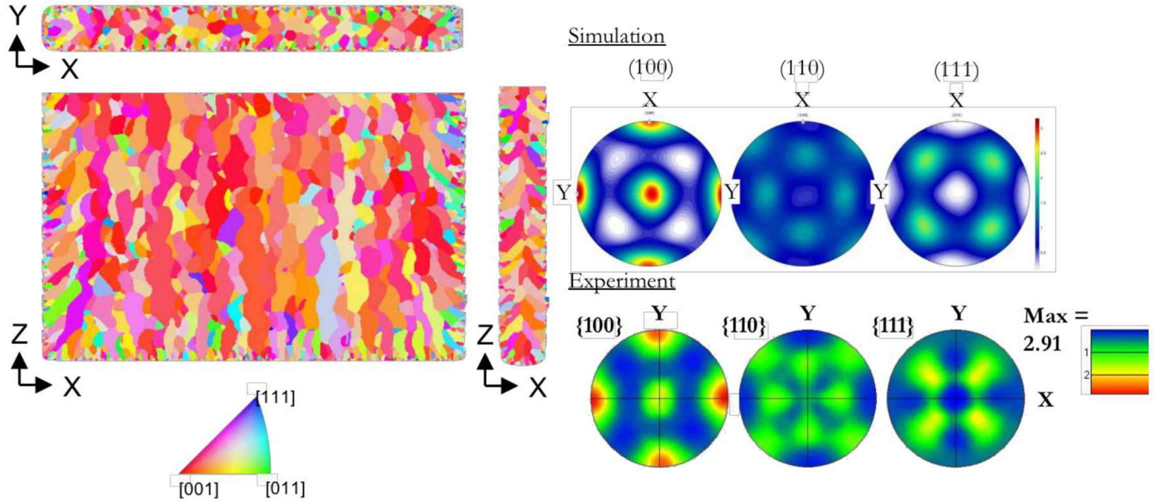
304L Tube, Johnson et al. *Computational Mechanics* 2018





All simulations performed with nucleation densities of 8e13

316L Stainless Steel Column



Stainless Steel Thin Wall Texture Prediction

http://spparks.sandia.gov

Theron Rodgers, Mario Martinez, Dan Moser

Material Assurance

Material formation concurrent w/geometry

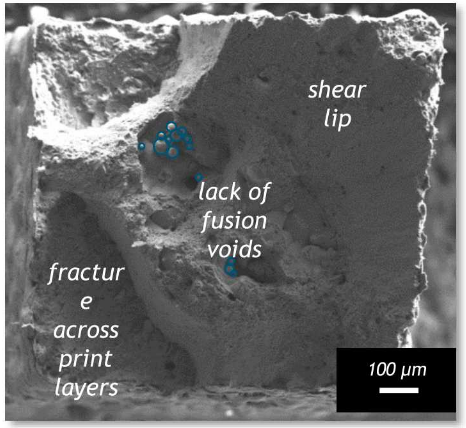
- want to predict part/material performance
  - feedstock certs inadequate for performance
- **<u>how to ID a bad part?</u>**
  - complexity isn't "free"
  - requires significant design margins and/or rigorous post-process inspection / validation

Quantify <u>critical</u> material defects & <u>useful</u> signatures

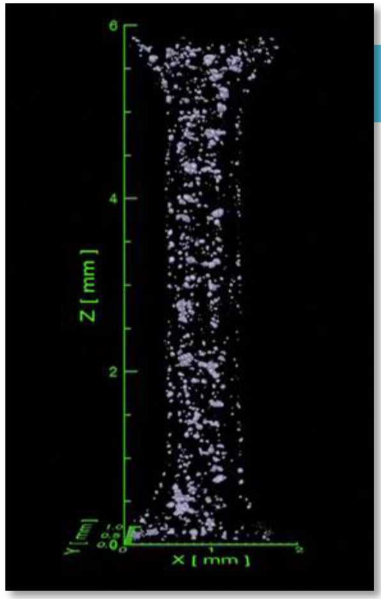
- D-tests, NDE, process monitoring, mod-sim, ?

Understand mechanistic impacts on properties

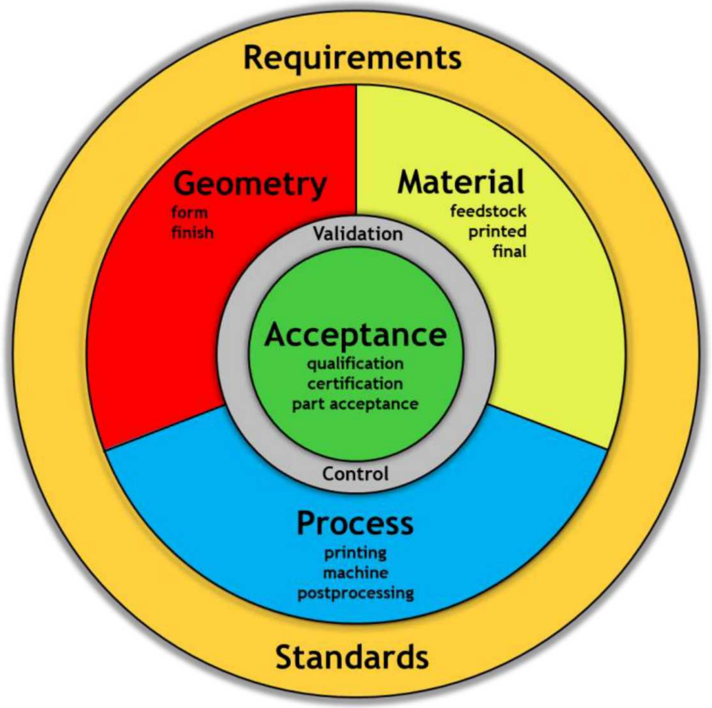
- build process-structure-property relationships to predict **<u>margins & reliability</u>**
- characterize stochastic response to design for **<u>uncertainties</u>**
- provide scientific basis for qualification of AM metals for high consequence applications



17-4PH dogbone fracture surface



17-4PH dogbone porosity



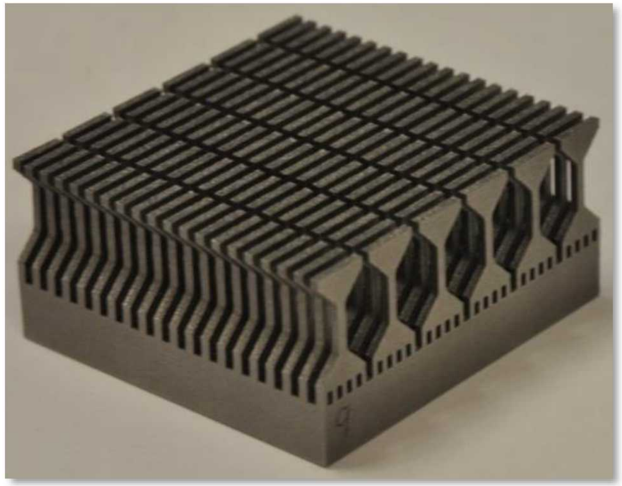
Lack of Control Produced Uncertainty in Early AM Metals

17-4PH parts requested from external vendor in 2015
- analysis confirmed 17-4PH composition, but unexpected microstructure

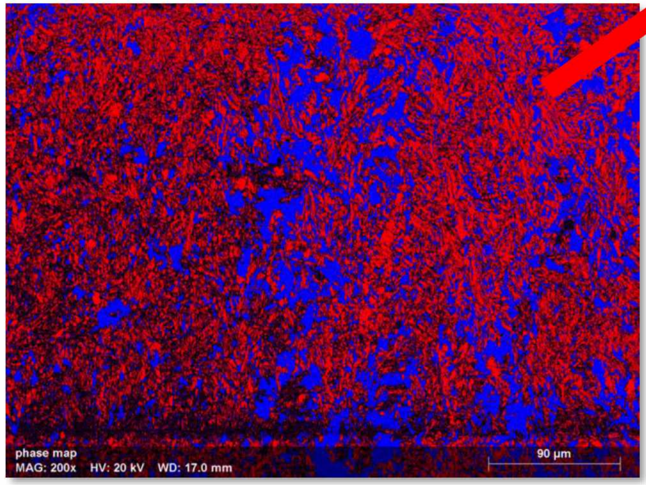
Sandia did not know or control
- feedstock pedigree, machine, build environment, process inputs or post-processing steps

Not-surprisingly, extensive material variability observed

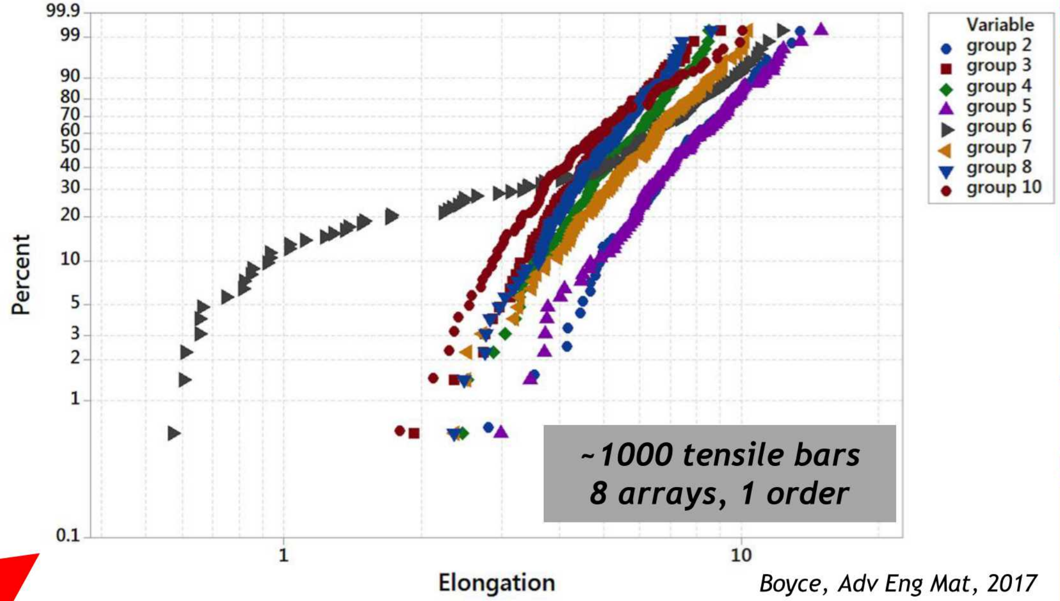
nominally 17-4PH high throughput tensile (HTT) sample w/120 dogbones, 1x1mm gage x-section, printed by an external vendor



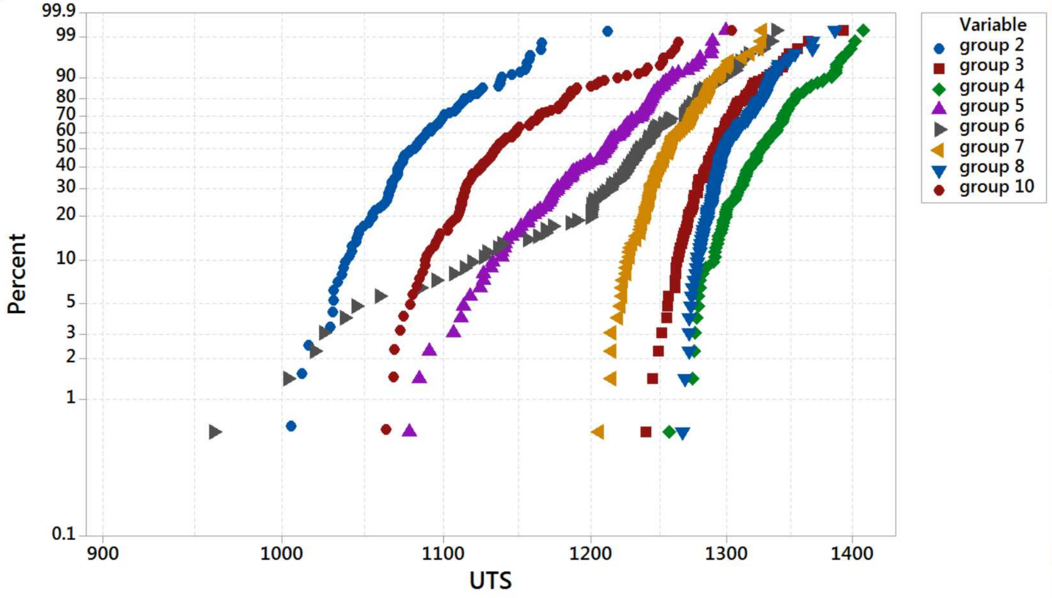
*Salzbrenner, **Journal of Materials Processing Technology**, 2017*



unexpected microstructure with 43% austenite, 57% martensite



Boyce, Adv Eng Mat, 2017



*Boyce, **Advanced Engineering Materials**, 2017*

Process Knowledge & Control Reduces Material Variability

316L stainless steel

- more robust material

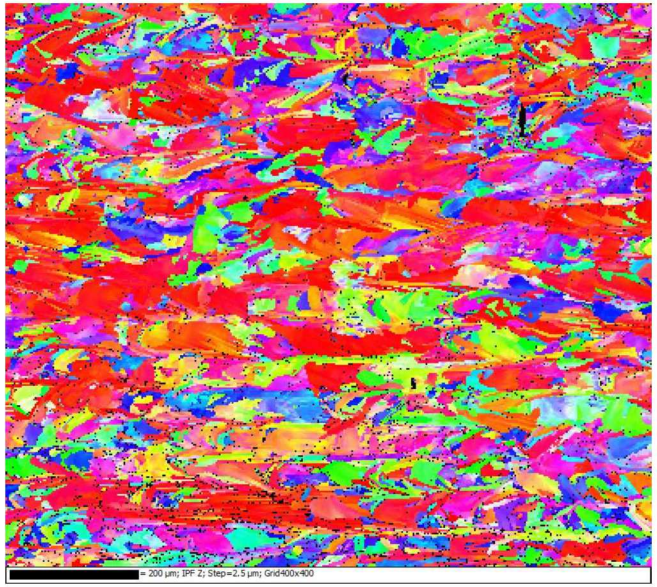
3D Systems ProX 200

- process space mapped & machine performance characterized

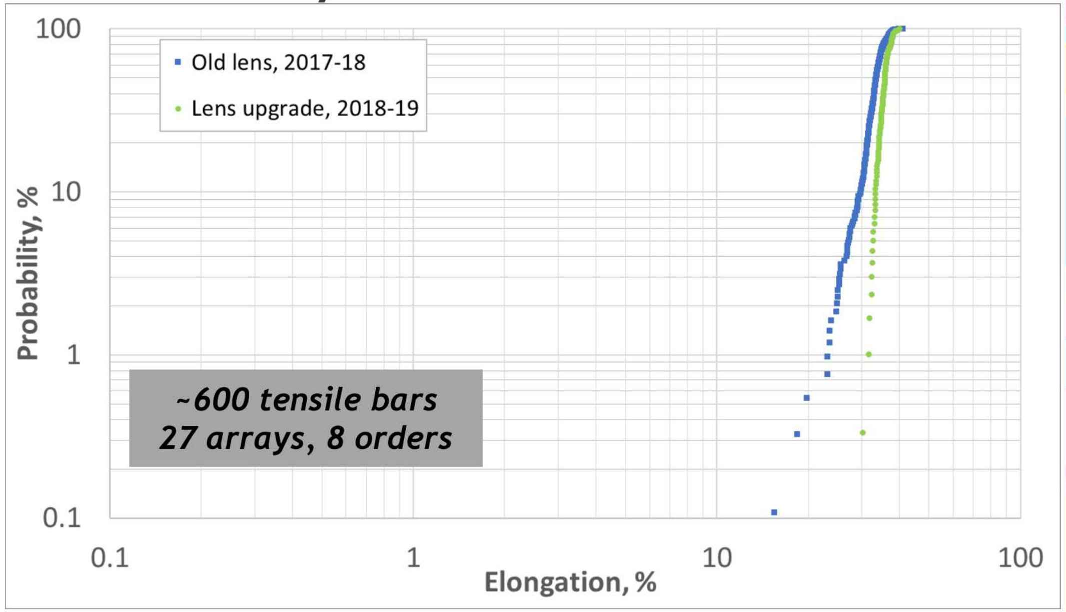
controlling & logging every part, build & powder cycle

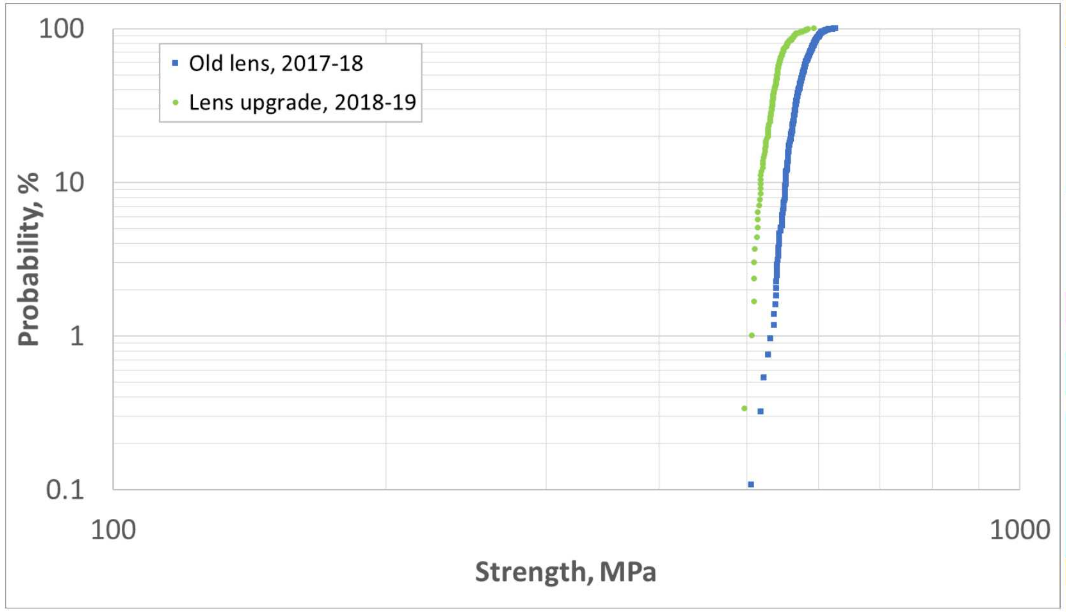
- feedstock pedigree, build environment, process inputs, post-processing
- printing & testing artifacts w/build cycles
- storing feedstock, process & printed material data in GRANTA
- capabilities for in-situ machine & process monitoring

build plate w/process artifacts



baseline 316L SS microstructure





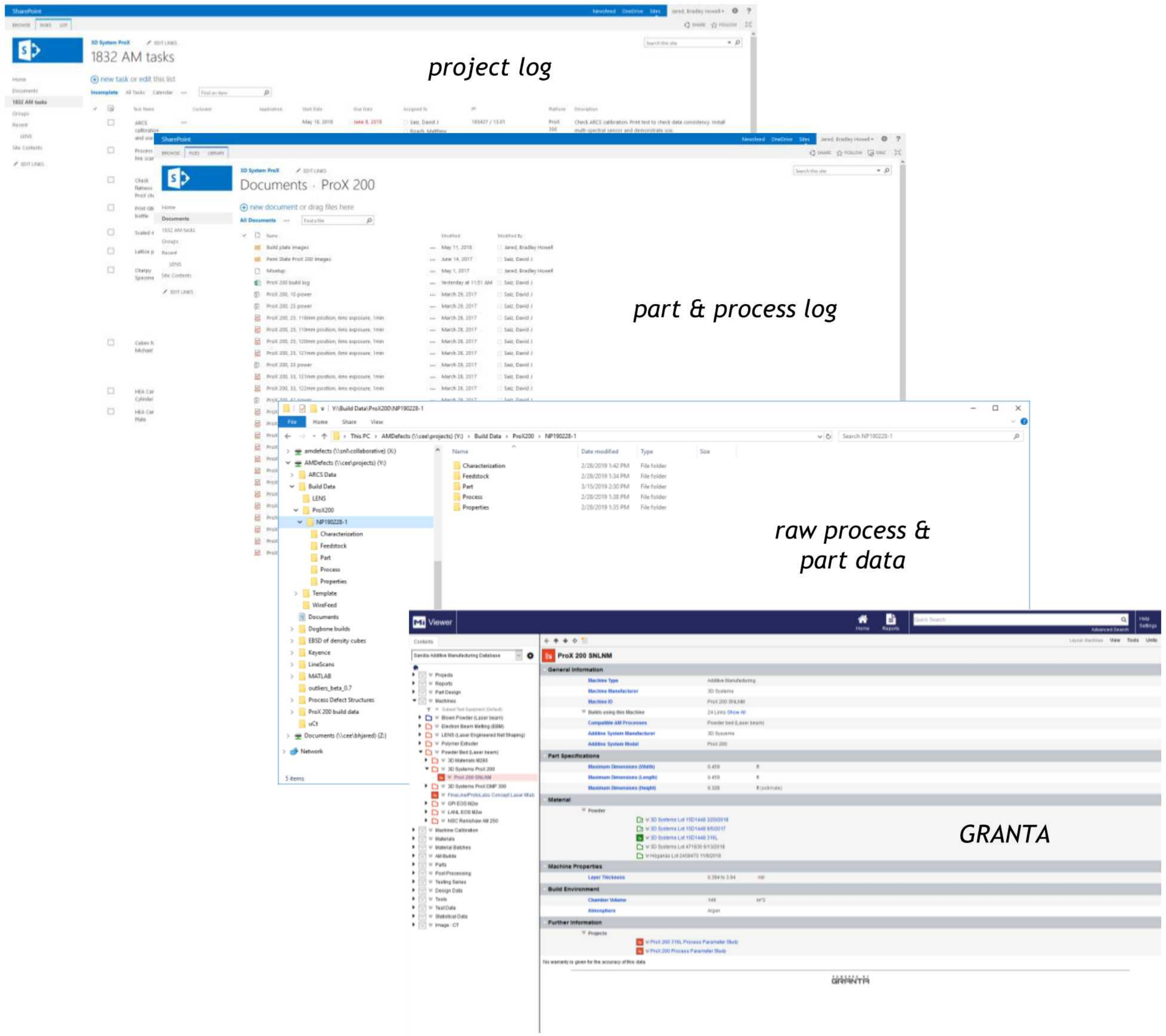
Data Management is a Critical Challenge Being Addressed

Sharepoint site
- 5Gb storage
- project log – customer, project / program, part CAD files / drawings, requirements, schedule
- part & process log file – build identifier, powder, reuse cycle, process settings, process file name, notes
- as-printed build pictures

Machine computers (lab)
- machine & process build files
- process data – ARCS, in-situ sensor data (thermal, optical, acoustic)
- feedstock data – Aspex SEM image analysis, EDS composition

\\CEE\Projects\AM Defects\BuildData share folder
- >100Gb storage
- feedstock – powder data, rheology, specification, etc.
- part – CAD file, drawing, specs, build pictures
- process – build file, in-situ process data
- property – tensile, density, Charpy, hardness, corrosion, etc.
- characterization – metallography (optical, SEM, TEM, EBSD), metrology (surface finish, geometry), computed tomography, functional testing

GRANTA
- feedstock, machine, process, material data



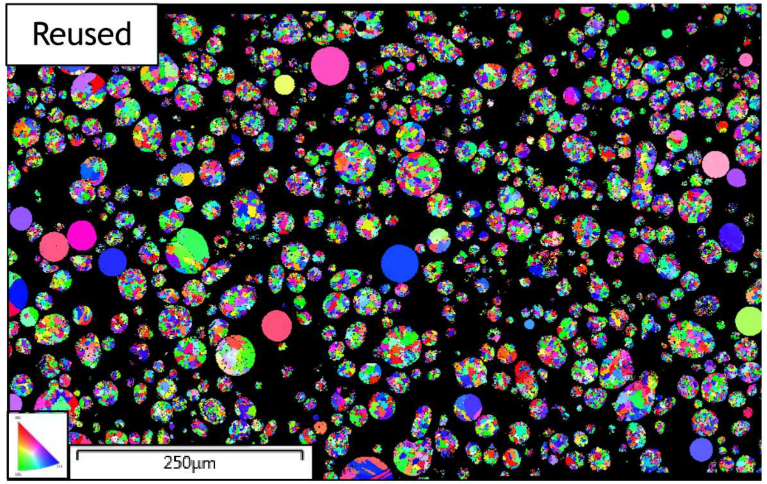
Monitoring Powder Reuse

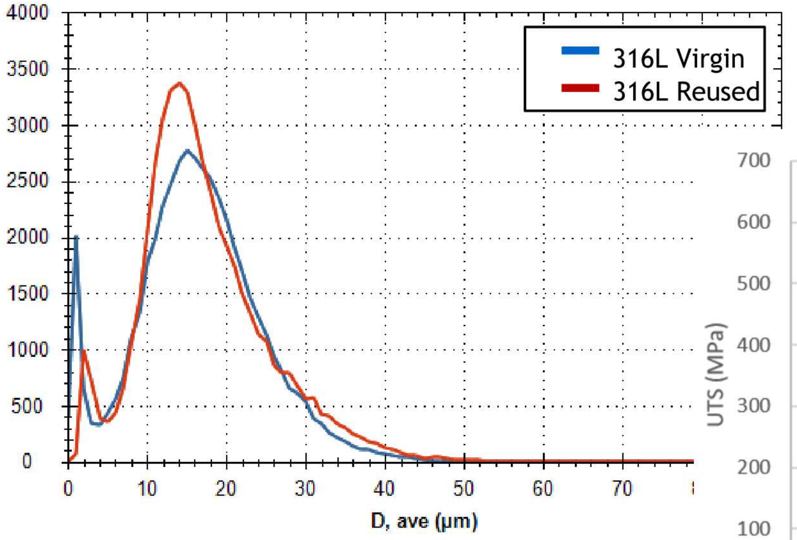
Tracking powder size, morphology & EDS composition w/reuse

- satellites & agglomerates increase
- observe highly spherical, ferrite particles
- increase in fines & reduction in larger particles
- collected over 30 reuses w/powder under Ar

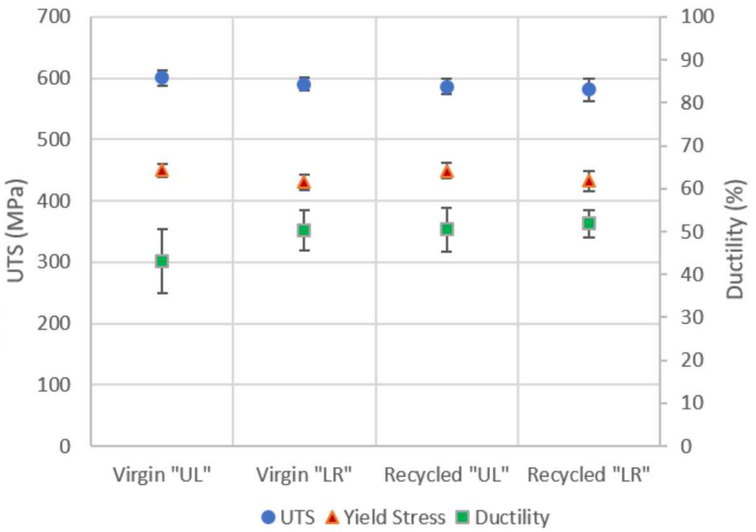
Material properties remain stable

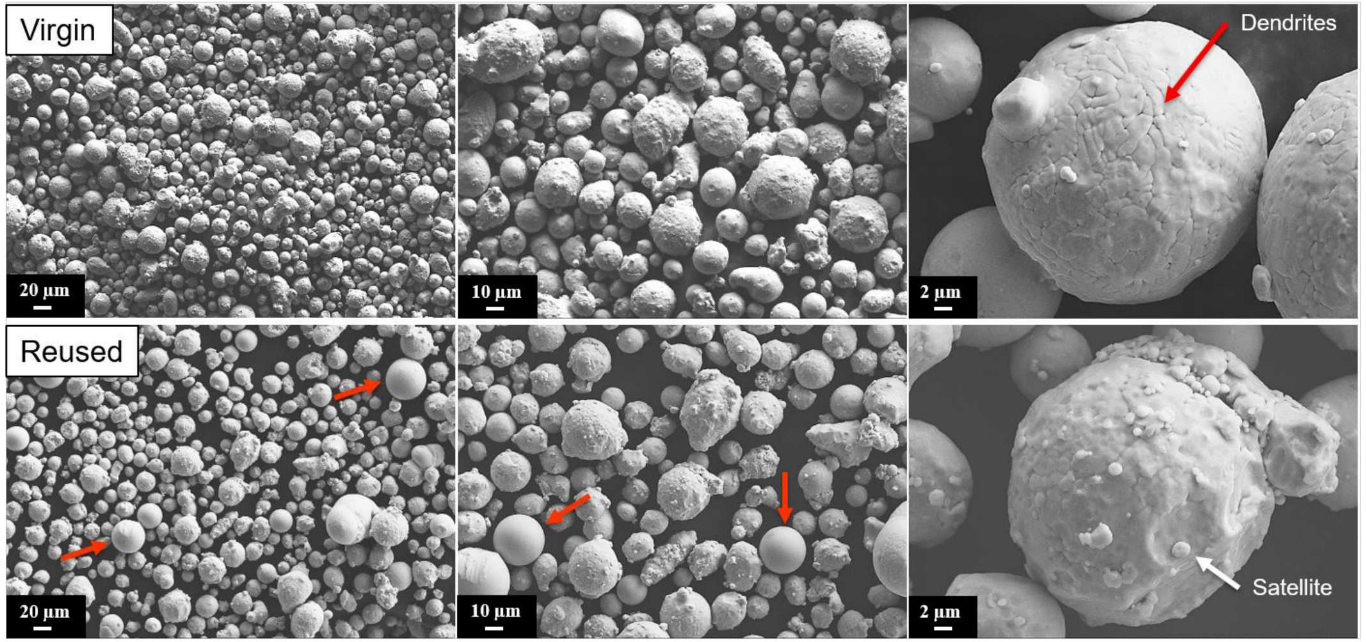
316L SS is a robust material for processing & properties





Virgin: 7.90 g/cm^3
Reused: 7.81 g/cm^3





Heiden, ***Add. Mfg.***, 2019

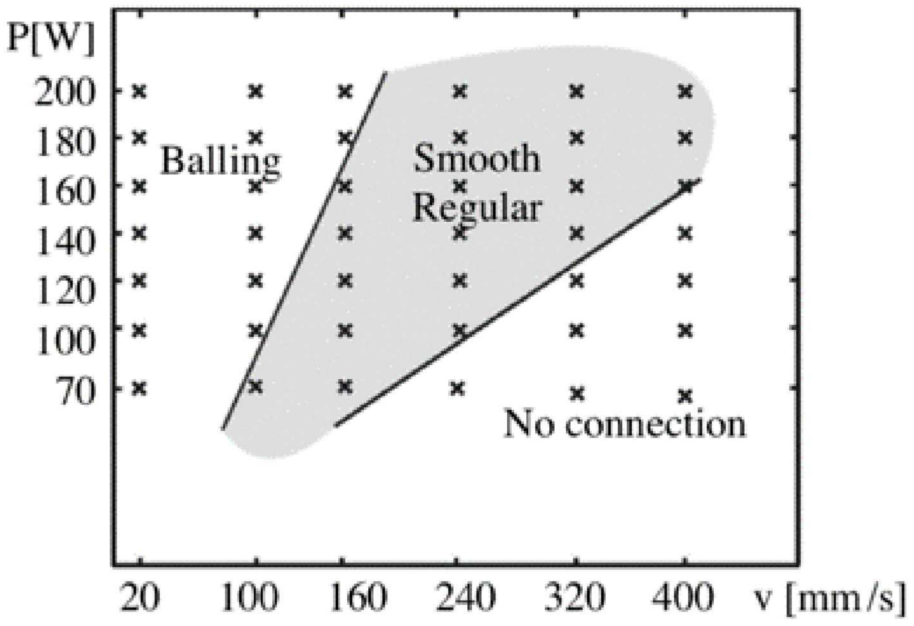
Process Optimization

AM metal qualification remains a challenge for high consequence systems

- machine metrology is a critical
- what are process tolerances & margins?
- does a truly optimal process state exist?
- can optimization be performed faster & cheaper?

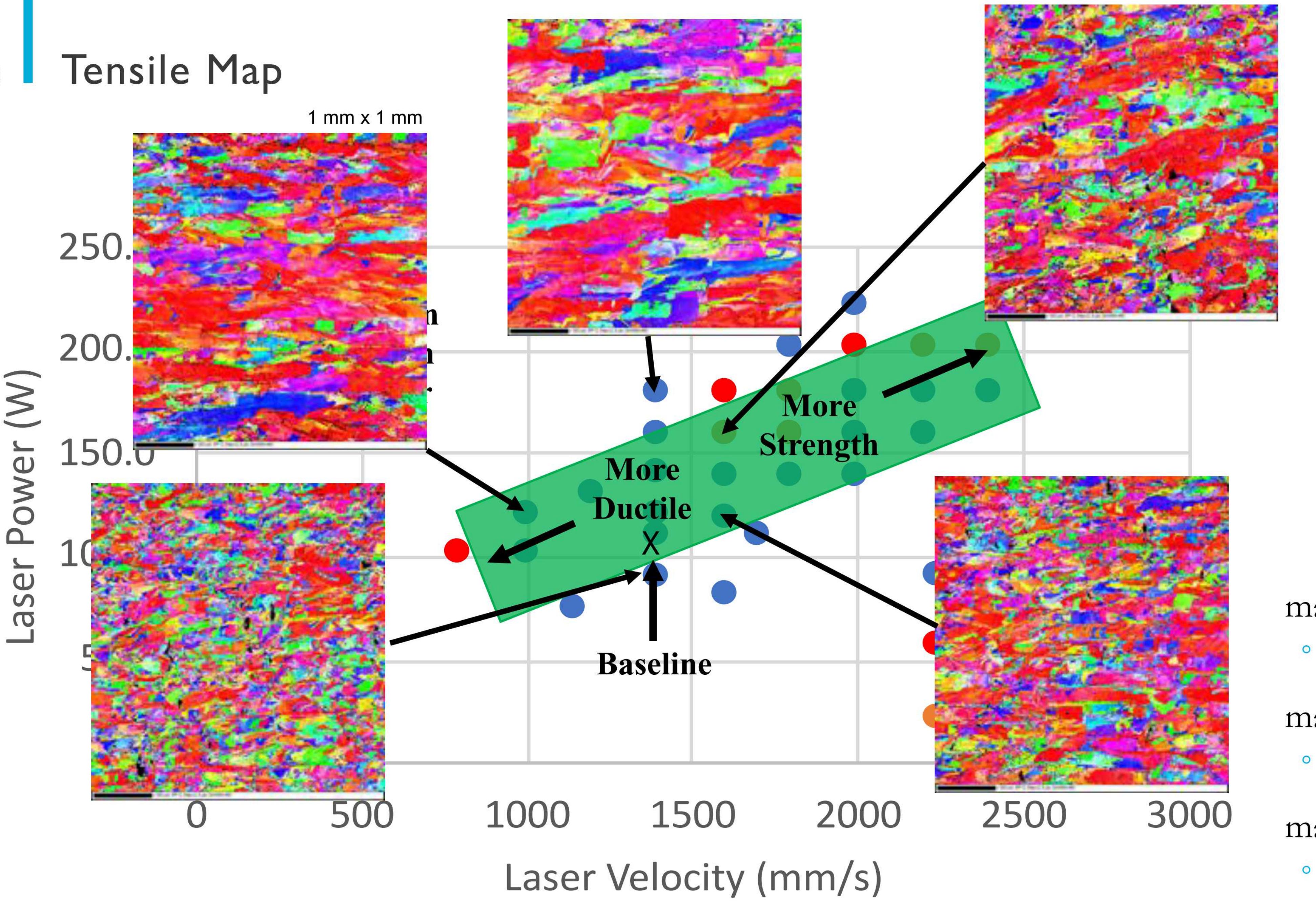
Explore process maps

- parameters
  - laser power (10-240W), velocity (50-2800mm/sec)
  - powder layer thickness (30, 40μm), average powder diameter (15.0, 25.0μm), laser focus offset (-1.5 to +3.5mm)
- performance metrics
  - surface finish, form error, density, tensile properties, Charpy toughness, microstructure
- experiment forms
  - line scans, area pads, density cubes, HTT tensile, Charpy



Kruth, **Rapid Prototyping Journal**, 2008

Tensile Map



max YS: 489 Mpa
- @ 200 W, 2200 mm/s

max UTS: 621 Mpa
- @ 200 W, 2000 mm/s

max ductility: 66%
- @ 120 W, 1000 mm/s

Josh Koepke, MS Thesis, UNM Dept of ME, 2019

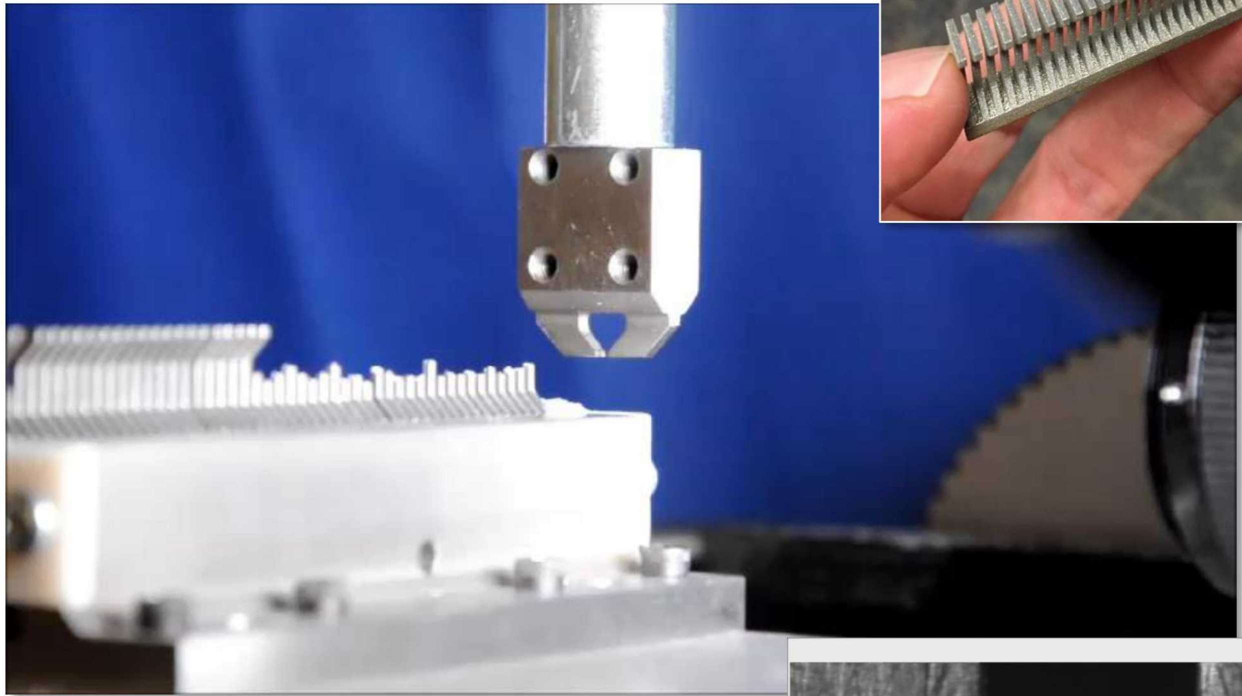
High Throughput Testing - Alinstante

Properties… In an instant
- printing is fast
  - hundreds of samples in days
- test/measurement is common constraint

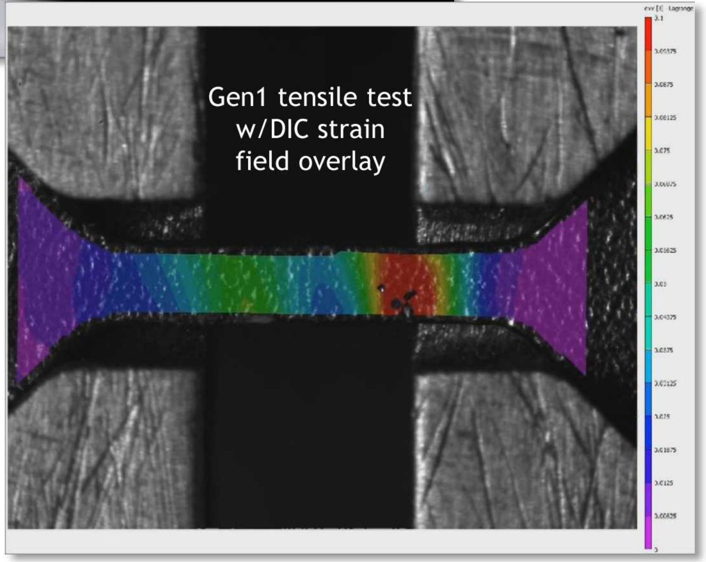
Need automation & robotics
- consistent, rapid, & efficient

Alinstante wish list:

Properties	**Structure**	**Process**
Tensile strength	Geometry	Surface remediation
Ductility	Roughness	Heat treatment
Toughness	Porosity	Subtractive machining
Hardness	Chemistry	Coating
Wear & friction	Phase content	Joining
Permeability	Grain Size	Integration
Thermal expansion	Crystal Texture	etc.
Reactivity/corrosion	Residual stress	
Electrical conductivity	Dislocation content	
Resonance	etc.	
etc.		



*Heckman, **Mat. Sci. Eng. A**, submitted*



robotic work cell for material characterization

Brad Boyce

Corrosion

Need: Corrosion performance of AM structural metals is largely unknown, critical for qualification of high reliability systems in many service environments.

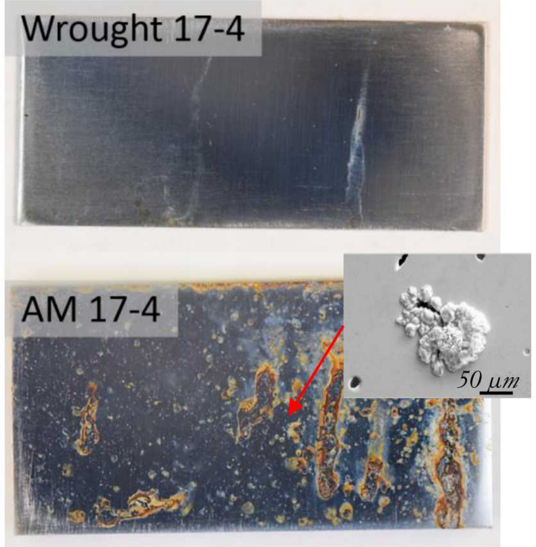
Approach: define processing-microstructure-corrosion performance relationships, identify strategies to control and predict reliability

Findings

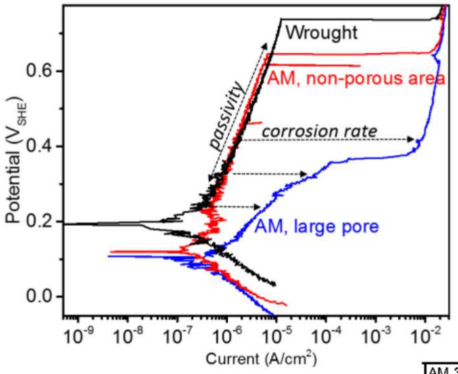
- Porosity can comprise AM stainless steels to the first order
- Detrimental second phase inclusions common in conventionally processed stainless steels are inhibited by SLM and DED – fast cooling rates
- Reducing porosity can impart superior performance over conventionally processed 304, 316 SS in some environments

New Directions

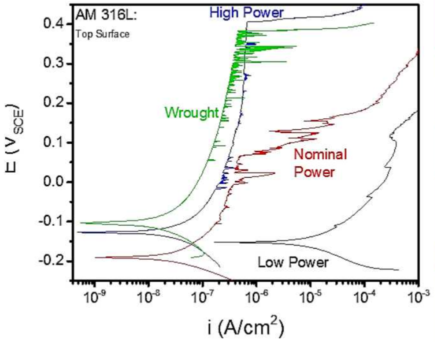
- Heat treatment and sensitization effects of AM SS
- Stress corrosion cracking AM metals
- Stainless AM CCA metals

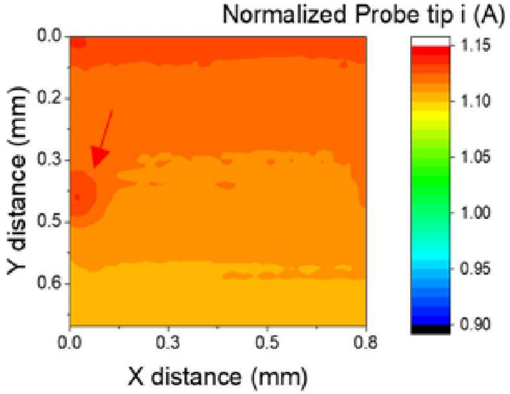


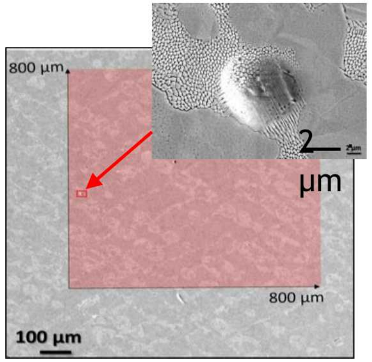
conventional wrought and AM 17-4PH coupons after B117 salt fog corrosion test



electrochemical measurements reveal lack of fusion defects compromise 304L and 316L stainless steel corrosion resistance





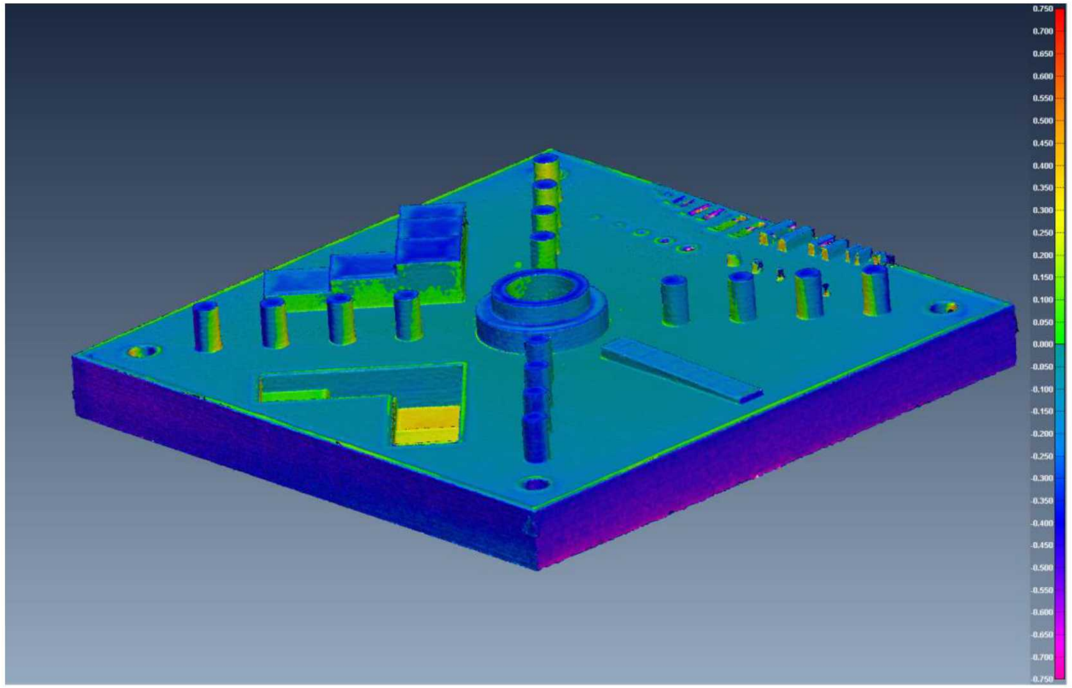


advanced microelectrochemical techniques are used to relate corrosion behavior to microstructure allowing for hierarchal identification of “weakest link” features

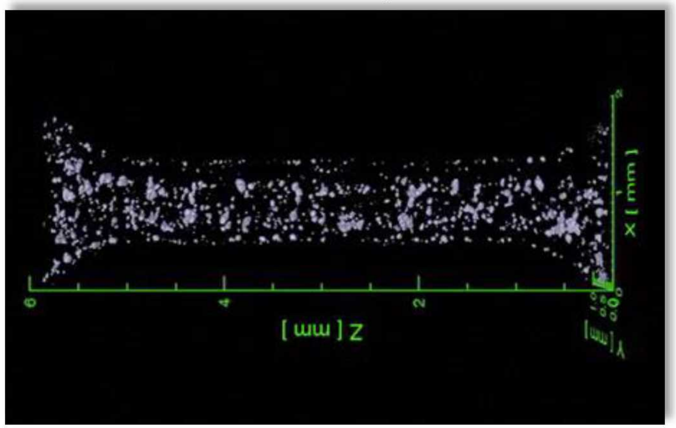
Eric Schindelholz

Non-Destructive Evaluation

computed tomography

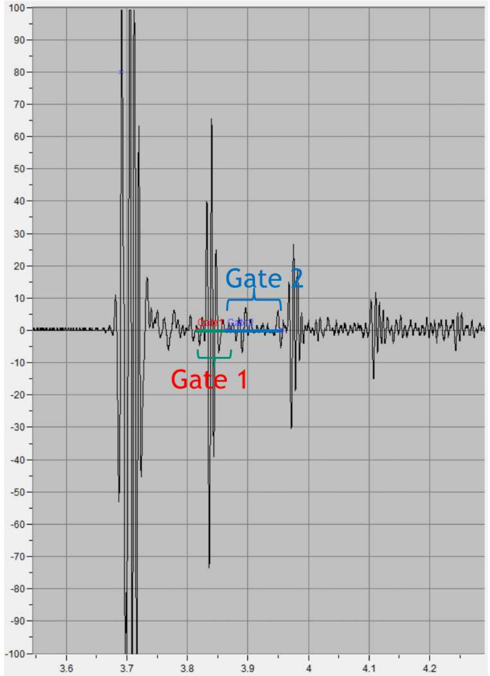


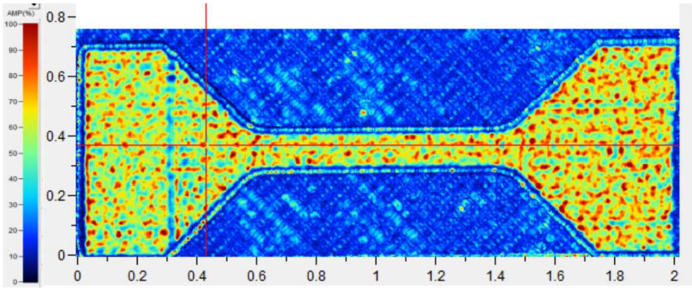
dimensional inspection



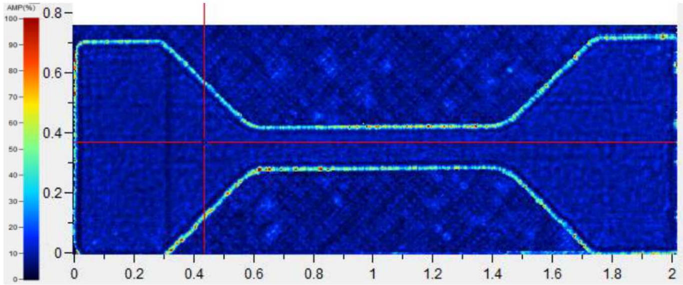
porosity assessments

pulse-echo ultrasound

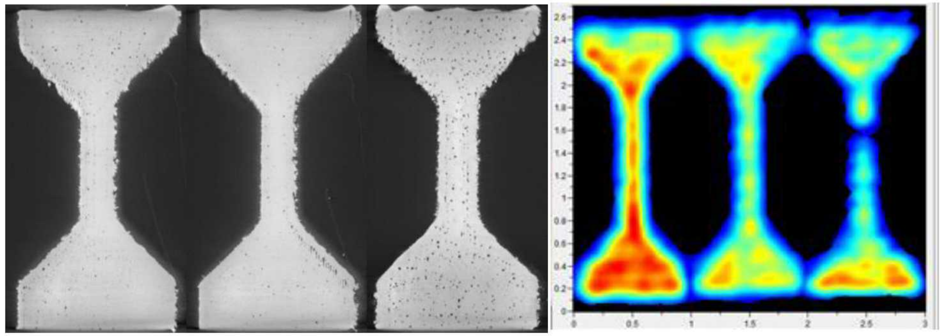




Gate 1 signal



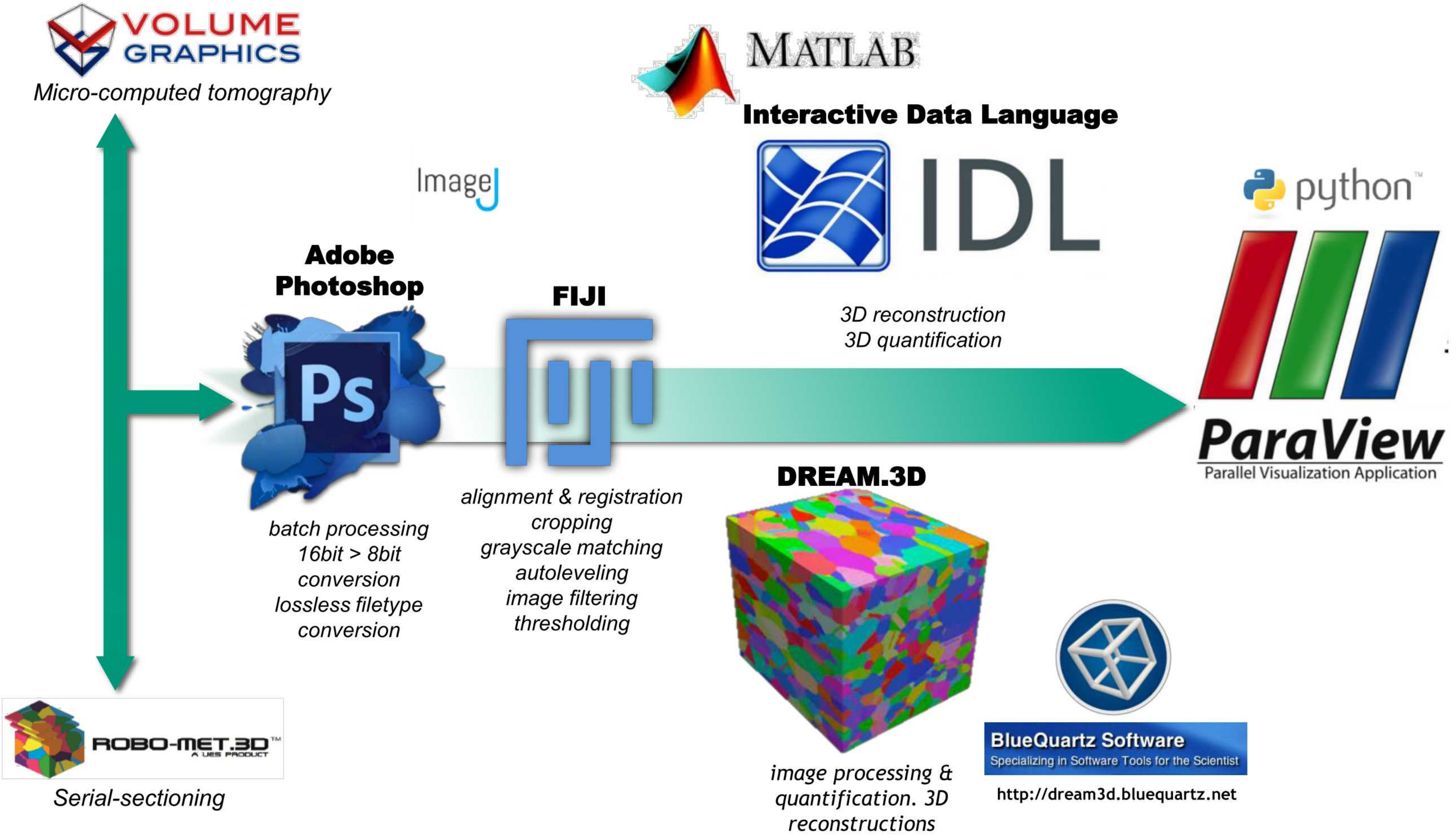
Gate 2 signal

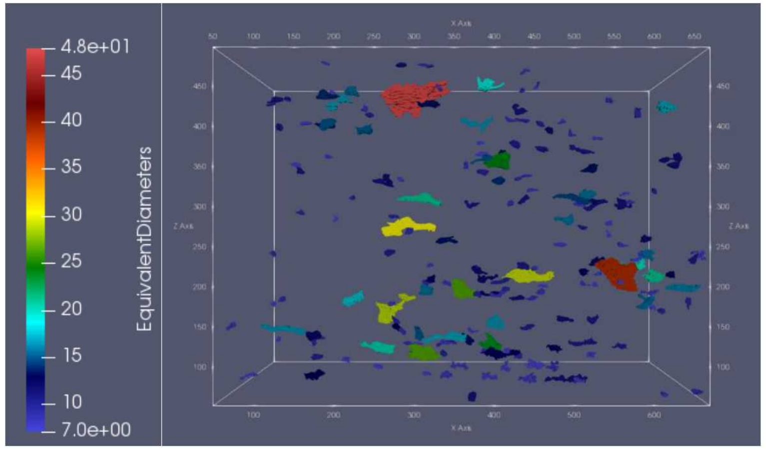


CT images of 98% (left), 96% (center) & 93% (right) dense Al10SiMg dogbones (left) & attenuation of 10MHz ultrasonic backwall reflections (right)

David Moore, Burke Kernen, Kyle Thompson, Ciji Nelson, Sarah Stair

Material Reconstruction





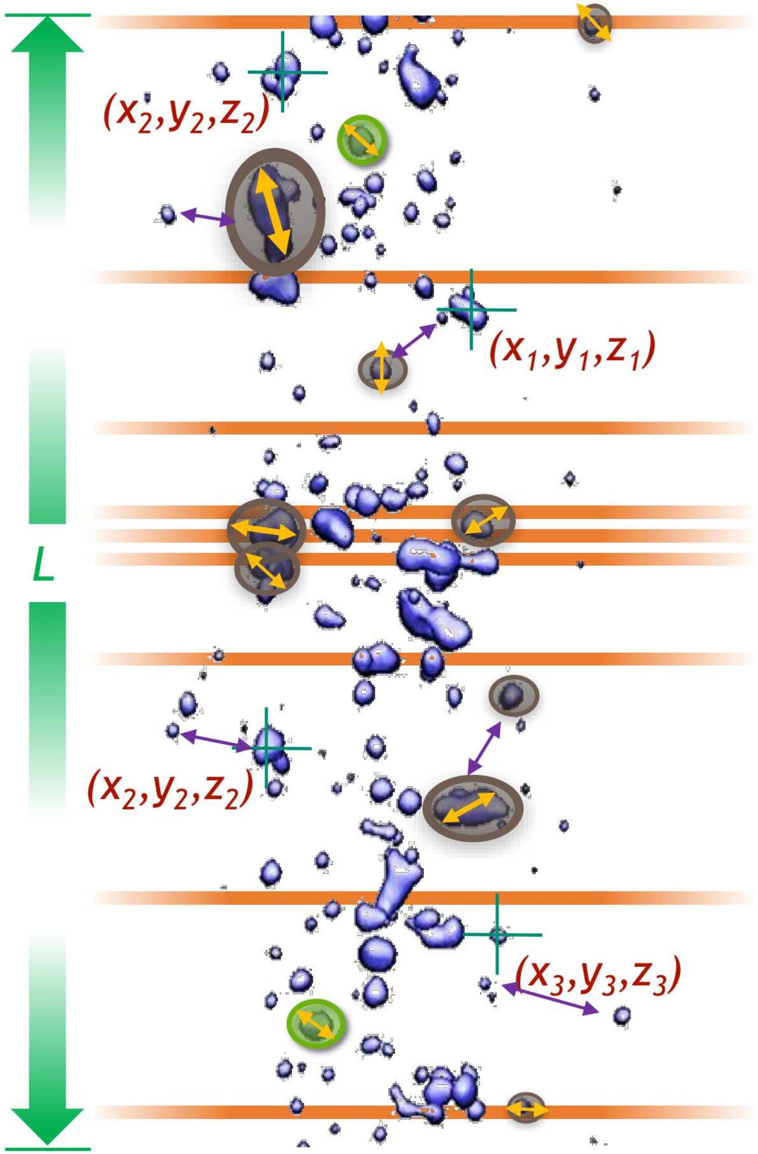
porosity map generated using DREAM.3D near the 10 & 20μm pores

Tools developed for material reconstruction & mapping pore locations to diagnostic signals

- data analytics & processing streams are crucial, complex and not optimized

Jon Madison, Thomas Ivanoff

Defect Characterization



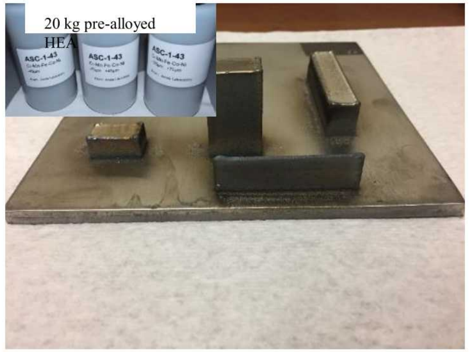
- Total volume of defects *(V_{tot})*
- Pore volume fraction *(V_{fract})*
- Spatial location of pores *(x, y, z)*
- Total number of defects *(N)*
- Total defects/length *(N/L)*
- Average defect volume ($V_{avg.}$)*
- Average equivalent spherical diameter ($ESD_{avg.}$)*
- Average cross-sectional area ($CSA_{avg.}$)*
- Average nearest neighbor distance ($NND_{avg.}$)*

How do we *best* represent the defect populations present?

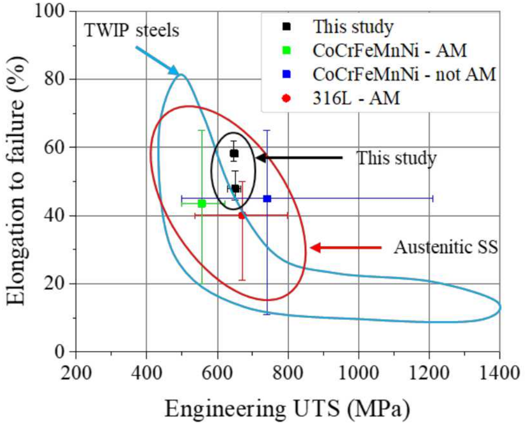
AM Alloy Development (preview for later webinar)

Thrust 1: Transition Metal High Entropy Alloys

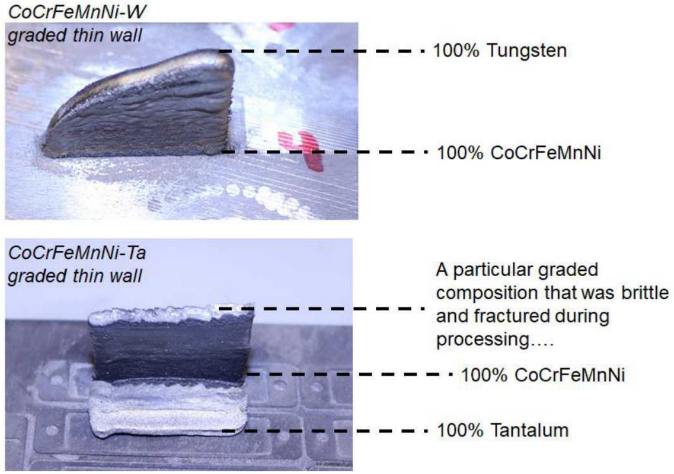
LENS processed CoCrFeMnNi HEA - >99% relative density

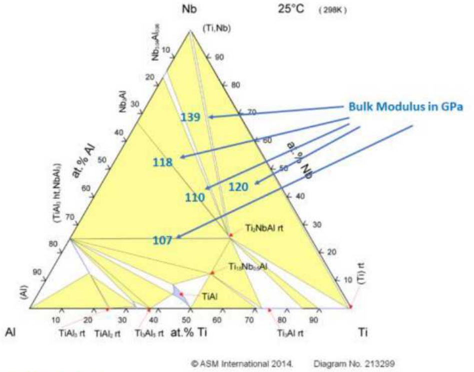


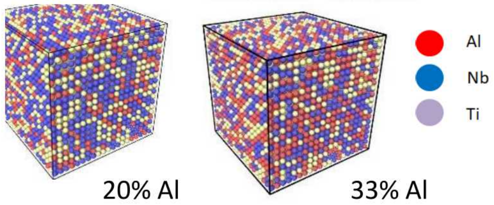
High strength and high ductility in as-built AM form



Thrust 2: Rapid exploration of High Entropy Alloy and Compositionally Complex Alloy phase space



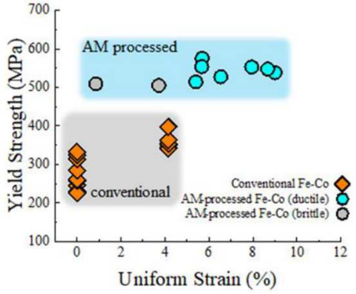


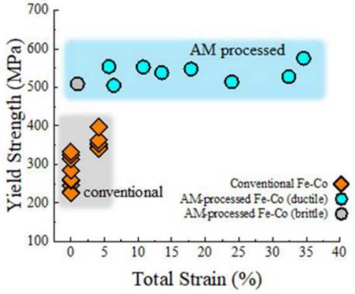


Thrust 3: Advanced Magnetic Alloys

AM-process magnetic alloys

Emergent material behavior





Other Ongoing & Developing AM Thrusts

- *Refractory HEAs and CCAs*
- *Bulk metallic glasses/amorphous alloys*
- *AM solidification modeling of HEAs/CCAs*
- *Deformation, corrosion, and wear/tribological behavior of HEAs/CCAs*

Collaborators: Ames Lab, Lehigh, UIUC, Texas A&M, Bucknell, ORNL

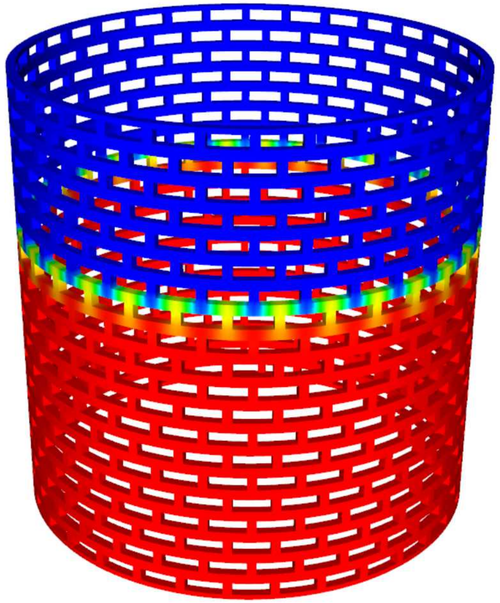
Andrew Kustas, Nic Argibay, Michael Chandross

Lattices

Growing interest for designers in applications

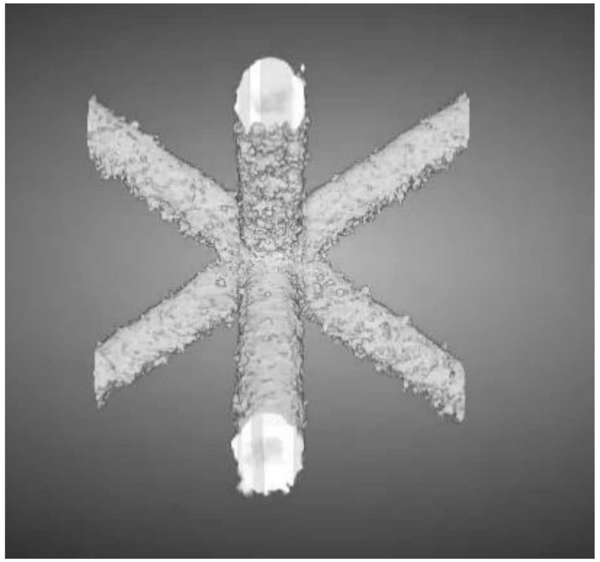
Challenges

- design to requirements
- representative material properties
- metrology & inspection

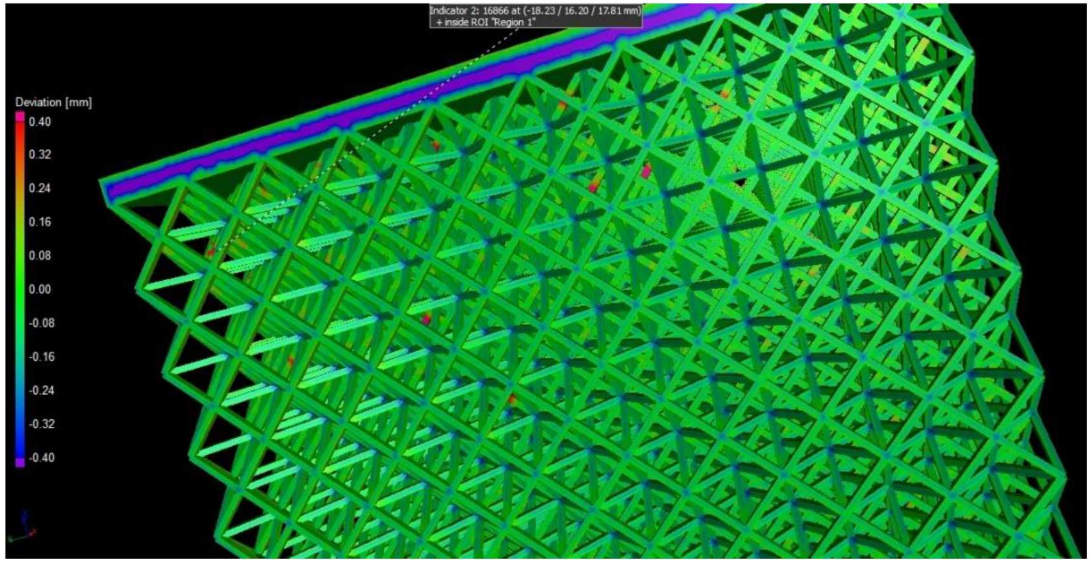


latticed tube simulation

latticed part in 316L SS



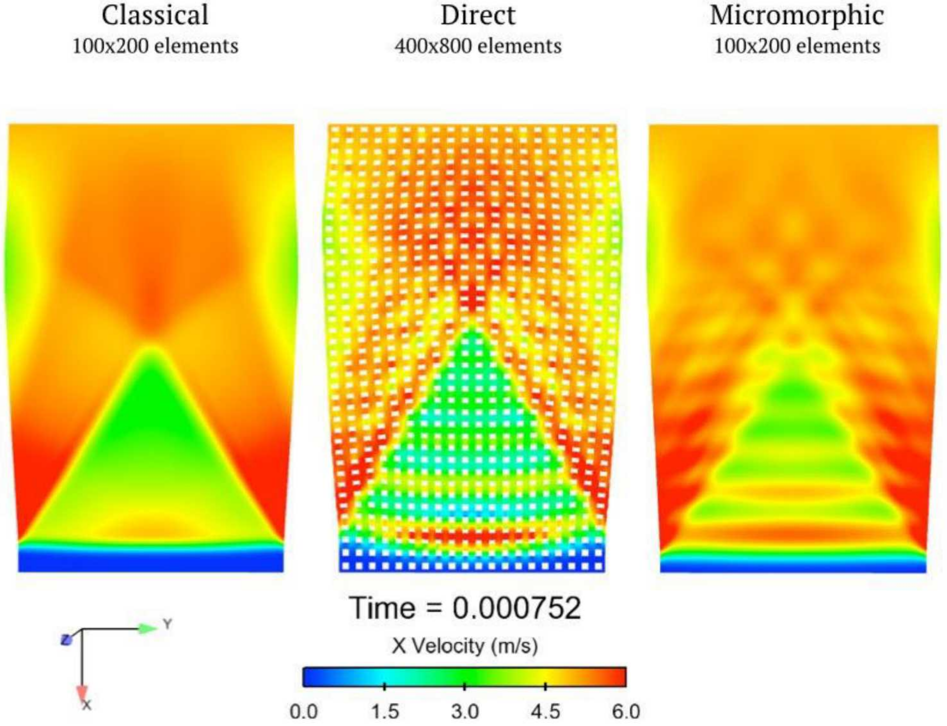
Zeiss Xradia 520 Versa µCT of struts & node

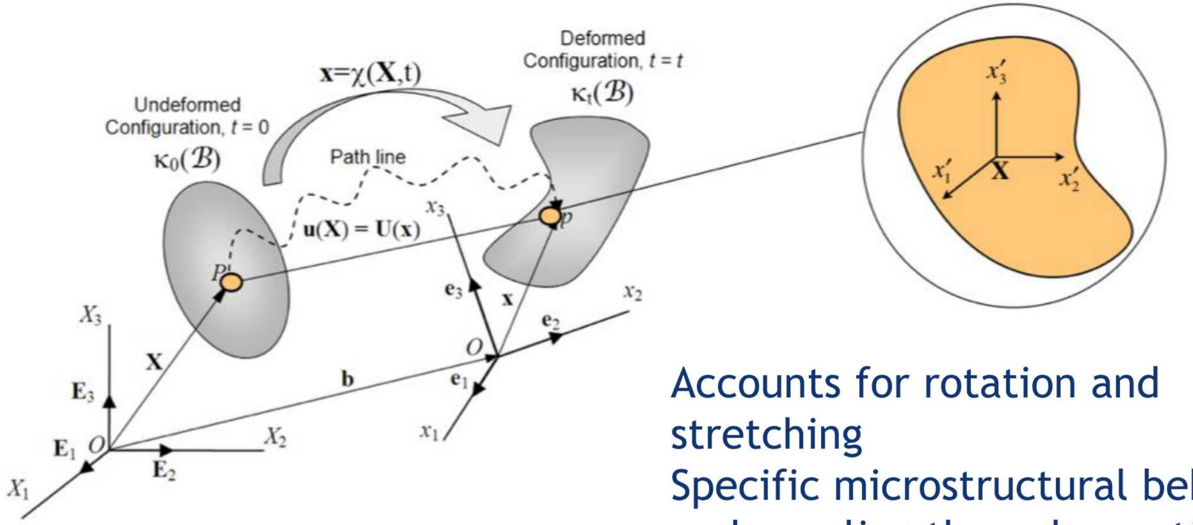


Ti6Al4V CT data from Nikon 450, red = missing struts, green = nominal, purple = oversized

Micromorphic Model Enables Fast Simulations of Lattice Metamaterials to Enable Design Optimization

Accounting for Underlying “Microstructure” With Additional DOFs: Micromorphic Approach

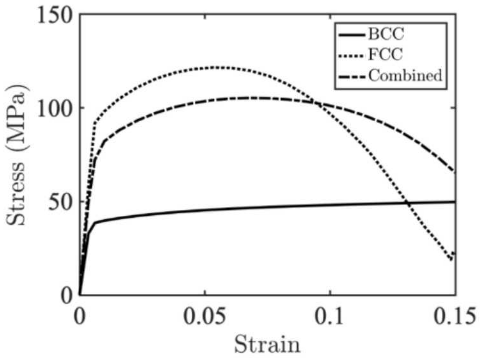


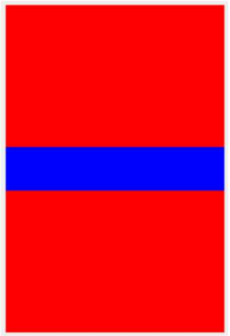


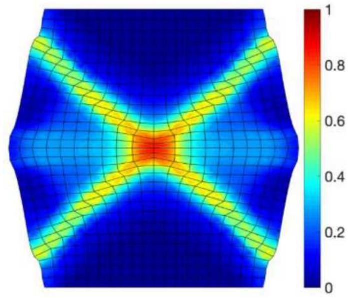
Accounts for rotation and stretching

Specific microstructural behavior and coupling through constitutive response

Enables simulation of combination of Lattices which Leads to Improvement in Energy Dissipation.







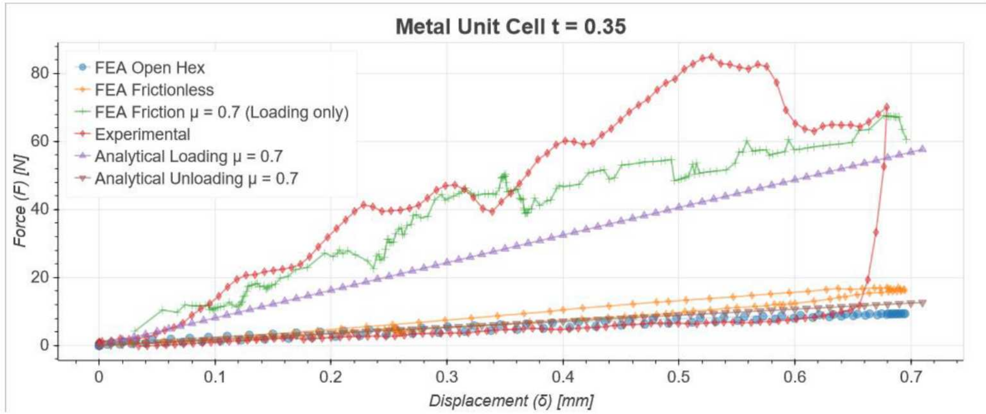
Ryan Alberdi, Brad Boyce, Remi Dingreville

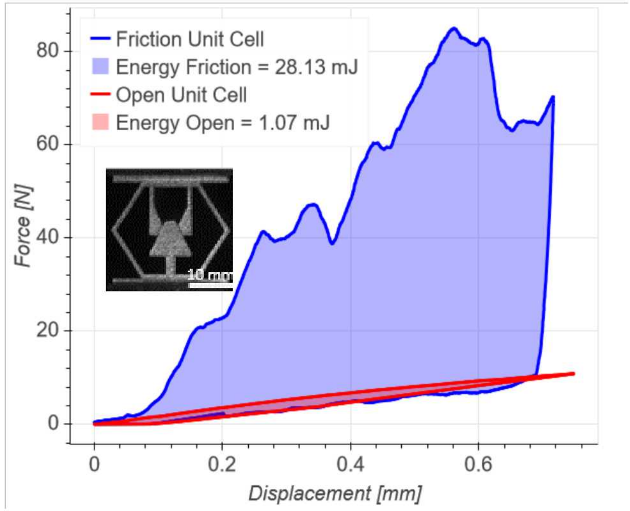
Vibration Mitigation Using Friction Dissipation

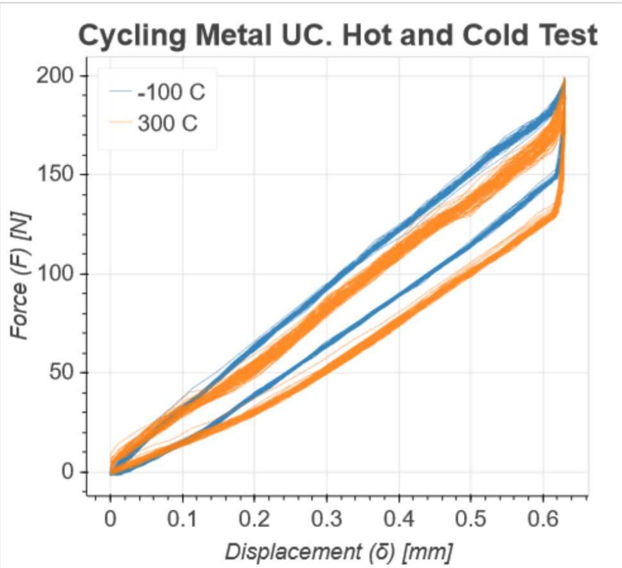
Developed analytical and FEA simulations which accurately predict energy dissipation. Enables optimization.

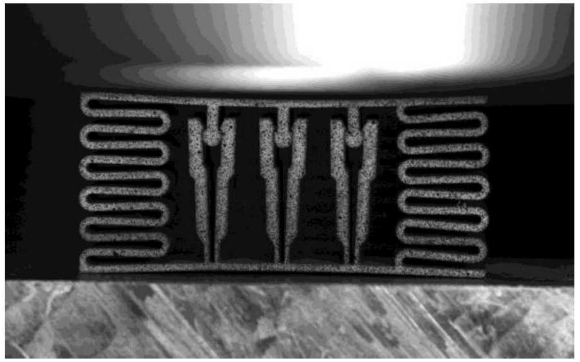
Tested unit cell in hot and cold environments to demonstrate energy dissipation outside of viscoelastic material operating environments.

Developed and tested new vibration unit cell designs.









- Rubbing elements dissipate energy
- Broad band dissipation across large frequency range
- Independent of displacement or velocity

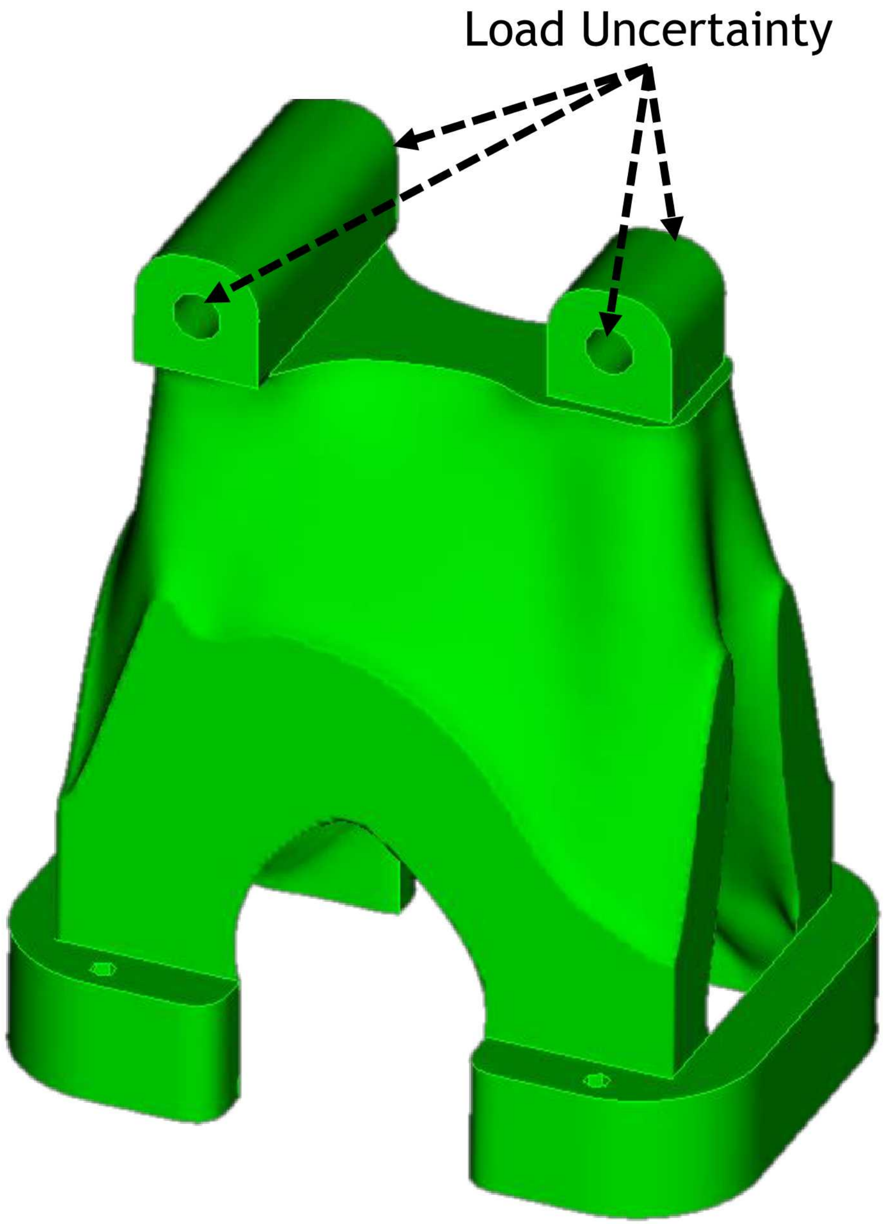
Brad Boyce, Bradley Jared, Nicholas Leathe, Anthony Garland, Zach Casias

Questions?

Bradley Jared, PhD, bhjared@sandia.gov, 505-284-5890

PLATO Uncertainty Awareness

Deterministic



Non-Deterministic

Brett Clark, Josh Robbins, Miguel Aguilo

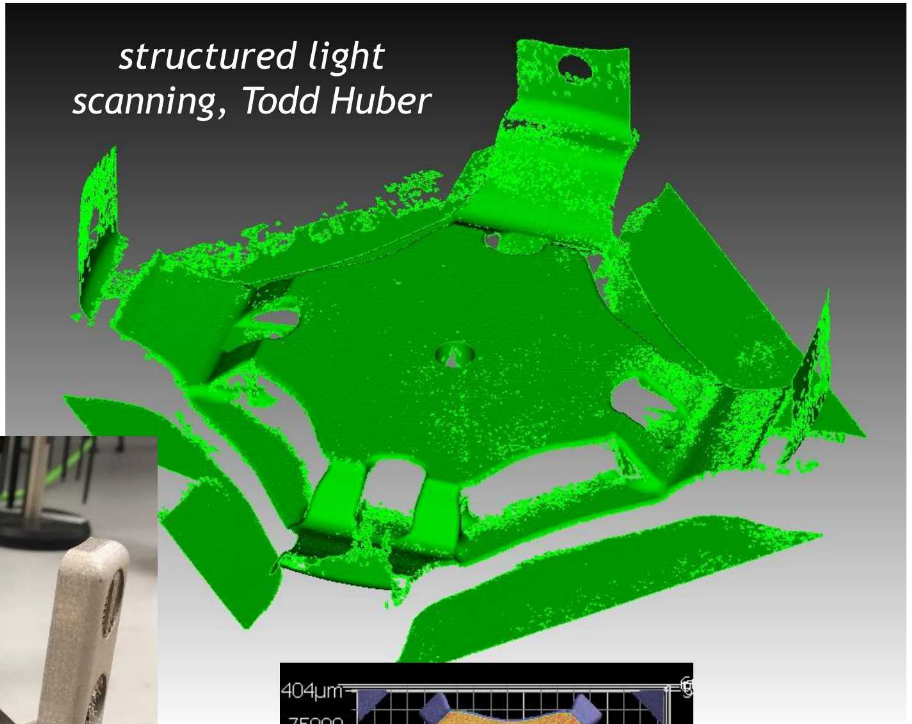
Metrology

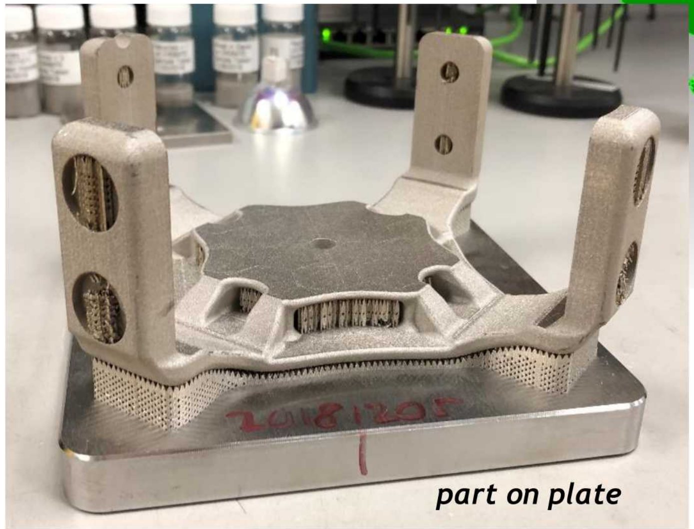
Measuring complex topologies is non-trivial

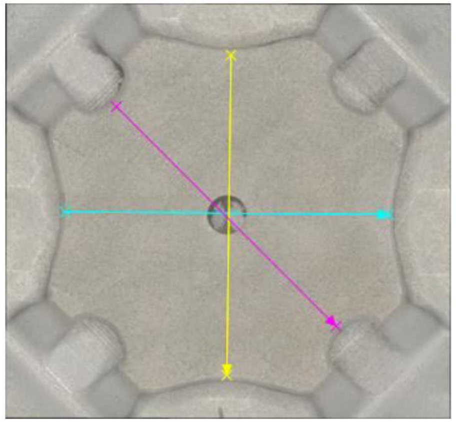
- access
- slopes
- surface roughness
- data management & analysis

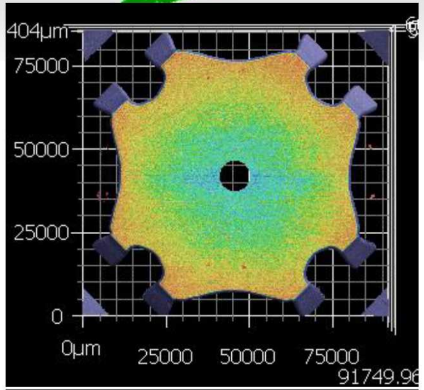
Significant part distortion

- build plate & part
  - top surface of legs parallelism to center plane
    - on plate = 25-100μm
    - off plate = 280-300μm
- will part mate assembly
- where are proper datums?
  - surface finish acerbates (printing, supports)

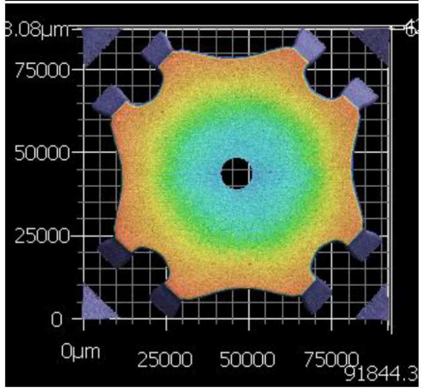








part on plate,
form = 68.2μm



part removed,
form = 188.2μm

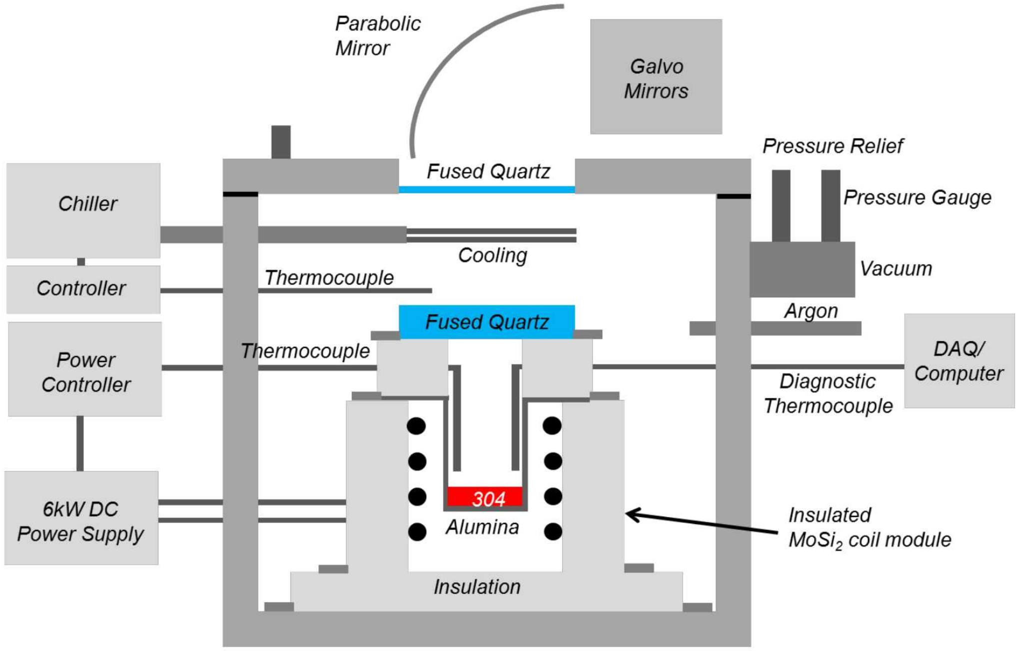
Calibration Testbed for IR Sensors

Using passive microwave radiometry to measure emissivity & temperature

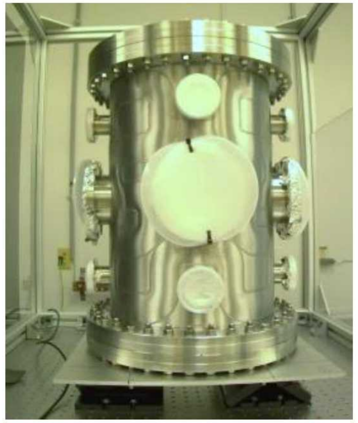
- measures %R of 137 GHz radiation from surface
- 20-1500°C, 2 Torr in Ar chamber
- expected uncertainty ~10°C

- Initial use is IR Camera calibration
- Extreme dynamic range (cryogenic temperatures to millions of Kelvin)
- Linear relationship between radiated power and temperature enabling *single-point black body calibration*.
- Thermal Return Reflection (TRR) technique enables real-time measurement of emissivity.

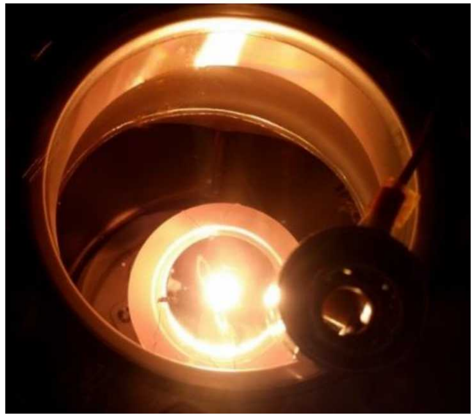
MIT collaboration



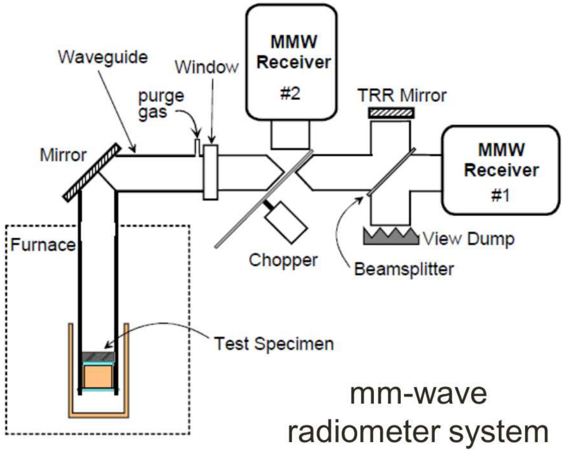
metrology testbed layout



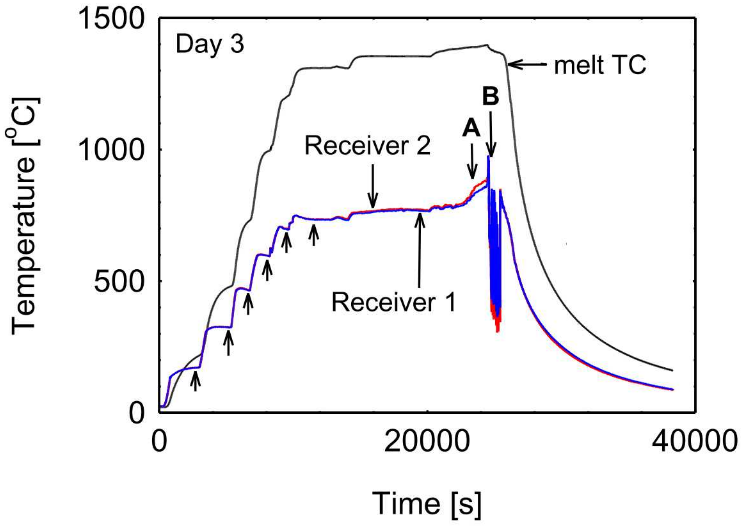
vacuum chamber



1500 °C furnace in operation



mm-wave radiometer system schematic



radiometric temperature from receivers showing freeze/melt cycles of 316L SS

Eric Forrest, Primary Standards Lab