SAND2019-7002PE

Material Assurance in Metal Additive Manufacturing for High Consequence Systems

PRESENTED BY

Bradley Jared

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SAND 2018-8025 C

Outline

Sandia overview
- motivations
- processes
- qualification
- computational tools
- characterization / metrology

Process optimization
- machine metrology
- mapping

Process control
- critical defects
- artifacts
- in-situ monitoring

Sandia National Laboratories

A National Security Science & Engineering Laboratory
- "Exceptional service in the national interest"

Nuclear Weapons

Defense Systems & Assessments

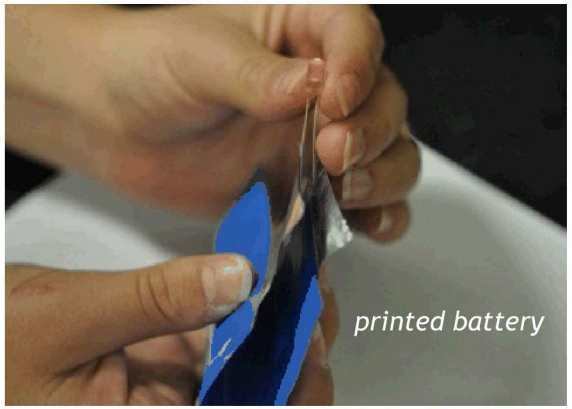
Energy & Climate

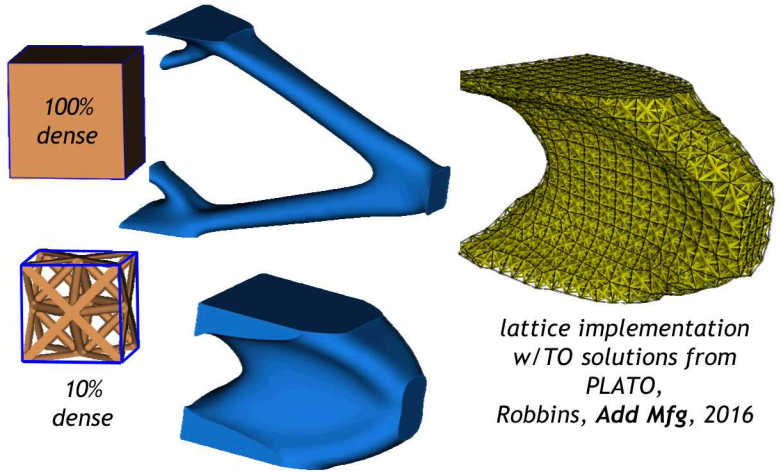
International, Homeland, & Nuclear Security

SNL's Additive Interests

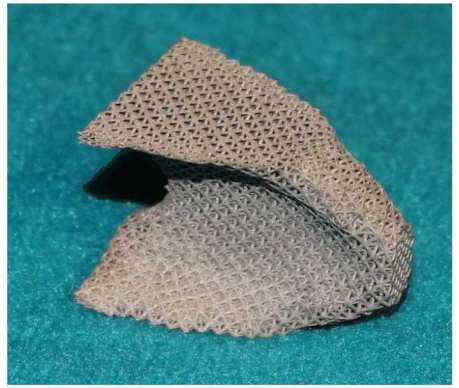
Reduce risk, accelerate development
- simplify assembly & processing
- prototypes, test hardware, tooling & fixturing

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"





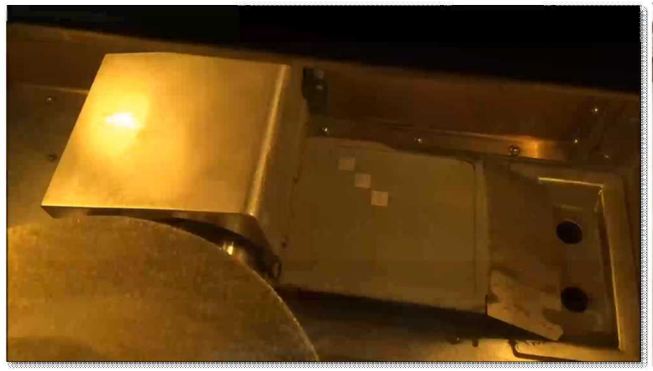
*lattice implementation w/TO solutions from PLATO, Robbins, **Add Mfg**, 2016*

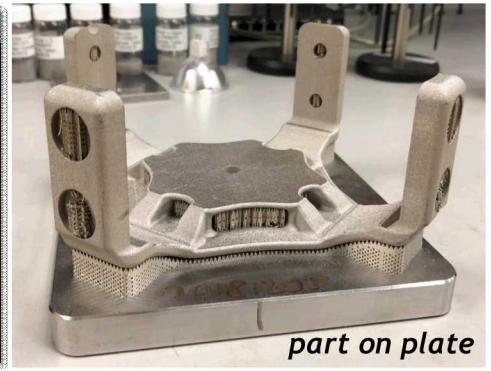


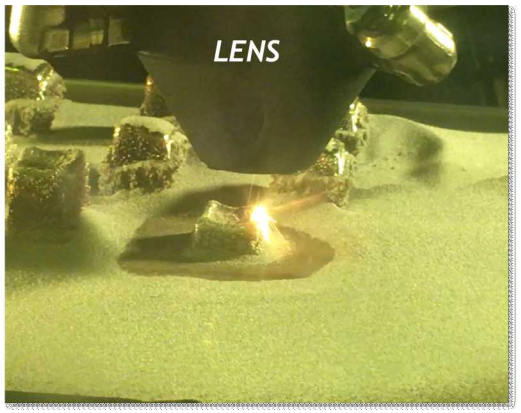
316L SS lattice part

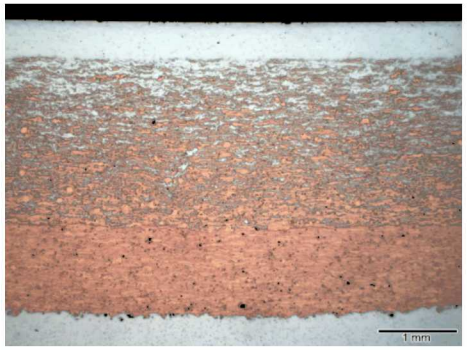
Sandia Processes

metal

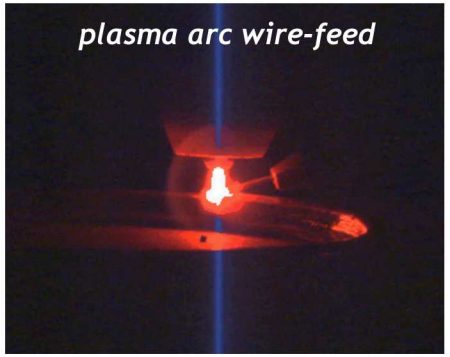


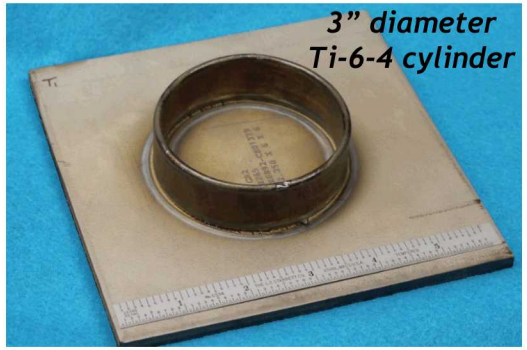




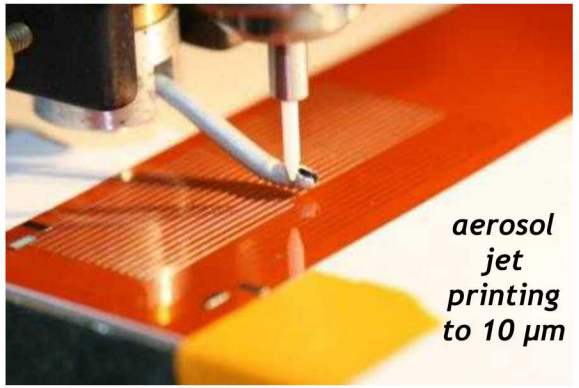


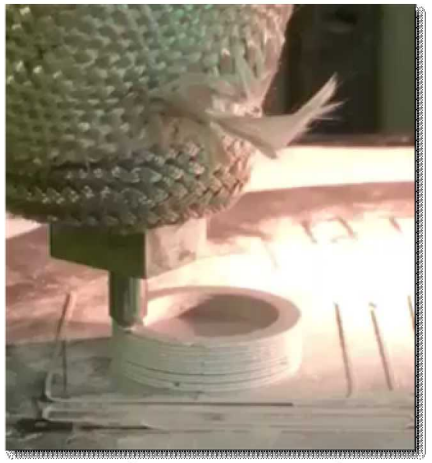
Cu-Al plasma sprayed graded density coating



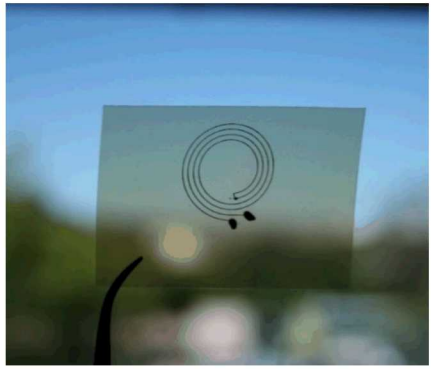


direct write

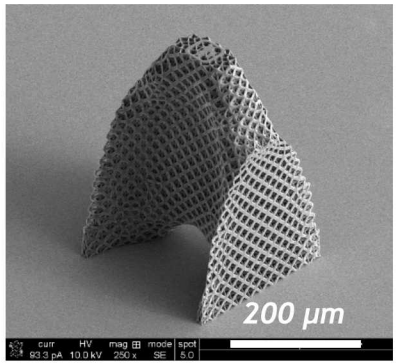




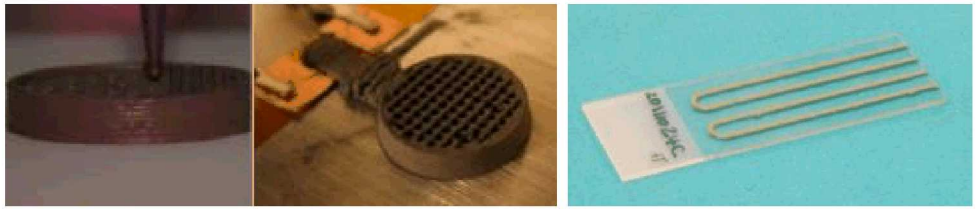
ceramic-thermoplastic 3D (CT3D) printing alumina



room temperature cure of conductive traces on polymer film



Nanoscribe two-photon lithography



energetic materials

Material Assurance

Material formation concurrent w/geometry

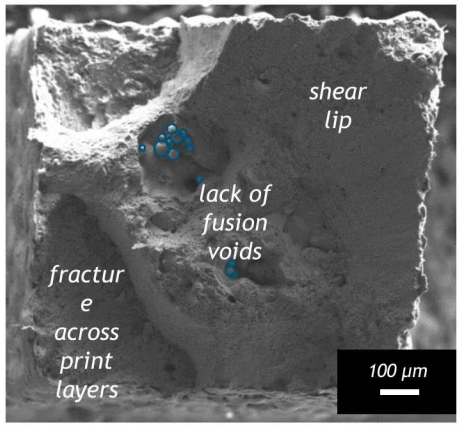
- want to predict part/material performance
  - feedstock certs inadequate for performance
- **how to ID a bad part?**
  - complexity isn't "free"
  - requires significant design margins and/or rigorous post-process inspection / validation

Quantify critical material defects & useful signatures

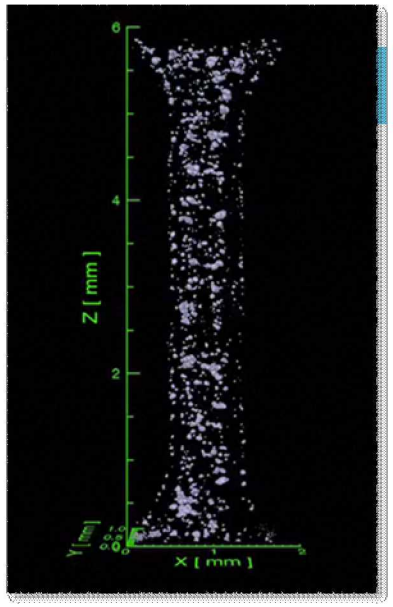
- D-tests, NDE, process monitoring, mod-sim, ?

Understand mechanistic impacts on properties

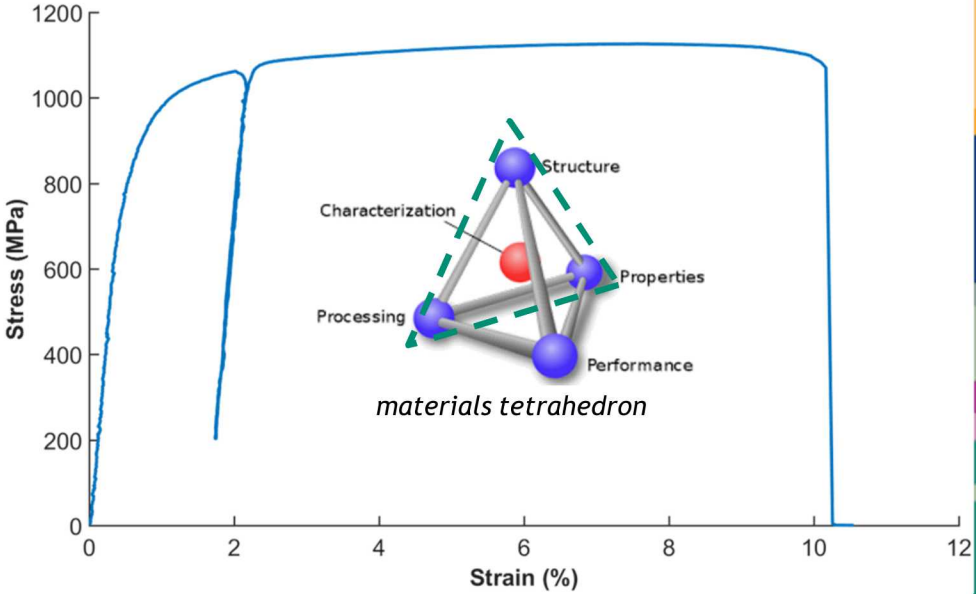
- build process-structure-property relationships to predict margins & reliability
- characterize stochastic response to design for **uncertainties**
- provide scientific basis for qualification of AM metals for high consequence applications



17-4PH dogbone fracture surface



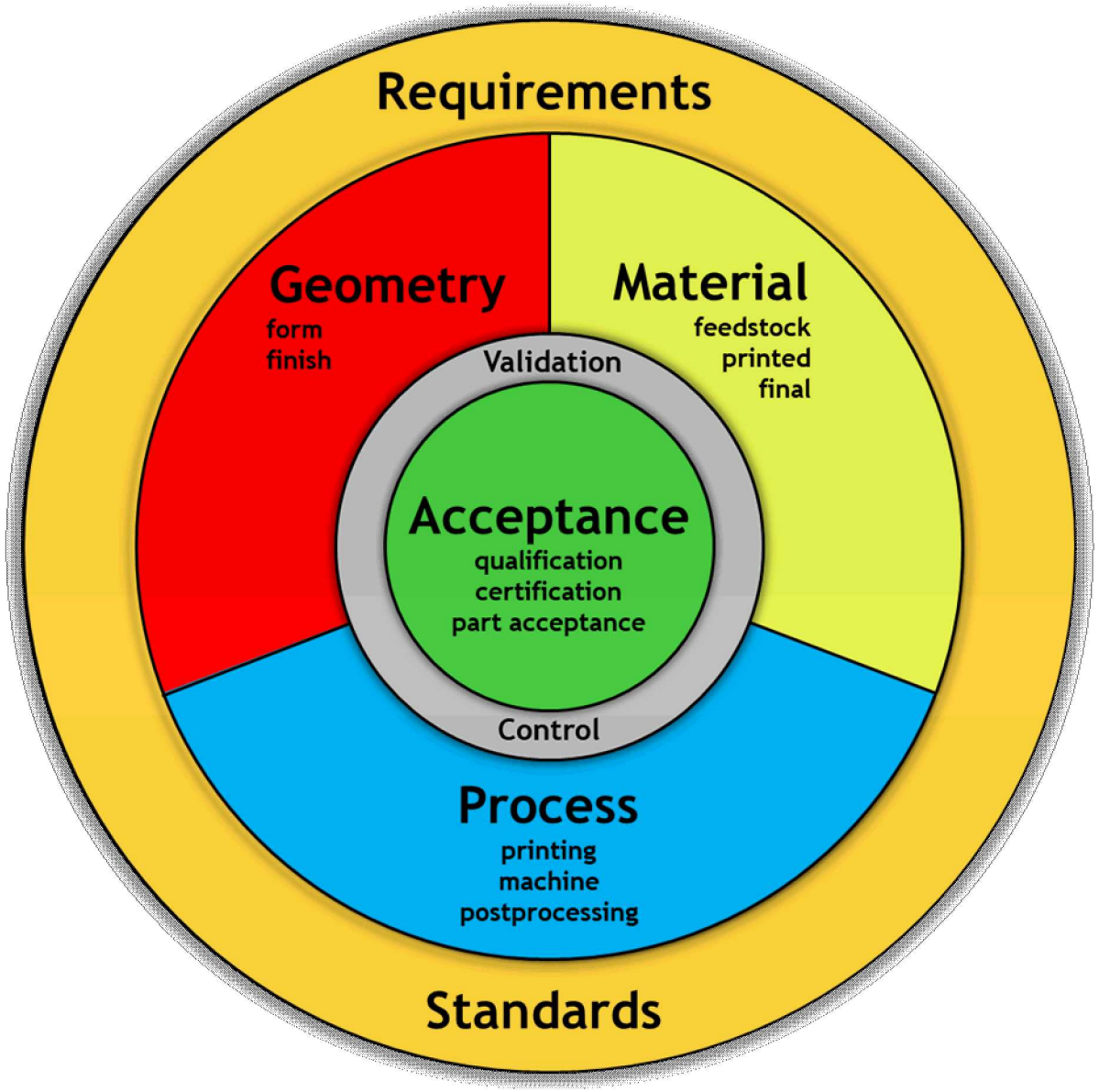
17-4PH dogbone porosity



materials tetrahedron

17-4PH dogbone stress-strain response

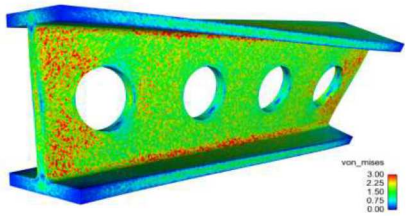
Foundational Elements of Qualification



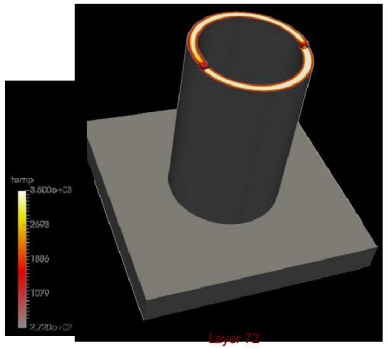
Qualification Tomorrow

"Changing the Engineering Design & Qualification Paradigm"

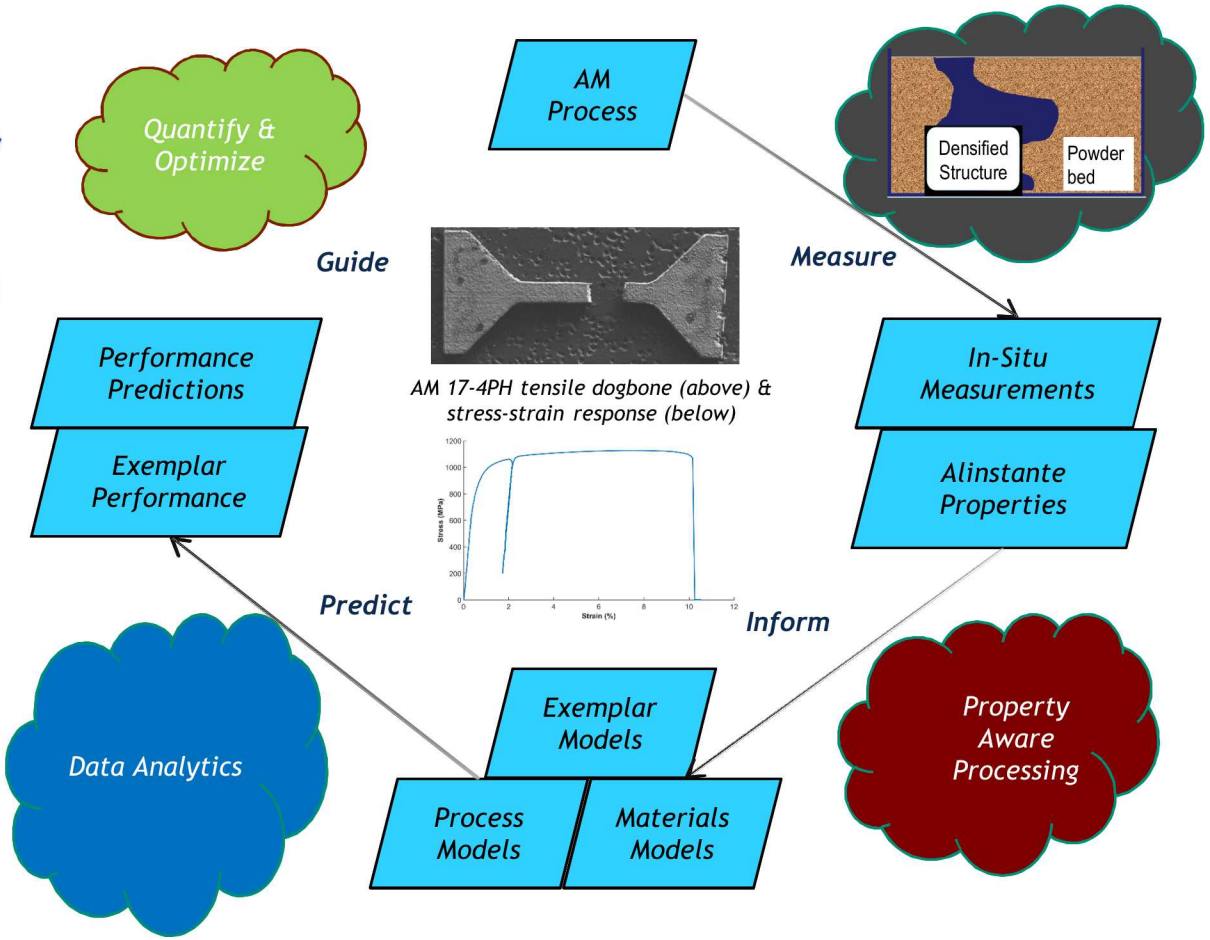
- leverage AM, in-process metrology & HPC to revolutionize product realization
- accelerating design to production



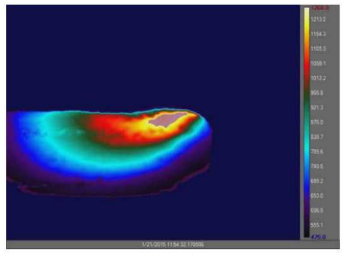
material / part performance simulation



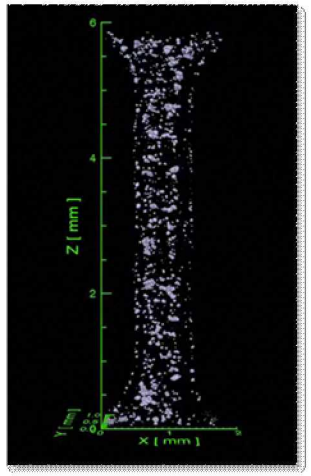
process simulation



AM 17-4PH tensile dogbone (above) & stress-strain response (below)



thermal history during bi-directional metal deposition



17-4PH dogbone porosity

Allen Roach

PLATO Design Platform

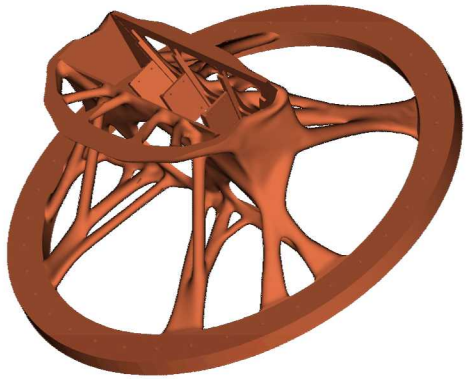
End-user environment for physics-based design using topology optimization

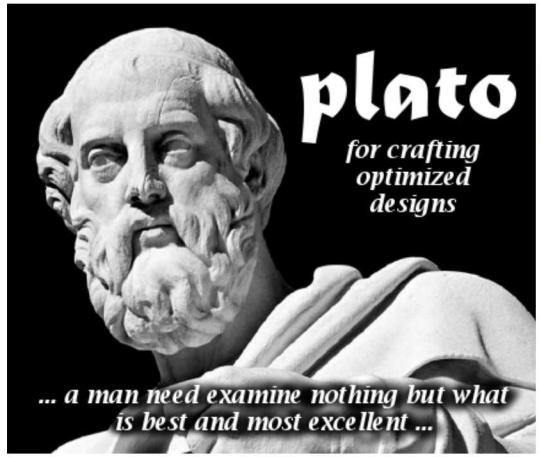
HPC-enabled: physics, optimizers, services, …

Interactive design feedback and user control

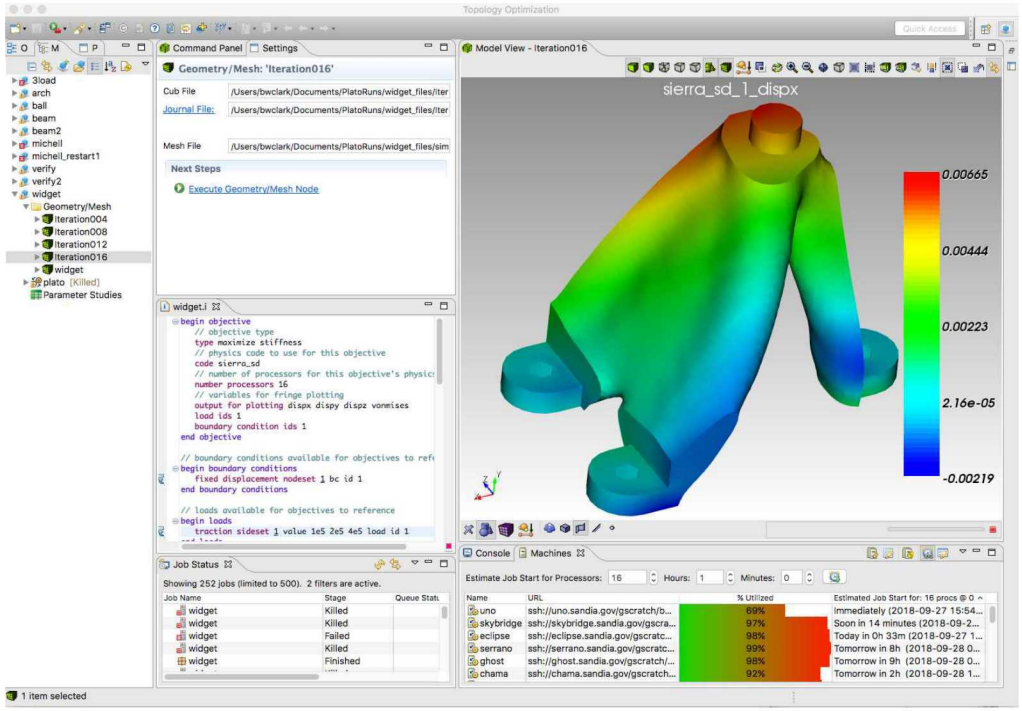
Smooth, print-ready designs

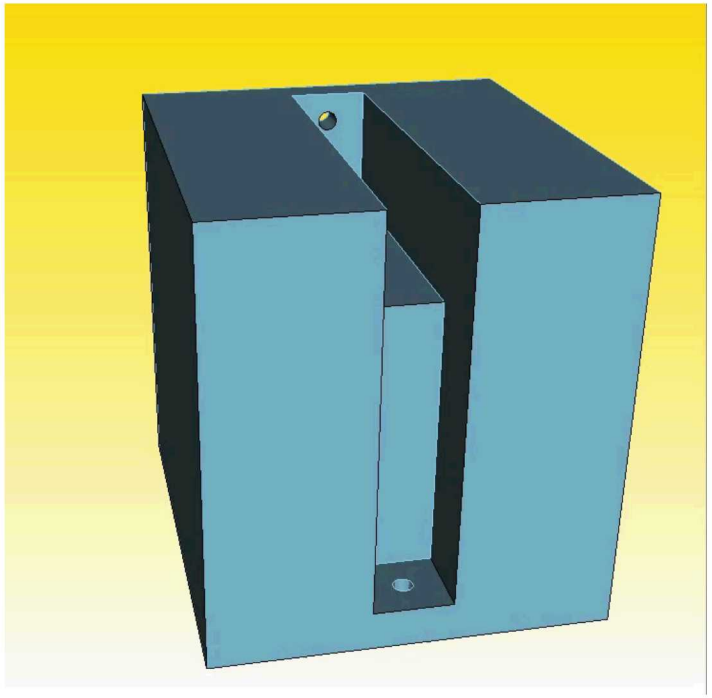
Extensible architecture

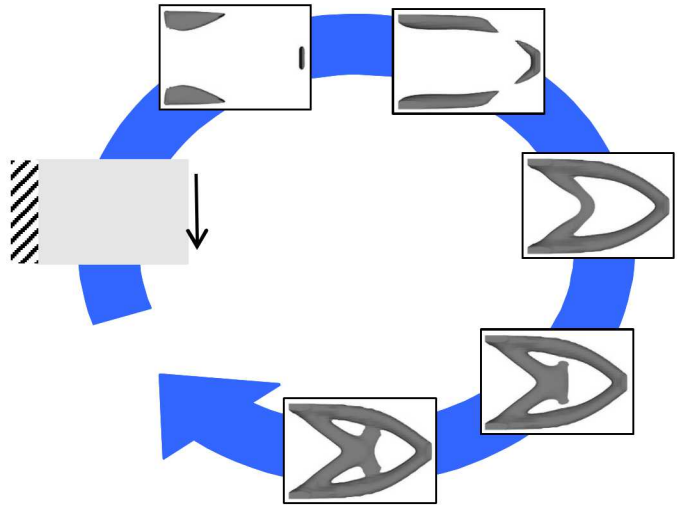




Website: www.sandia.gov/plato3D
Github: https://github.com/platoengine/platoengine
email: plato3D-help@sandia.gov







Interactive design feedback and user control

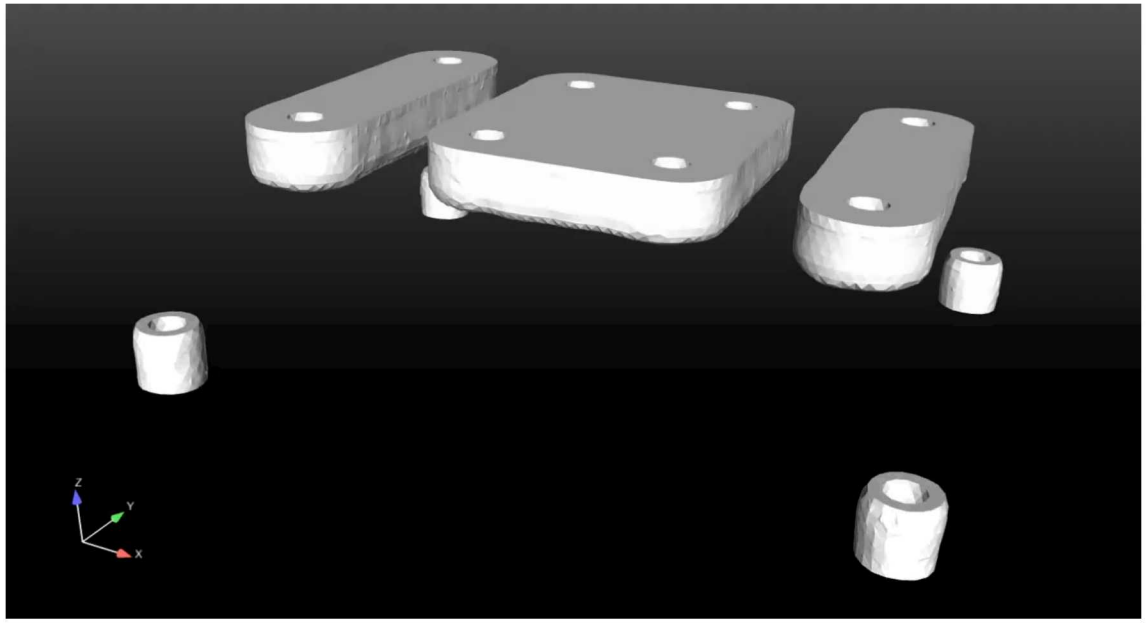
Brett Clark, Josh Robbins, Miguel Aguilo

Optimization-Based Design for Manufacture

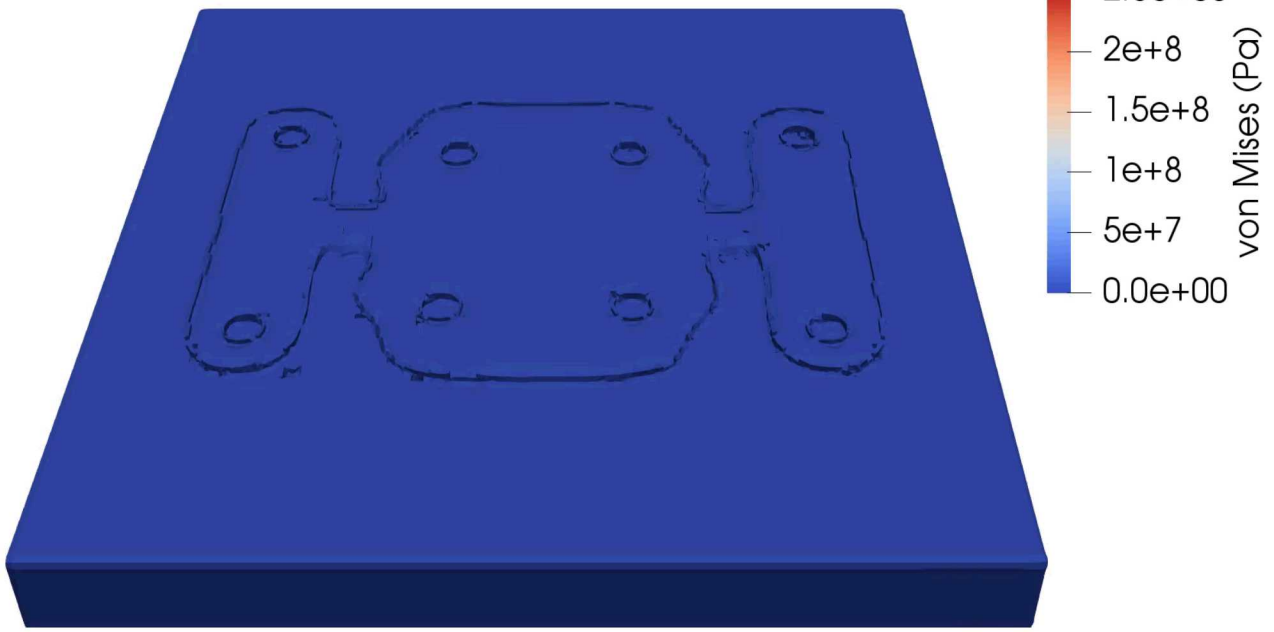
"Manufacturability" objectives: integrate manufacturing process awareness into optimization-based design tools to enable manufacturability and performance

- 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



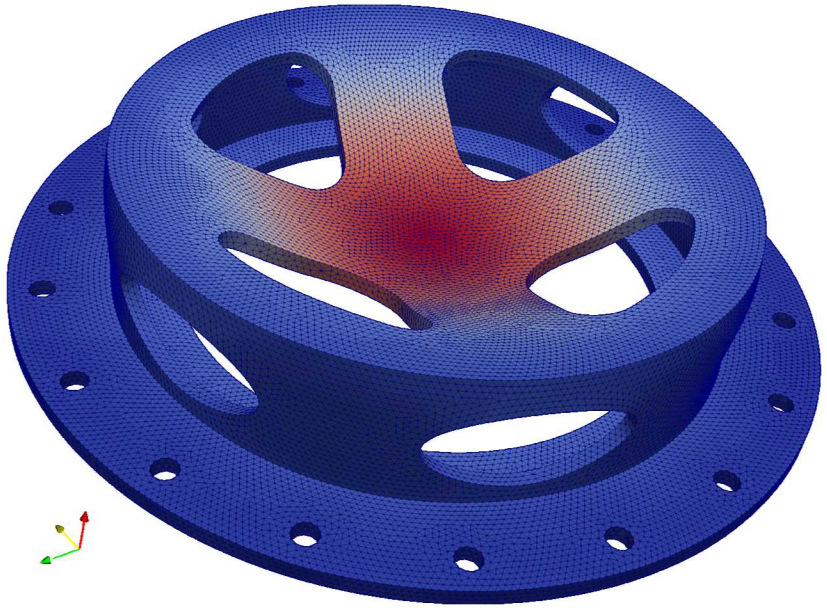
coupled thermo-mechanics TO geometry generation, maximized stiffness & heat conduction



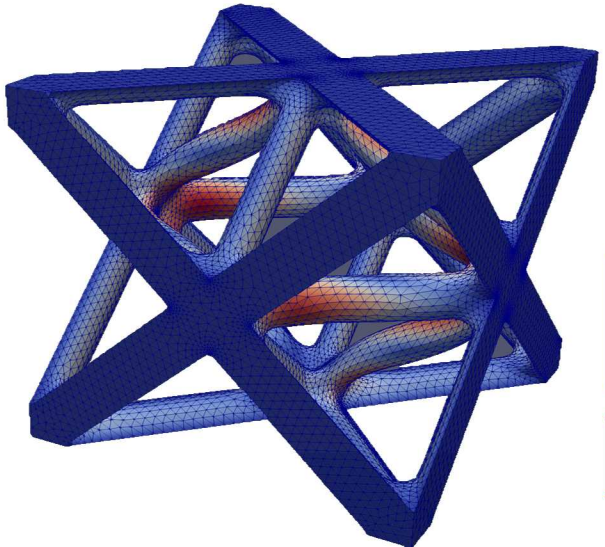
residual stress prediction from high-fidelity process simulation

Josh Robbins, Brett Clark, Miguel Aguilo

DARPA TRADES Design Ecosystem



Plato Analyze



Modeling

M

plato
for crafting optimized designs

Plato Engine

https://github.com/platoengine

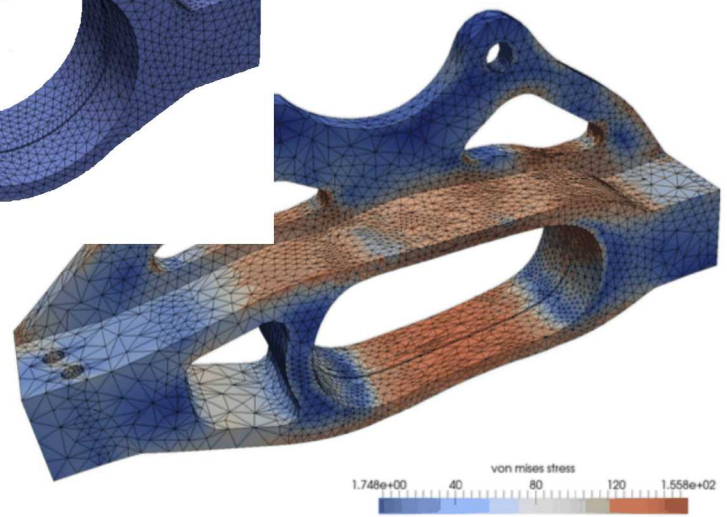
A

Analysis

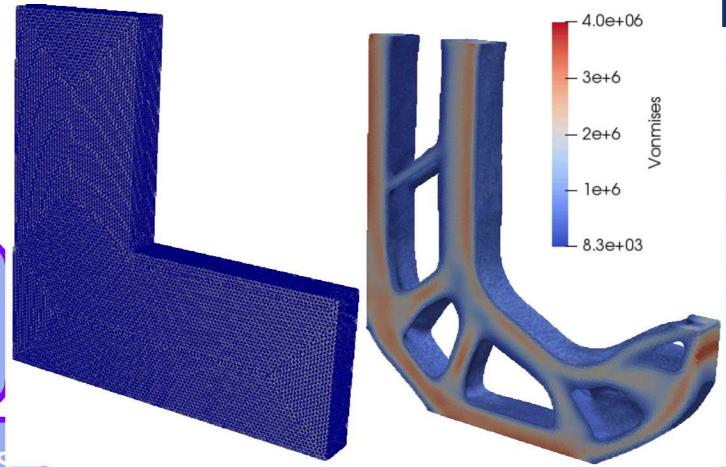
S

Synthesis

Plato Model

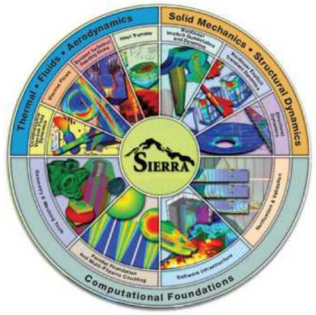


Plato Optimize



Miguel Aguilo, Brett Clark, Josh Robbins

Models Bridging Length Scales



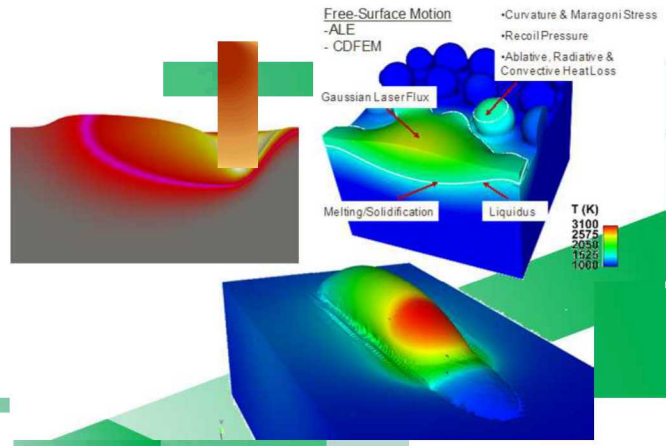
LAMMPS

ARIA

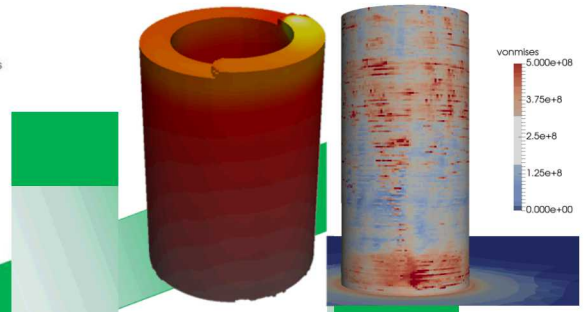
ADAGIO

SPPARKS

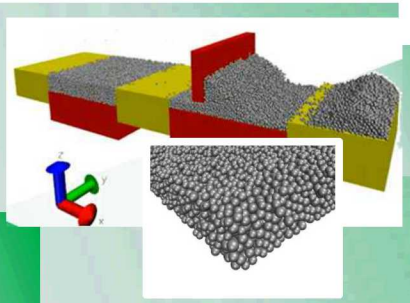
Solidification Scale Thermal
M. Martinez, B. Trembacki, D. Moser



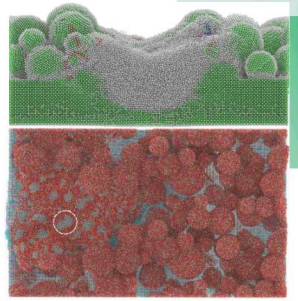
Build Scale Thermal + Mechanics
K. Johnson, K. Ford, L. Beghini, M. Stender & J. Bishop



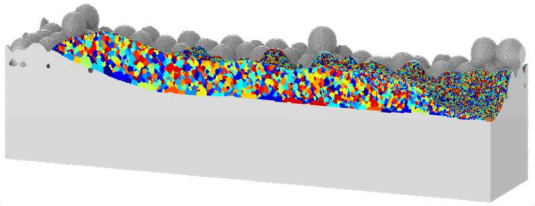
Powder Spreading
D. Bolintineanu



Powder Behavior
M. Wilson



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

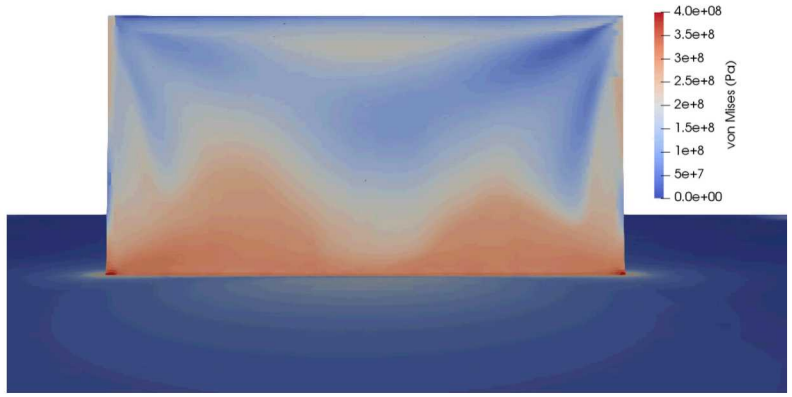


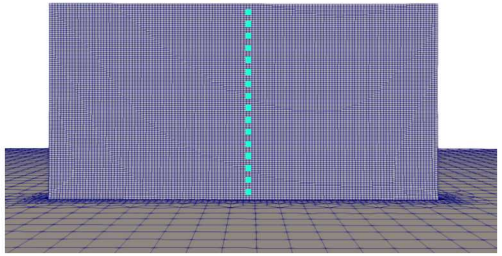
Build Scale Microstructure
T. Rodgers, J. Madison

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

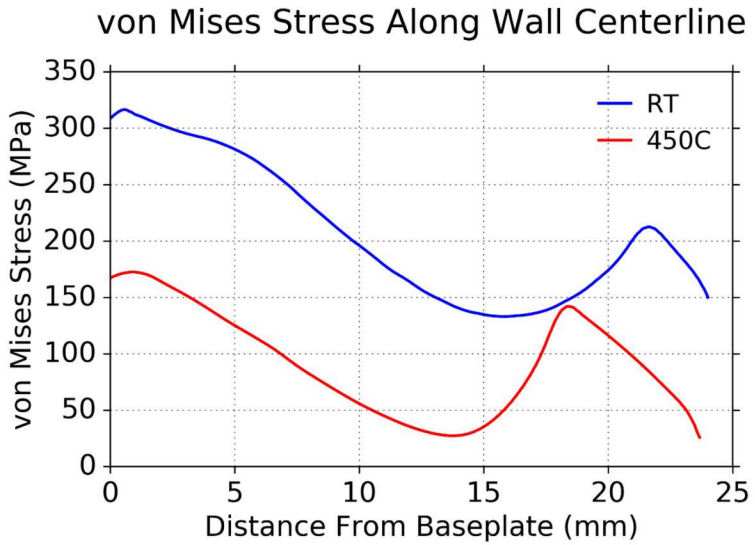
Length Scale (m)

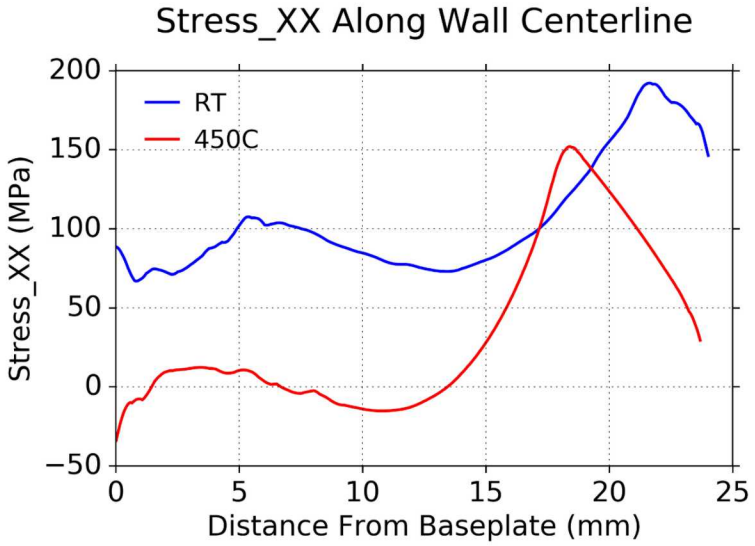
High Fidelity Process Models Provide Resolution at Each Laser Pass





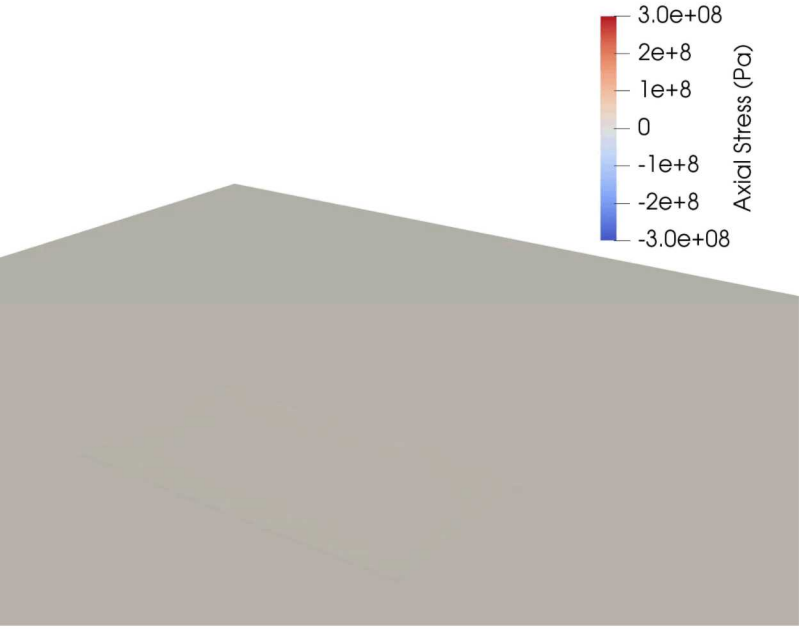
304L Two Pass LENS Thin Wall Build Study Examining Baseplate Preheating Effects



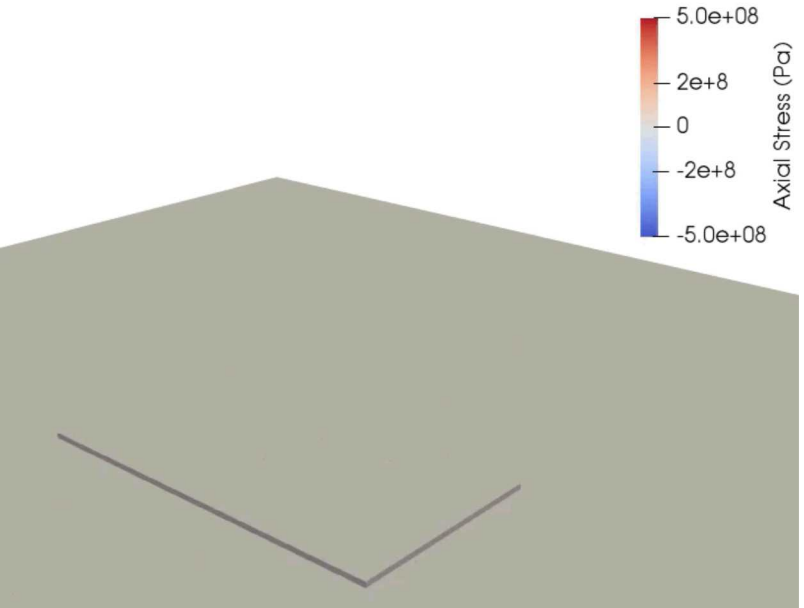


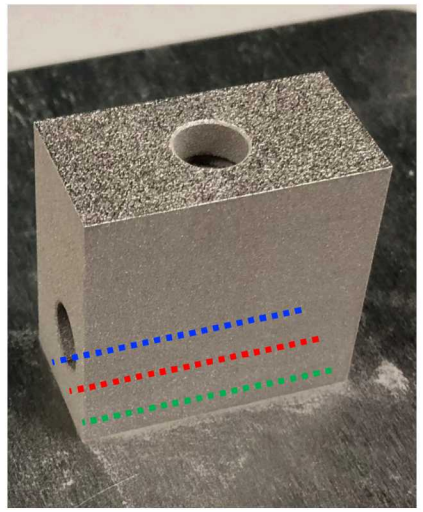
Kyle Johnson

High Fidelity Models Inform Reduced Order Models

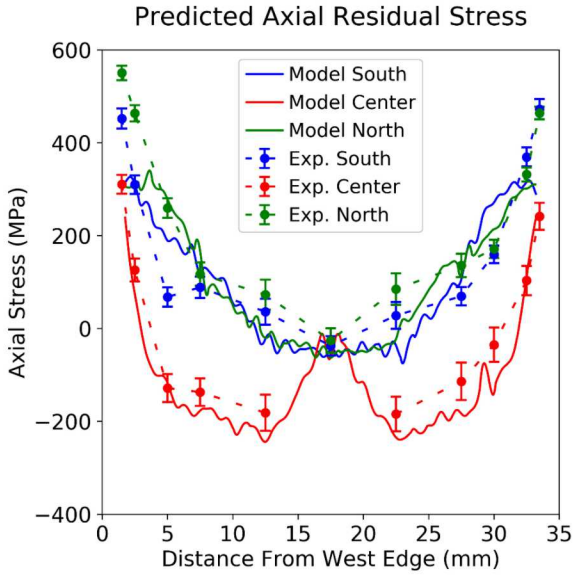


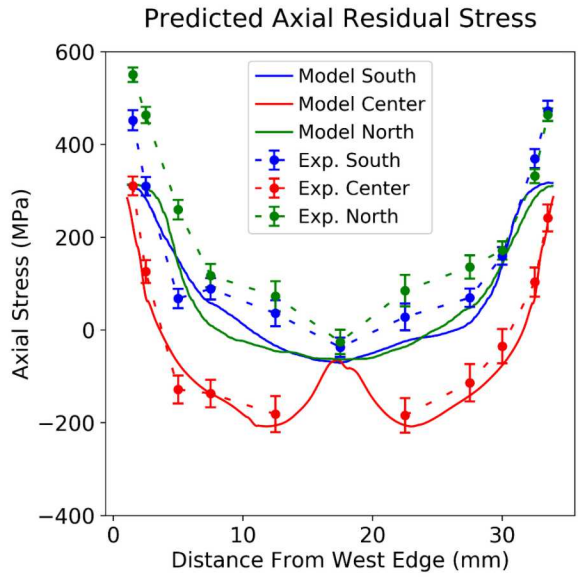
Enlarged Heat Source* and Layer Thickness
100 cpus
6 hrs (~real time)





Mechanical Inherent Strain
60 cpus
30 minutes

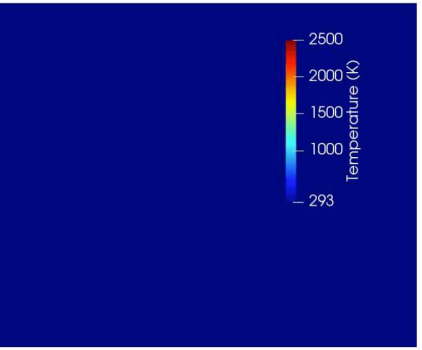




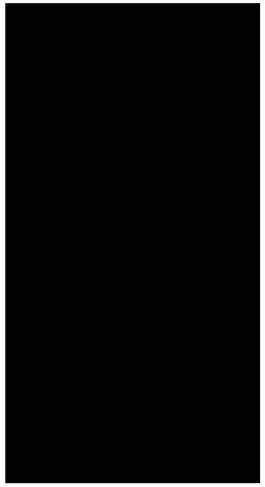
* Similar to Hodge et al. 2014 and 2016, Ganeriwala et al. 2019

Kyle Johnson

Microstructure Prediction in Stochastic Parallel PARticle Kinetic Simulator (SPPARKS)



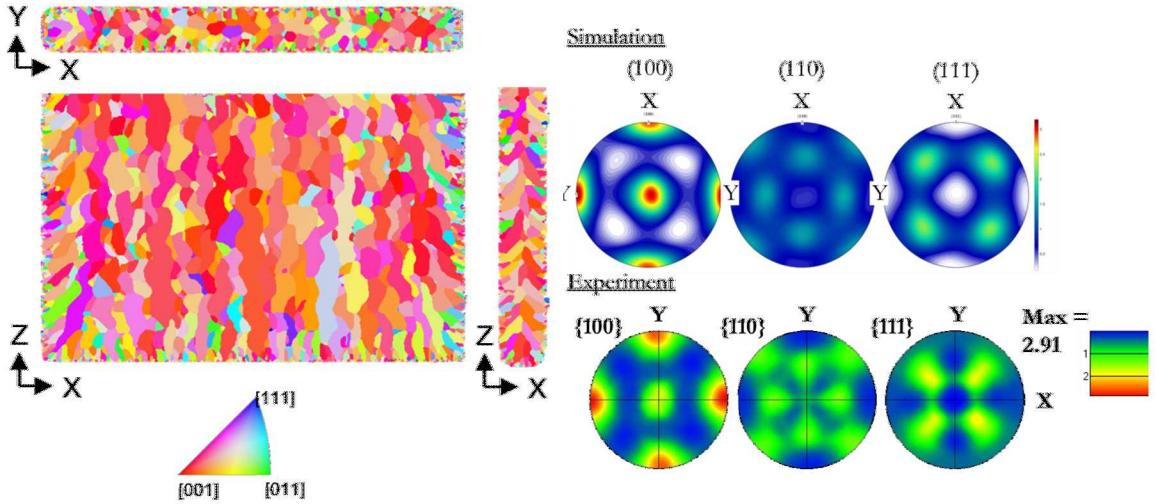
Thermal Simulation from Sierra/Aria (Thermal/Fluid Solver)



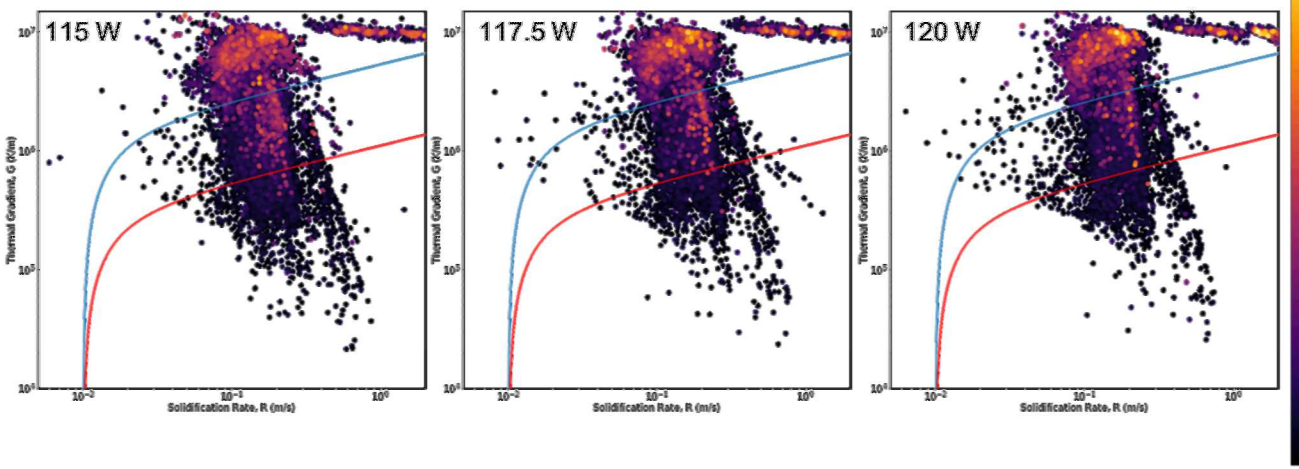
Single Continuous Build

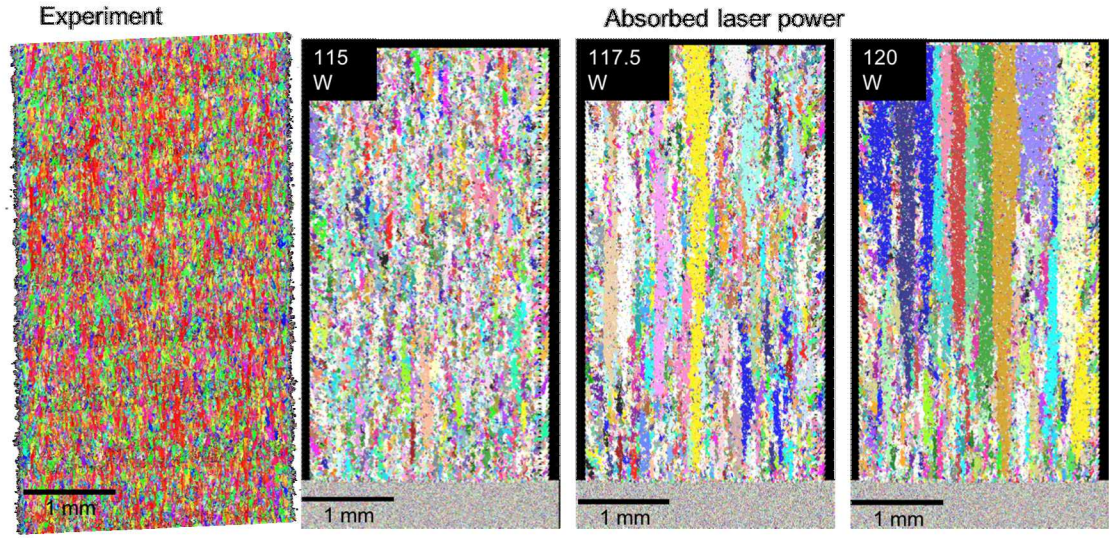
Double Build (8 second delay in between layers)

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



Stainless Steel Thin Wall Texture Prediction





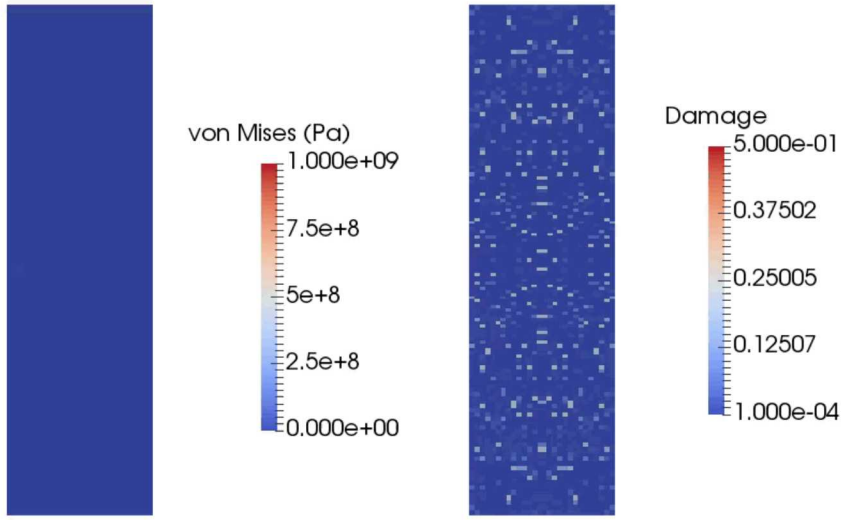
All simulations performed with nucleation densities of 8e13

316L Stainless Steel Column

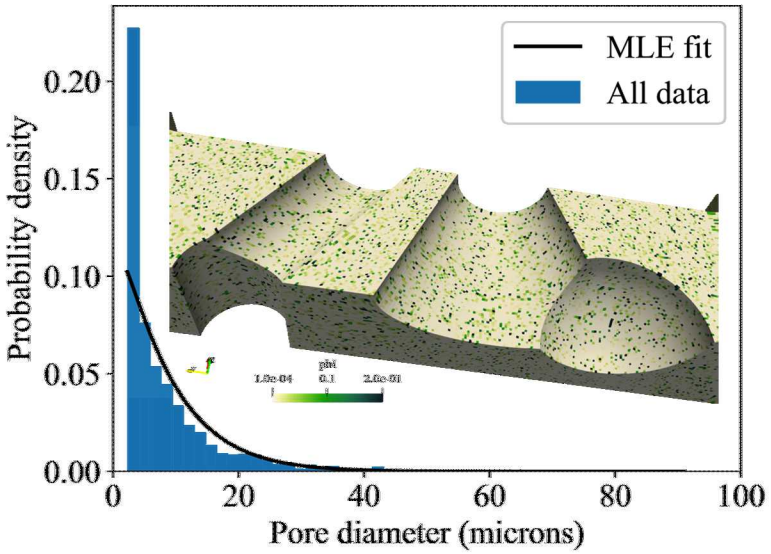
http://spparks.sandia.gov

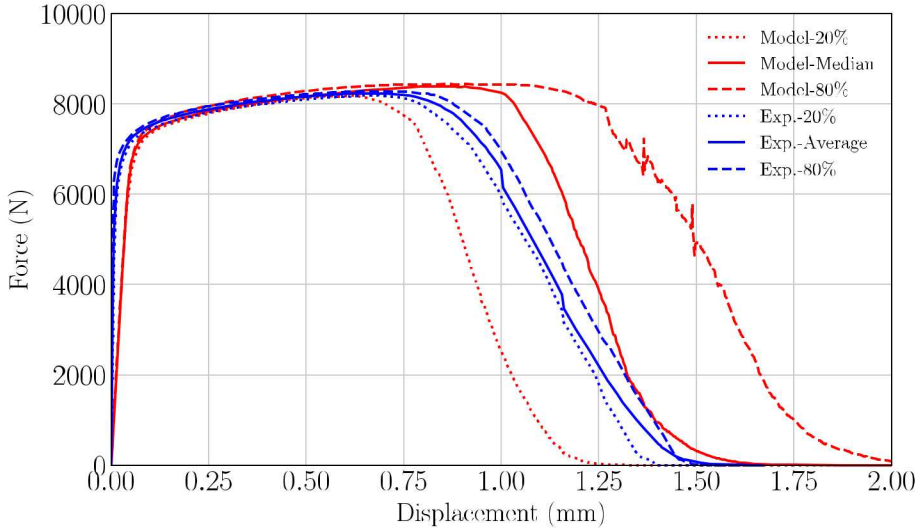
Theron Rodgers, Mario Martinez, Dan Moser

Predicting Part Performance

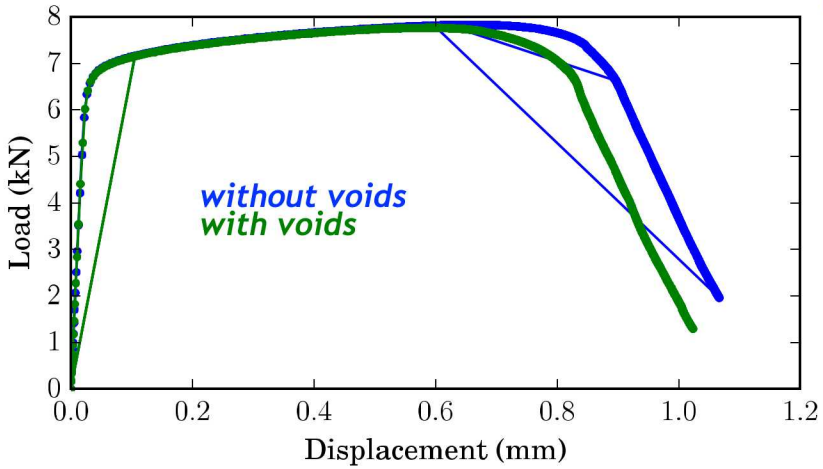


representing porosity as initial damage

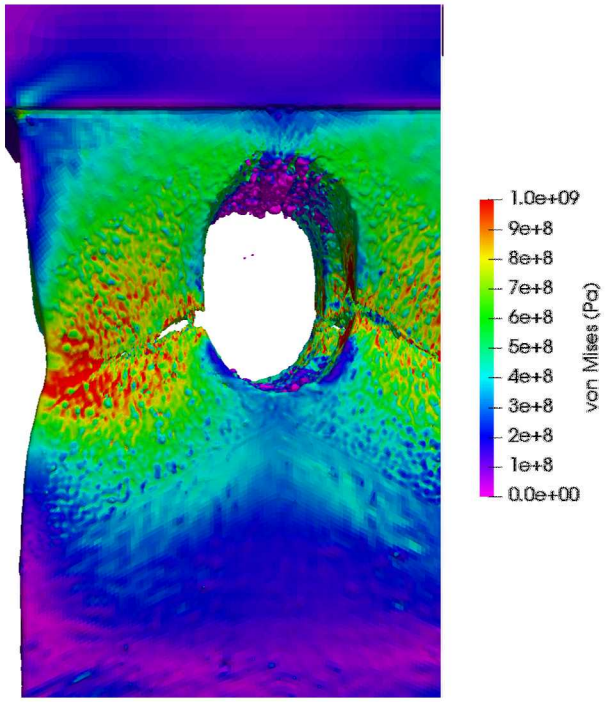




SNL/NM prediction for 3rd Sandia Fracture Challenge



material response changes w/voids & surface roughness



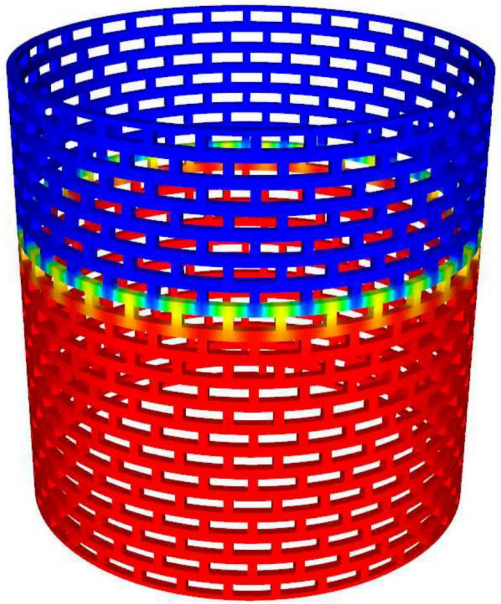
Kyle Johnson, Kyle Karlson, Brad Boyce

Lattices

Growing interest for designers in applications

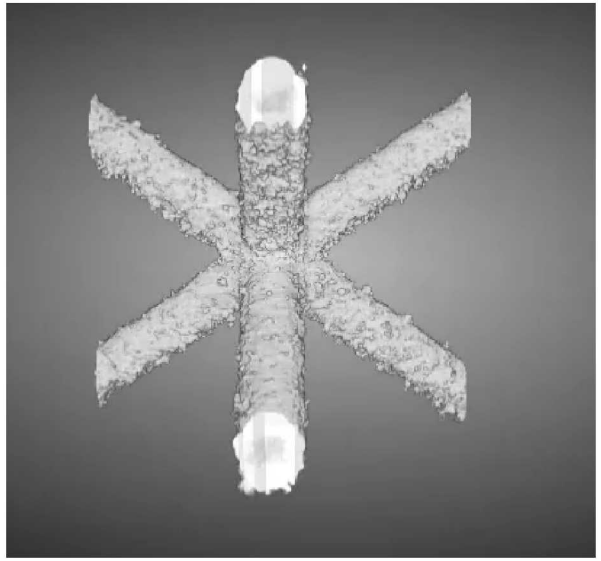
Challenges

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

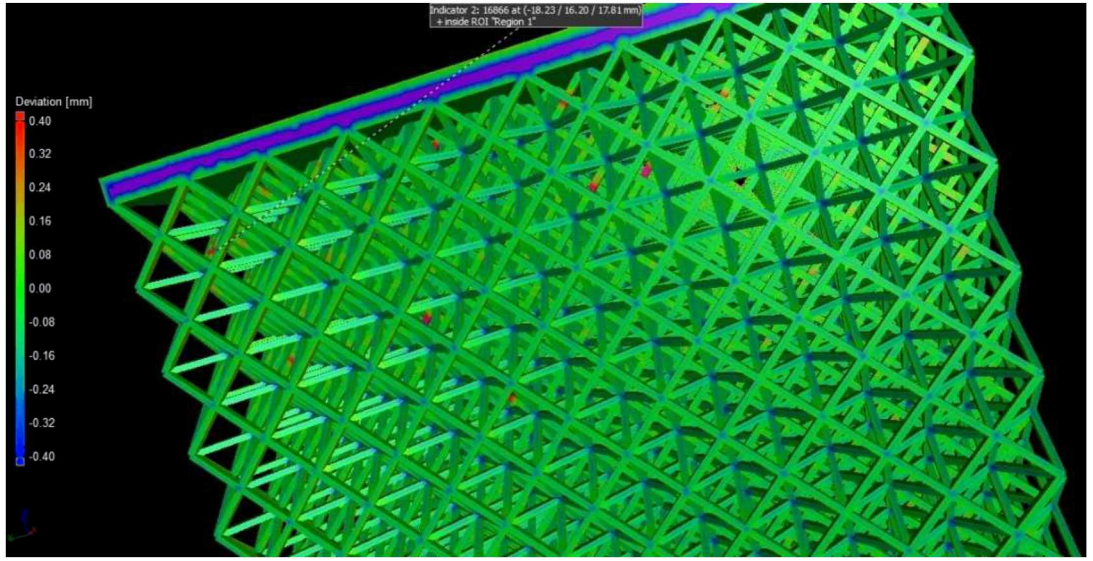


latticed tube simulation

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

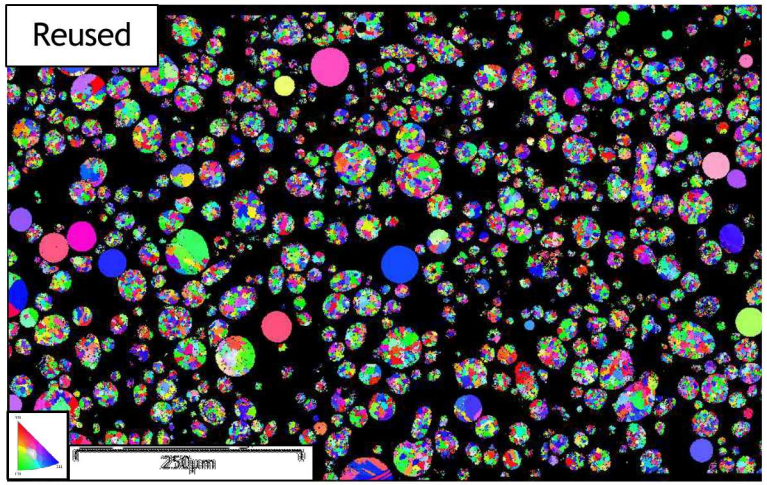
Monitoring Powder Reuse

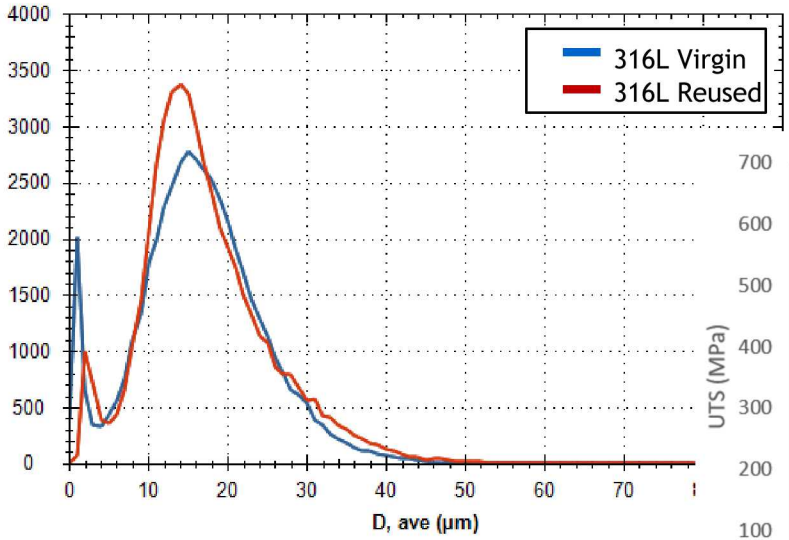
Tracking powder size, morphology & EDS composition w/reuse

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

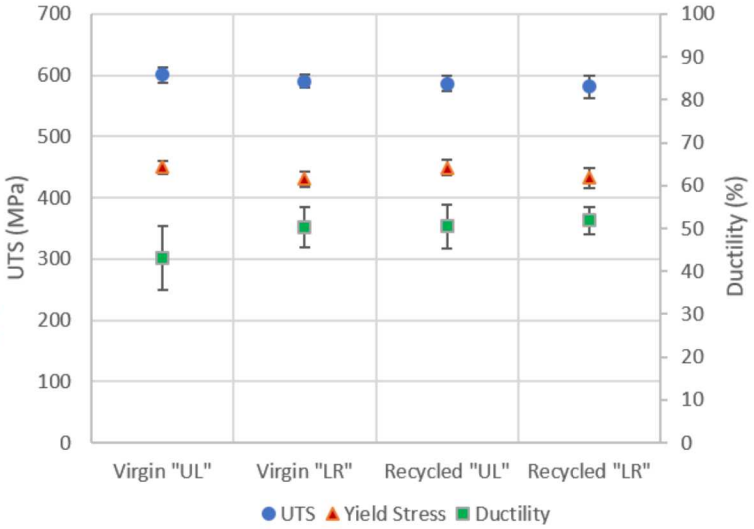
Material properties remain stable

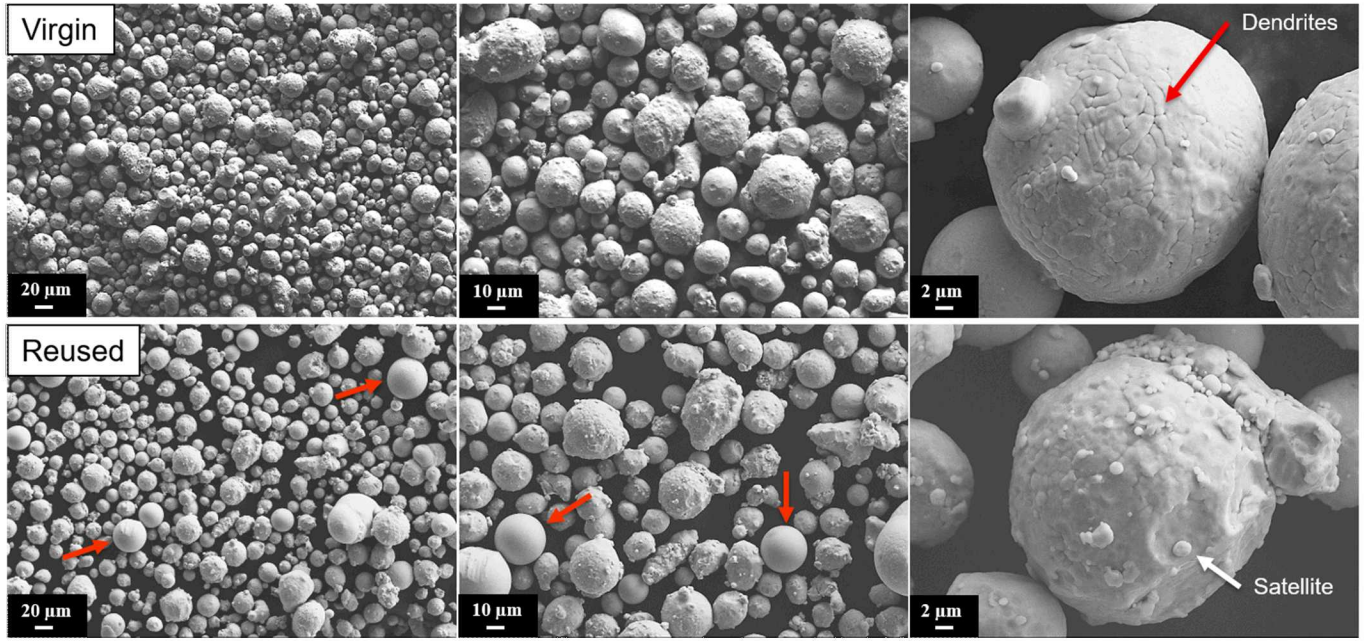
316L SS is a robust material for processing & properties





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





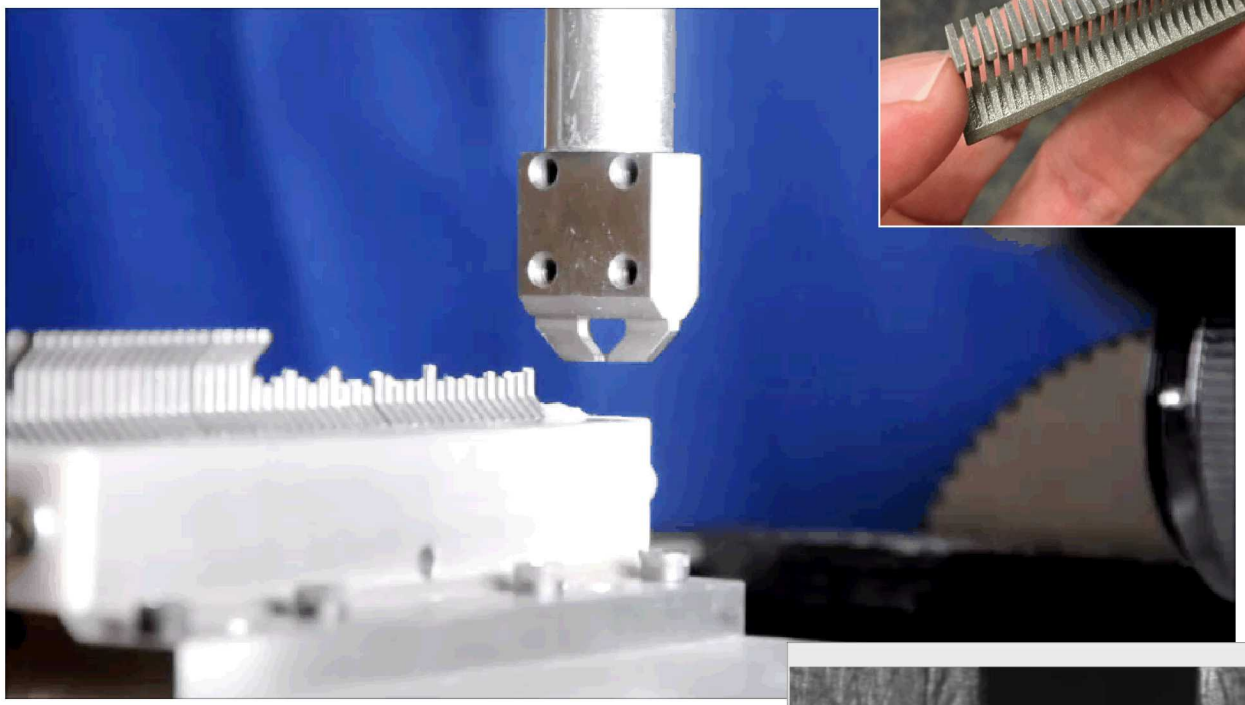
Heiden, Add. Mfg., 2019

High Throughput Testing - Alinstante

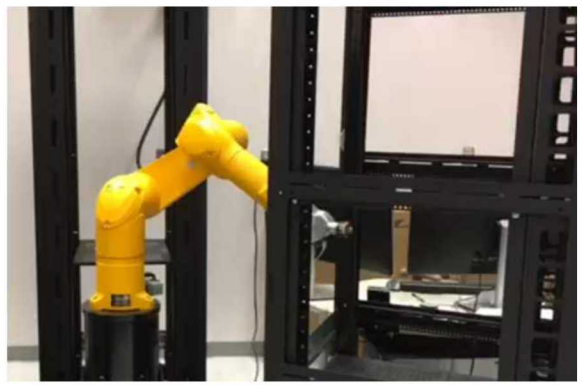
Properties… In an instant
- commonly resource constraint

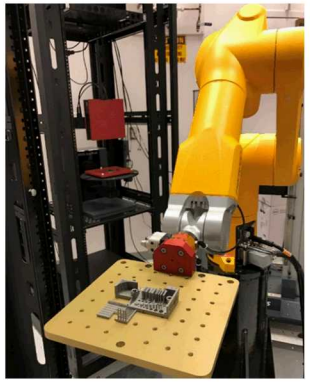
Automation & robotics

Consistent, rapid, & efficient

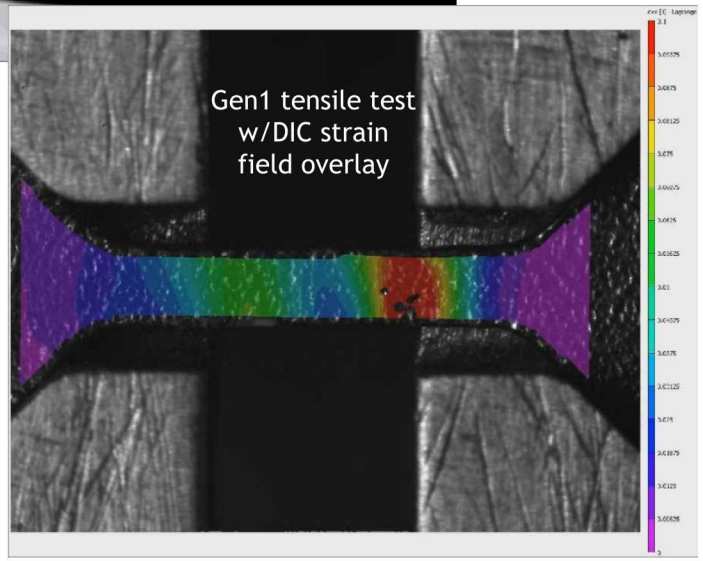


Properties	**Structure**	**Process**
Tensile strength	Geometry	Surface remediation
Ductility	Roughness	Heat treatment
Toughness	Porosity	Subtractive machining
Hardness	Chemistry	Coating
Wear & friction	Phase content	Joining
Permeability	Grain Size	Integration
Thermal expansion	Crystal Texture	etc.
Reactivity/corrosion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





robotic work cell for material characterization



Brad Boyce

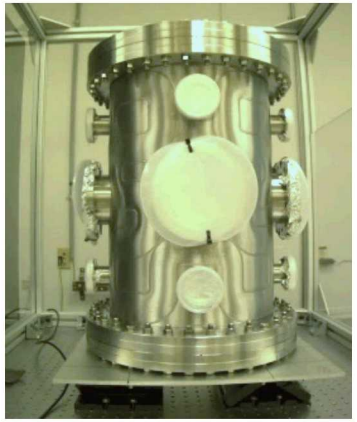
Calibration Testbed for IR Sensors

Using passive microwave radiometry to measure emissivity & temperature

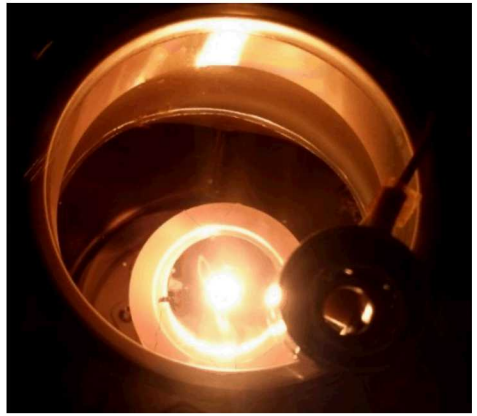
- measures %R of 137 GHz radiation from surface
- 20-1500 ° C, 2 Torr in Ar chamber
- expected uncertainty ~10°C

- 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.

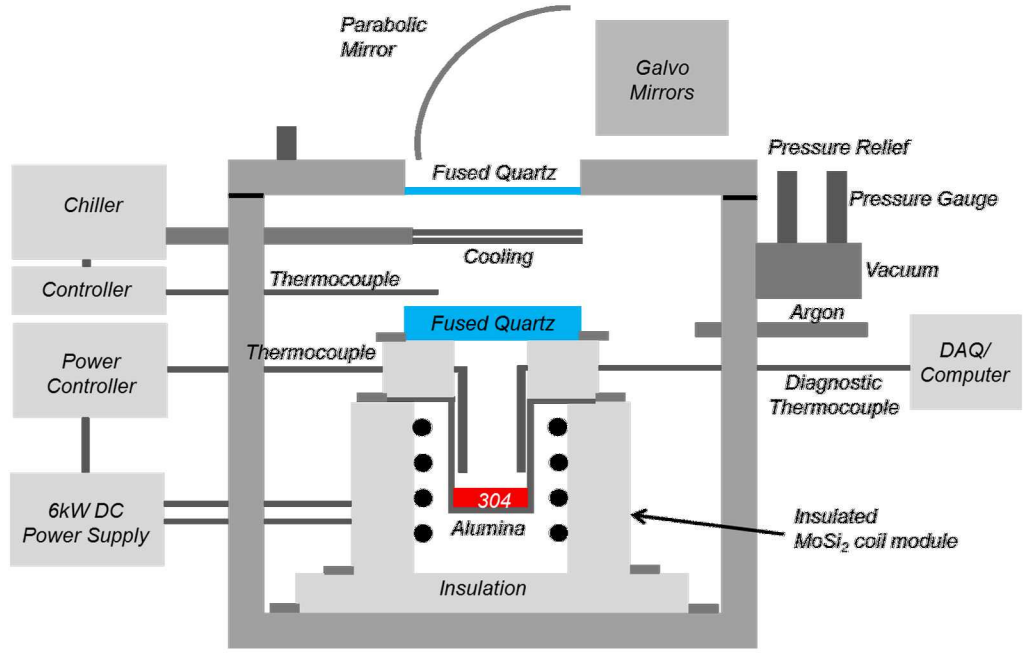
MIT collaboration



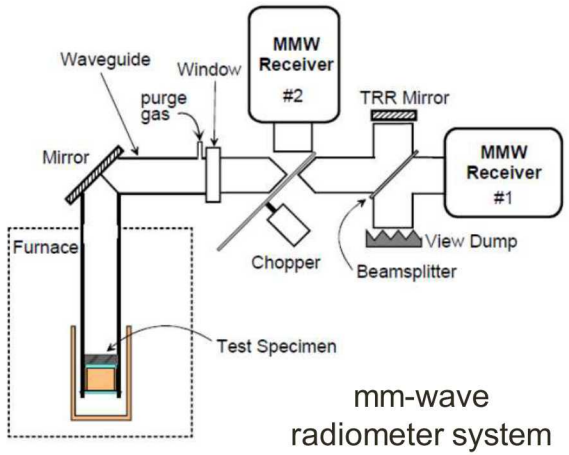
vacuum chamber



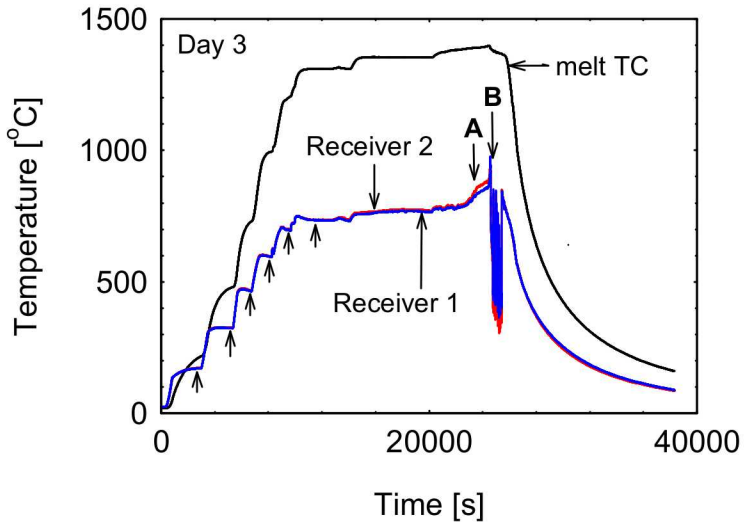
1500 °C furnace in operation



metrology testbed layout



mm-wave radiometer system schematic

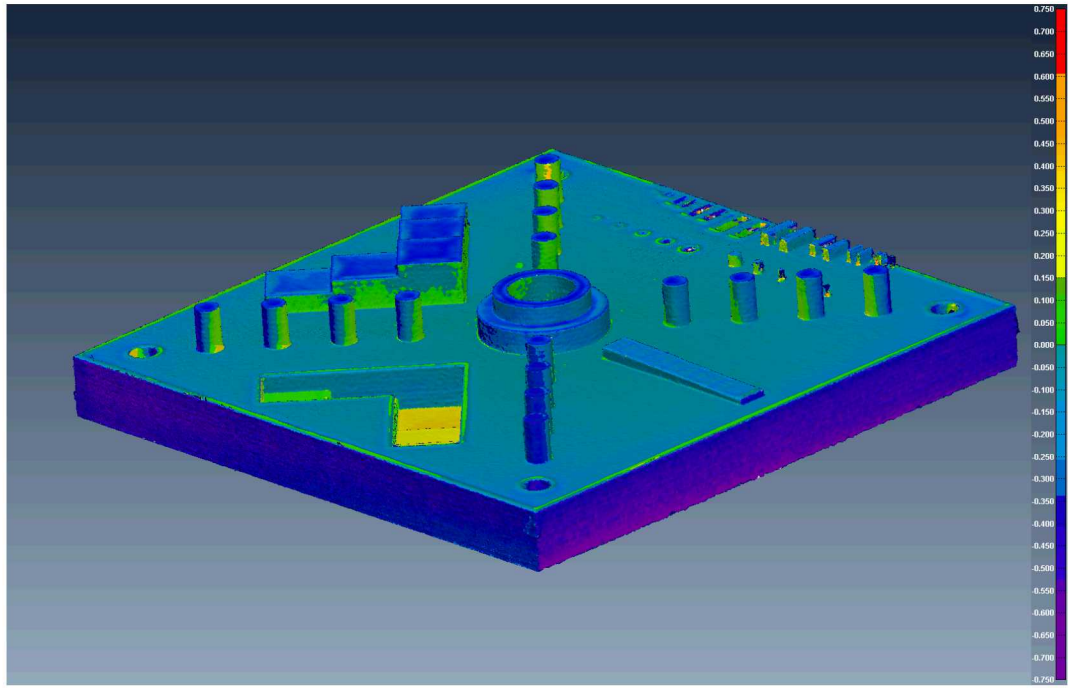


radiometric temperature from receivers showing freeze/melt cycles of 316L SS

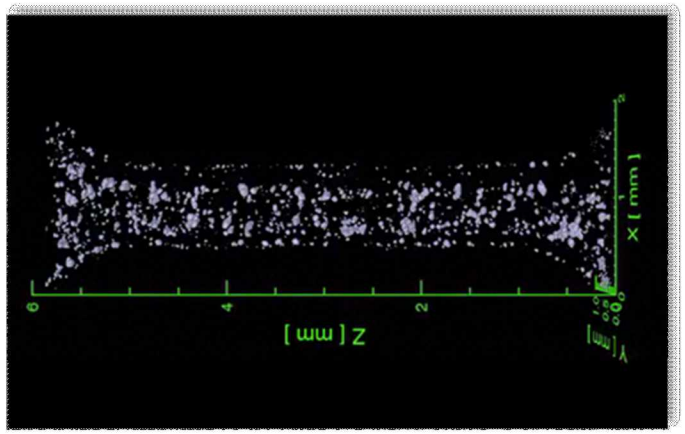
Eric Forrest

Non-Destructive Evaluation

computed tomography

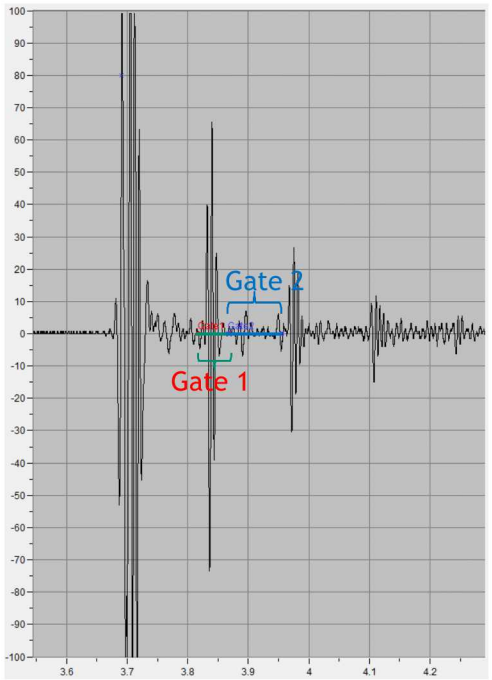


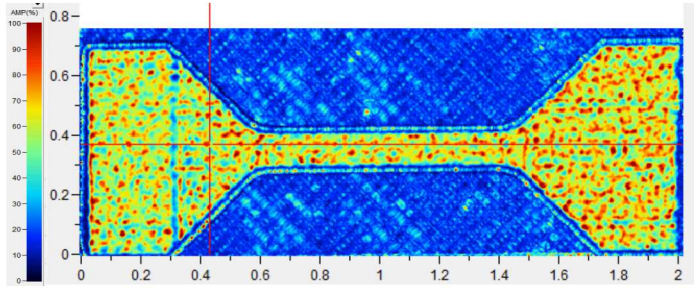
dimensional inspection



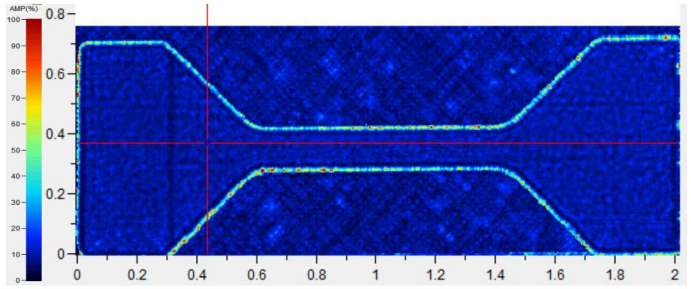
porosity assessments

pulse-echo ultrasound

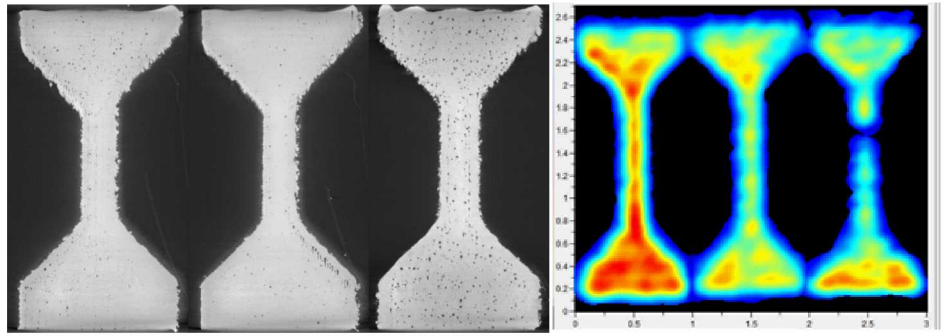




Gate 1 signal



Gate 2 signal



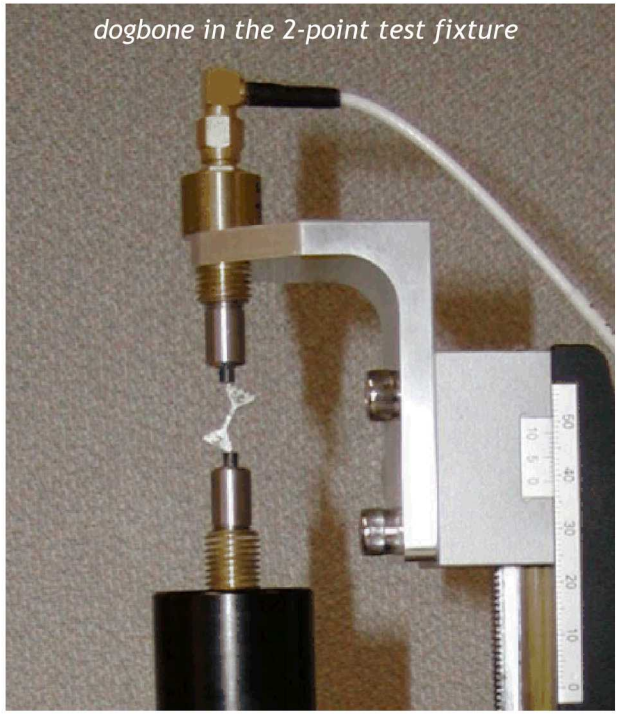
CT images of 98% (left), 96% (center) & 93% (right) dense Al10SiMg dogbones (left) & attenuation of 10MHz ultrasonic backwall reflections (right)

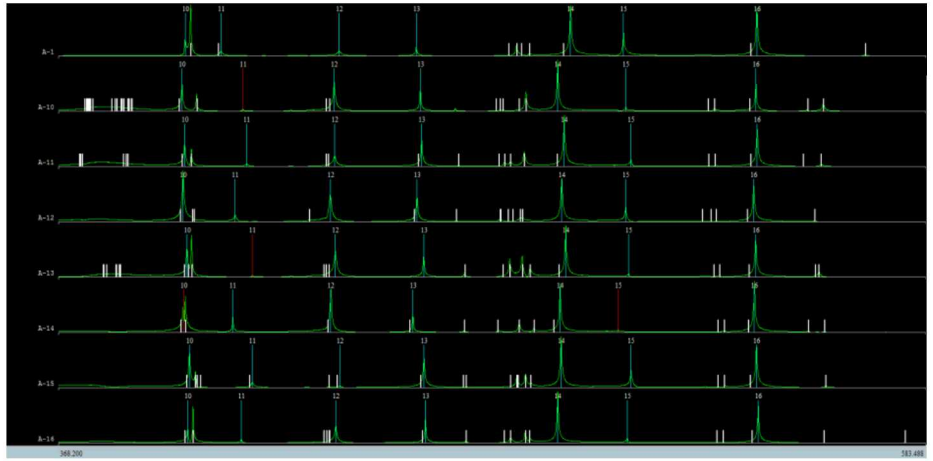
David Moore, Burke Kernen, Kyle Thompson, Ciji Nelson, Sarah Stair

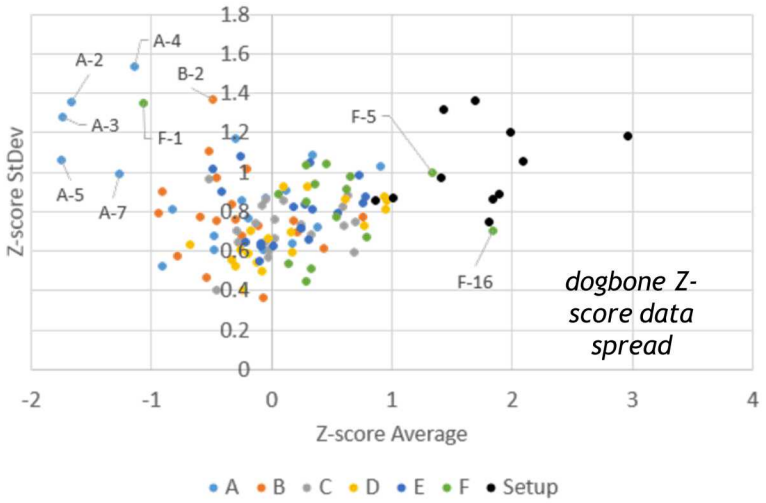
Resonant Ultrasound Spectroscopy

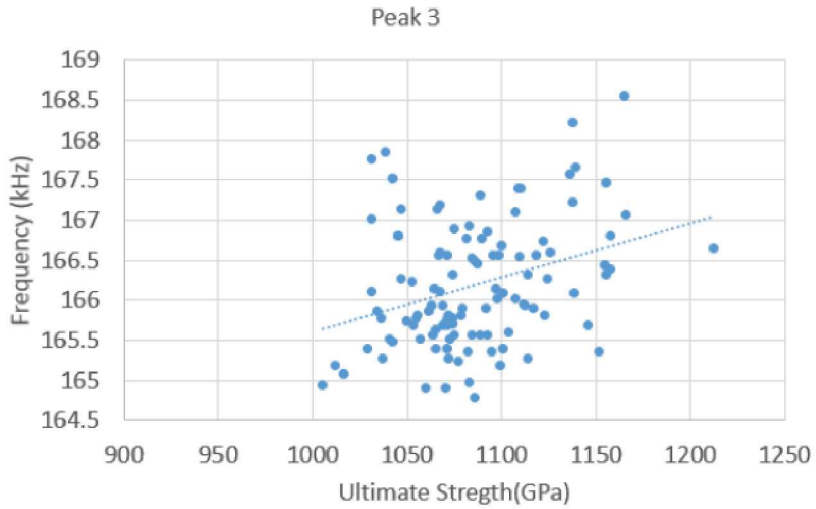
Swept sine wave input from 2-point transducer
- spectrum = 74.2 kHz to 1.6 MHz
- intent is to identify outliers, variations, process limits, defects

Identified 19 resonance peaks
- Z-score compares peak frequency w/average & std. dev.
- no strong trends across 17-4PH dogbone population


dogbone in the 2-point test fixture


resonance response spectra





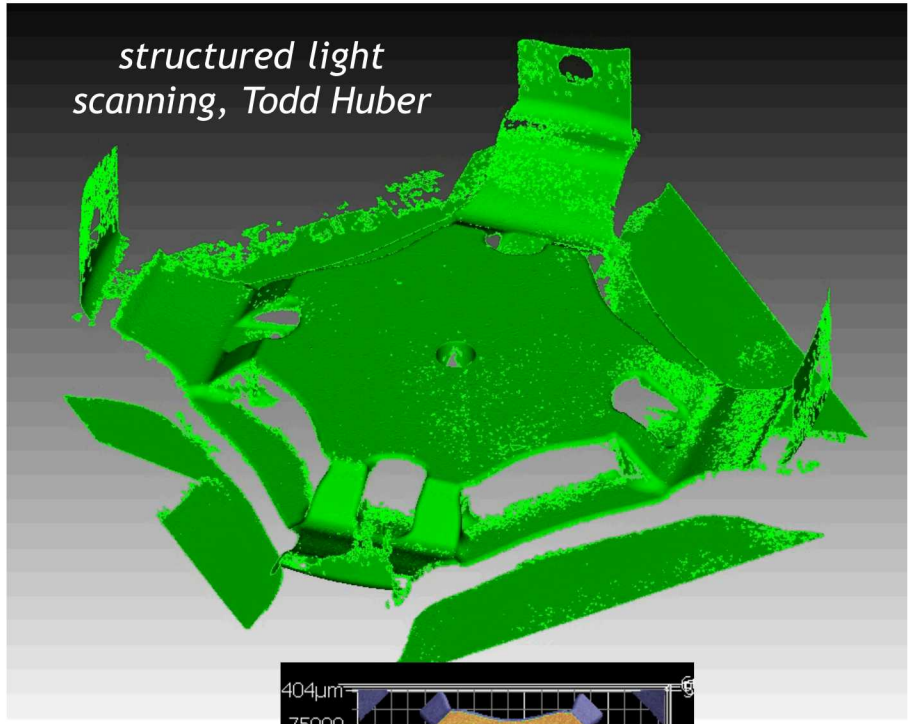
Metrology

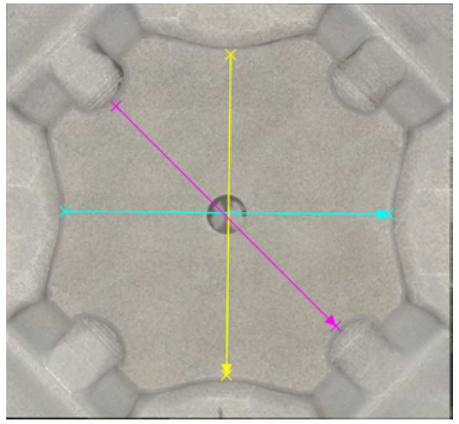
Measuring complex topologies is non-trivial

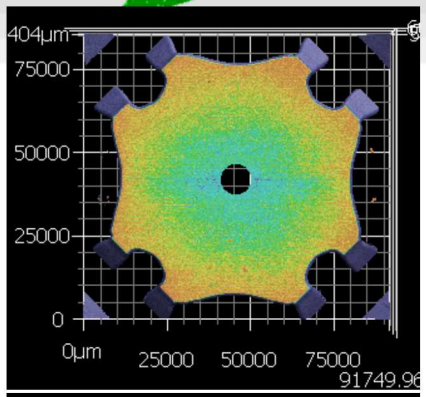
- access
- slopes
- surface roughness
- data management & analysis

Significant part distortion

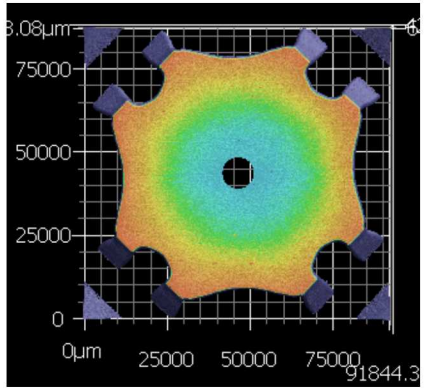
- build plate & part
  - top surface of legs parallelism to center plane
    - on plate = 25-100µm
    - off plate = 280-300µm
- will part mate assembly
- where are proper datums?
  - surface finish acerbates (printing, supports)







part on plate, form = 68.2µm



part removed, form = 188.2µm

Motion Stage Errors

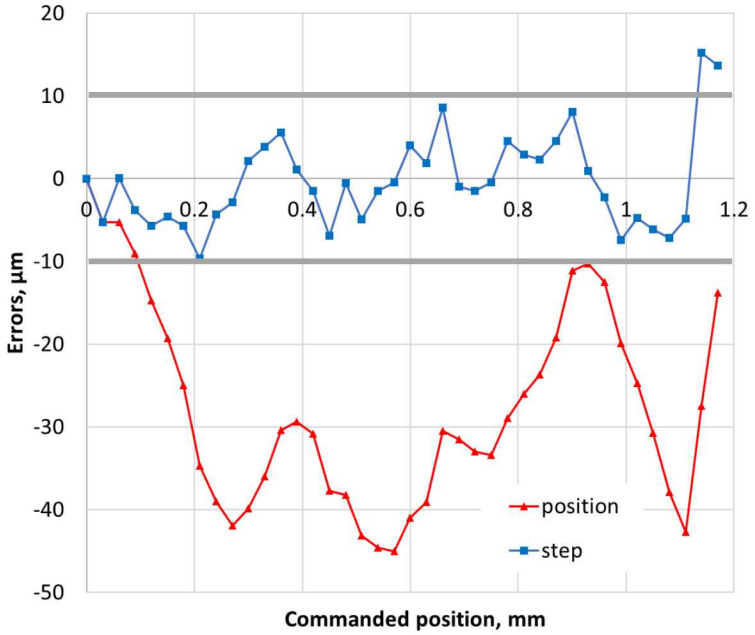
100mm ball screw drives
- supply piston – controls powder dosage
- build piston – controls layer thickness

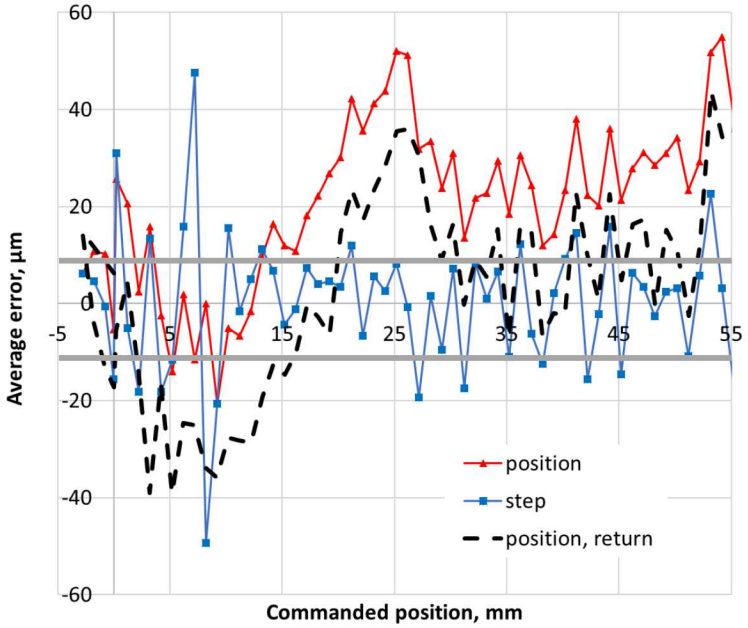
Measurements
- LJ-V7200 laser profiler
  - range: ±48mm
  - Z repeatability: 1μm

Build piston testing
- simple linear motion
- step errors ~ powder size
  - errors increase w/step size

supply piston drive (left) & build piston drive (right)

Keyence LJ-V7200 focused onto build plate

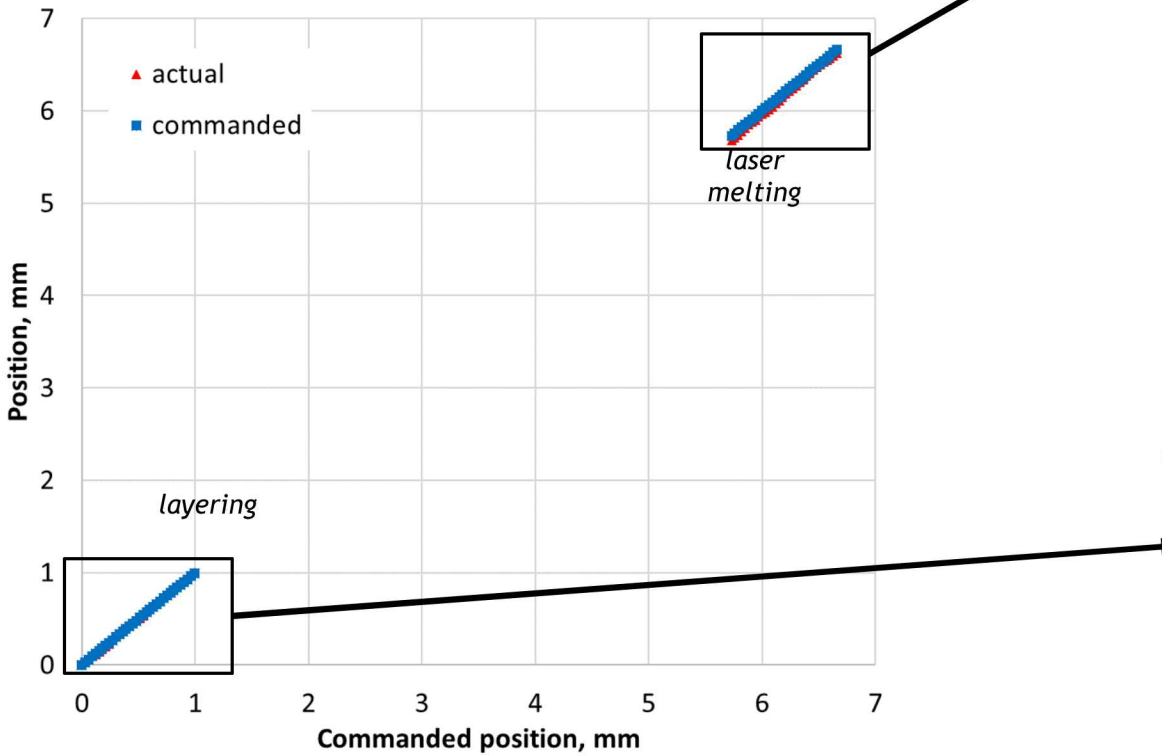


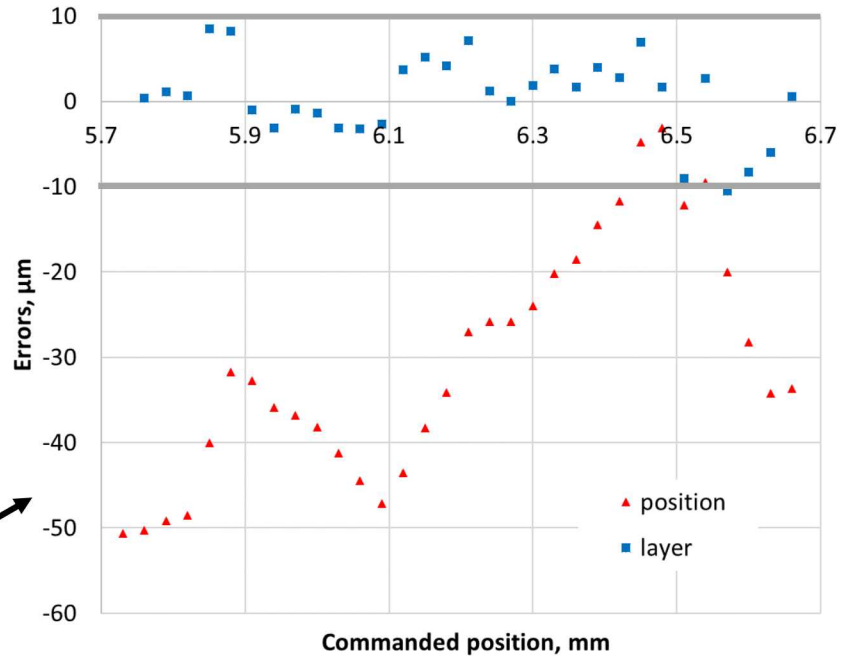


Build Process Errors

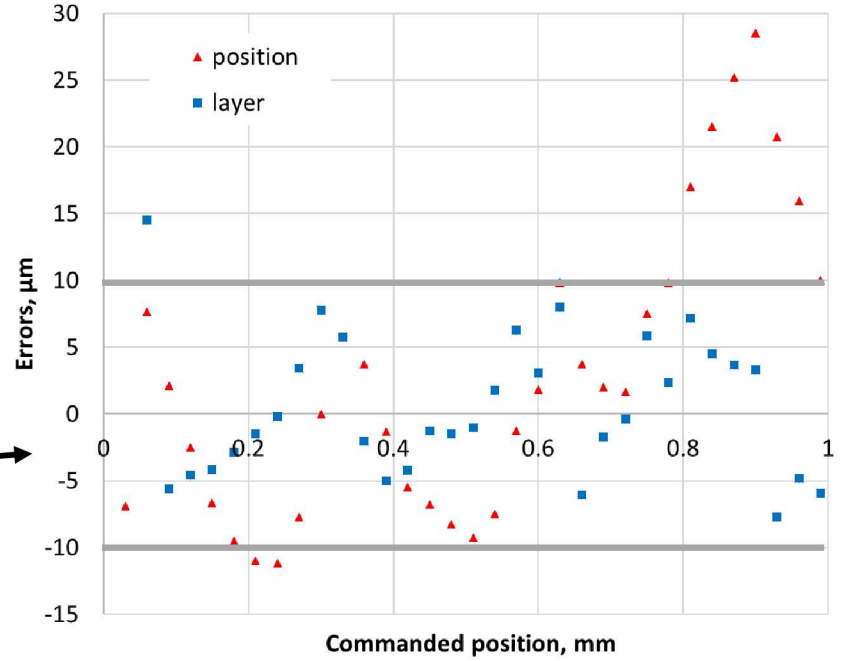
Replicate build process

- 30μm layers, layer then laser melting locations
- step errors ~ powder size
  - problem?
  - process exhibits some "self-healing"





laser melting location => focus offset

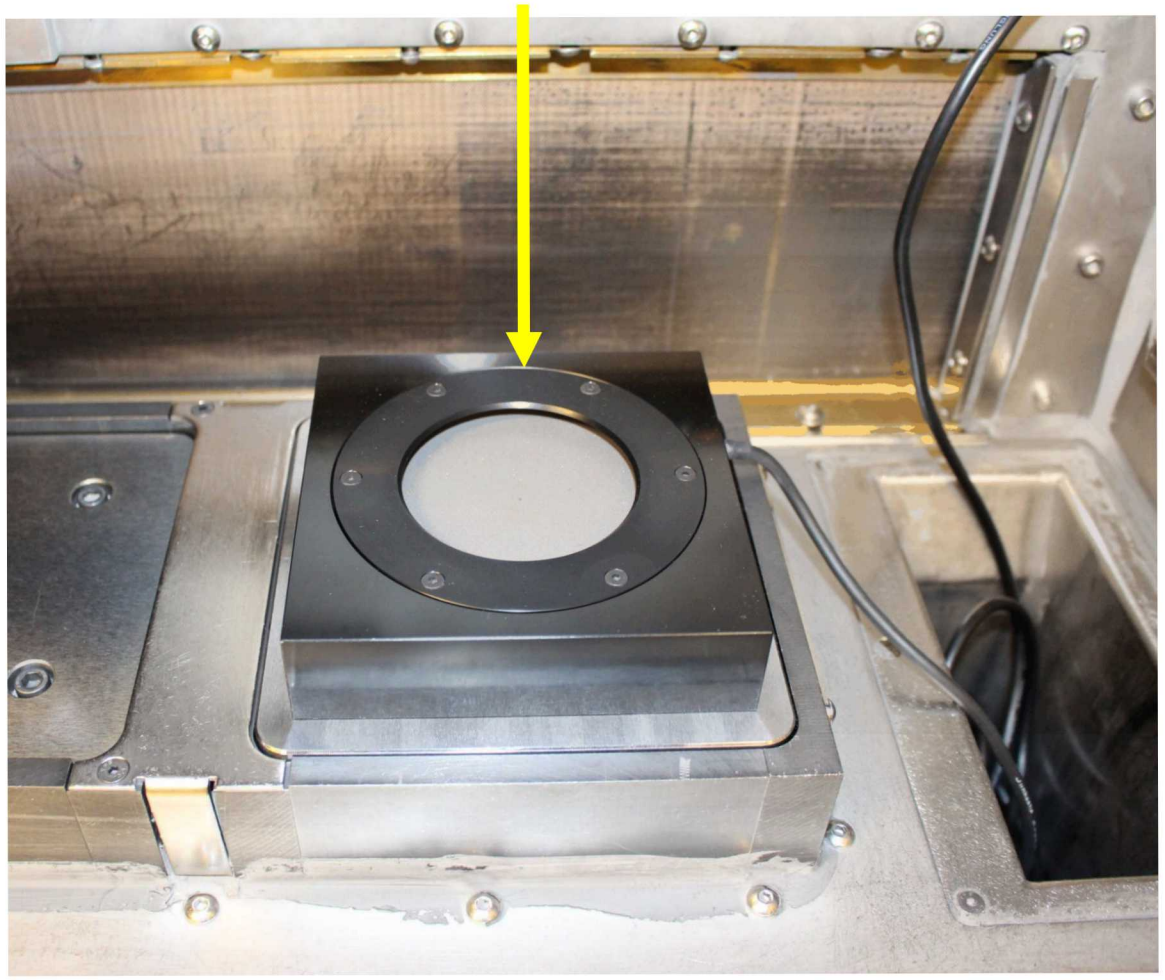


layering location => layer thickness

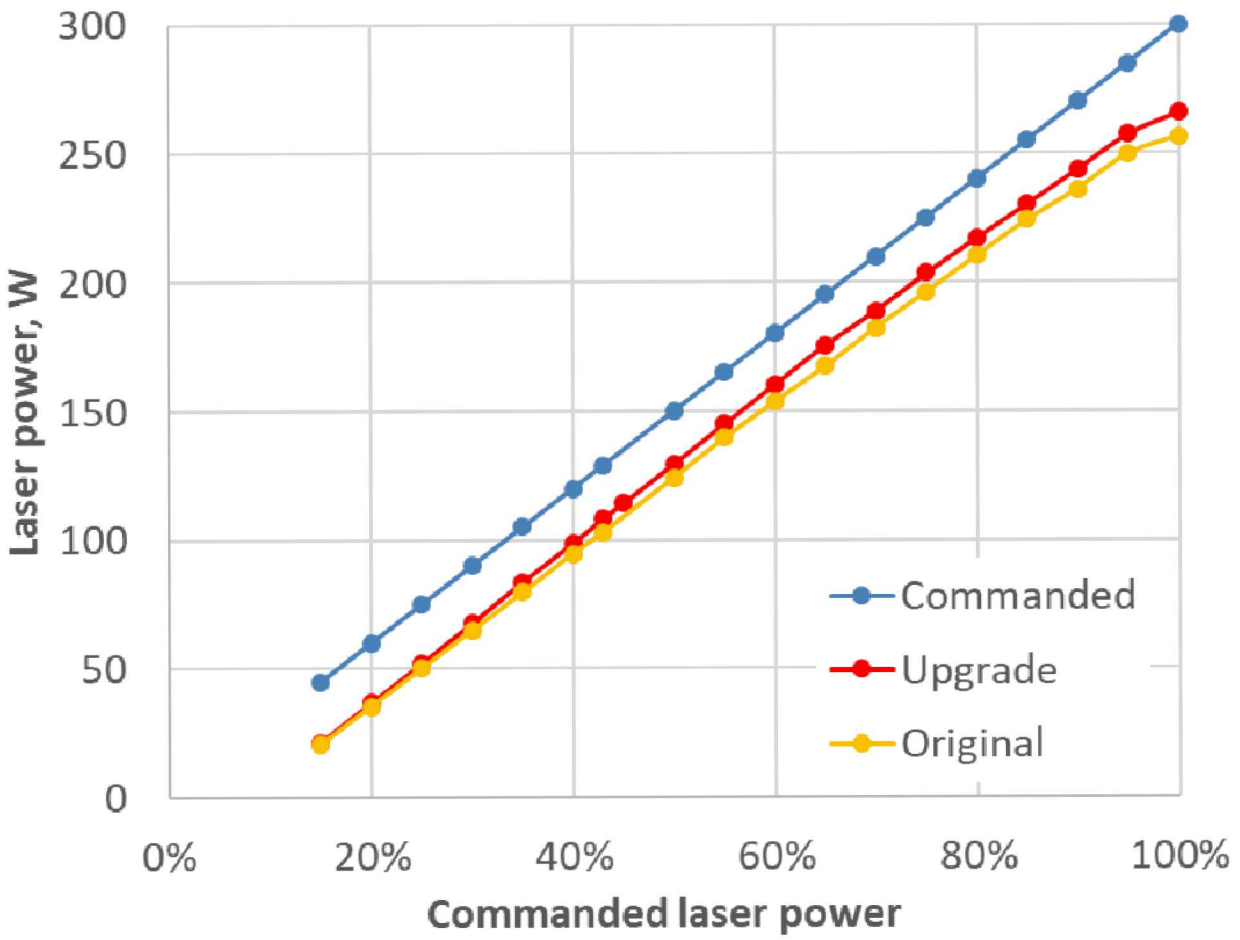
Laser Power @ Build Plate

Want power @ powder layer, not machine setting

- required for accurate & repeatable process optimization



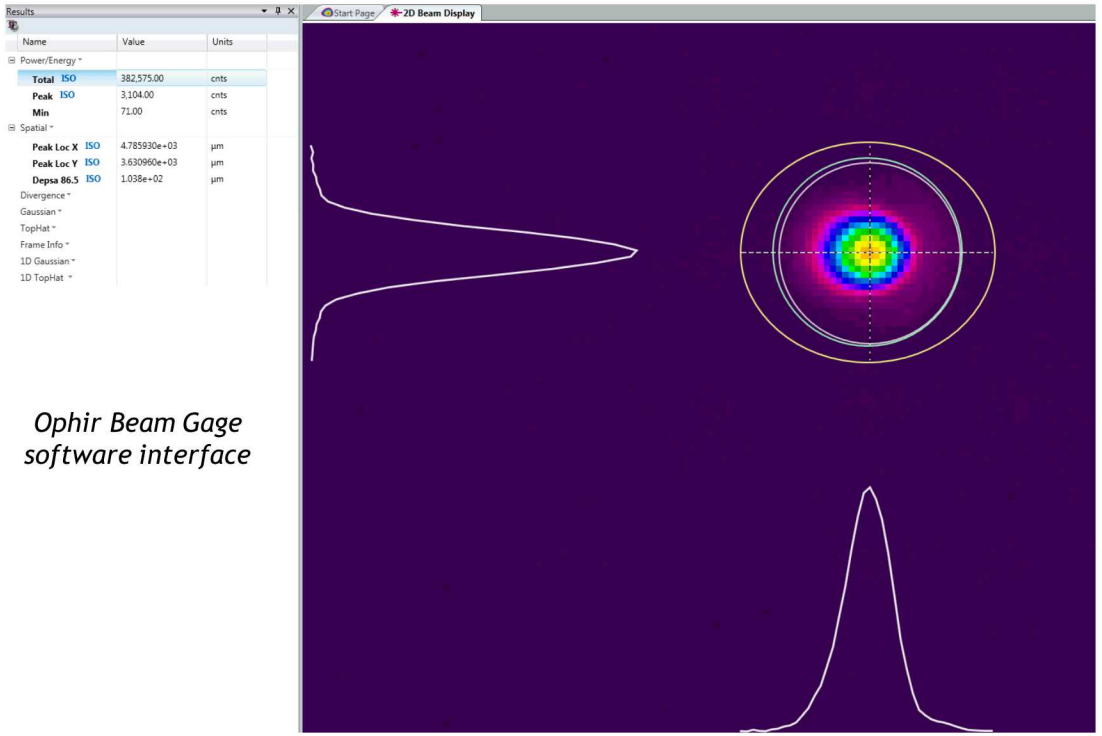
Ophir L50(300)A-LP1 power meter on the build plate



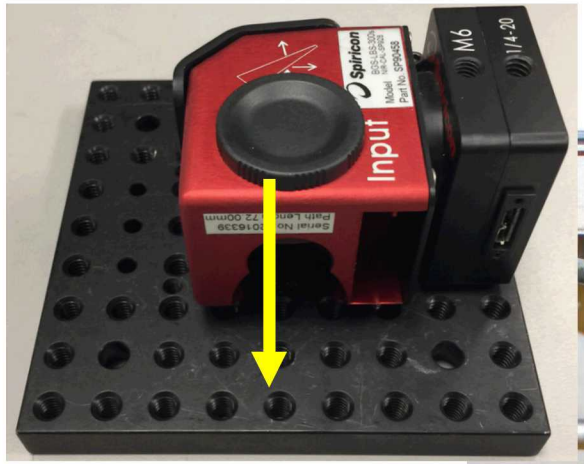
Beam Profiling

Measured

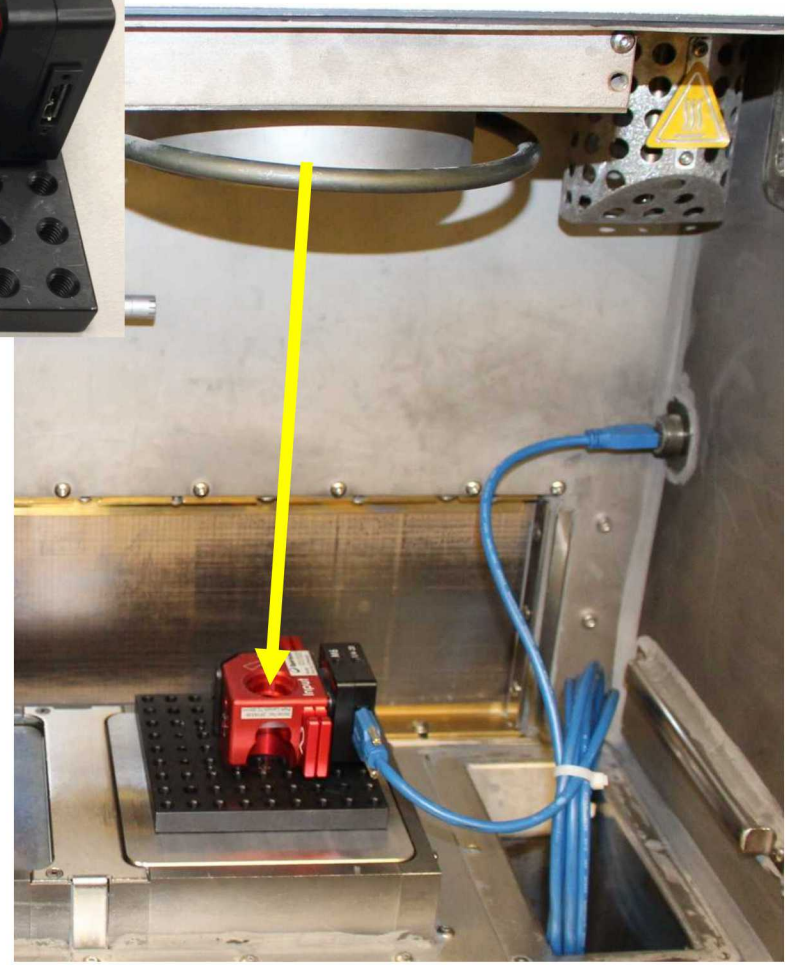
- diameter along optical axis
  - variation w/laser power
- temporal response
  - heating & cooling
- original & upgraded f-theta optics

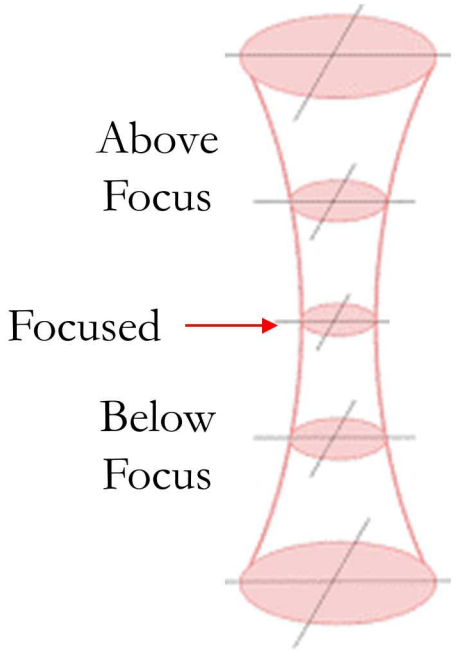


Ophir Beam Gage software interface



Ophir SP 928 profiler on the build plate

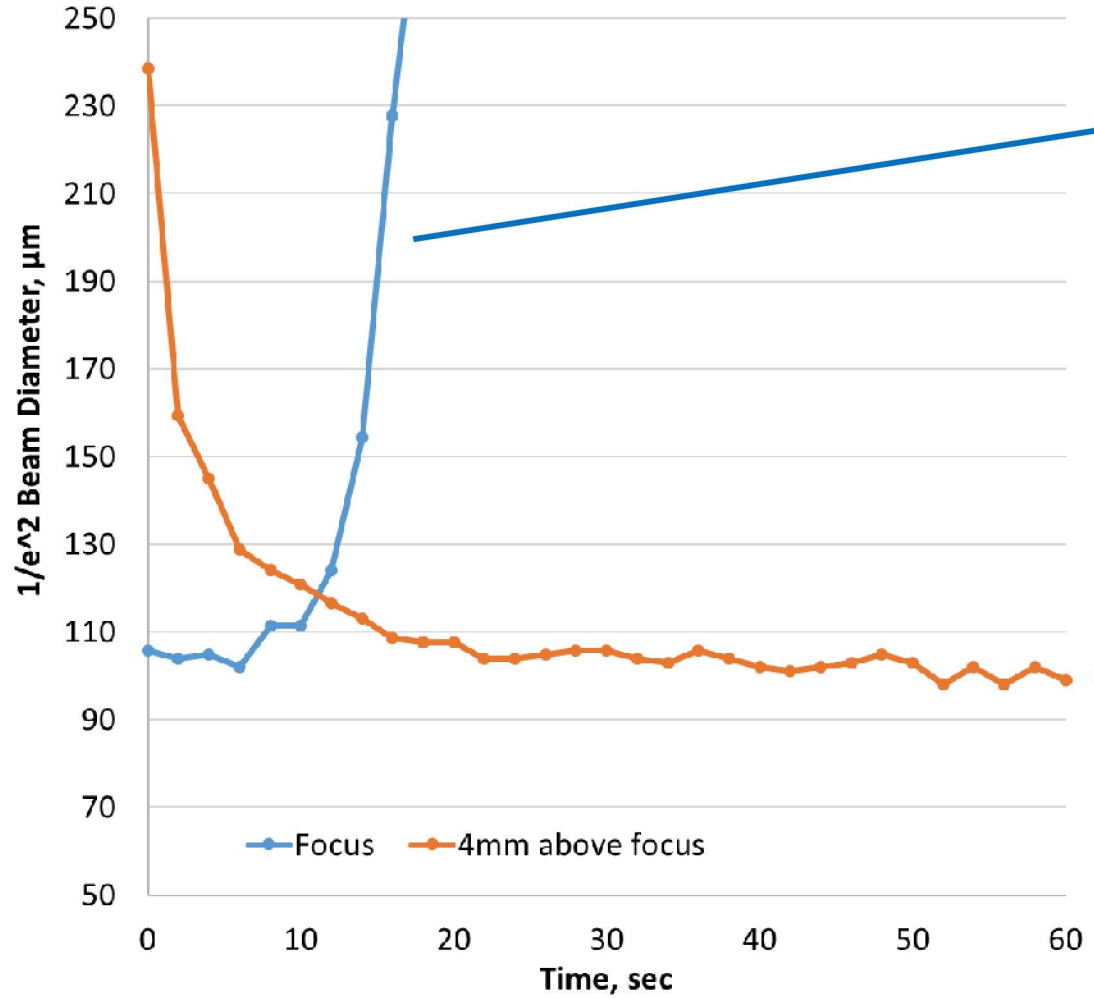


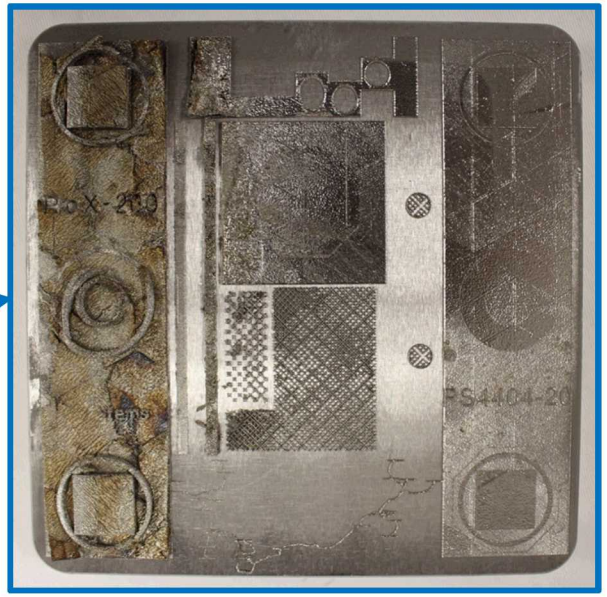


Original F-Theta Diameter Variation w/Time & Stage Position

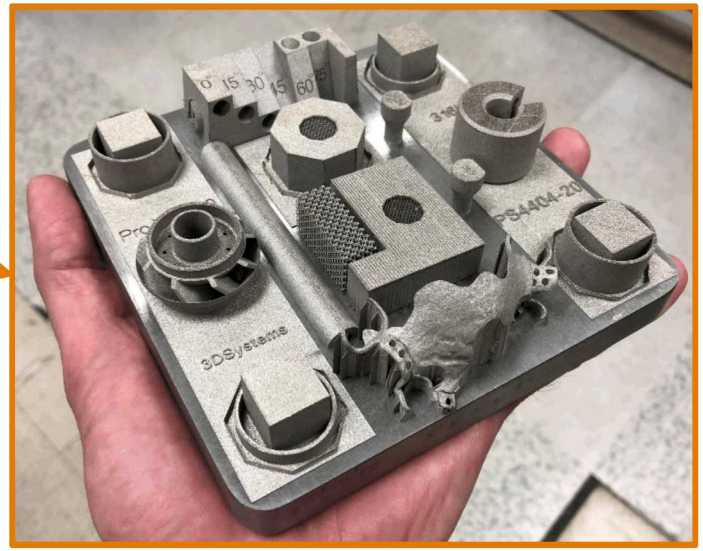
Thermal lensing obscures optimal focus for a realistic build cycle

- introduces challenges & uncertainties to part & material generation





nominal focus offset

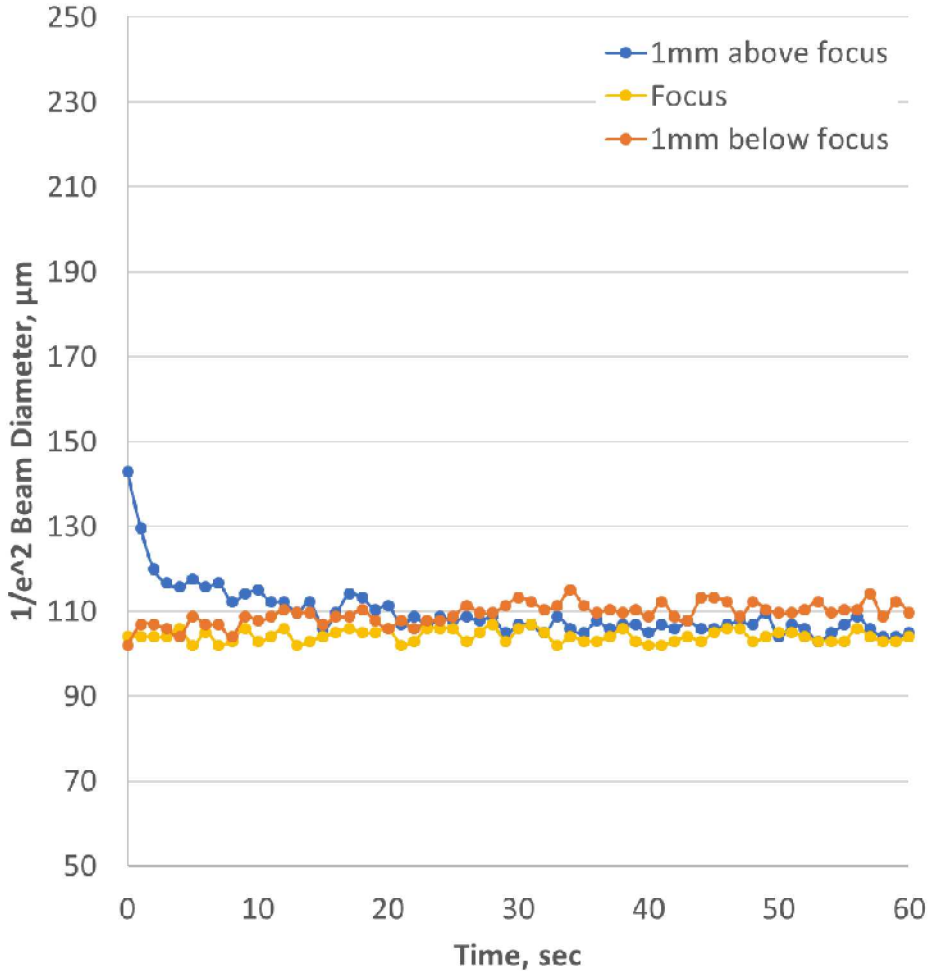


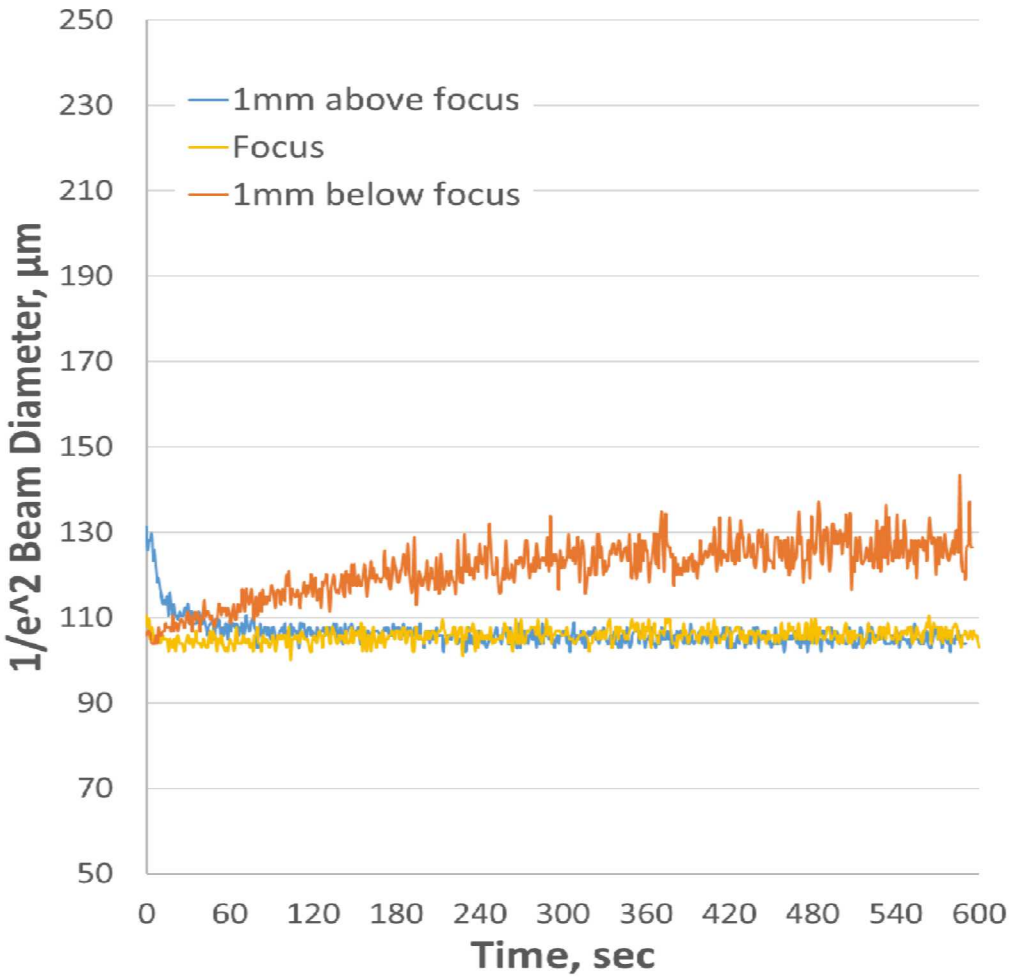
4mm focus offset

F-Theta Upgrade Diameter Variation w/Time & Stage Position

Dramatic reduction in thermal lensing & improved repeatability / consistency

Critical to on-going process optimization efforts

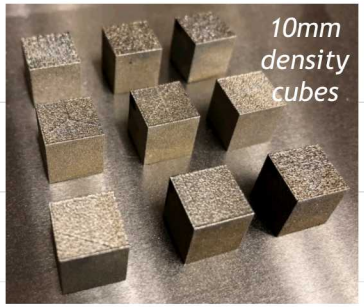


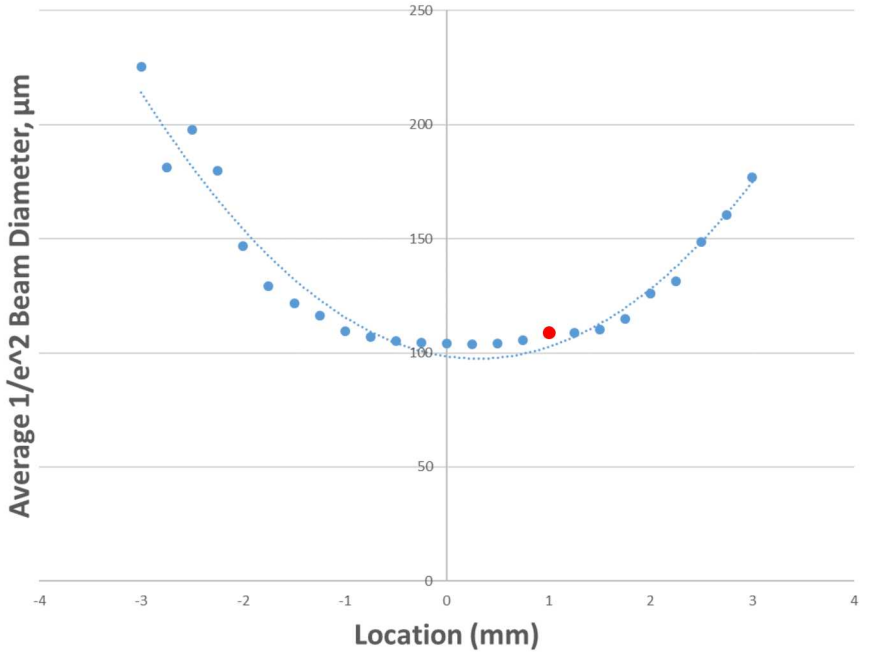


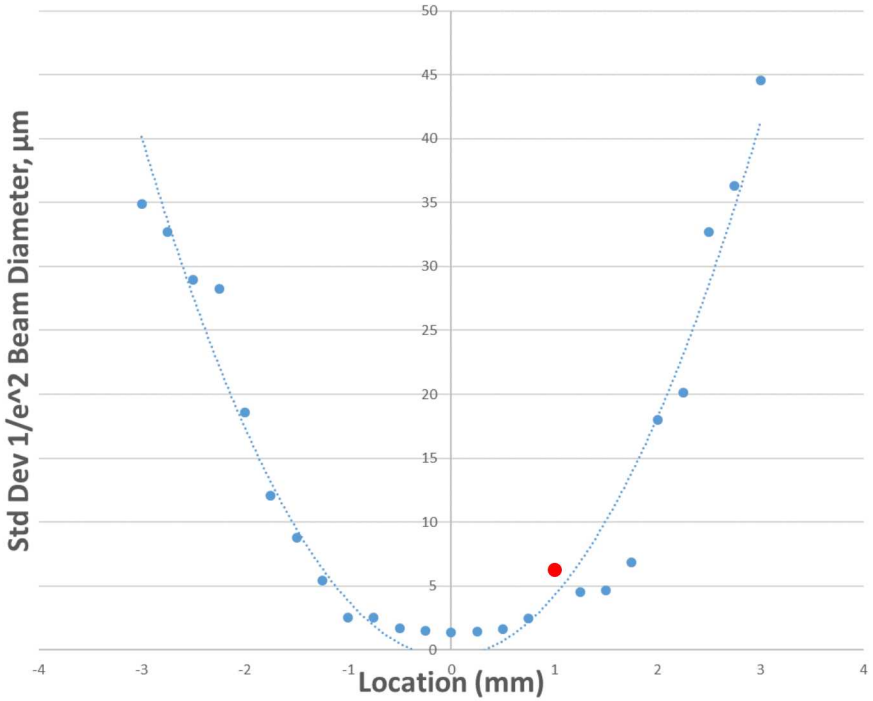
F-Theta Upgrade Focal Distance

How critical is build plate location relative to laser focus?

- "optimal" process appears to be +1mm from "focus"
- presumably plasma plume impacts optimal offset







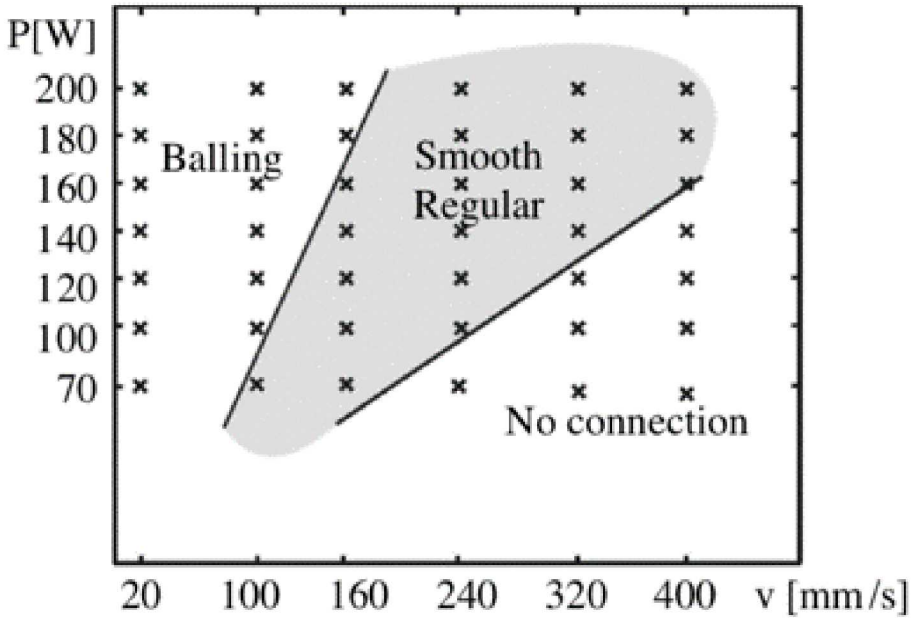
Process Optimization

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

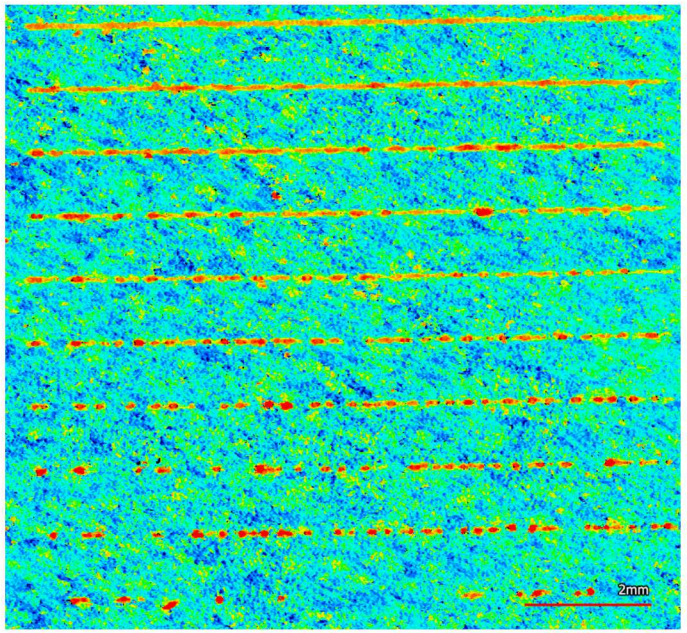
- parameters
  - laser power (10-240W), velocity (50-2800mm/sec)
  - powder layer thickness (30, 40µm), average powder diameter (15.0, 25.0µm), laser focus offset (-1.5 to +3.5mm)
- performance metrics
  - surface finish, form error, density, tensile properties, Charpy toughness, microstructure
- experiment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



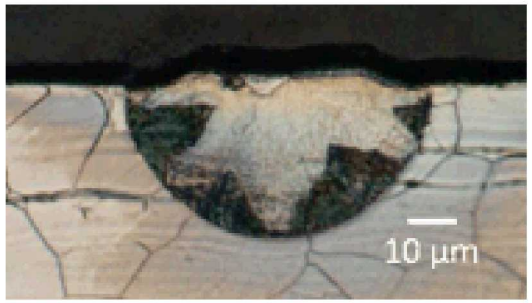
Kruth et al, (2008) "Application of dimensional analysis to selective laser melting", Rapid Prototyping Journal, Vol. 14 Issue: 1, pp.15-22

Josh Koepke, MS Thesis, UNM Dept of ME, 2019, "The Influence of Process Variables on Physical and Mechanical Properties in Laser Powder Bed Manufacturing"

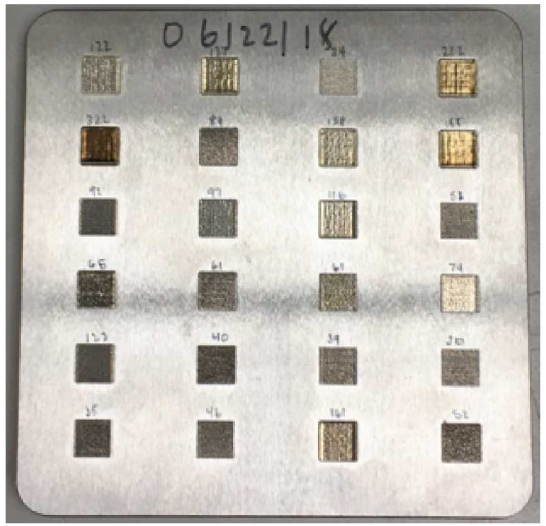
Process Maps: Line Scans, Area Pads & Density Cubes



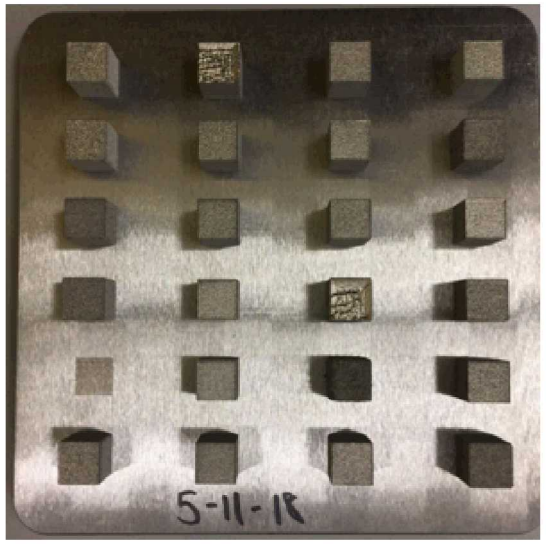
100 W, 250 to 2500 mm/s on pad



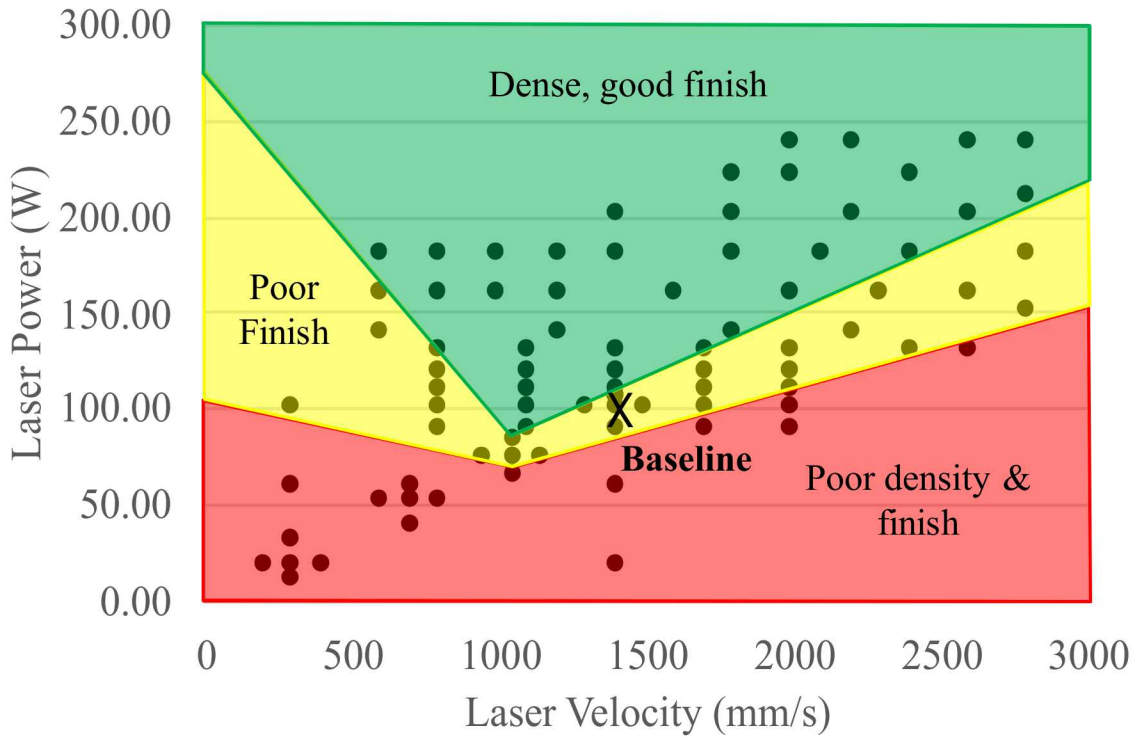
melt pool on plate, 100W, 1500 mm/s



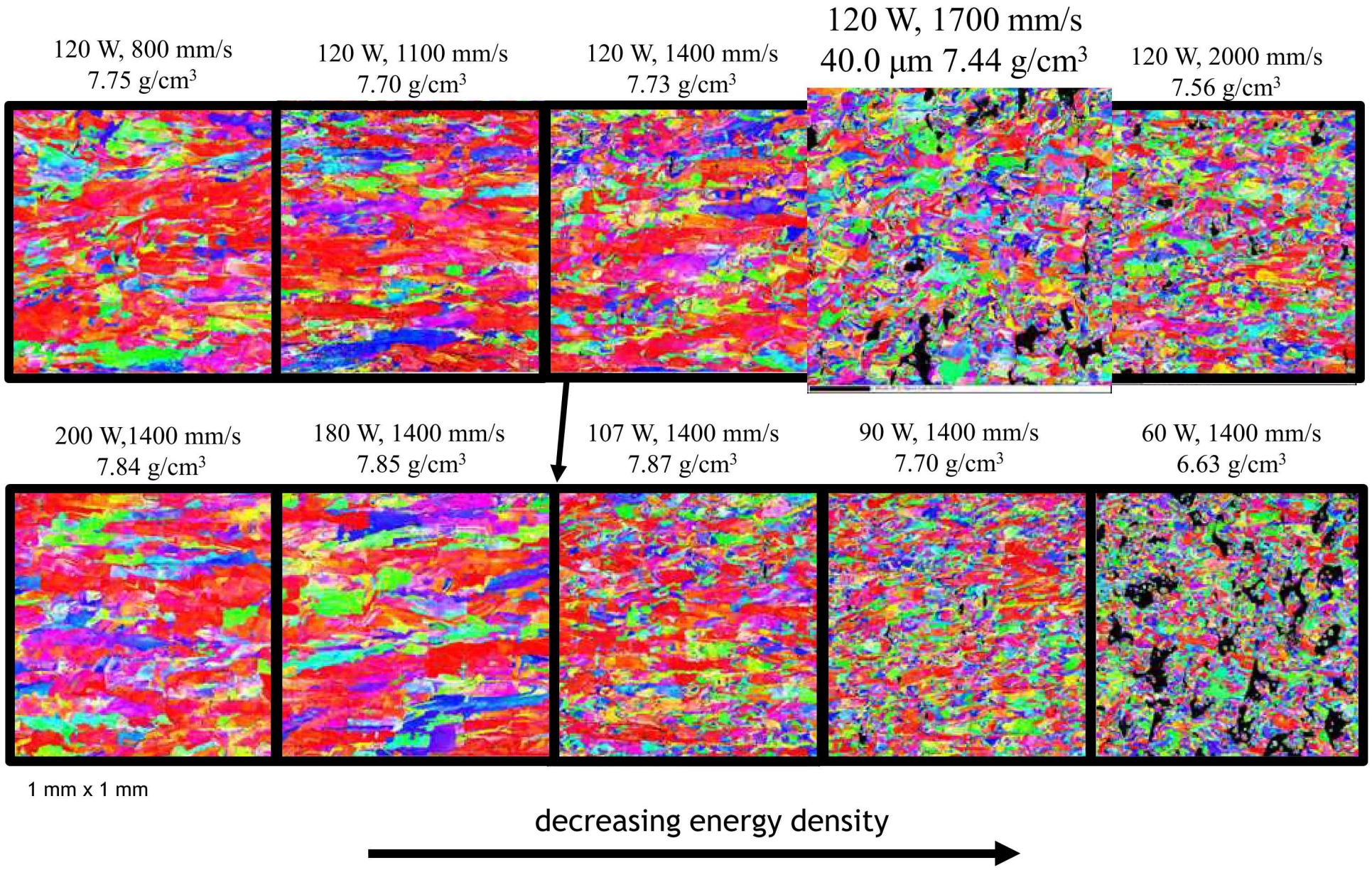
area pads



density cubes



Material Microstructures, 30µm Layer Thickness

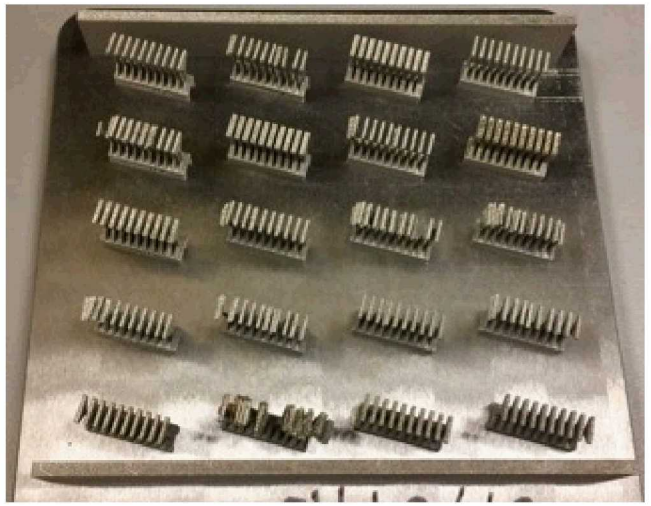


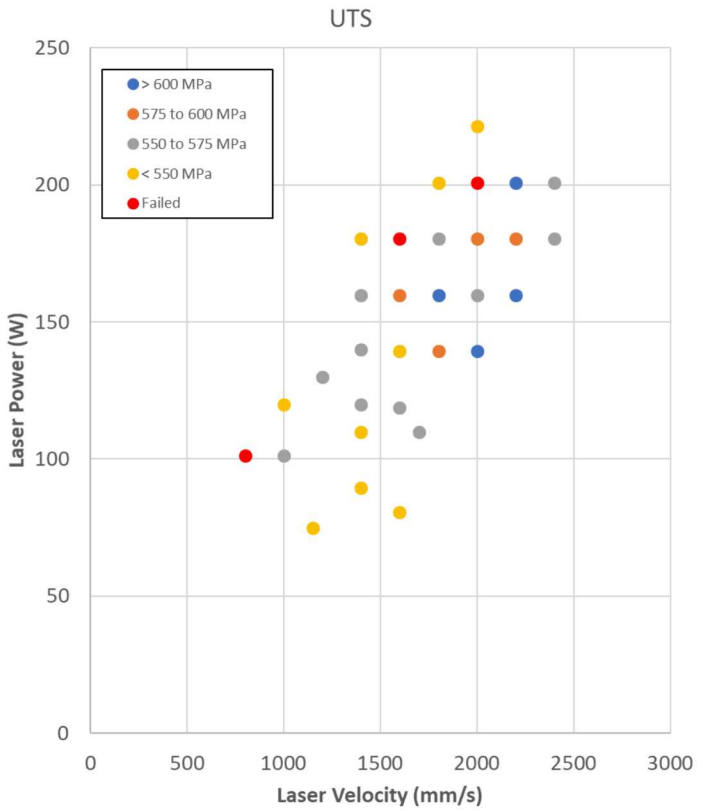
High-Throughput Tensile

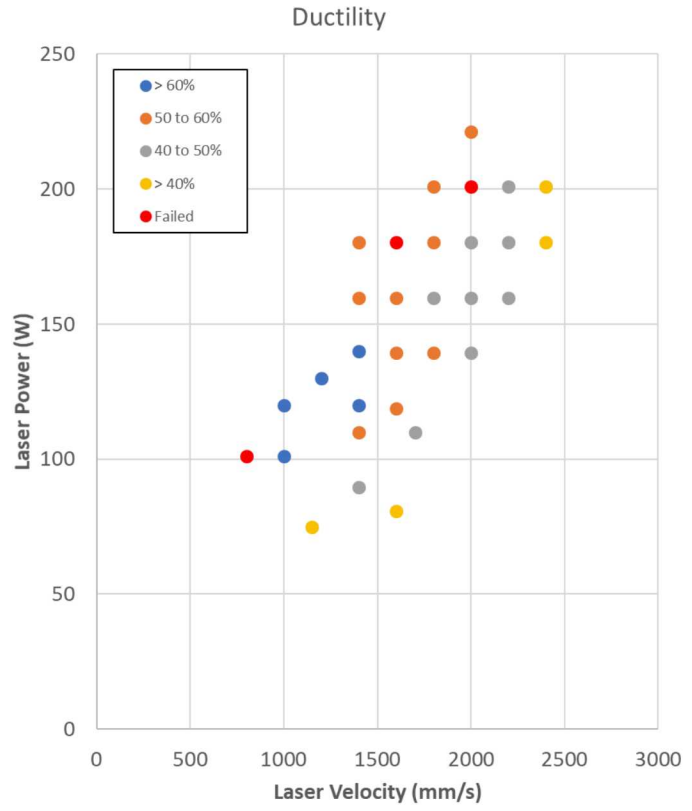
1x1x4mm gauge section, 10 or 25 dogbones per array
- five build plates
- varied power & velocity near process plateau

>500 dogbones tested
- density (Archimedes)
- surface roughness
- mechanical properties
  - UTS, YS, modulus, ductility

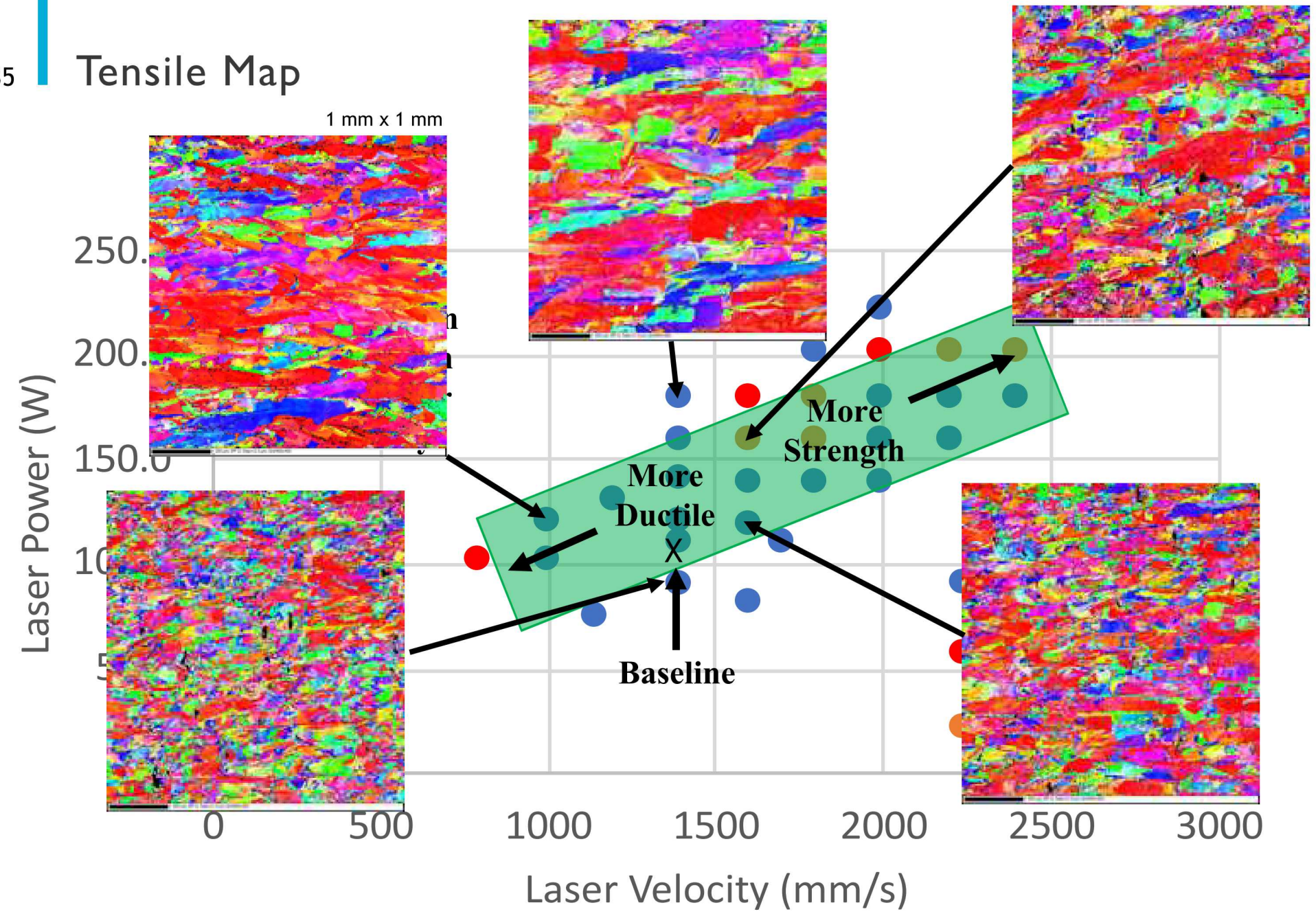
process "plateau" depends on requirements
- density isn't a definitive process metric
- properties & manufacturability trades
  - how do properties scale w/feature & geometry?







Tensile Map

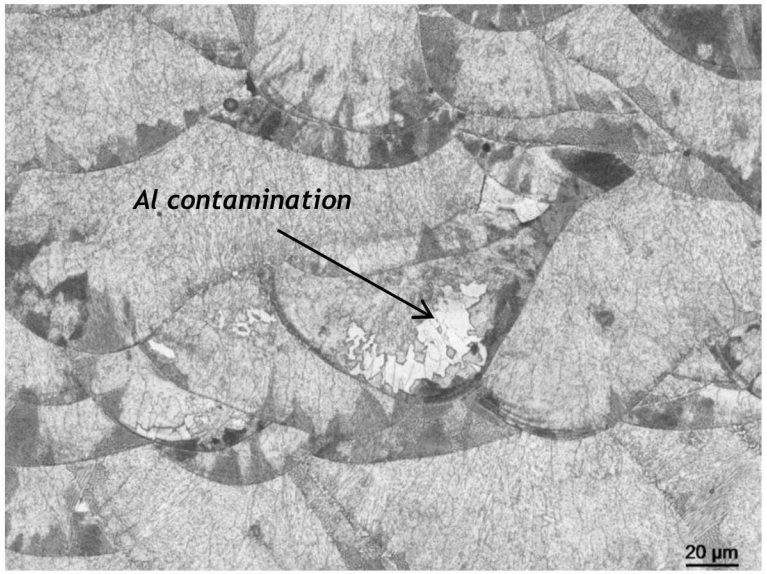


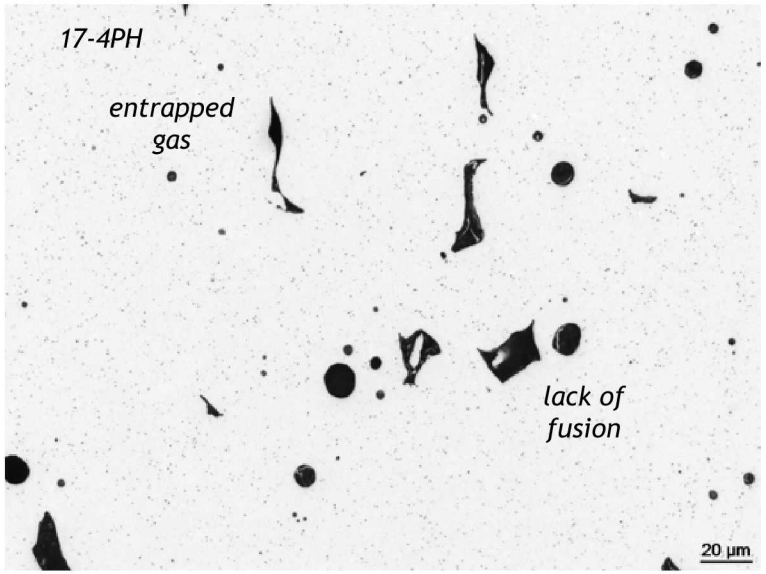
max YS: 489 Mpa
- @ 200 W, 2200 mm/s

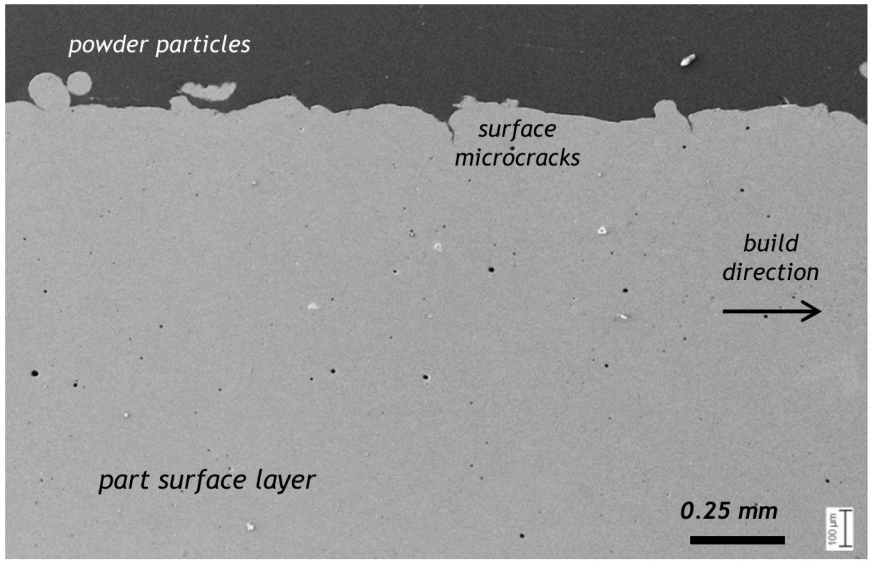
max UTS: 621 Mpa
- @ 200 W, 2000 mm/s

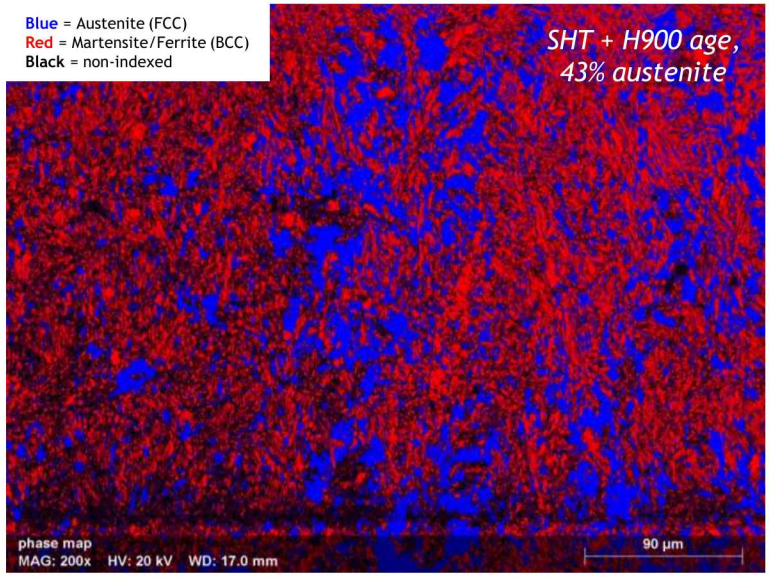
max ductility: 66%
- @ 120 W, 1000 mm/s

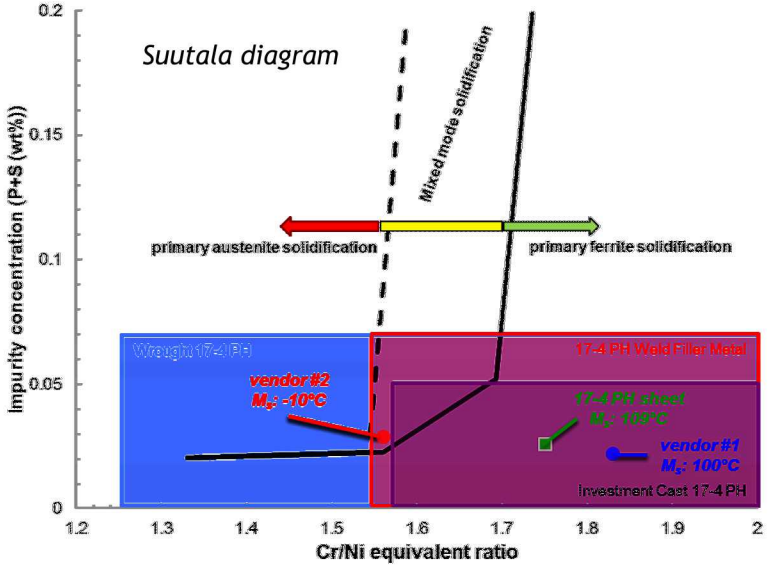
AM Material Defects Represent Multiple Failure Modes

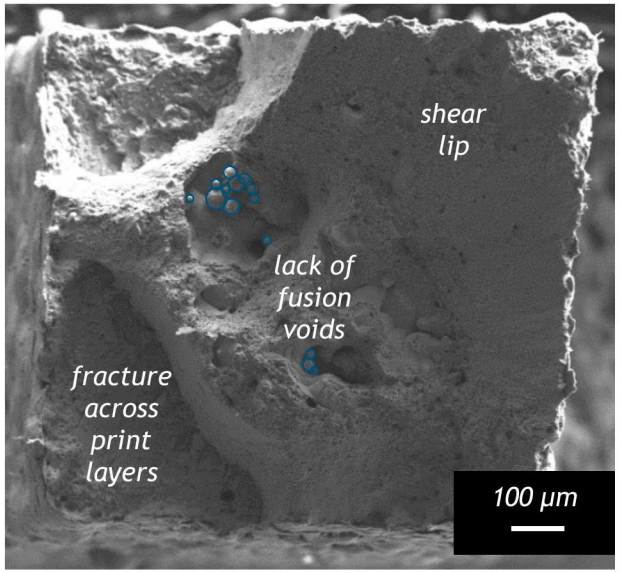












defect dominated failure, 2% elongation, 17-4PH

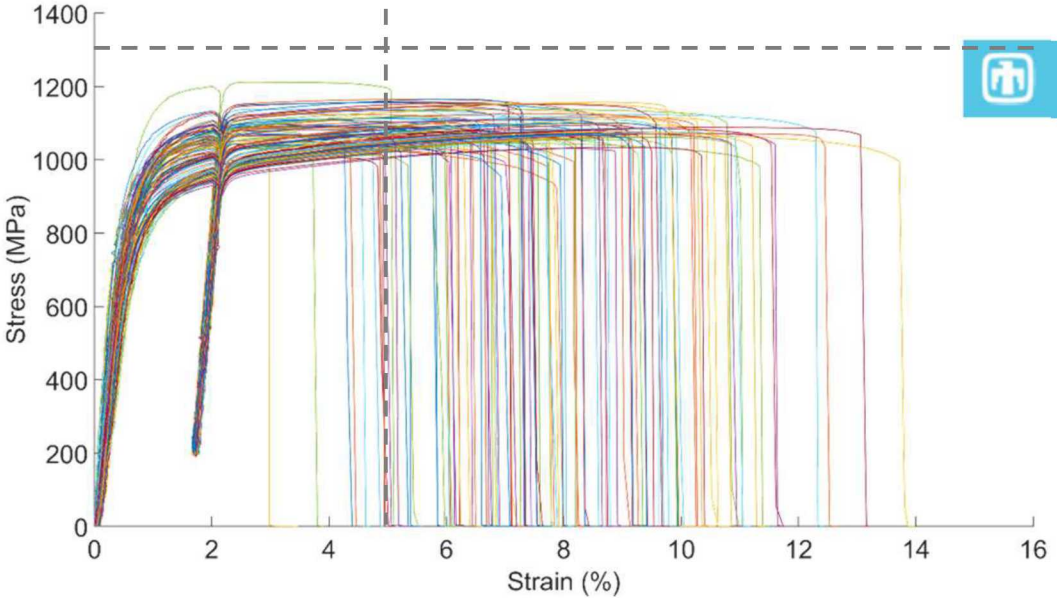
Stochastic Response

Defect dominated failure

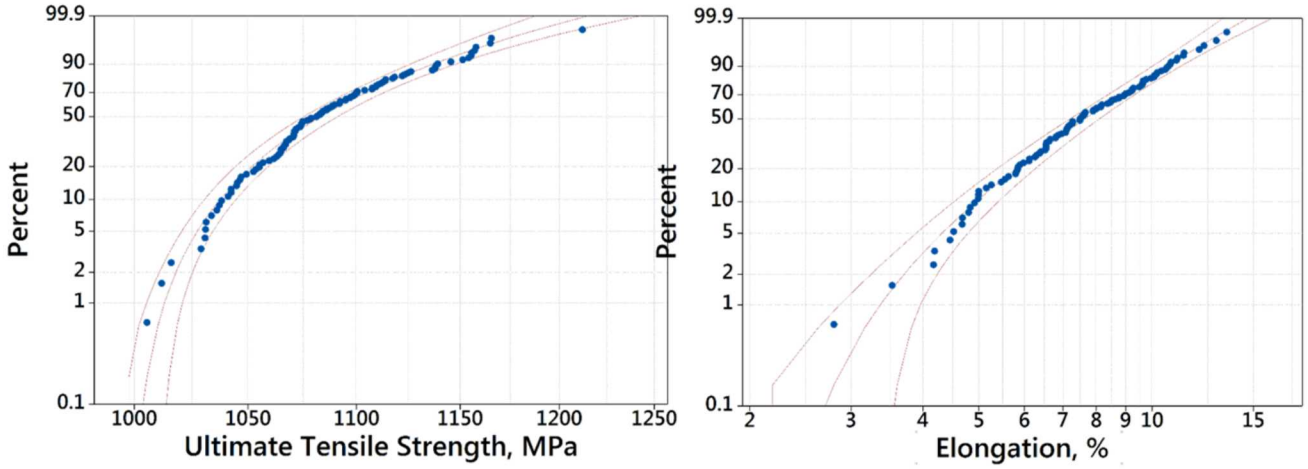
- 3-parameter Weibull informs design threshold
- ductile dimples & shear rupture planes
- voids & lack-of-fusion boundaries are likely crack nucleation sites

Extensive performance variations

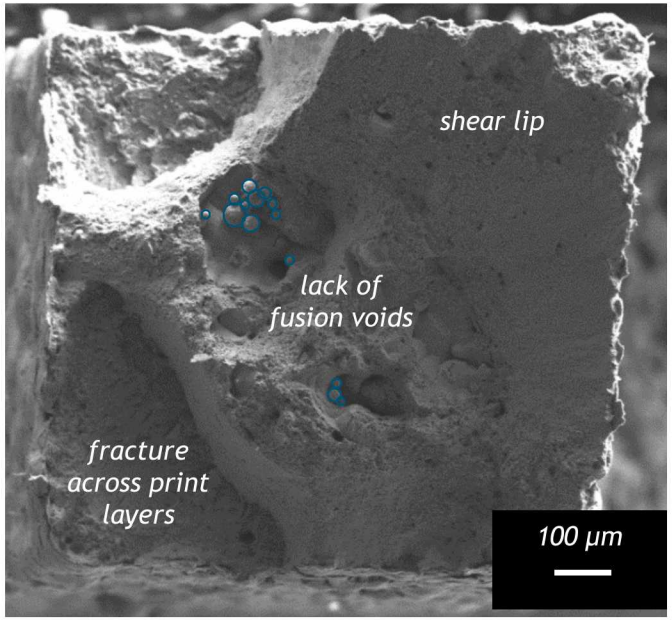
- can inter-build performance be predicted?



110 stress-strain curves for 17-4 PH after SHT+H900



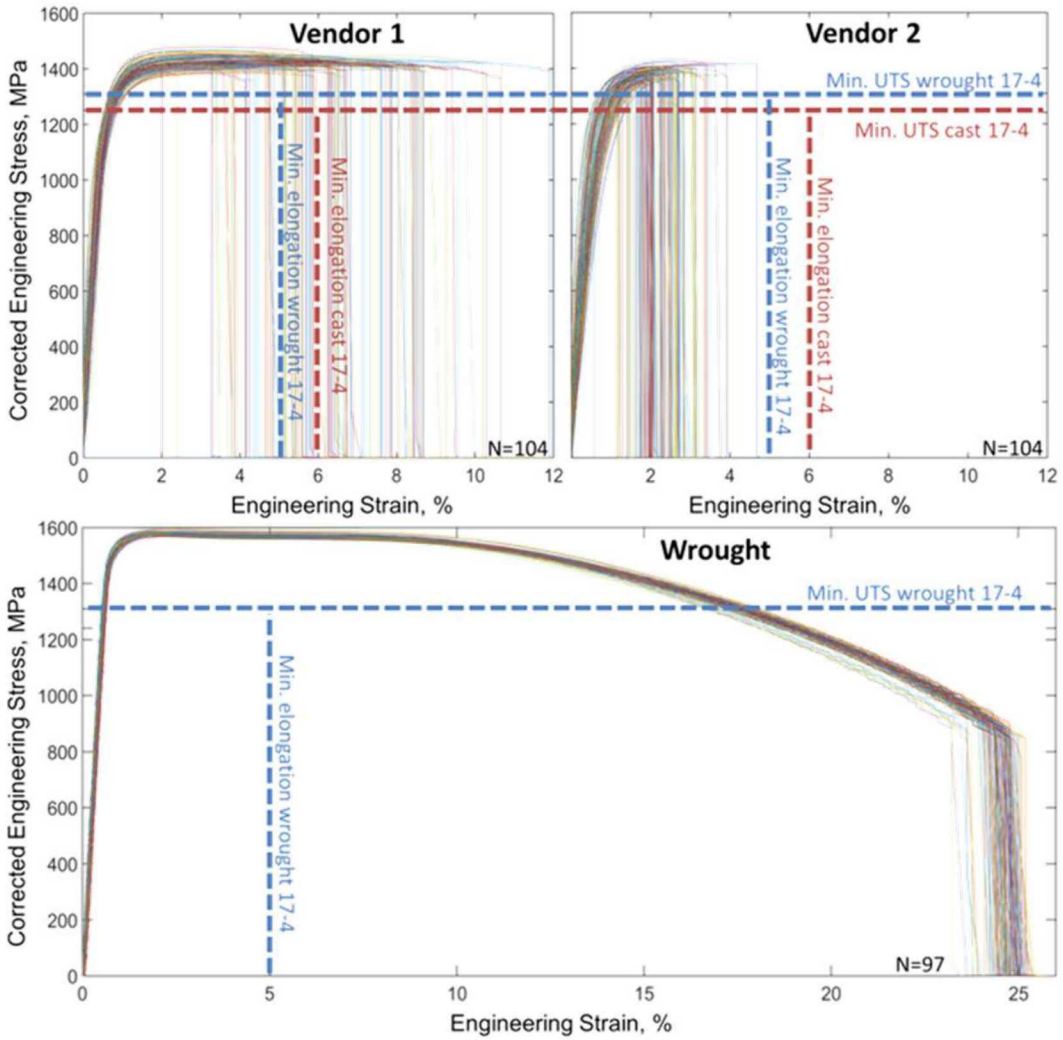
material performance fit to 3-parameter Weibull distributions



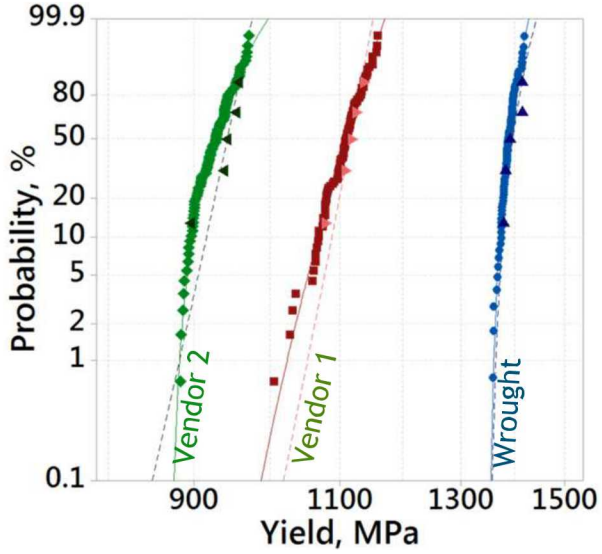
failure at 2% elongation, SHT+H900

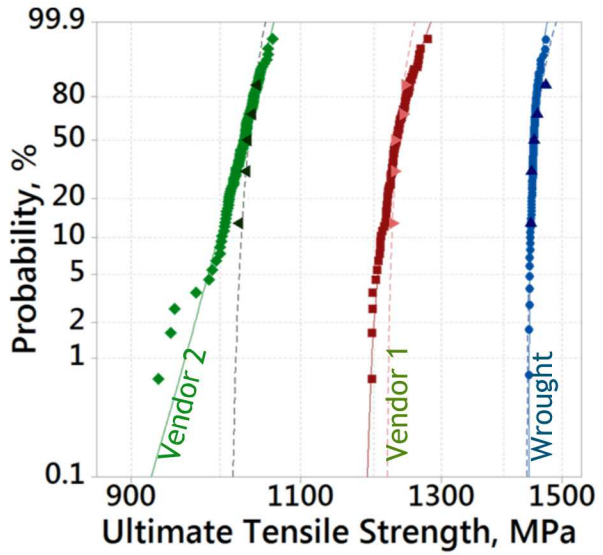
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

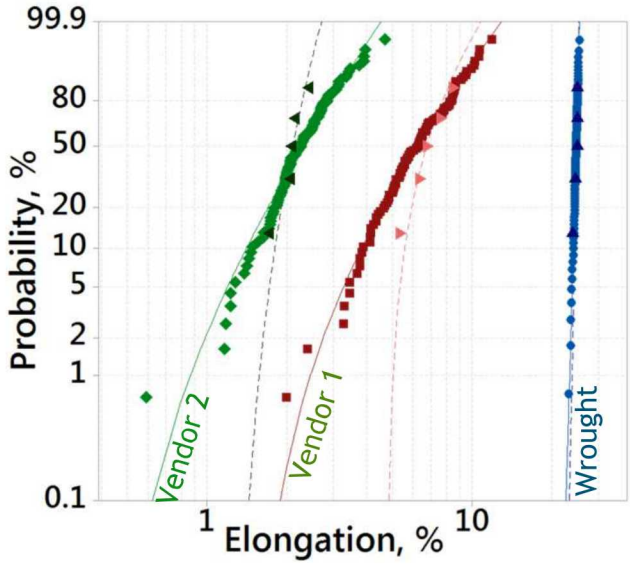
AM vs. Wrought 17-4PH



H900 data for vendor 1 (top left), vendor 2 (top right) & wrought (bottom) w/corrected stress area







AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

Lack of Control Produced Material Uncertainty in Early AM Metals

17-4PH parts requested from external vendor in 2015

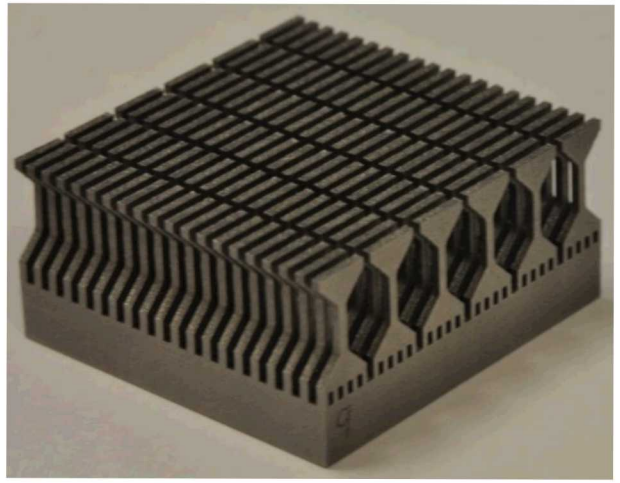
- analysis confirmed 17-4PH composition, but unexpected microstructure

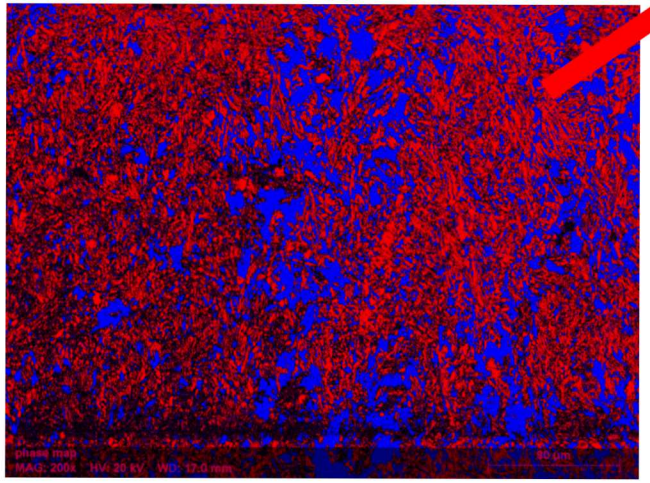
Sandia did not know or control

- feedstock pedigree, machine, build environment, process inputs or post-processing steps

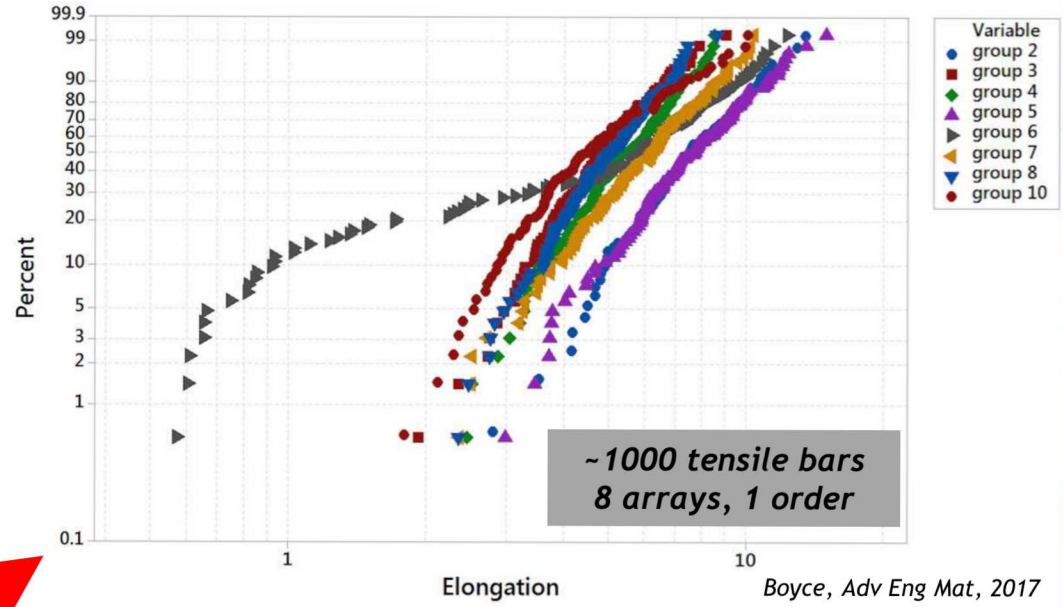
Not-surprisingly, extensive material variability observed

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

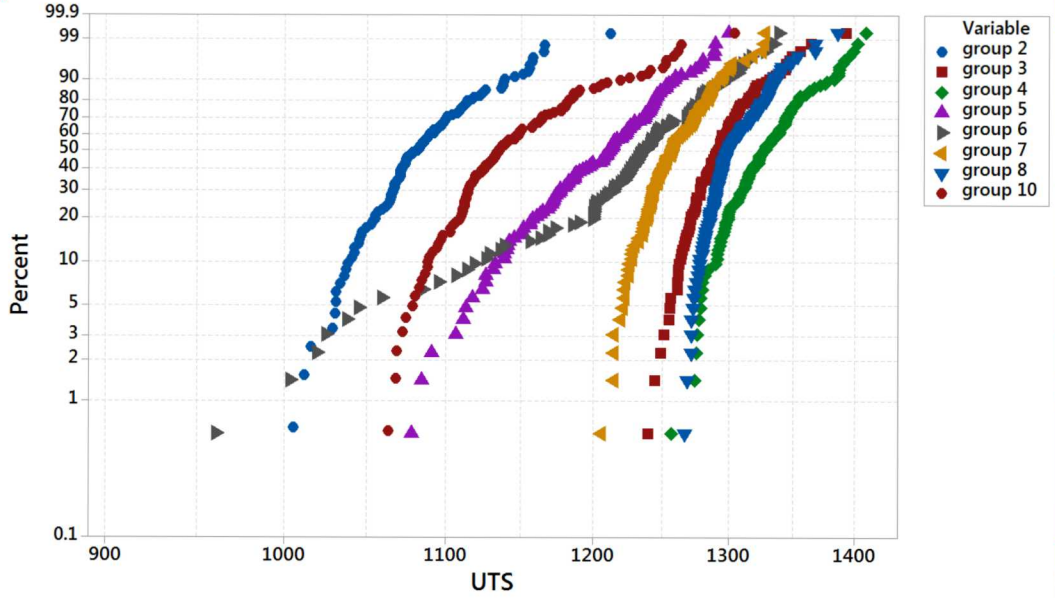




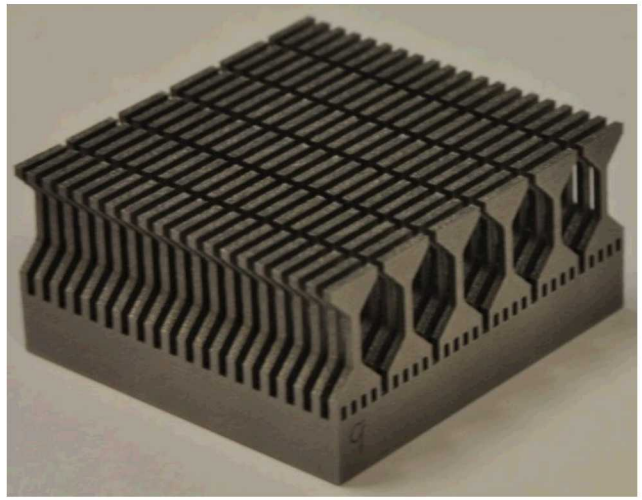
unexpected microstructure with 43% austenite, 57% martensite



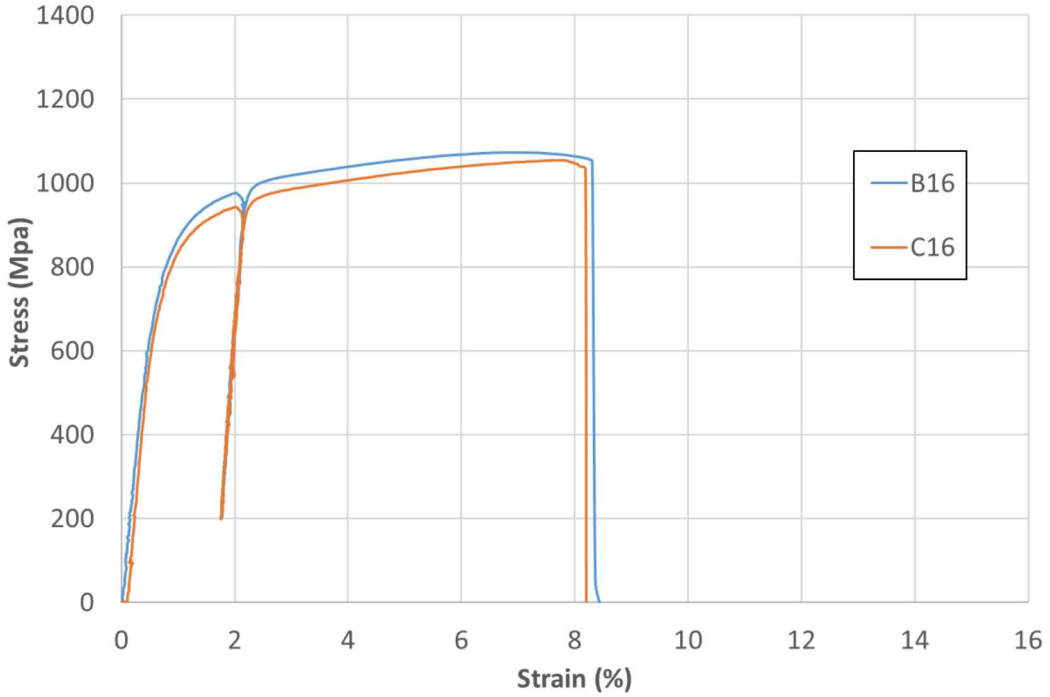
Boyce, Adv Eng Mat, 2017



Difficulties Predicting 17-PH Behavior



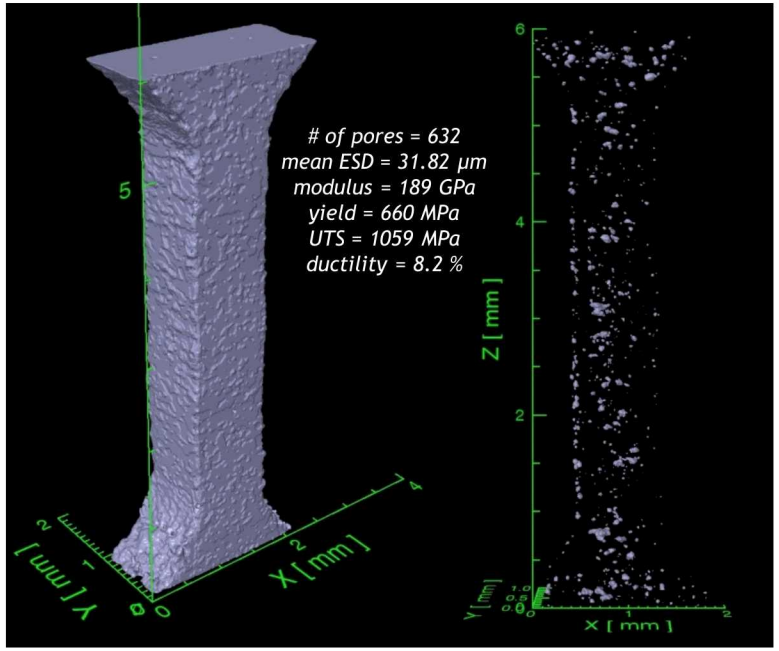
high throughput test sample w/120 dogbones,
1x1mm gage x-section



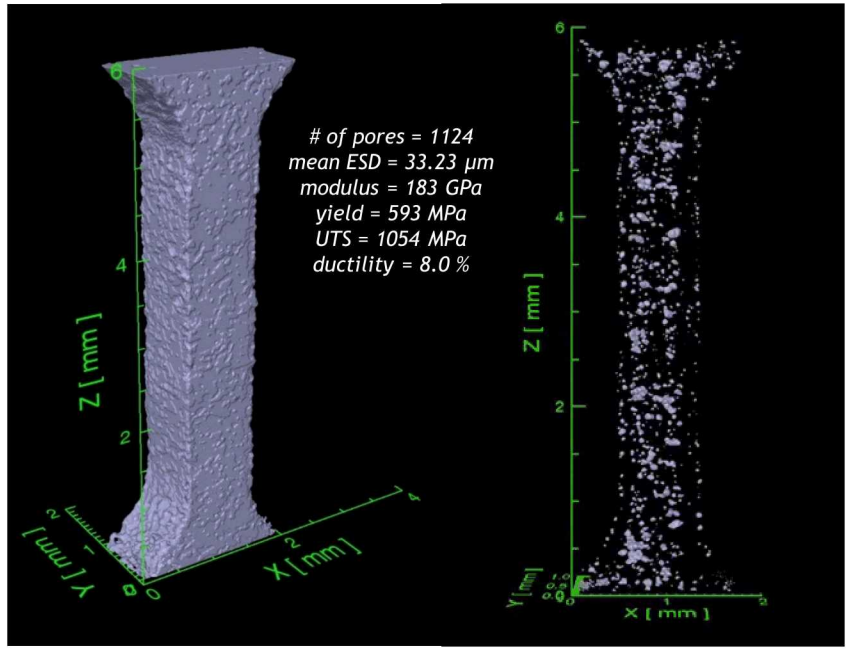
Material uniformity
- microstructure gradients
- porosity
- surface roughness
- unknown feedstock & process inputs
- residual stress / part deformation

Simple geometry
- uniform axial tension

Measurement inconsistency



dogbone B,16 CT surface image (left), porosity map (right)



dogbone C,16 CT surface image (left), porosity map (right)

ESD = equivalent spherical diameter

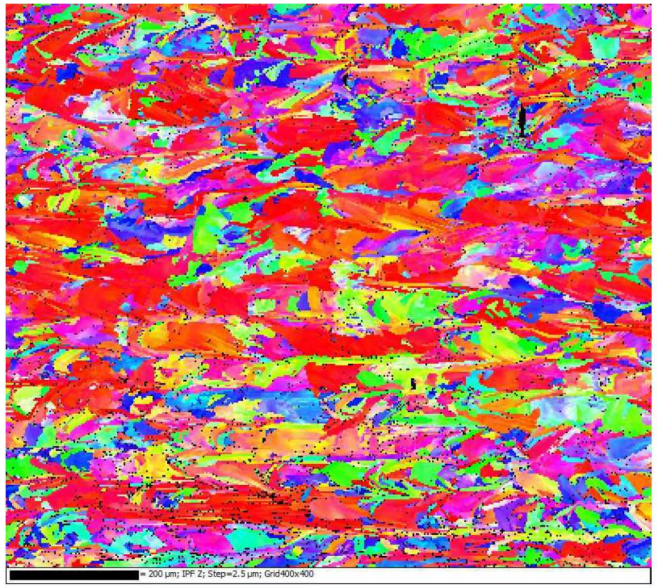
Process Knowledge & Control Reduces Material Variability

316L stainless steel
- more robust material

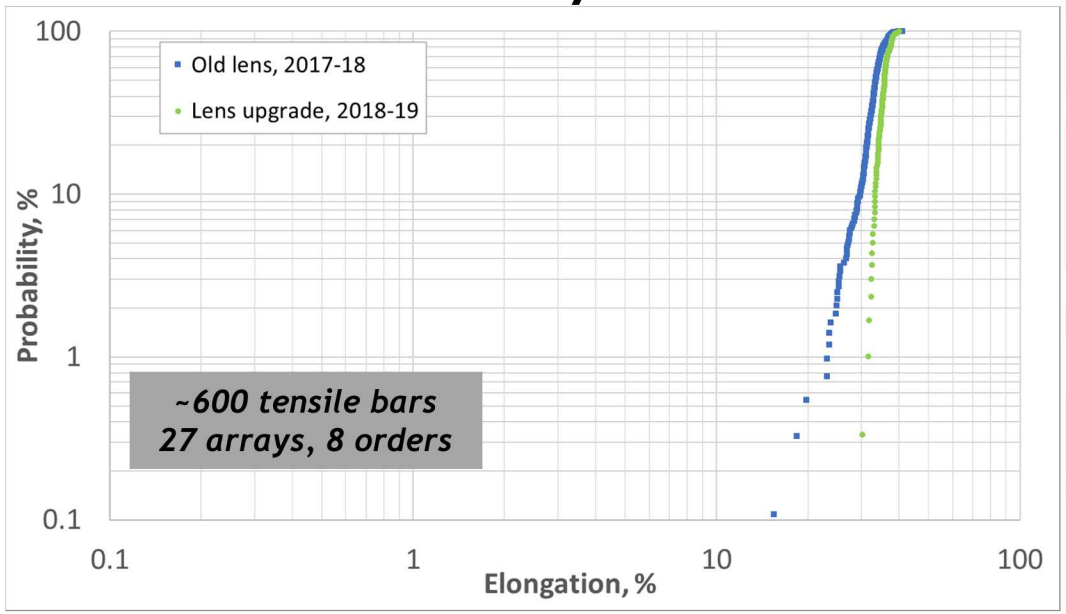
3D Systems ProX 200
- process space mapped & machine performance characterized

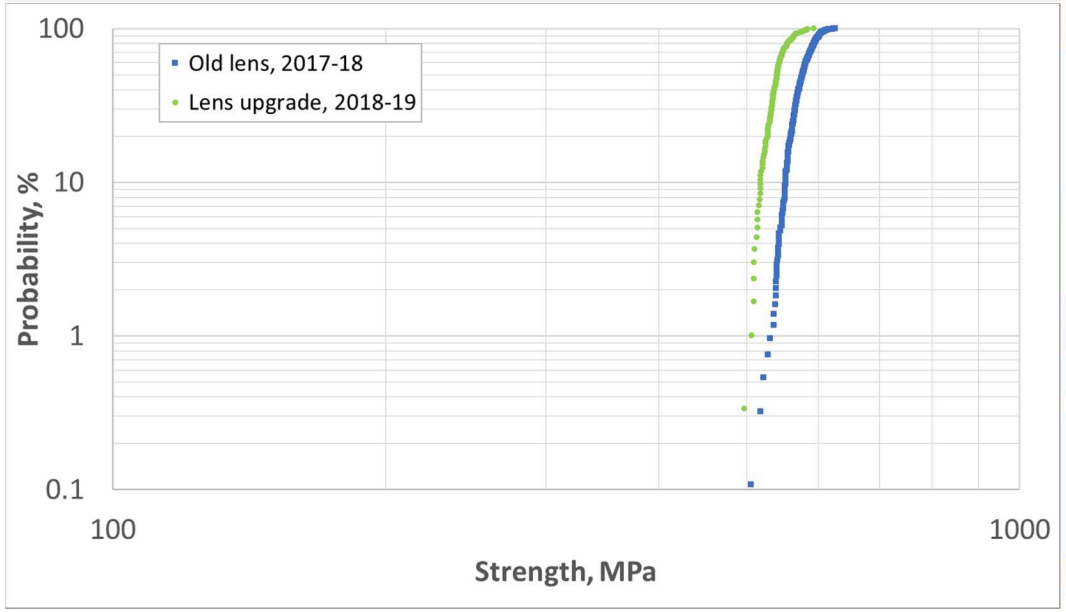
controlling & logging every part, build & powder cycle
- feedstock pedigree, build environment, process inputs, post-processing
- printing & testing artifacts w/build cycles
- storing feedstock, process & printed material data in GRANTA
- capabilities for in-situ machine & process monitoring

build plate w/process artifacts



baseline 316L SS microstructure

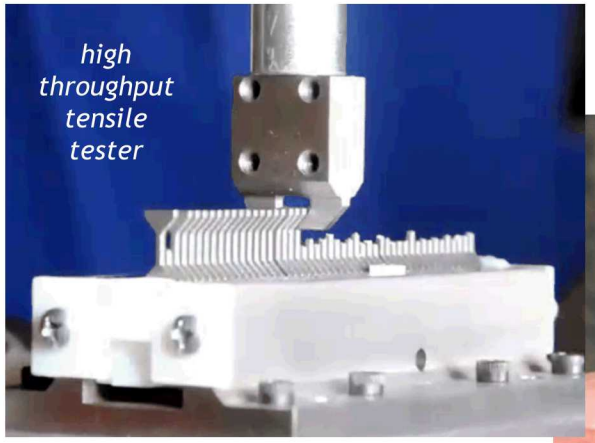


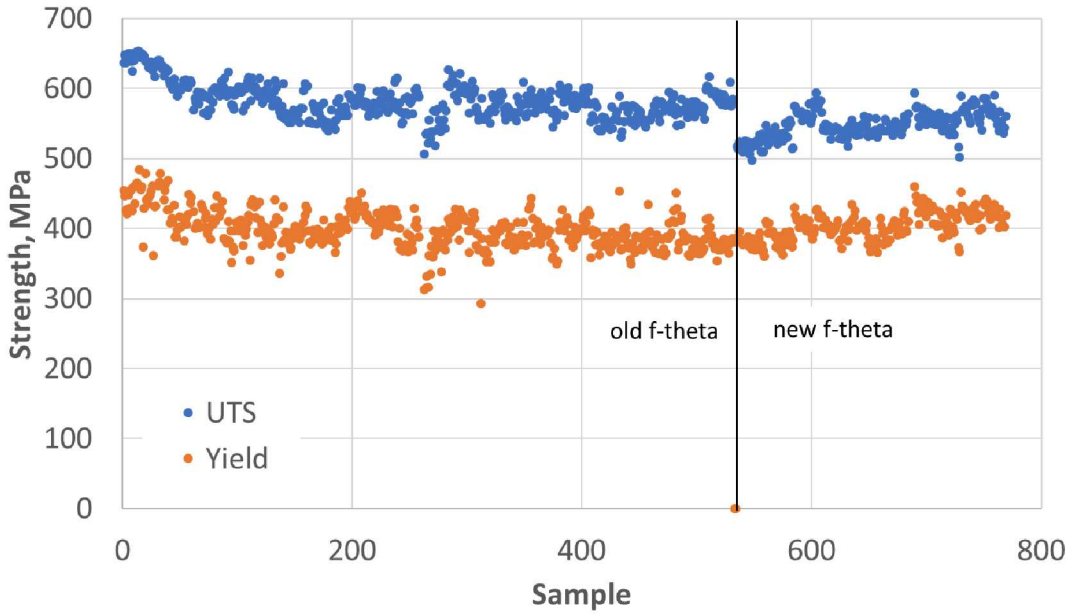


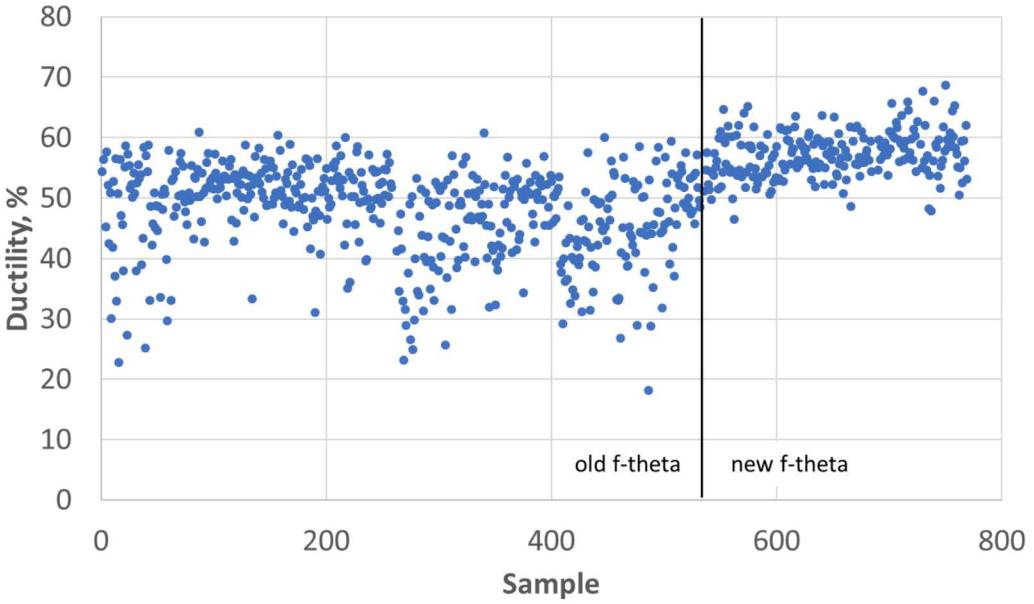
316L SS Tensile Data Over Time

High-throughput tensile data

- 25 & 10 dogbones per build plate
  - 1x1x4mm gauge section
- two powder lots
  - same composition and ave. powder diameter
- transitions correspond to machine, powder or process changes





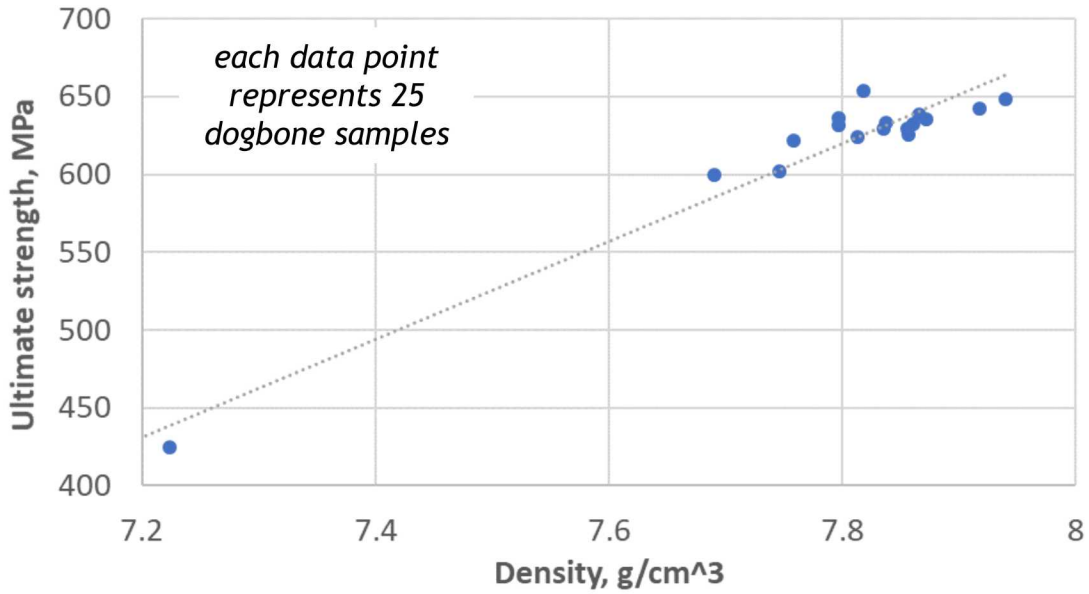


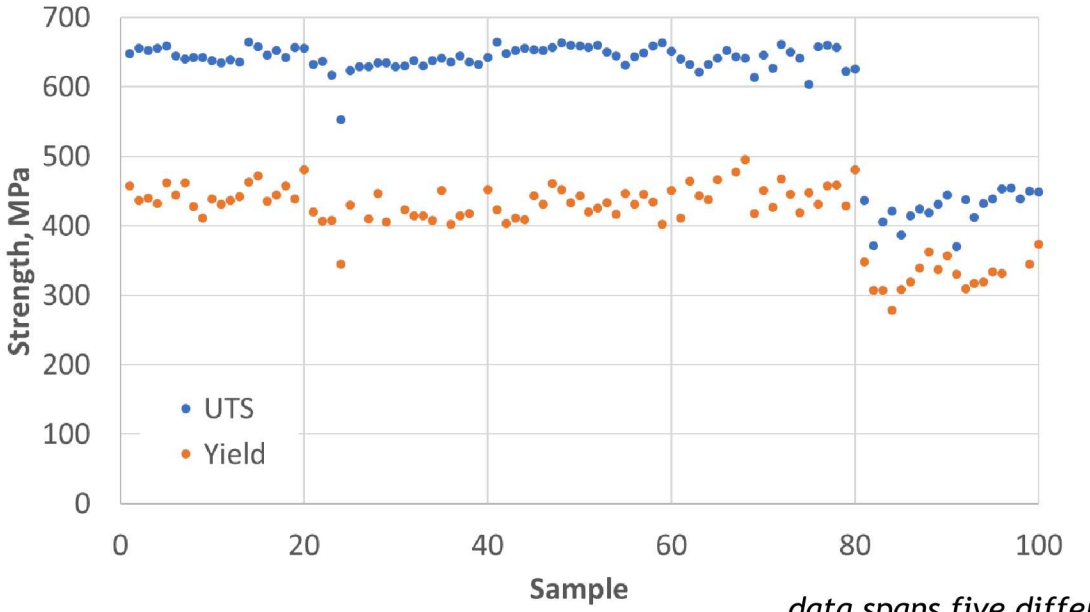
Property Distributions

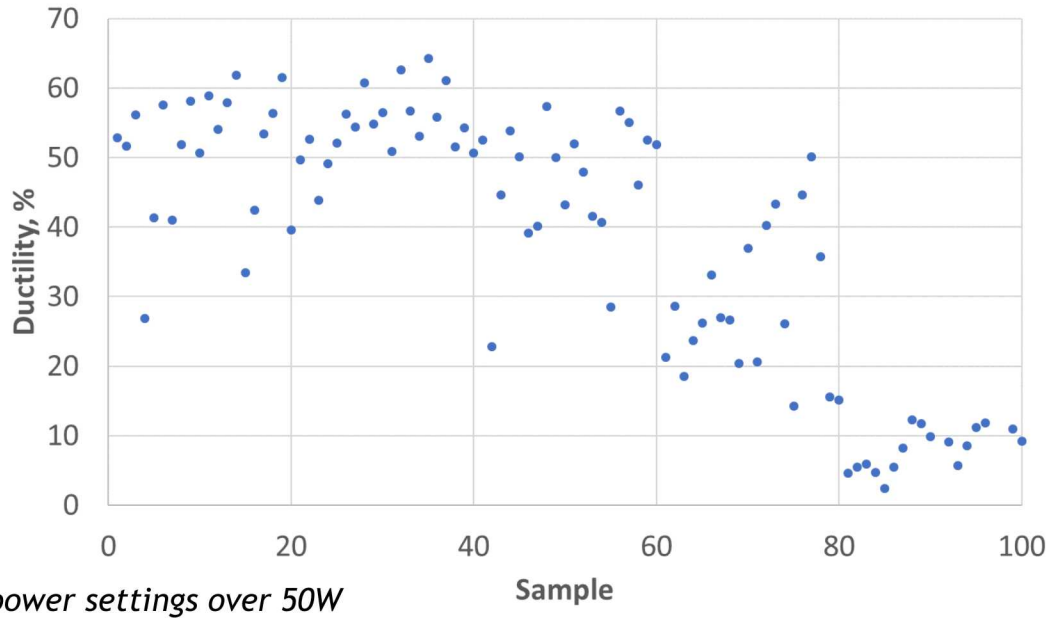
Must consider material performance distributions

Explicit material correlations can be established

Inter-build variation can exceeds intra-build variation







data spans five different power settings over 50W

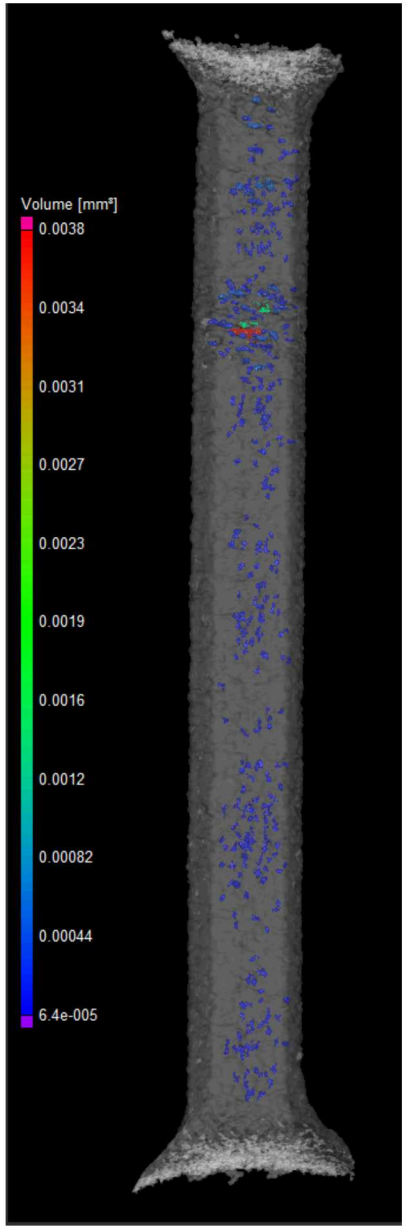
Gross Defect Failure Remains a Concern

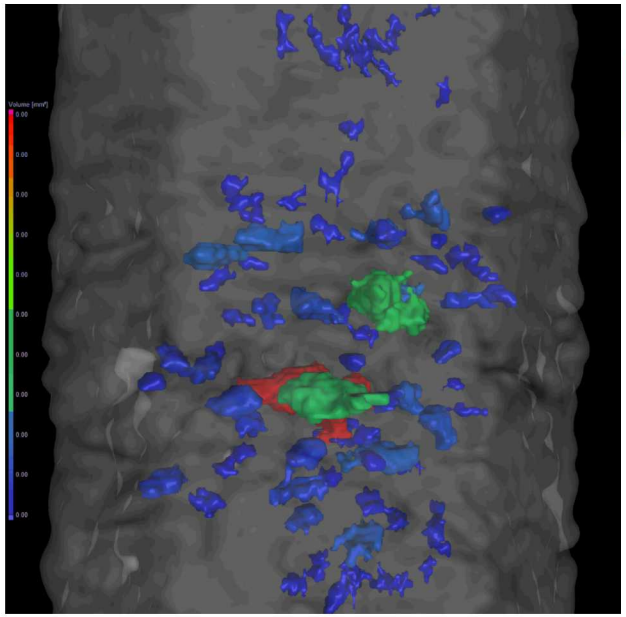
316L SS tensile dogbone
- 1x1x10mm gage section
- Fein Focus 225kV
  - 12.6µm voxels

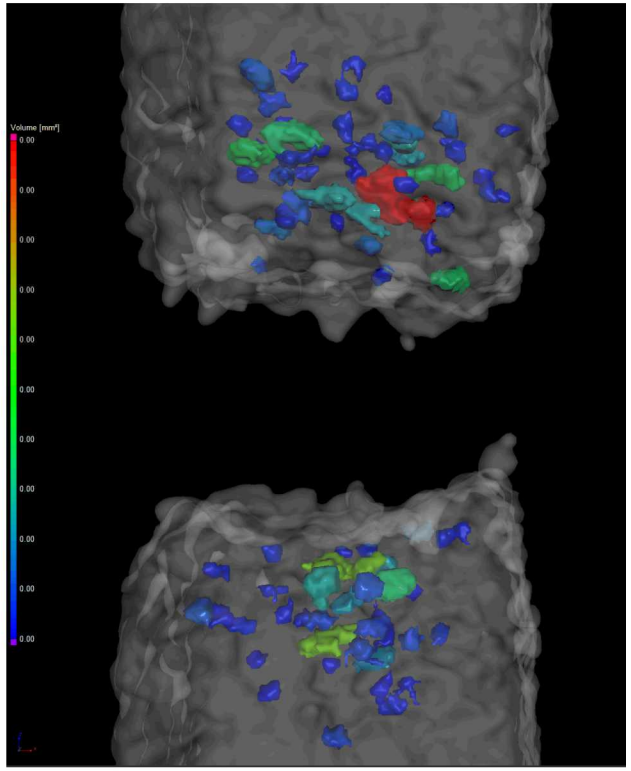
Gross defects observed
- equivalent diameter scales
  - red: ~190µm
  - green: ~140µm
  - blue: ~80µm

Failure initiated near largest pore
- pore deformation observed

Identifying gross defects is reasonable
- establishing tolerances remains challenging







Process Monitoring – Multiple Signatures are Available

Thermal
- Stratonics ThermaViz two-color pyrometer
- IR cameras: FLIR C2, A310 & SC6811

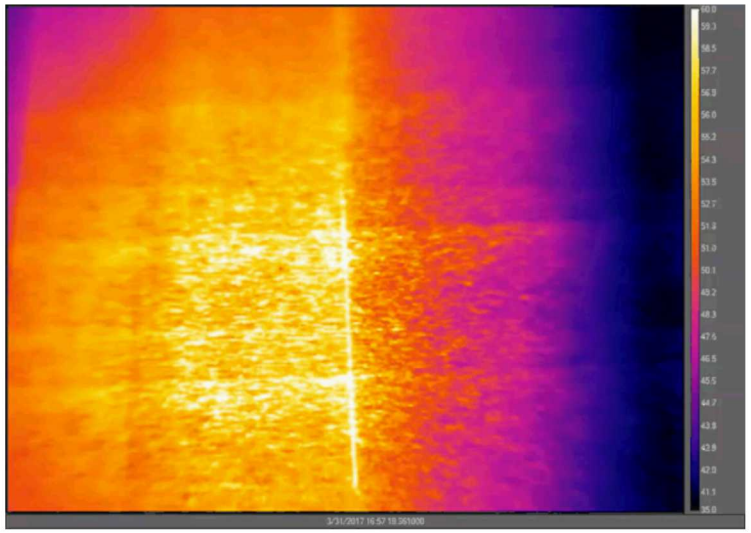
Optical
- Photron PhotoCam Speeder V2 high speed cameras
- blue light illumination
- Ocean Optics LIBS2500plus spectrometer
- Keyence LJ-V7020 & LJ-V7200 laser line scanners

Acoustic
- audio microphone, acoustic emission

3D Systems Open Protocol platform
- PSU multi-spectral sensor

Managing & analyzing data streams is crucial
- large
- non-linear correlations

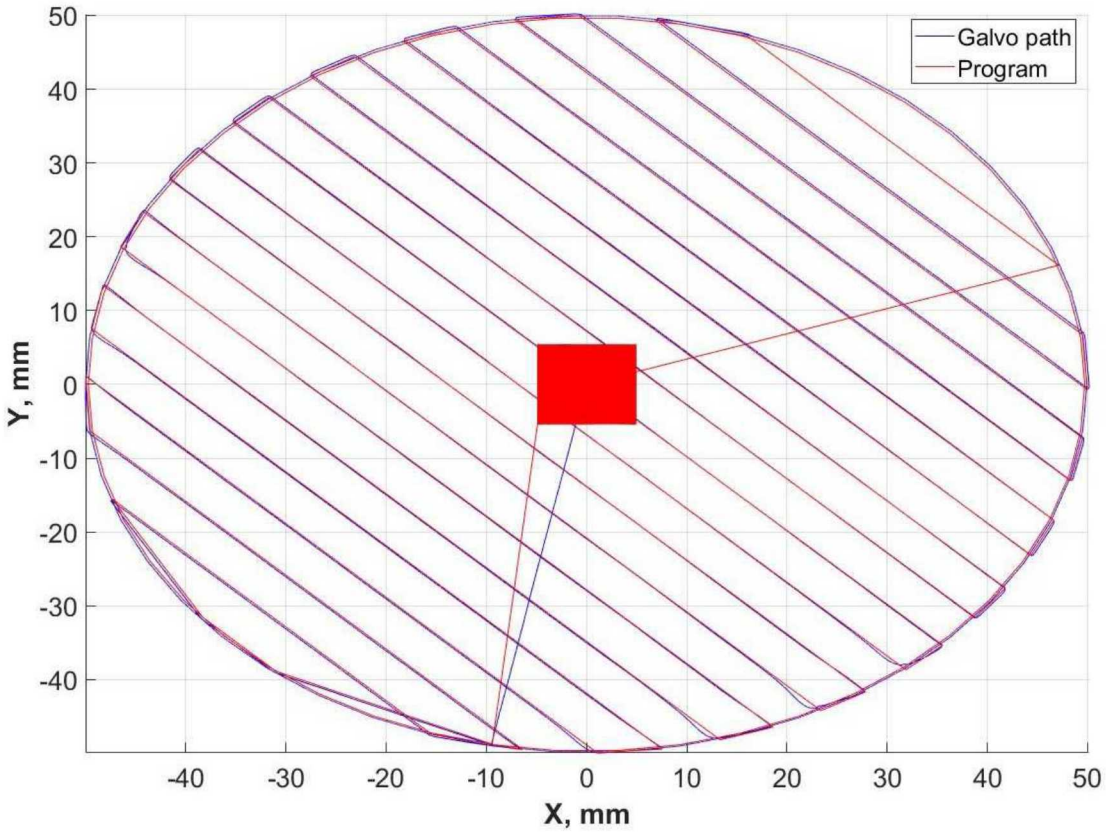
ThermaViz installed in the ProX 200



FLIR A310, laser on plate, ~100W, 1.4m/sec, 125µm hatch, 100µm beam dia.

Photron high speed optical melt pool video

Real-Time Machine Monitoring Reveals Process Perturbations

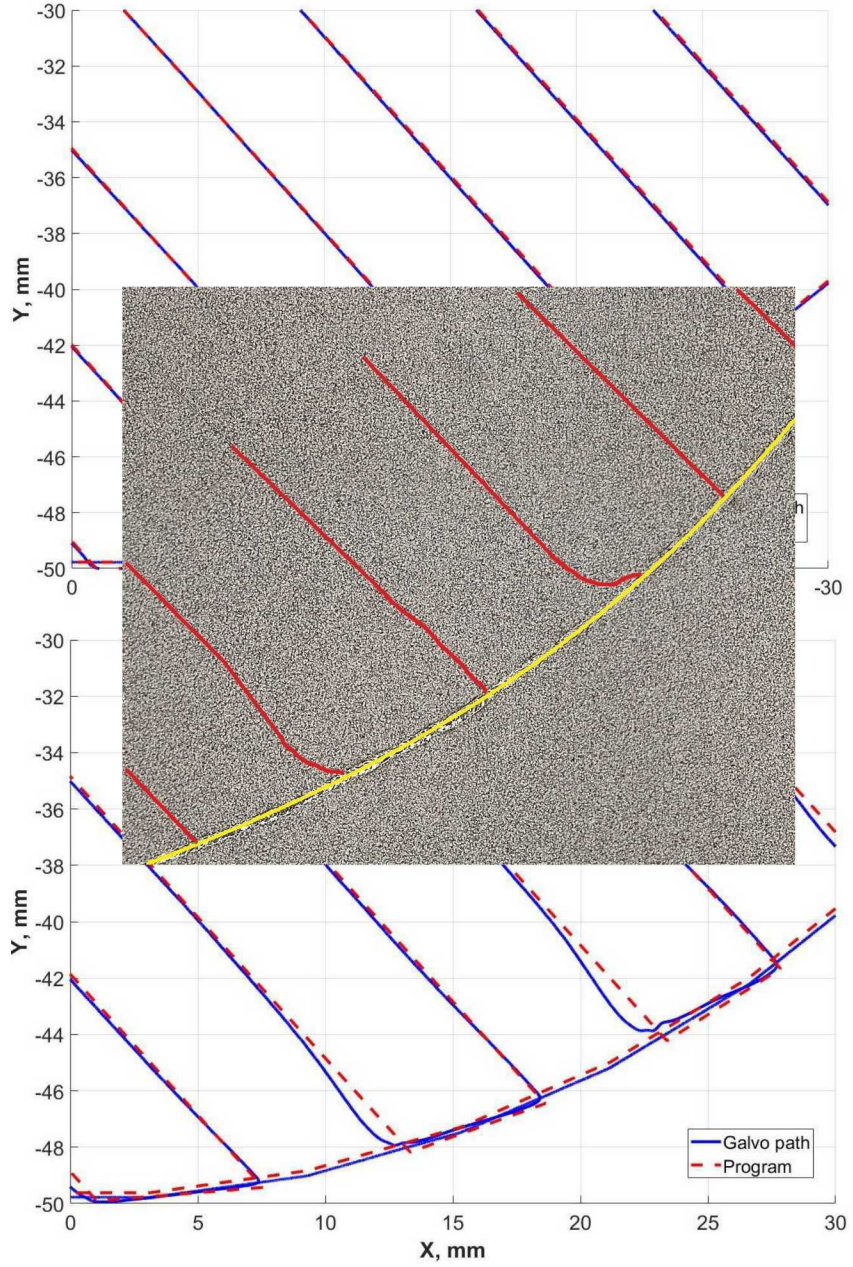


ARCS output for a simple test pattern

- Archive, Research, Control, Synchronization (ARCS)
  - Penn State, 3D Systems collaboration
- motion @ 100kHz

desired motion

galvo errors



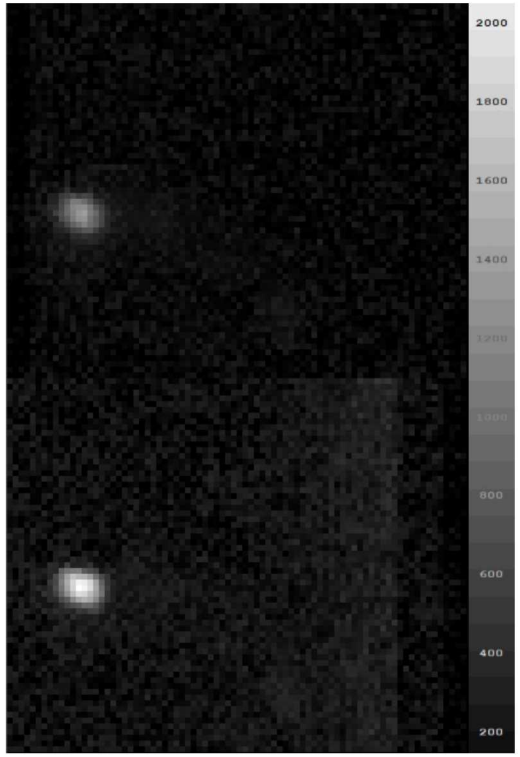
Two Color Pyrometry Melt Pool Monitoring

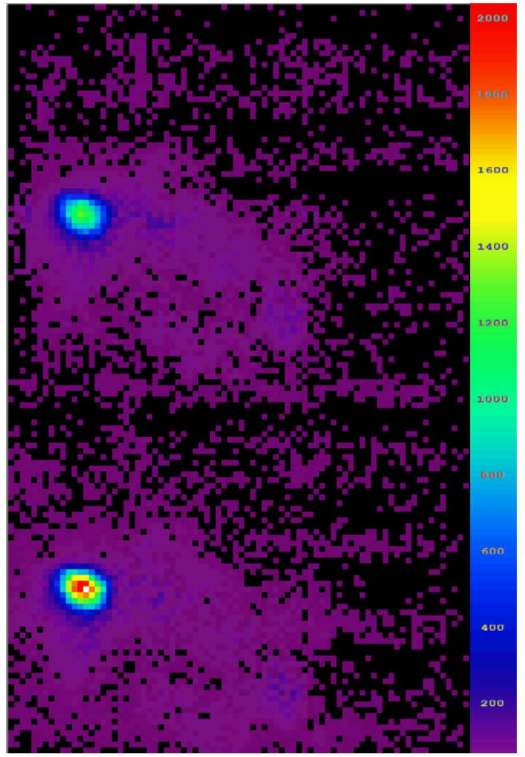
Stratonics Therma-Viz two-color pyrometer
- CMOS imagers, ~20µm/pixel
- 750 & 900nm filters (short & long)
- $T_{pixel} \cong func(I_1/I_2)$

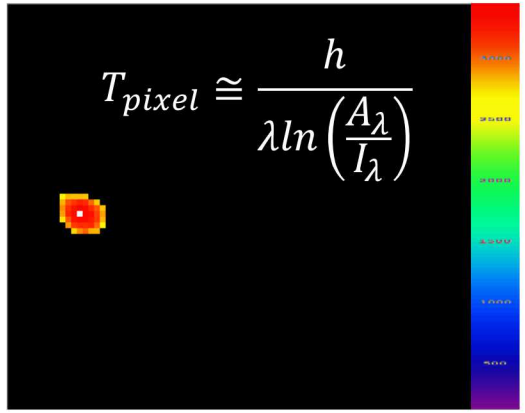
Fixed field, angled side viewing
- FOV: 80 x 65 pixel (1.6 x 1.3mm)
- frame rate: 6-7kHz
- exposure: 90µsec

Challenges
- data rate
- image resolution & registration
- emissivity variation across melt pool
  - unquantified temperature uncertainties

ThermaViz installed in the 3D Systems ProX 200







ThermaViz raw intensity data (left), radiance data (center) & melt pool temperature (right)

Pyrometry Signal Analysis

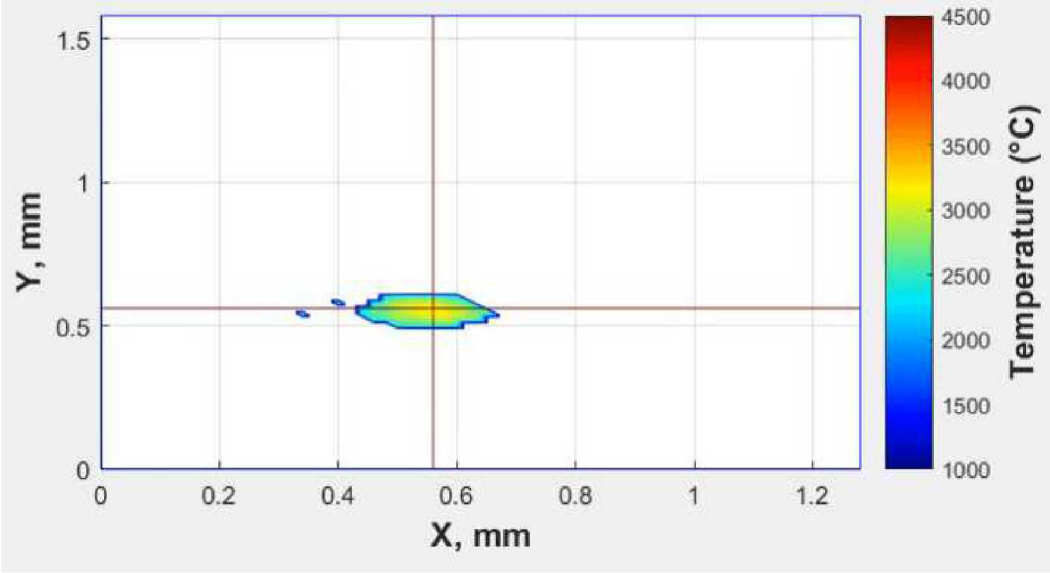
Registration tied to process layers

Melt pool metrics

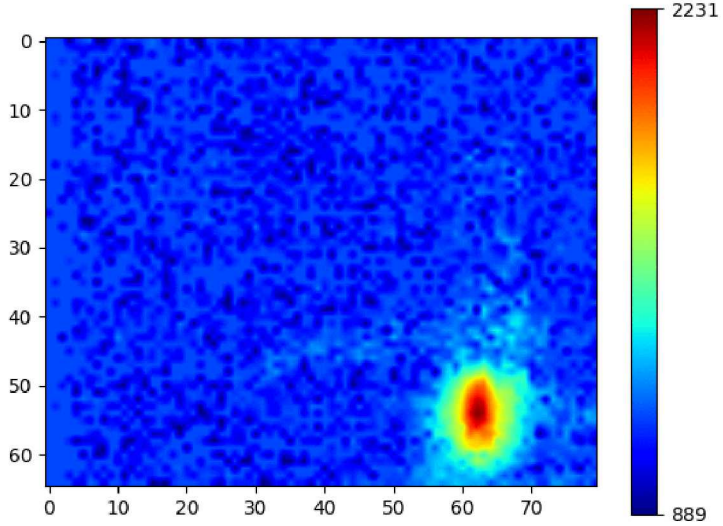
- peak temperature, centroid location, area, length, width, kurtosis, skewness

Two approaches

- process experiments
  - Matlab, Stratonic CSVs, 10s-100s images
- porosity column builds
  - Python scripts, Stratonic ‘raw.viz’ files, 100k images quickly (minutes)
  - compute pool properties using contour data



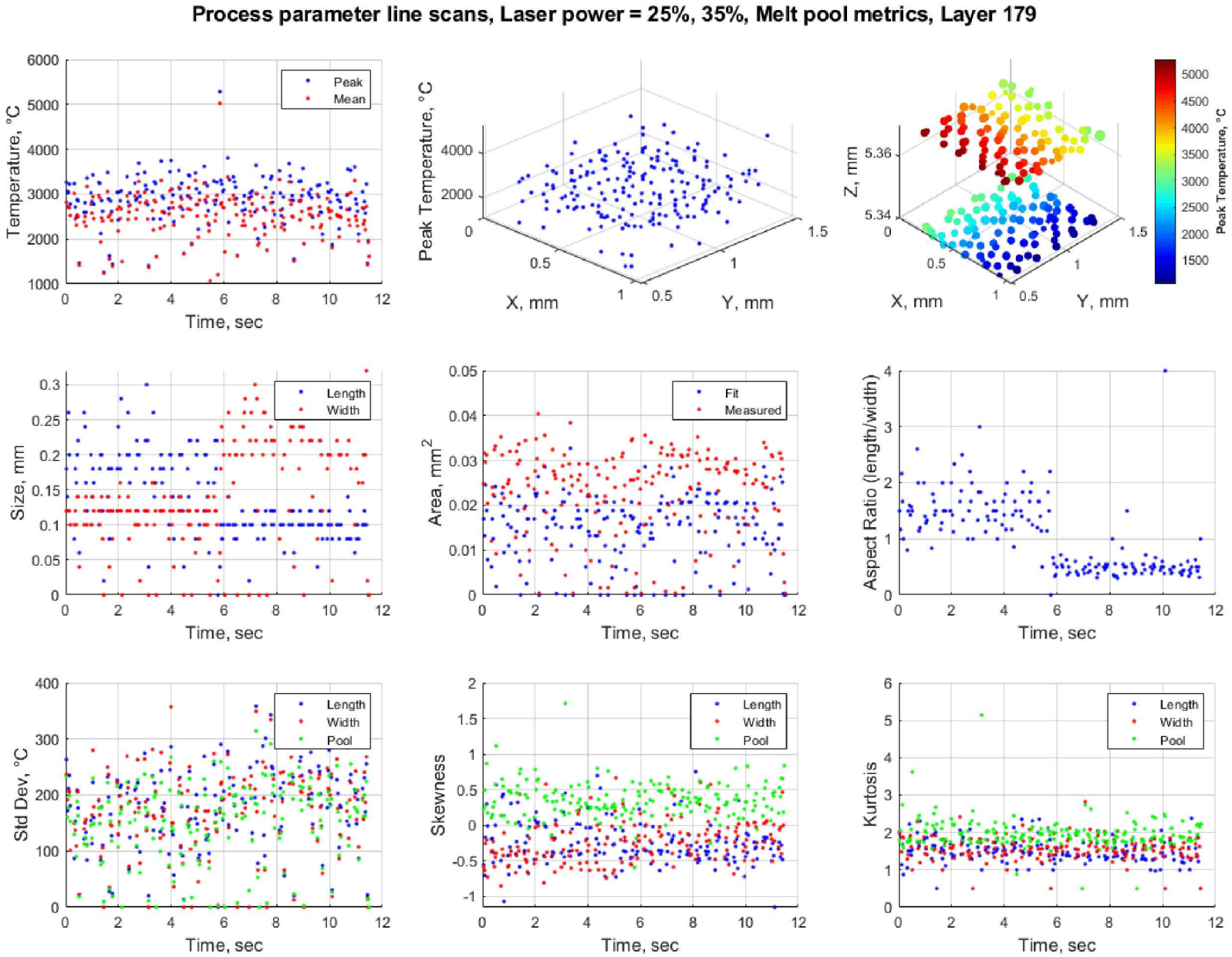
layer 155 melt pool temperature, Matlab analysis of Stratonics software output



melt pool motion, nominal settings, Python script analyzing raw image data

Melt Pool Metrics

Which are most important / indicative of void structures?



Material Reconstruction

VOLUME GRAPHICS

Micro-computed tomography

MATLAB

Interactive Data Language

IDL

ImageJ

Adobe Photoshop

batch processing
16bit > 8bit conversion
lossless filetype conversion

FIJI

alignment & registrat
cropping
grayscale matchin
autoleveling
image filtering
thresholding

3D reconstruction
3D quantification

python

ParaView
Parallel Visualization Application

DREAM.3D

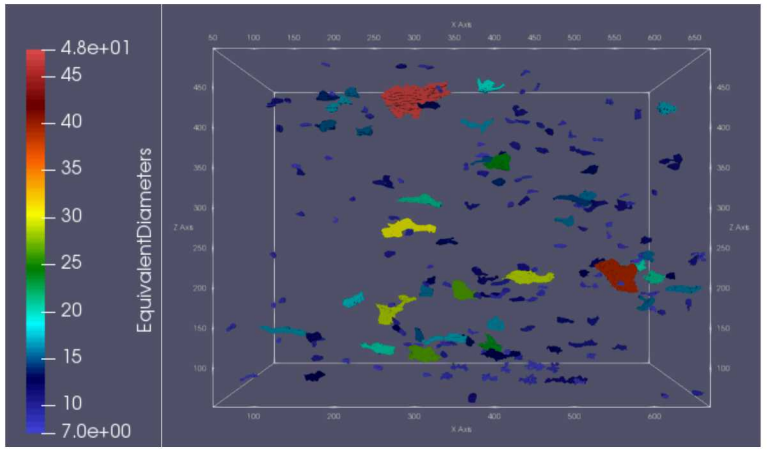
image processing & quantification. 3D reconstructions

BlueQuartz Software
Specializing in Software Tools for the Scientist

http://dream3d.bluequartz.net

ROBO-MET.3D™
A UES PRODUCT

Serial-sectioning



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

Sandia National Laboratories

Intentional Porosity Structure

Design

- 1-10 layer thickness
  - 30-300µm
- 1x1x5.25mm column
  - 175 layers
  - 87,500 T-V frames per part

Fabrication

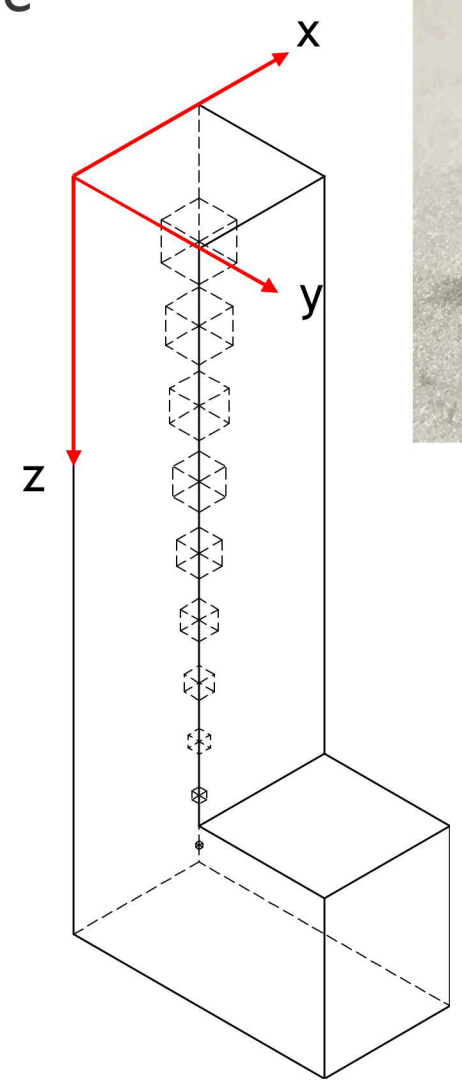
- 316L stainless steel
- 3D Systems ProX 200 laser powder bed fusion

Material characterization

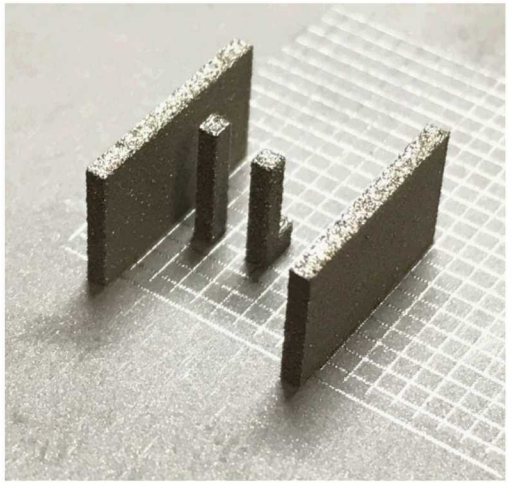
- Zeiss Xradia 520 Versa µCT
- voxel resolution ~ 2µm

Data analysis

- pore size detection limit
- seek to correlate spatial sensor data (X,Y,Z,time) to material porosity (X,Y,Z)
- non-trivial effort

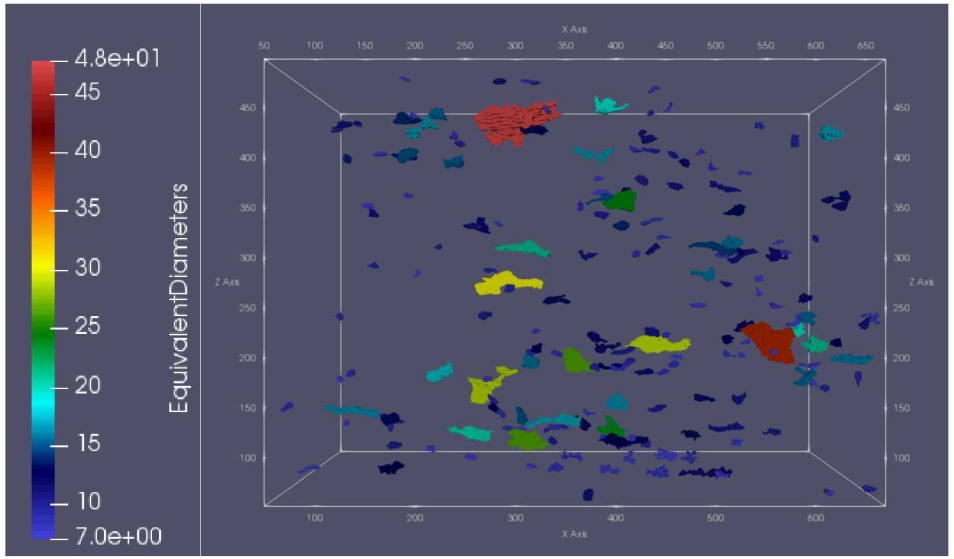


captured holes structure design



1x1x5mm 316L SS column w/support walls

captured defect holes part CT image



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

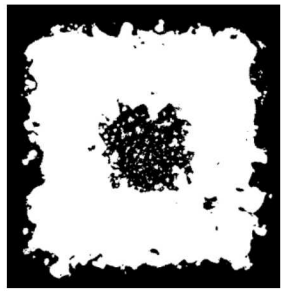
Process-Structure Correlations

Exploring correlation of μCT voids w/thermal signatures

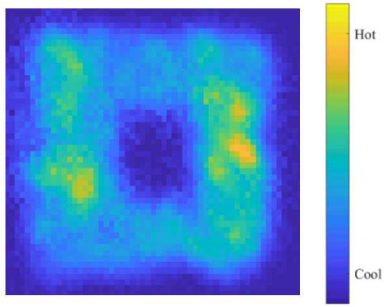
- sizes
  - μCT: 2x2x2μm
  - pyrometer: 20x20x30μm
  - multiple μCT voxels map to one pyrometer voxel
- registration is first step before correlating statistical measures
  - μCT & pyrometer data reveal part warpage => data sets are misaligned
- binning & scaling of pyrometer data produces best registration
  - layerwise implementation appears best

Correlating voids to melt pool response

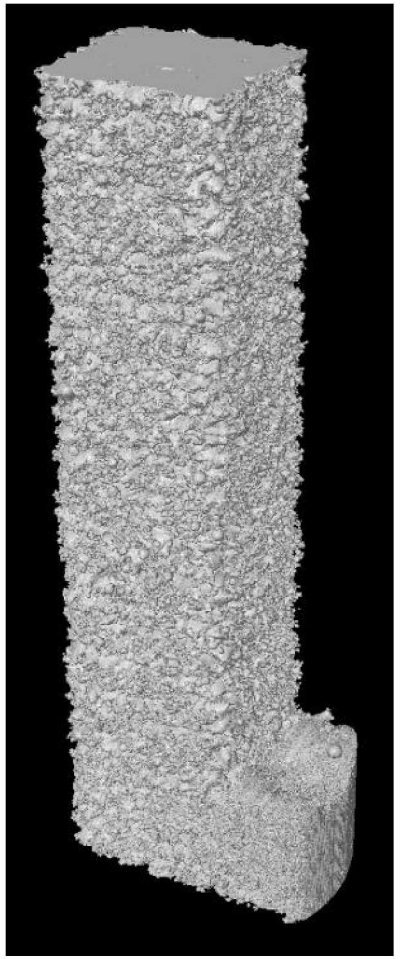
- where are signatures found?
  - same layer, above, below?

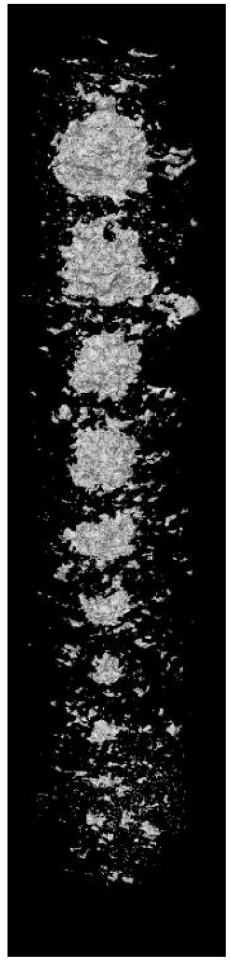


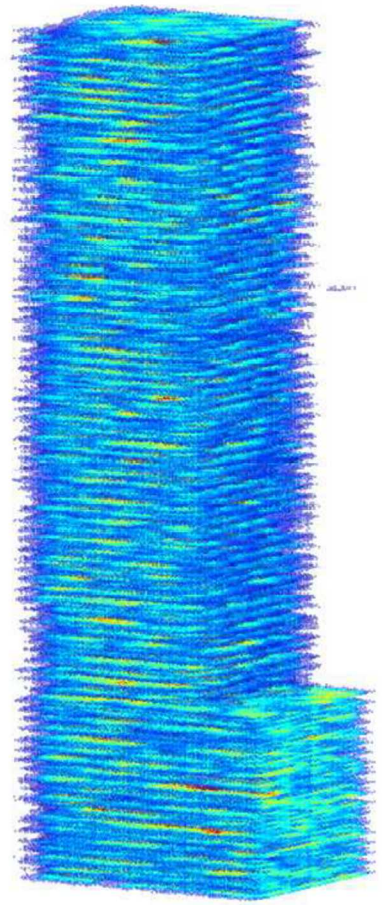
μCT bitmap



melt pool temperatures





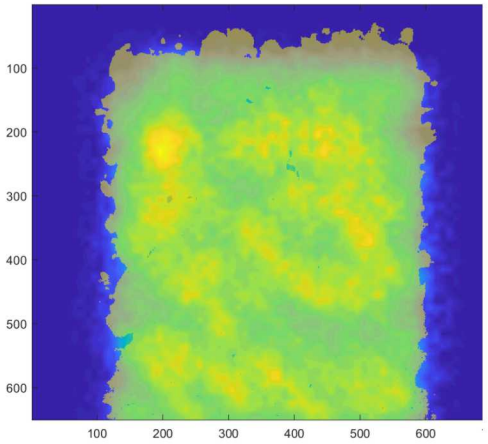


pyrometer data reconstruction

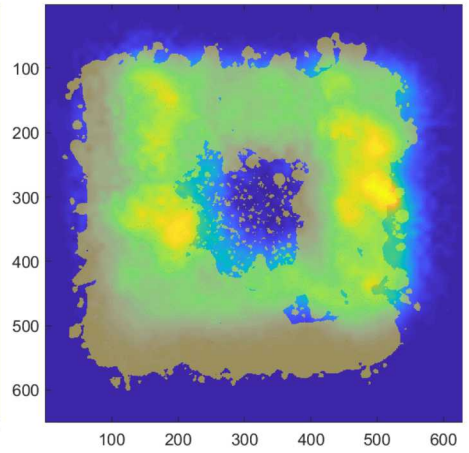
1 mm

μCT reconstruction

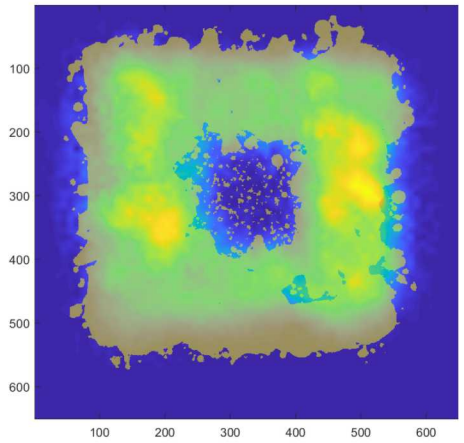
Registration & Feature Detection



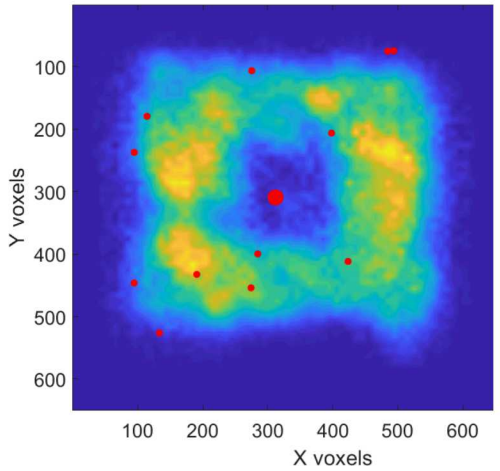
good overlap at the base of the part

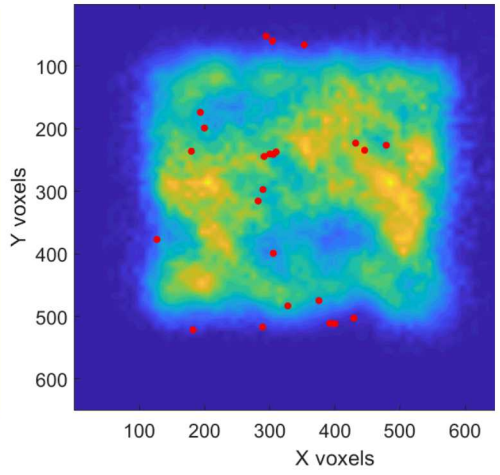


poor overlap at the top

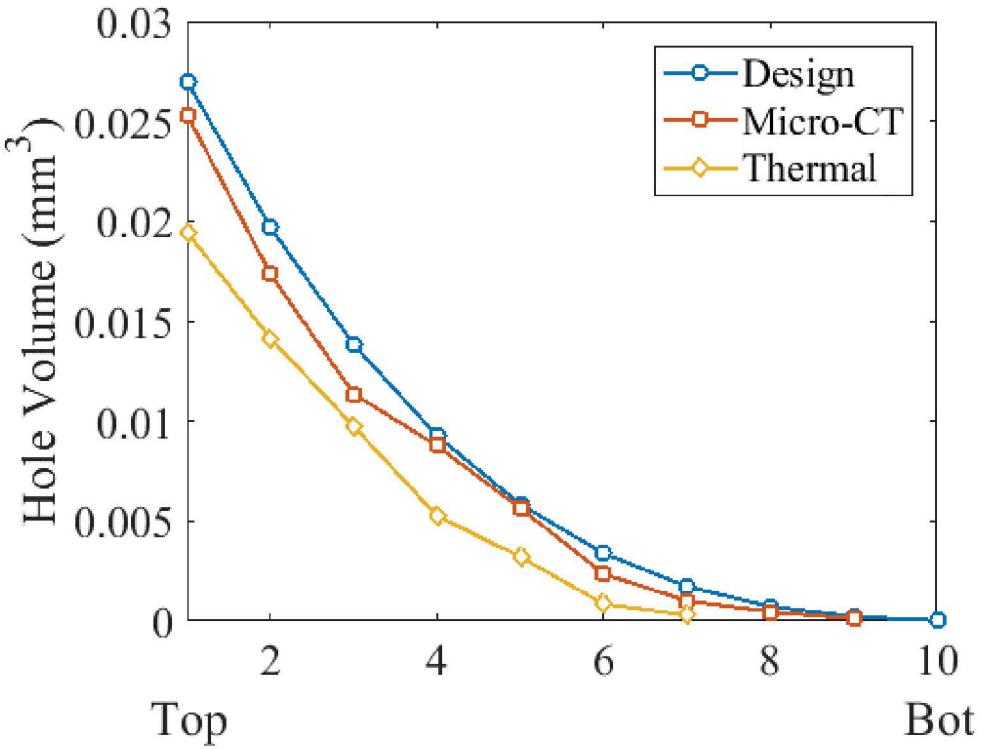


layer-by-layer registration improves overlap at top



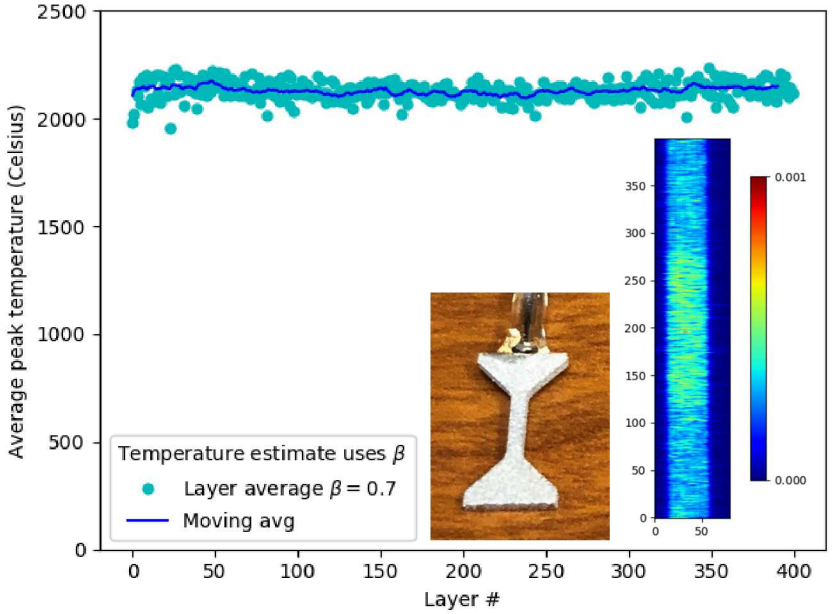


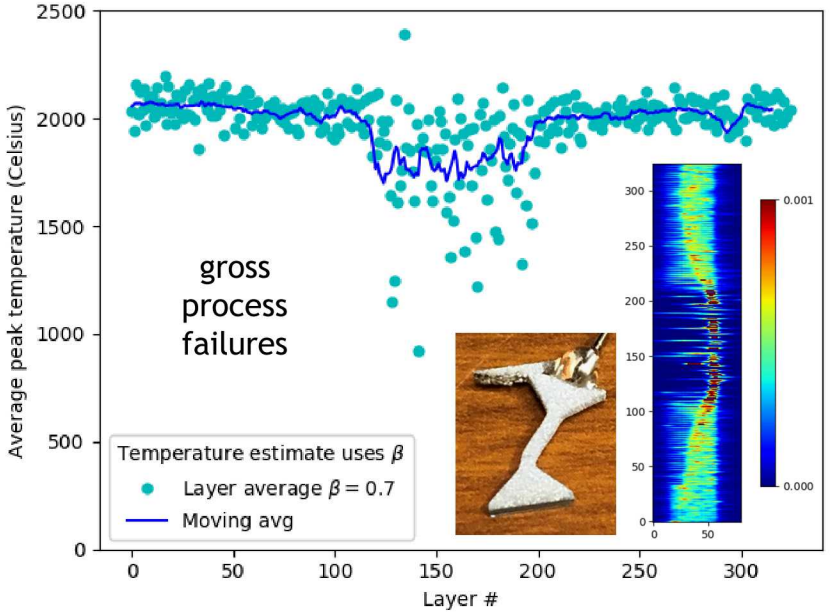
void projections onto thermal layers, red dots scaled to void volume & located at centroid, intentional void (left) & solid material (right)



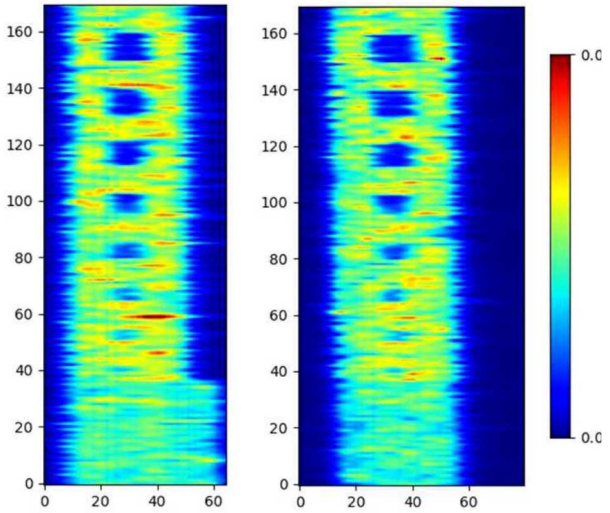
comparison of intentional defect volumes, large voids are relatively easy to identify

Correlating Process Signatures w/Material Structures

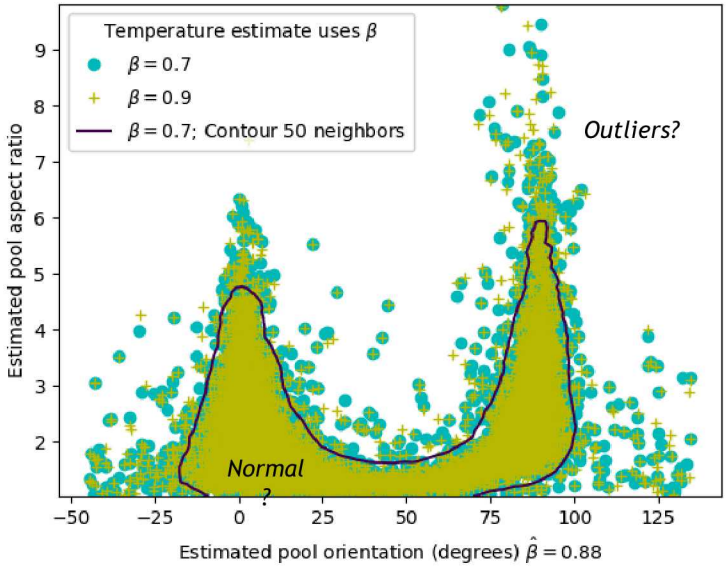


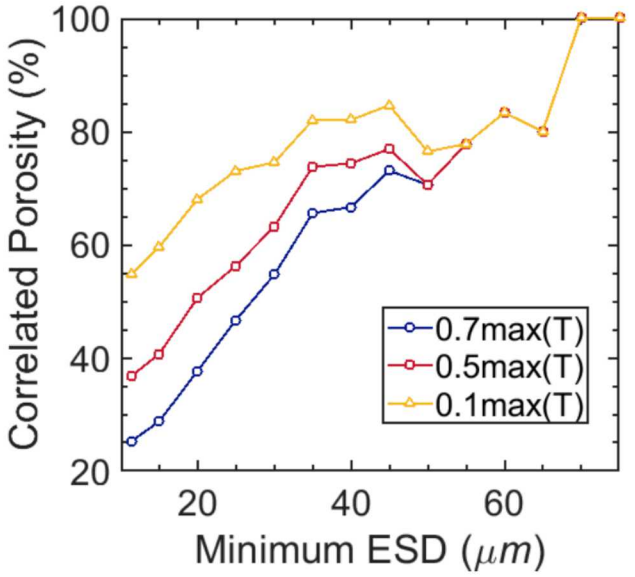


melt pool outliers via ***machine learning*** correlate local void porosity



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



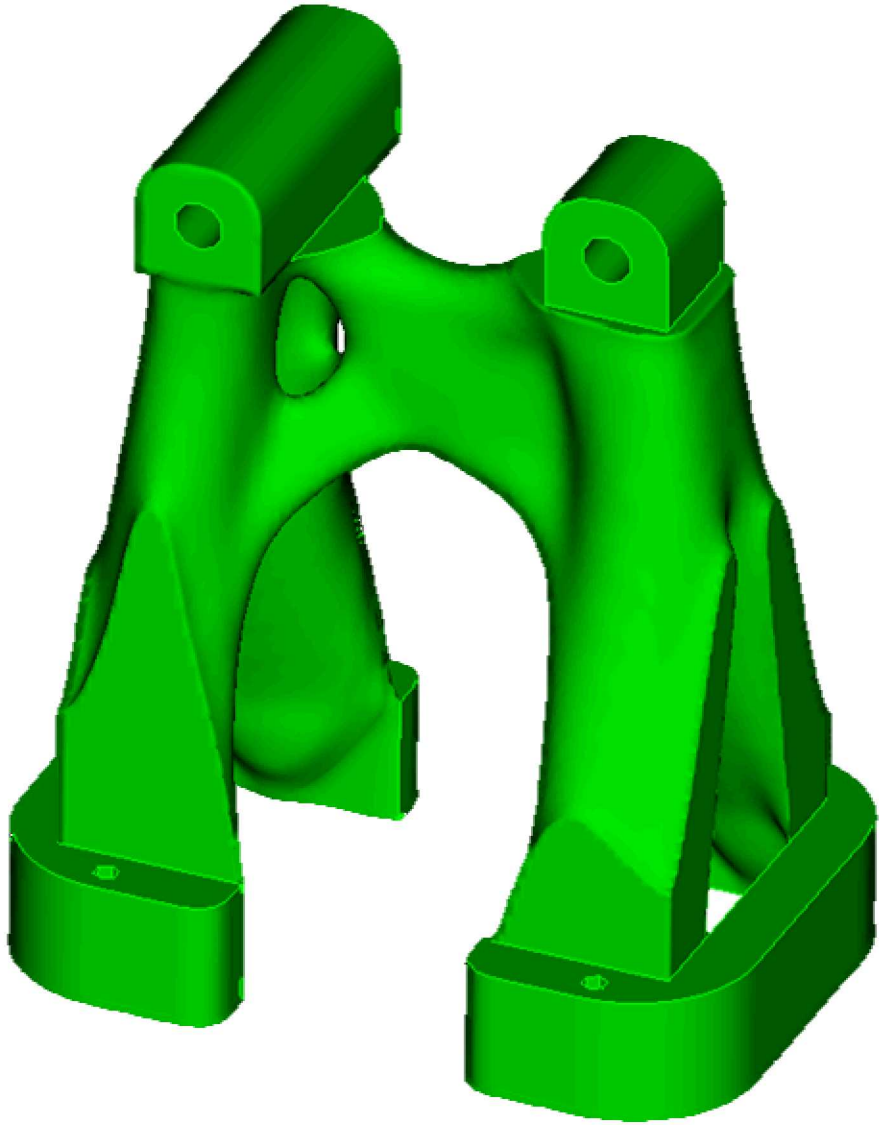


John Mitchell, paper in process

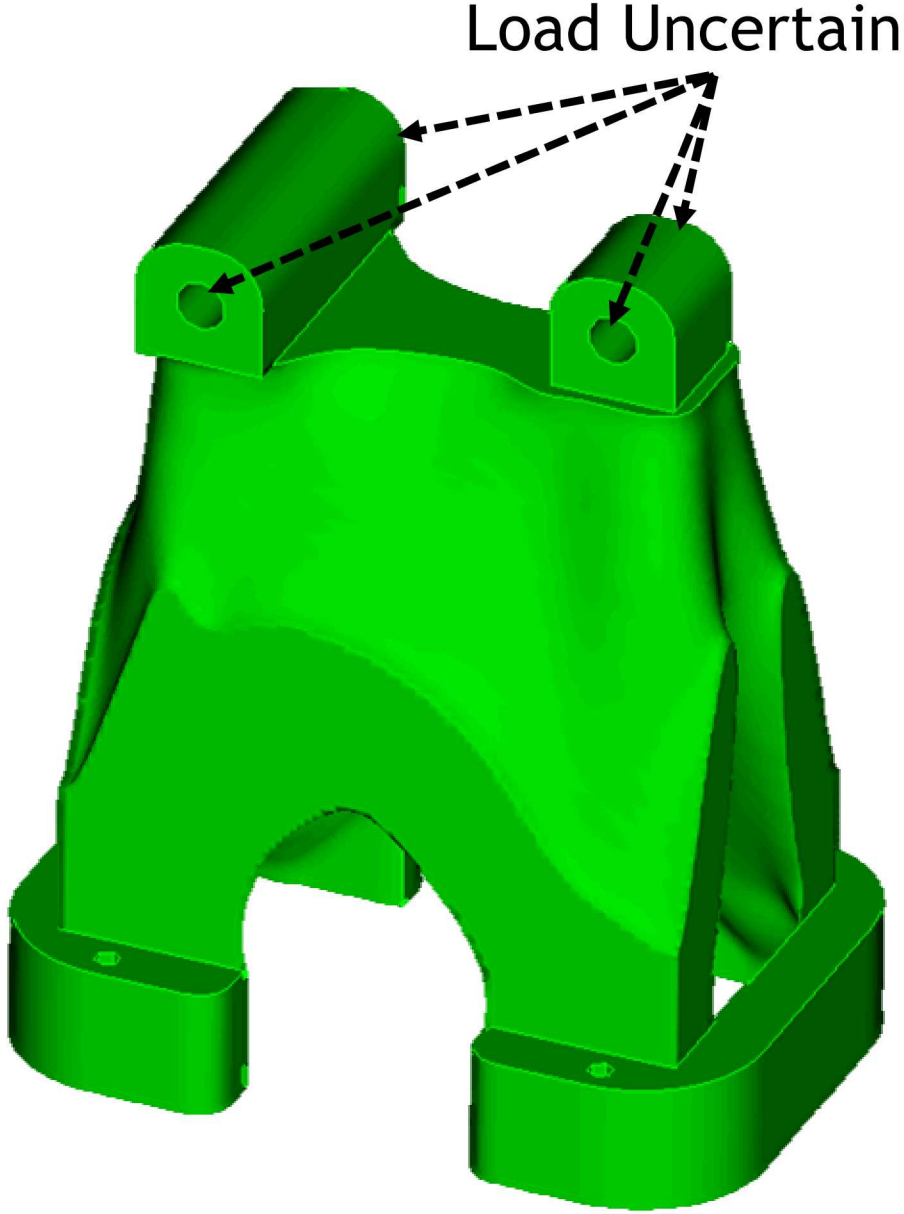
Questions?

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

Uncertainty Awareness



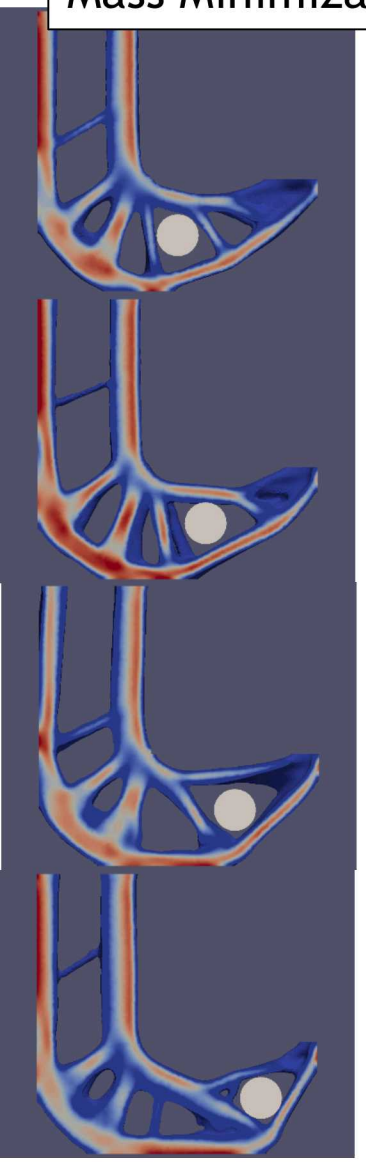
Deterministic



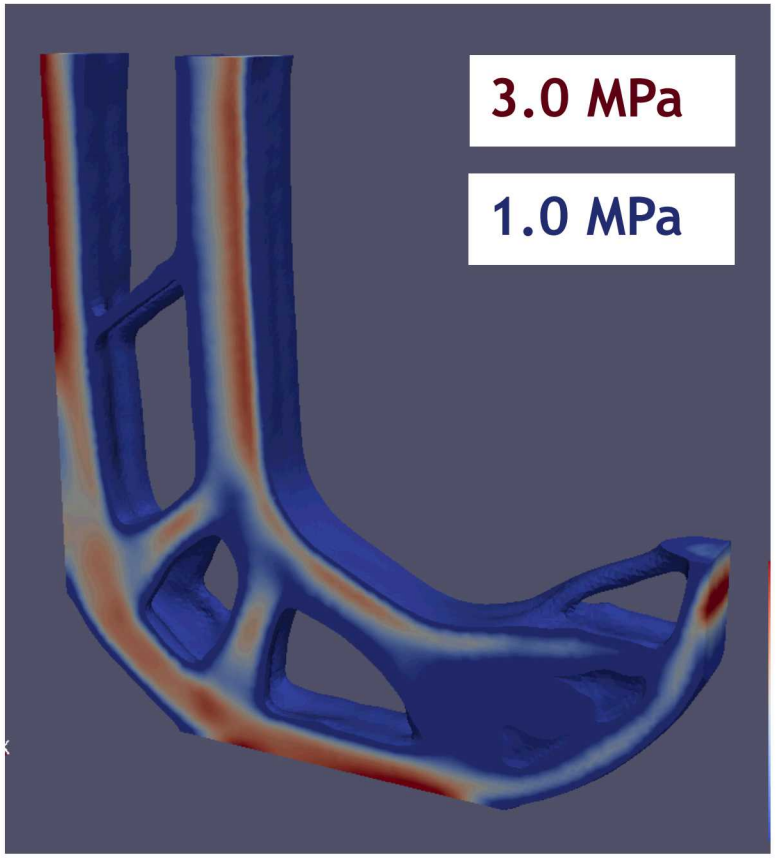
Non-Deterministic

Progress

Mass Minimization



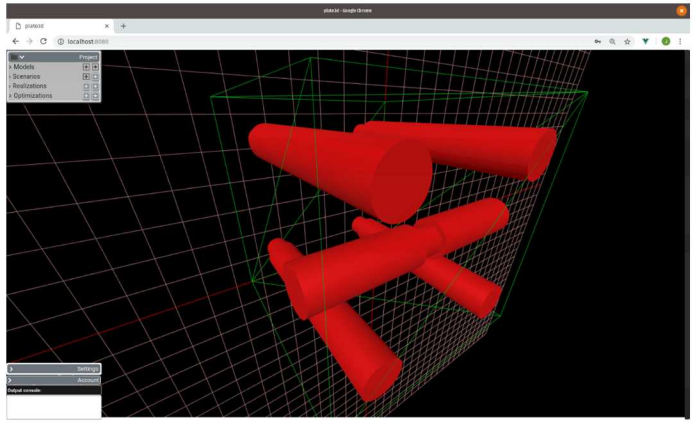
- Objective: Mass
- Scenario: Load w/ Stress Constraint

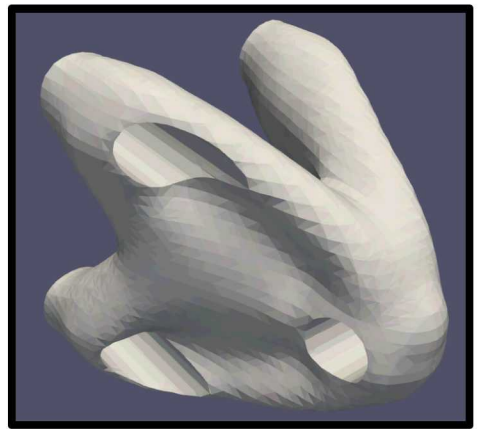


Stress constrained mass minimization formulation courtesy of Prof. Glaucio Paulino, Georgia Tech.

Compliance Minimization

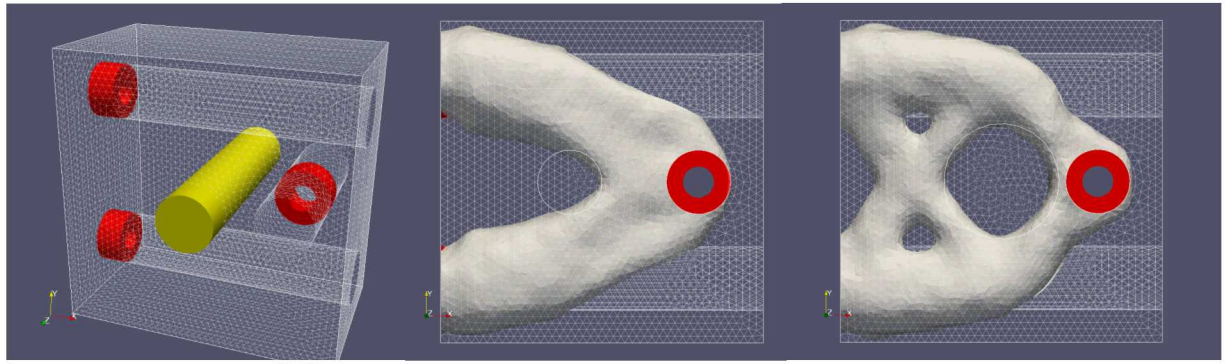
- Objective: Compliance
- Scenario: Multiple mechanical loads





Thermomechanical Compliance

- Objective: Internal Elastic Energy
- Scenario: Load w/ Thermal Strains



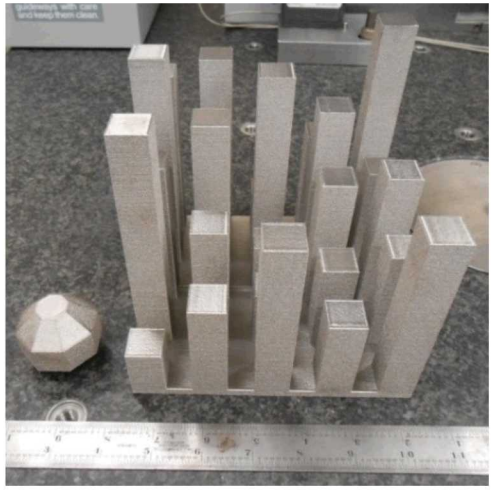
Metrology

Unique challenges for processes, equipment & parts

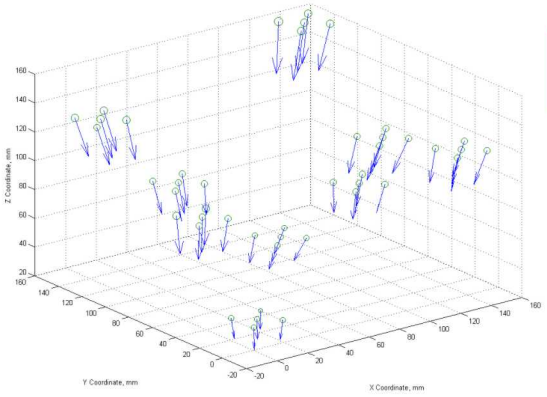
- geometry depends on material, process, machine, orientation, supports, post-processing…
- equipment accuracy generally exceeds process

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

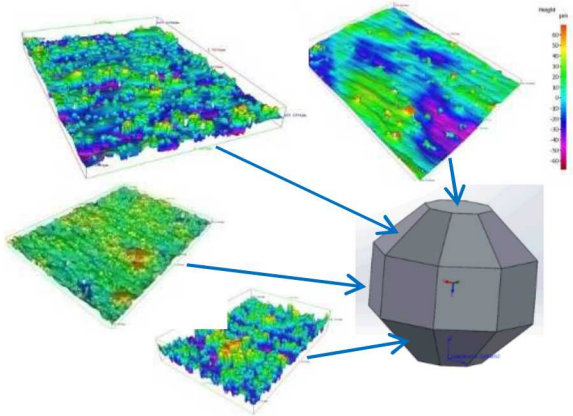


Ti-6Al-4V polyhedron & "Manhattan" artifacts

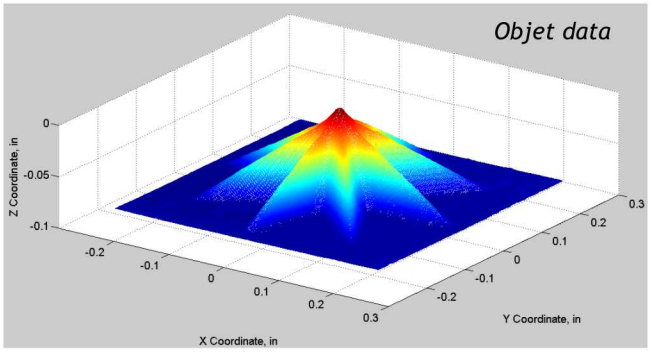


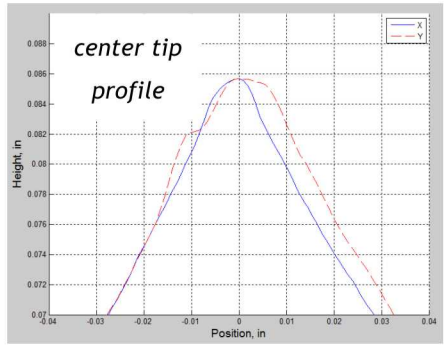
Ti "Manhattan" error map

17-4 PH "death" star



17-4 PH polyhedron texture anisotropy map



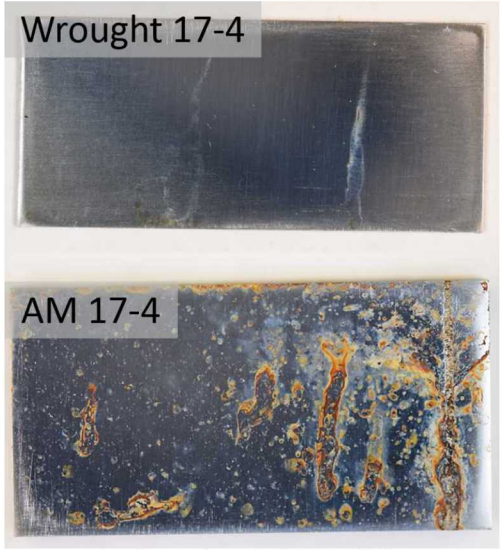


Corrosion

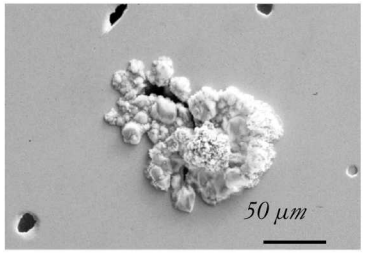
Exploring
- performance of PBF stainless steels relative to conventional materials
- linkages to processing-microstructure

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

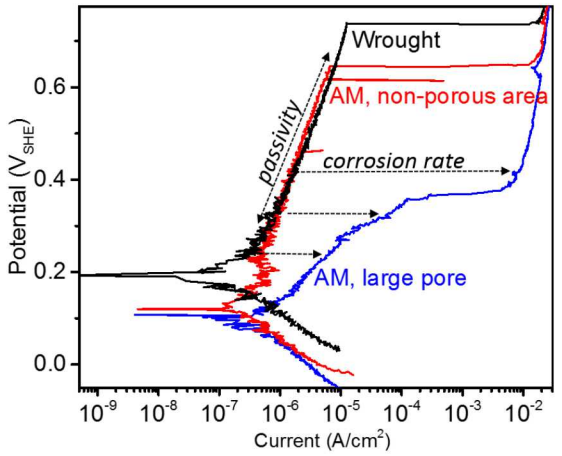
Underway
- performance characterization of 304L and 316L
- impact of varied process conditions & surface finish on passivity



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

Rosenthal Model

Predicts heat distribution from a moving heat source during welding

- Provides an estimated melt geometry

$$T_f - T_0 = \frac{q}{2\pi kR} e^{-\frac{v(w+R)}{2\alpha}}$$

- Modified ("Prediction of lack-of-fusion porosity for powder bed fusion" Tang et al)

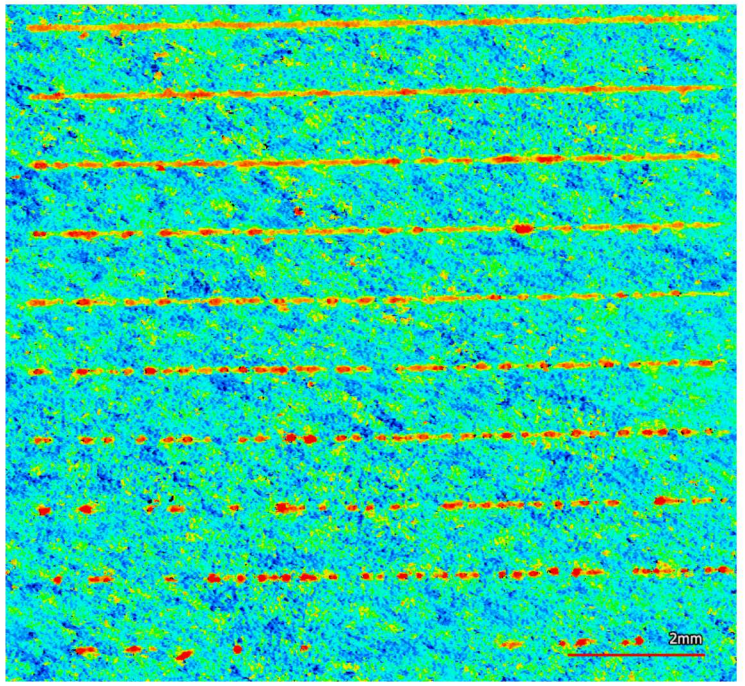
$$W = 2\sqrt{\frac{2q}{e\pi\rho C_p(T_f - T_0)v}}$$

- W – width of melt pool
- q – laser power * absorptivity of material
- v – laser velocity
- T_f – melting temperature

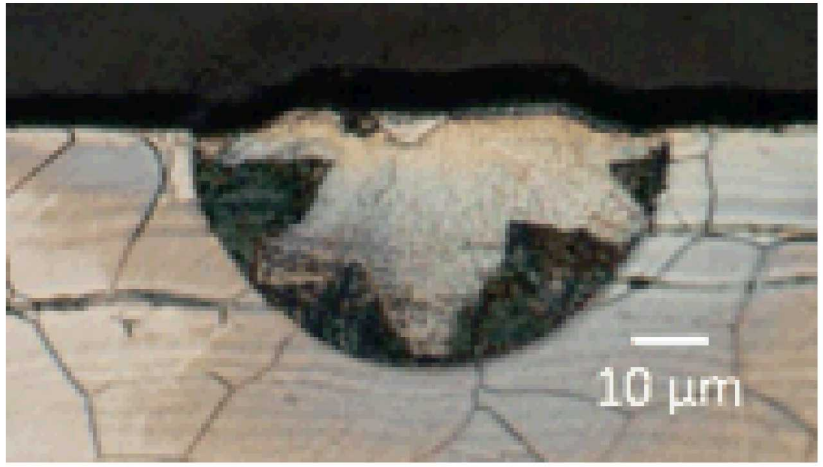
Line Scans

Substrates: bare plate, powder layer on 20 layer AM pad
- 60 lines on each substrate 1.0 cm long

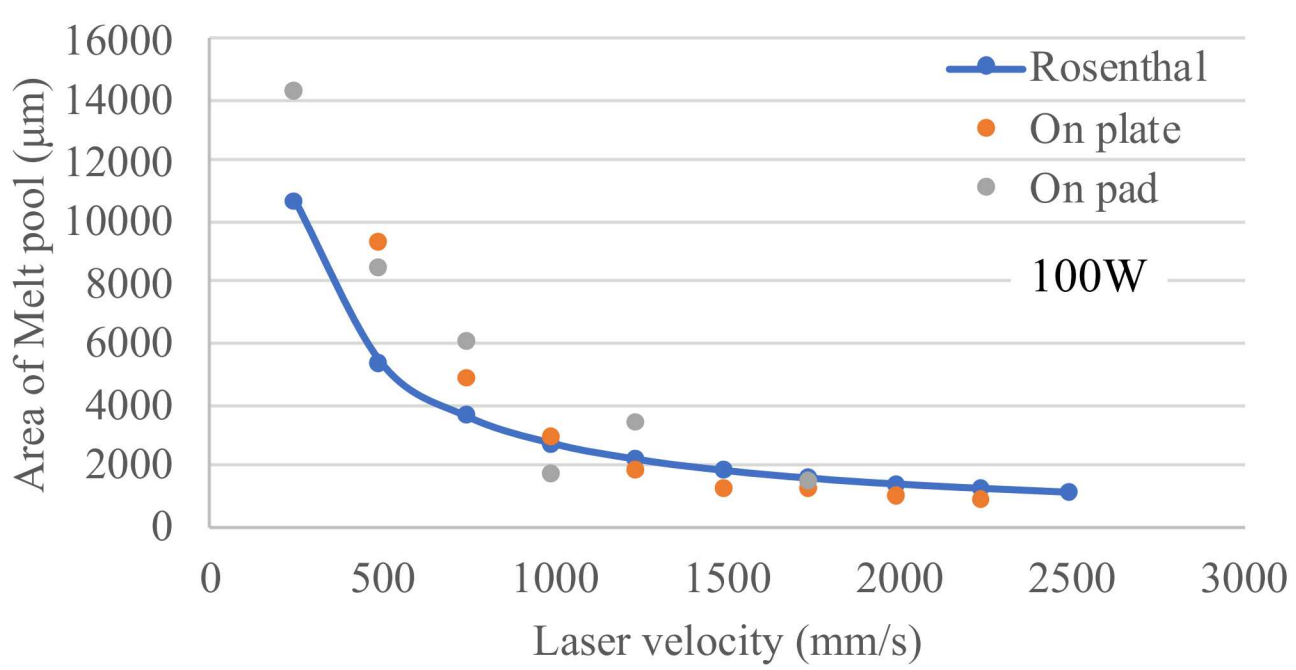
Establish relevance of simple Rosenthal model
- capturing melt pool geometry via metallography
- useful to define nominal process boundaries



100 W, 250 to 2500 mm/s on pad

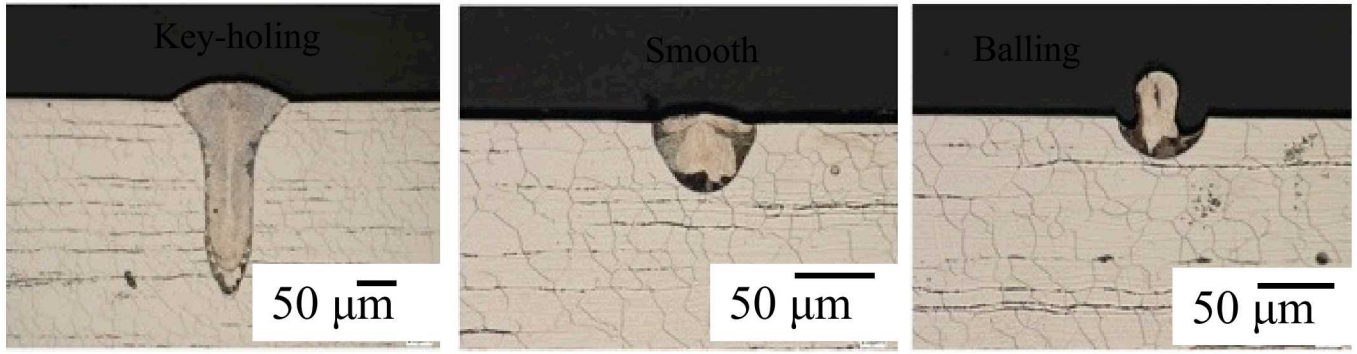


melt pool on plate, 100W, 1500 mm/s

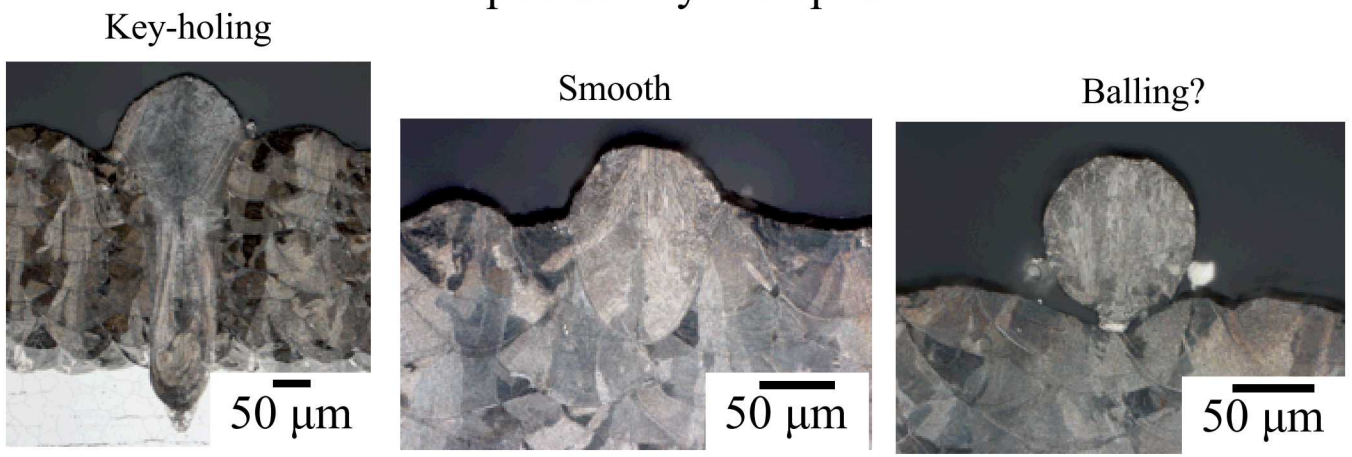


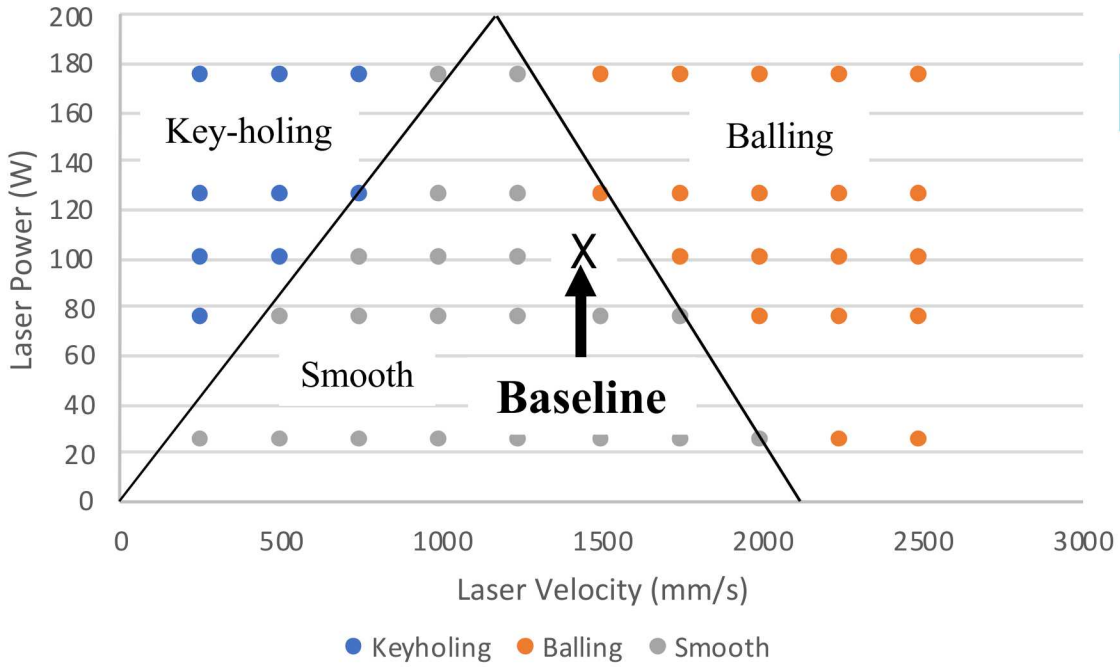
Line Scans: Plate vs. Powder Layer on Pad

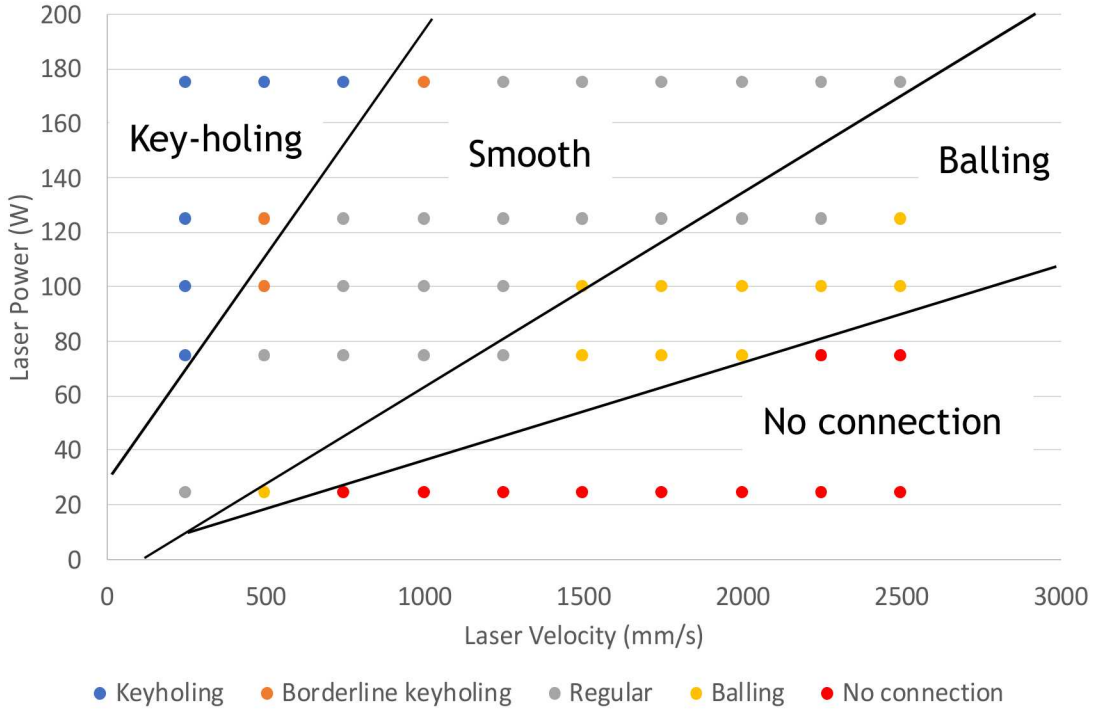
on plate



powder layer on pad

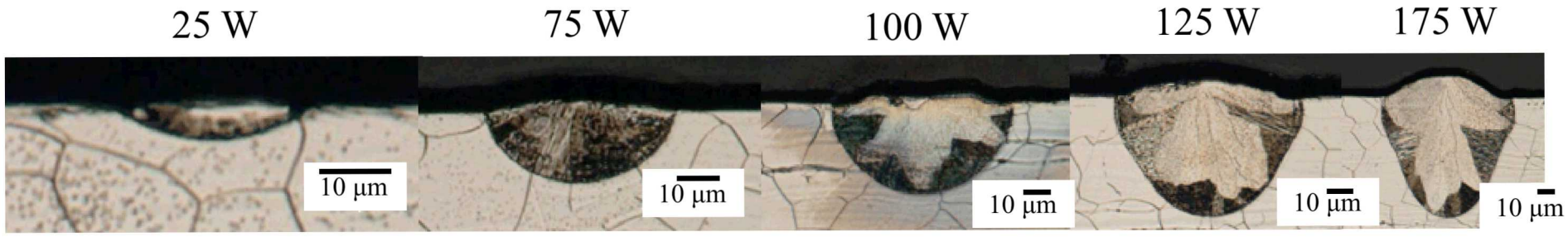




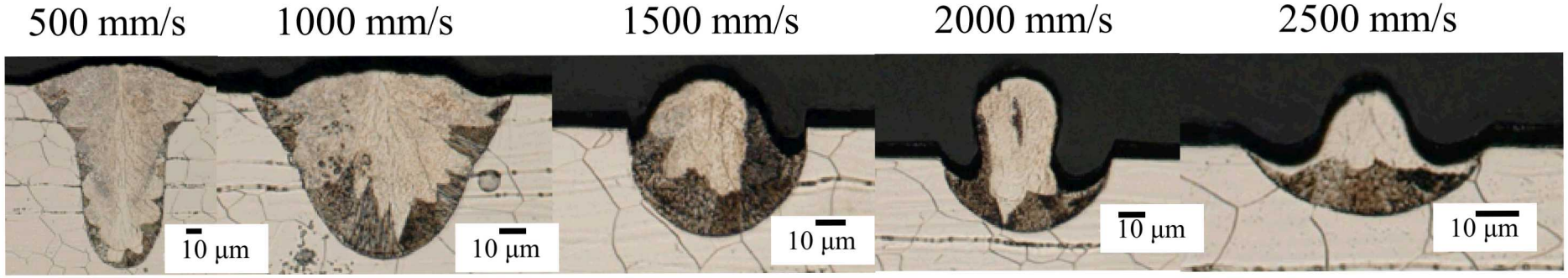


Experimental Results – Line Scans on Plate

1500 mm/s Velocity



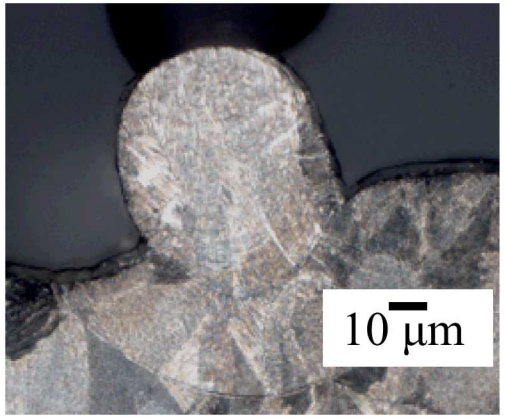
125 W Power



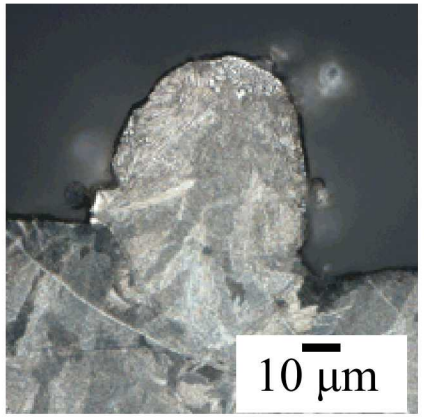
Experimental Results – Line Scans on Powder on AM Pad

1500 mm/s Velocity

125 W

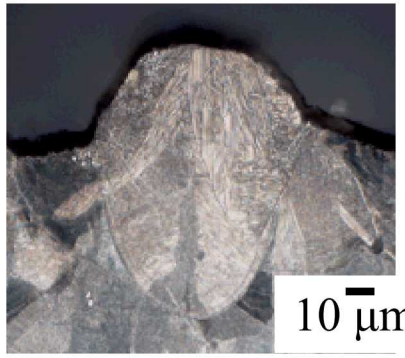


175 W

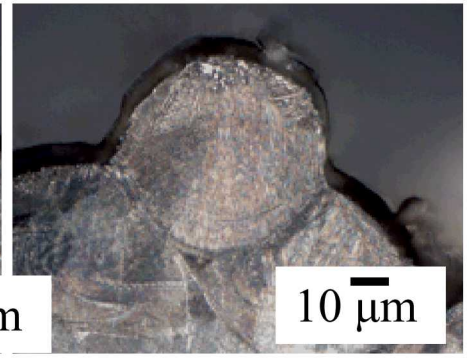


125 W Power

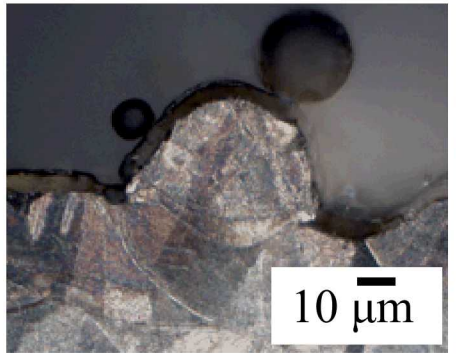
500 mm/s



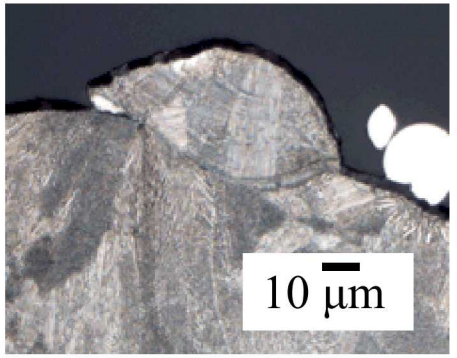
1000 mm/s



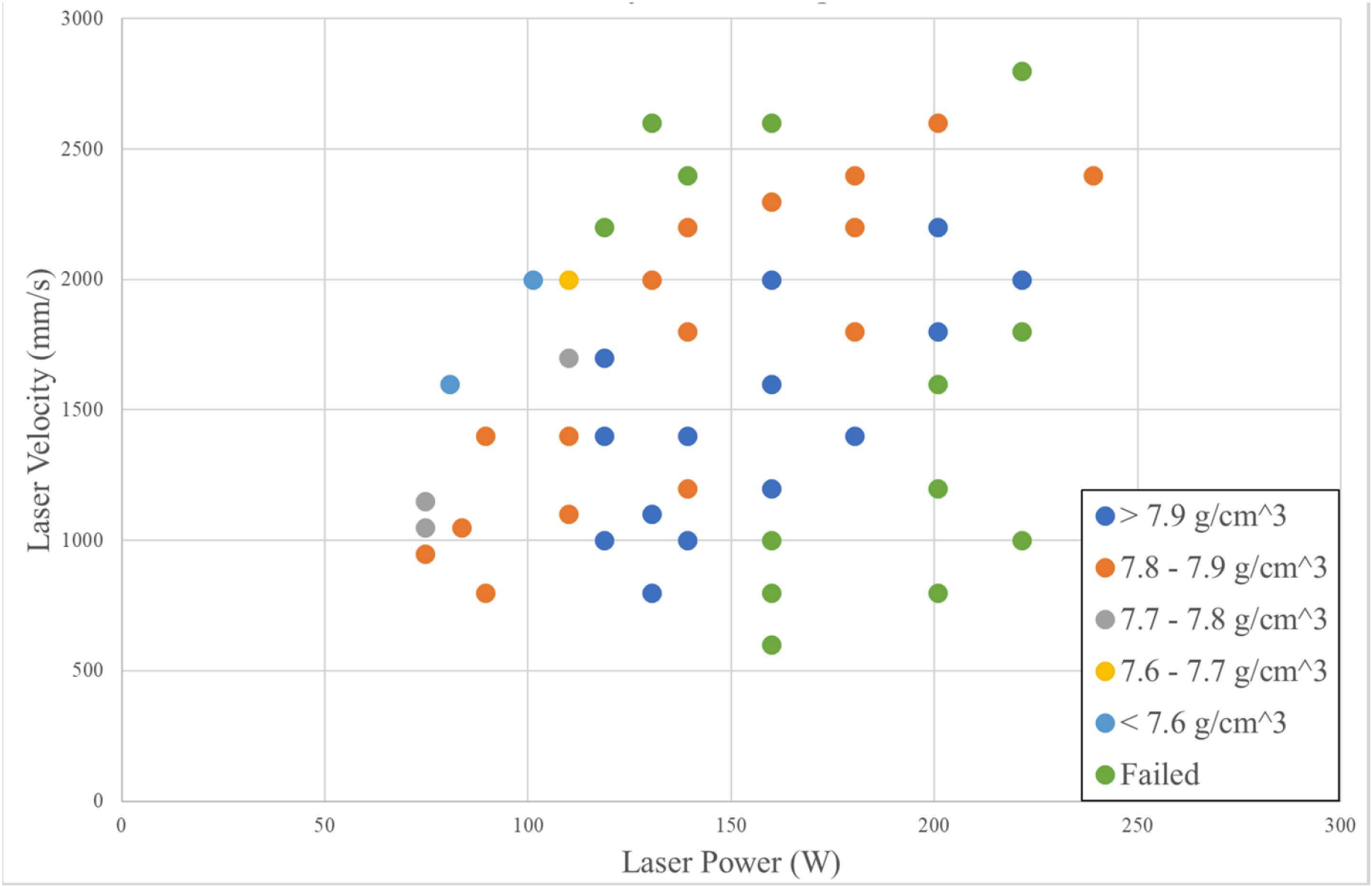
1500 mm/s



2000 mm/s



HTT Sample Density Map

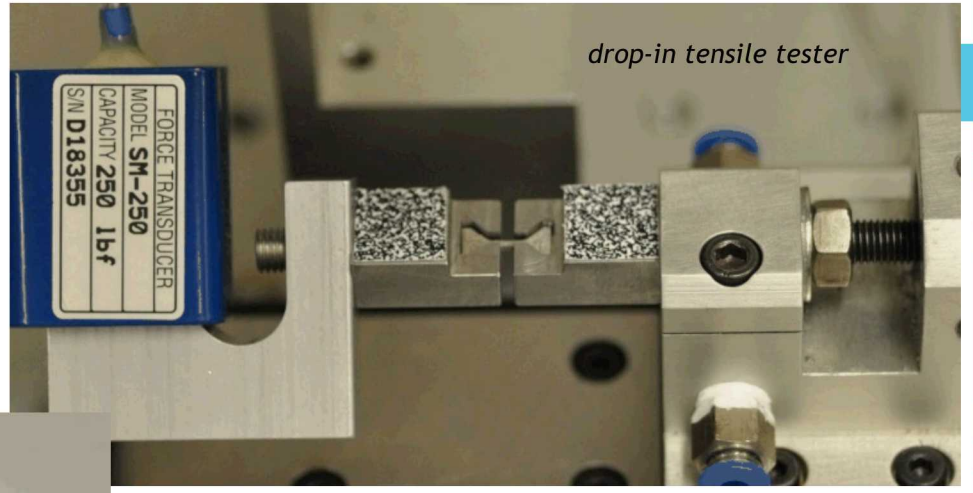


17-4PH Inter-Build Study

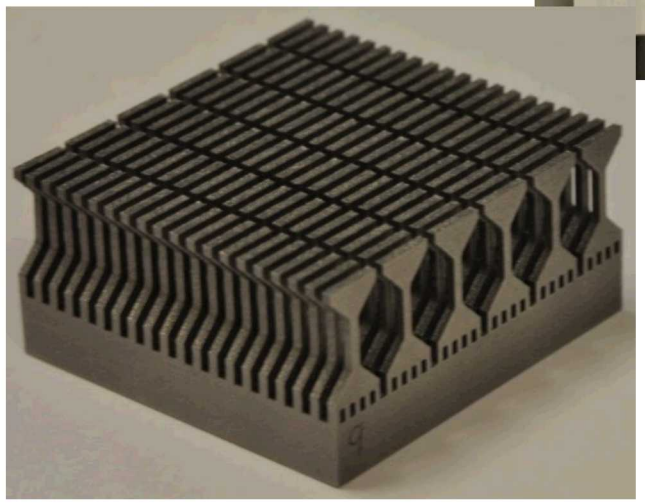
Exploring as alternate to 304L
- higher strength w/multiple strengthening mechanisms

Monolithic build w/110 dogbones
- custom design per ASTM
- external vendor w/constant process
  - Concept Laser M2
- SHT + H900 HT @ Sandia

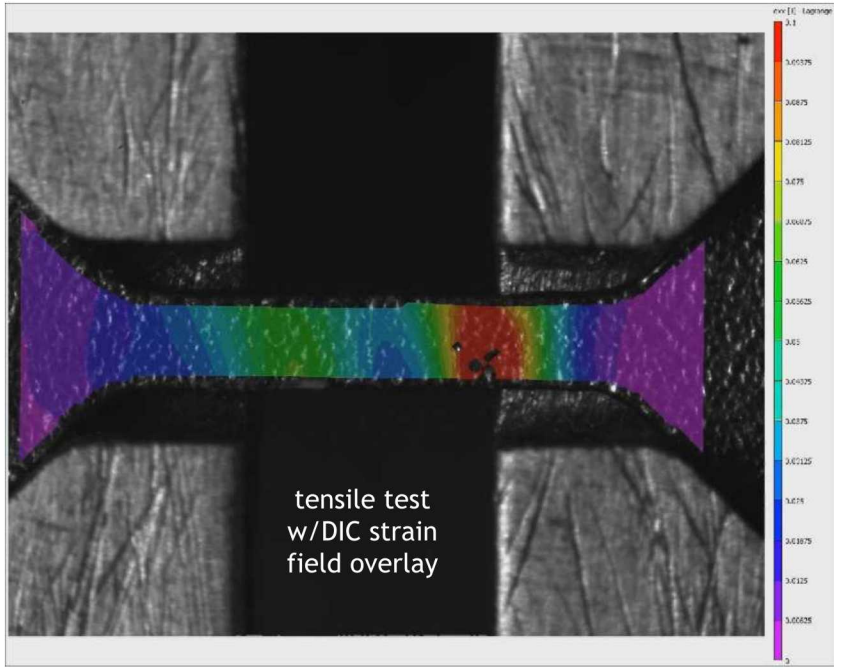
High-throughput testing
- digital image correlation (DIC)
- custom dogbone per ASTM
- necessary to rapidly capture material distributions
- applicable for the lab & production



drop-in tensile tester



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


tensile test w/DIC strain field overlay

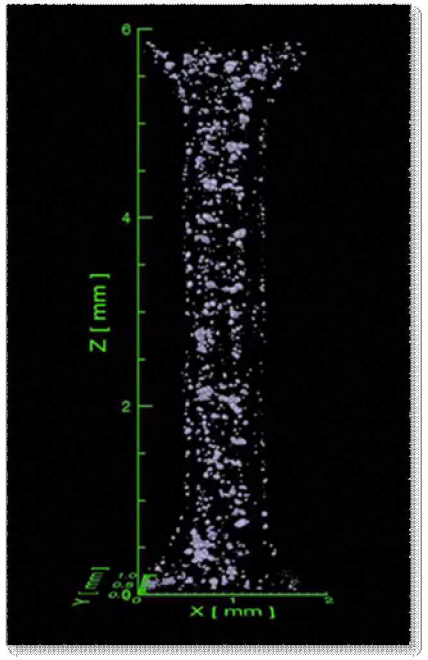
Salzbrenner, B., **Journal of Materials Processing Technology**, 2017; Boyce, B., **Advanced Engineering Materials**, 2017

Material Characterization

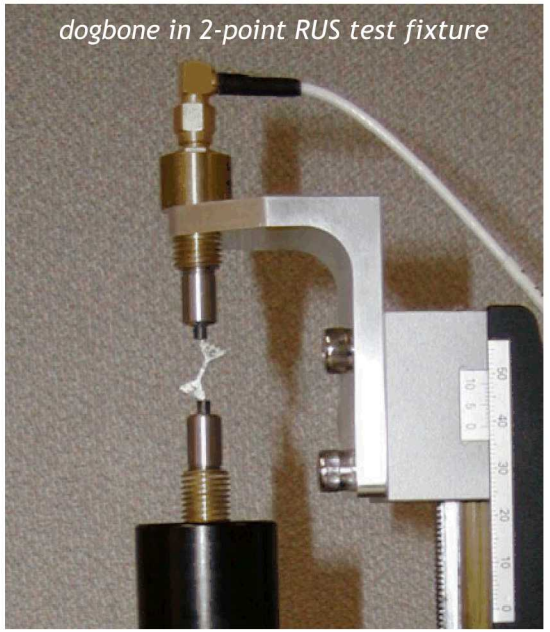
NDE before testing
- *detect defects, performance correlations*
- density (Archimedes)
- resonant ultrasound spectroscopy (RUS)
- optical surface measurements
- computed tomography (CT)

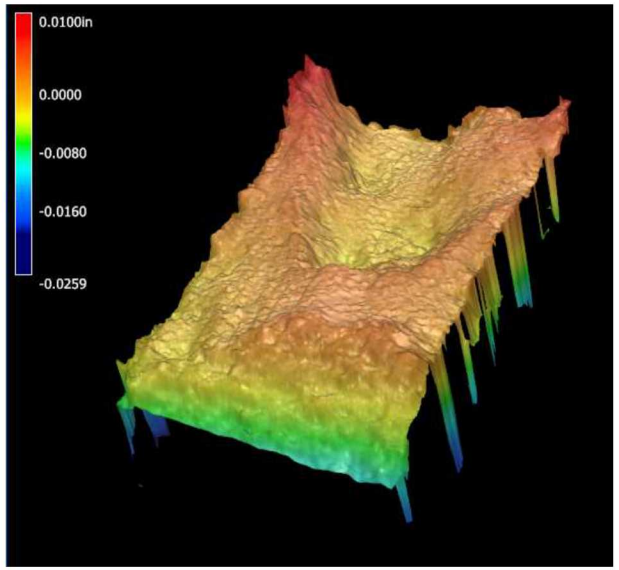
Post mortem after testing
- *inform performance & failure mechanisms*
- fractography
- metallography
- composition
- XRD

Do reasonable defect signatures exist which tie to part performance?



17-4PH dogbone porosity


dogbone in 2-point RUS test fixture



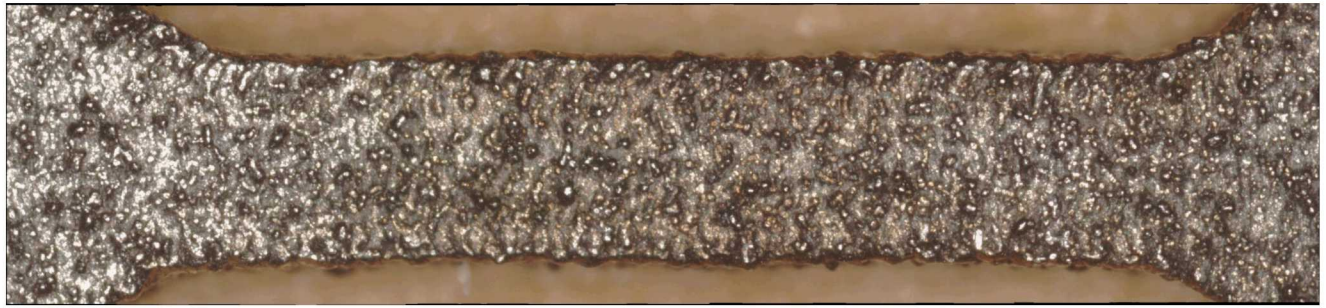
fracture surface

Implicit Part Correlations

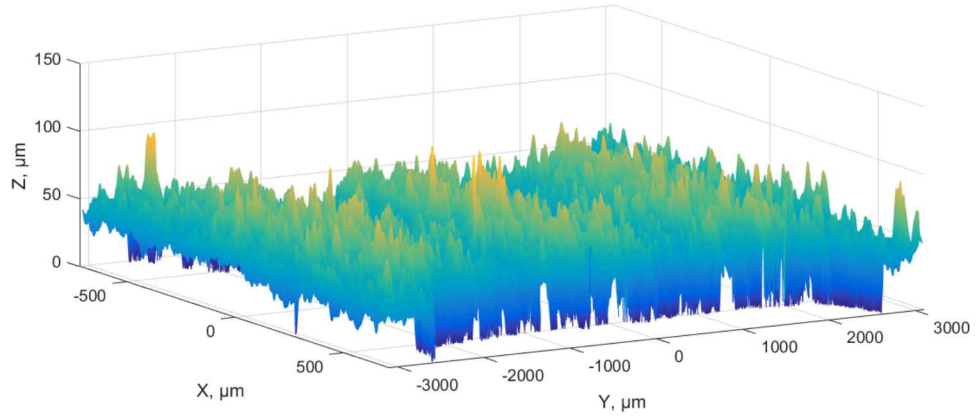
Archimedes density

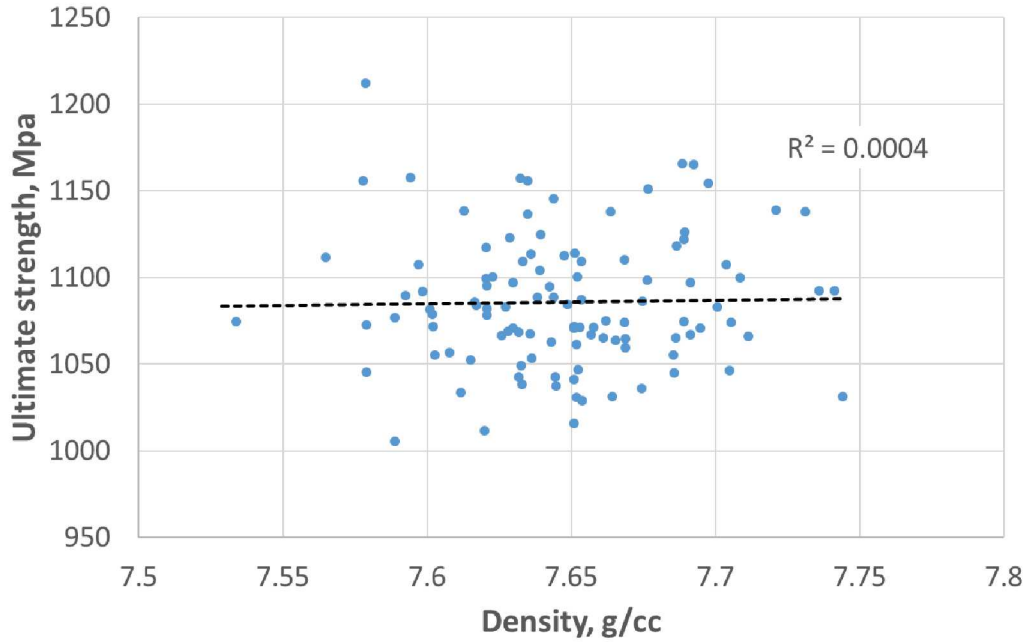
Surface finish

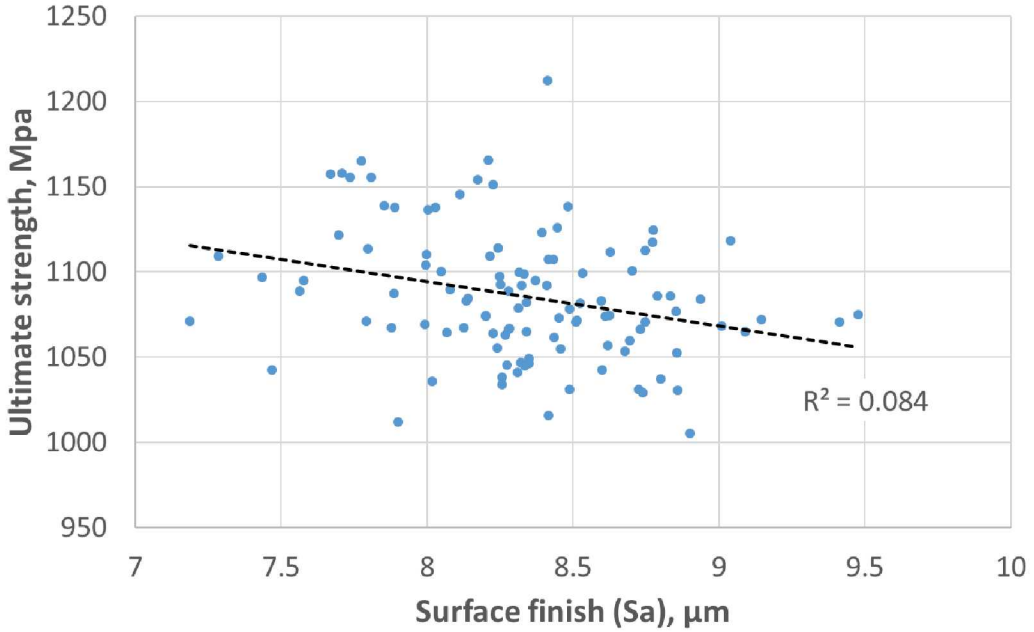
No significant trends observed



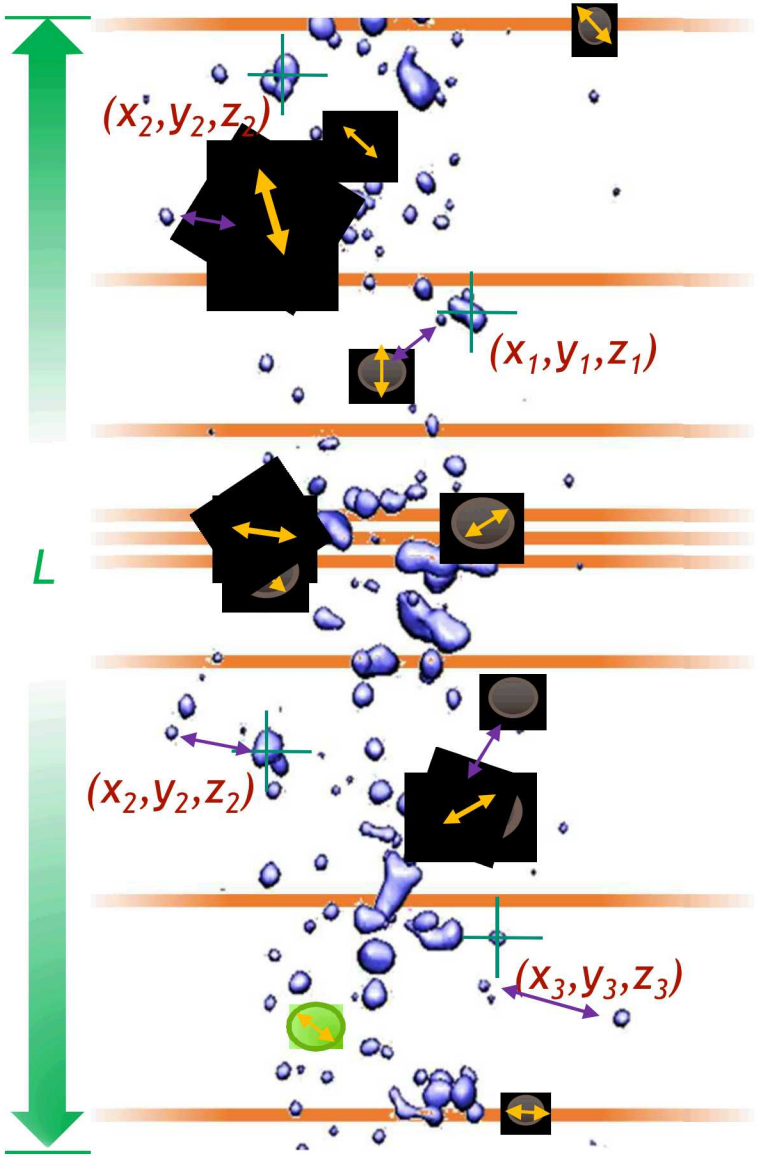
17-4PH dogbone surface roughness







Defect Characterization

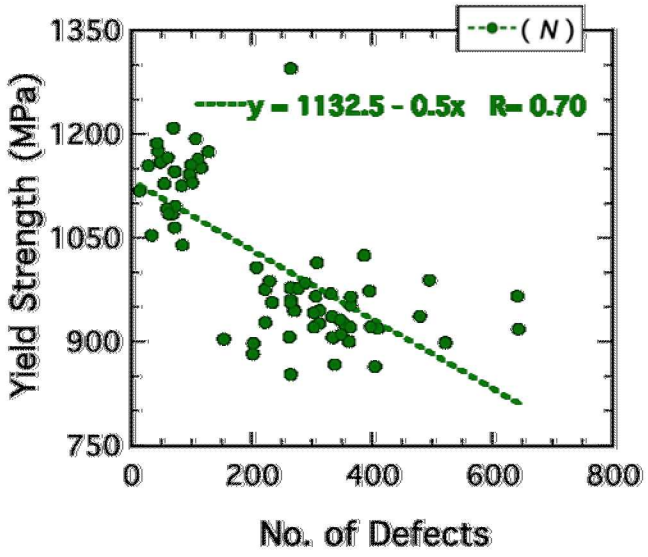


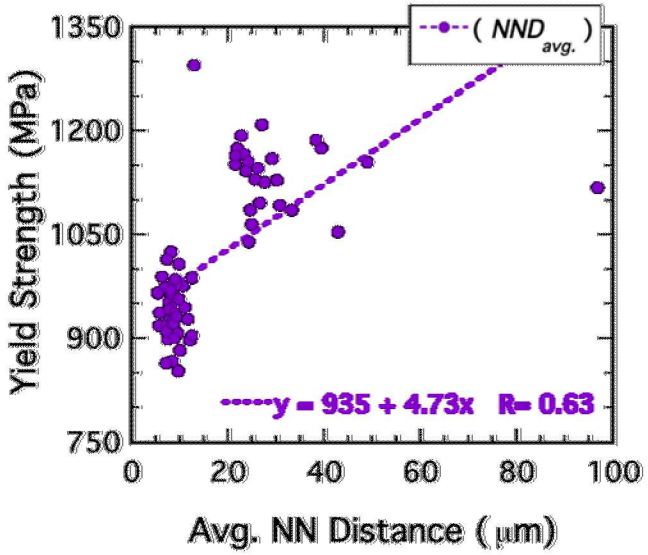
- Total volume of defects (V_{tot})
- Pore volume fraction (V_{fract})
- Spatial location of pores *(x, y, z)*
- Total number of defects *(N)*
- Total defects/length *(N/L)*
- Average defect volume ($V_{avg.}$)*
- Average equivalent spherical diameter ($ESD_{avg.}$)*
- Average cross-sectional area ($CSA_{avg.}$)*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

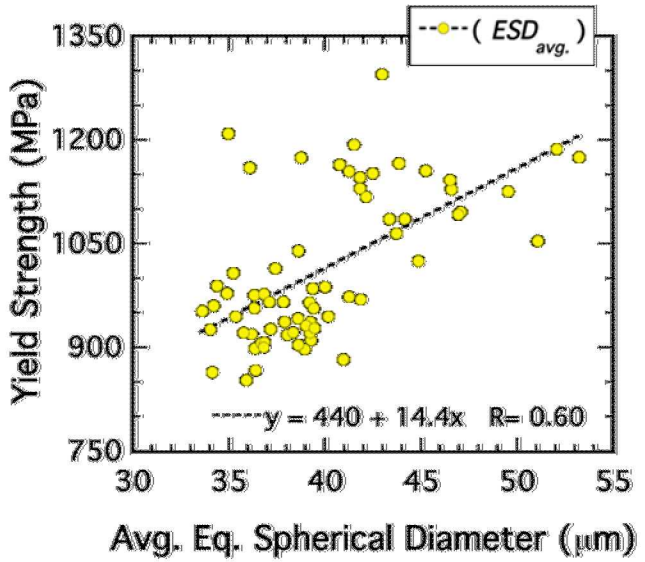
How do we *best* represent the defect populations present?

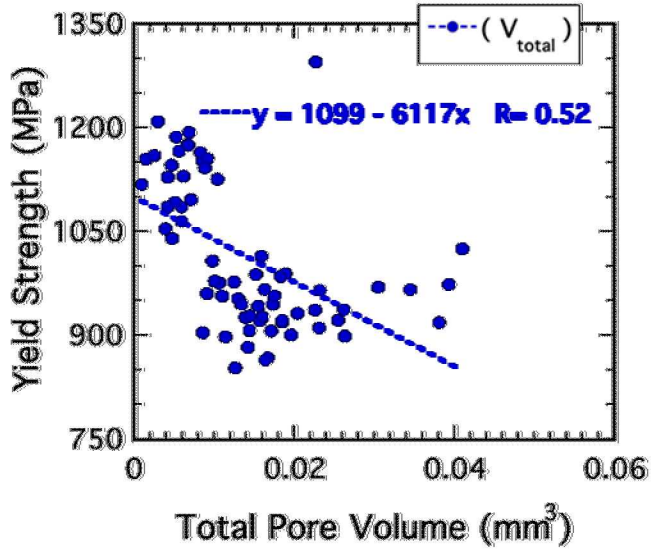
Madison, J., **QNDE**, "Corroborating Tomographic Defect Metrics with Processing Parameters & Mechanical Response in Metal AM", *In press*.

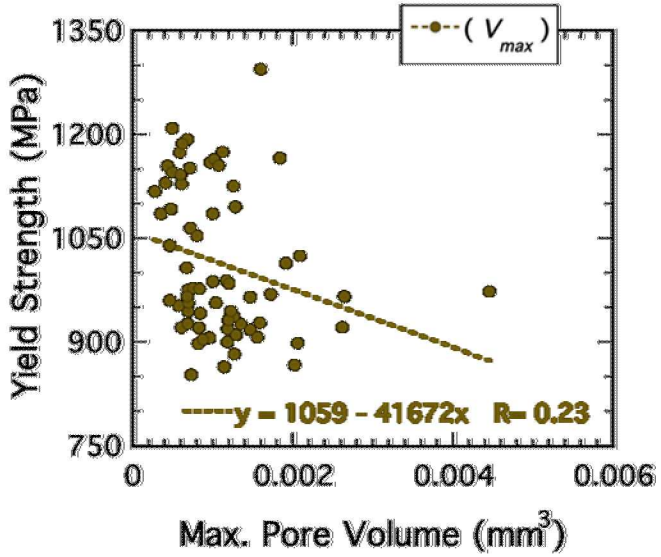
Simple Statistical Correlations Are Inadequate







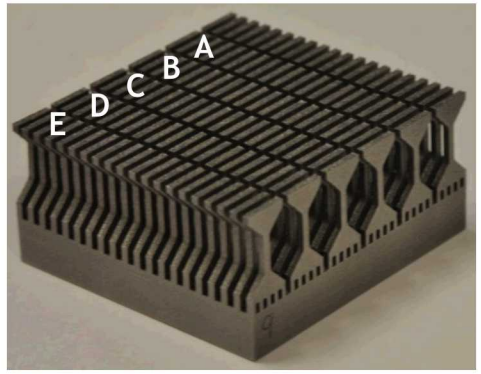




Measure	R^2
No. of Defects	0.50
Avg. NN Distance (mm)	0.40
Avg. ESD (mm)	0.36
Max CSA Redux (mm^2)	0.38
Total Pore Volume (mm^3)	0.27
Avg. Defect Vol. (mm^3)	0.25
Max CSA Redux (%)	0.24
Maximum Pore Size	0.07
Seven factor multivariate regression	0.60

Global Void Projections vs. Performance

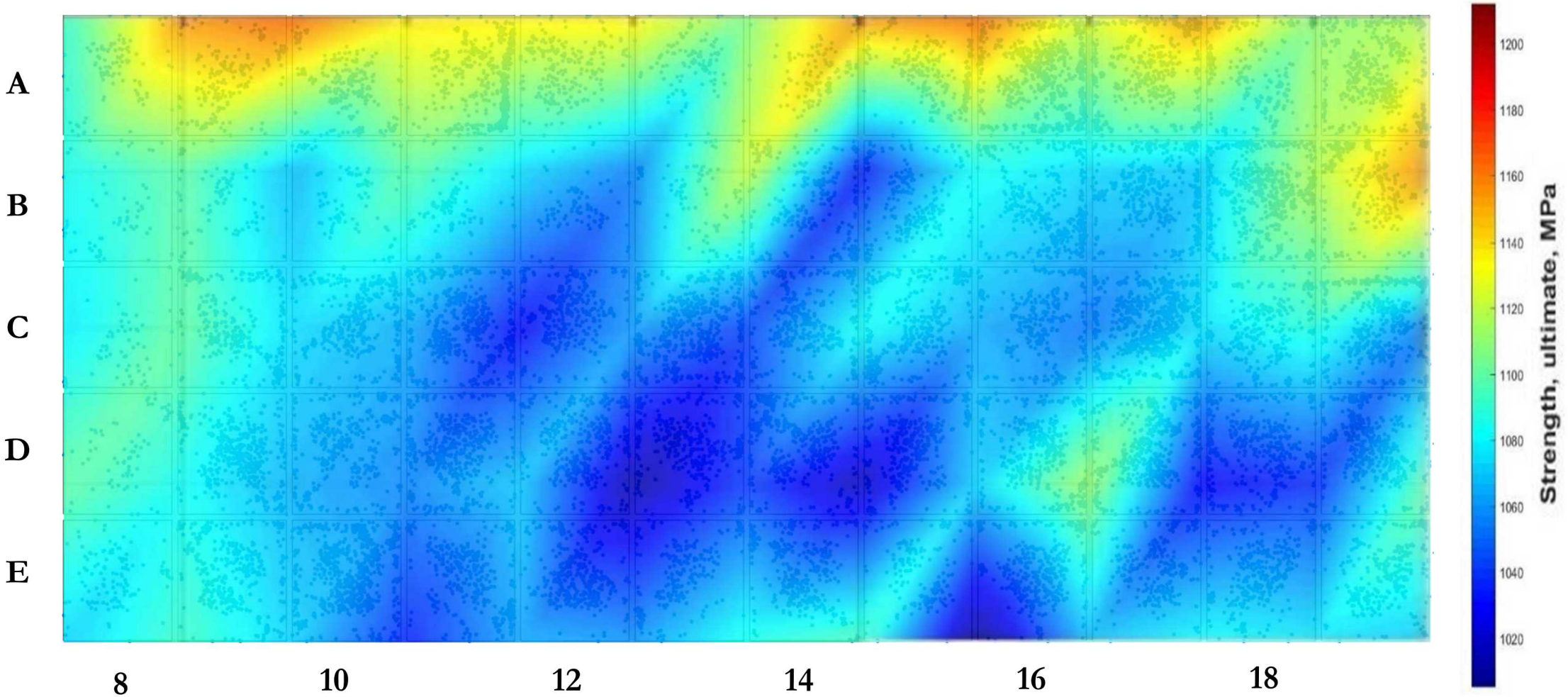
17-4PH high throughput test sample



Reconstruct dogbones into printed array geometry

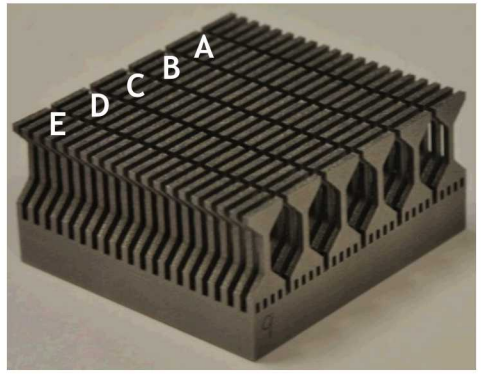
Top down void projection through each gauge section

- squares represents each dogbone in its printed location



Global Void Projections vs. Performance

17-4PH high throughput test sample



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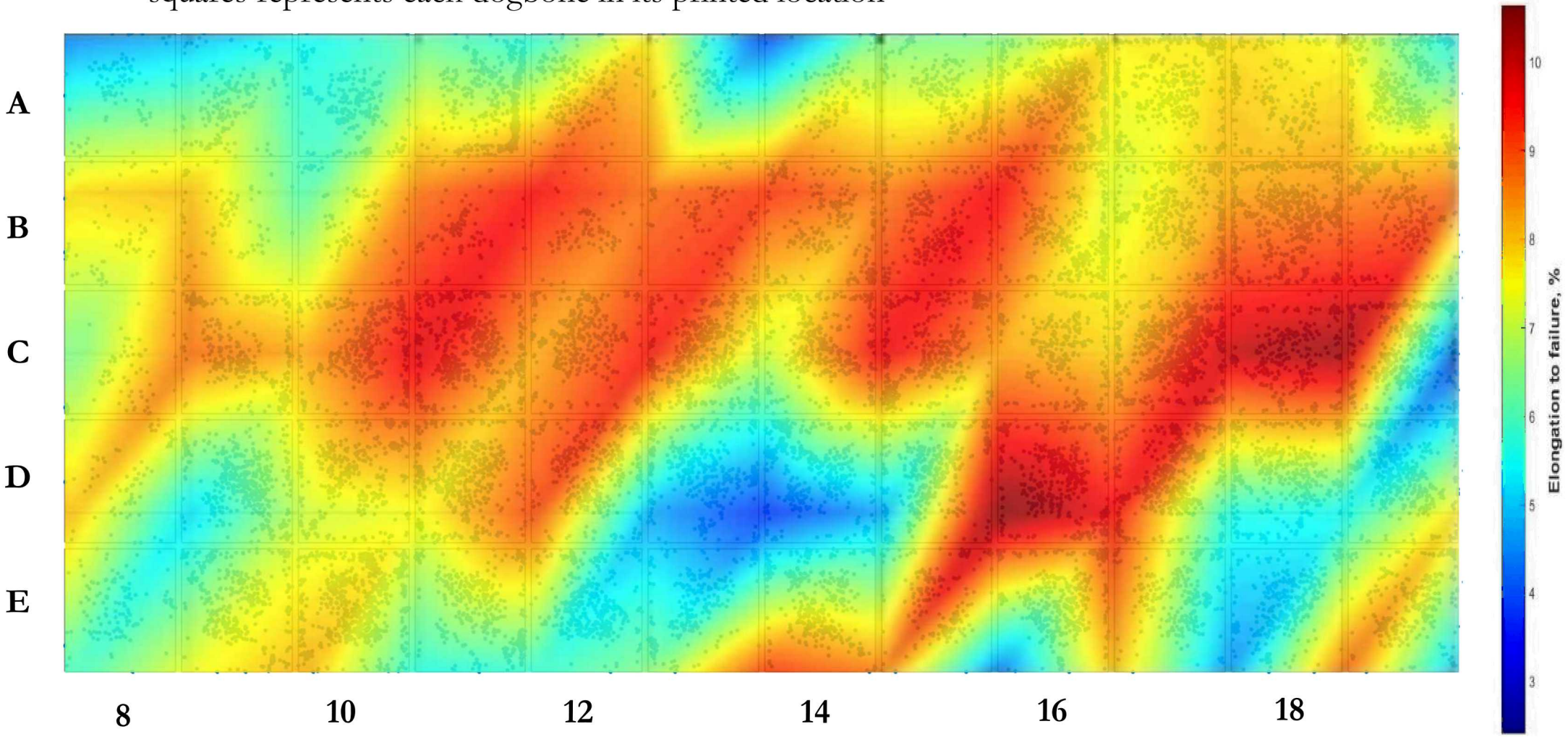
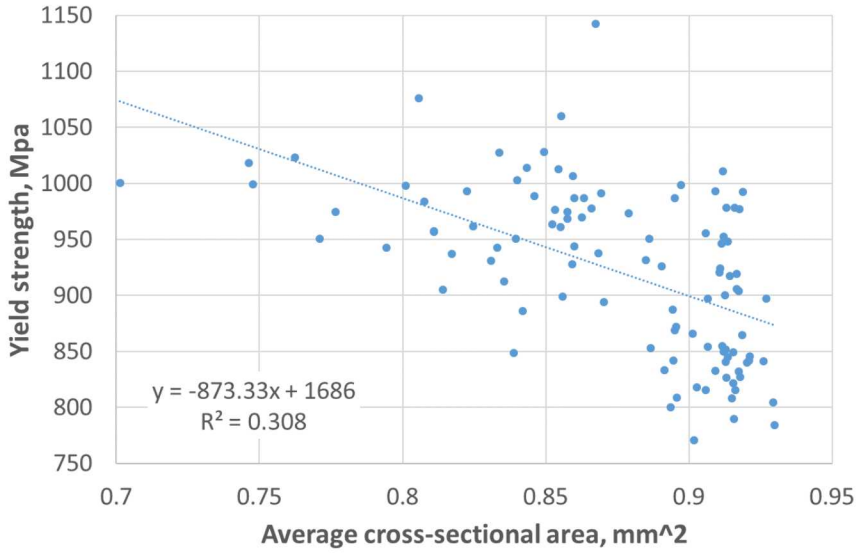


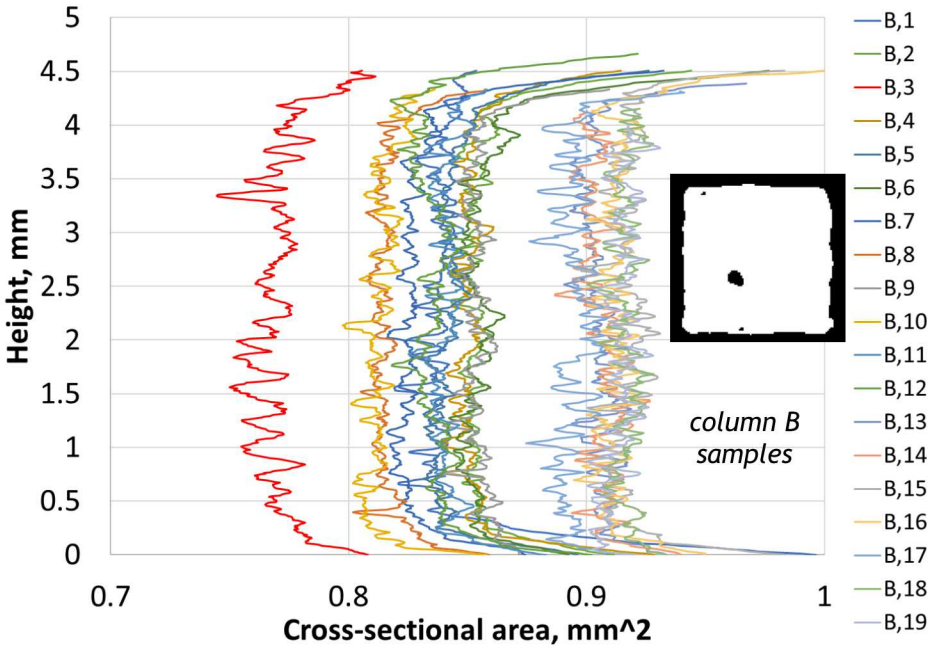
Fracture Location

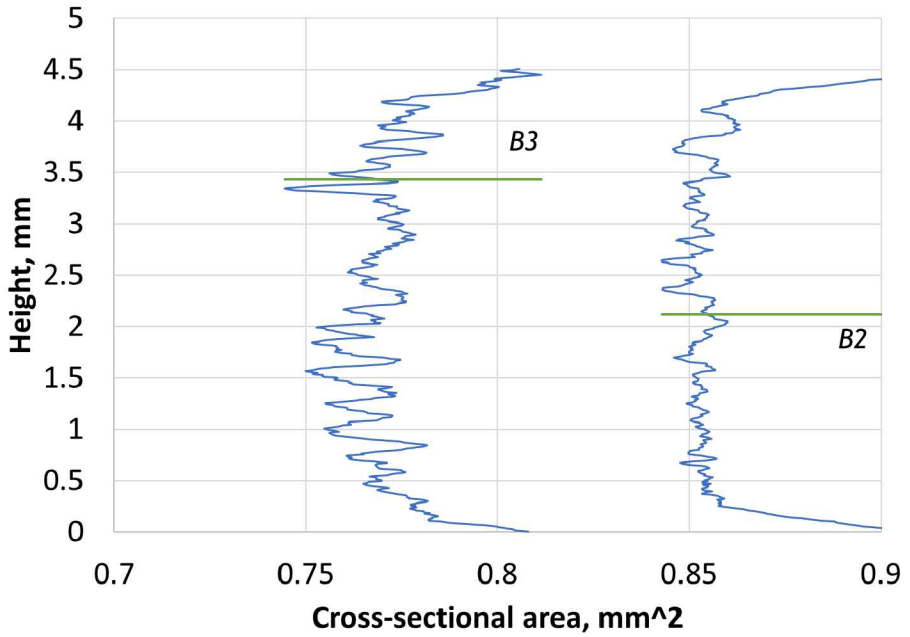
Can forensic trends be identified?

CT data analysis

- calculate cross-section per layer
- gage sections are rough & porous
- fractures can correspond to minimum areas
- general trend remains weak





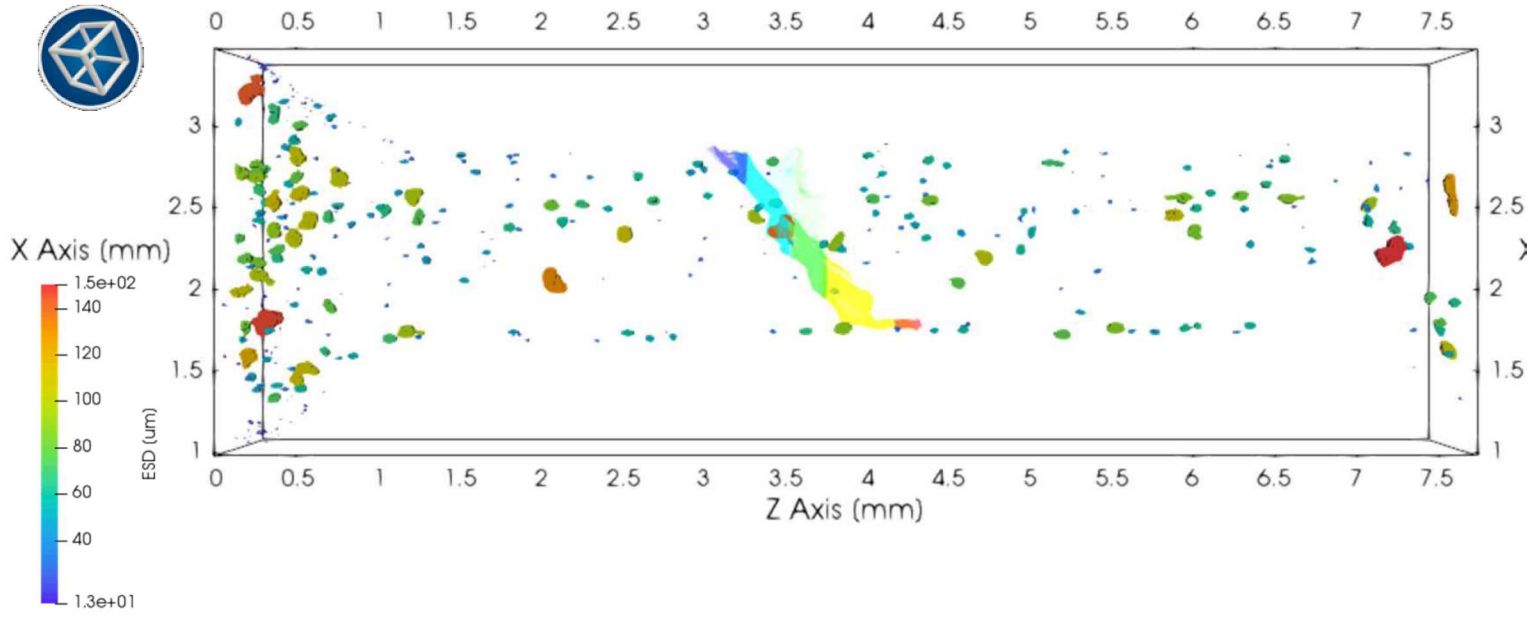


Fractography

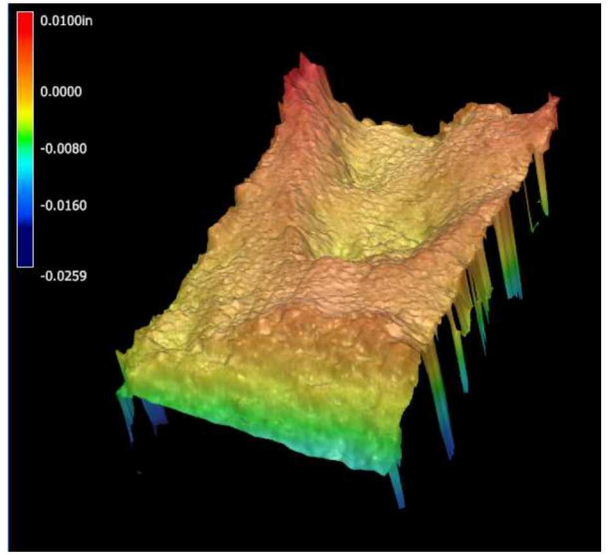
Defect dominated failure observed

Increasing data fidelity & integration

- overlay fracture surface w/porosity map using DREAM.3D
- roughness inhibits registration accuracy
- fracture surface may correlate to large pore



B2, fracture surface optical image by structured light scanning



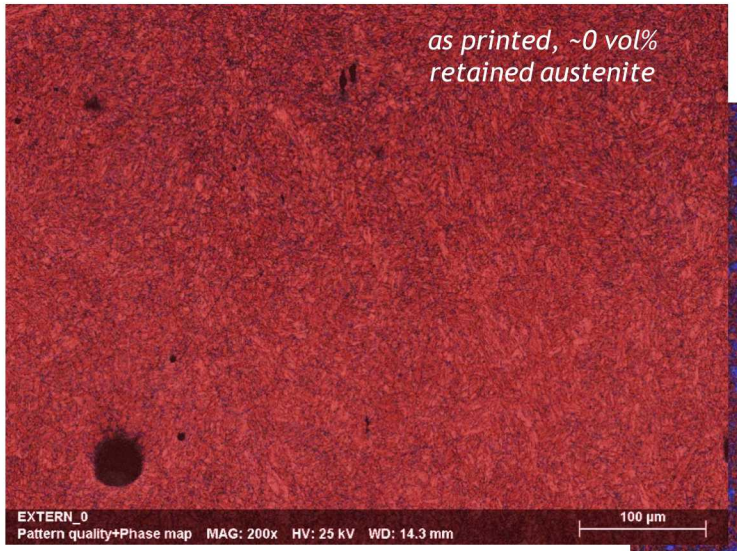
B2, fracture surface topography by structured light scanning

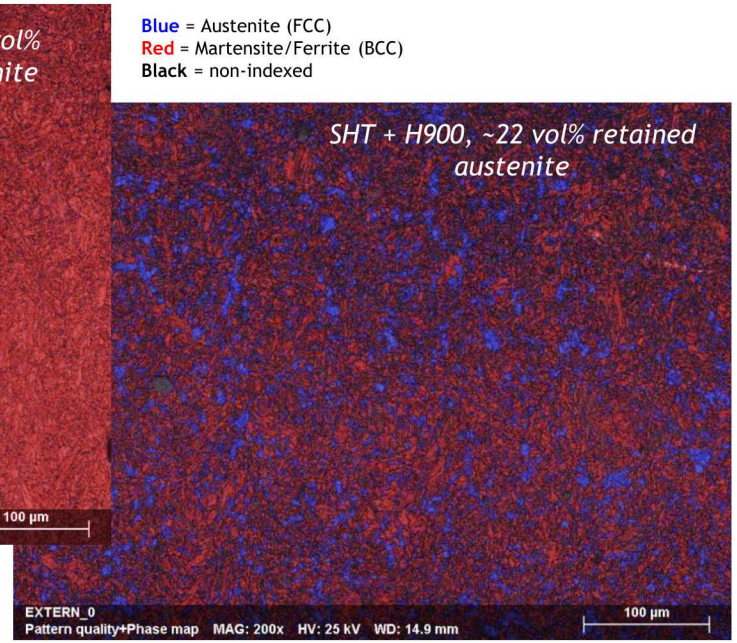
Microstructure Examination

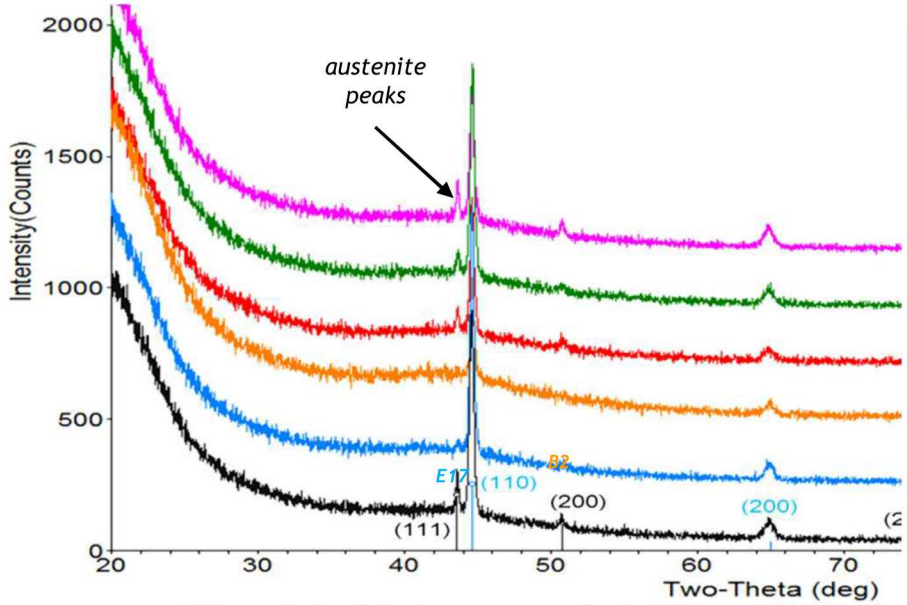
Compositional analysis identified no anomalies

XRD revealed unexpected austenite variation in X-Y

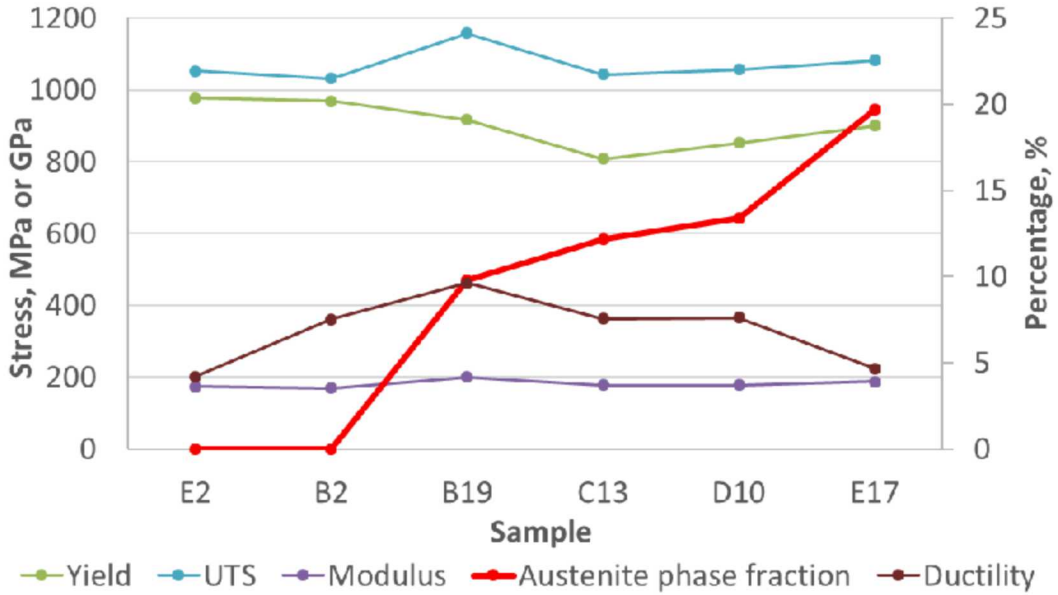
- what about Z?
- further complication to dogbone performance
- source = powder, atmosphere?







XRD analysis of dogbones across the build sample



material performance variation w/austenite phase fraction

Wrought 316L

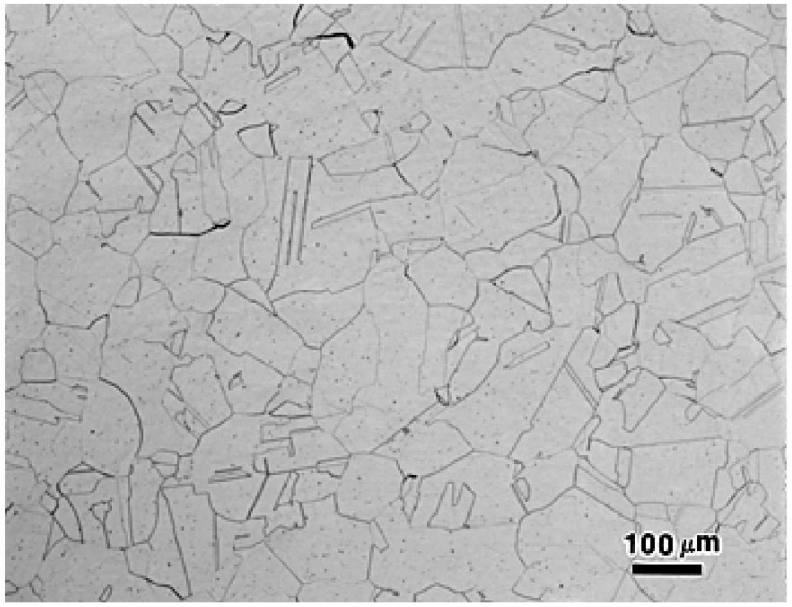
1/16 Hard

- solution annealed @ 1080°C, water cooled & hot rolled plate

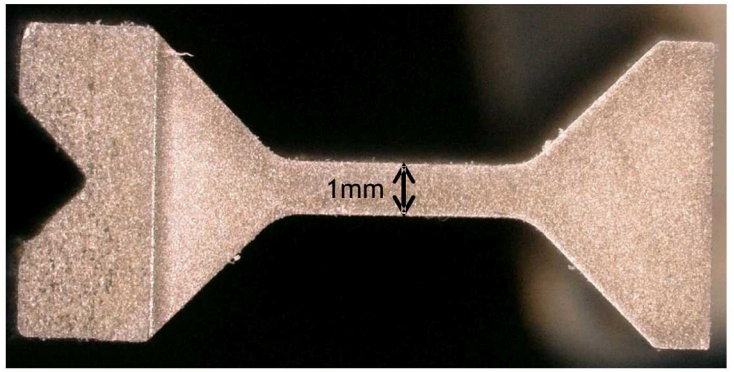
Specifications, minimums

- 1/16 hard: 310MPa yield, 585MPa UTS, 35% elongation
- 1/8 hard: 380MPa yield, 690MPa UTS, 25% elongation

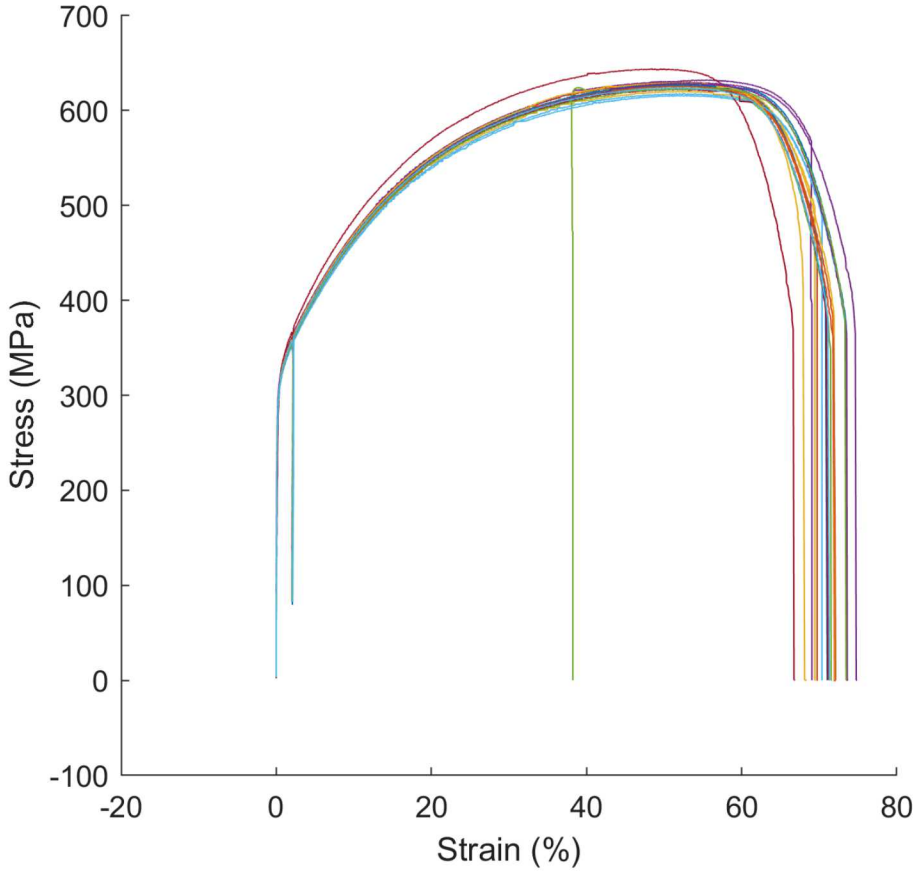
Equiaxed grain structure



annealed 316L SS grain structure, Vander Voort, 2011



dogbone array end view, machined from wrought 316L SS



wrought 316L SS stress-strain response, 20 samples

As-Printed

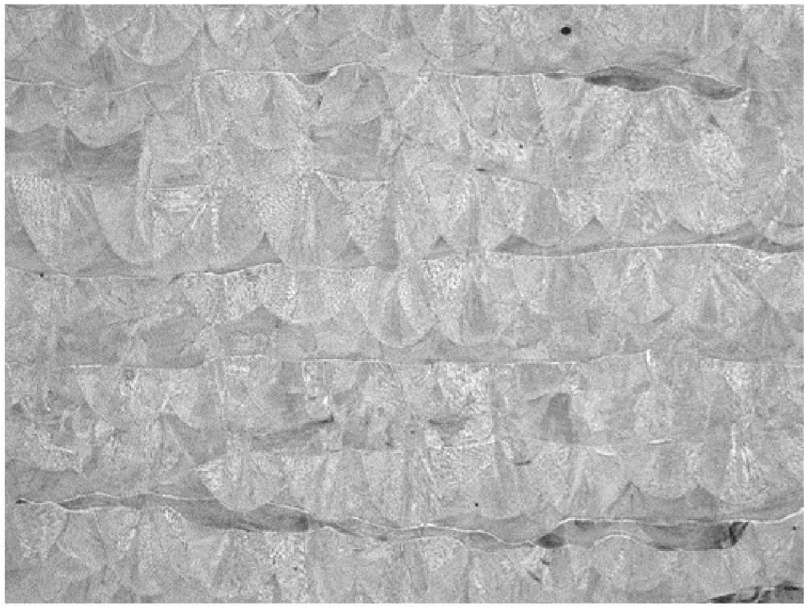
Nominal parameters

- 103W, 1400mm/sec, 50µm cross feed, 100µm beam diameter

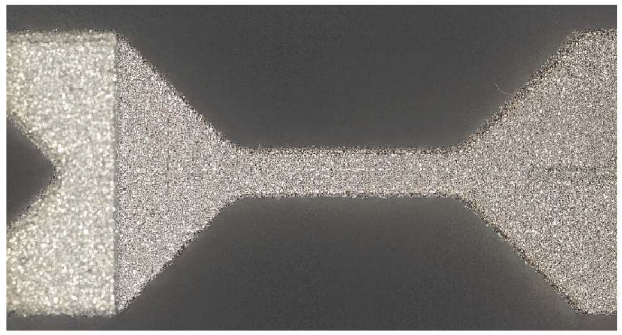
Rapid solidification produces higher yield strength

- consistent microstructure observed across process & feedstock changes
- laser-wise process structure clearly evident

Significant surface roughness

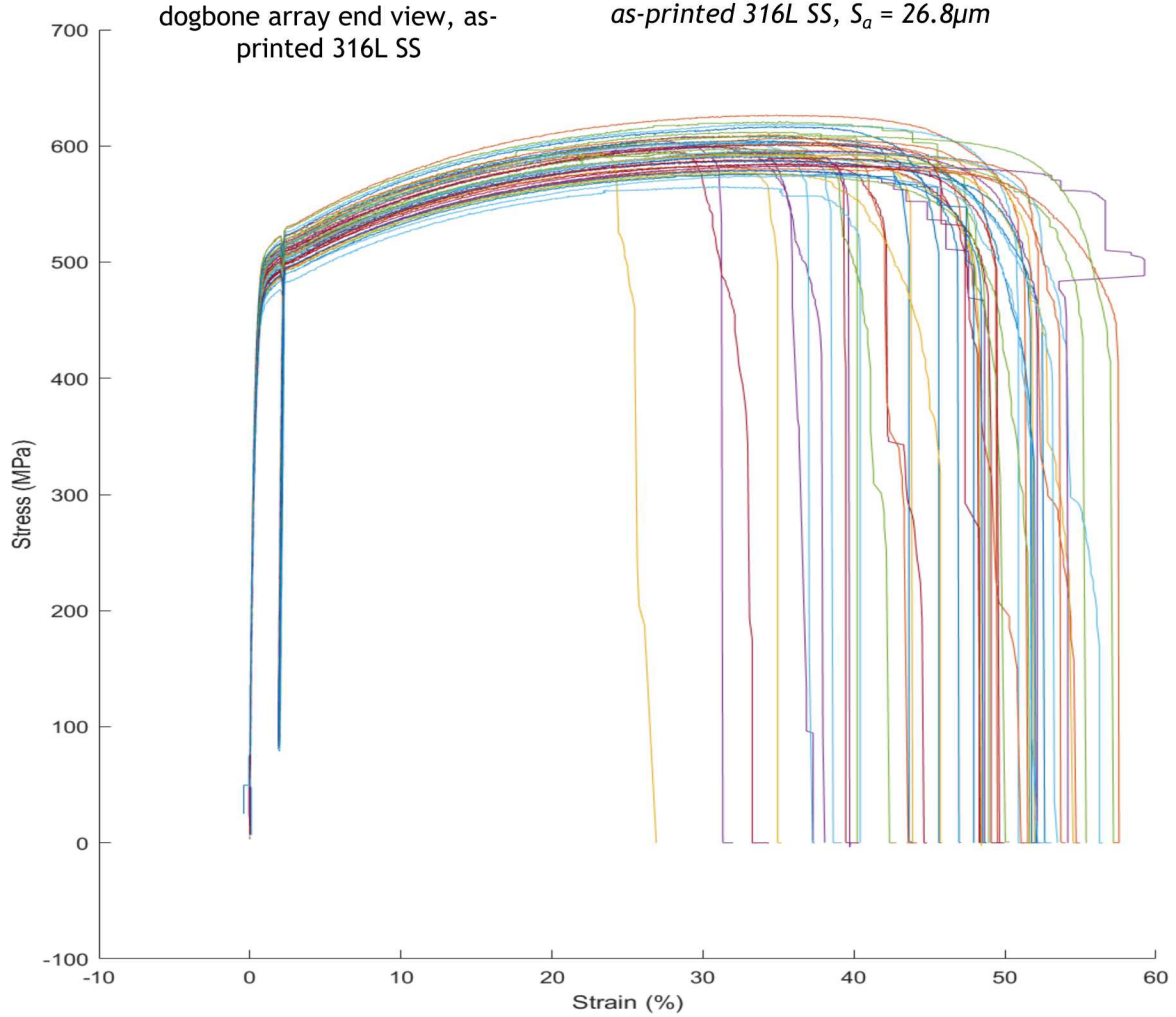


as-printed 316L SS grain structure, D. Susan



dogbone array end view, as-printed 316L SS

as-printed 316L SS, S_a = 26.8µm



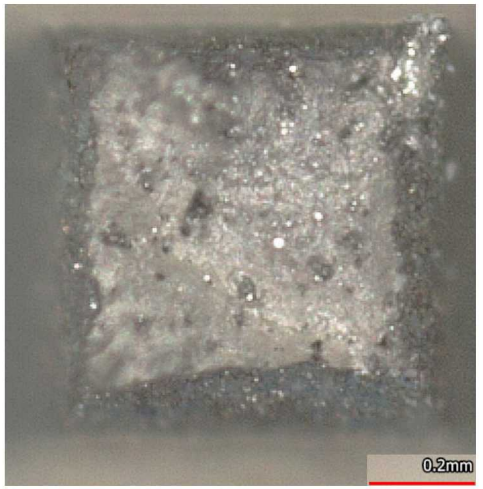
as-printed 316L SS, 50 samples

Machined

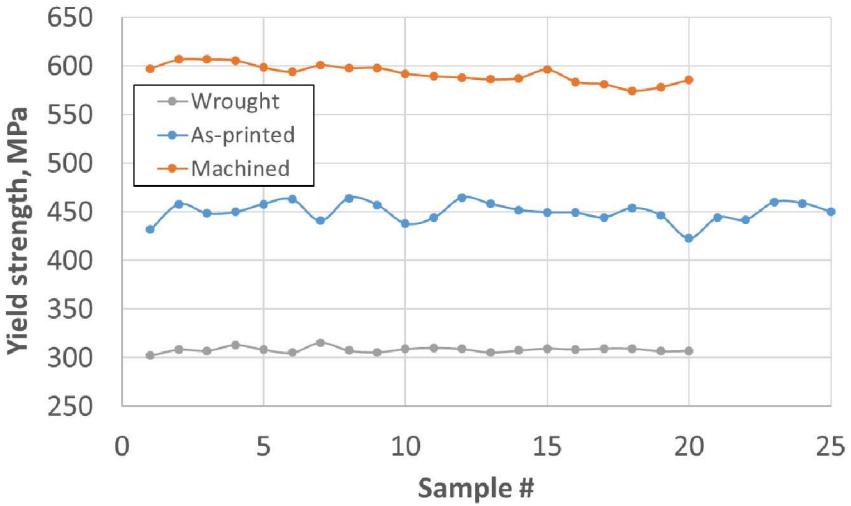
Intent
- eliminate surface finish influence
- explore print orientation
  - vertical strength < horizontal, 45° orientations

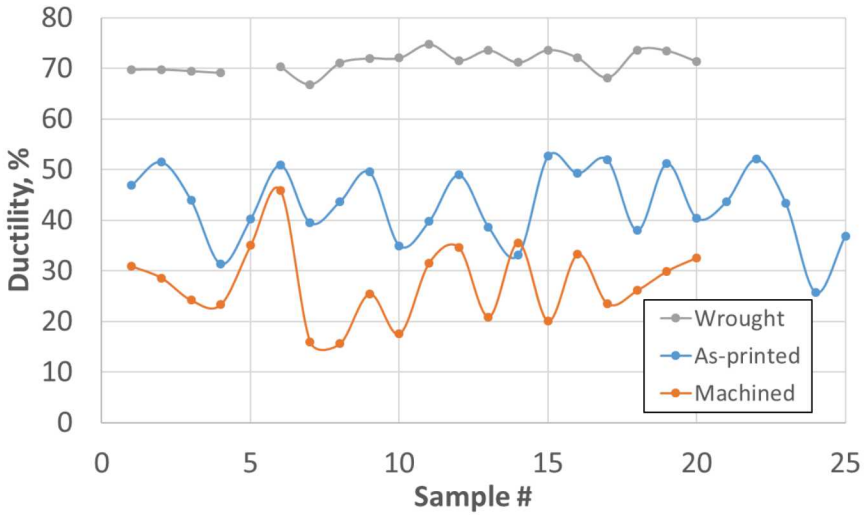
Increases strength, reduces ductility
- see more "traditional" fracture surface

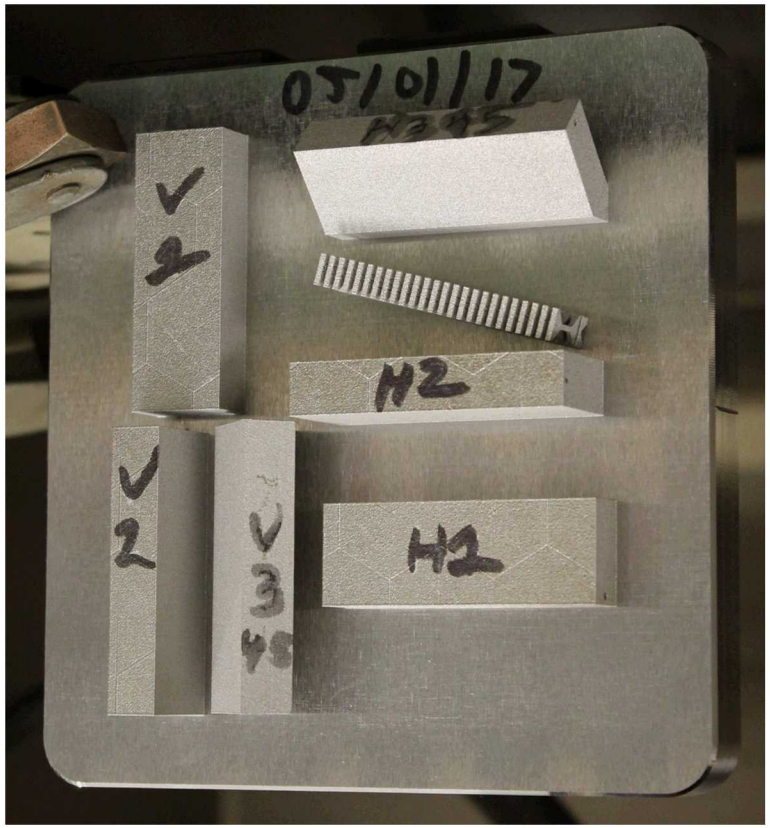
machined 316L SS, S_a = 2.1µm



machined 316L SS, fracture surface







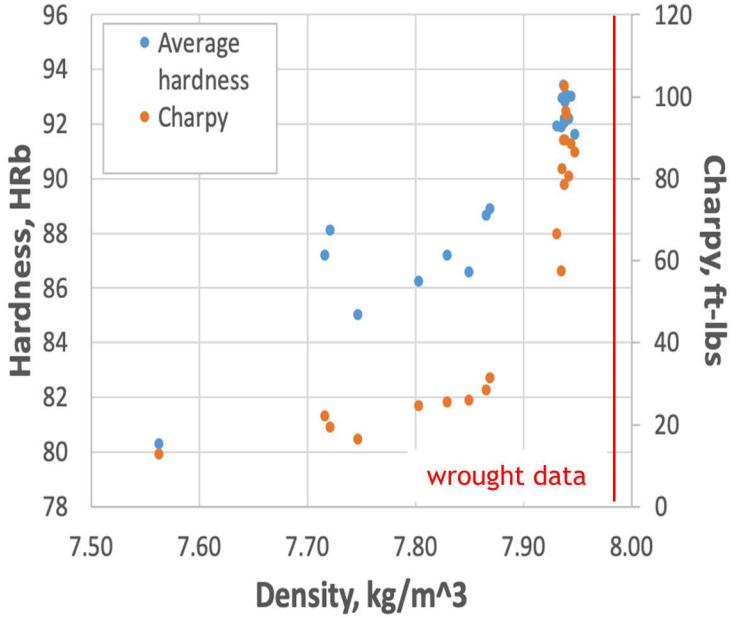
build plate orientation, as printed in the ProX 200

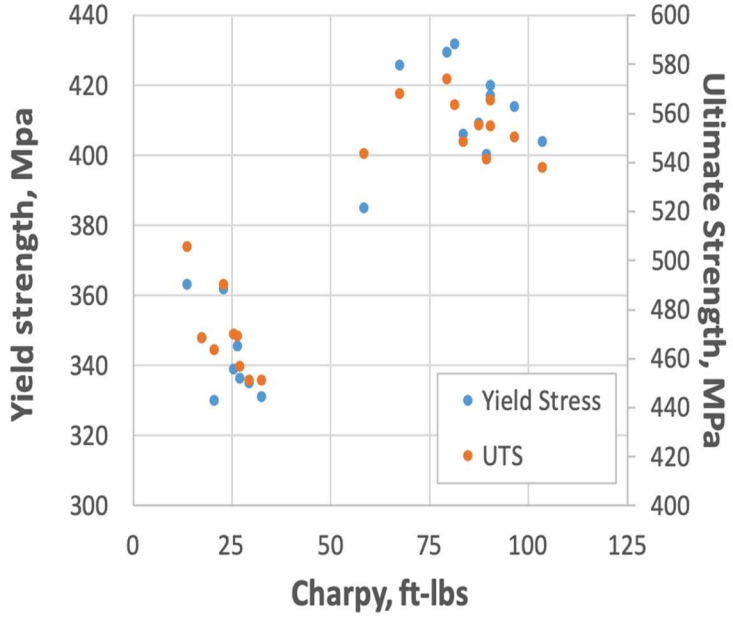
Build Plate Coupons

Charpy
- density
- hardness @ 4 spots
- Charpy impact toughness

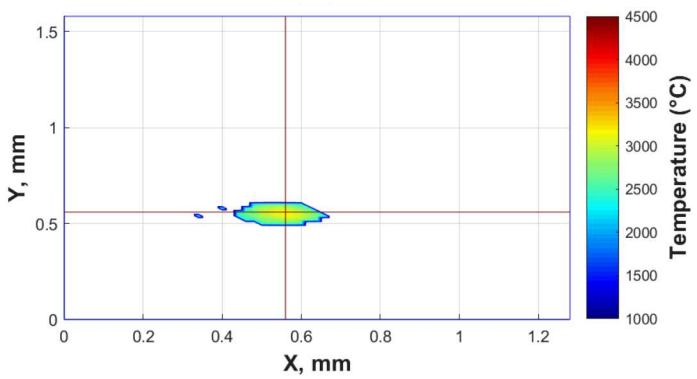
High-throughput tensile
- modulus
- strength – yield, ultimate
- ductility

build plate w/process artifacts





Temperature Maps Developed Per Layer



frame #3

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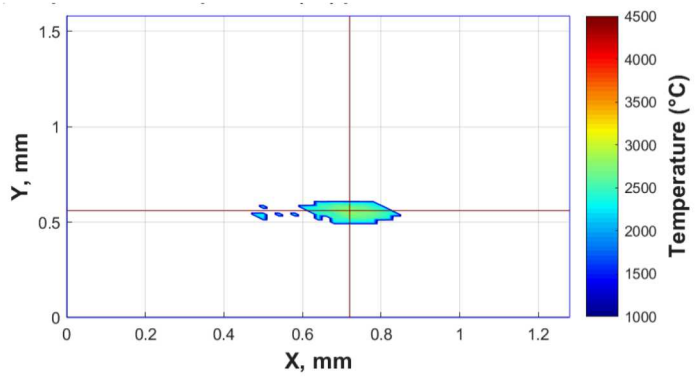
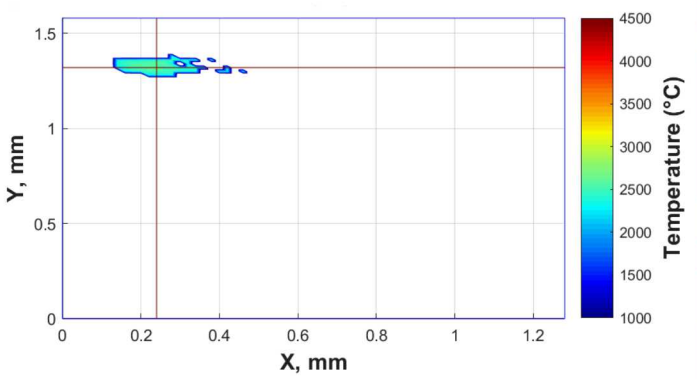


frame #4

+ … +



frame #184

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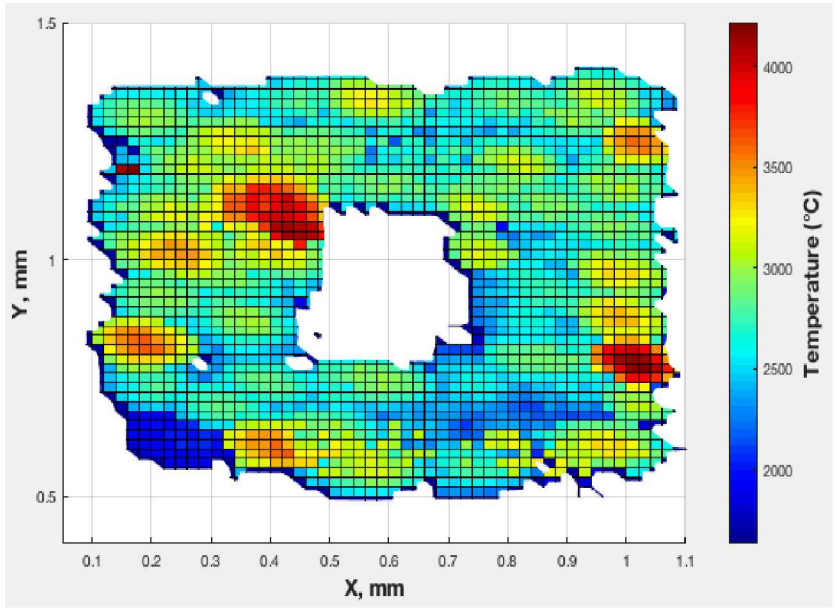

max temperature value @ each pixel across all frames

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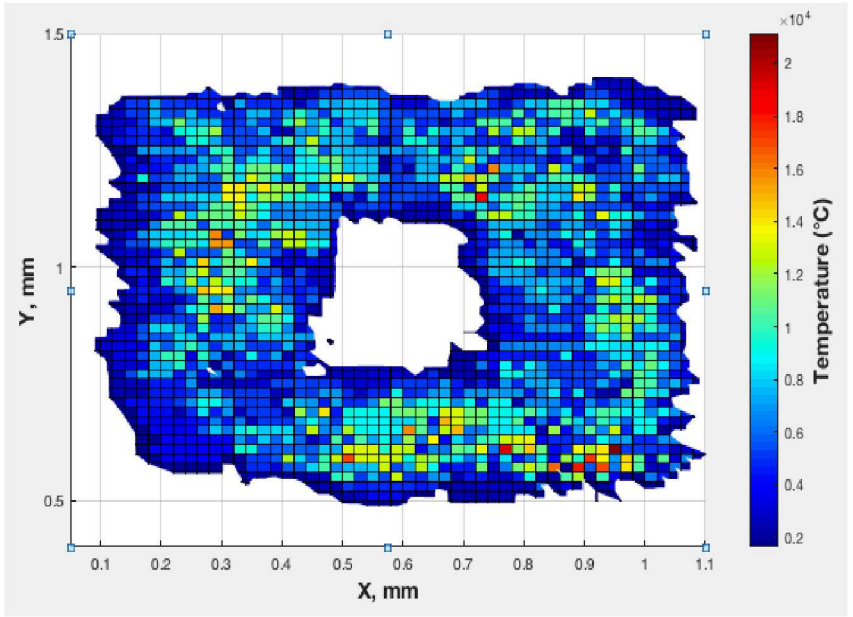

sum all temperature values @ each pixel across all frames