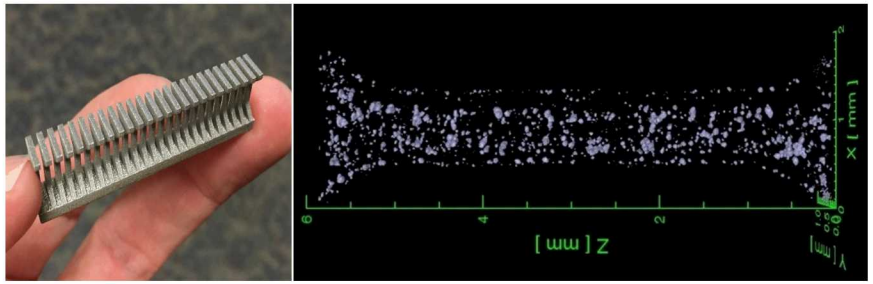
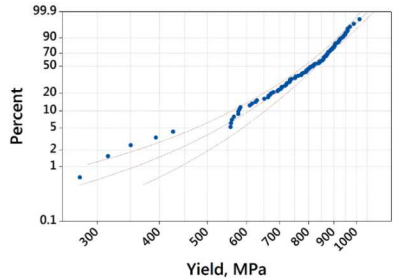
SAND2018-2903PE

The Challenges and Consequences of Uncertainties in Metal Laser Powder Bed Fusion

Bradley Jared

Materials Engineering & Manufacturing S&T





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Outline

- Background
- Motivation
- 17-4PH inter-build study
  - structure-performance
- 316L intra-build study
  - process-structure-performance
- In-situ diagnostics
  - process-structure
- Summary

- opportunities for material design, collaboration

Acknowledgements

- Structure-performance research
  - Brad Boyce, Jon Madison, Jake Ostien, Jeff Rodelas, Brad Salzbrenner, Laura Swiler, Olivia Underwood, David Saiz, Kevin Webb (Georgia Tech), Burke Kernan
- Process-structure research
  - Jon Madison, Laura Swiler, David Saiz, John Mitchell, Erich Schwaller (UNM), Josh Koepke (UNM), Thomas Ivanoff, Daryl Dagel
- Topology optimization
  - Ted Blacker, Brett Clark, Josh Robbins, Miguel Aguilo

Sandia National Laboratories

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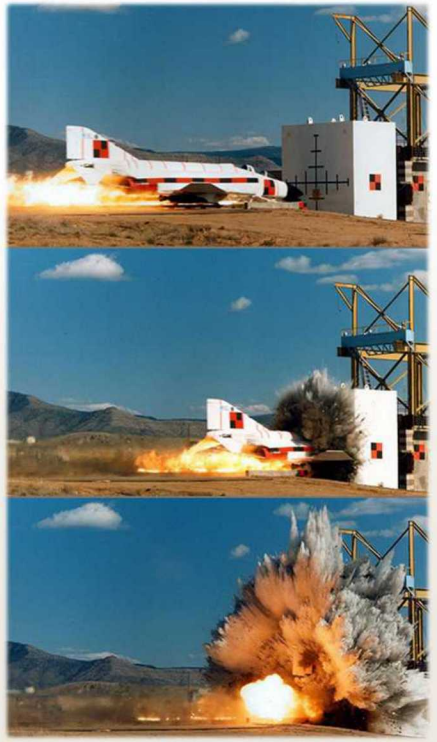
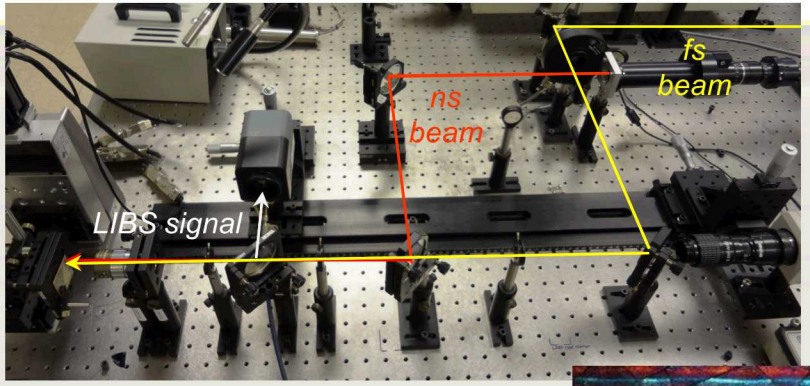
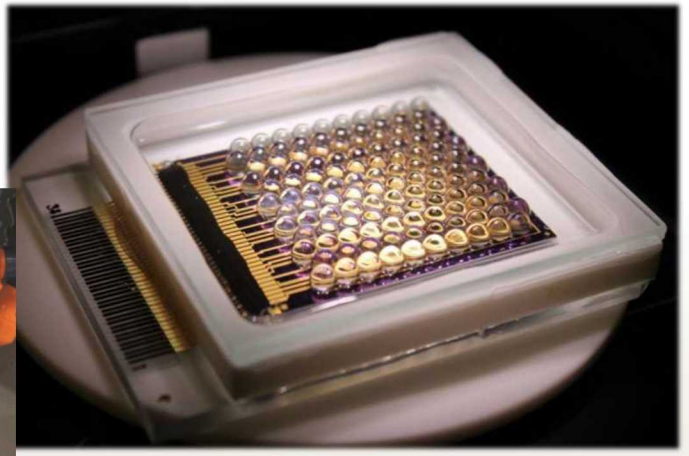


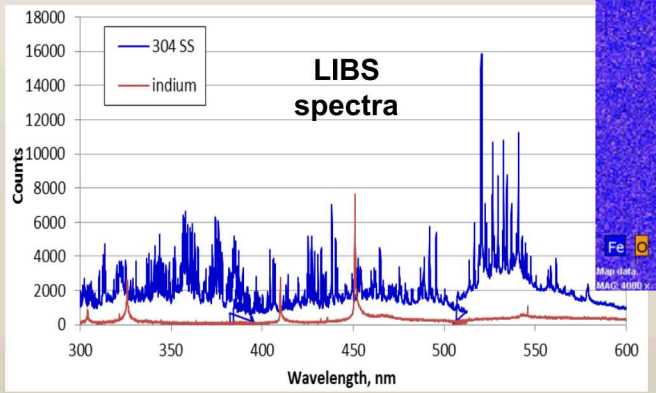
Laser & Precision Manufacturing

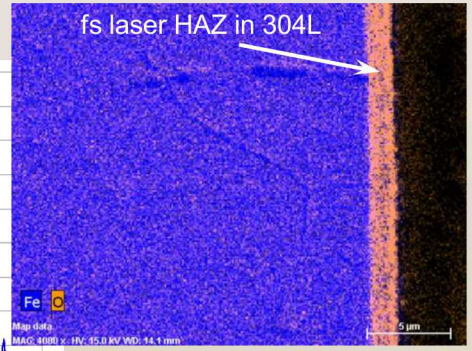


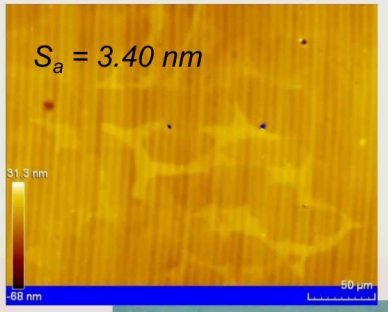


microsystems-enabled photovoltaics (*MEPV) module,* Jared, ***Opt Exp***, 2014

pulsed laser processing

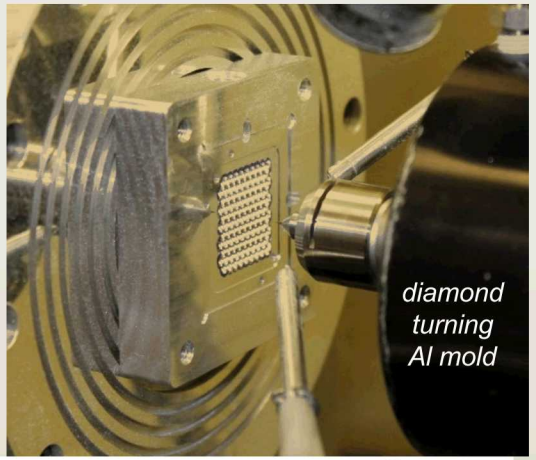


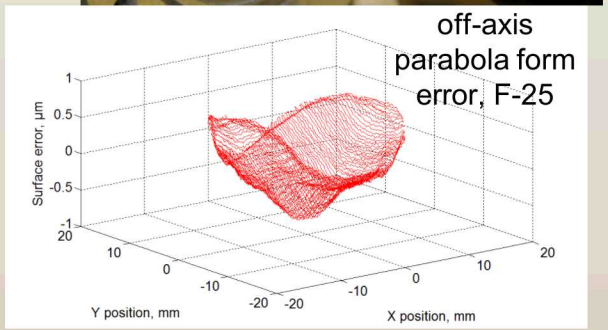




precision machining

non-rotationally symmetric freeform mirror, *Boye,* **Opt Eng**, *2013*

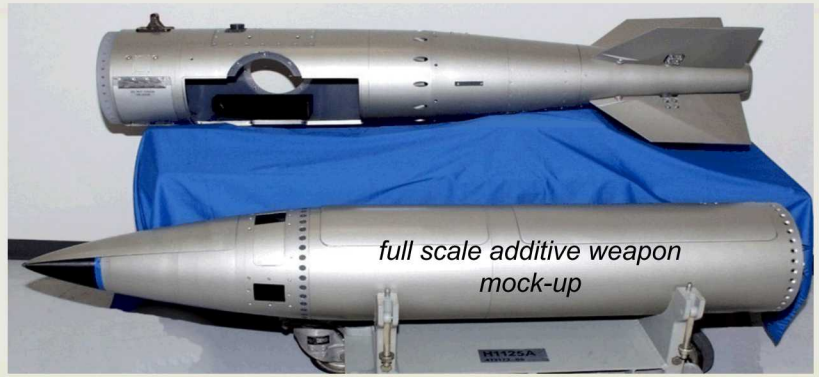


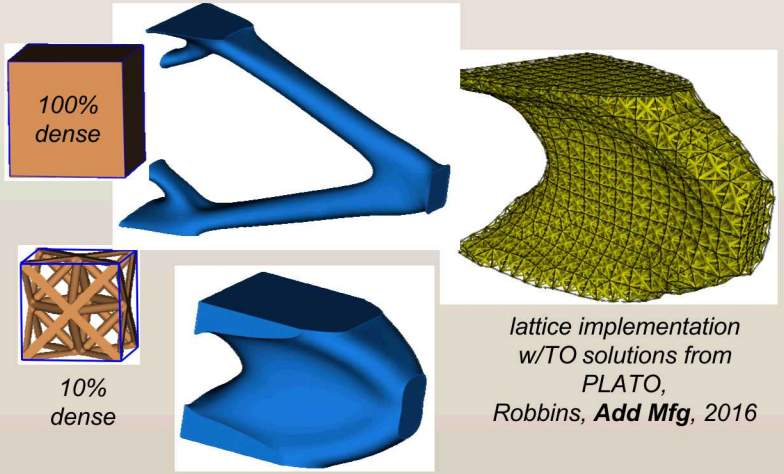


SNL's Additive Interests

- 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"

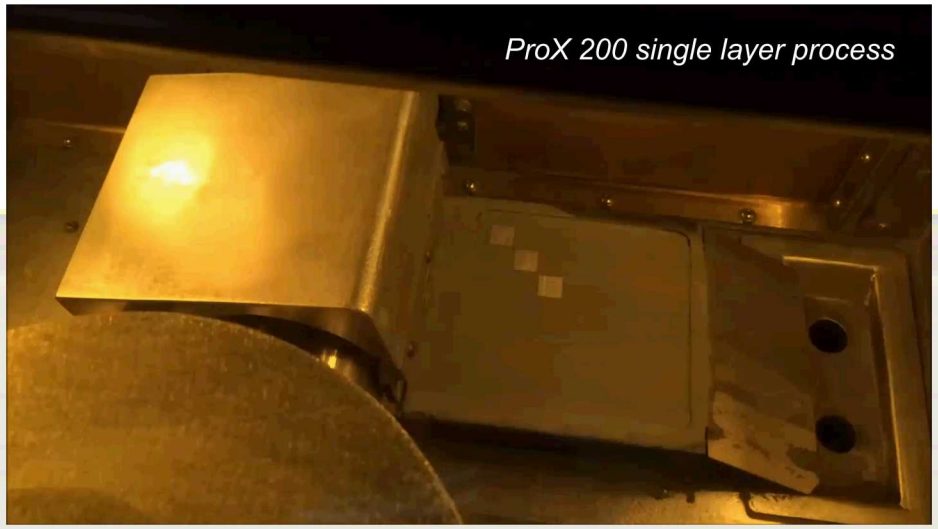
prototype AM mirror & structure



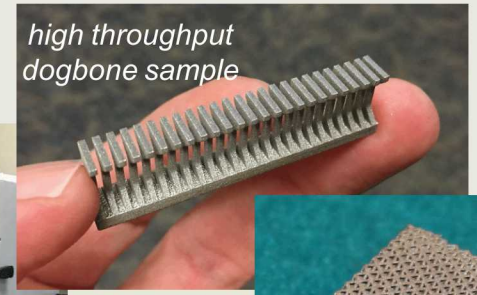


*lattice implementation w/TO solutions from PLATO, Robbins, **Add Mfg**, 2016*

Powder Bed Fusion



- 3D Systems ProX 200 @ Sandia
  - 1070nm laser, 300W max power
  - scan speed = 1.4m/sec
    - 30µm powder layer, 100µm beam diameter, 50µm overlap
    - deposition rate ~100 mm3/min
  - 10^5-10^6 °C/sec heating & cooling rates
  - melt pool depth ~ 2-3x layer thickness
  - research platforms for process & material characterization
  - 316L SS
- Part capabilities
  - 0.001-0.002" best accuracy
  - surface finish
    - >5-10 µm Sa (~ casting)
    - worse for downward surfaces
  - geometry limits
    - wall thickness > 100 µm, overhangs < 45°
  - single material
    - > 99% density
    - strength typically near to, but less than wrought
    - anisotropic properties

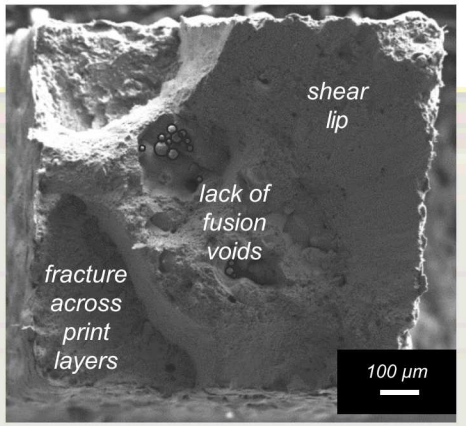


Material Assurance

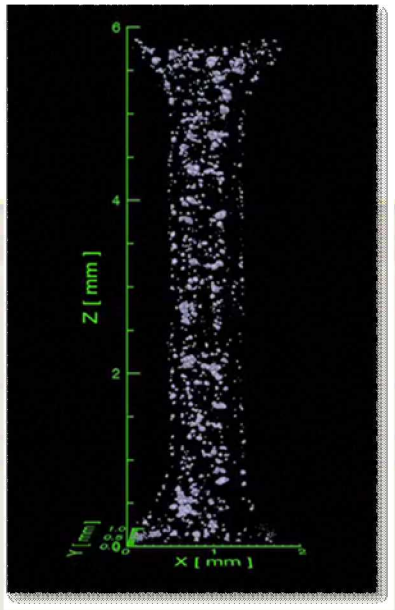
- Material formation concurrent w/geometry
  - want to predict part/material performance
    - feedstock certs inadequate for performance
  - **how to ID a bad part?**
    - complexity isn't "free"
    - requires significant design margins and/or rigorous post-process inspection / validation

- Quantify critical material defects & useful signatures
  - D-tests, NDE, process monitoring, mod-sim, ?

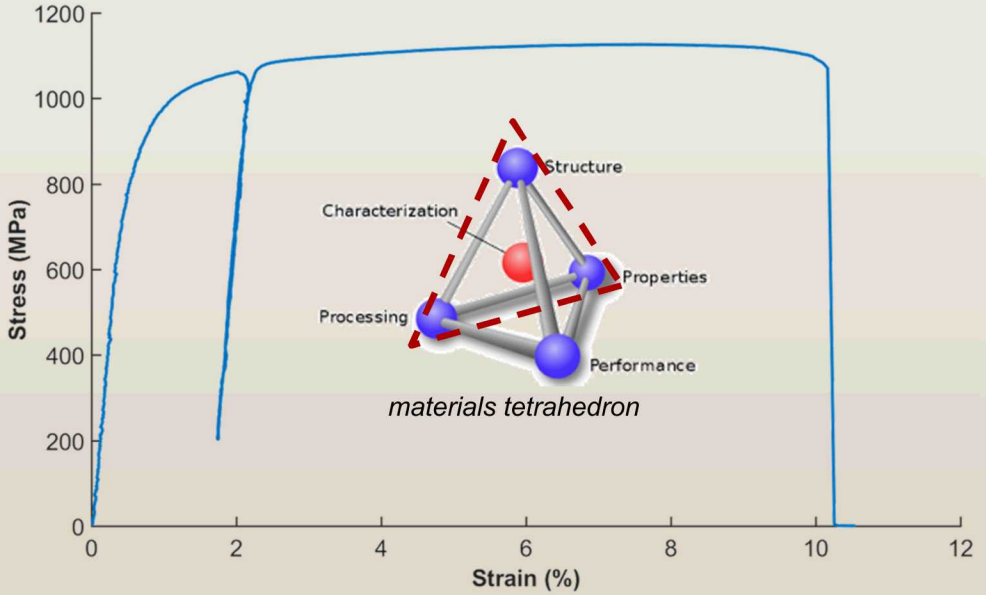
- Understand mechanistic impacts on properties
  - build process-structure-property relationships to predict margins & reliability
  - characterize stochastic response to design for uncertainties
  - provide scientific basis for qualification of AM metals for high consequence applications



17-4PH dogbone fracture surface

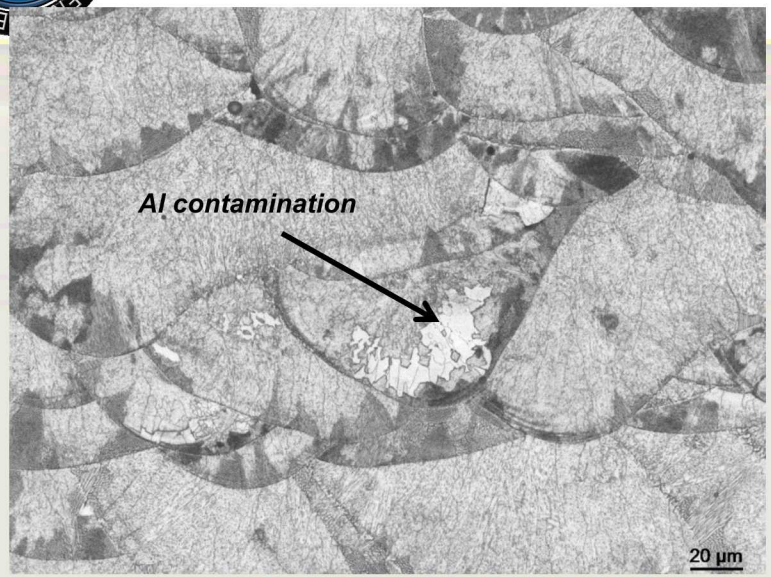


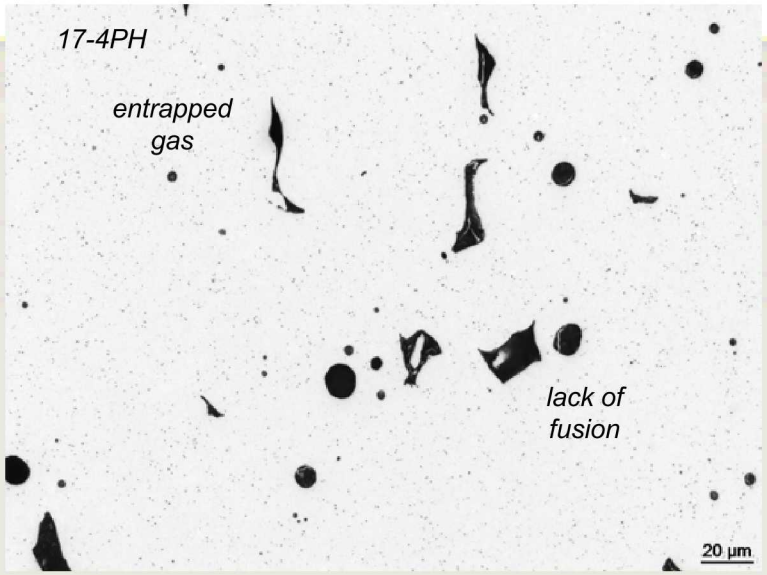
17-4PH dogbone porosity

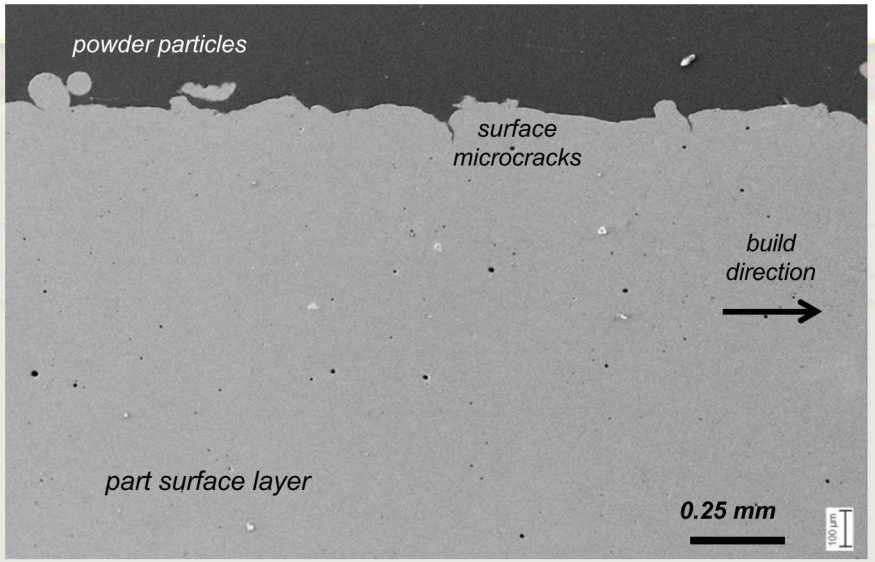


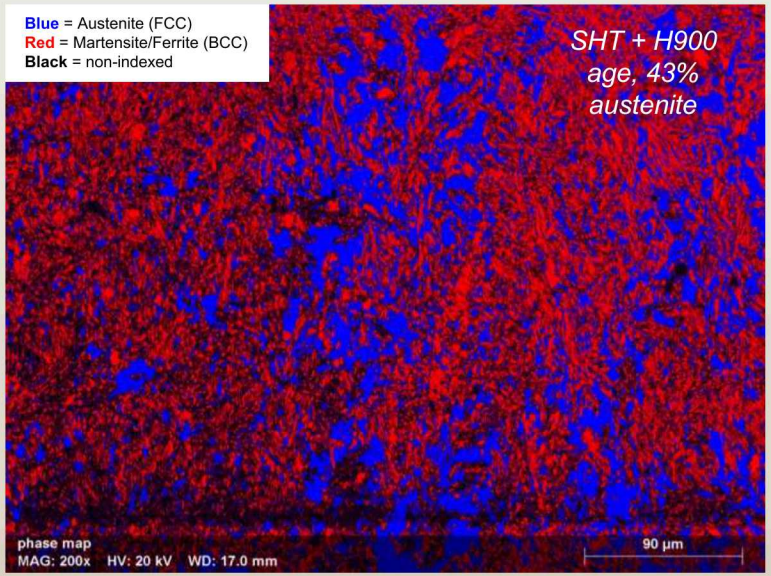
17-4PH dogbone stress-strain response

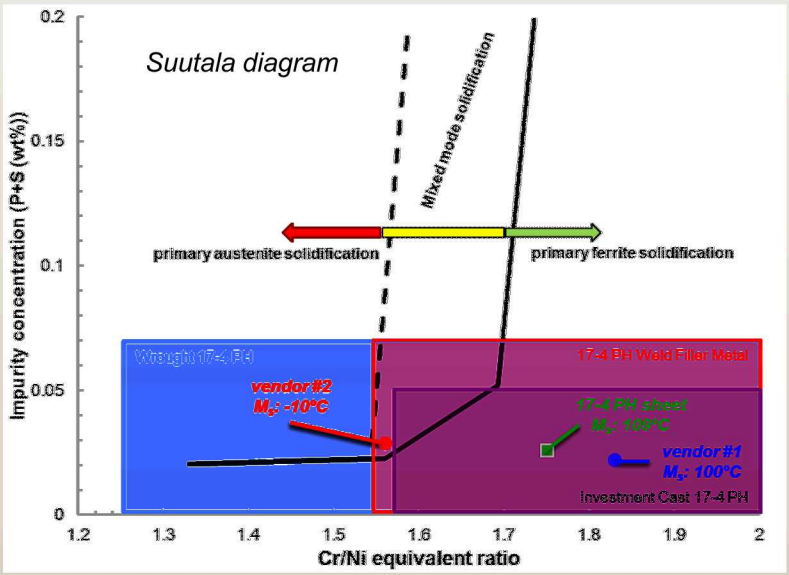
Representative Material Defects



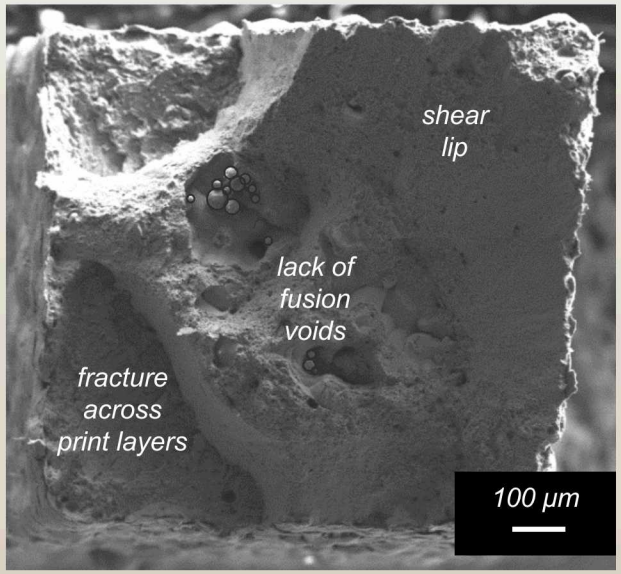






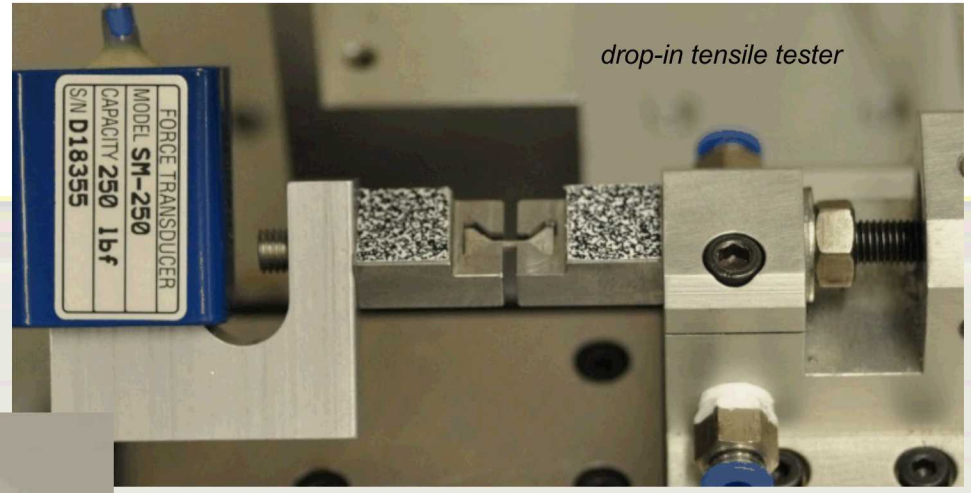


defect dominated failure, 2% elongation, 17-4PH

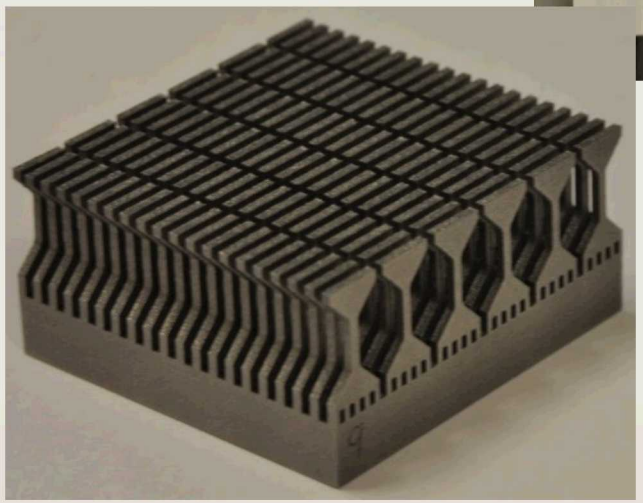


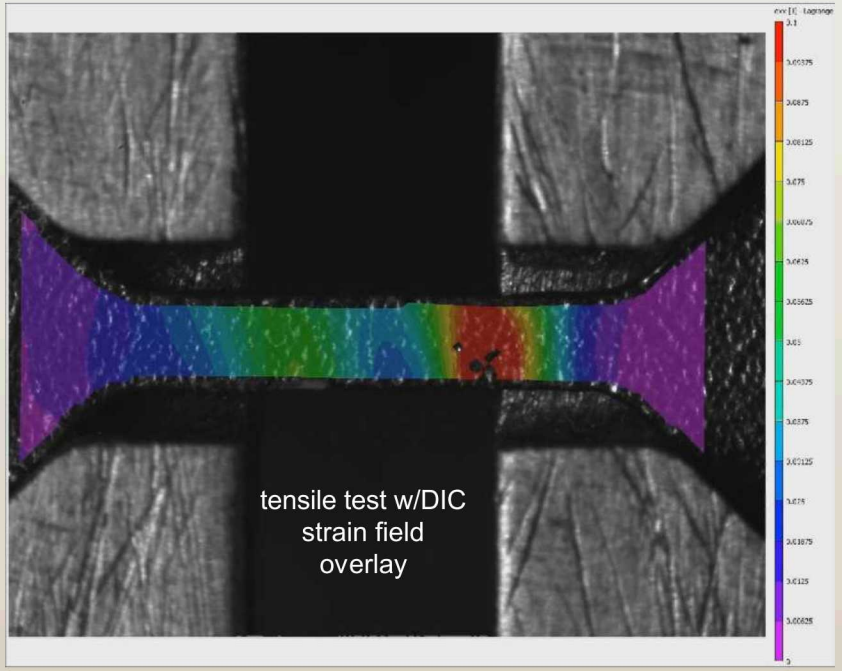
17-4PH Study

- 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

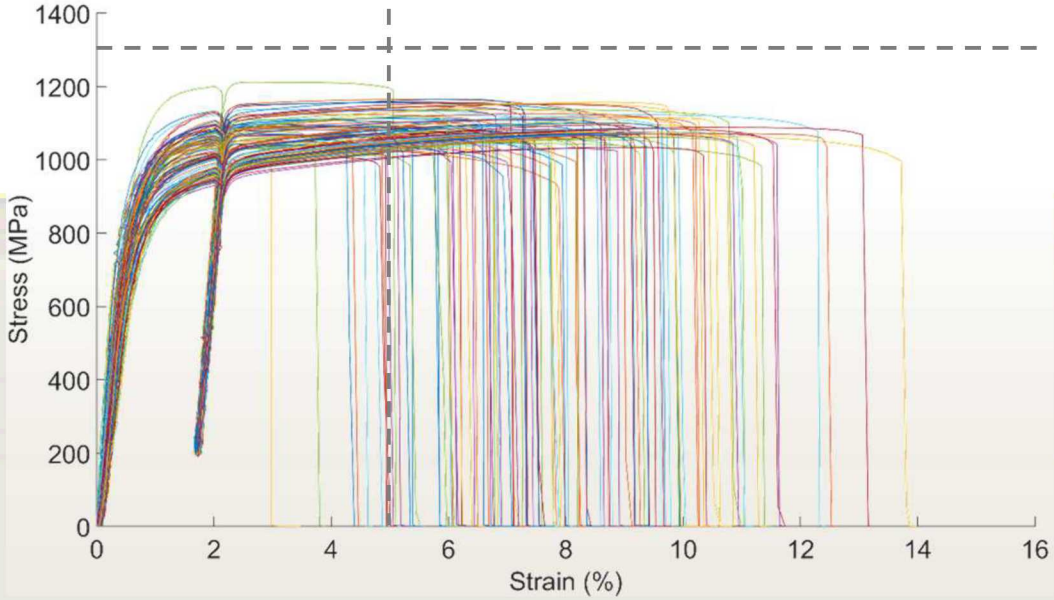

high throughput test sample w/120 dogbones, 1x1mm gage x-section


tensile test w/DIC strain field overlay

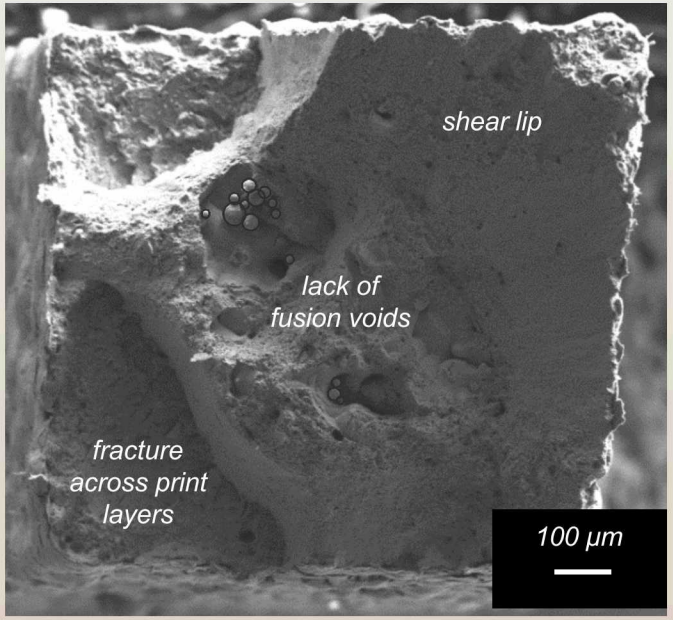
Stochastic Response

- Defect dominated failure
  - 3-parameter Weibull fits inform 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



failure at 2% elongation, SHT+H900

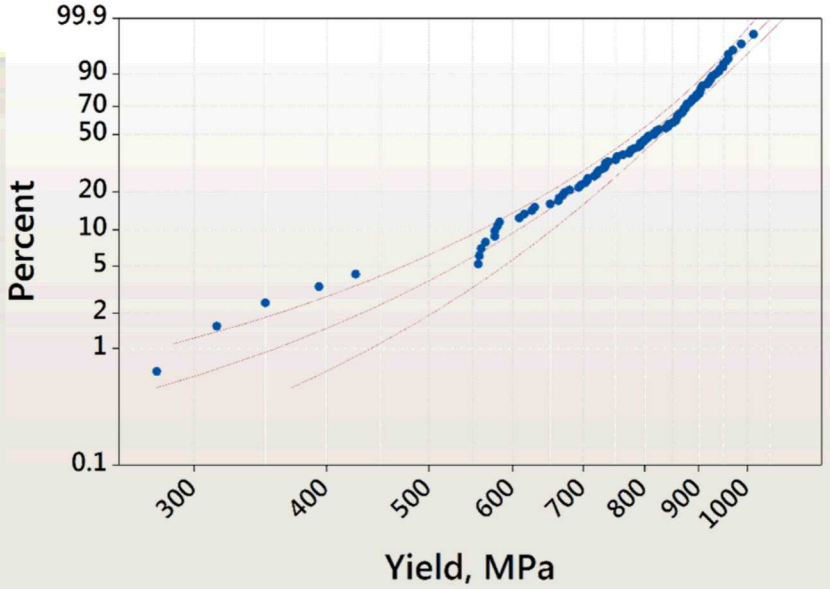
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

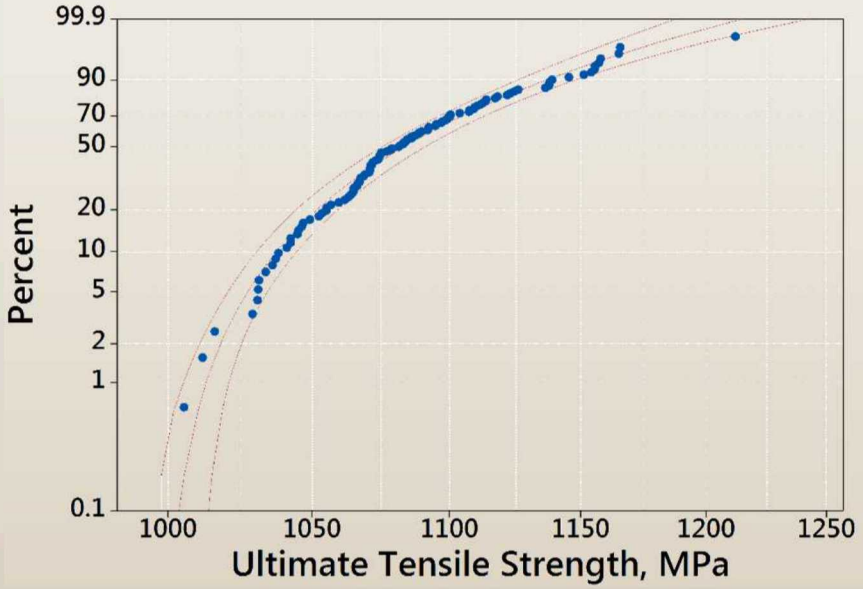
Material Performance Fit to 3-Parameter Weibull Distributions

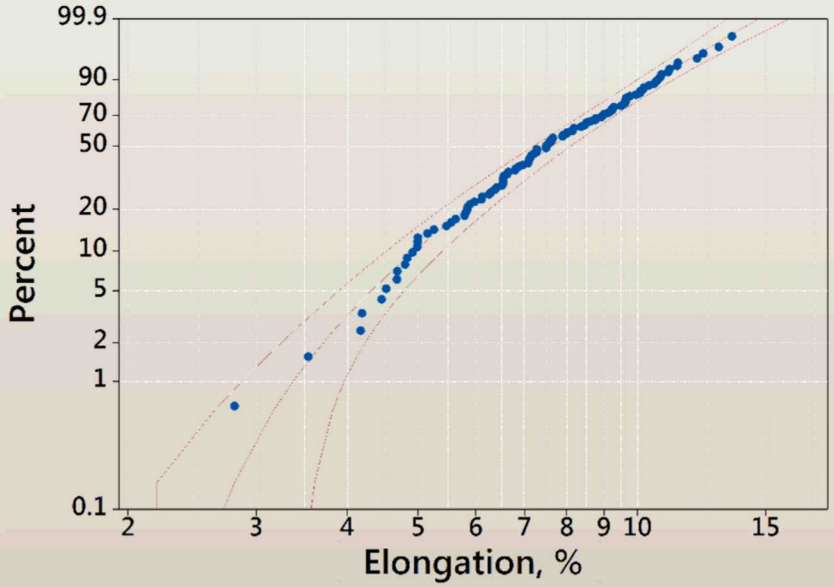
- Based on weakest link theory

$$P = 1 - \exp\left[-\left(\frac{\sigma - \sigma_0}{\sigma_\theta - \sigma_0}\right)^m\right]$$

- where
  - P = probability of failure at stress, σ
  - m = Weibull modulus, i.e. scatter
  - σ_θ = characteristic strength
  - σ_o = threshold, strength where P = 0

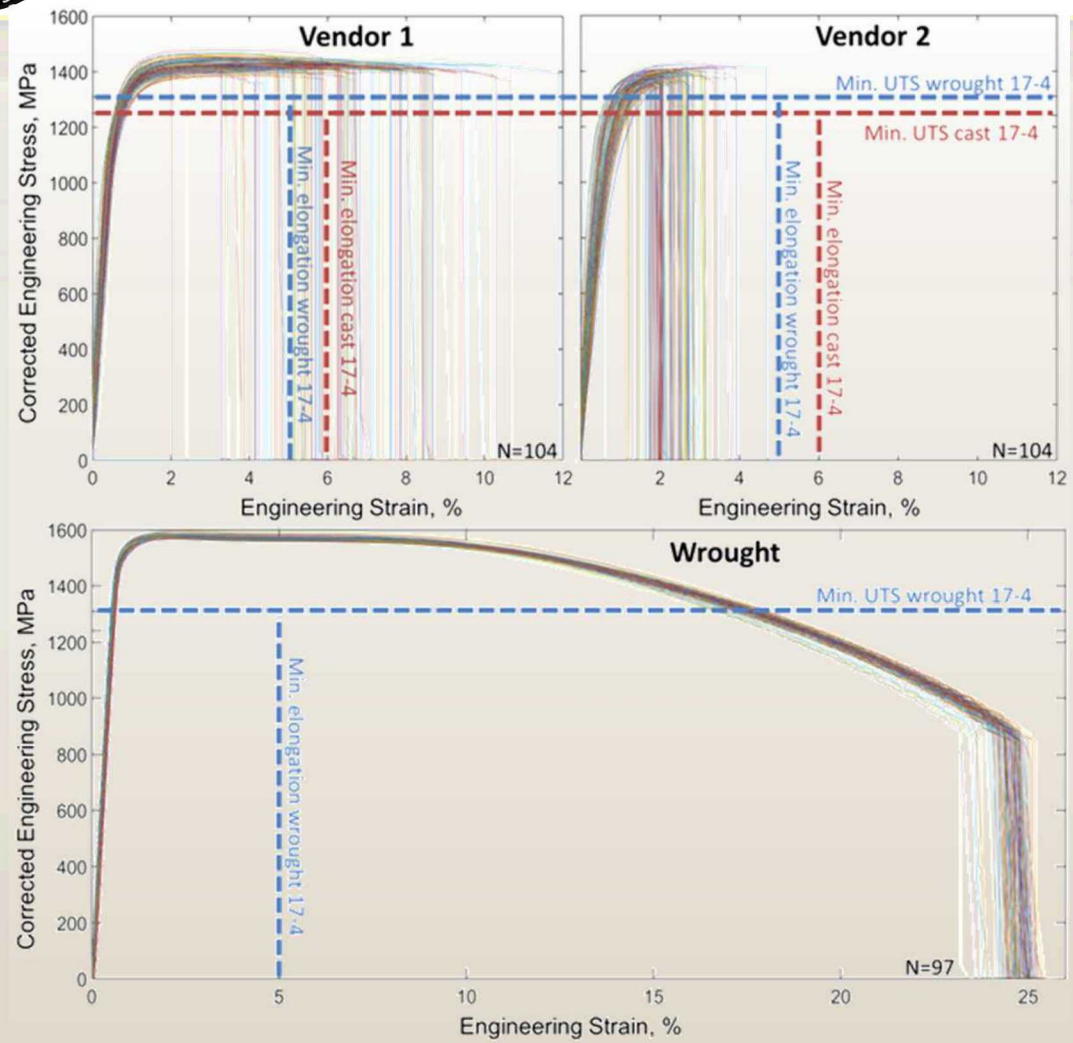




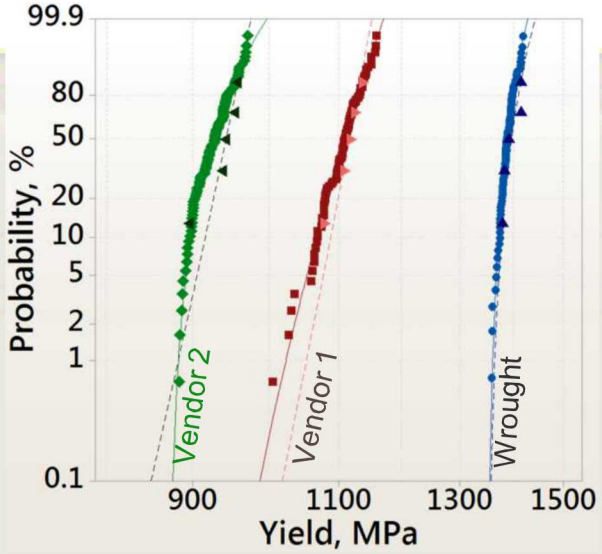


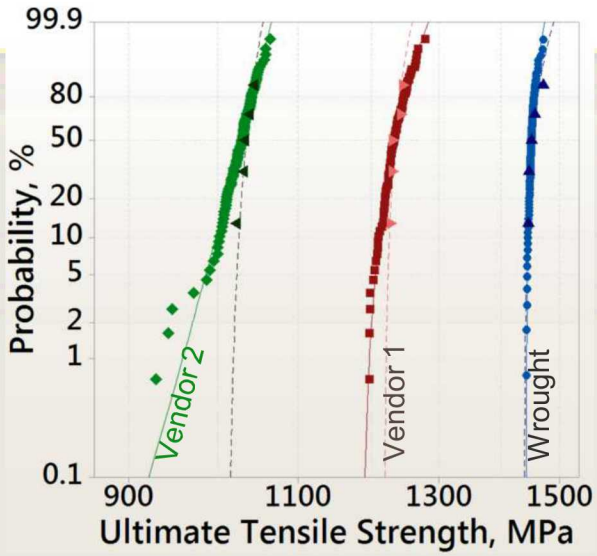
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

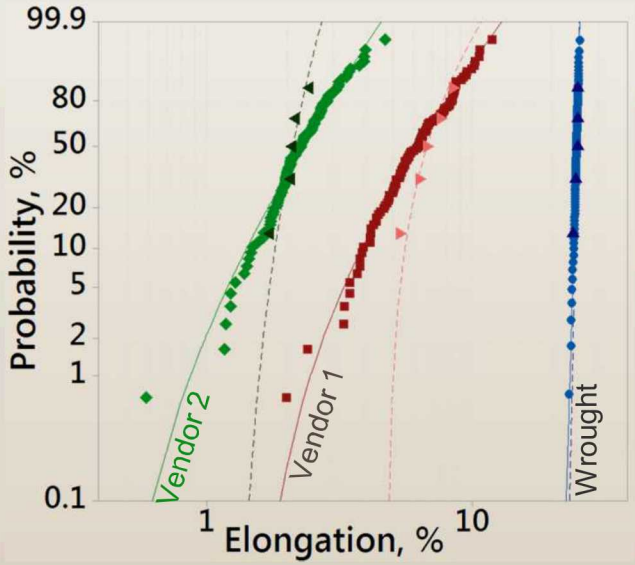
AM vs. Wrought 17-4PH



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





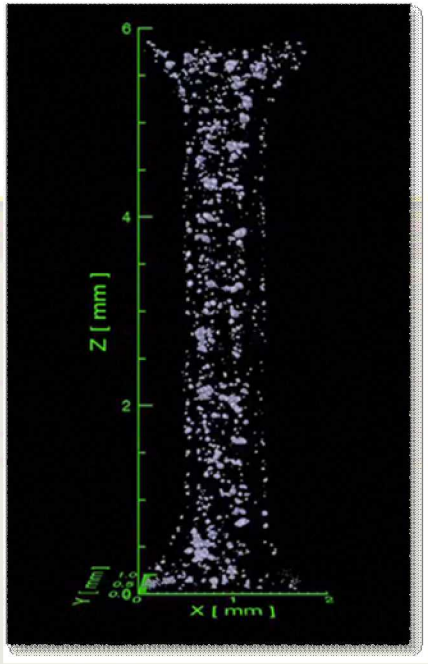


AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

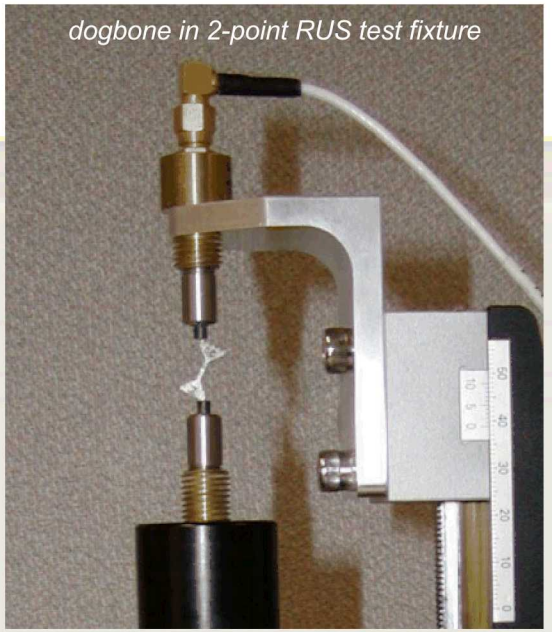
Material Characterization

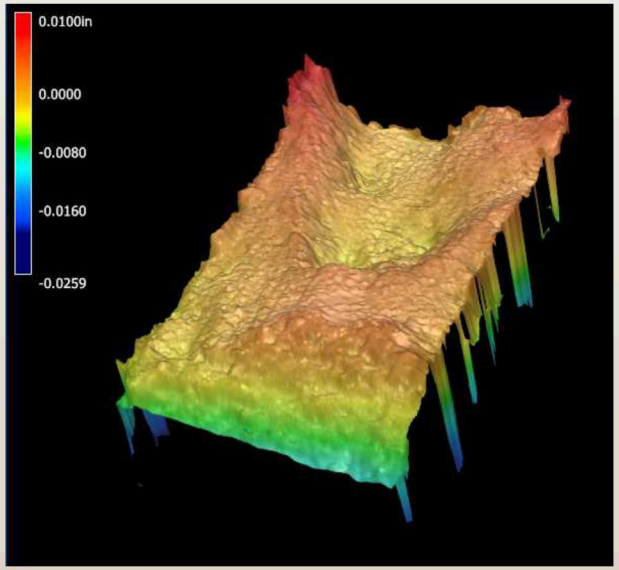
- NDE before testing
  - detect defects, performance correlations
  - density (Archimedes)
  - resonant ultrasound spectroscopy (RUS)
  - optical surface measurements
  - computed tomography (CT)
- Post mortem after testing
  - inform performance & failure mechanisms
  - fractography
  - metallography
  - composition
  - XRD

- **Do reasonable defect signatures exist which tie to performance tests?**



17-4PH dogbone porosity

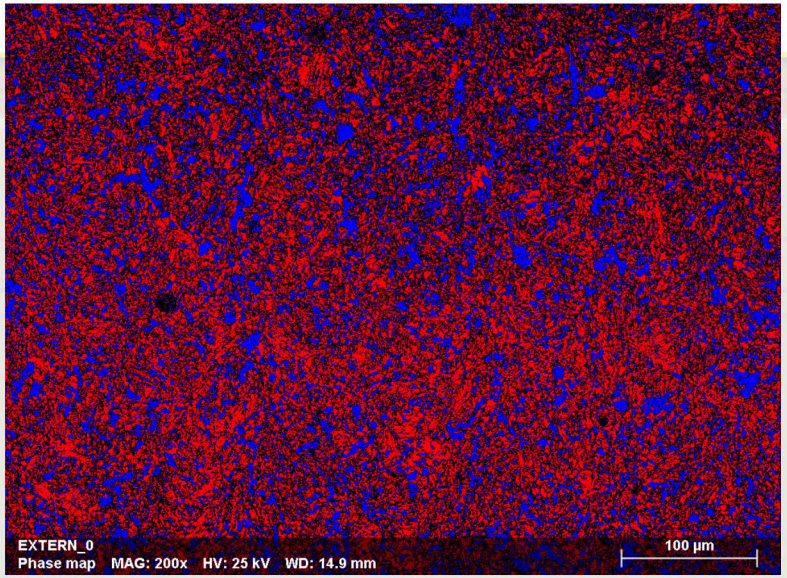




fracture surface

Metallurgical Interrogations

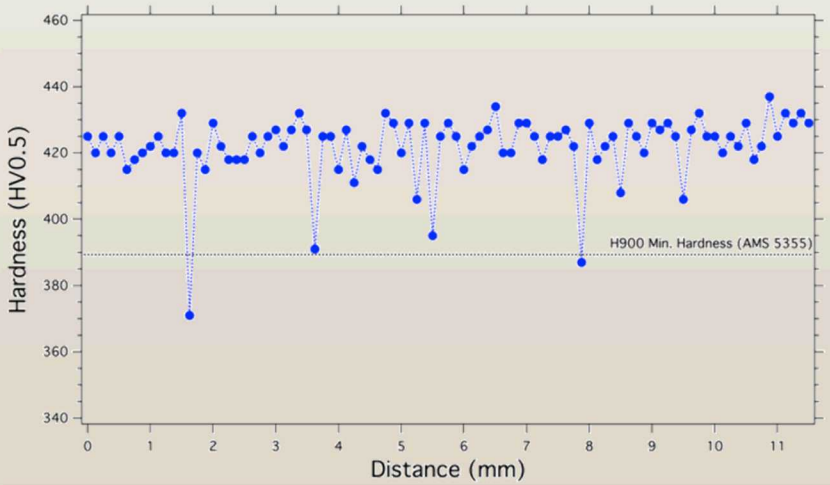
- Microstructure
  - optical, SEM, EBSD, WDS micro-probe
- Composition
  - LECO combustion, ICP mass-spec, XRD
  - powder analysis
- Microhardness



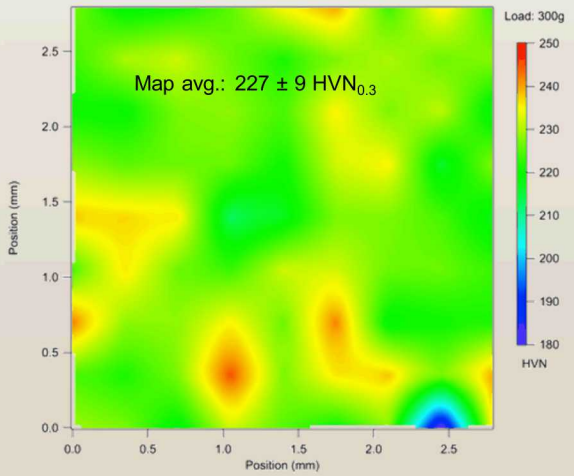
EBSD phase map, SHT+H900, 22% retained austenite

Element	Vendor 1, run 2 (wt%)
Cr	16.64
Mo	0.045
Si	0.38
Nb	0.3
V	0
W	0
Ti	0
Ta	0
Al	0
Ni	4.24
Mn	0.24
C	0.012
N	0.056
Co	0
Cu	4.05
P	0.019
S	0.003
O	0.100
Nb	0.30

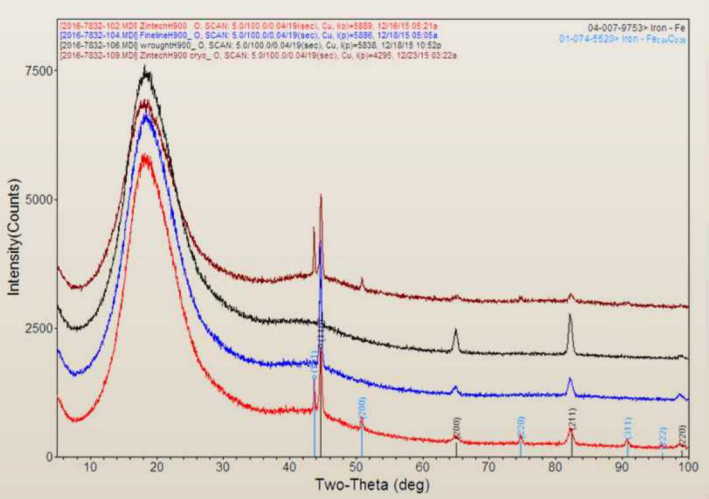
bulk chemical analysis



SHT+H900 microhardness along dogbone length

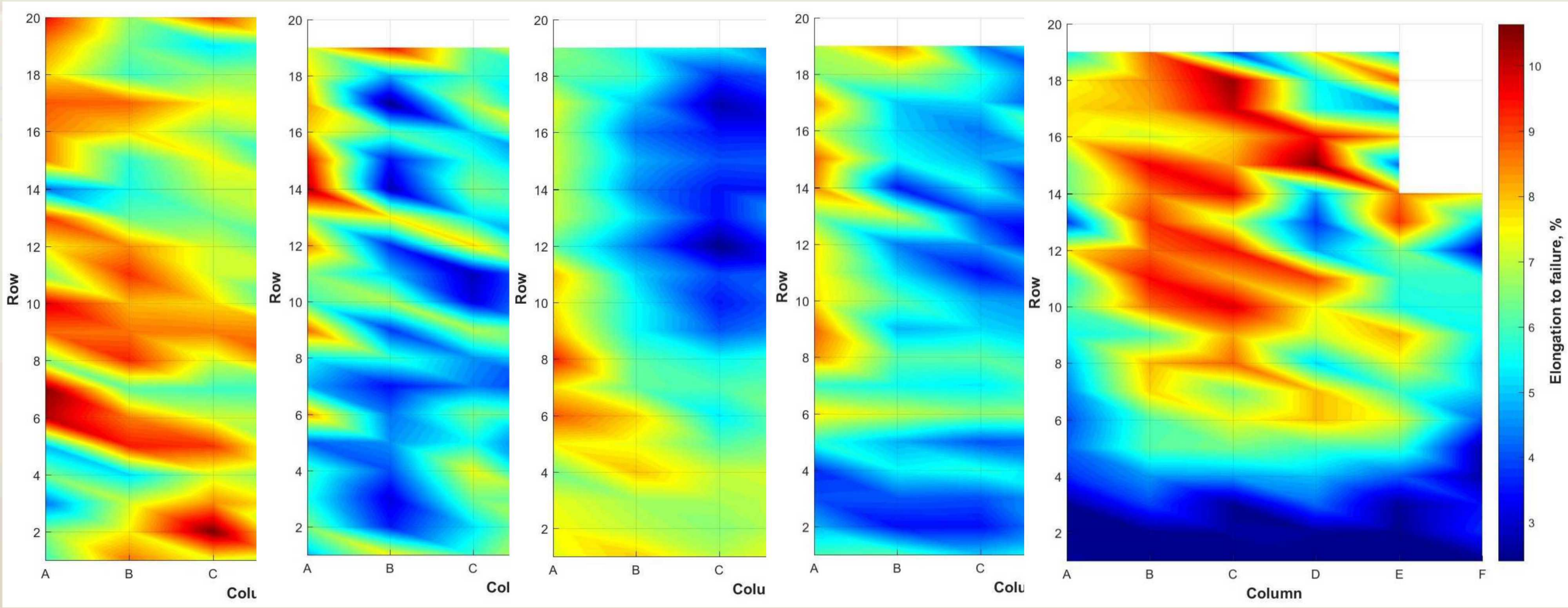


as-printed microhardness on gauge cross section



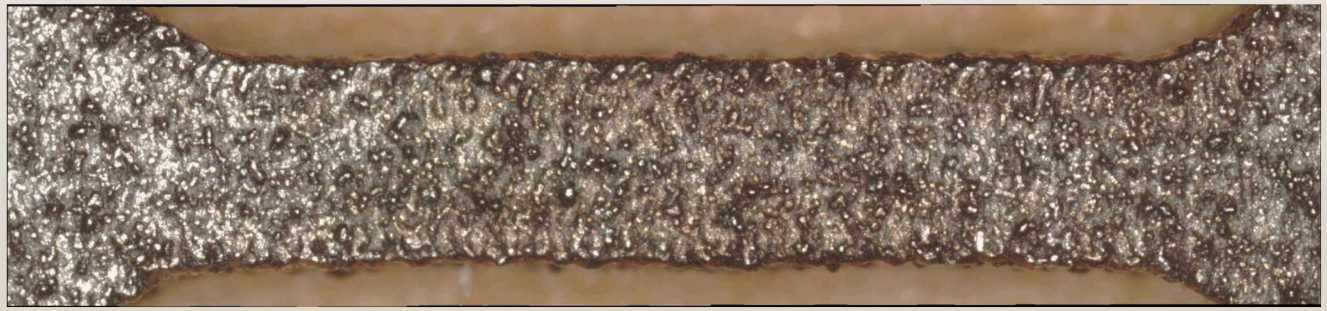
bulk XRD analysis

Trends Across the Part

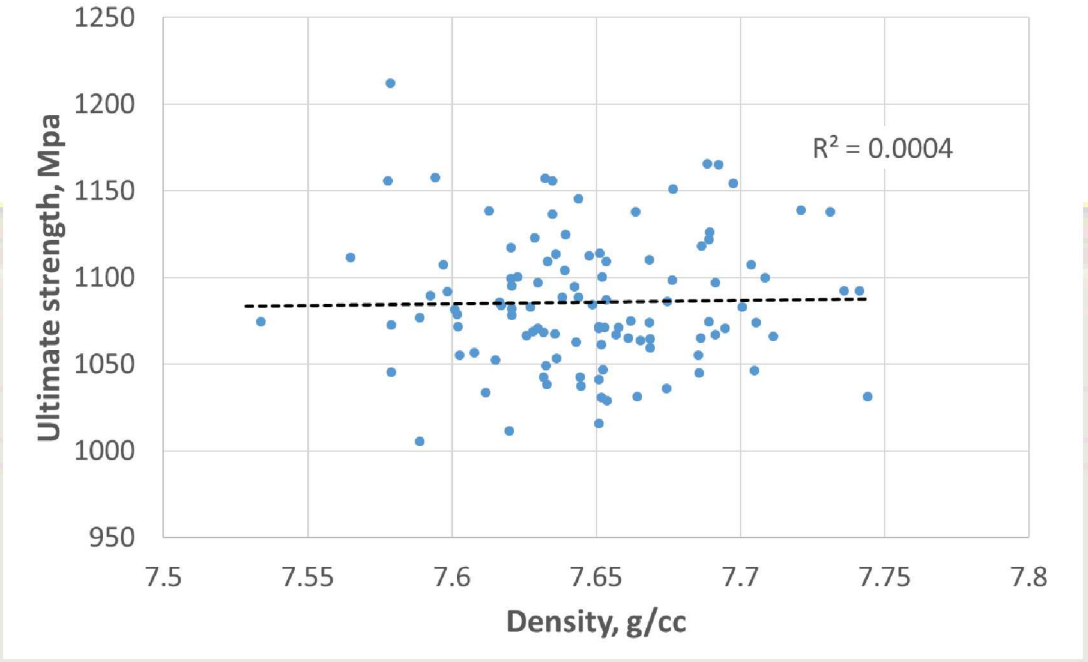


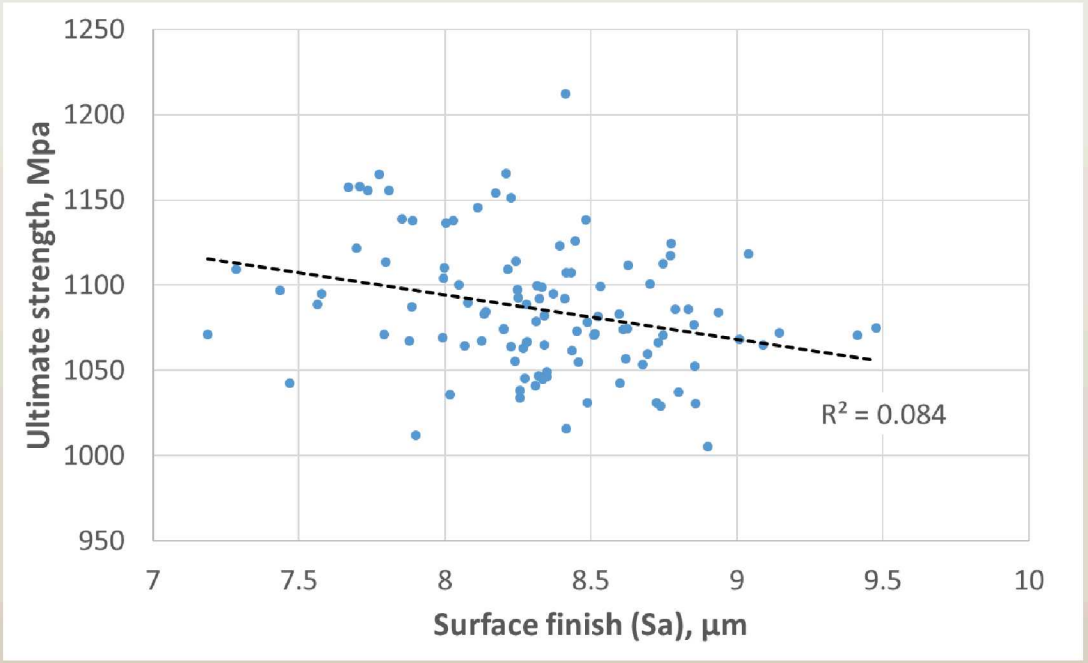
Implicit Part Correlations

- Archimedes density
  - stronger correlations w/process performance
- Surface finish
- No significant trends observed



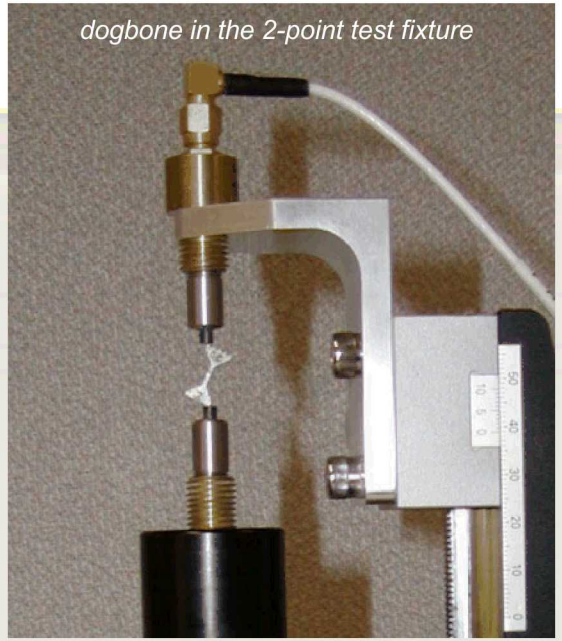
17-4PH dogbone surface roughness

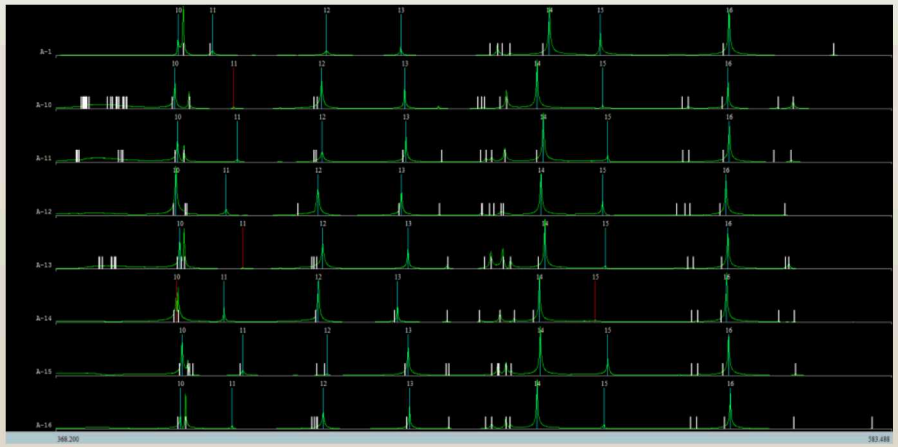




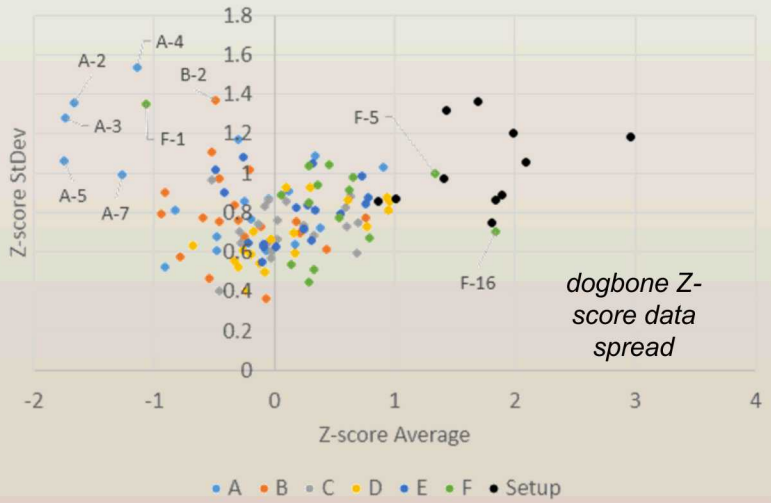
Resonant Ultrasound Spectroscopy

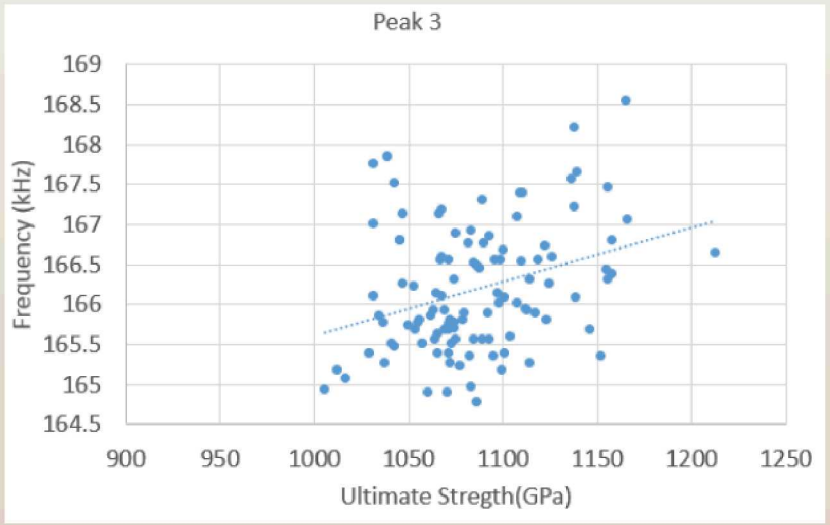
- Swept sine wave input from 2-point transducer
  - spectrum = 74.2 kHz to 1.6 MHz
  - intent is to identify outliers, variations, process limits, defects
- Identified 19 resonance peaks
  - Z-score compares peak frequency w/average & std. dev.
  - no strong trends across 17-4PH dogbone population





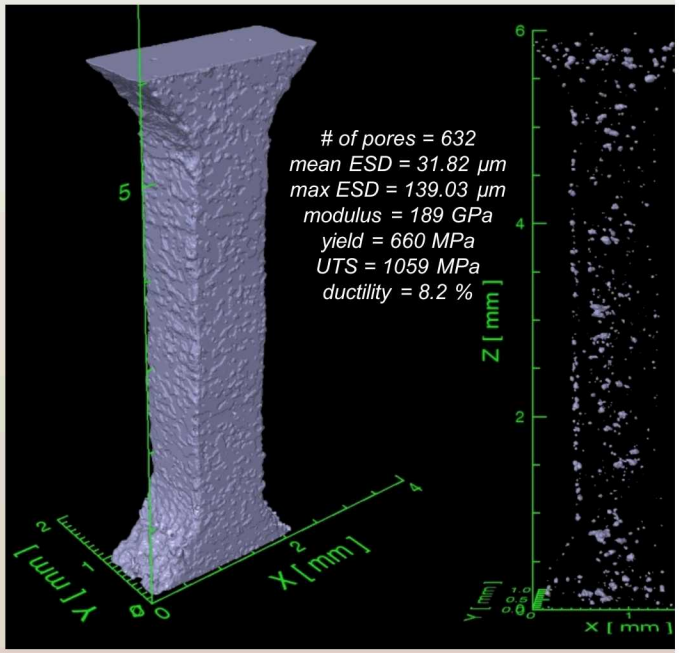
resonance response spectra



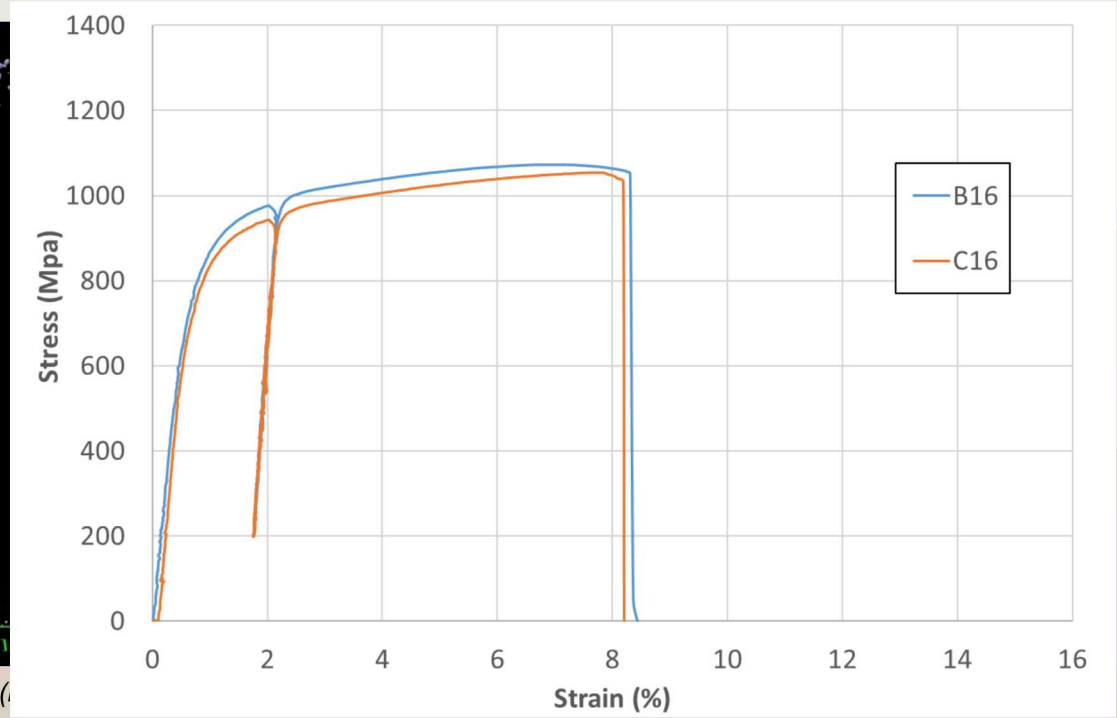


Explicit Porosity Measurements

- Computed tomography (CT)
  - NDE “gold standard” for porosity measurement
  - gage sections imaged w/resolution of 7 or 10 µm voxel edge length
- What can we see? Does it inform material behavior predictions?
  - justifiable for qualification and/or production?

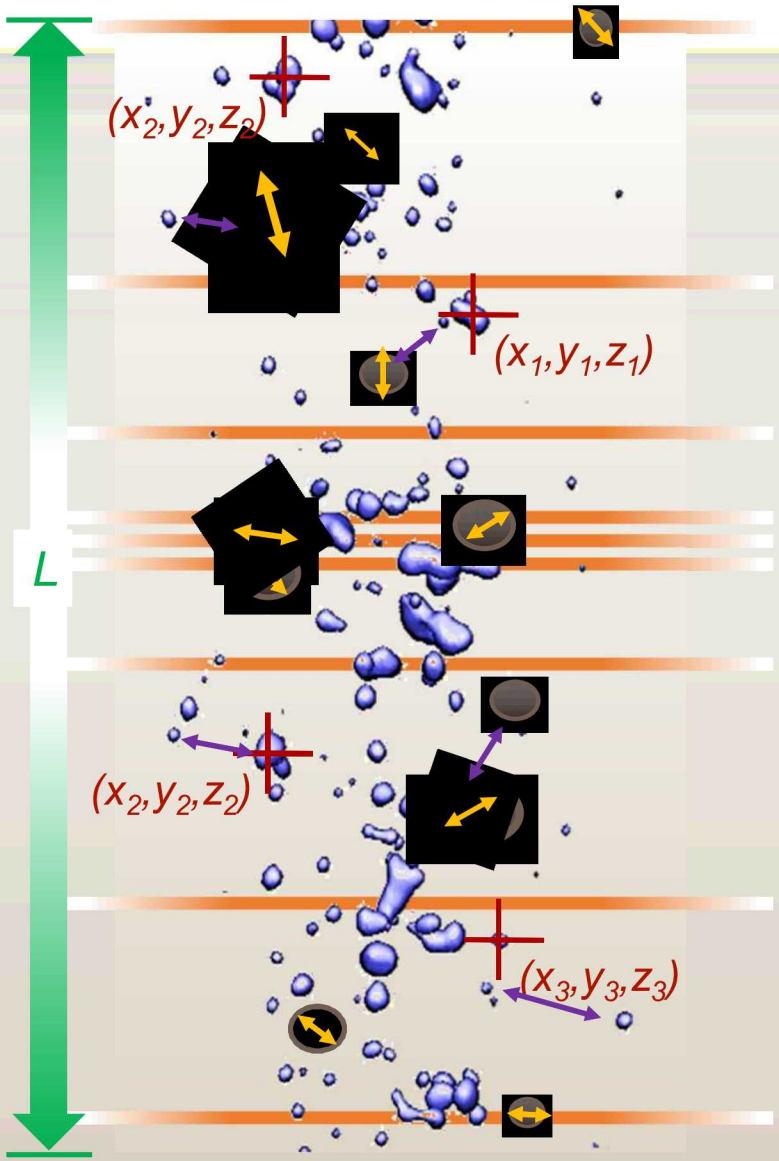


dogbone B,16 CT surface image (left), porosity map (



ESD = equivalent spherical diameter

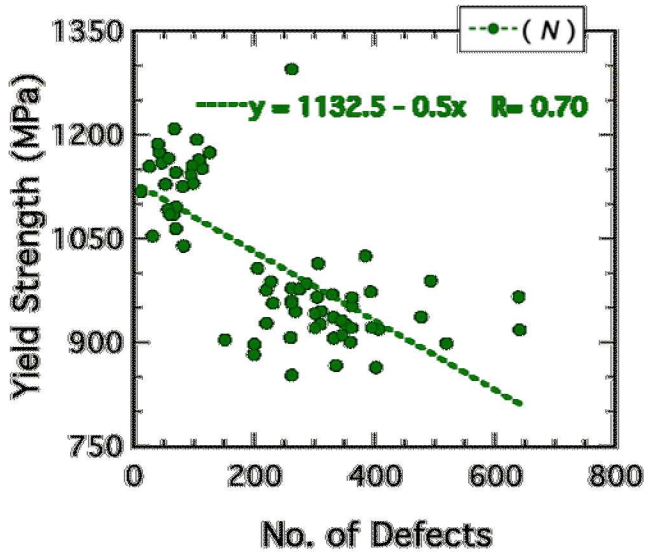
Defect Characterization

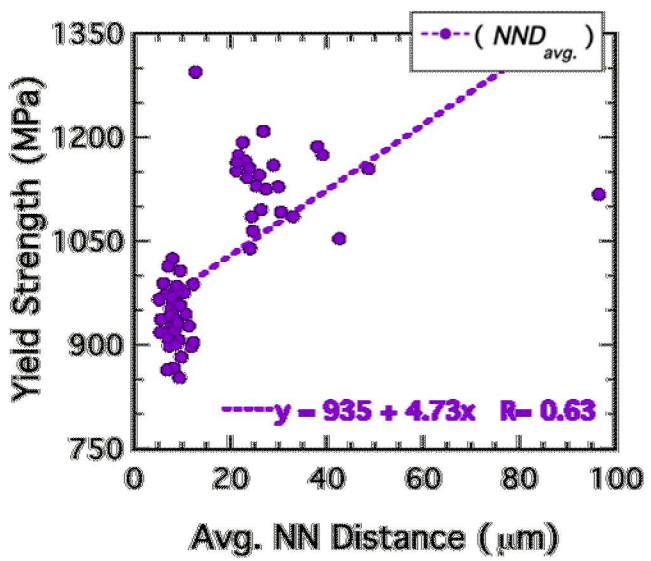


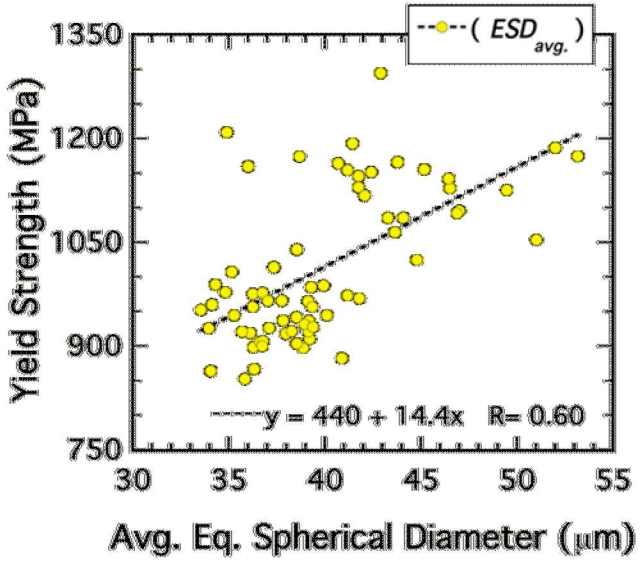
- Total Volume of Defects (V_{tot})
- Pore Volume Fraction (V_{fract})
- Spatial Location of Pores *(x, y, z)*
- Total Number of Defects *(N)*
- Total Defects/Length *(N/L)*
- Average Defect Volume ($V_{avg.}$)*
- Average Equivalent Spherical Diameter ($ESD_{avg.}$)*
- Average Cross-Sectional Area ($CSA_{avg.}$)*
- Average Nearest Neighbor Distance ($NND_{avg.}$)*

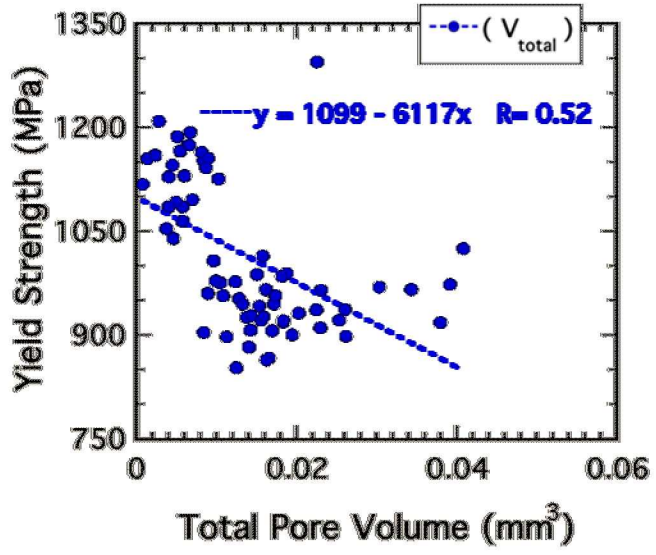
How do we *best* represent the defect populations present?

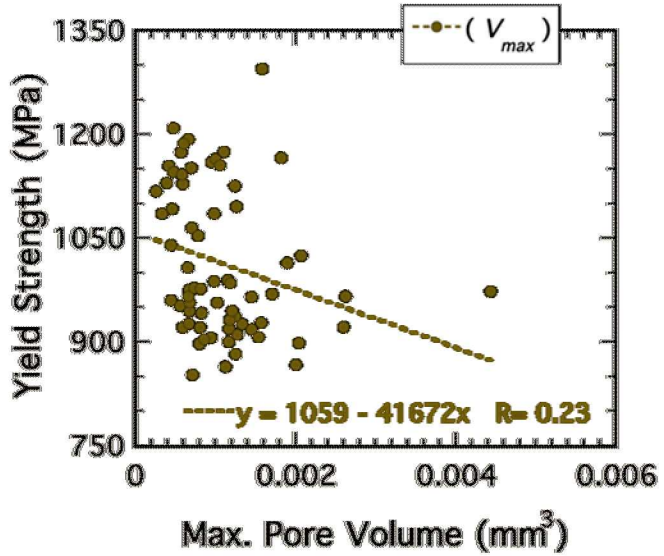
Statistical Correlations Are Elusive







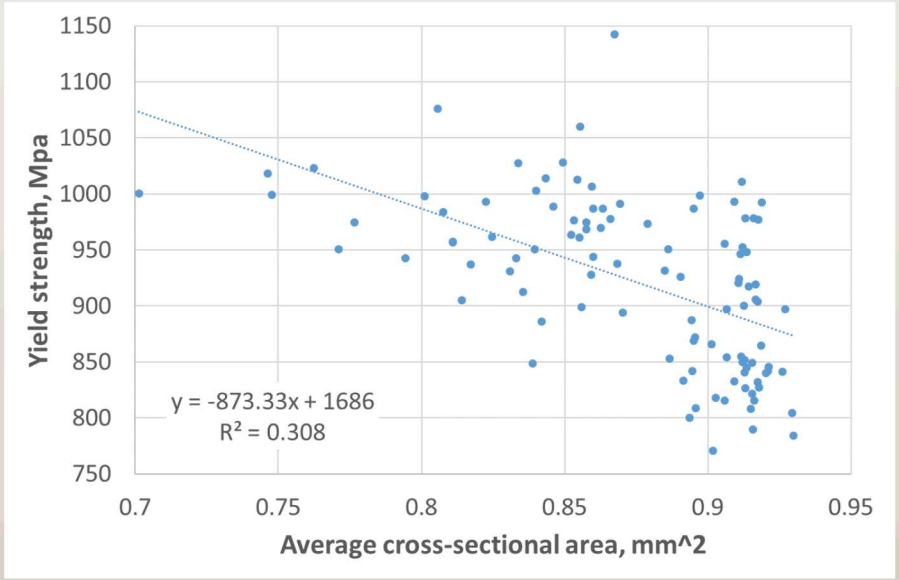


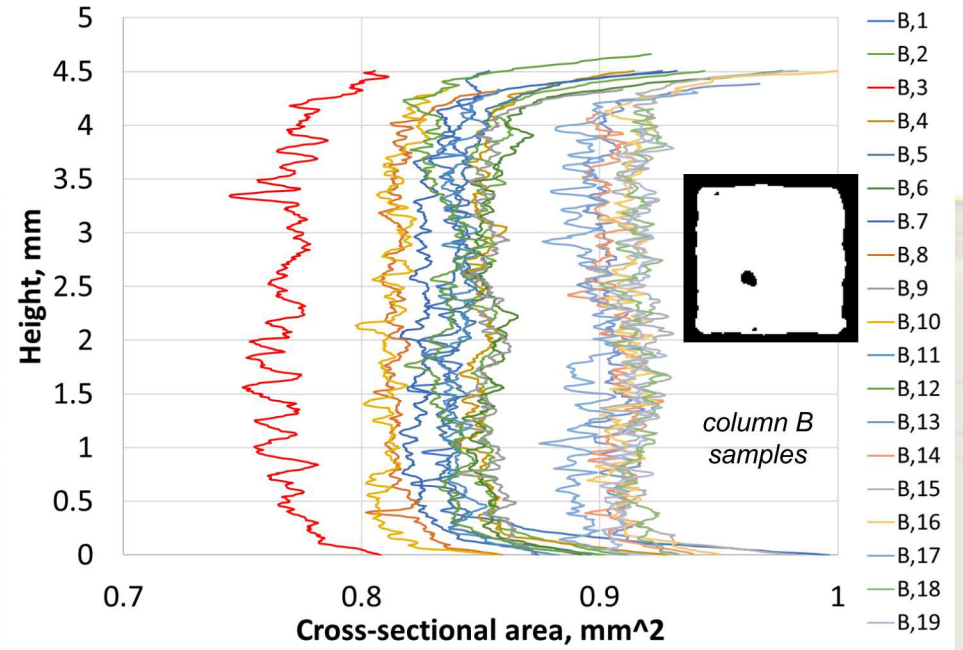


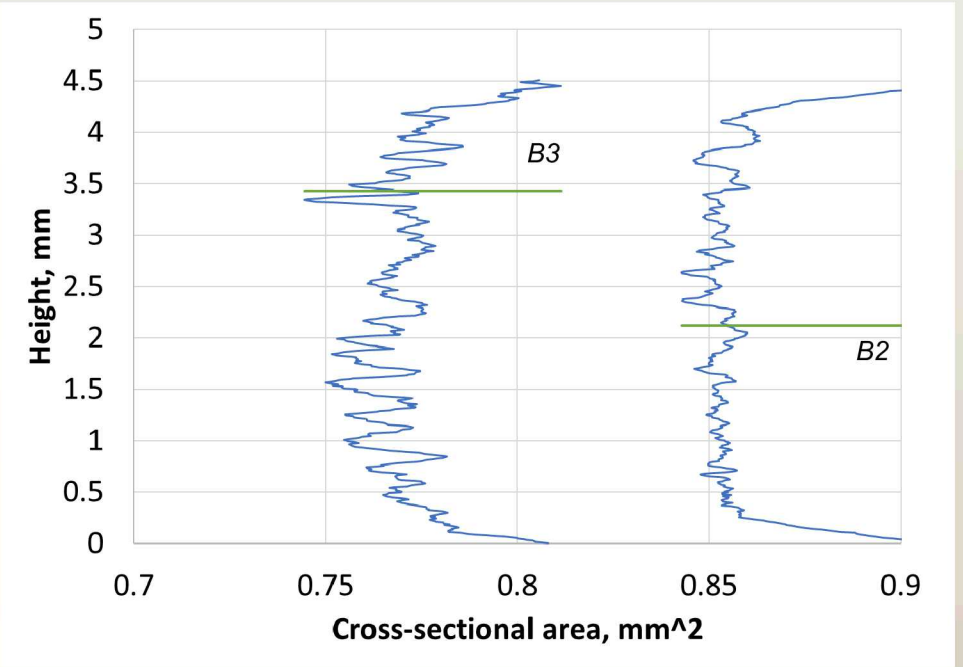
Measure	R^2
No. of Defects	0.50
Avg. NN Distance (mm)	0.40
Avg. ESD (mm)	0.36
Max CSA Redux (mm^2)	0.38
Total Pore Volume (mm^3)	0.27
Avg. Defect Vol. ($mm^{3)}$	0.25
Max CSA Redux (%)	0.24
Maximum Pore Size	0.07
Seven factor multivariate regression	0.60

Post Mortem Analyses

- Can forensic trends be identified?
- CT data analysis
  - calculate cross-section per layer
  - gage sections are rough & porous
  - fractures sometimes correspond to minimum areas
  - general trends remain weak



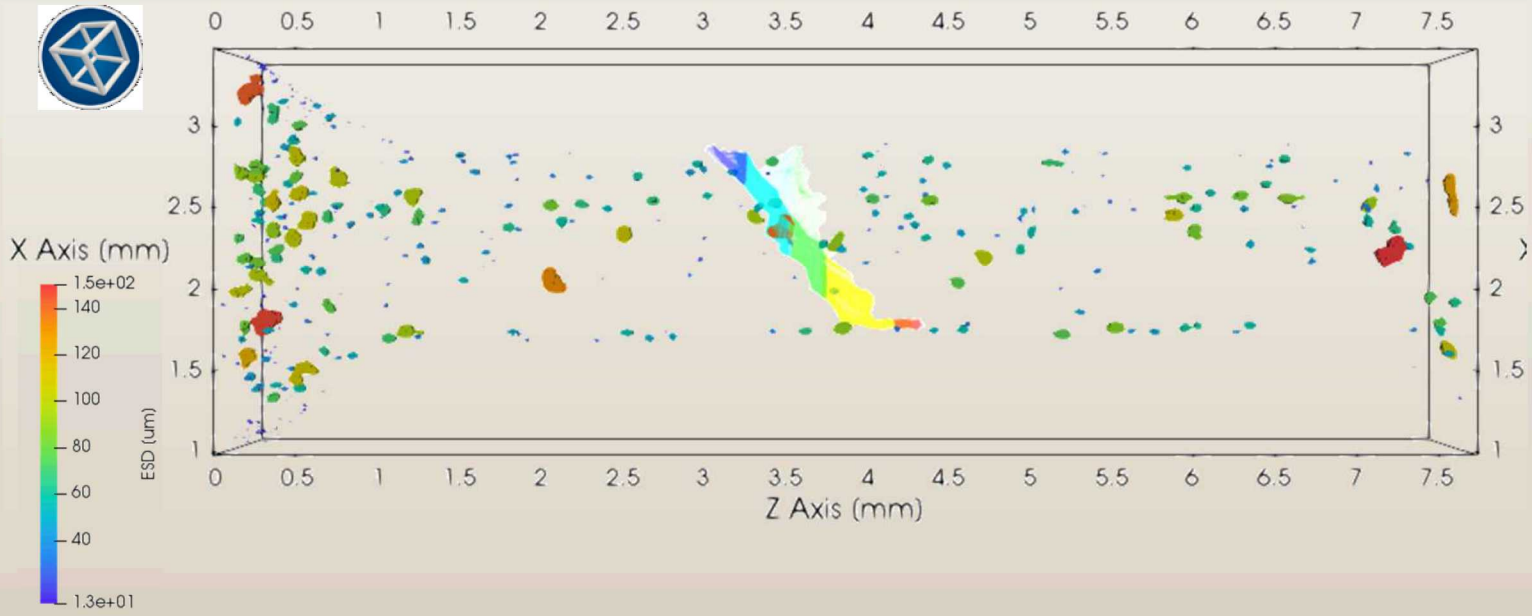


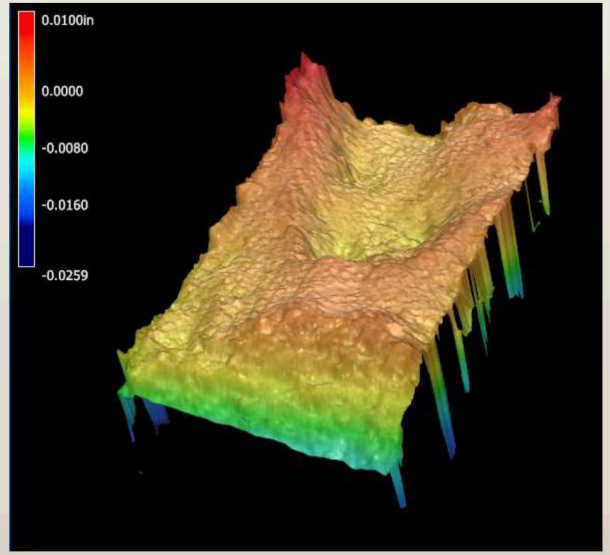


Fractography

- 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

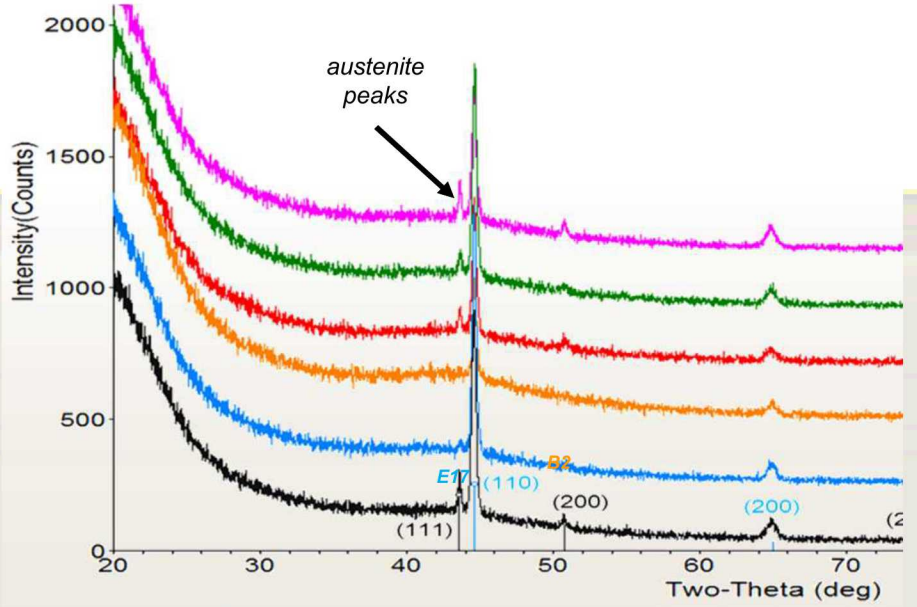
B2, fracture surface optical image by structured light scanning



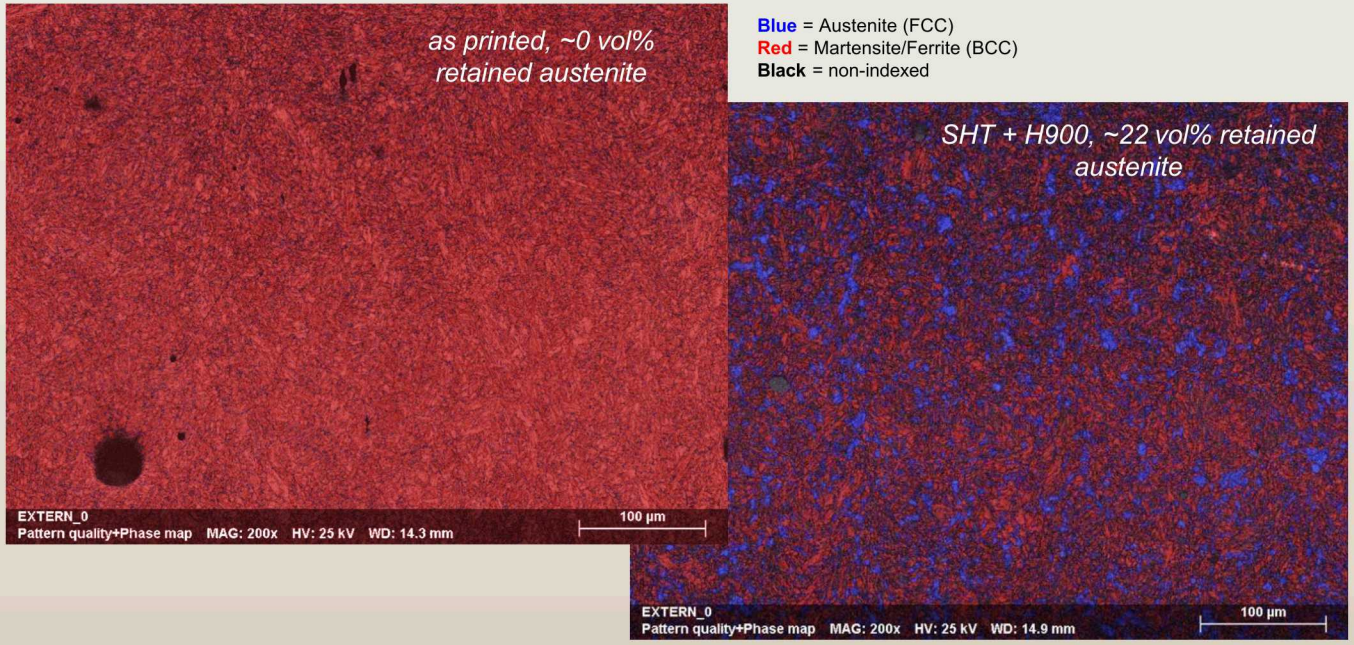


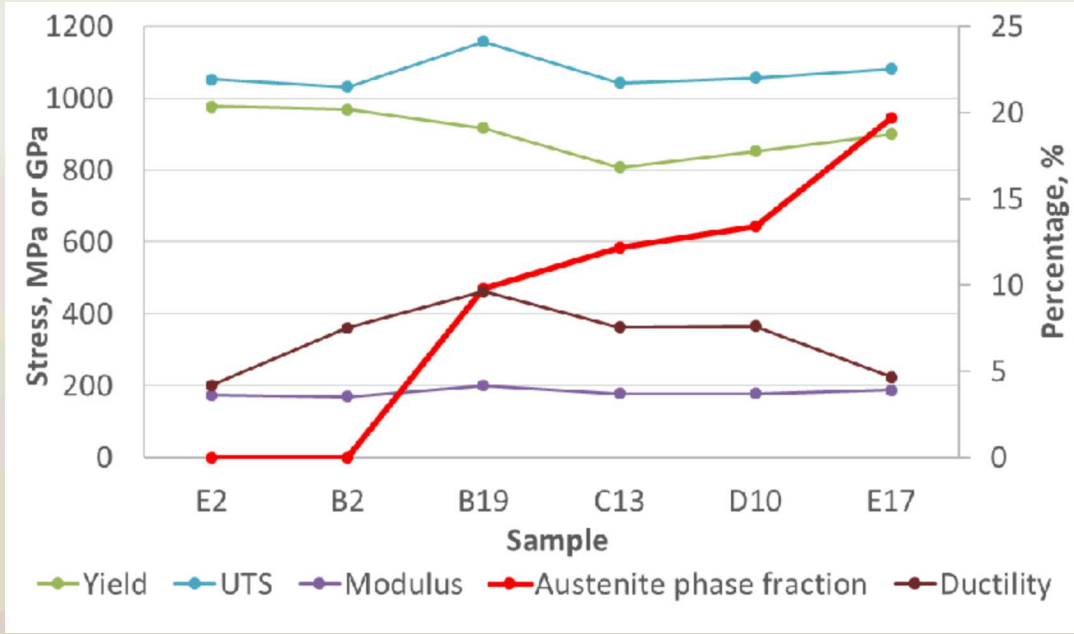
Microstructure Examination

- 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

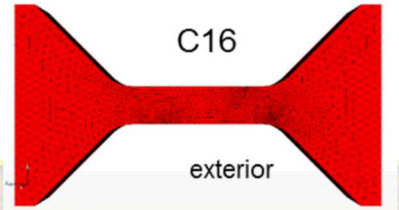


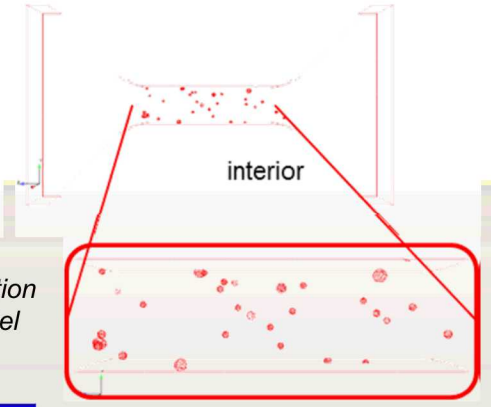


material performance variation w/austenite phase fraction

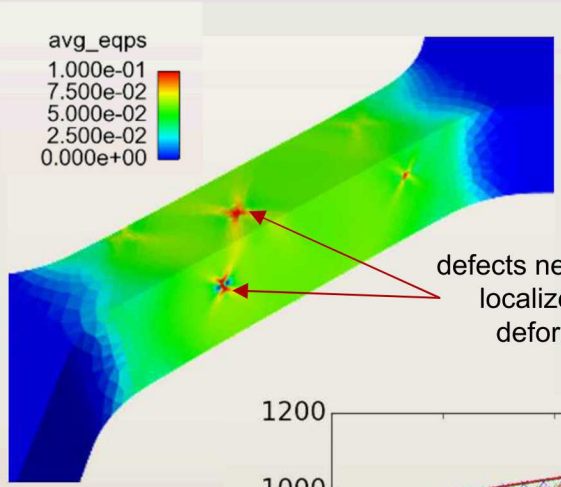
Material Models

- Want to inform & predict material variability
- Approach
  - explicitly subtract spherical CT porosity volumes from dogbones
  - solve tensile loading
    - ignore residual stress, surface finish & defects w/volume below ~90µm3
    - continuum properties calibrated to low porosity sample D16
  - leveraged in on-going efforts
- Expectations
  - large defects will intensify & localize deformation
  - microscale void mechanisms will drive failure

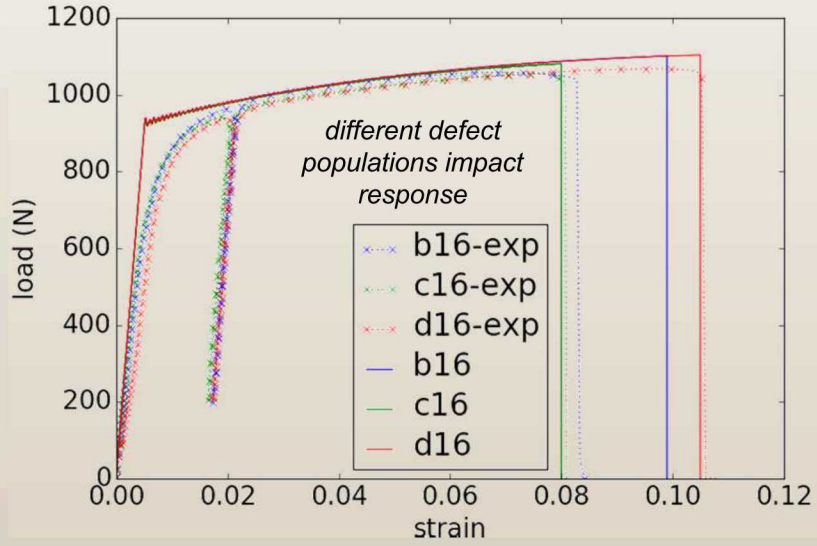




explicit defect representation applied to dogbone model

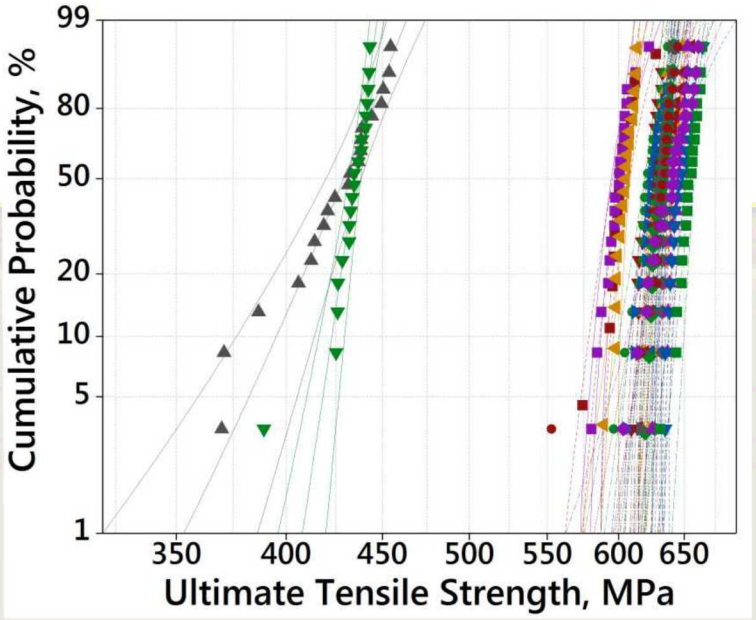


defects near surfaces localize plastic deformation

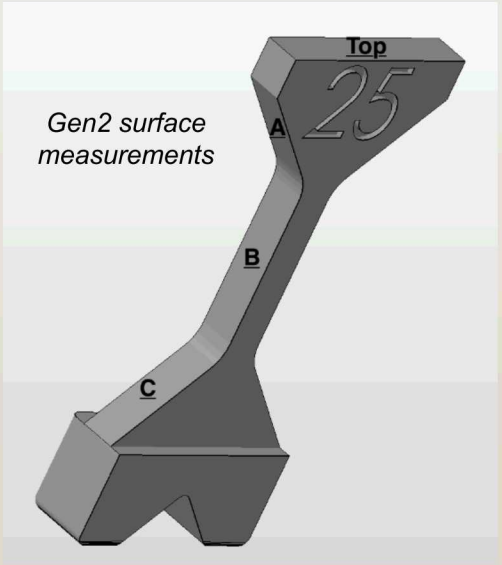


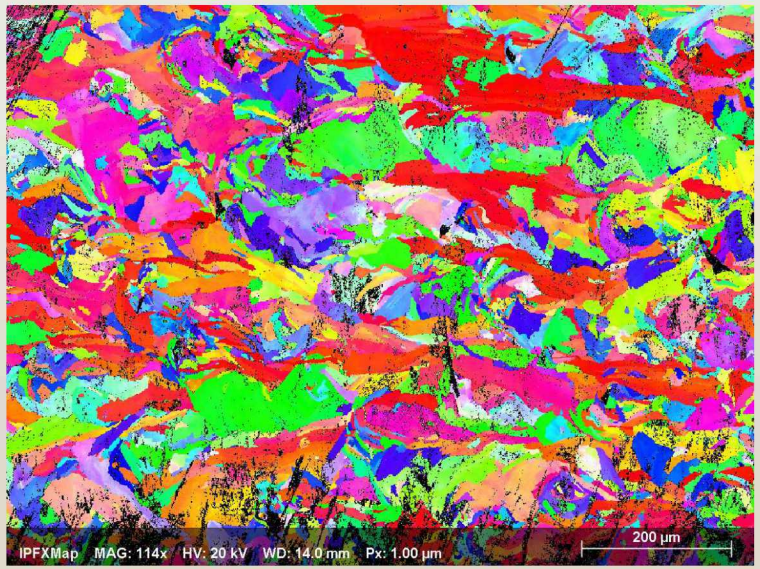
316L SS Study

- Exploring intra-build variations, process sensitivities / margins / optimization
  - leveraging analysis tools developed
- Sandia ProX 200
  - 25 dogbones / process setting
  - parameters
    - power, velocity, cross-feed, scan strategy, # parts/plate
    - represents ~2500 dogbones
    - Gen2 HTT development
  - measurements
    - top surface distortion (after EDM)
    - surface finish (top, side, angles)
    - Archimedes density
    - CT
    - resonance testing
    - tensile testing
    - metallography, fractography



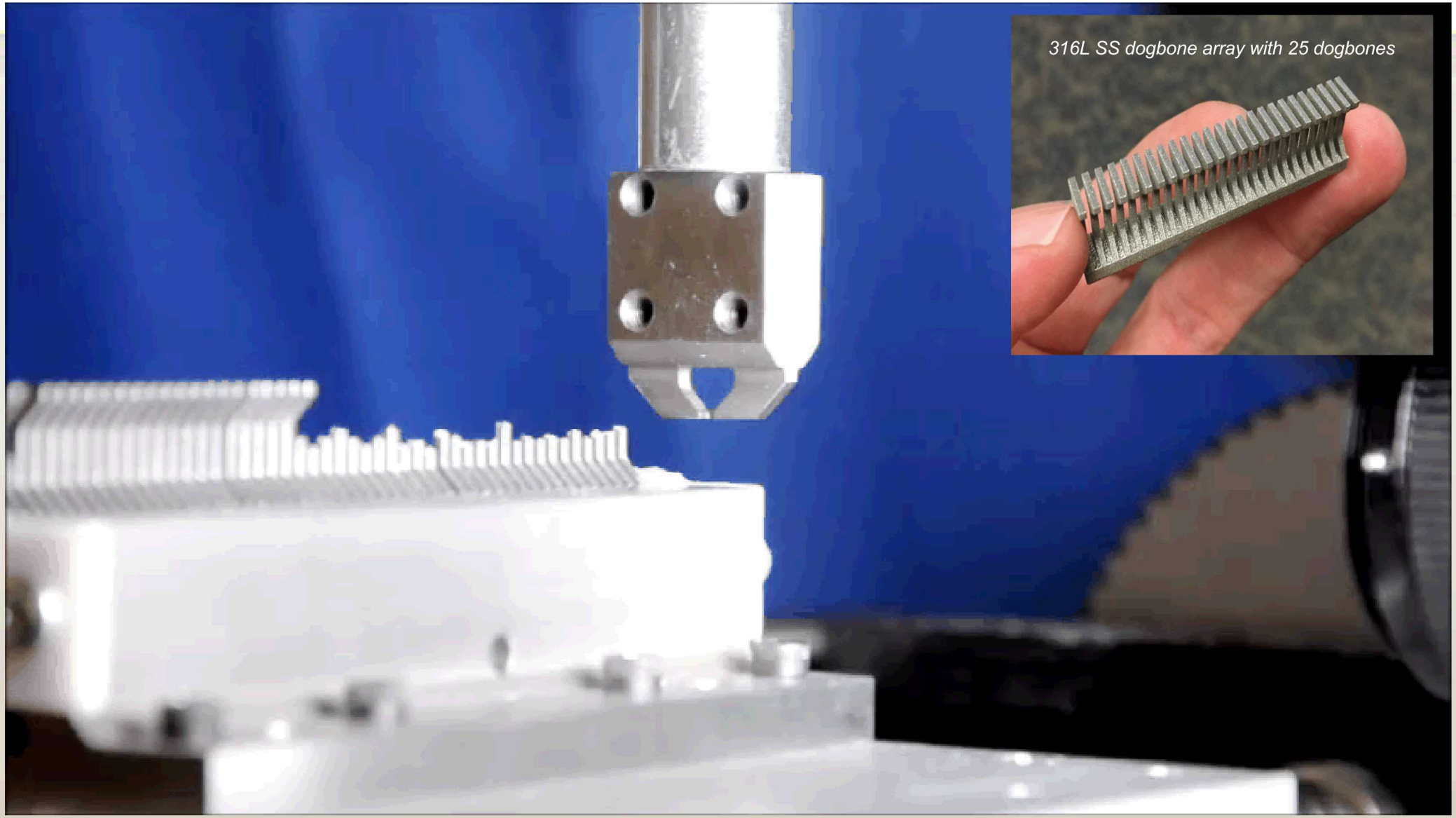
UTS variation w/power, velocity & scan pattern



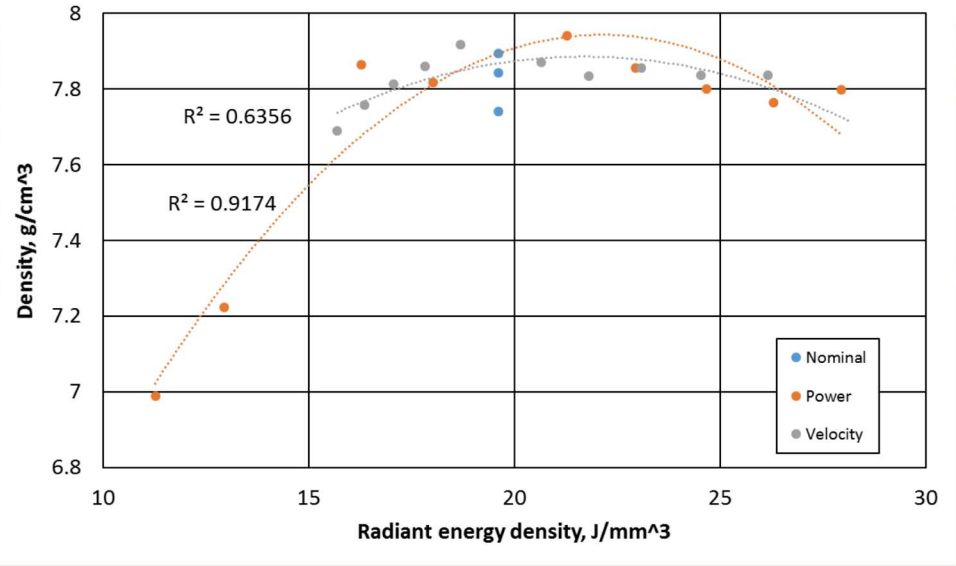


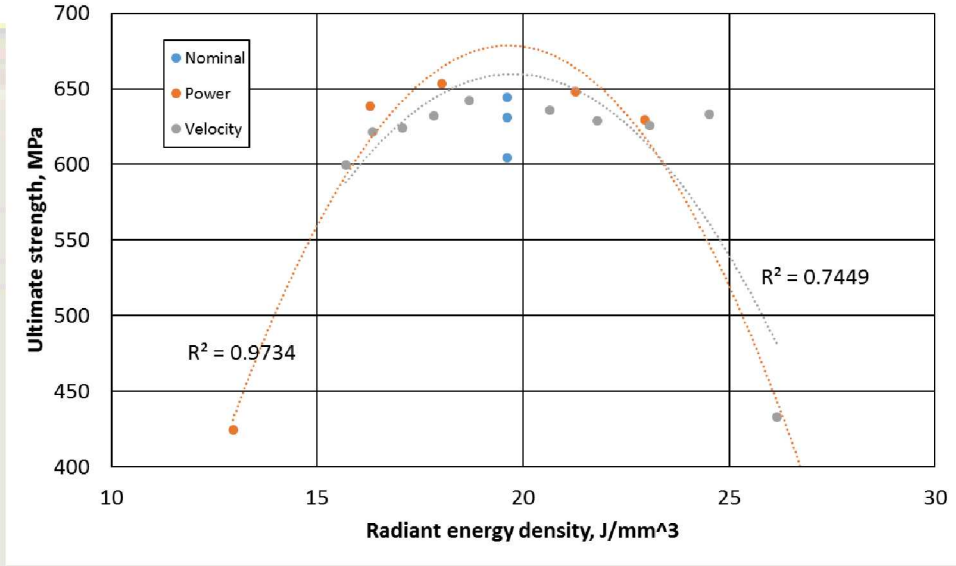
representative texture map via EBSD, phase content has been relatively consistent across process settings

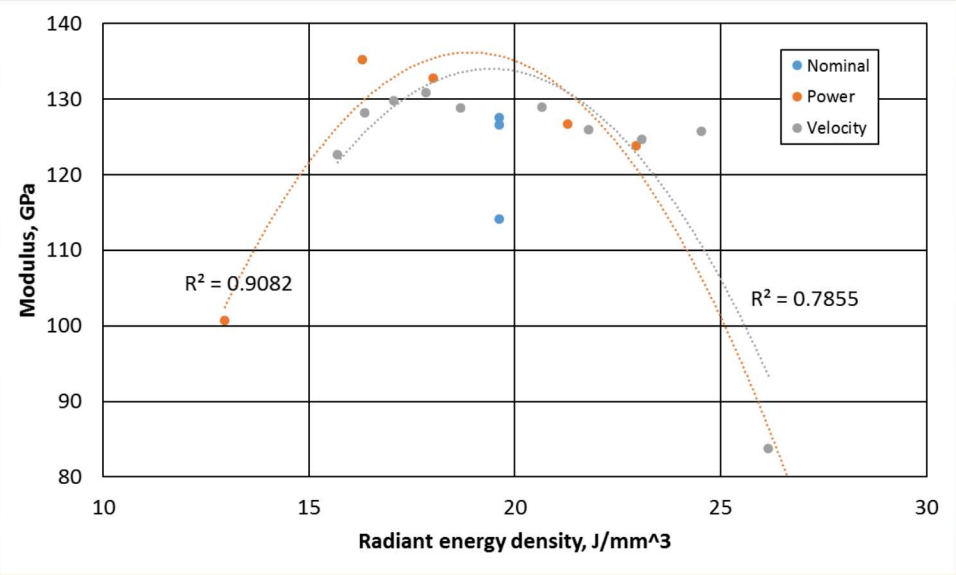
High Throughput Testing: Gen 2

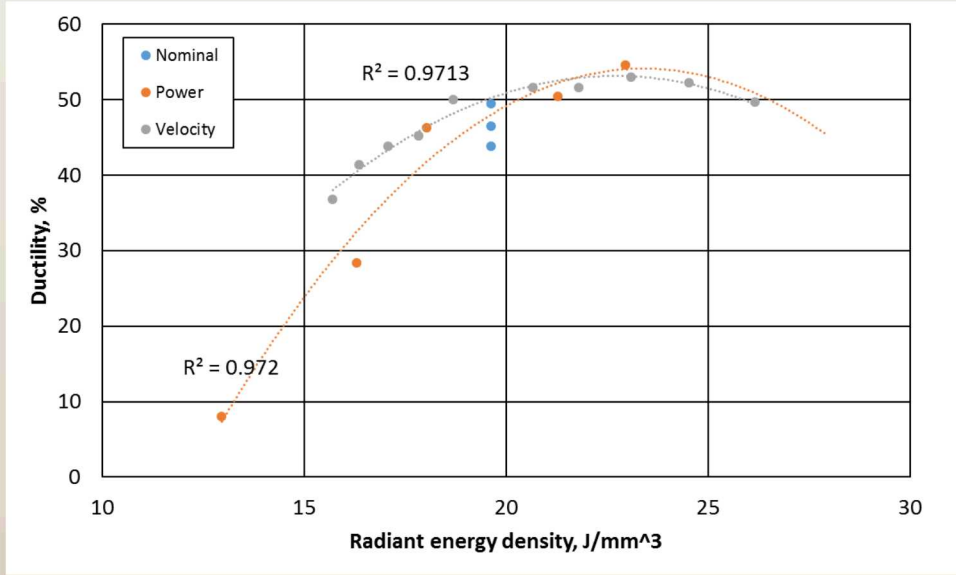


Intra-Build Process Trends

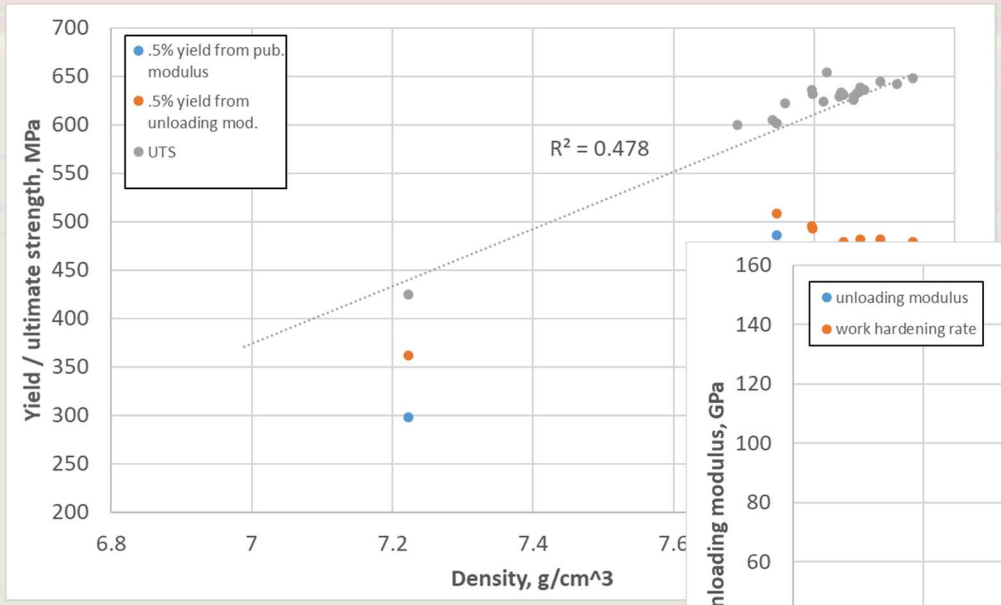


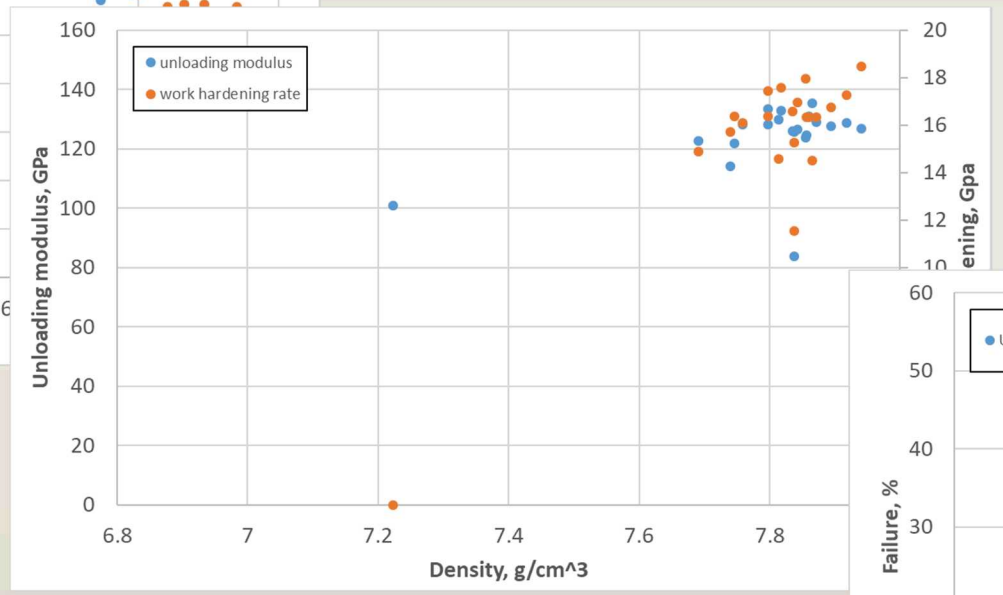


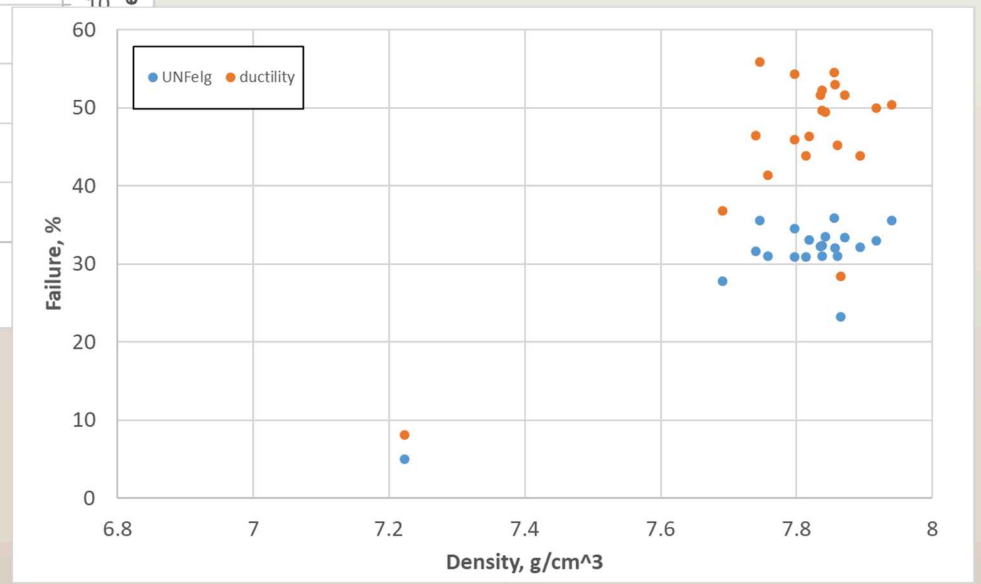




Intra-Build Process Trends

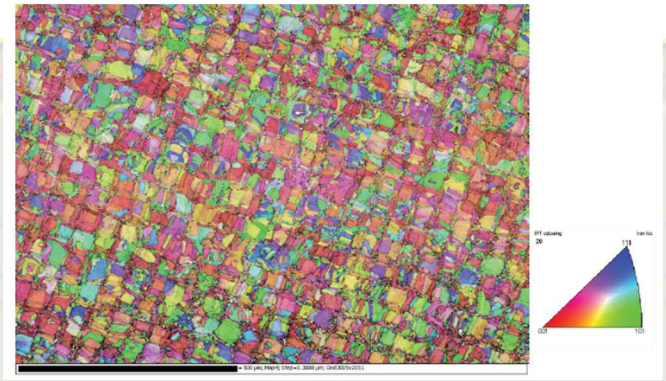




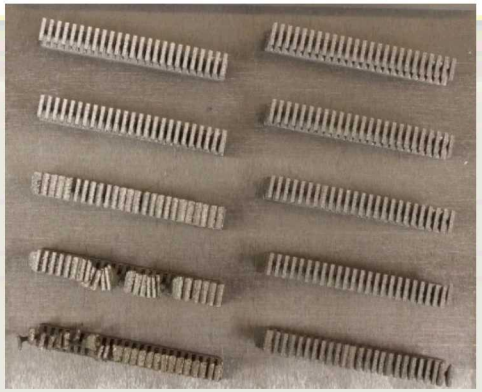


ProX 316L Process Development

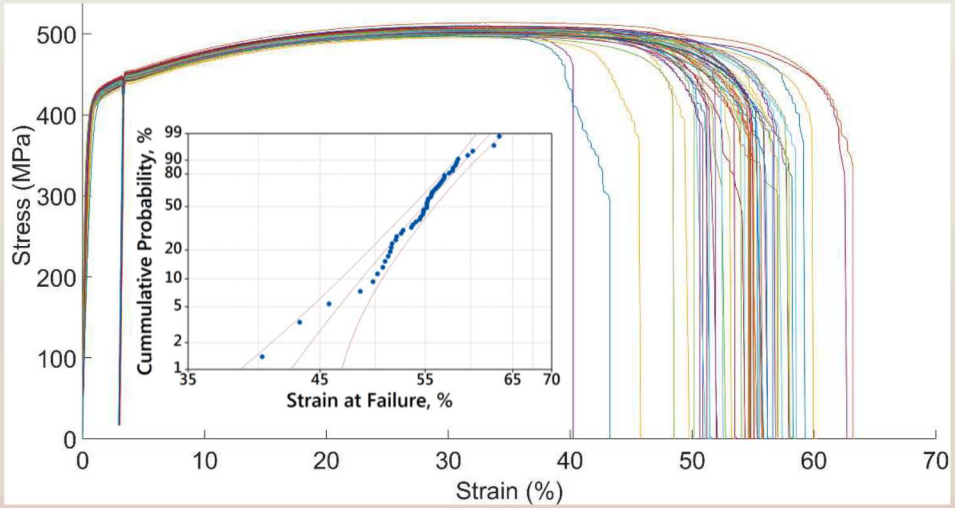
- Scope
  - process mapping w/CMU
  - process sensitivity study
  - powder reuse
  - machine metrology
  - in-situ process signatures
- Very robust material



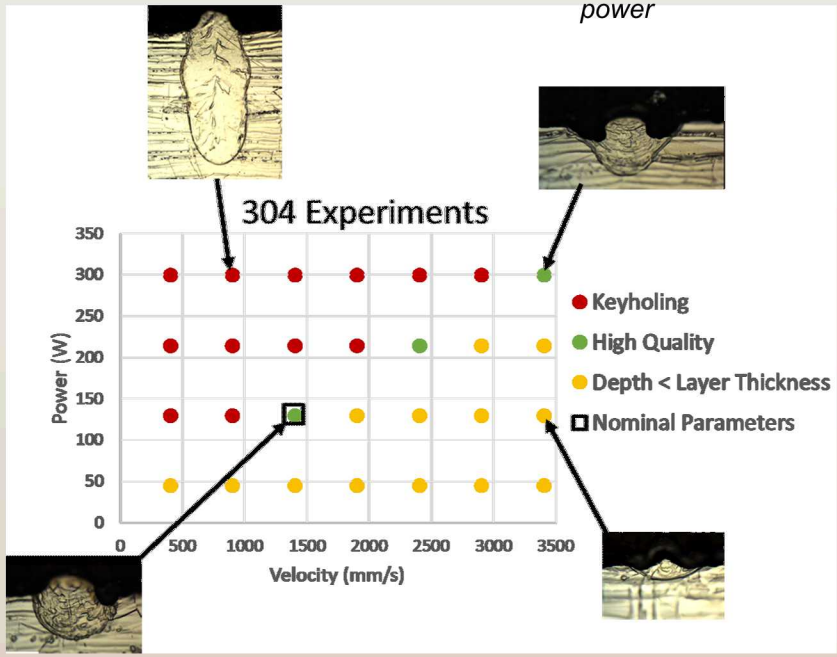
unique EBSD grain structure for 316L SS



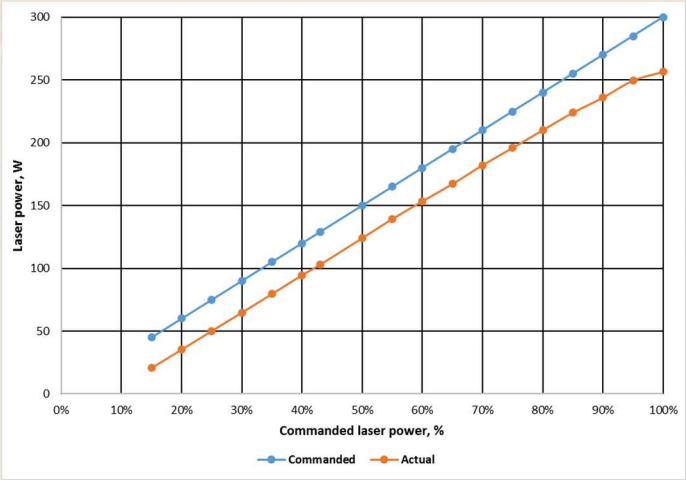
Gen 2 samples w/varying laser power

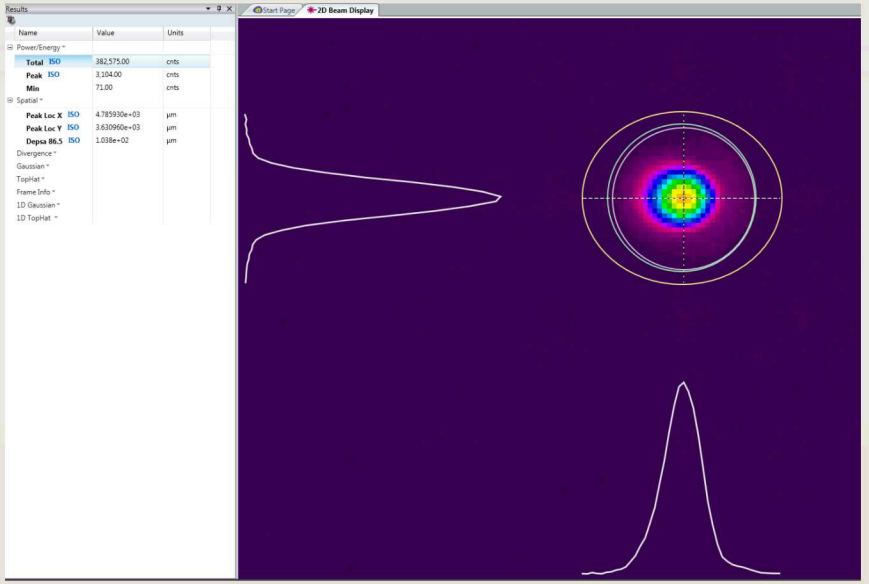


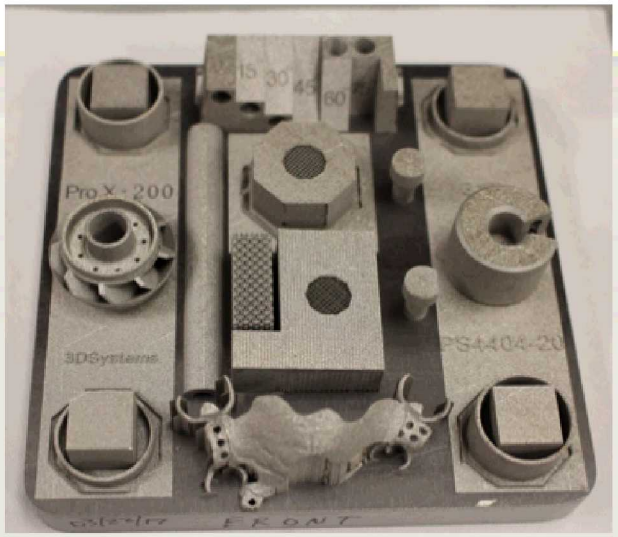
HTT 316L SS data, 50 1x1mm dogbone samples

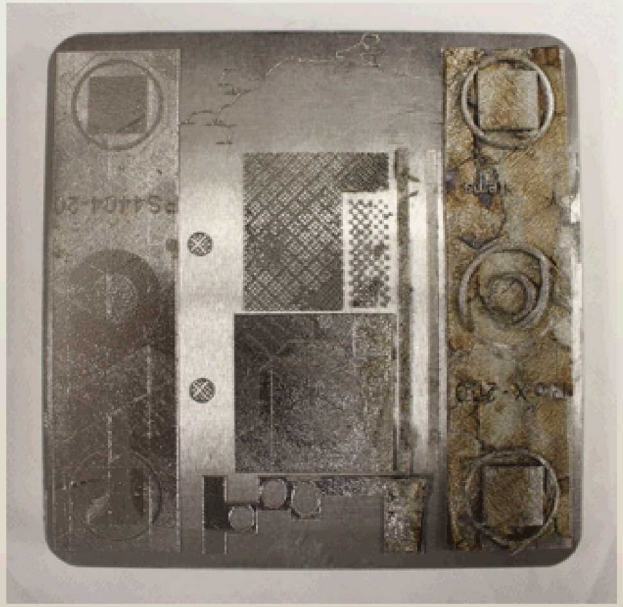


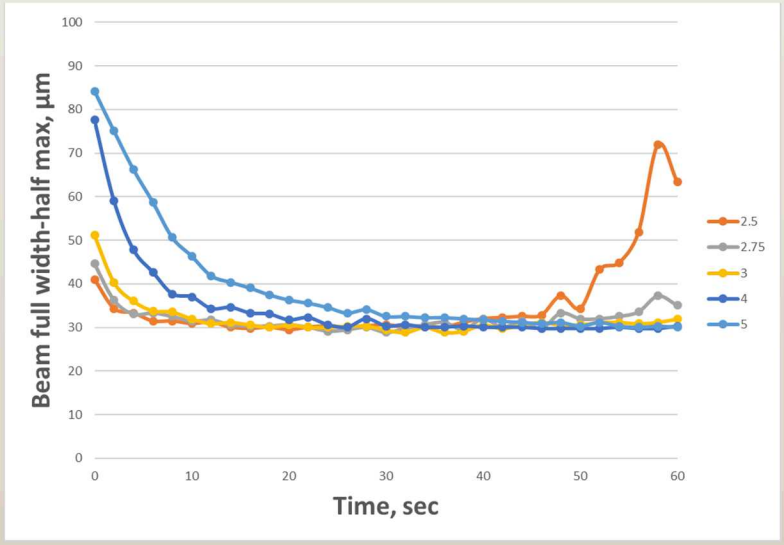
Beam Diagnostics





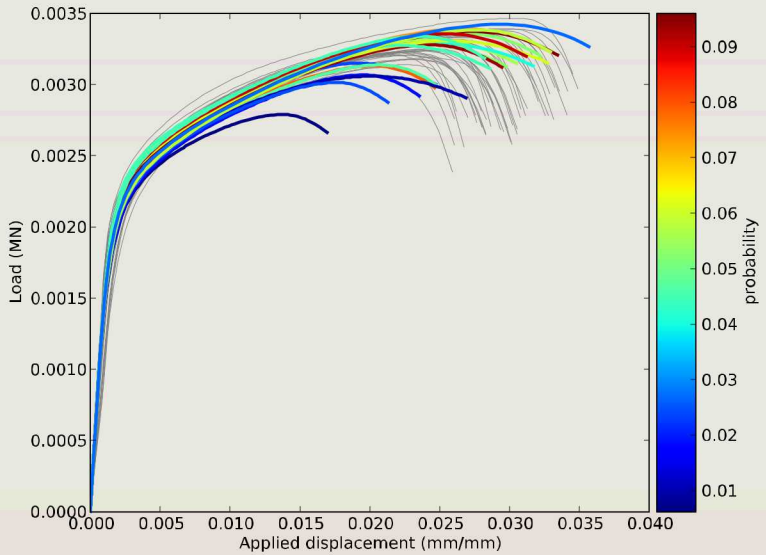






Structure-Properties Summary

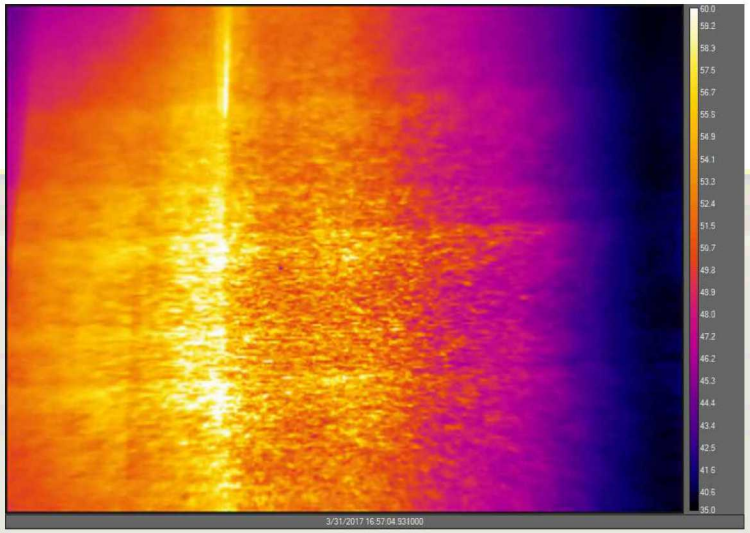
- Material assurance is a challenge
  - material behavior is complex
    - predictive inter-build correlations for 17-4PH have not been straight-forward
    - contributing factors include process, feedstock, measurement, surface finish, microstructure, residual stress, part geometry
  - orthogonal testing pursuing multiple signatures is invaluable (& necessary) for qualification / product acceptance
- Tools developed to interrogate & analyze defects
  - performance distributions can be captured efficiently & used to understand material & process
  - tracking intra-build population shifts may be possible
    - intra-build / process change correlations identified for 316L SS



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

Pursuing In-Situ Signatures

- 3D Systems ProX 200
  - 3D Systems Open Protocol platform
- 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
- Laser characterization
  - Ophir Spiricon SP928 beam profiler
  - Ophir L50(300)A-LP1 power meter

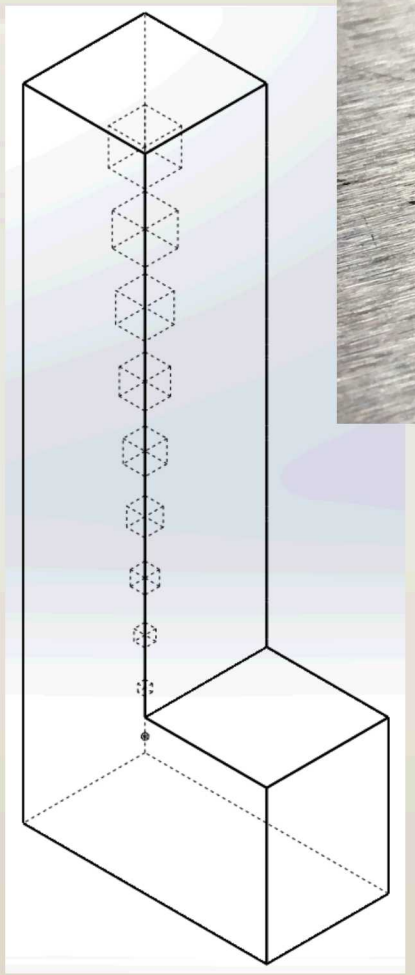


FLIR A310, laser on plate, ~100W, 1.4m/sec, 125µm hatch, 100µm beam dia.

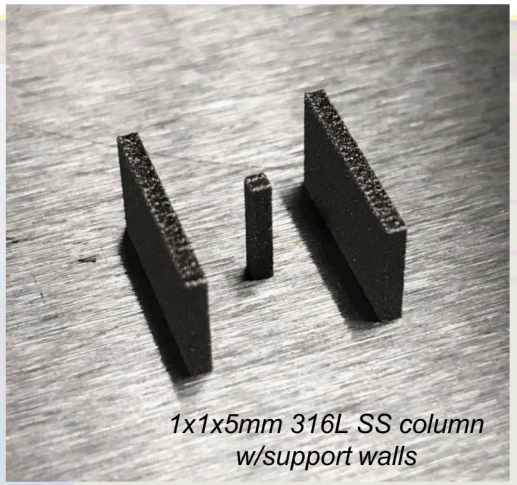
Photron high speed optical melt pool video

Intentional Porosity Structure

- Introduced intentional pores
  - 316L stainless steel
  - 1-10 layer thickness
    - 30-300µm
  - 1x1x5.25mm column
    - 175 layers
    - 87,500 T-V frames per part
- Tests are quick
  - data analysis is not…
  - seek to correlate spatial sensor data (X,Y,Z,time) to material porosity (X,Y,Z)

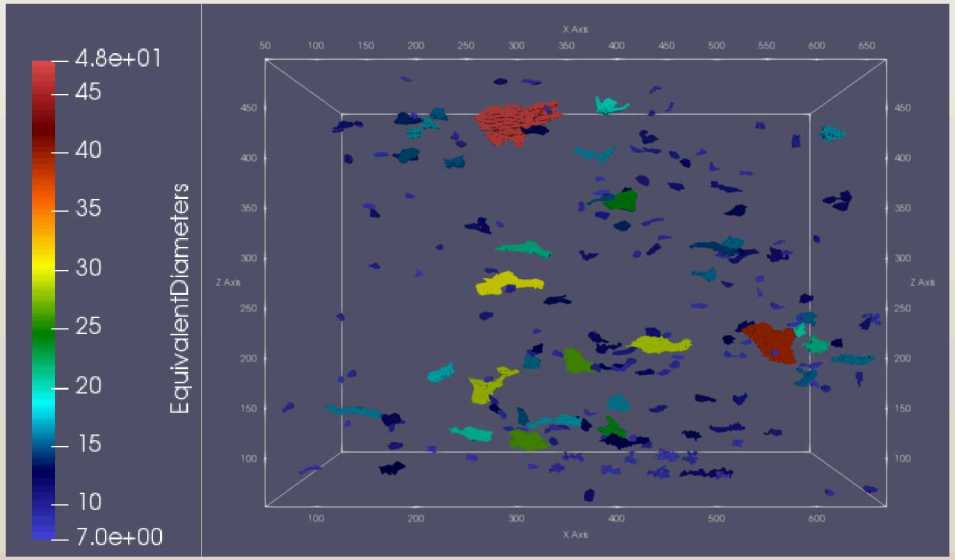


captured hole structure



1x1x5mm 316L SS column w/support walls

captured defect holes part CT image, Zeiss Xradia 520 Versa, voxel resolution ~ 2µm, Harlan Brown-Shaklee



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

Material Reconstruction

VOLUME GRAPHICS

Micro-computed tomography

MATLAB

Interactive Data Language

IDL

3D reconstruction
3D quantification

Adobe Photoshop

batch processing
16bit > 8bit conversion
lossless filetype conversion

FIJI

alignment & registrati
cropping
grayscale matching
autoleveling
image filtering
thresholding

DREAM.3D

image processing & quantification. 3D reconstructions

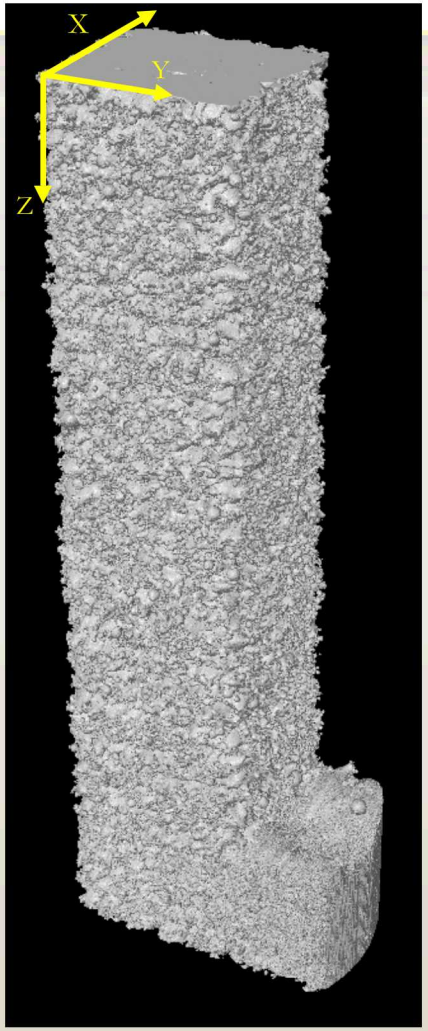
BlueQuartz Software
Specializing in Software Tools for the Scientist

http://dream3d.bluequartz.net

ParaView
Parallel Visualization Application

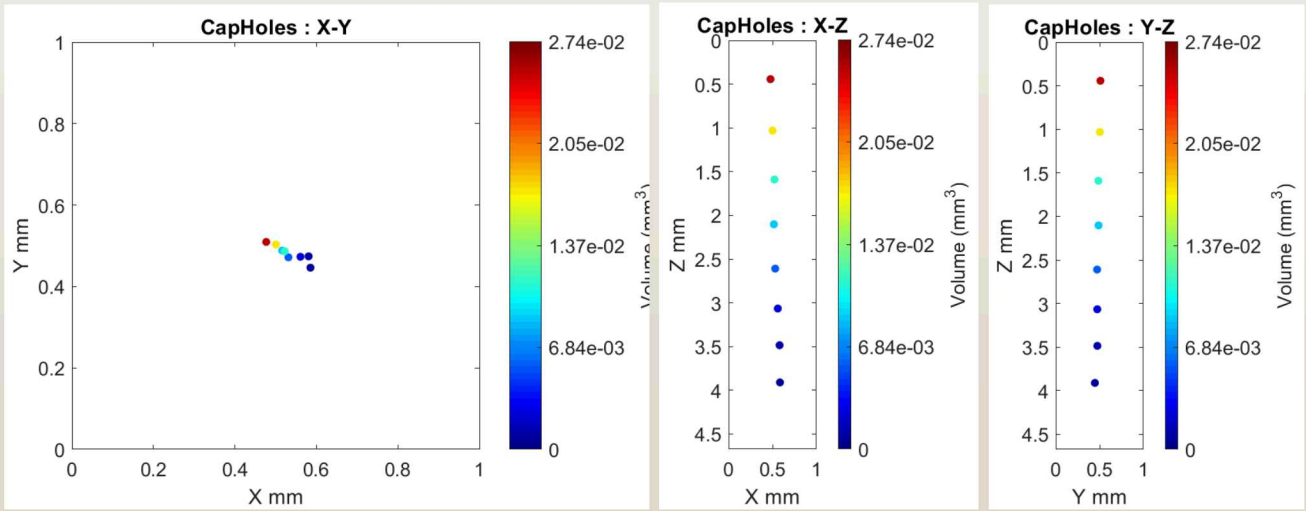
ROBO-MET.3D™
A UES PRODUCT

Serial-sectioning

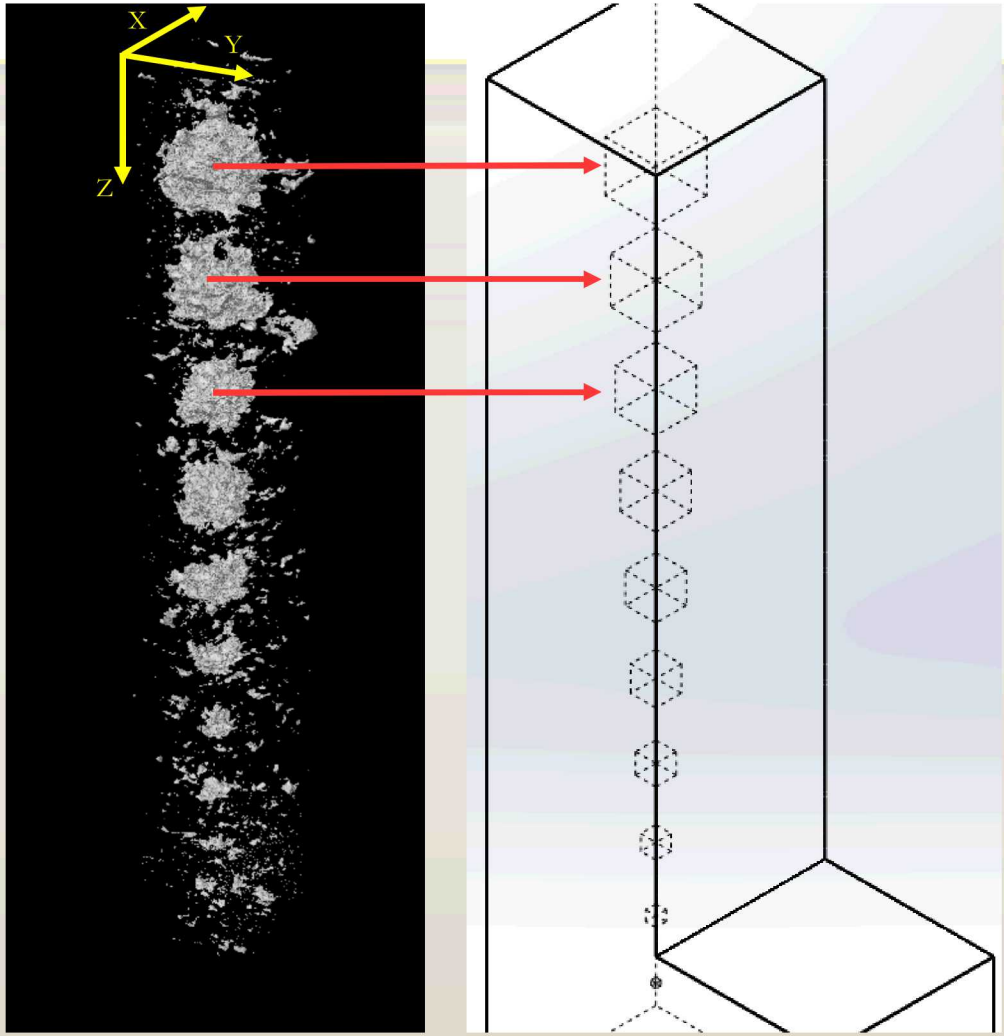


µCT Data Registration

- Rough surfaces create challenges
- Registering pore structures to nominal design
  - calculate top three hole centroid locations
  - calculate $\Delta(x,y,z)$ from design locations
  - remove slope & offsets

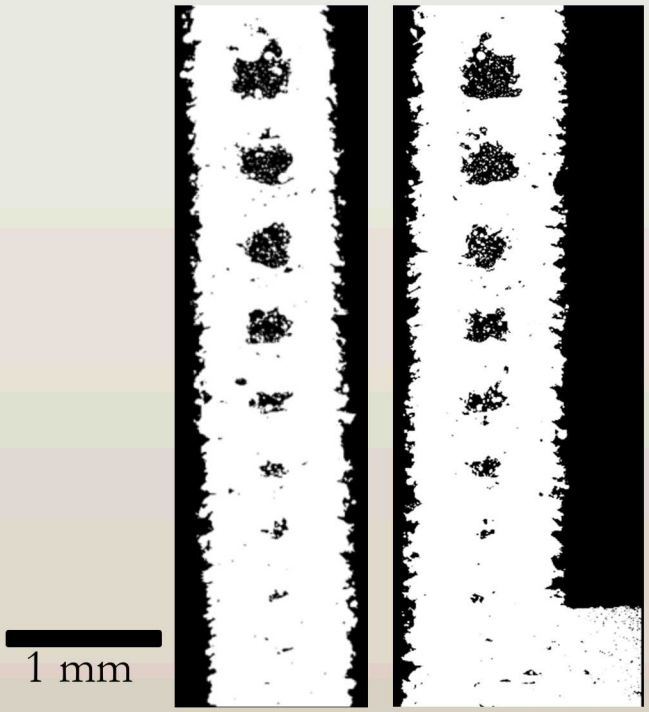


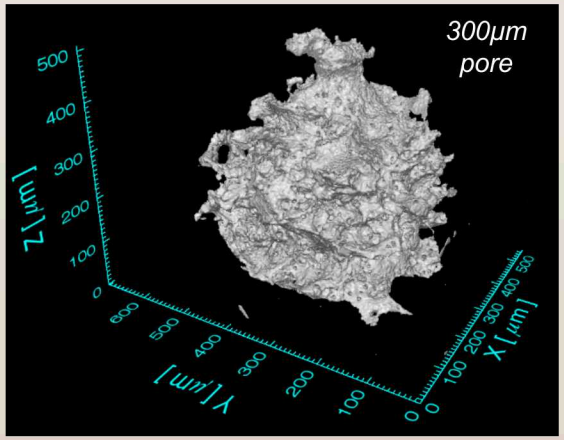
intentional pore locations showing data misalignment

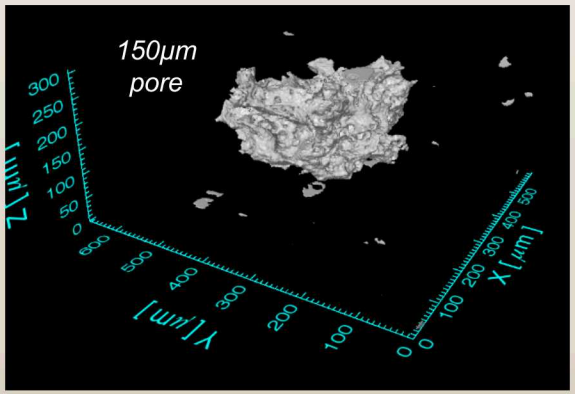


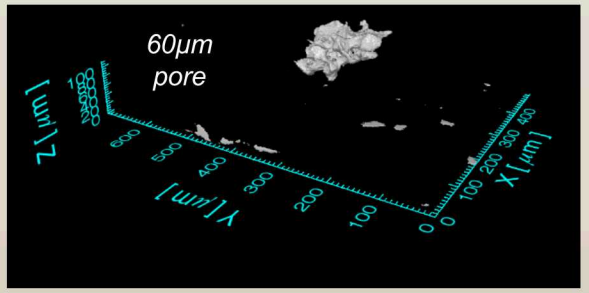
Pore Identification

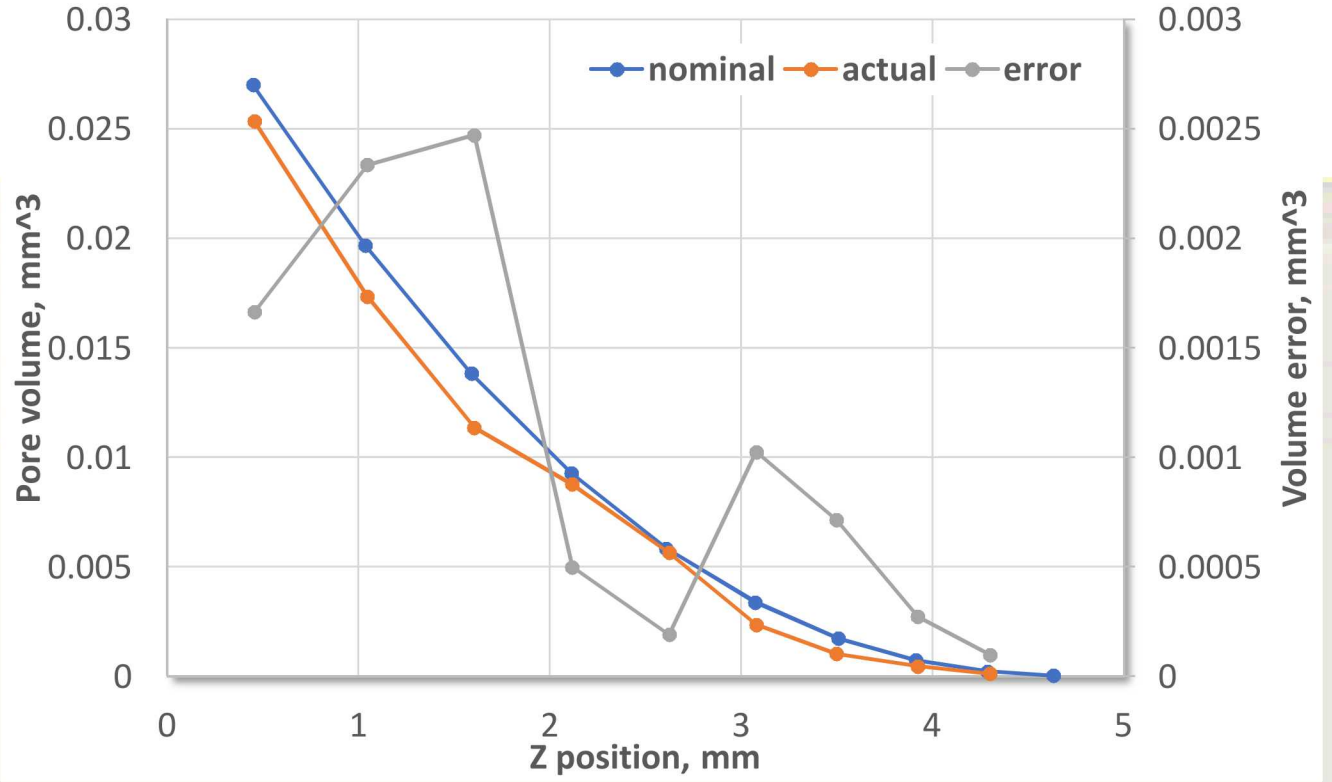
- Largest 9 pores easily distinguished by volume
- 30µm pore indistinguishable from process porosity by size







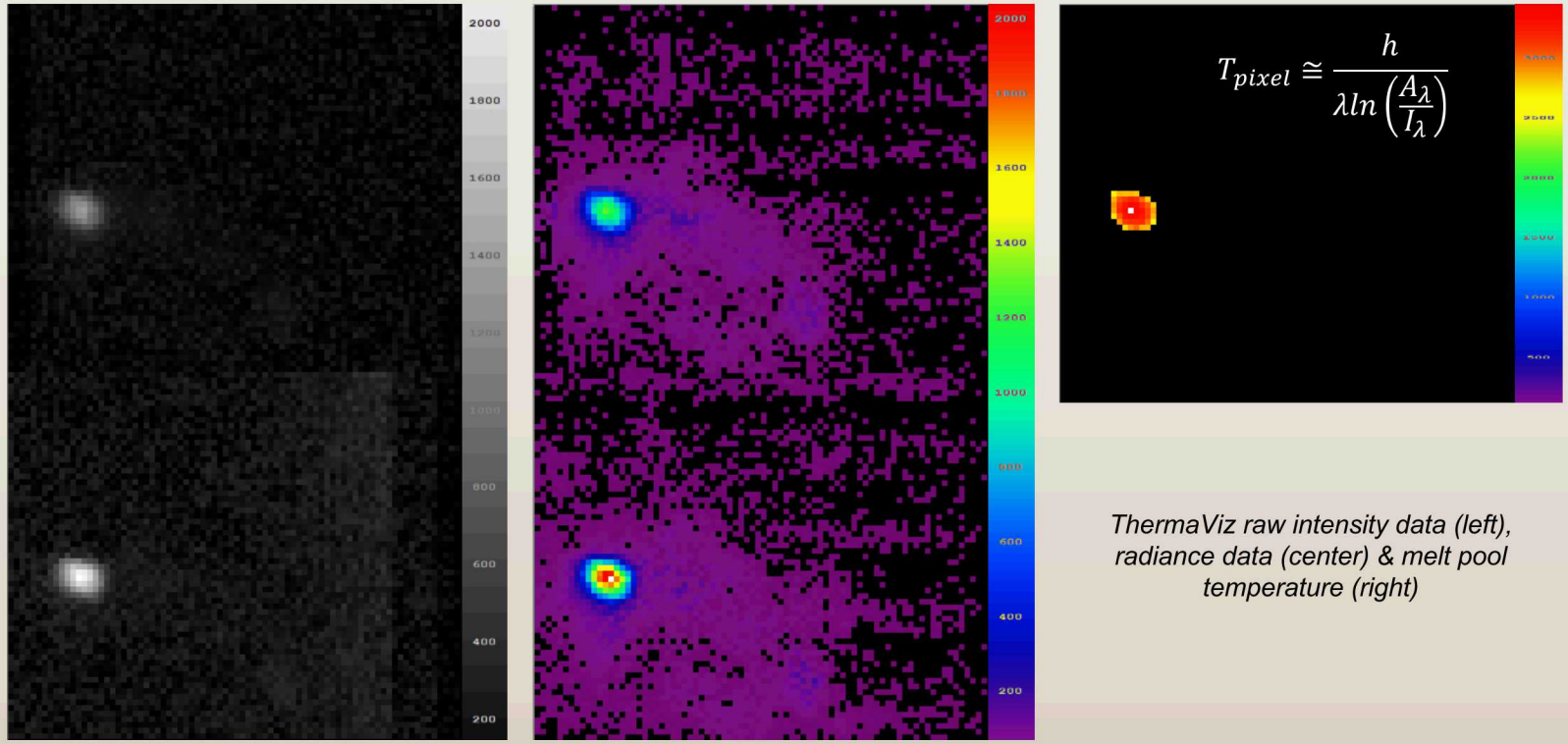




Melt Pool Monitoring

- 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 1.3 mm)
  - frame rate: 6-7kHz
  - exposure: 90µsec
- Challenges
  - data rate
  - image resolution & registration
  - emissivity variation across melt pool

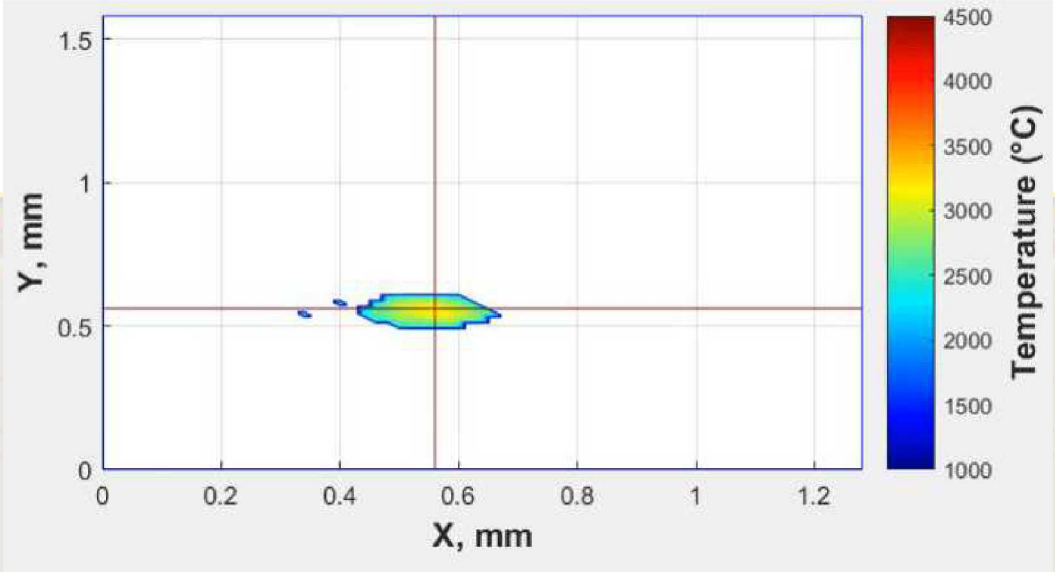
ThermaViz installed in the 3D Systems ProX 200



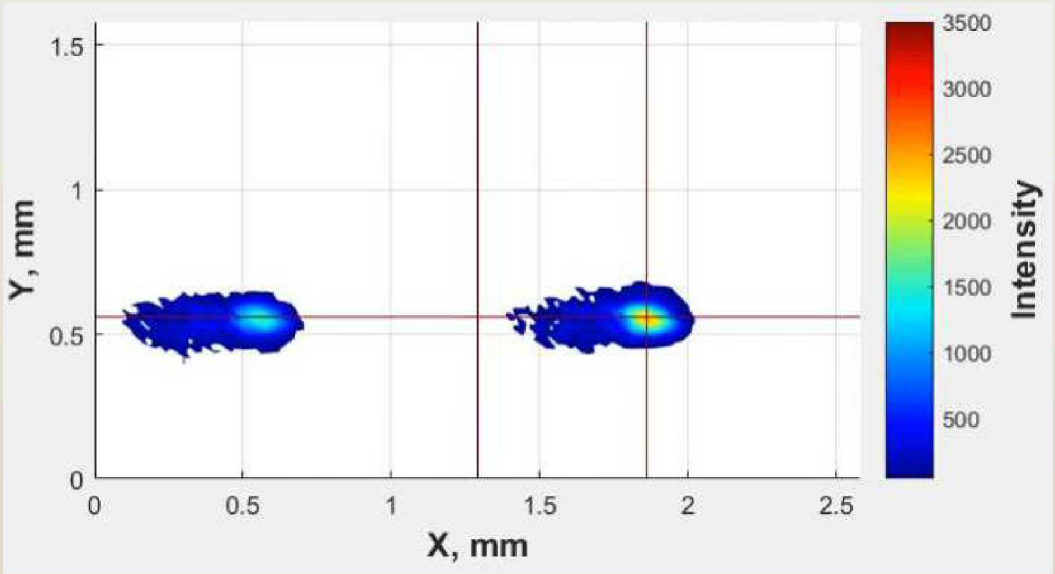
ThermaViz raw intensity data (left), radiance data (center) & melt pool temperature (right)

Therma-Viz Data 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

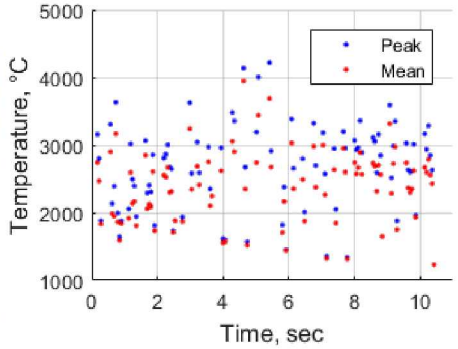


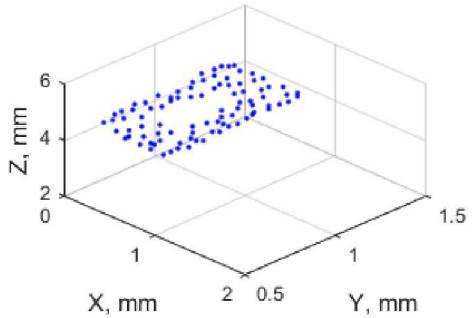
layer 155 melt pool temperature

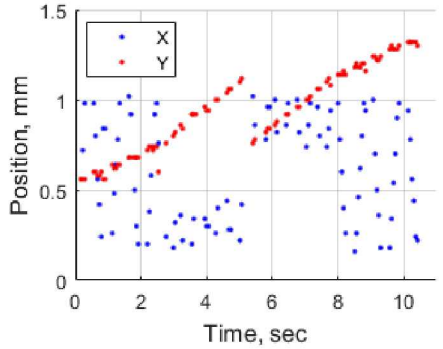


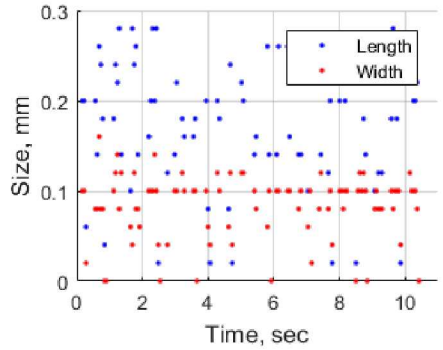
layer 156 melt pool raw intensity, short wavelength (left), long wavelength (right)

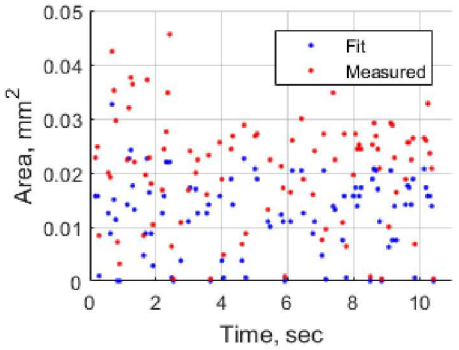
Melt Pool Metrics

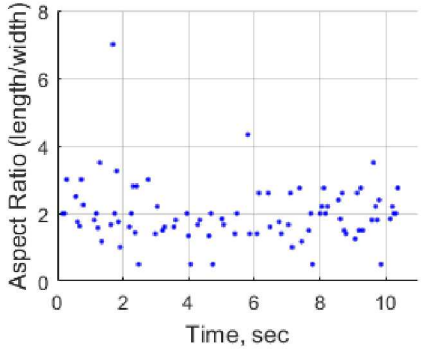


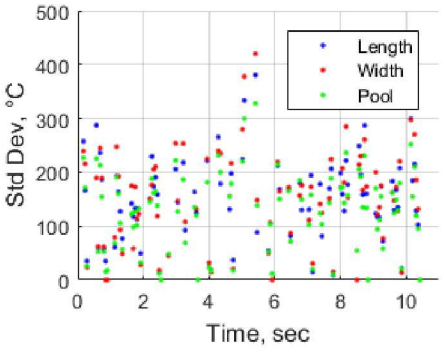


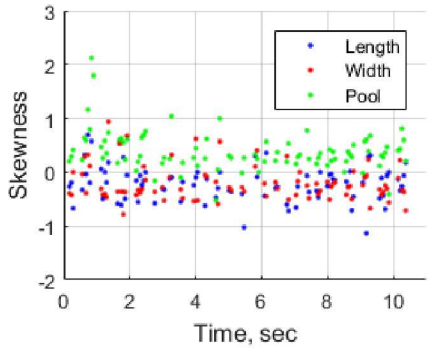


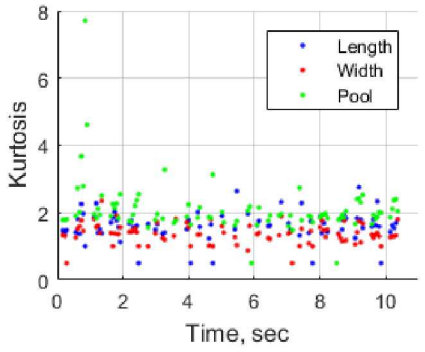






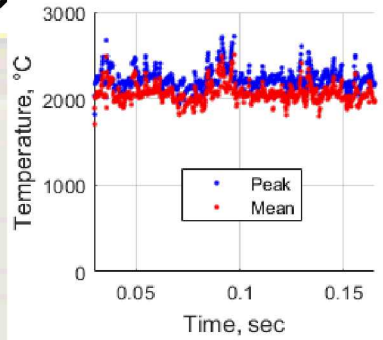


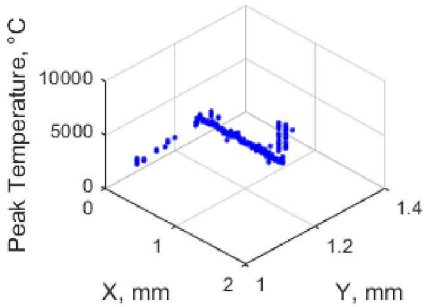


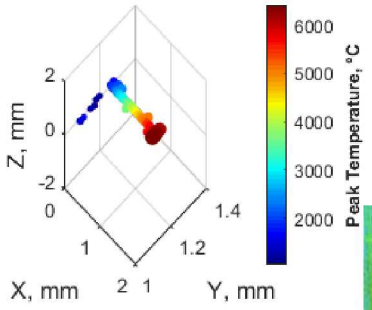


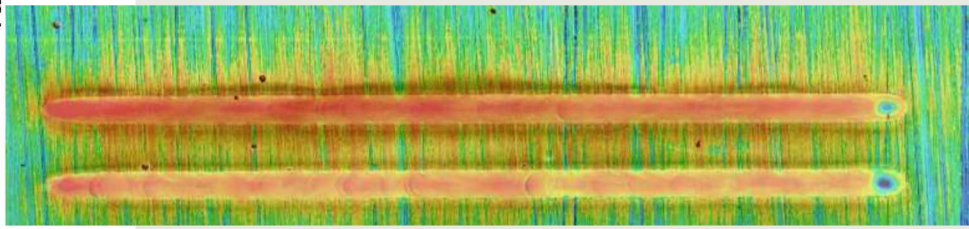
Line Scan on 316L Plate, 10mm/sec, 65W

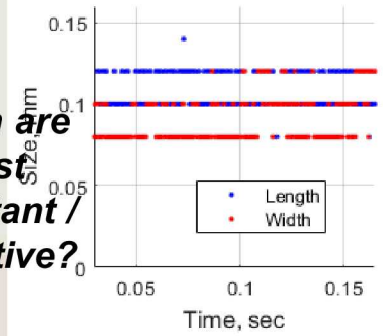
Which are most important / indicative?

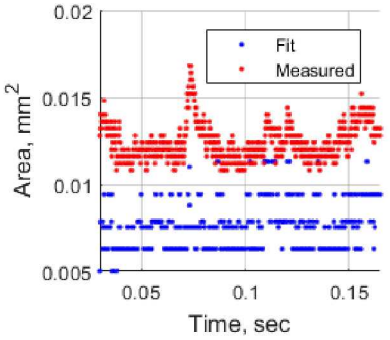


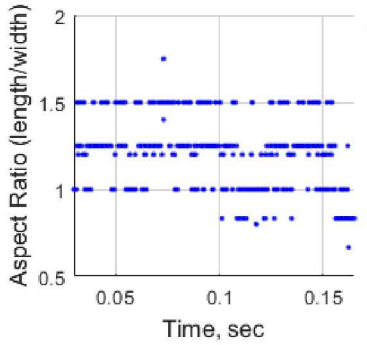


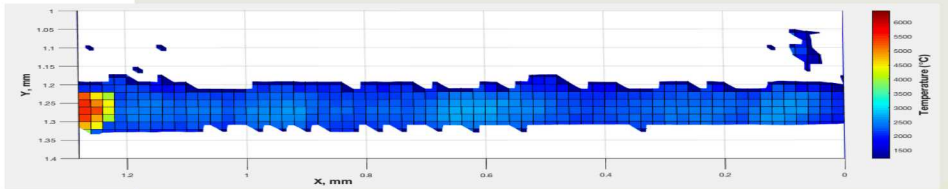


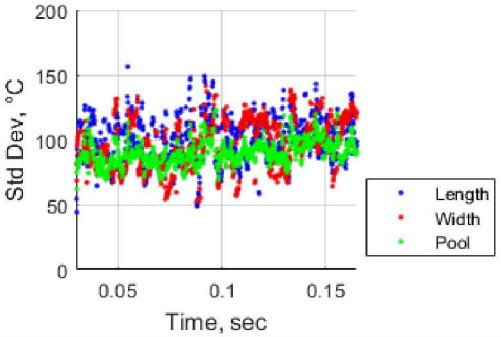


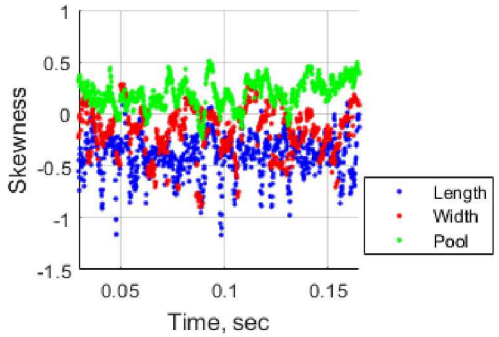


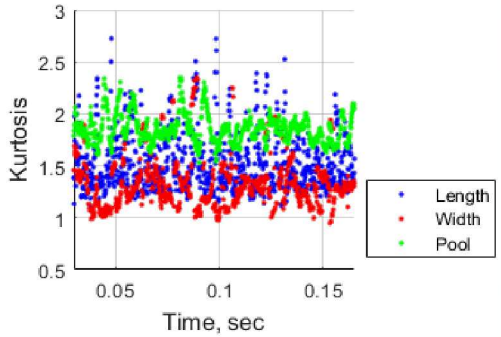


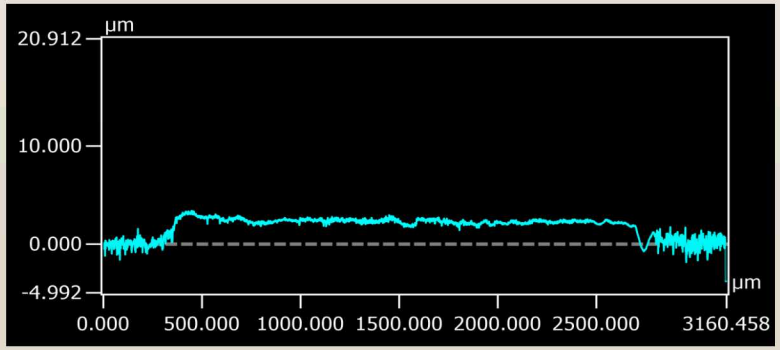




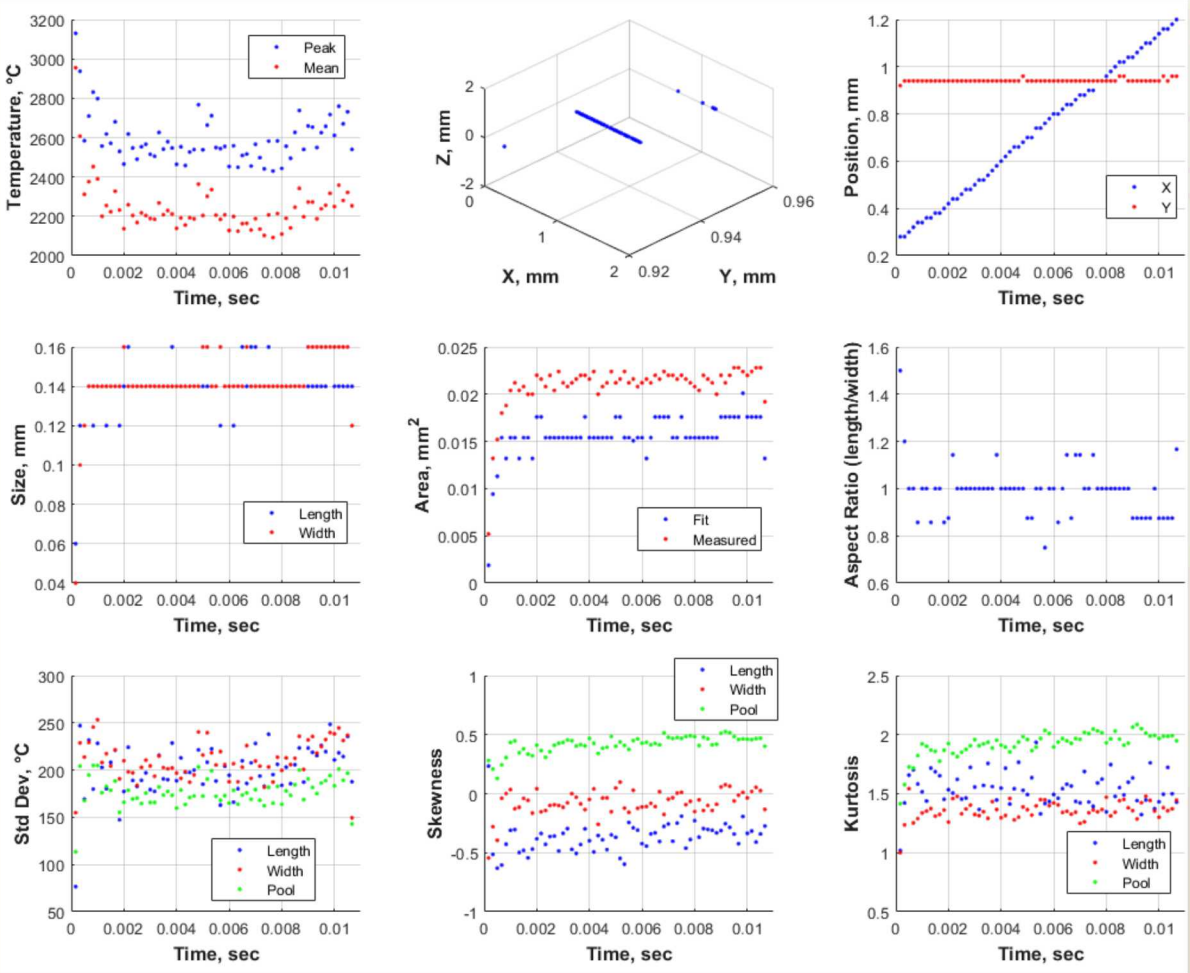


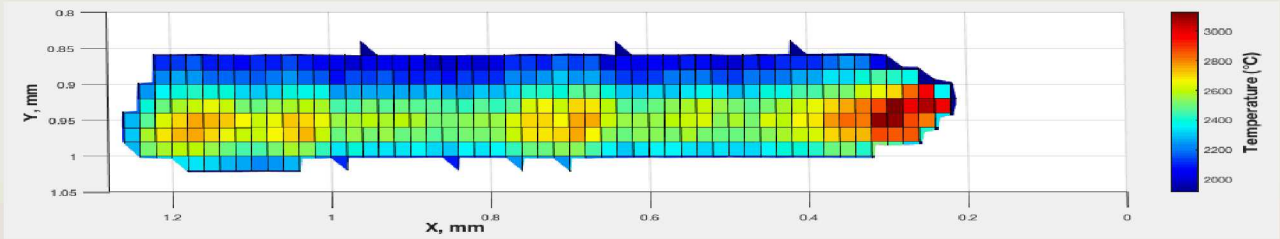


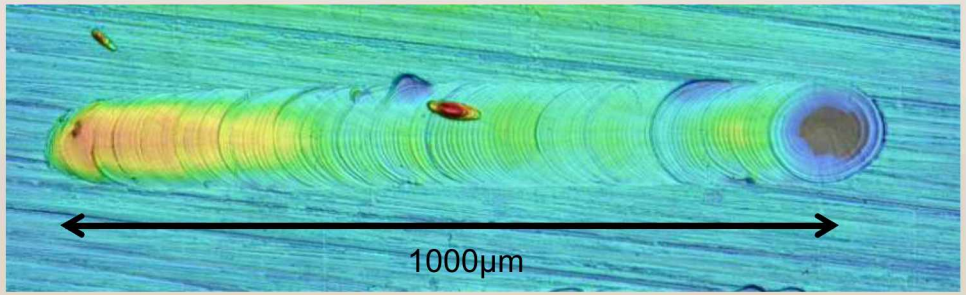




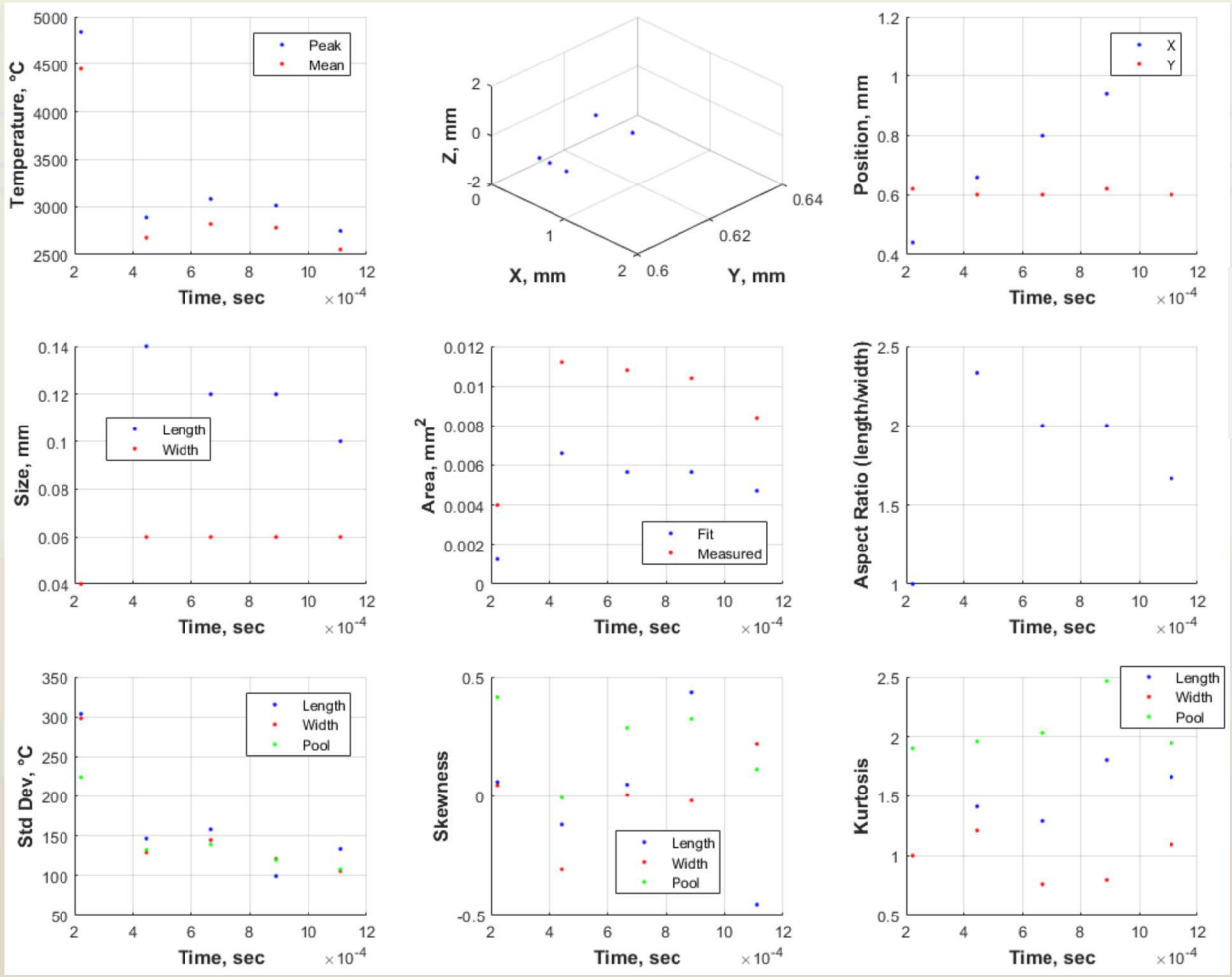
Line Scan on 316L Plate, 100mm/sec, 65W

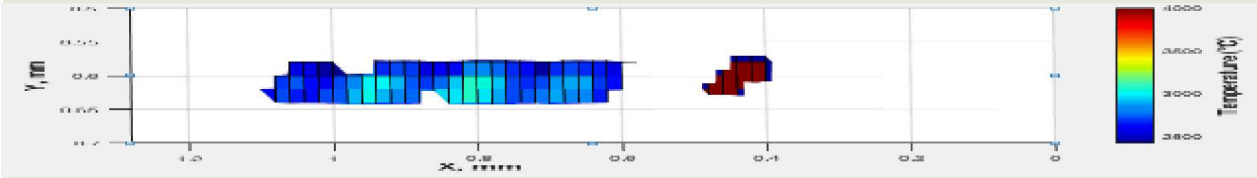


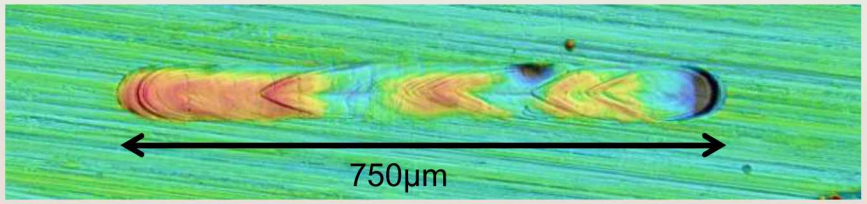




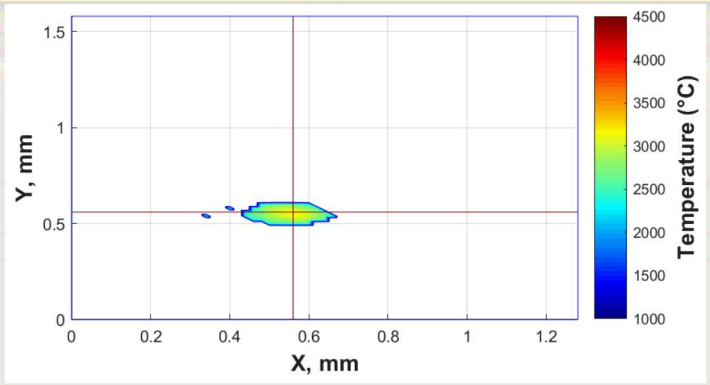
Line Scan on 316L Plate, 1000mm/sec, 65W





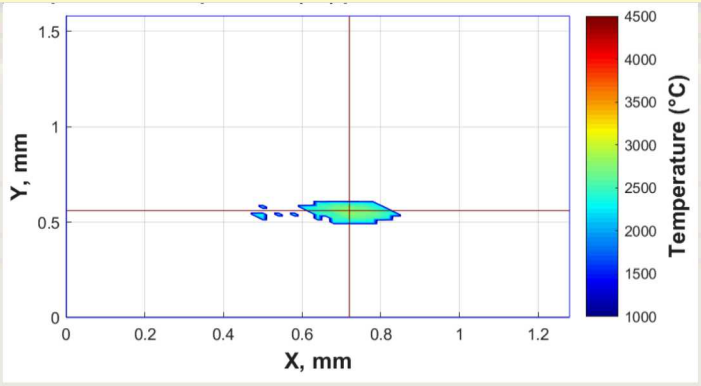


Temperature Maps Developed Per Layer



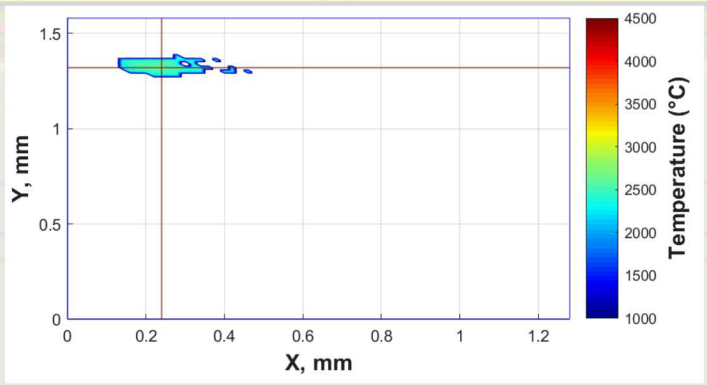
frame #3

+



frame #4

+ ... +



frame #184

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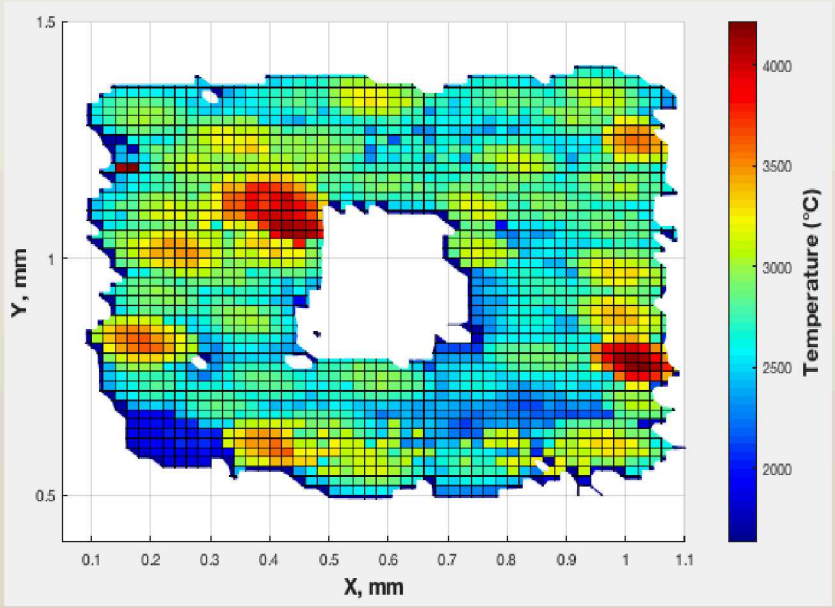

max temperature value @ each pixel across all frames

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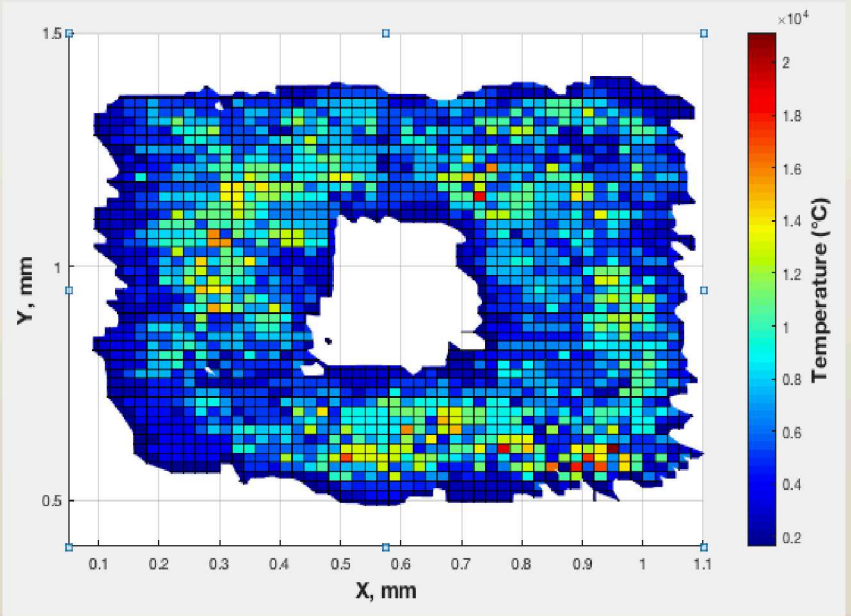
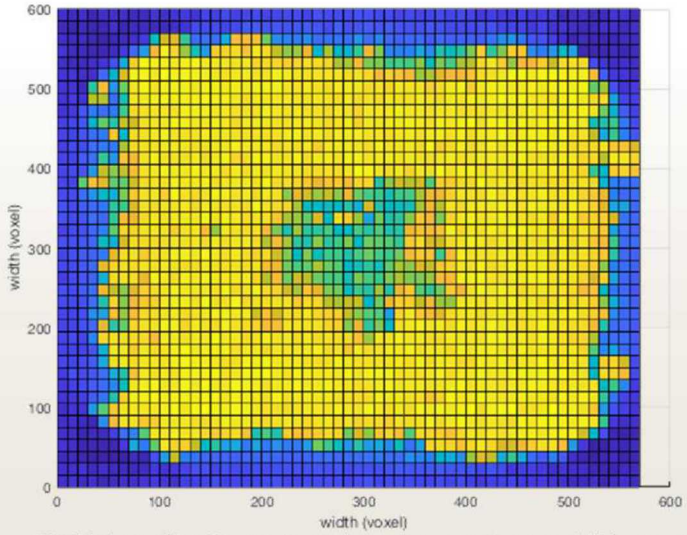
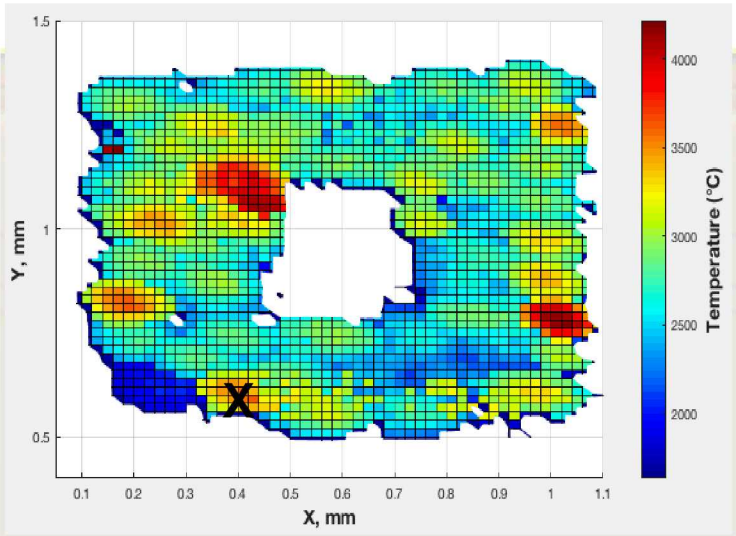


sum all temperature values @ each pixel across all frames

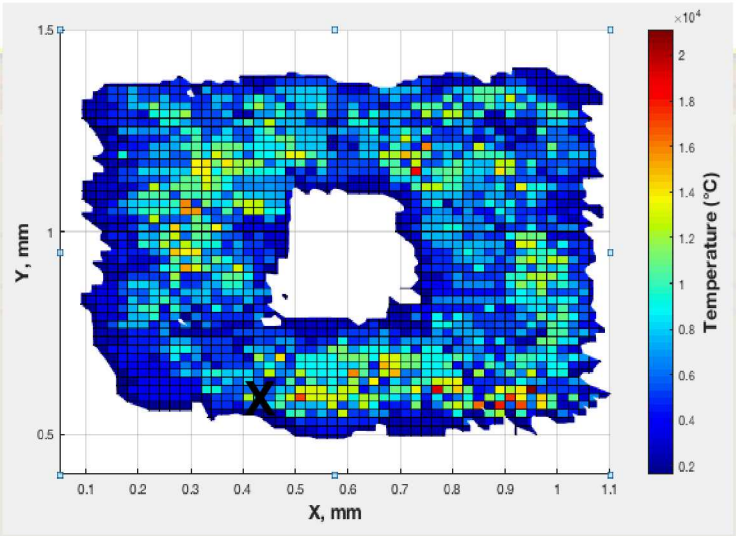
Data Correlations – 300µm Pore, Layer 155



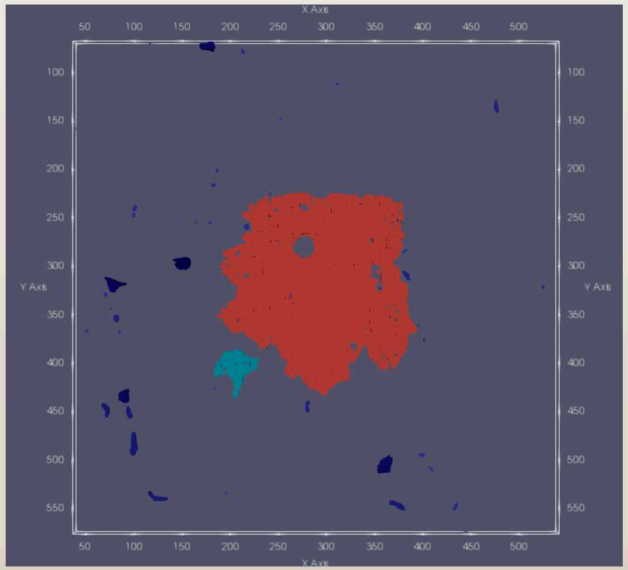
µCT intensity, 2 µm voxels averaged over 15 layers



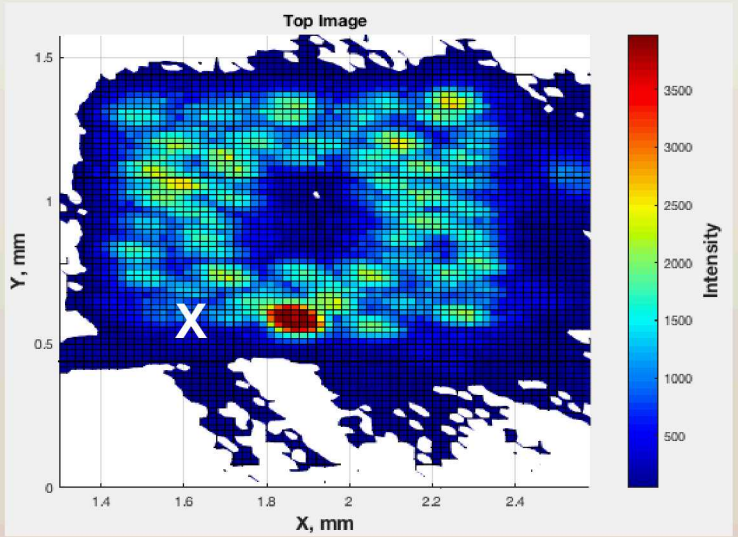
max temperature data



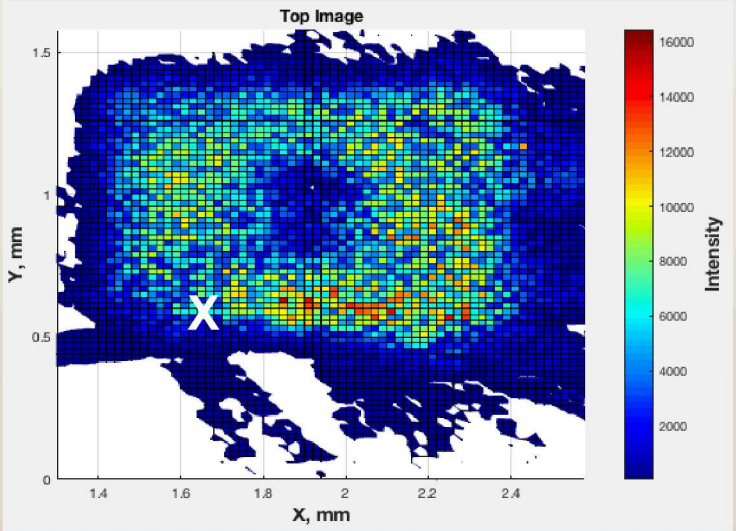
total temperature data



porosity

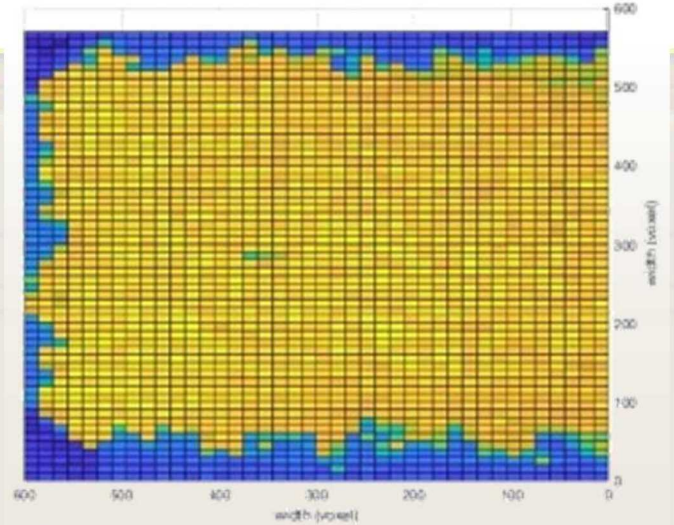


max intensity data, long wavelength

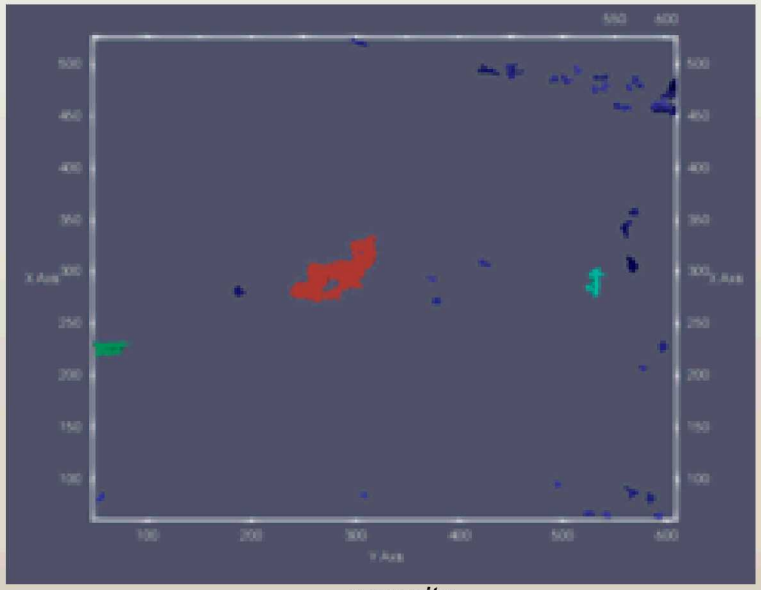


total intensity data, long wavelength

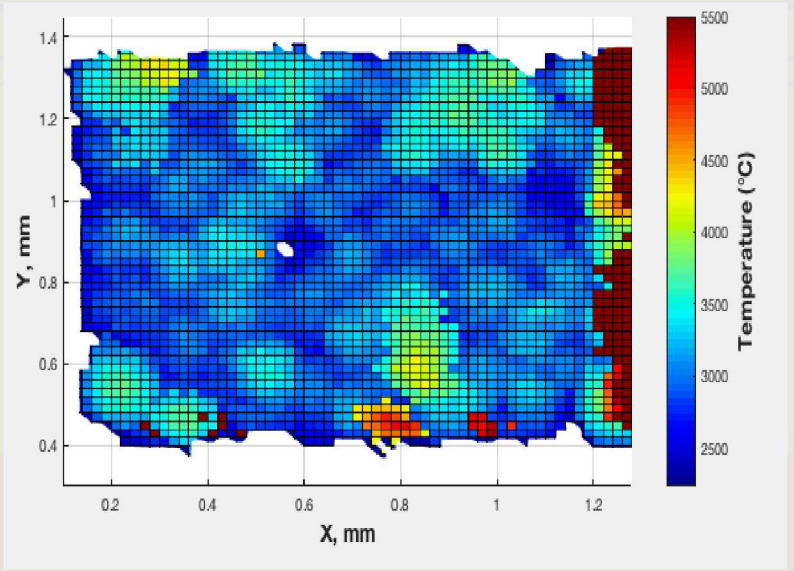
Data Correlations – 60µm Pore, Layer 31



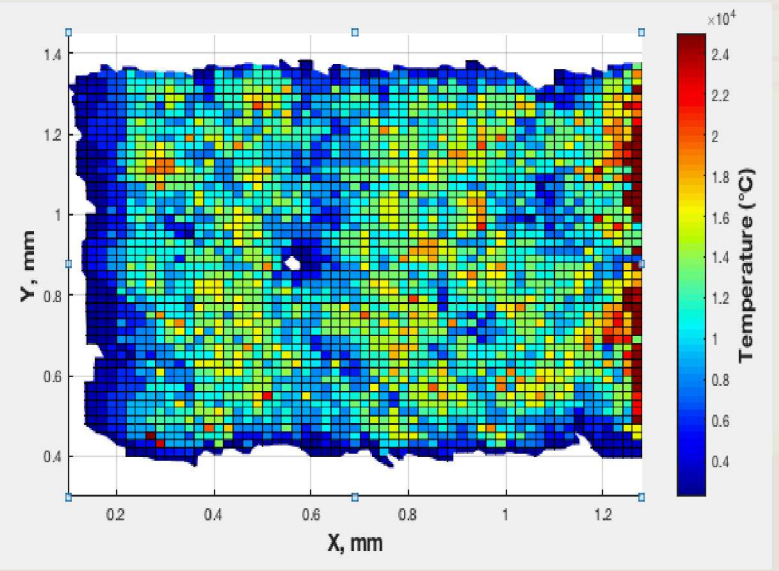
µCT intensity, 2 µm voxels averaged over 15 layers



porosity

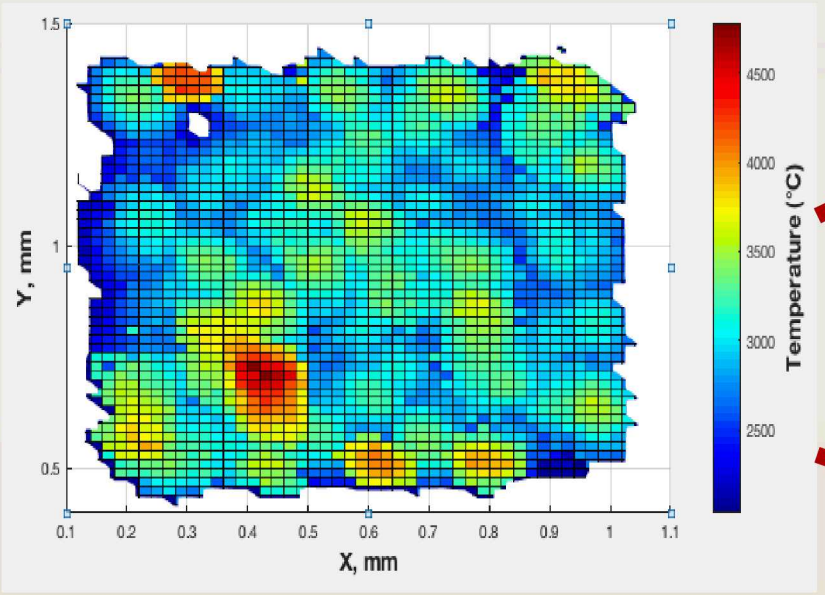


max temperature data



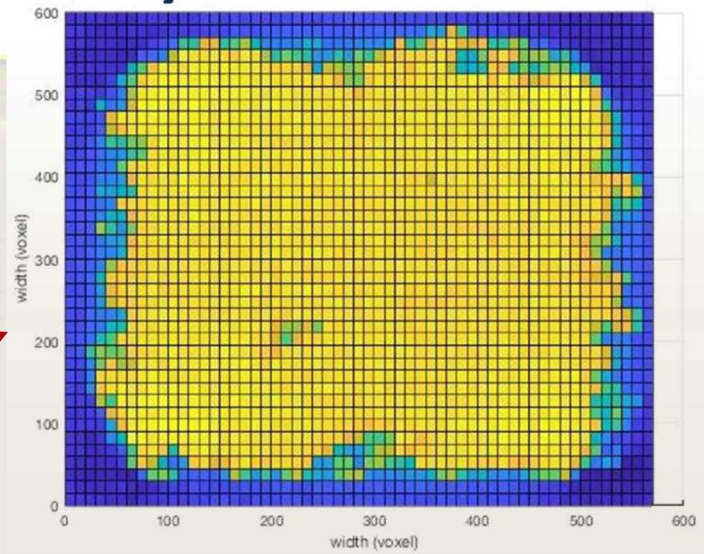
total temperature data

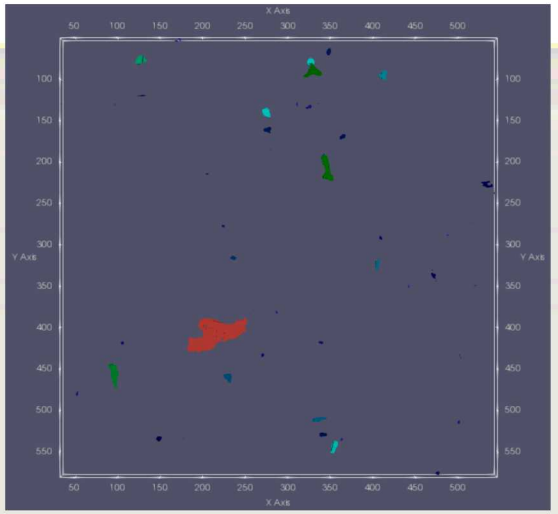
Finding Process Porosity



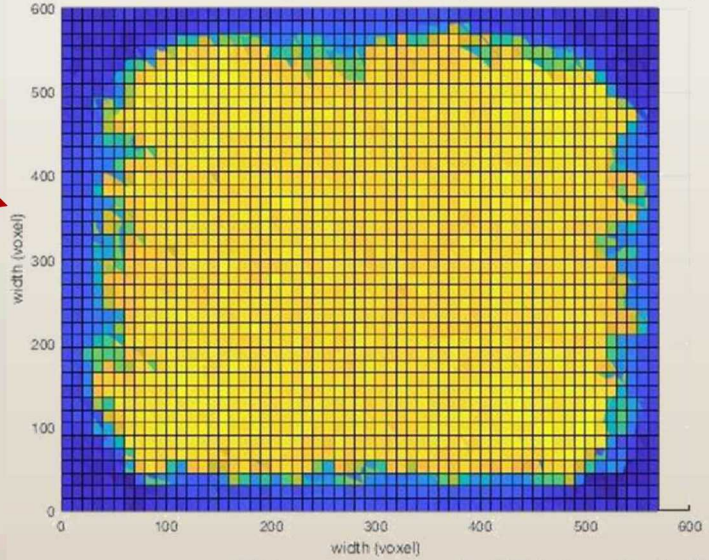
max temperature data, layer 173

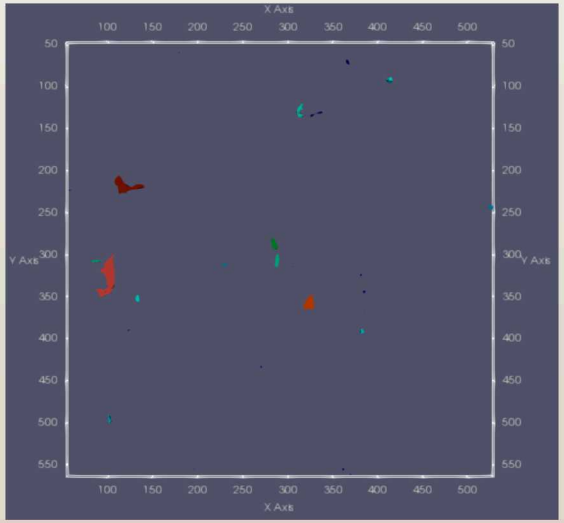
?





15 layer averaged µCT intensity (left) & porosity (right), layer 174

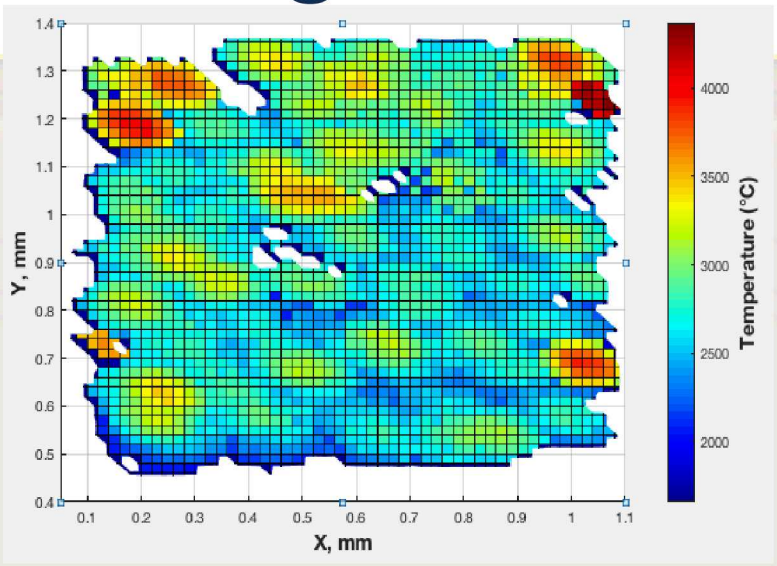




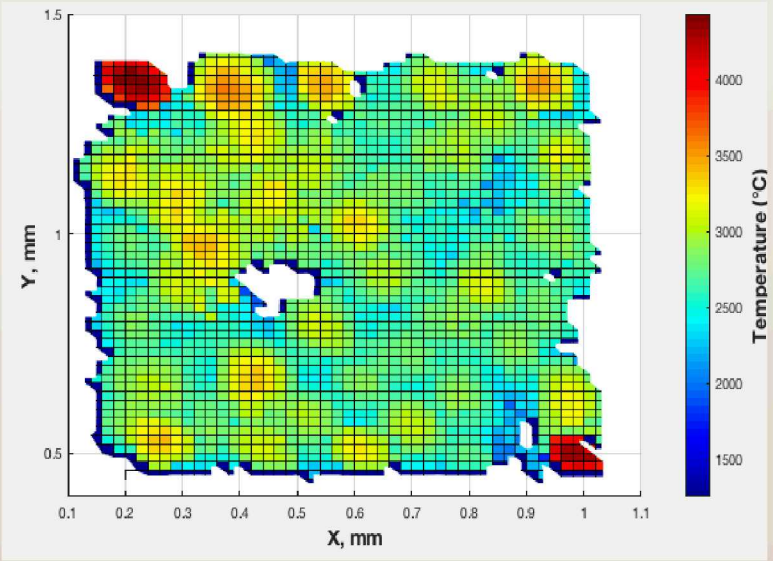
15 layer averaged µCT intensity (left) & porosity (right), layer 173

Finding Process Porosity

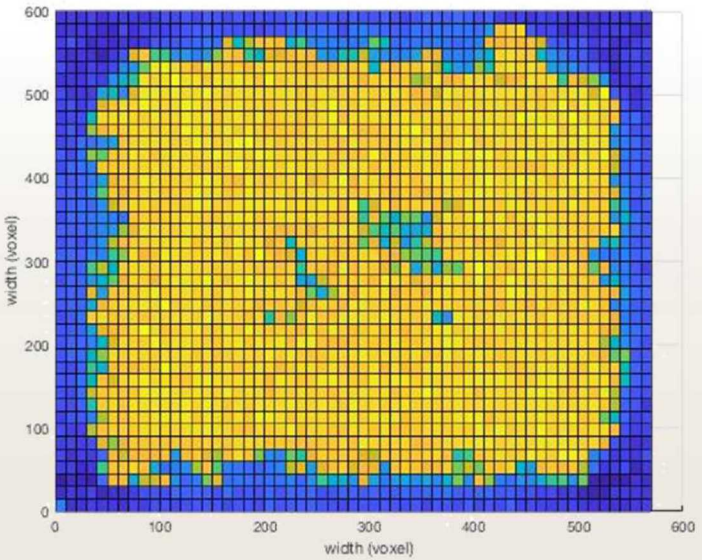
layer 166

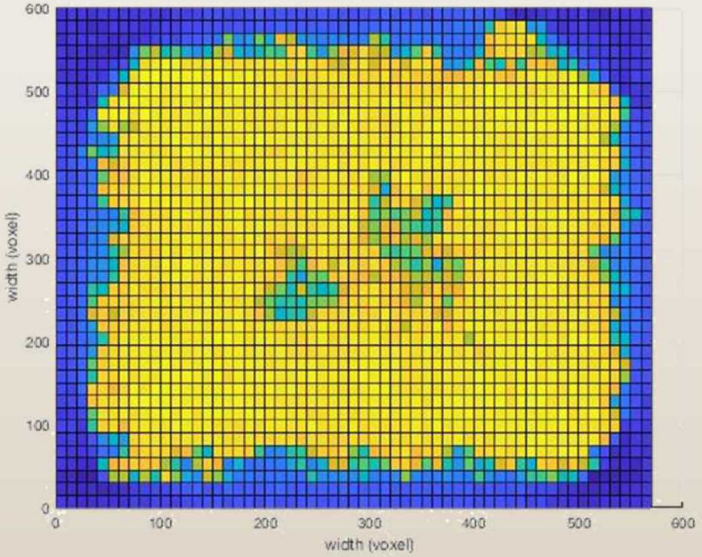


layer 165, overhang layer for 300μm pore

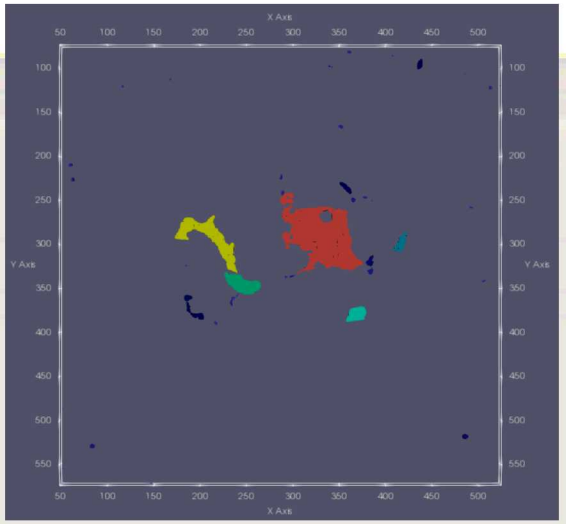


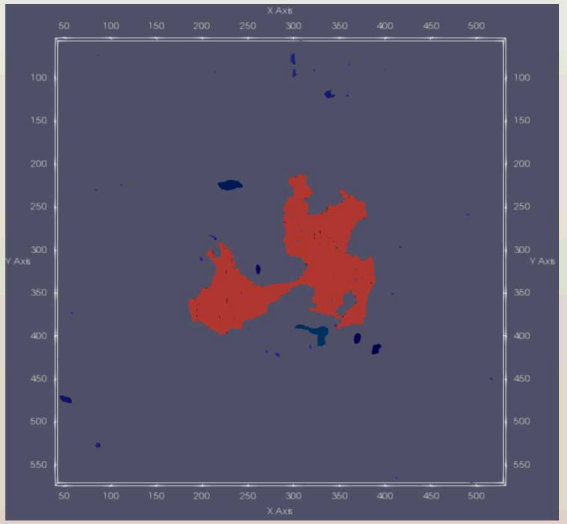
max temperature data





15 layer averaged μCT intensity

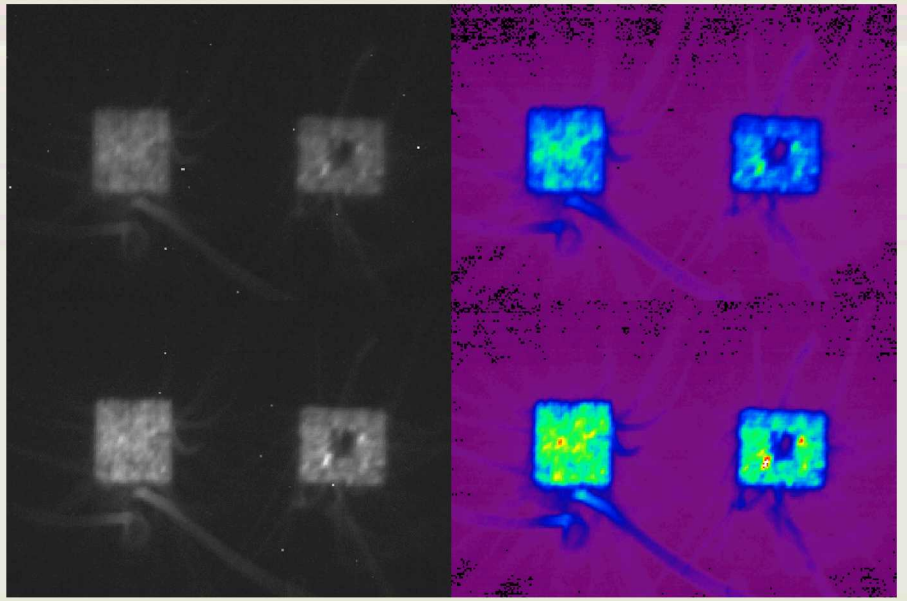


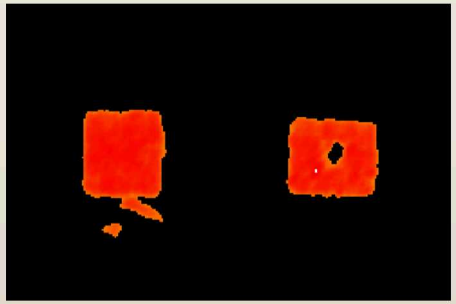


porosity

Process-Structure Summary

- Exploring two color pyrometry for porosity detection
  - absolute temperature accuracy is questionable
- Intentional porosity
  - observed in pyrometry data down to 60µm size
  - 30µm pores ~ same scale as process porosity
- Process porosity
  - correlations less straightforward
  - additional analyses on-going
- Is lower resolution & slower data rates still useful?
  - scale-up is a challenge

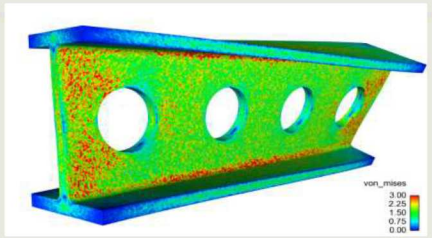




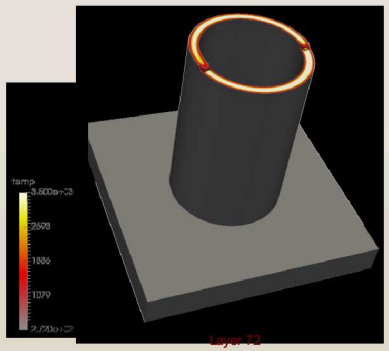
ThermaViz raw intensity data (left), radiance data (right) & melt pool temperature (bottom), 99ms exposure, 9Hz sample rate

Qualification Tomorrow

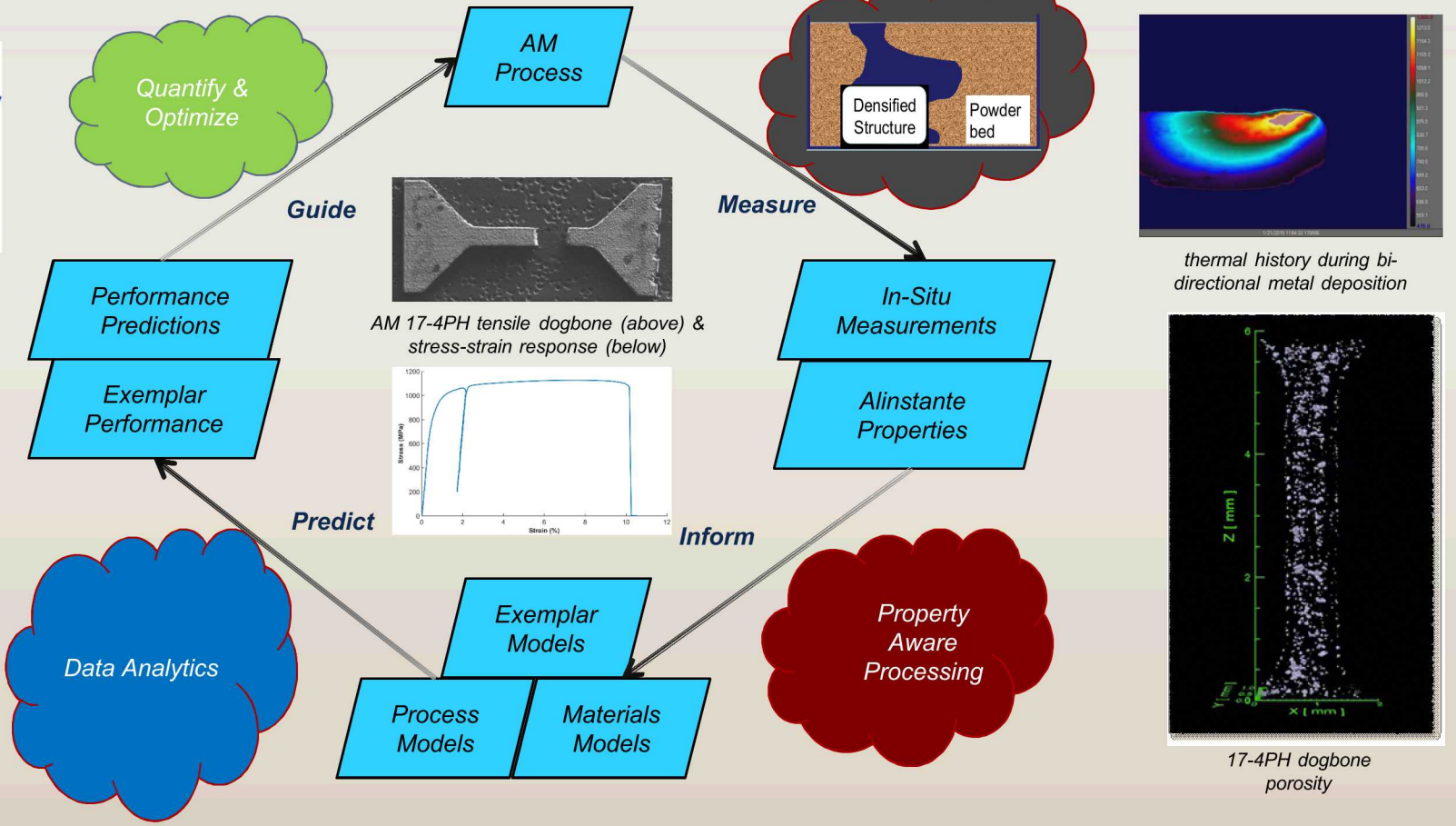
- "Changing the Engineering Design & Qualification Paradigm"
  - leverage AM, in-process metrology & HPC to revolutionize product realization



material / part performance simulation



process simulation

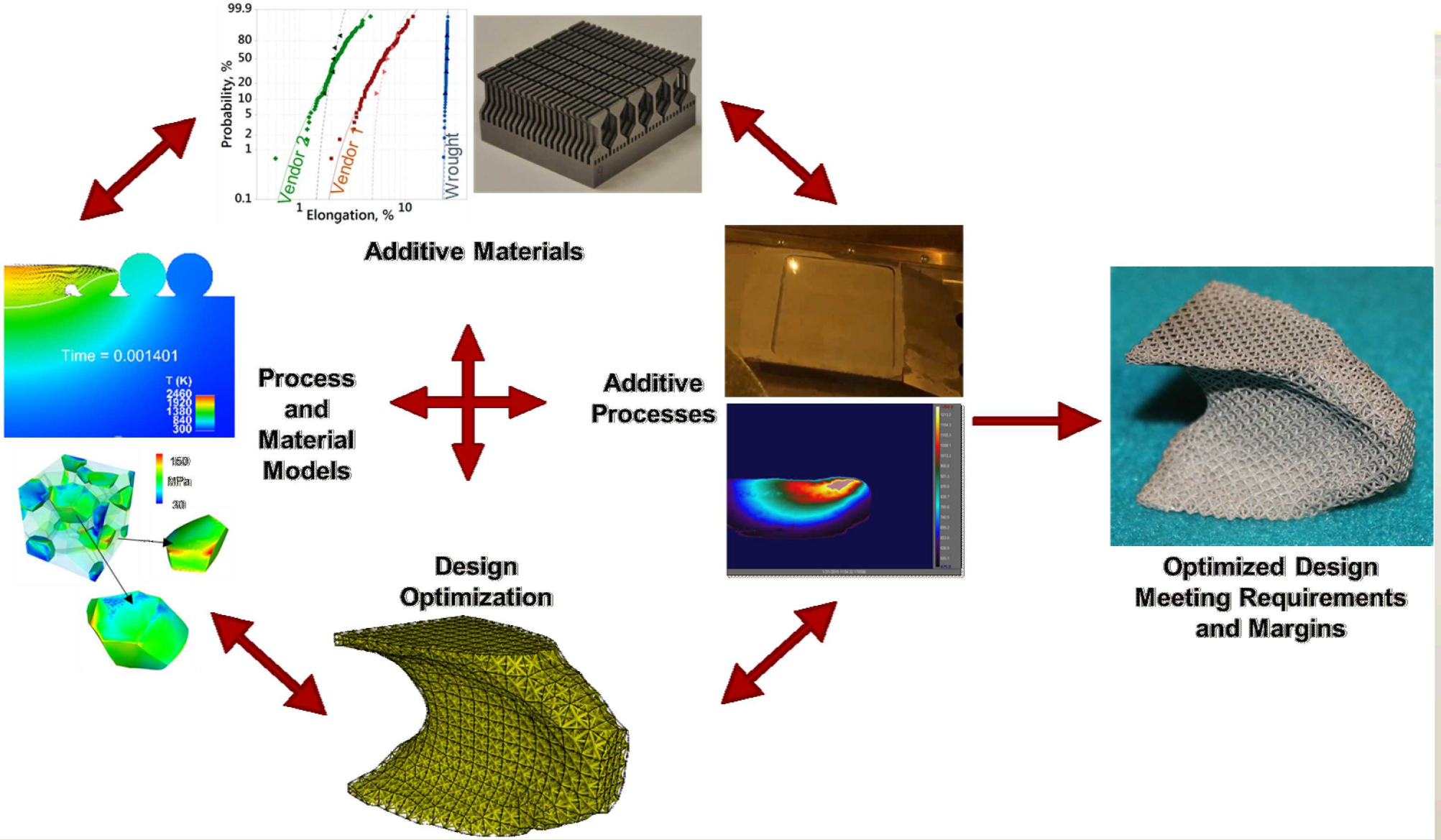


AM 17-4PH tensile dogbone (above) & stress-strain response (below)

thermal history during bi-directional metal deposition

17-4PH dogbone porosity

Wholistic Design Paradigm for AM

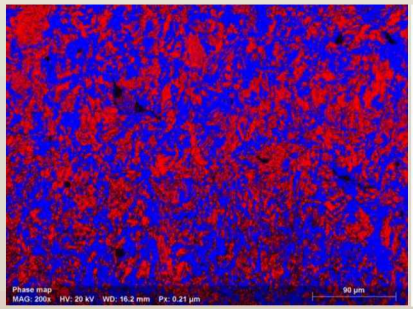


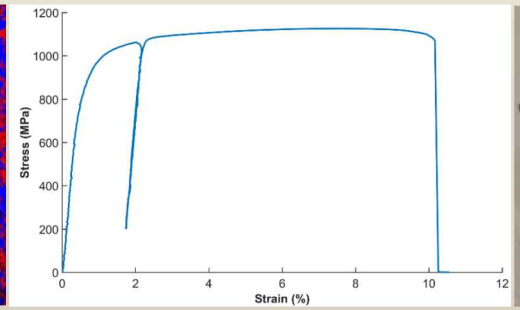
QUESTIONS?

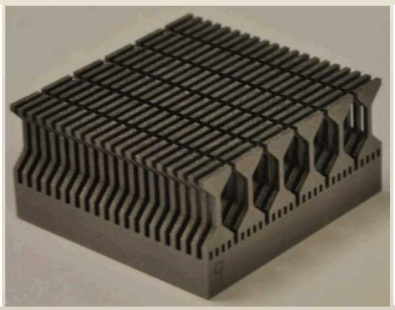
Bradley Jared, PhD

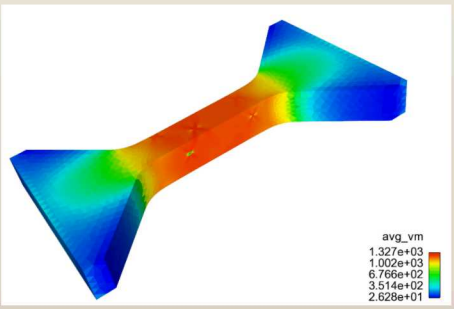
bhjared@sandia.gov

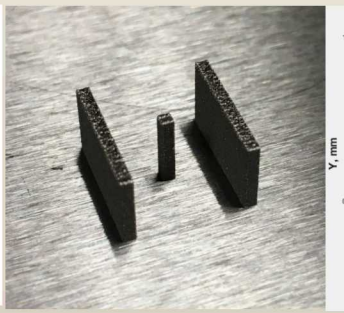
505-284-5890

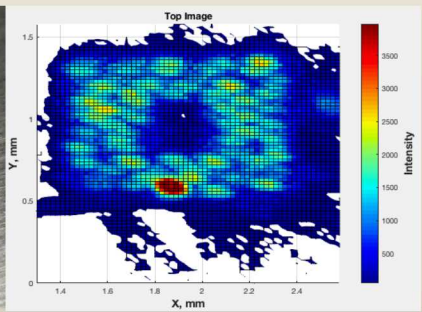




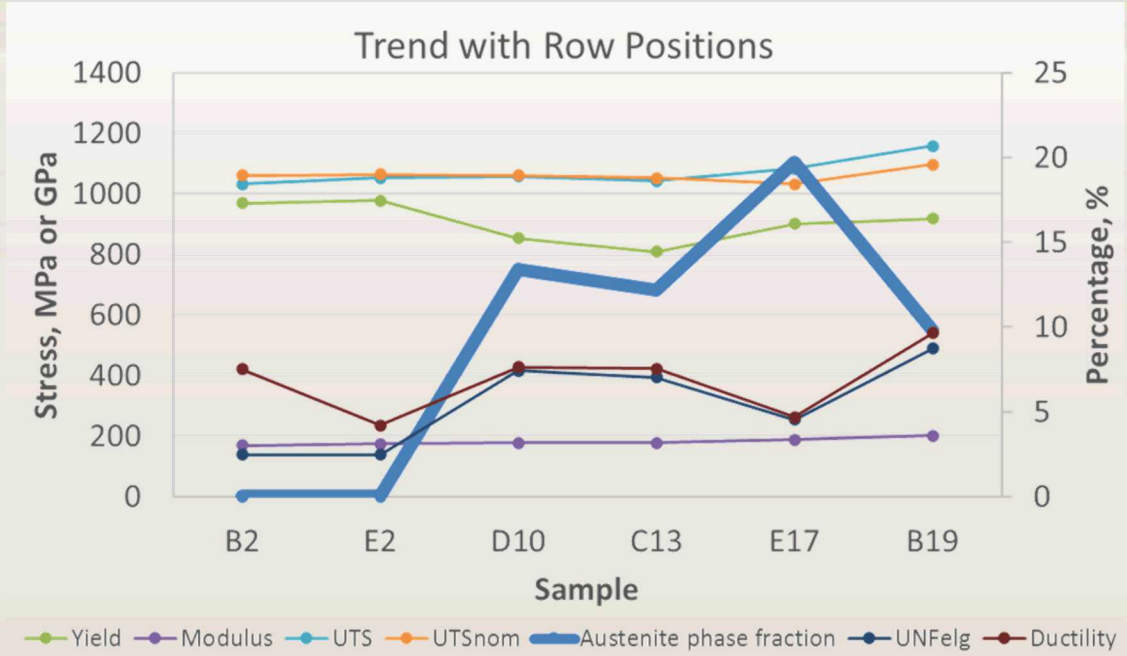


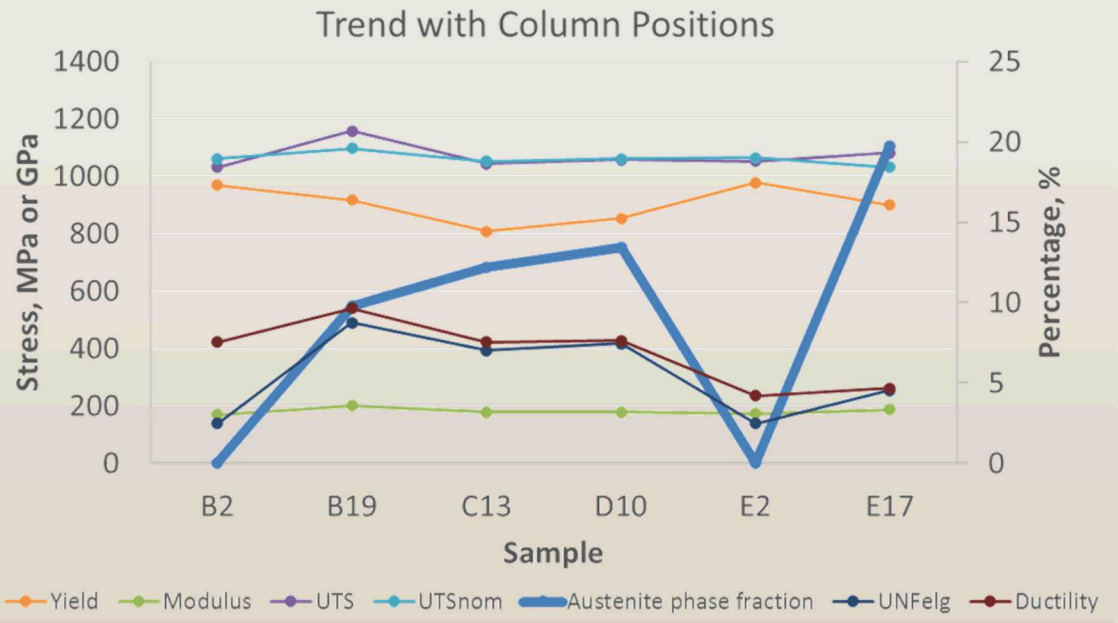






Austenite Spatial Variation



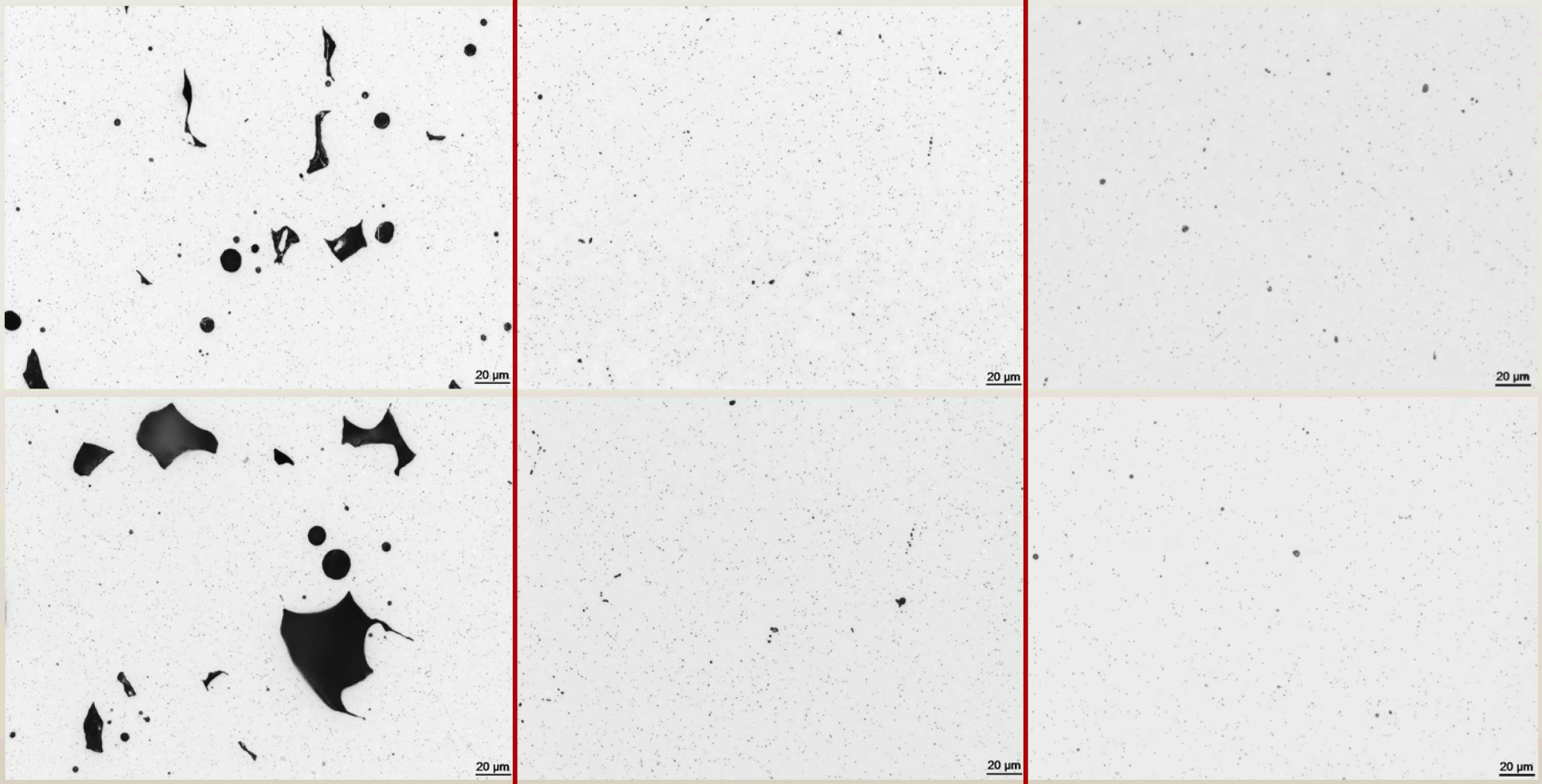


As-Polished Microstructures

As-printed (no HIP)

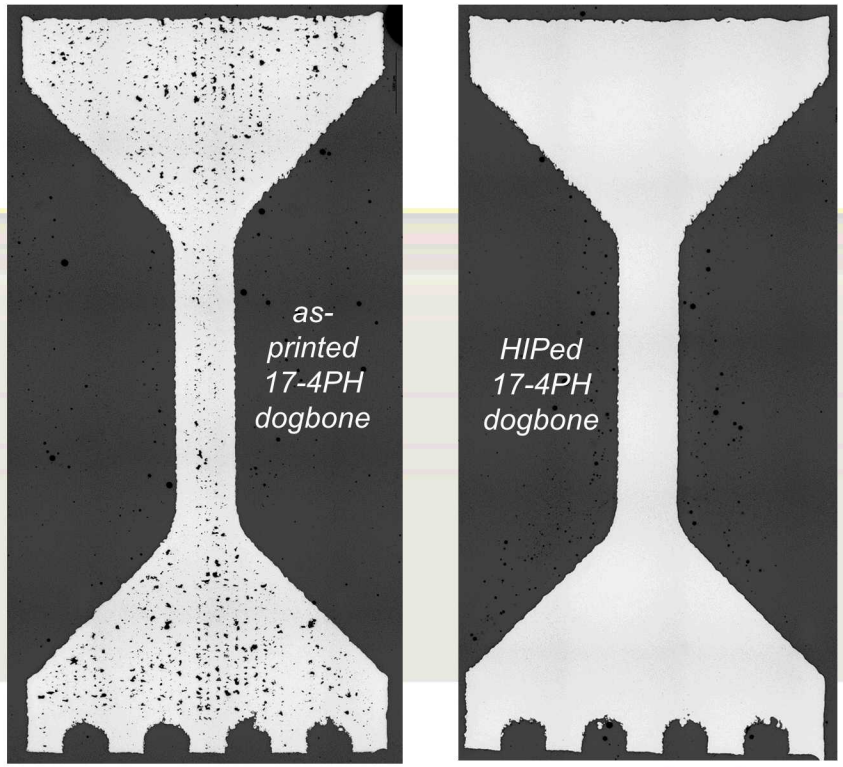
HIP (15 ksi, 1093°C, 6 hrs)

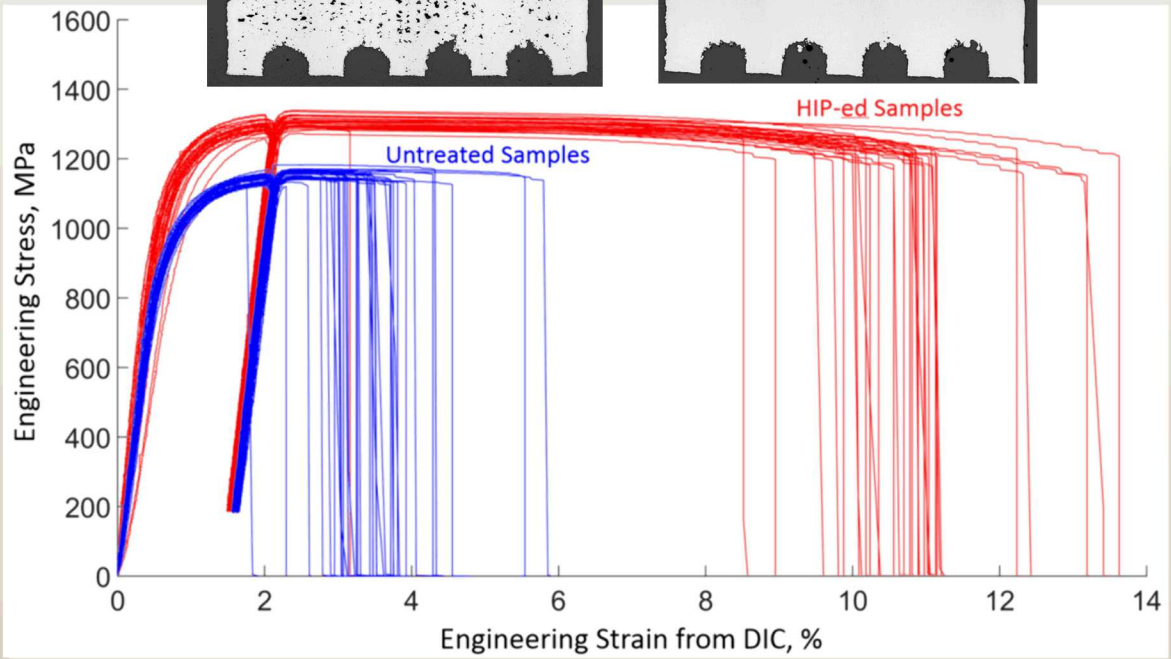
HIP (15 ksi, 1093°C, 6 hrs) + ambient pressure 1200°C, 2 hrs



Impact HIP on 17-4PH

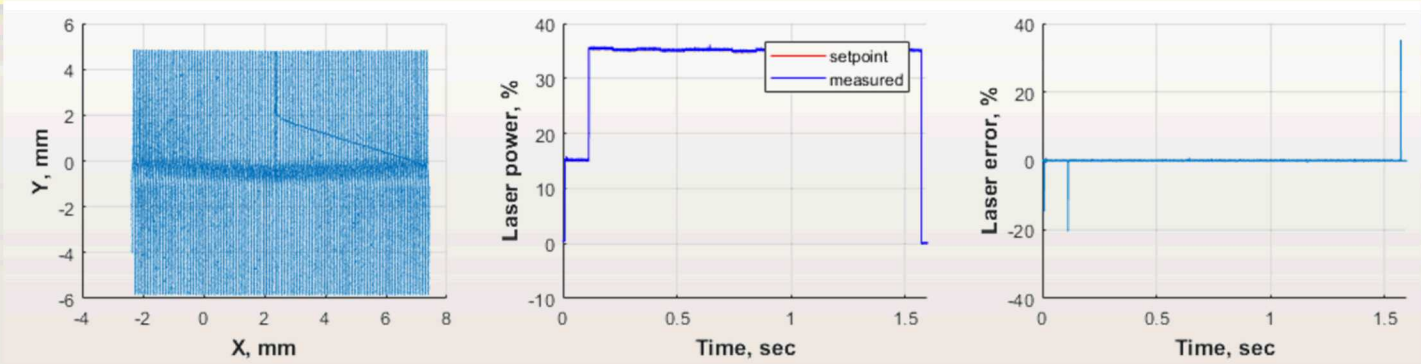
- 33 tensile bars were sent to external vendor for HIP, 4hr @ 1110°C, 100 MPa
- impact
  - collapsed internal porosity
  - decreased largest void size by ~80%
  - improved Weibull characteristic strength by 13%

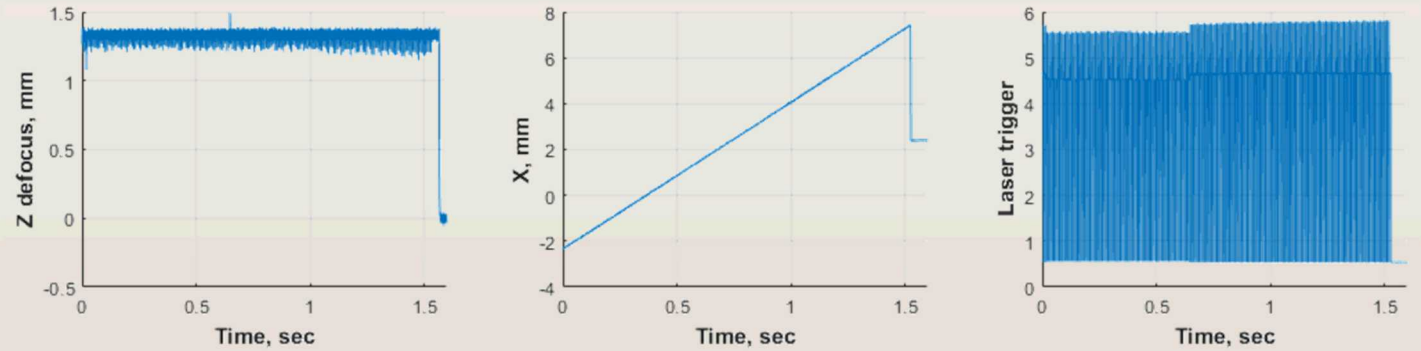


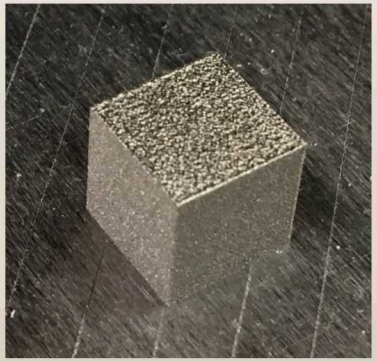


Archive, Research, Control, Synchroniz
Protocol

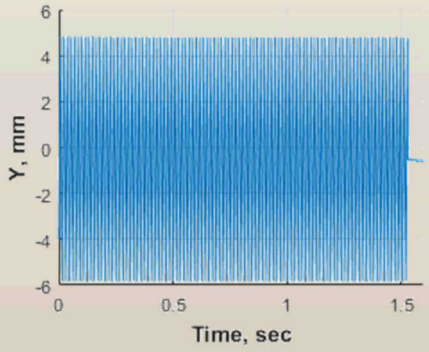
PennState
Applied Research Laboratory







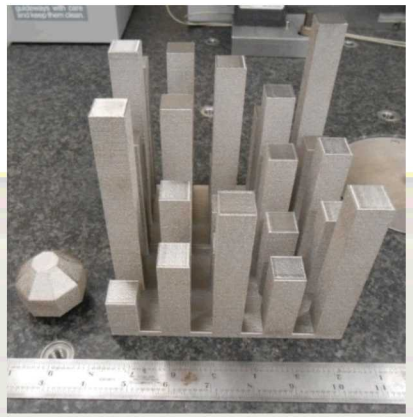
data for single layer of a 10mm cube sample



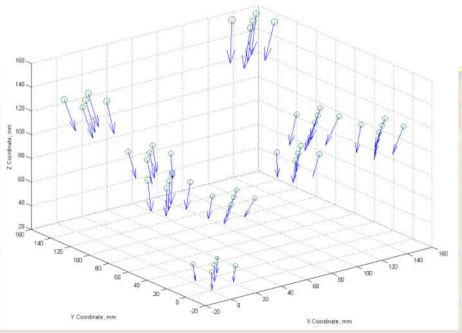
Metrology

- 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

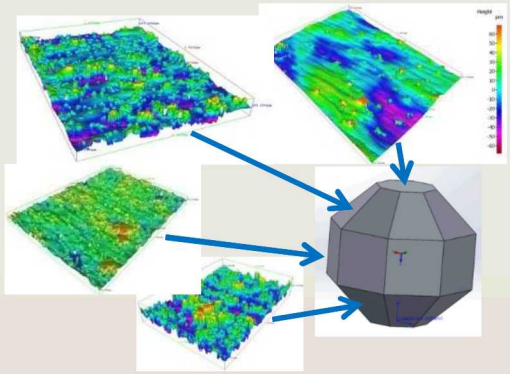


Ti-6Al-4V polyhedron & “Manhattan” artifacts

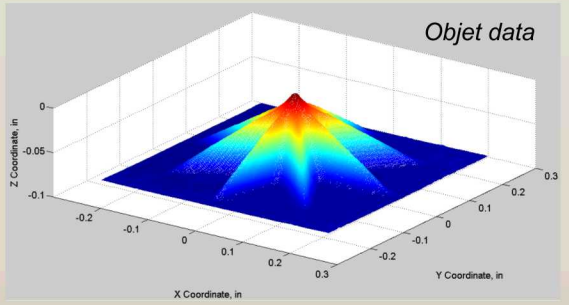


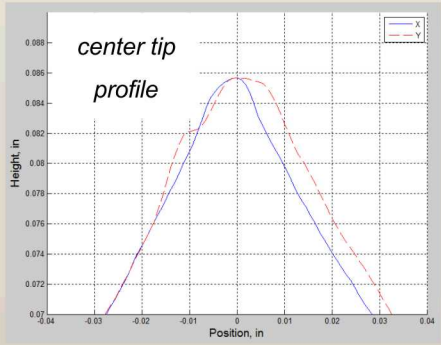
Ti “Manhattan” error map

17-4 PH “death” star



17-4 PH polyhedron texture anisotropy map



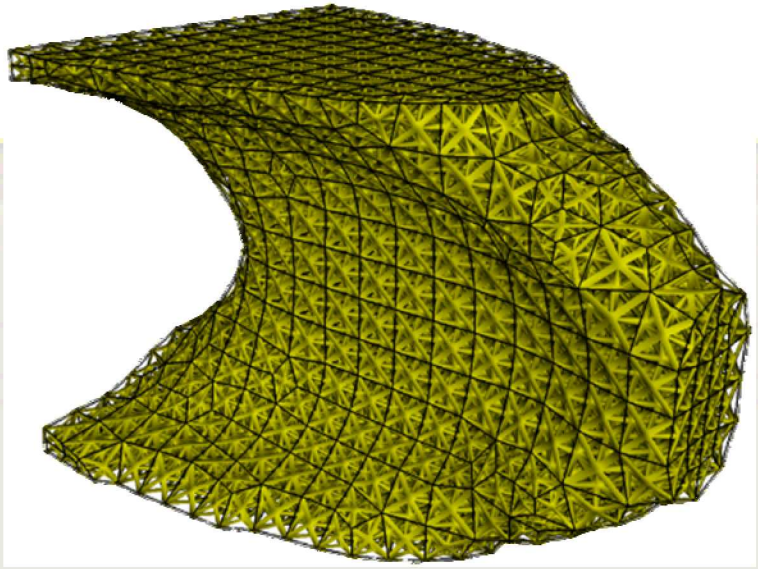


Outline

- Slow velocity line scans
  - address limited frame rate
  - on-plate
    - better temperature values?
    - need to look at dendrite arm spacing to get cooling rates
  - scatter vs. velocity, power on printed surface
- Melt pool response
  - shutter speed, sample rate
  - bead on plate, single powder layers
  - line & area scans
  - laser power, velocity, cross-feed
- Jon's data analysis – part leaning?

Motivation

- Optical systems are commonly constrained by size, weight & power
  - many “non-precision” applications are addressing using AM
- Opportunities exist for light-weight, reflective optics
  - geometrical complexity (i.e. integration, optimization)
  - new materials (& hierarchies)
  - rapid design & fabrication cycles
  - limits include
    - form accuracy
    - surface finish
    - material selection



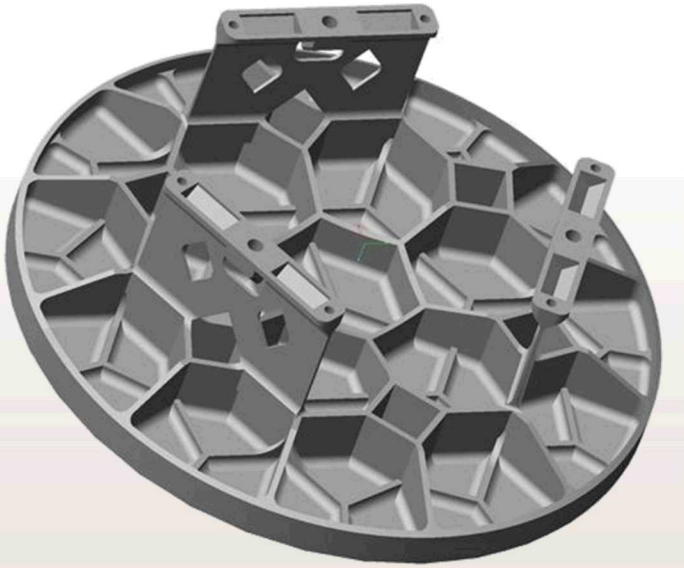
topology optimized part designed using lattice structures

direct write printed alumina part

Robbins, J., **Additive Manufacturing**, “An efficient and scalable approach for generating topologically optimized cellular structures for additive manufacturing “, 2016.

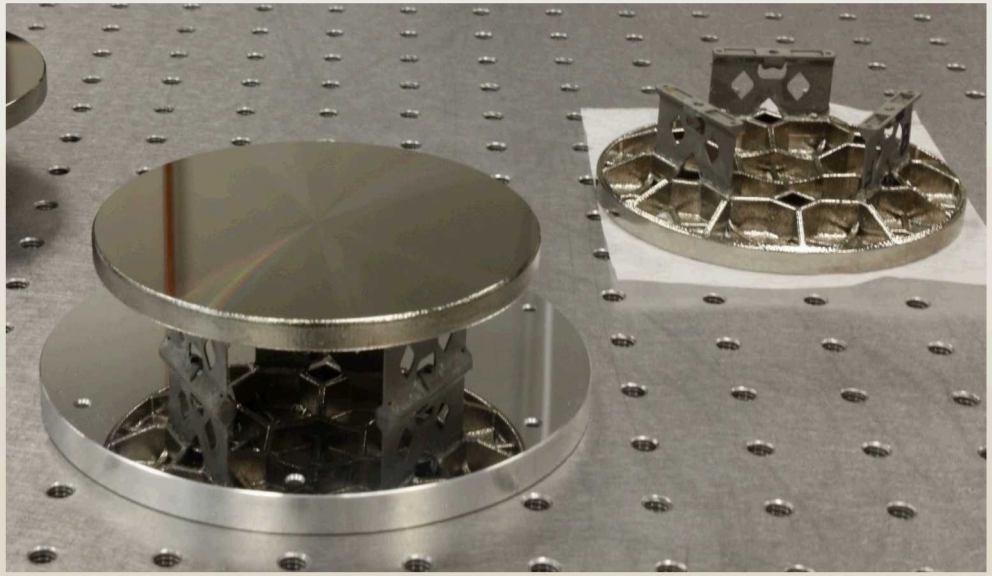
Integrated Mirror

- Design
  - 101.6mm diameter flat mirror
  - light-weighted w/conventional ribbing
  - alignment blade flexures integral w/monolithic structure



monolithic mirror structure design

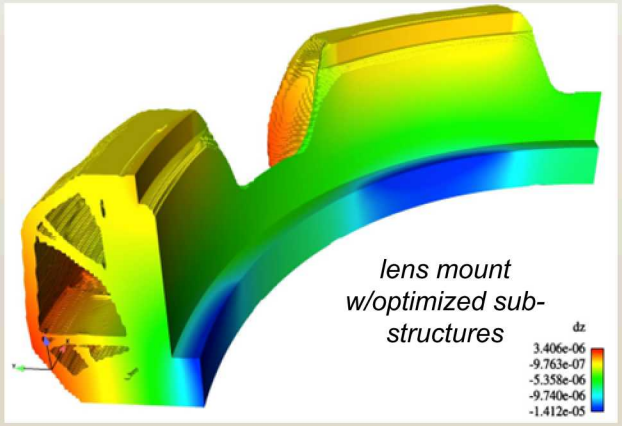
- Fabrication
  - printed in Ti6Al4V using laser-powder bed fusion
  - 0.5mm electroless Ni plating applied to front & rear faces
  - diamond turned mirror face
    - plating issues resulted in pitting, poor form & finish
  - lead time reduced from 18 to 3 months

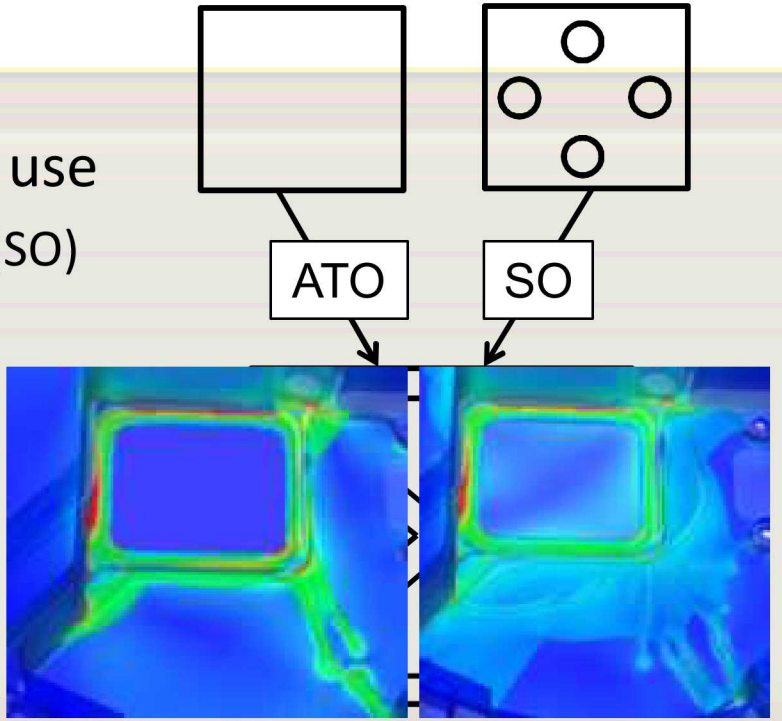


AM Ti6Al4V mirror w/diamond turned electroless Ni coating

New Design Freedom

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

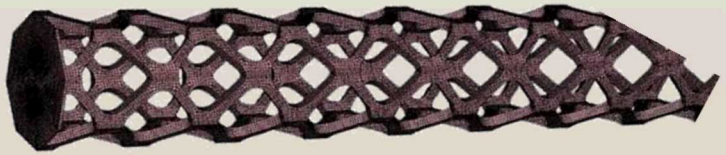




+ 0.55% volume
- 52% deflection

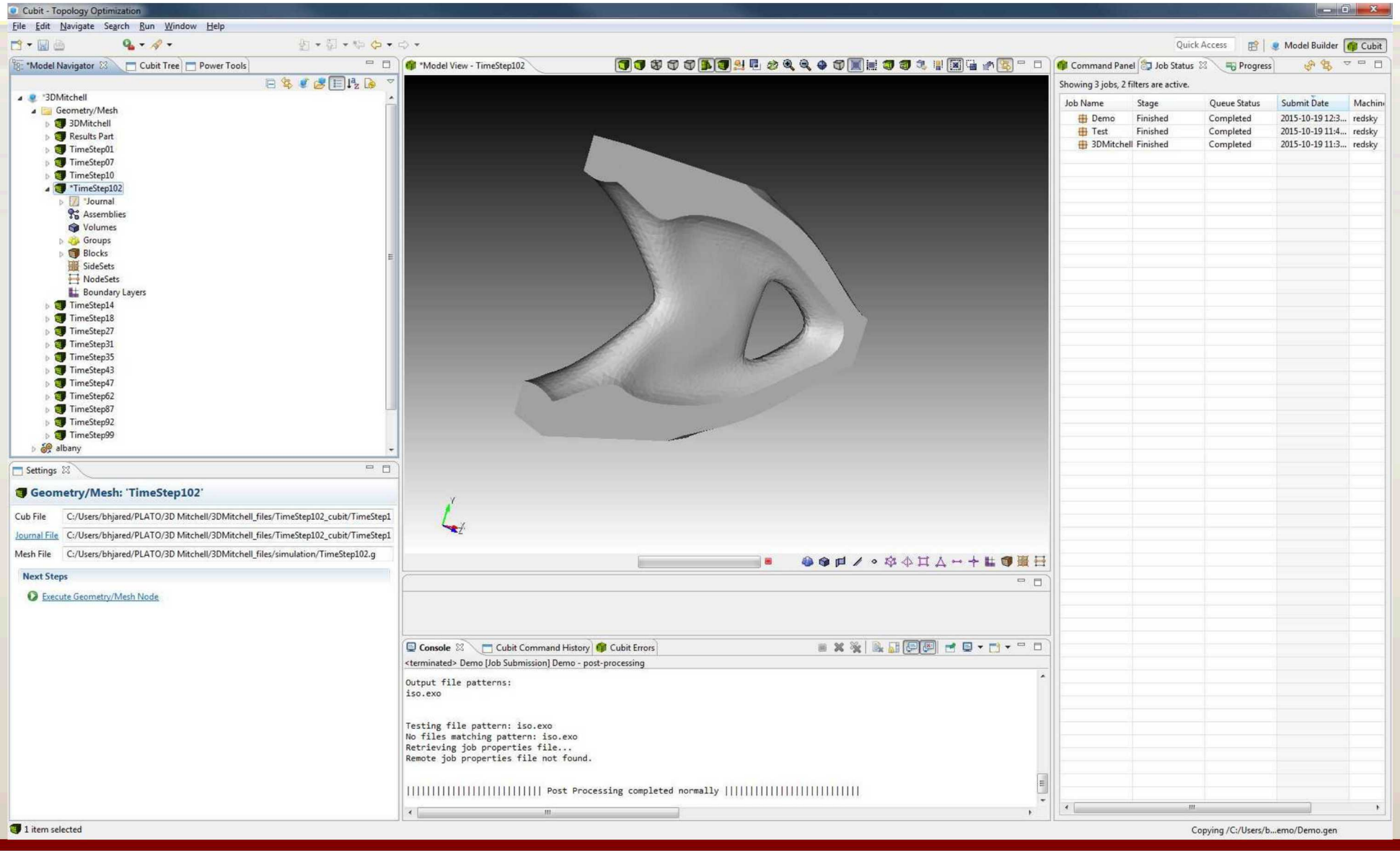
+ 3.3% volume
- 64% deflection

elasto-static stiffness optimization



solution for a bar in pure torsion resembles a cholla cactus

Sandia Analysis Workbench (SAW)

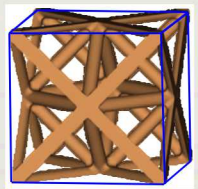


Joshua Robbins (1444), Tom Voth (1443), Miguel Aguilo (1542), Brett Clark & Ted Blacker (1543)

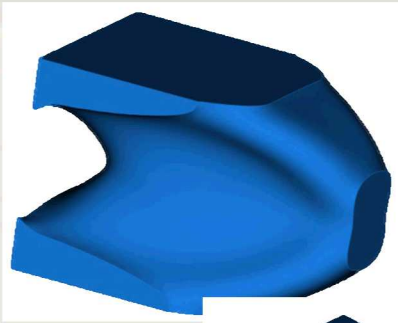
TO w/Lattice Structures

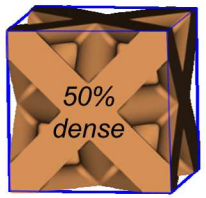
Optimizing stiffness w/fixed mass

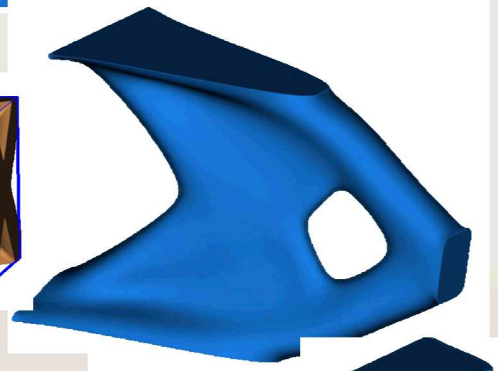
Tailored geometry avoids "loose ends"

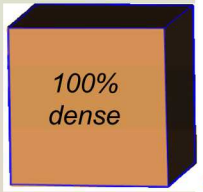


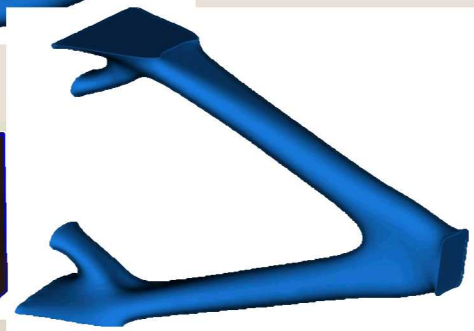
10% dense

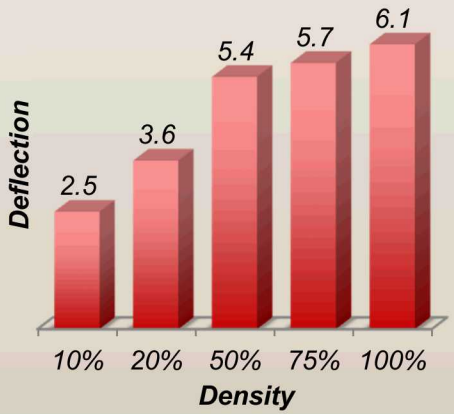


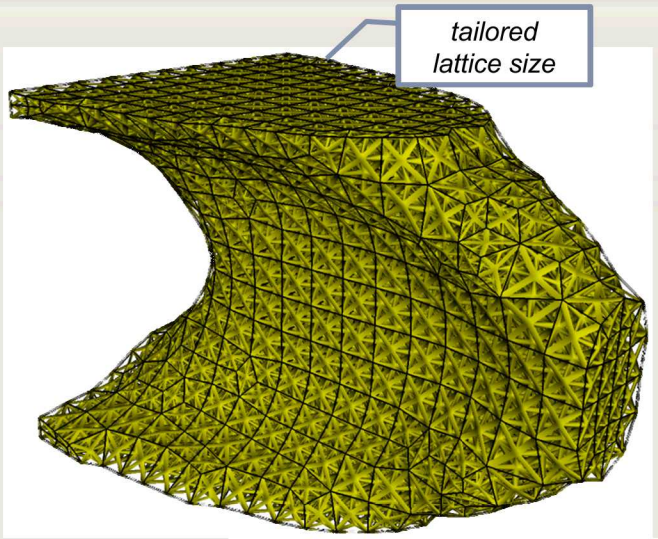


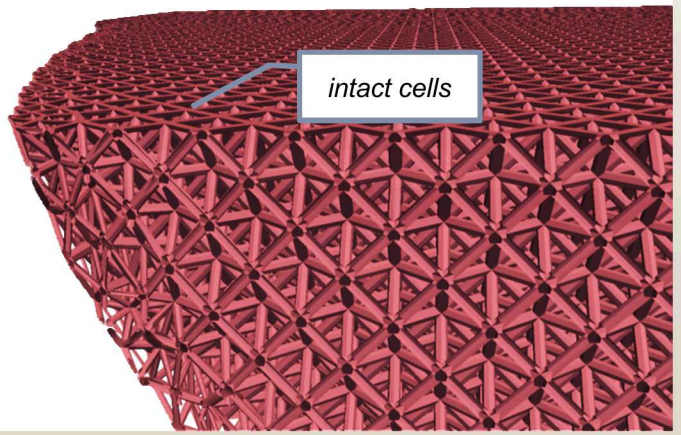








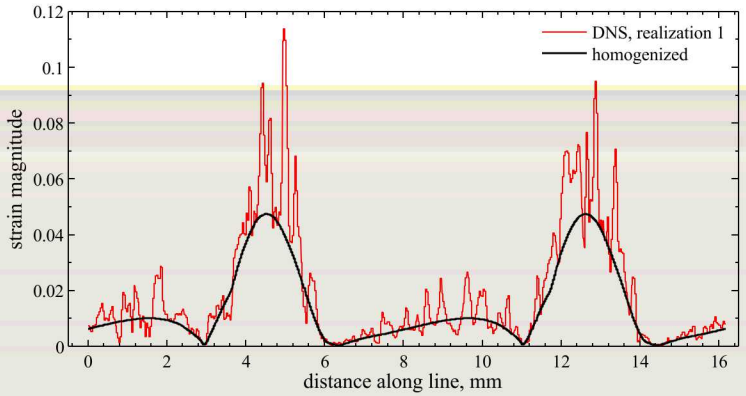




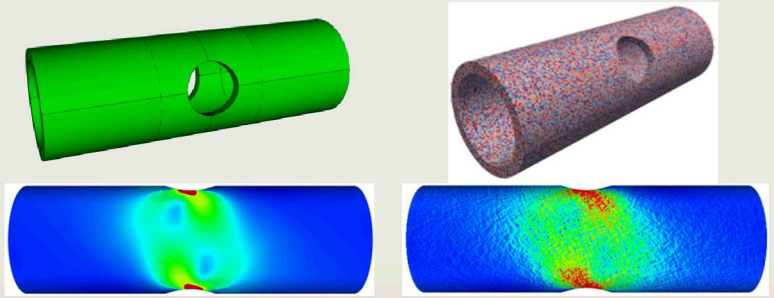
Joshua Robbins (1444), Tom Voth (1443), Miguel Aguilo (1542), Brett Clark & Ted Blacker (1543)

Engineered Materials

- Integrated Computational Materials Engineering (ICME)
  - materials analog to mechanical engineering
  - microstructure matters
- Voxel access introduces new opportunities for control & design
  - spanning multi-scales is difficult
  - metallurgical limits exist

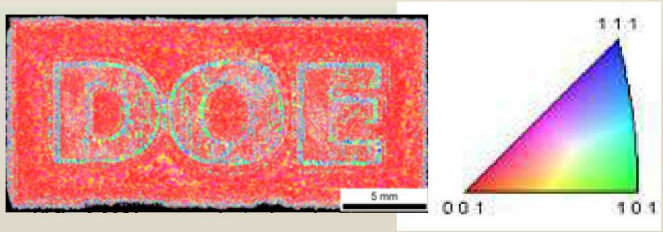


strain field due to tension-torsion

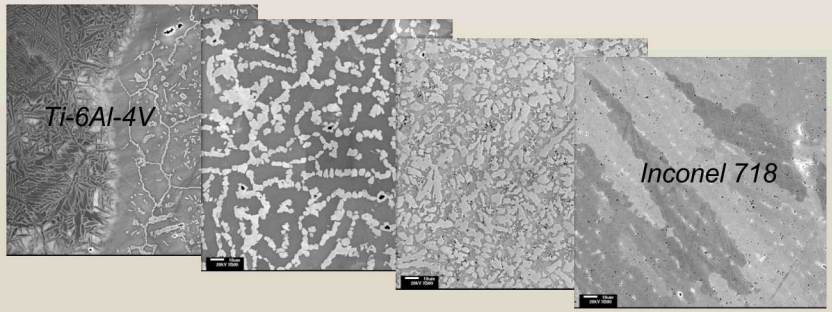


continuum model *crystal plasticity model*

AM Inconel 718 texture control demo by ORNL



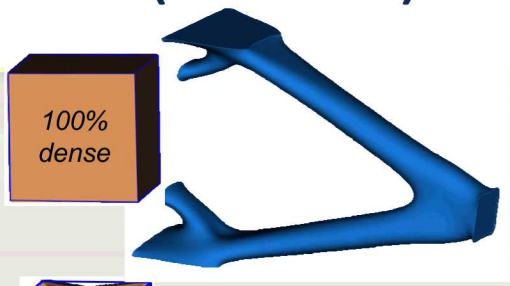
"We can now control local material properties, which will change the future of how we engineer metallic components," R. Dehoff

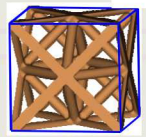


LENS® functionally graded materials

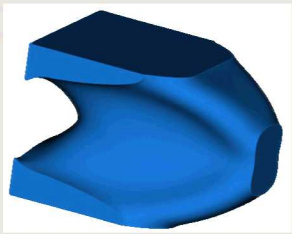
Plausible Topology Optimization (PLATO)

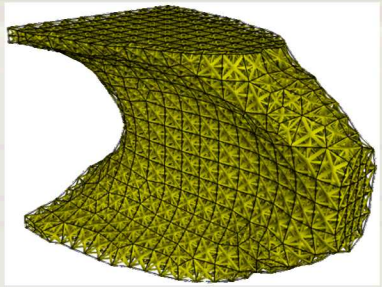
- SIERRA implementation
  - available for government use
- Current capabilities
  - SAW user interface
  - elasto-static & thermal solutions
  - load cases
    - displacement, surface or body loads, CG, temperature, flux
  - anisotropic, multi-materials
  - lattices
  - parallel HPC processing
- Future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



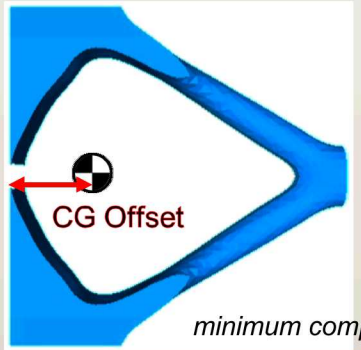


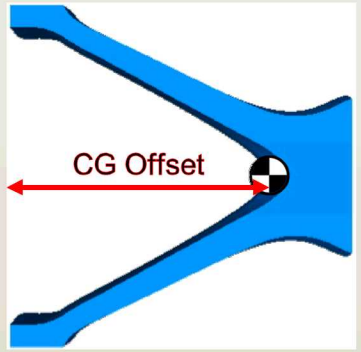
10%
dense





lattice implementation w/TO solutions





minimum compliance w/fixed CG location

Abstract

- Additive manufacturing (AM) offers unprecedented opportunities to design complex geometries and optimized topologies for performance gains inaccessible under conventional manufacturing constraints. However, to facilitate adoption in high consequence applications, fundamental questions regarding the intrinsic reliability and repeatable performance of additive metals must be answered. Distinct from traditional subtractive processes, component geometry and material are formed concurrently in additive processes and preclude an a priori knowledge of material performance from feedstock properties. Of interest are powder bed fusion processes where a laser scans across successive layers of metal powder to fuse material and generate a desired part geometry. Such layerwise processing enables access to volume elements, i.e. voxels, throughout every part with opportunities for material control but also defect formation.
- Predicting material performance is challenging for powder bed processes since it involves complex melting and solidification interactions, and is implemented on equipment with limited capabilities for process control and/or defect tracking. Consequently, material performance is commonly indeterminate and introduces unacceptable uncertainties for certifying and qualifying additive components. On-going research is working to reduce these uncertainties by exploring the process-structure-properties triad of stainless steel alloys. Material characterization and testing is identifying the nature of critical defects, quantifying their impact on material properties, correlating their presence with processing conditions, and developing a basis for understanding defect formation mechanisms. Thus, critical defect “signatures” will be presented to provide a predictive framework for quantifying material performance distributions using techniques that span in-situ process monitoring, post-process computed tomography, metallography and tensile testing.