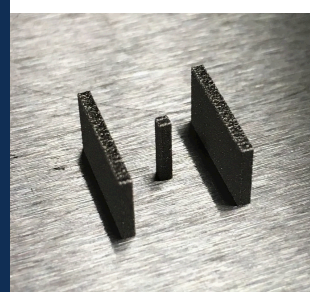
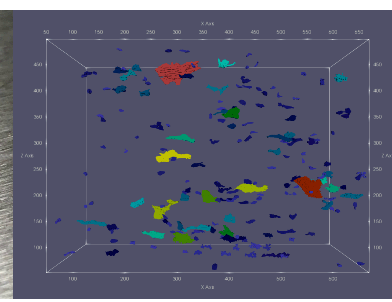
SAND2017-11708PE

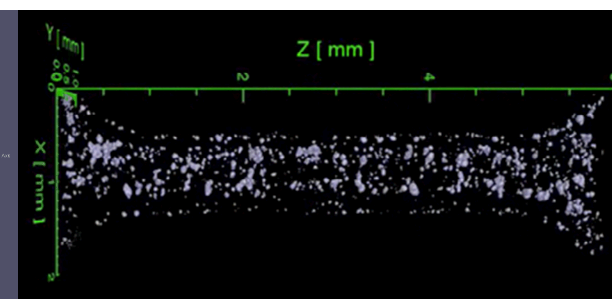
Sandia AM Research

Bradley Jared

Materials Engineering & Manufacturing S&T







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Sandia National Laboratories

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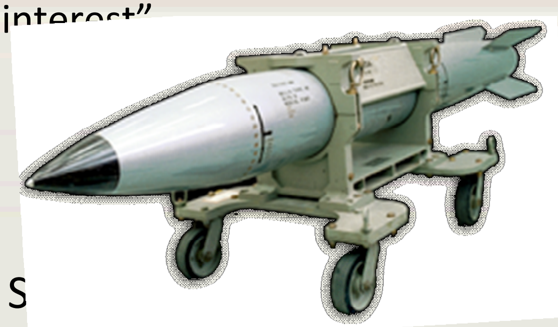
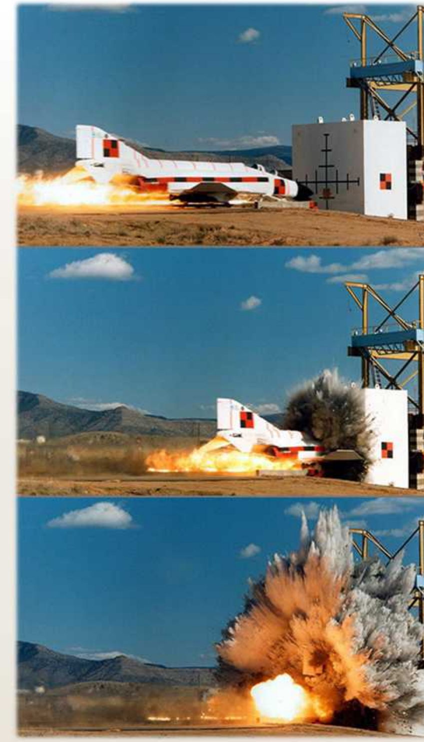
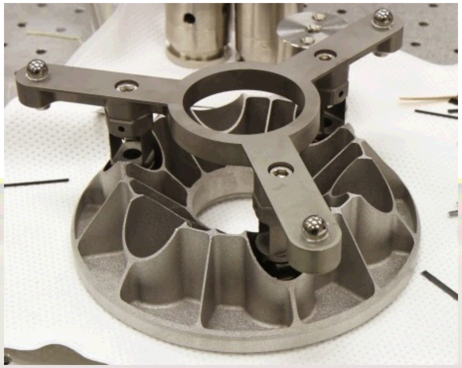




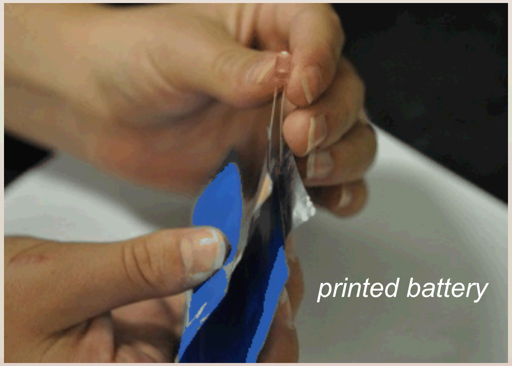
SNL’s Additive Interests

- 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”



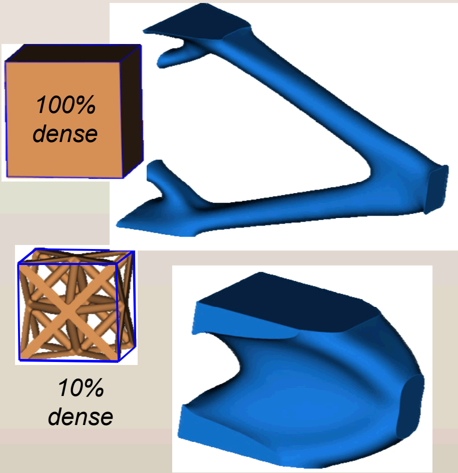
prototype AM mirror & structure

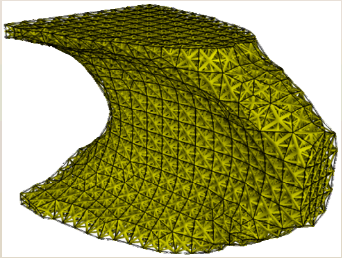
full scale additive weapon mock-up



printed battery

printing of alumina

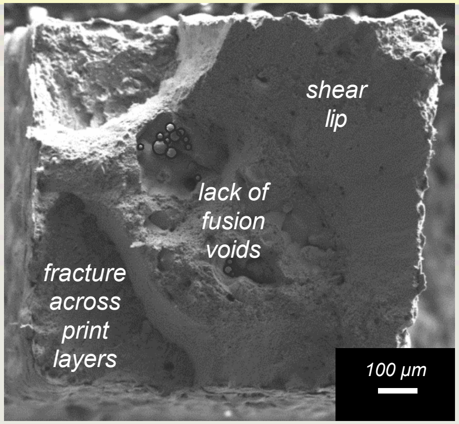




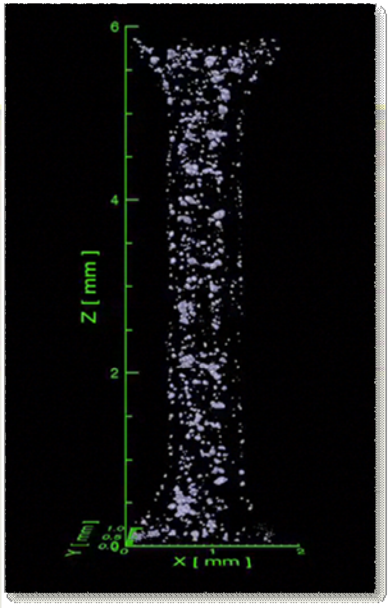
lattice implementation w/TO solutions from PLATO

Material Assurance

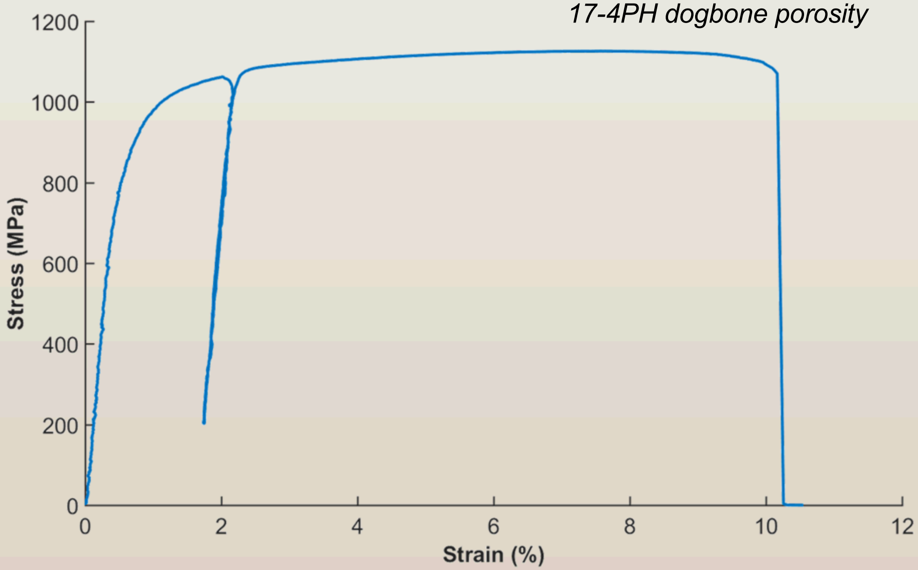
- Material formation concurrent w/geometry
  - want to predict part/material performance
  - **<u>how to ID a bad part?</u>**
    - complexity isn't "free"
    - requires significant design margins **and/or** rigorous post-process inspection / validation
- Quantify *<u>critical</u>* material defects & *<u>useful</u>* "signatures"
  - D-tests, NDE, process monitoring, mod-sim, ?
- Understand mechanistic impacts on properties
  - build process-structure-property relationships to predict 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

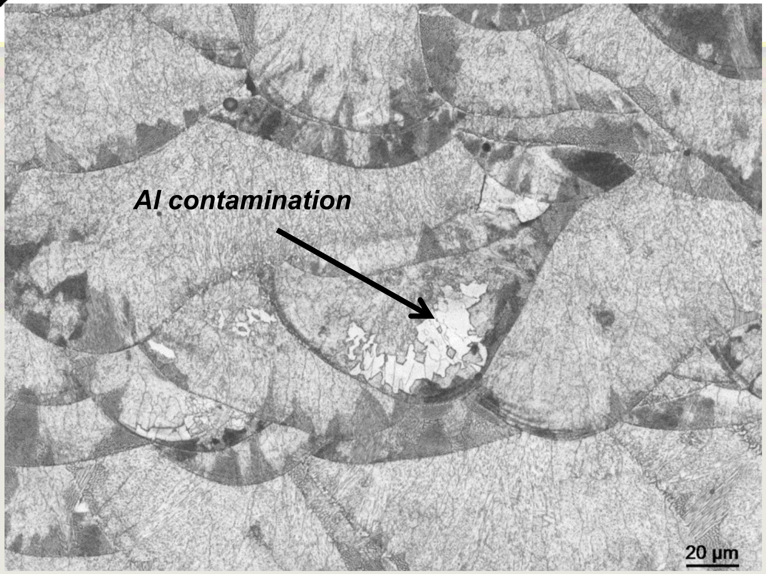


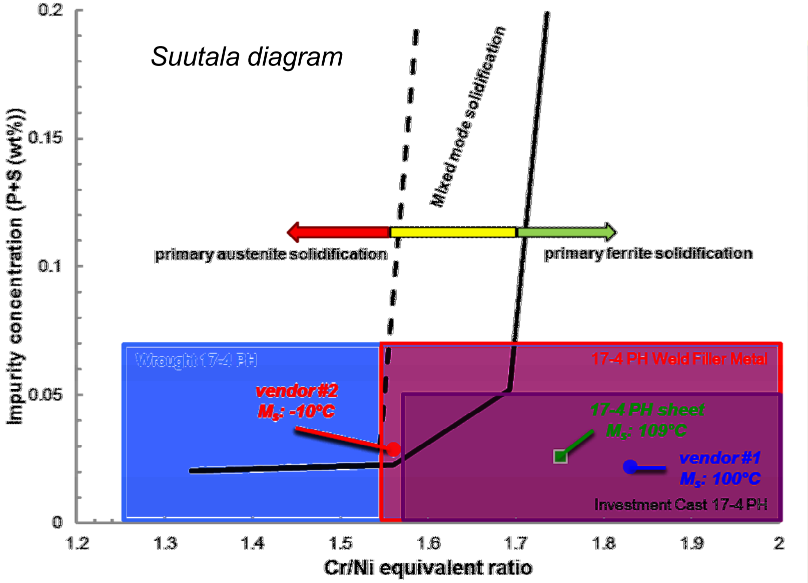
17-4PH dogbone porosity

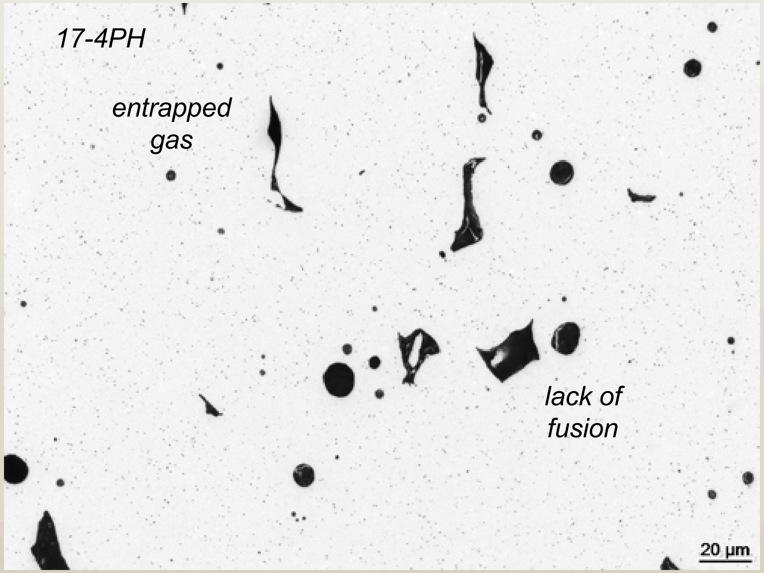


17-4PH dogbone stress-strain response

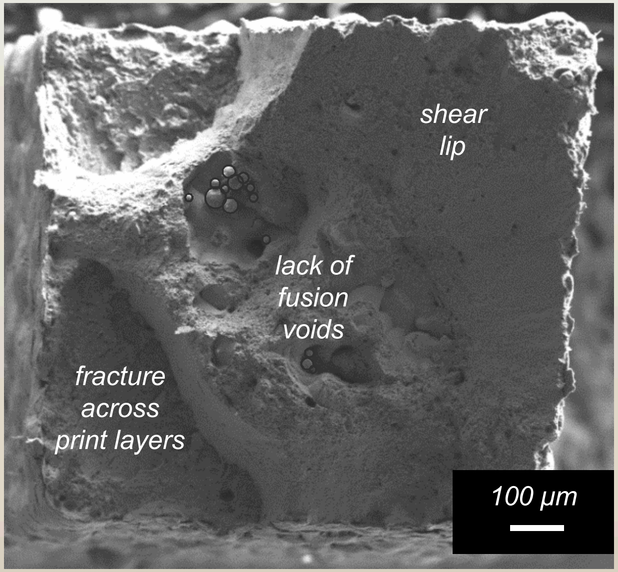
Representative Material Defects







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



Powder Bed Fusion

- Growing activity for metal parts
  - supporting wide-ranging SNL missions
  - research platforms for process & material characterization

- 3D System machines
  - two ProX 300, one ProX 200
  - motivations
    - roller powder compression
    - process flexibility
    - domestic OEM
  - materials
    - now: 316L
    - future: Kovar, 304L, 17-4Ph, 13-8Mo

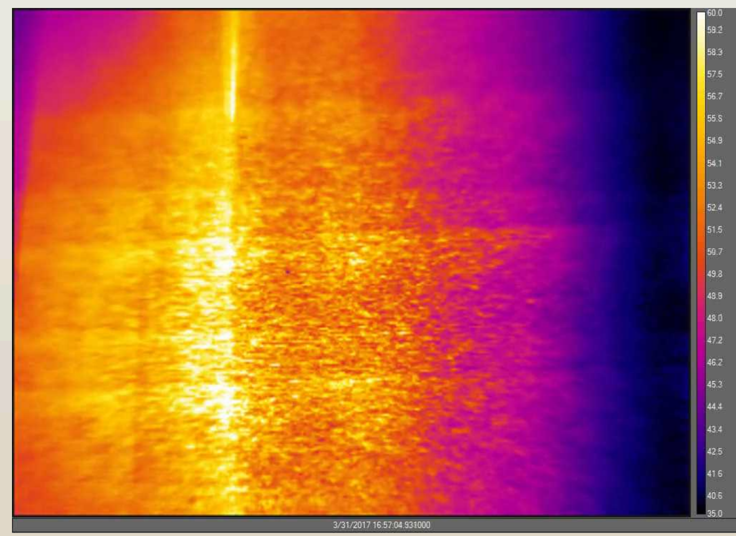
ProX 200, materials science lab

ProX 300

Pursuing In-Situ Signatures

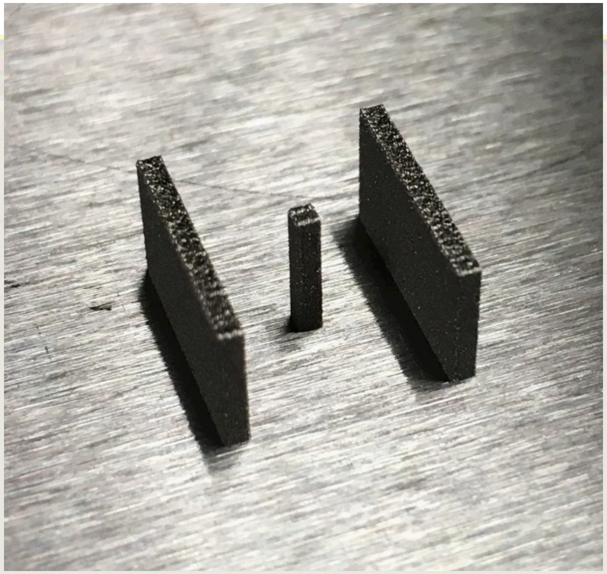
- Defect Detection project collaboration
  - seek to correlate spatial sensor data (X,Y,Z,time) to material porosity (X,Y,Z)
  - focused to date on installation, operation & calibration
- Thermal
  - Stratonics ThermaViz two-color pyrometer
  - FLIR C2, A310 & SC6811 IR cameras
- Optical
  - Photron PhotoCam Speeder V2 high speed cameras
  - blue light illumination option
  - Ocean Optics LIBS2500plus spectrometer
  - Keyence LJ-V7020 & LJ-V7200 laser displacement sensor line scanners
- Acoustic
  - audio microphone, acoustic emission
- Laser characterization
  - Ophir Spiricon SP928 beam profiler
  - Ophir L50(300)A-LP1 power meter
- 3D Systems Open Protocol platform

ThermaViz installed in the ProX 200



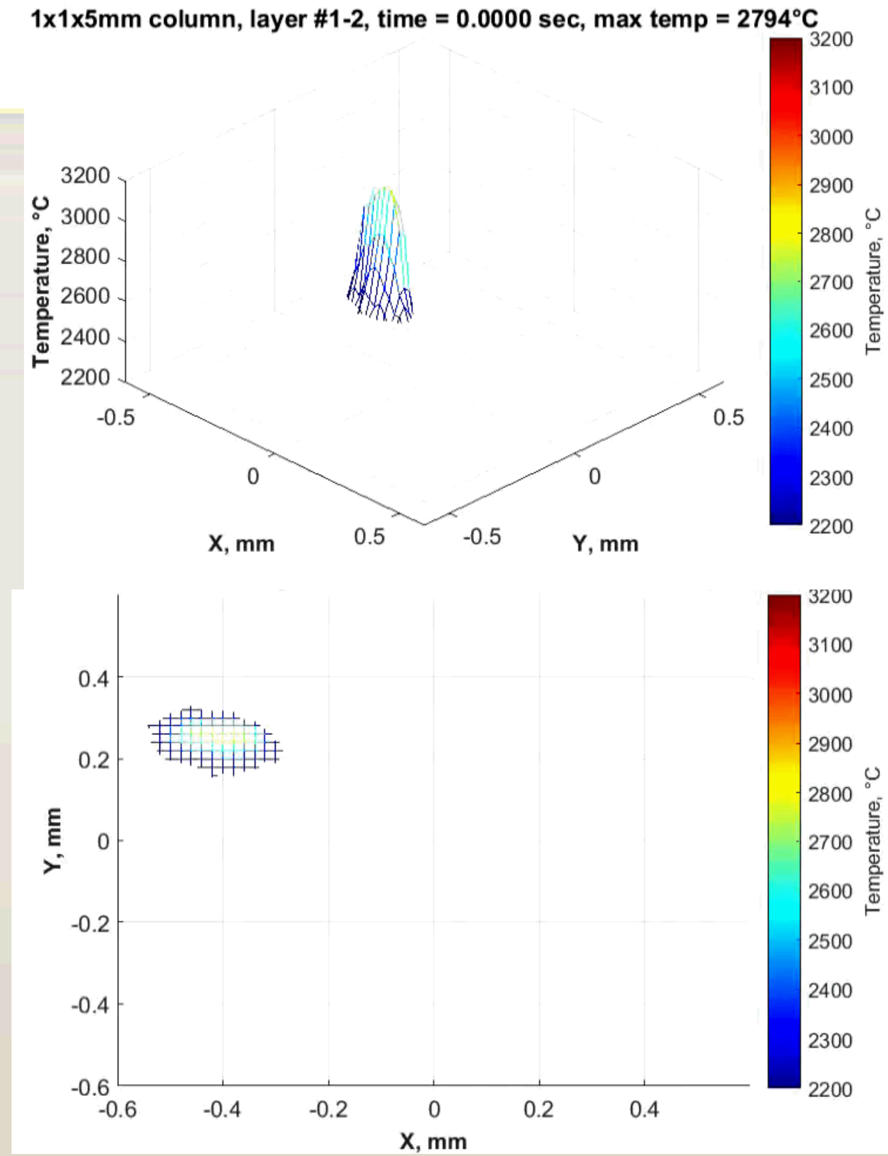
FLIR A310, laser on plate, ~100W, 1.4m/sec, 125μm hatch, 100μm beam dia.

Melt Pool Data



1x1x5mm 316L SS column for ThermaViz experiments

Photron high speed optical melt pool video

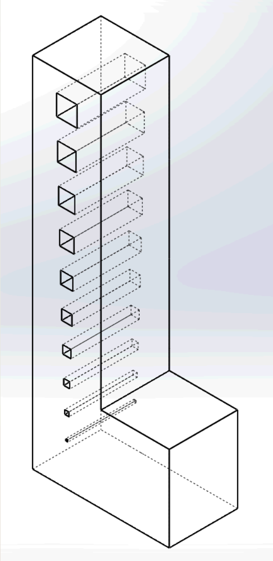


ThermaViz layer data for 1x1x5mm 316L SS column

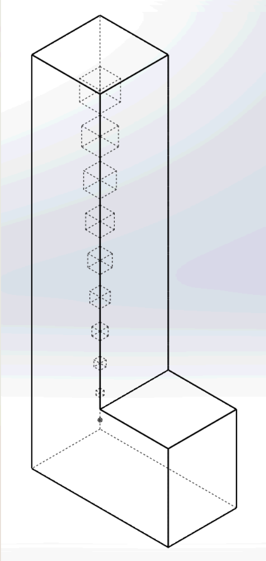
Exploring Melt pool signatures

- Introduced intentional defect structures
  - 1-10 layer thickness “pores”
    - 30-300μm
  - 1x1x5mm column
  - Stratonics @ ~7kHz
  - how do we manage the data set?
    - ~100,000 thermal images per part

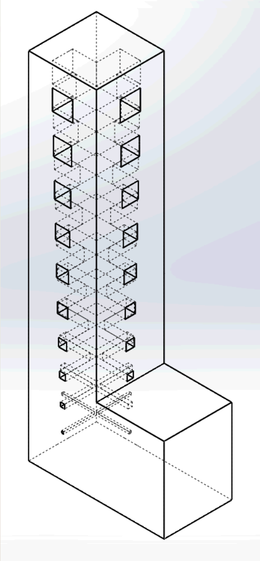
- Melt pool response
  - shutter speed, sample rate
  - bead on plate, single powder layers
  - line & area scans
  - laser power, velocity, cross-feed
    - power exhibits strongest trends
  - tests are quick
    - data analysis is not…



thru holes

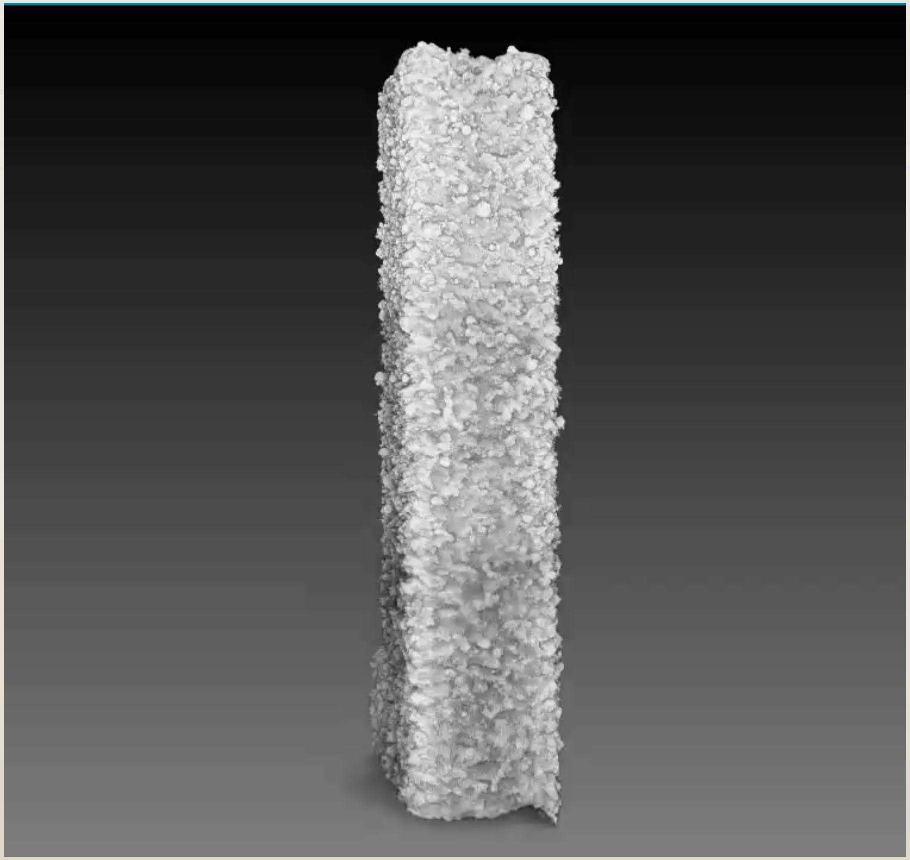


captured hole structure

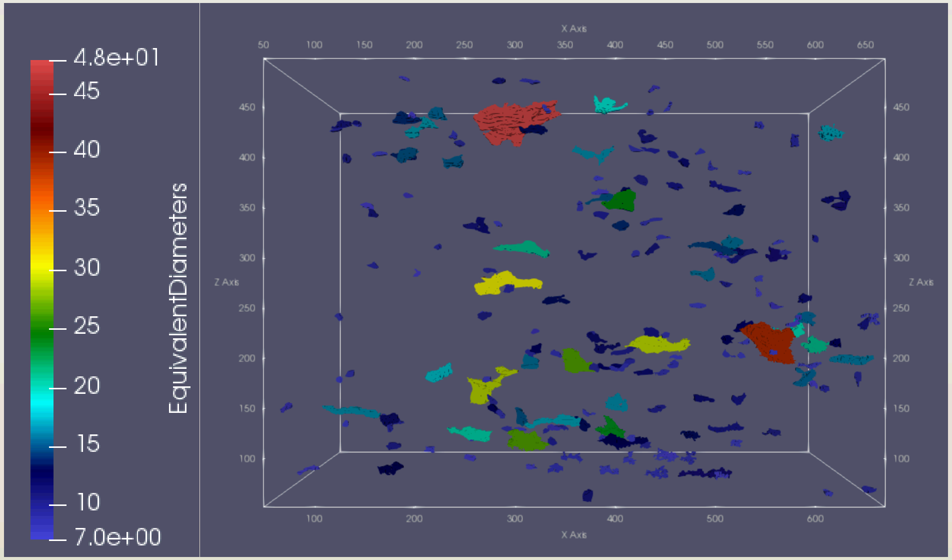


crossed thru holes

Defect Structure CT Data



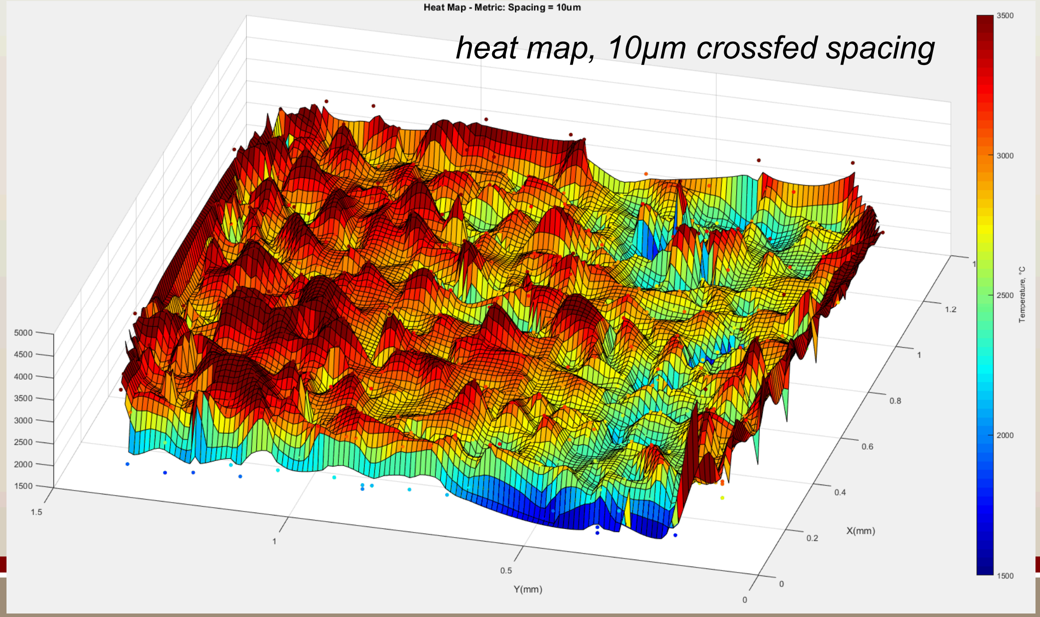
captured defect holes part CT image, Zeiss Xradia Versa
voxel resolution ~ 2μm

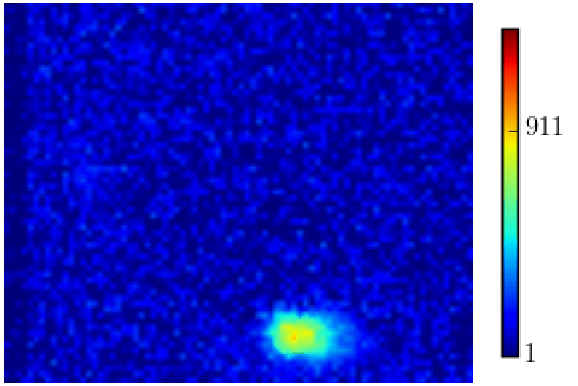


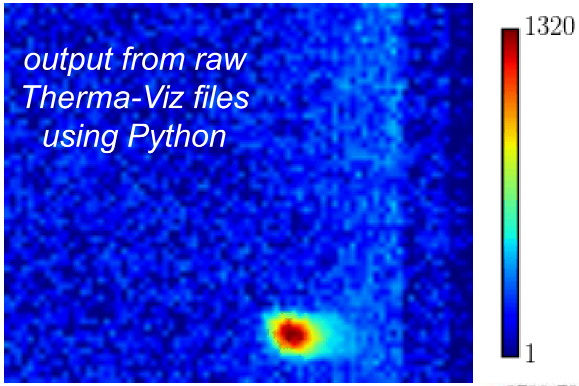
porosity map generated using DREAM.3D near the 10 & 20μm defects

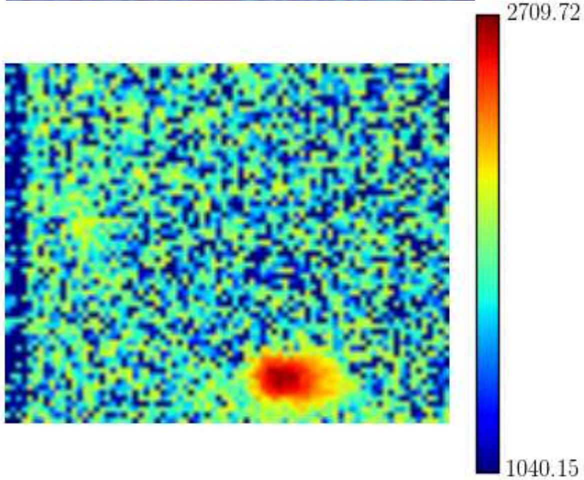
Therma-Viz Data Analysis

- Melt pool metrics
  - peak temperature
  - centroid location
  - area, length, width
  - kurtosis, skewness
- Python script applied to 100k images

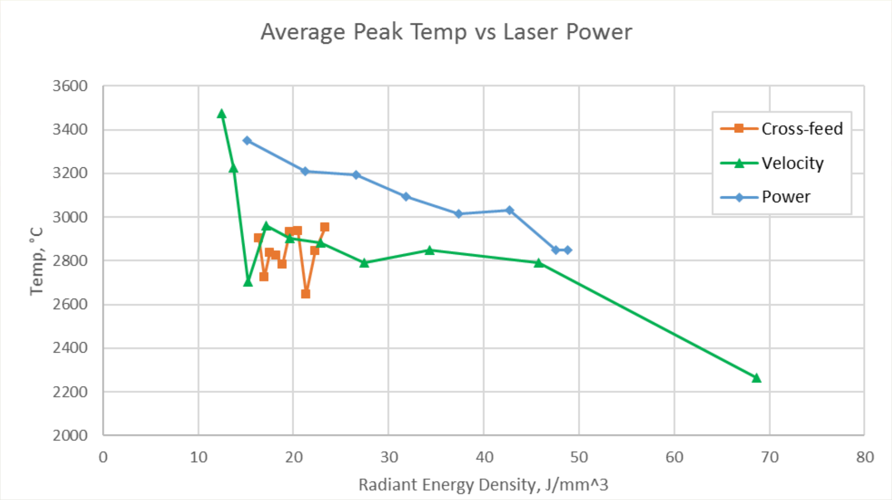


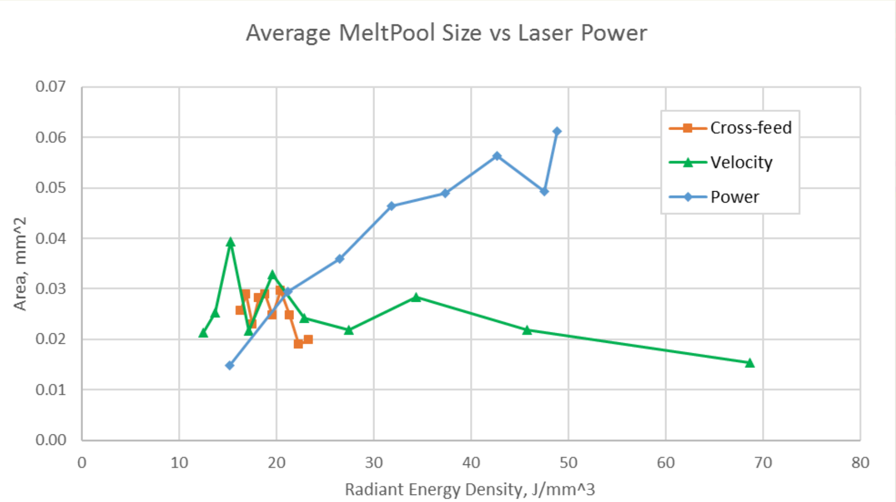


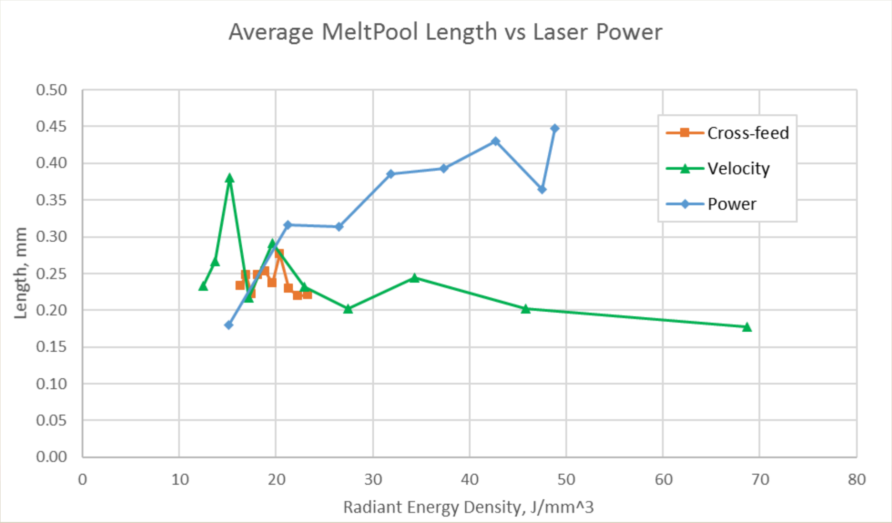


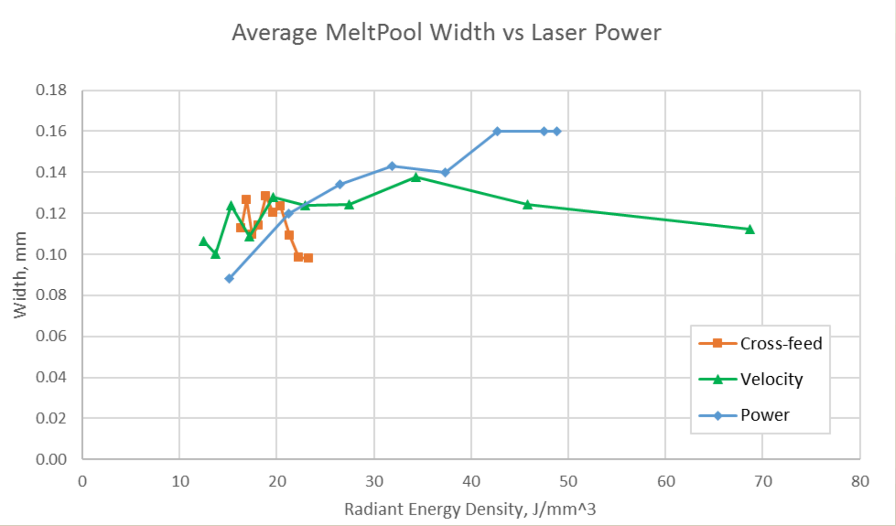


Melt Pool Dynamics

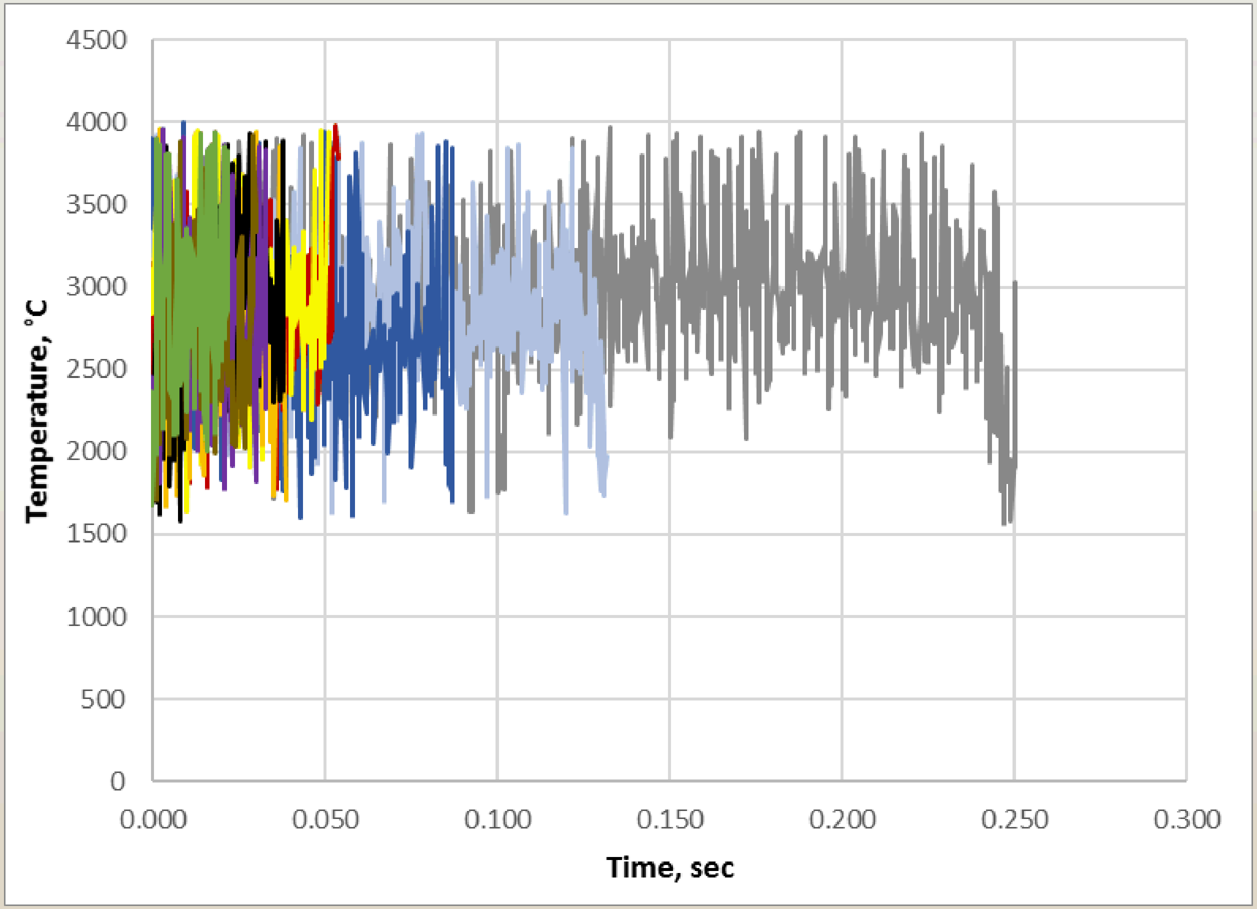




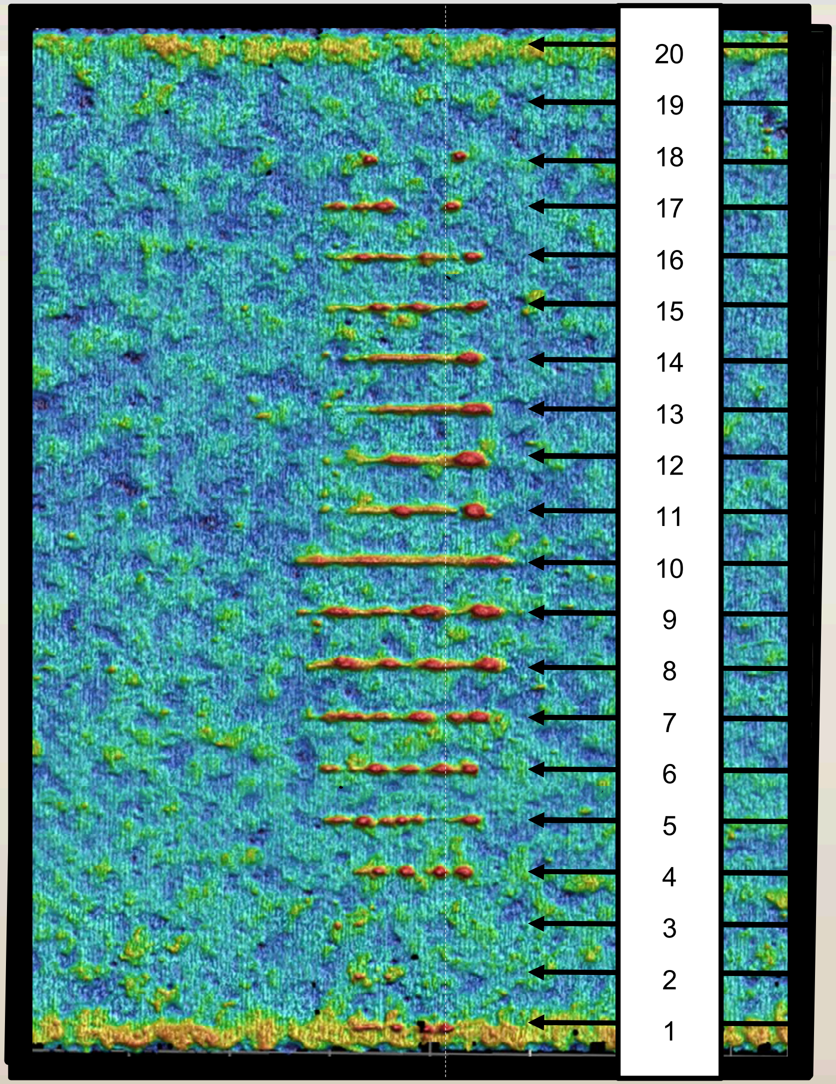




Dynamic Thermal Response



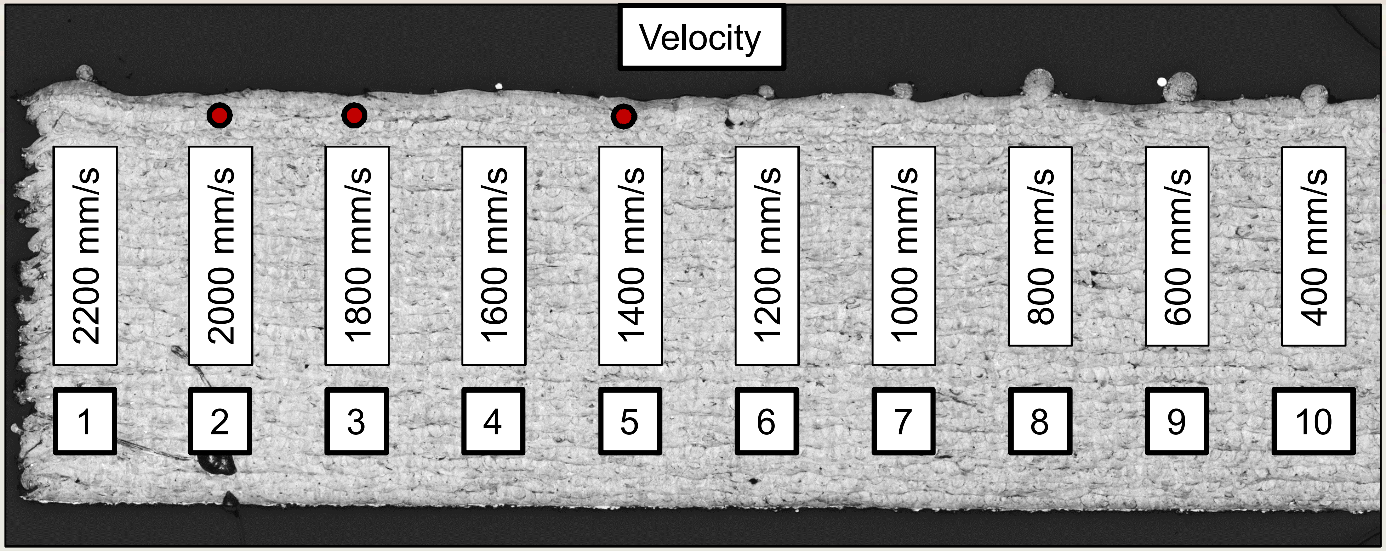
Line Scans



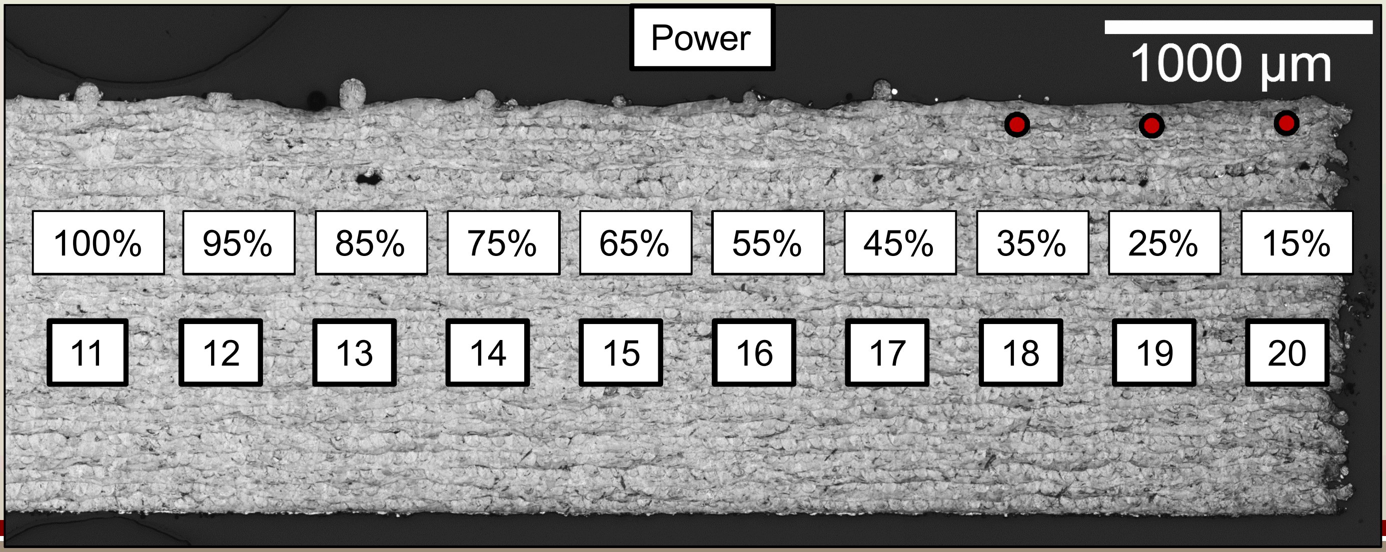
Scan	Velocity
1	2200 mm/s
2	2000 mm/s
3	1800 mm/s
4	1600 mm/s
5	1400 mm/s
6	1200 mm/s
7	1000 mm/s
8	800 mm/s
9	600 mm/s
10	400 mm/s

Scan	Power
11	100%
12	95%
13	85%
14	75%
15	65%
16	55%
17	45%
18	35%
19	25%
20	15%

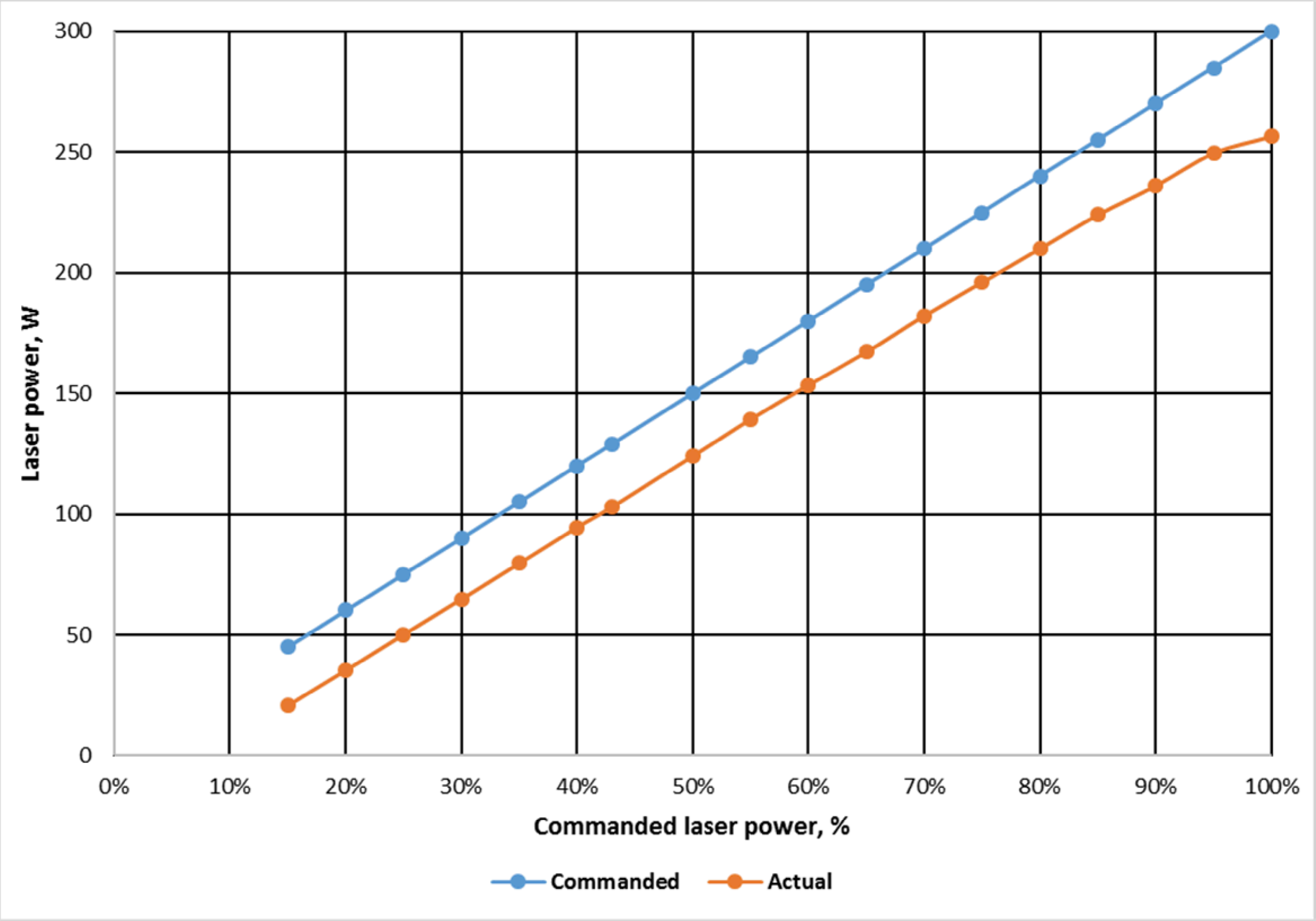
Weld Microscopy



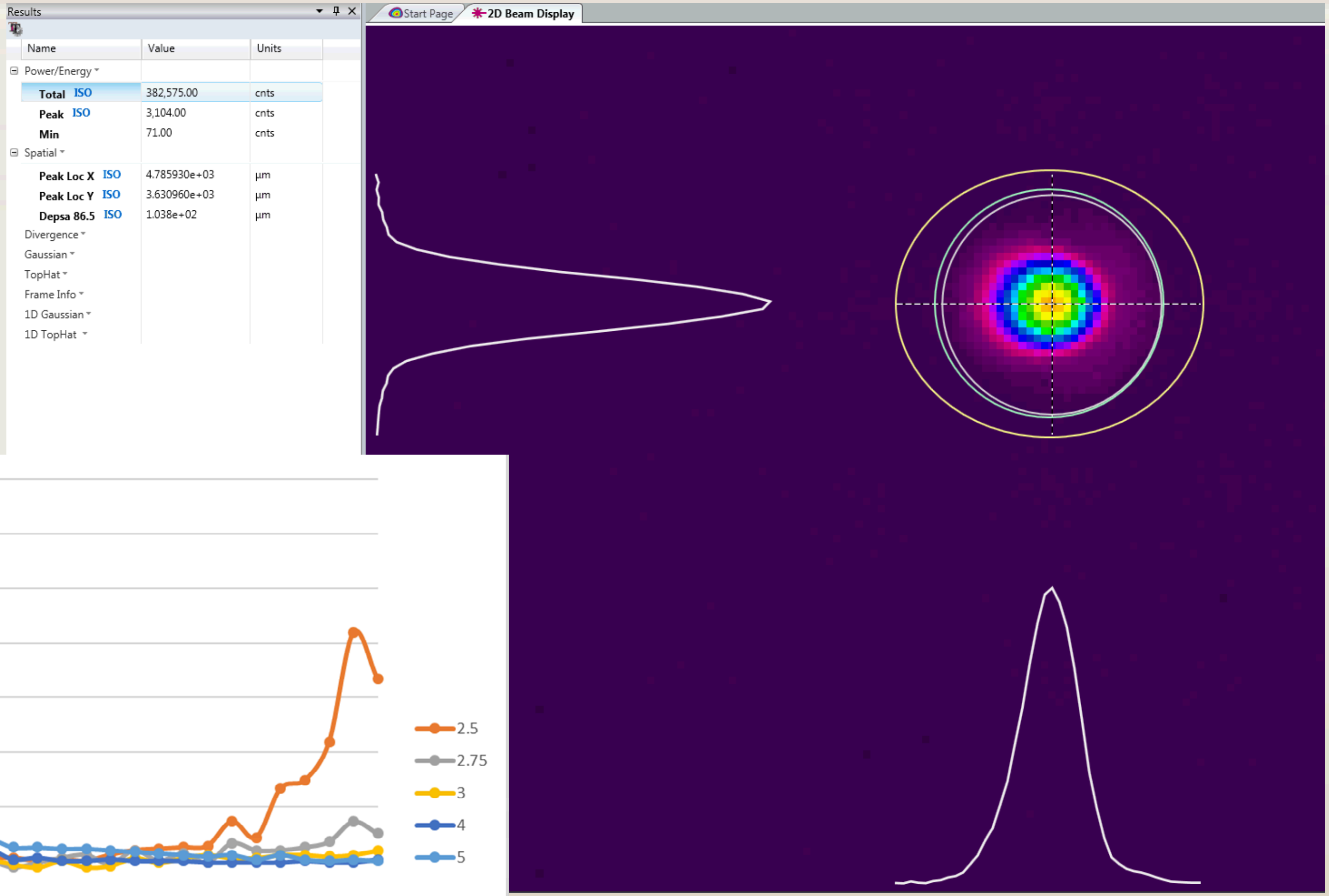
- Capturing melt pool widths & depths



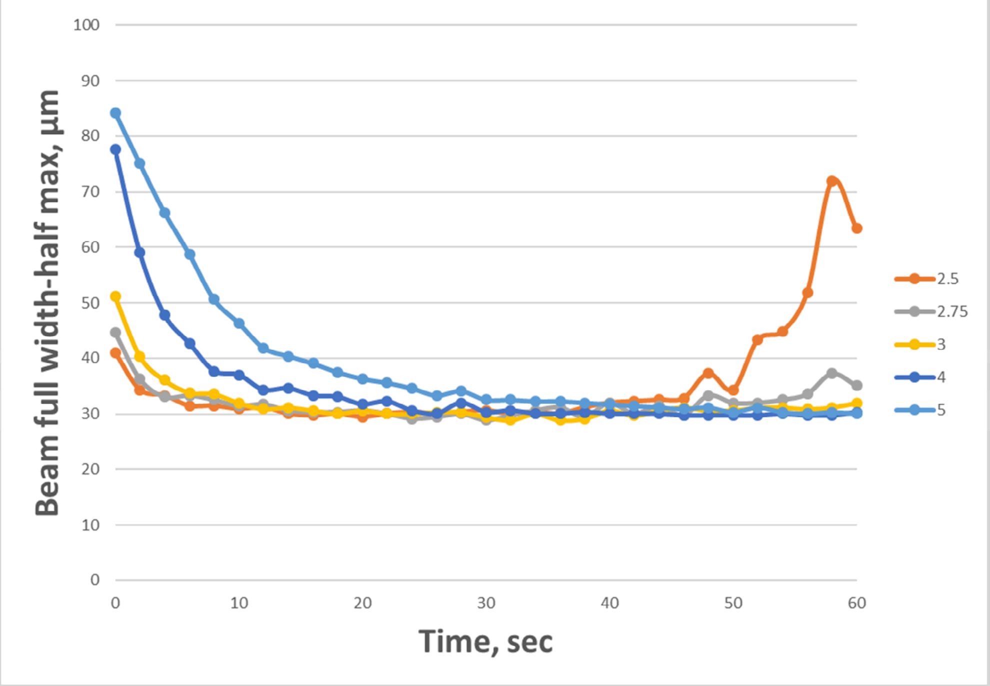
Beam Diagnostics



Beam Diagnostics

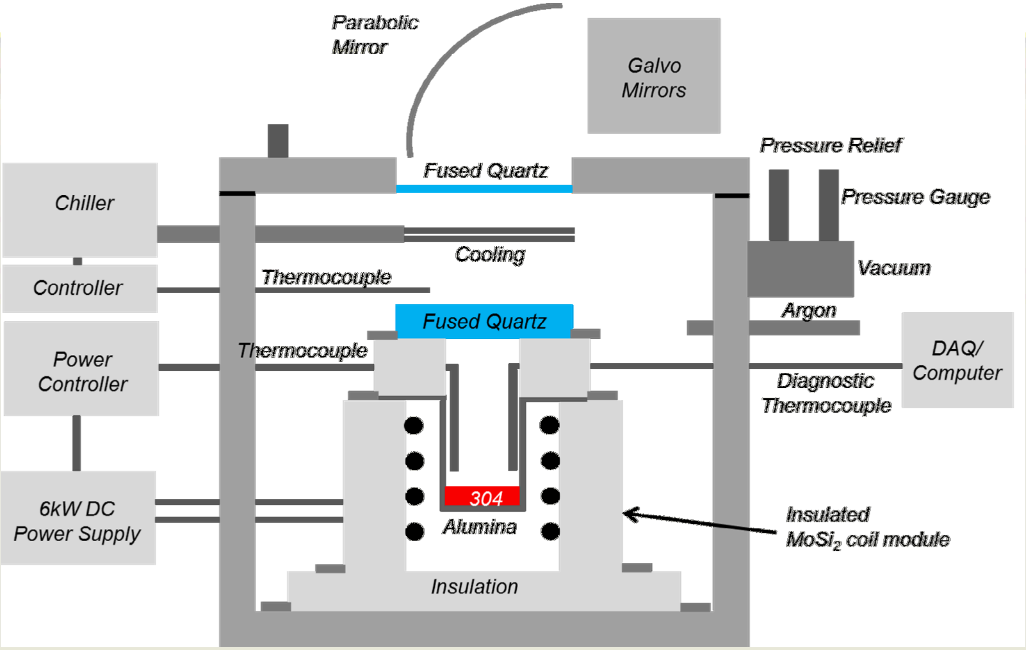


Name	Value	Units
Power/Energy		
Total ISO	382,575.00	cnts
Peak ISO	3,104.00	cnts
Min	71.00	cnts
Spatial		
Peak Loc X ISO	4.785930e+03	µm
Peak Loc Y ISO	3.630960e+03	µm
Depsa 86.5 ISO	1.038e+02	µm
Divergence		
Gaussian		
TopHat		
Frame Info		
1D Gaussian		
1D TopHat		

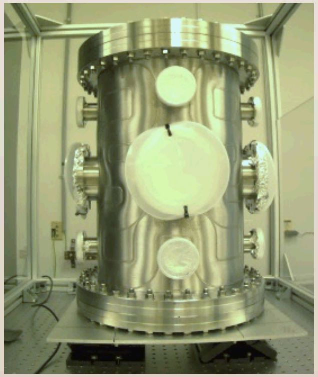


Calibration Testbed for IR Sensors

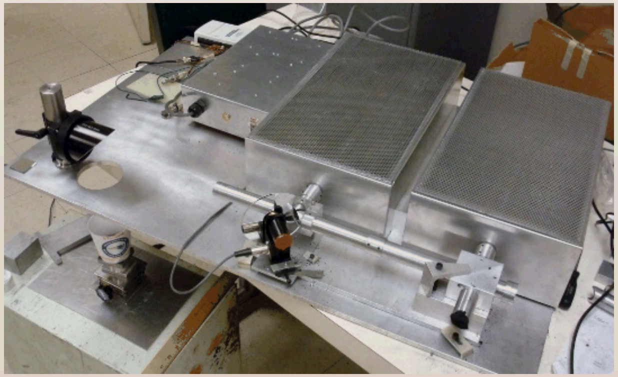
- Using microwave radiometers to measure emissivity & temperature
  - measures %R of 137 GHz radiation from surface
  - 20-1500°C, 2 Torr in Ar chamber
  - expected uncertainty ~10°C
- MIT collaboration



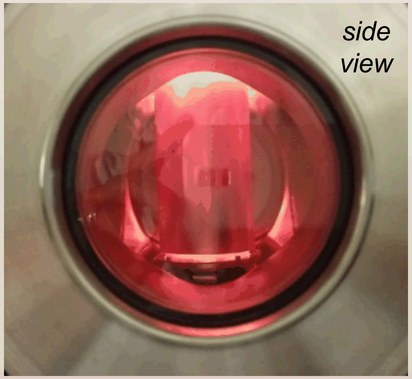
metrology testbed layout

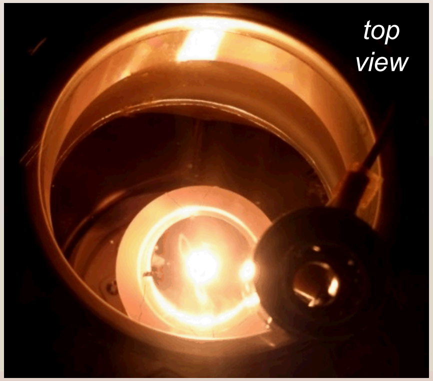


vacuum chamber



137 GHz radiometers





1500 °C furnace in operation

QUESTIONS?

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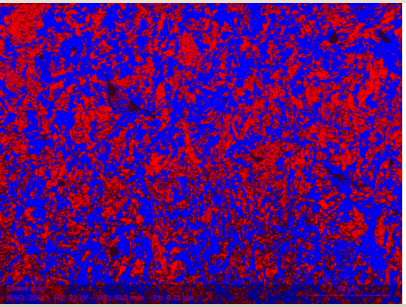
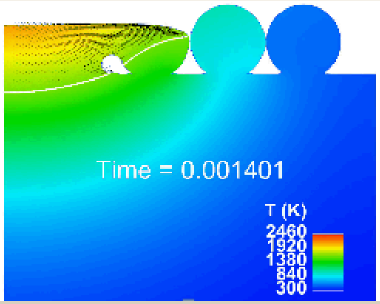
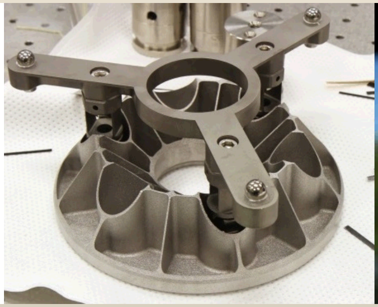
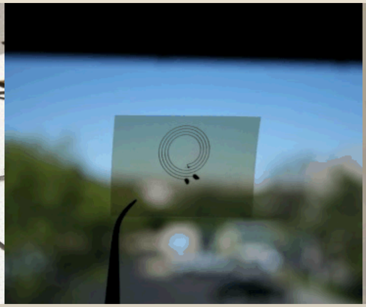
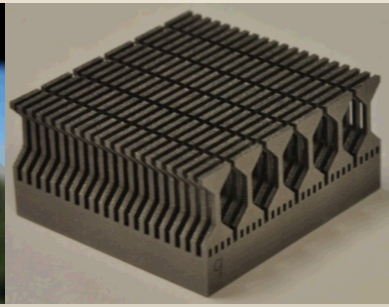




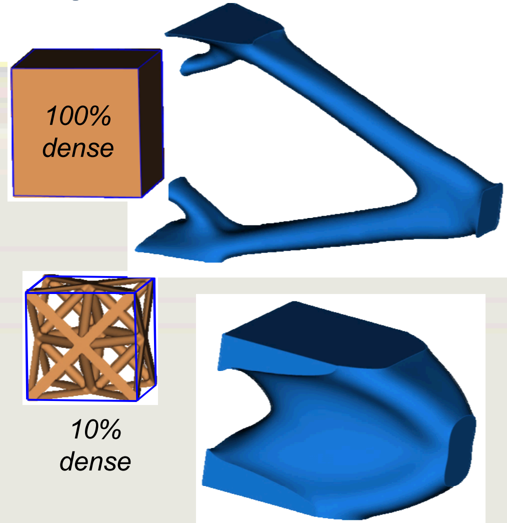


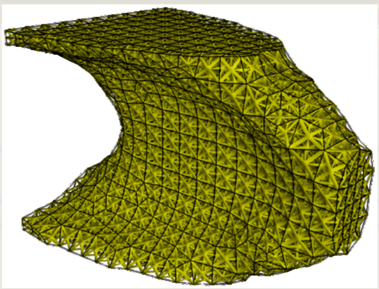


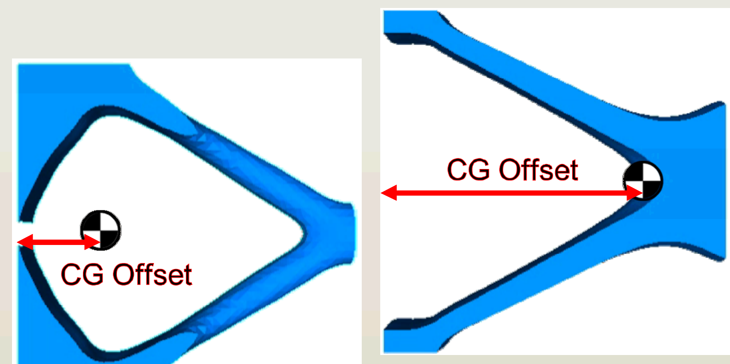


Plausible Topology Optimization (PLATO)

- 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



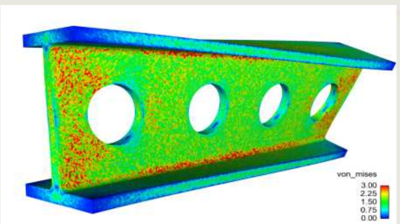

lattice implementation w/TO solutions



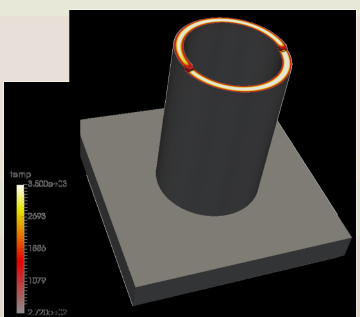
minimum compliance w/fixed CG location

Qualification Tomorrow

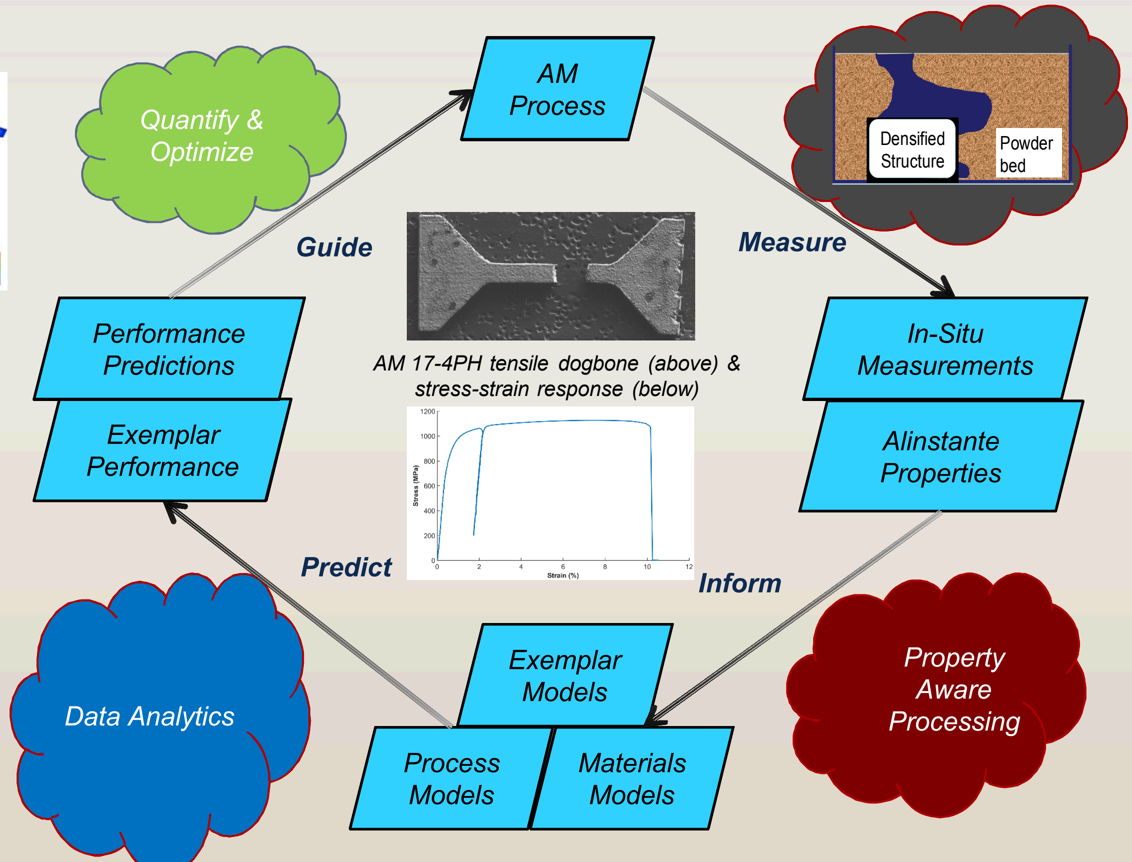
- "Changing the Engineering Design & Qualification Paradigm"
  - leverage AM, in-process metrology & HPC to revolutionize product realization



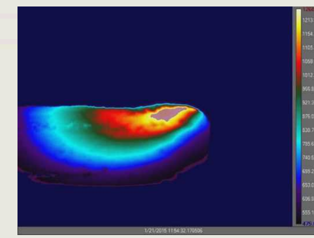
material / part performance simulation



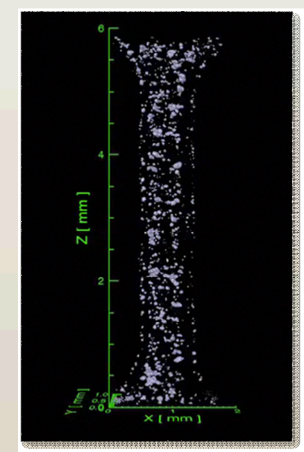
process simulation



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

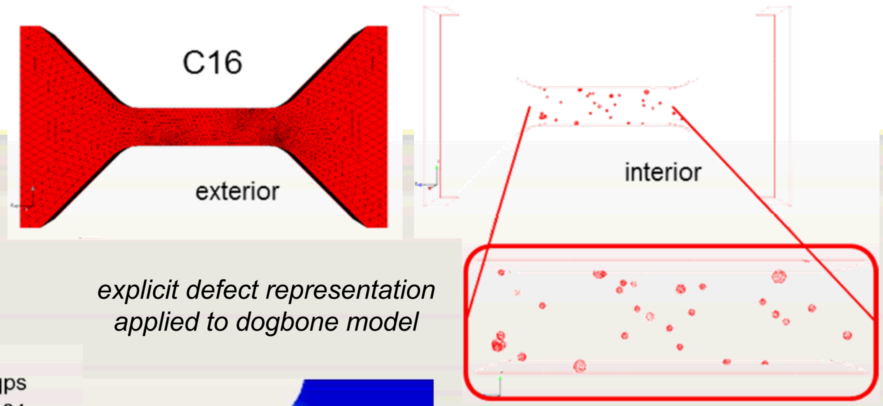


thermal history during bi-directional metal deposition

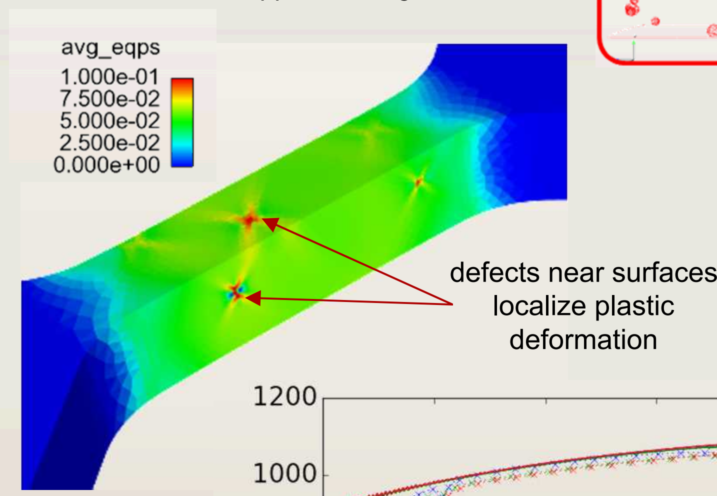


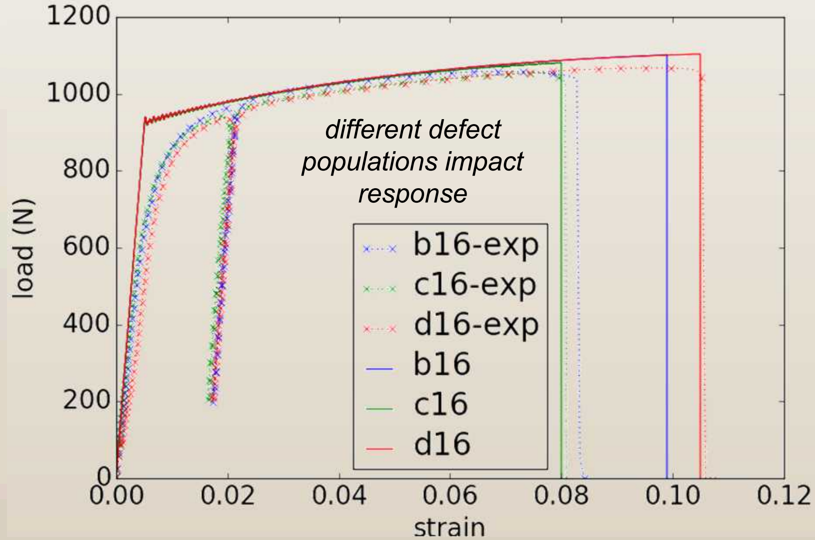
17-4PH dogbone porosity

Material Models



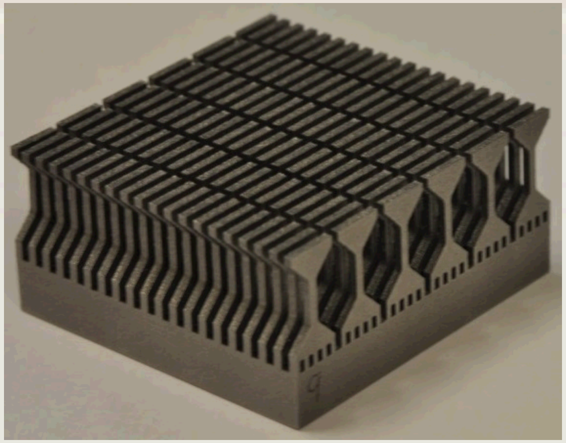
- Want to inform & predict material variability
- Approach
  - explicitly subtract spherical CT porosity volumes from dogbones
  - solve tensile loading
    - ignore residual stress, surface finish & defects w/volume below ~90µm^3
    - continuum properties calibrated to low porosity sample D16
- Expectations
  - large defects will intensify & localize deformation
  - microscale void mechanisms will drive failure



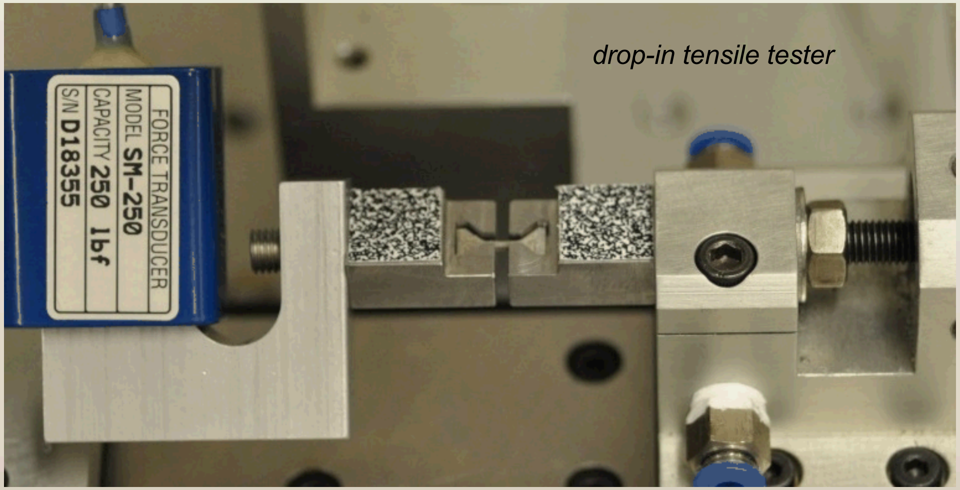


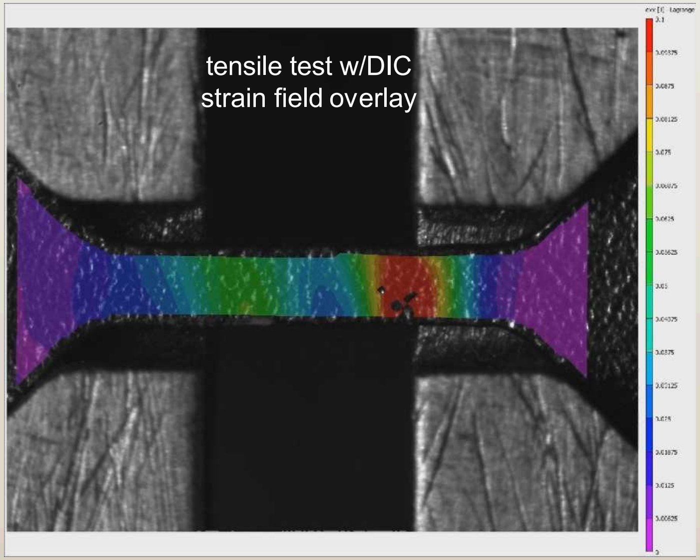
High Throughput Tensile Testing

- 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
  - SHT + H900 HT @ Sandia
- High-throughput testing
  - digital image correlation (DIC)
  - necessary to rapidly capture material distributions
  - applicable for the lab & production



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

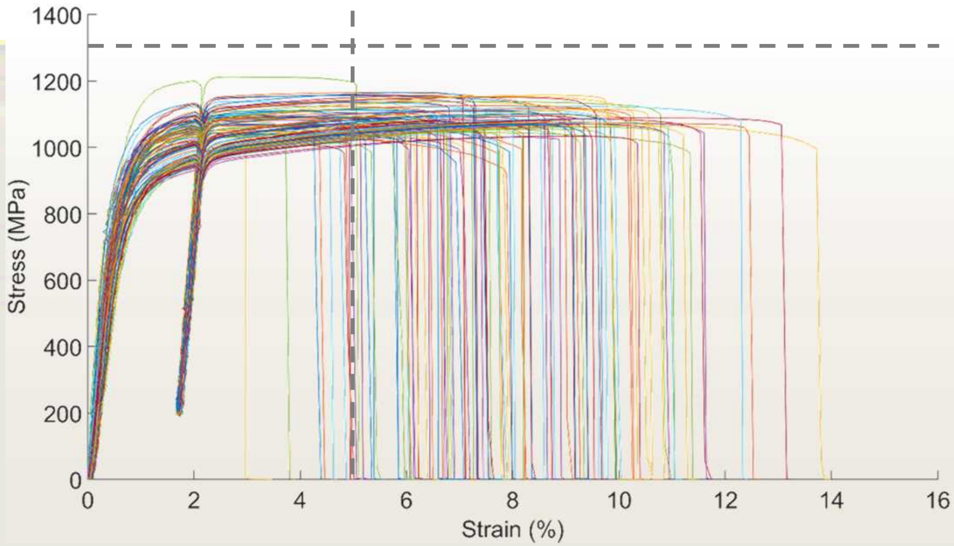




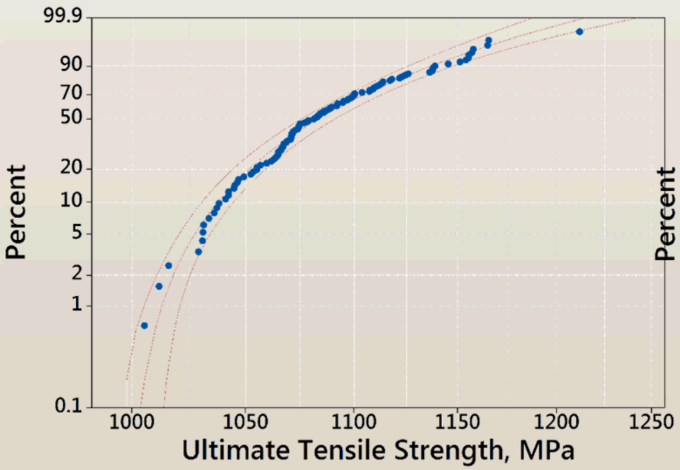
Salzbrenner, B., **Journal of Materials Processing Technology**, 2017; Boyce, B., **Advanced Engineering Materials**, 2017

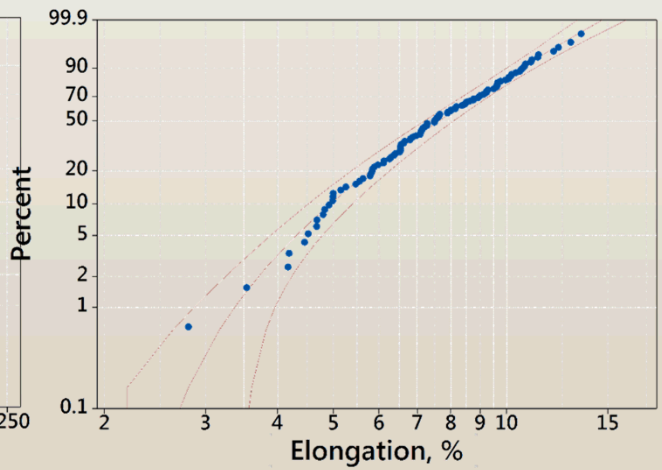
Stochastic Response

- 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?

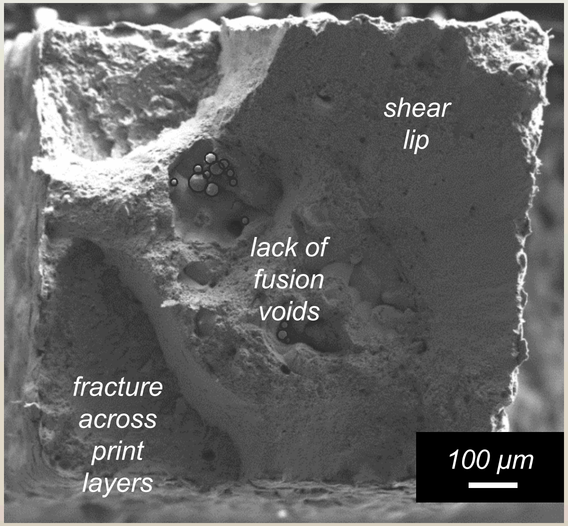


110 stress-strain curves for 17-4 PH after SHT+H900





material performance fit to 3-parameter Weibull distributions



failure at 2% elongation, SHT+H900

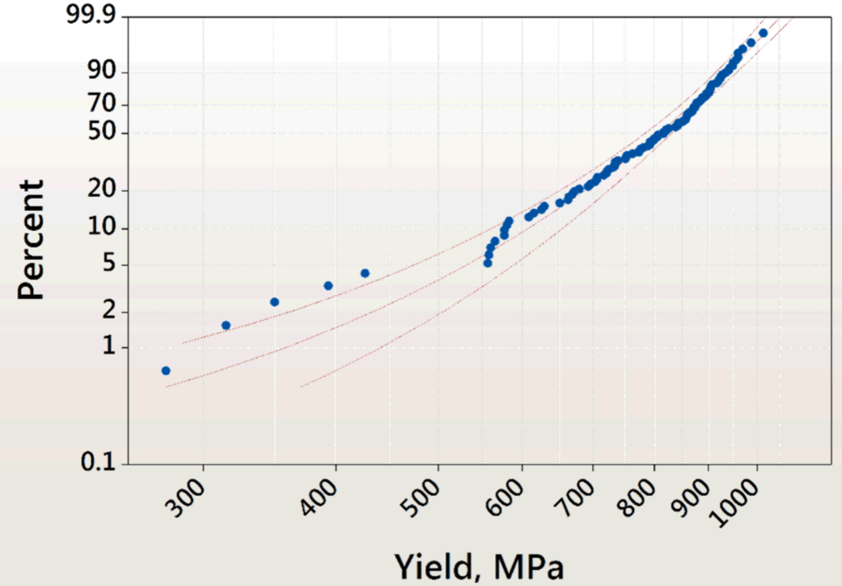
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

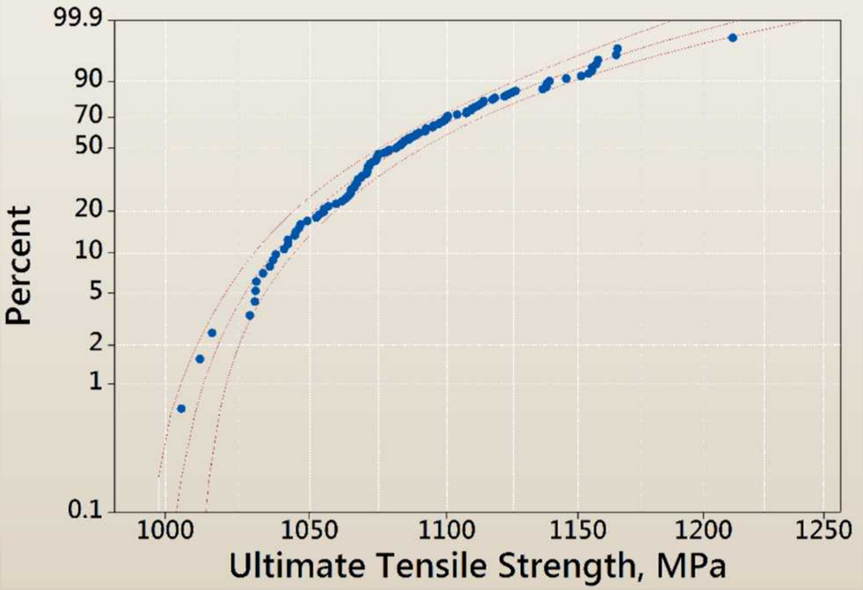
Material Performance Fit to 3-Parameter Weibull Distributions

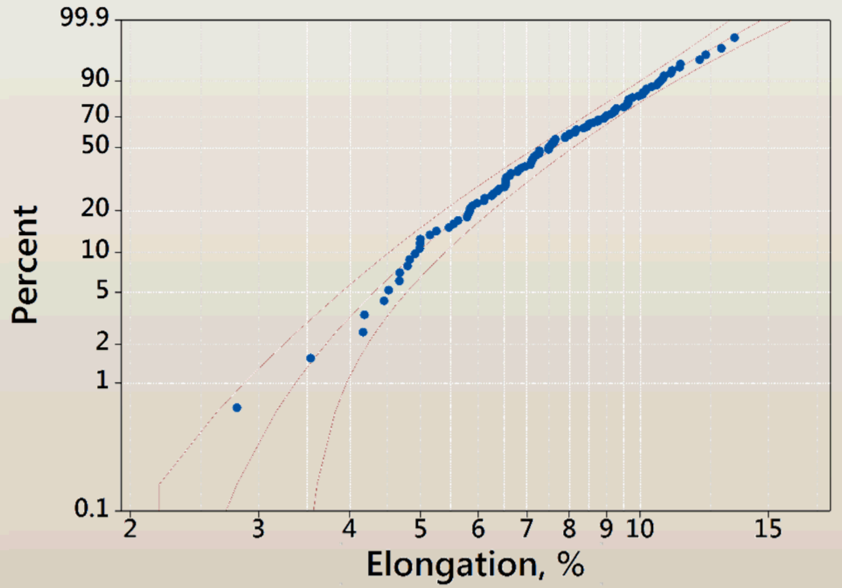
- Based on weakest link theory

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

- 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

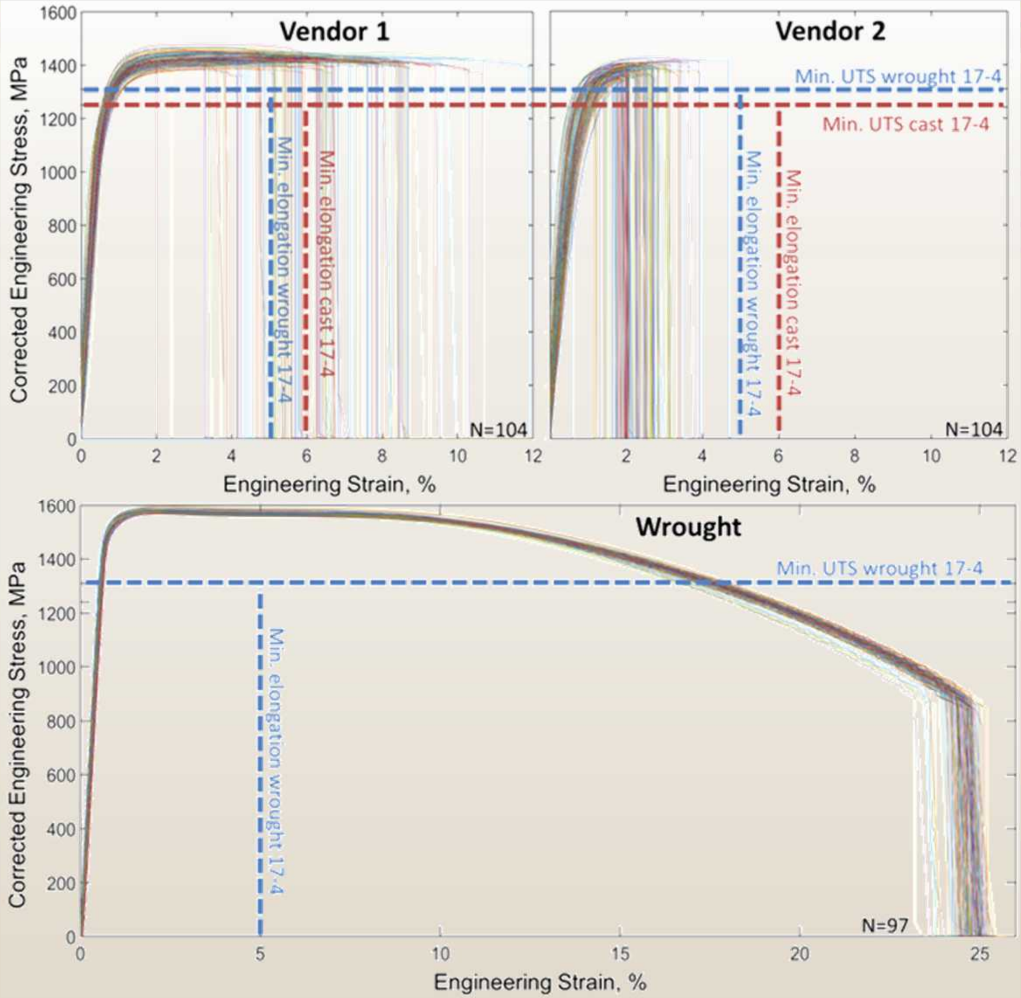




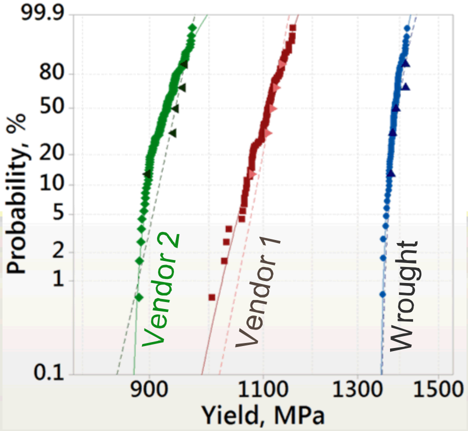


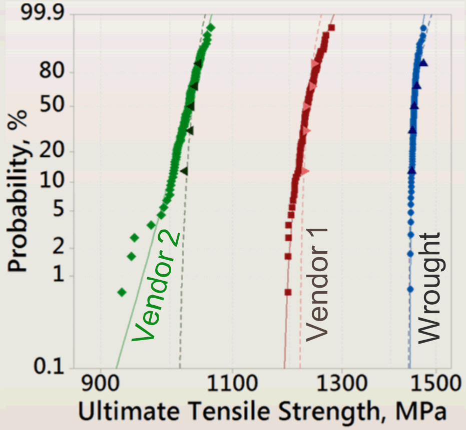
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

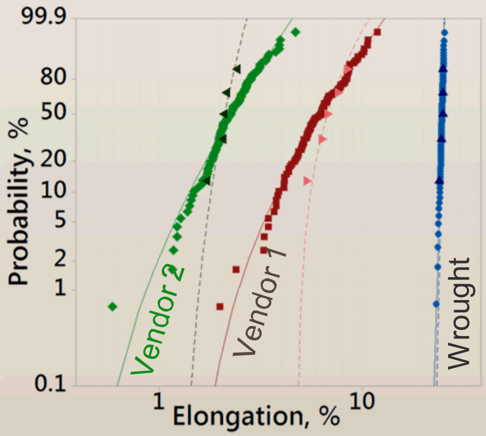
AM vs. Wrought 17-4PH



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





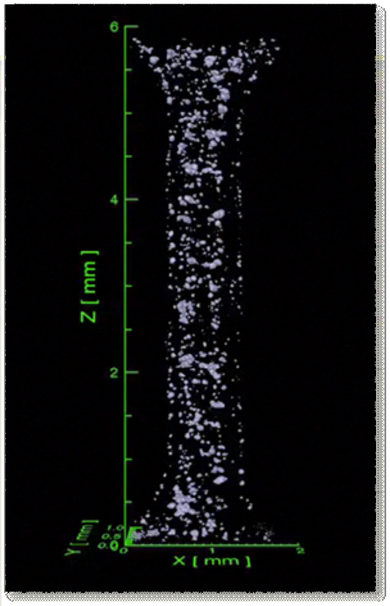


AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

Material Characterization

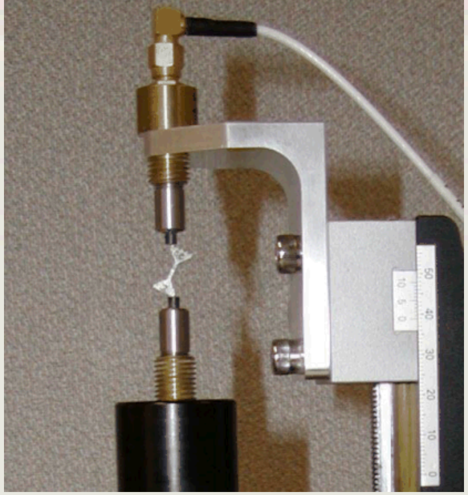
- NDE before testing
  - detect defects, performance correlations
  - density (Archimedes)
  - resonant ultrasound spectroscopy (RUS)
  - optical surface measurements
  - computed tomography (CT)
- Post mortem after testing
  - inform performance & failure mechanisms
  - fractography
  - metallography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

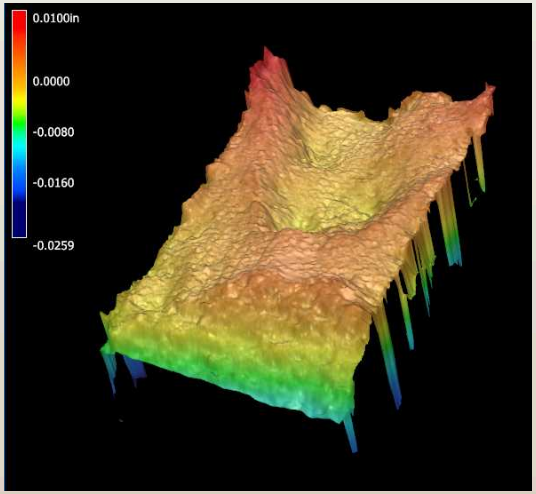
- **Do reasonable defect signatures exist which tie to performance tests?**



17-4PH dogbone porosity

dogbone in 2-point RUS test fixture

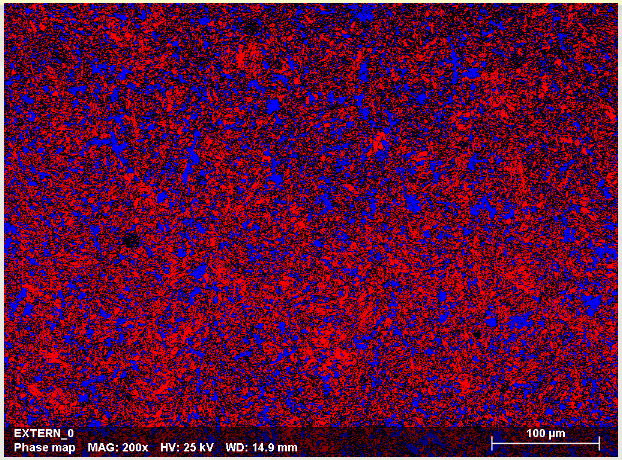




fracture surface

Metallurgical Interrogations

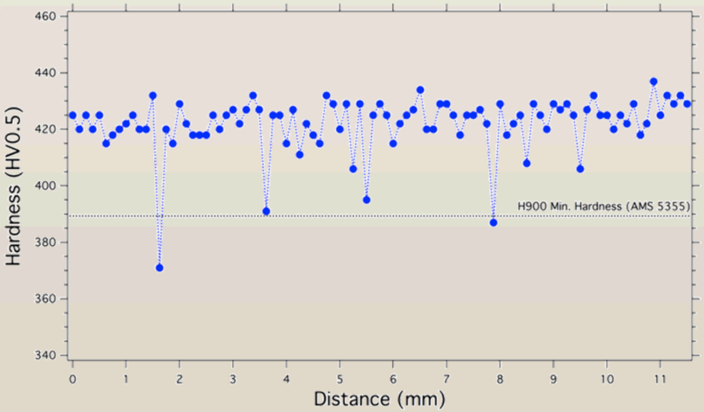
- Microstructure
  - optical, SEM, EBSD, WDS micro-probe
- Composition
  - LECO combustion, ICP mass-spec, XRD
  - powder analysis
- Microhardness



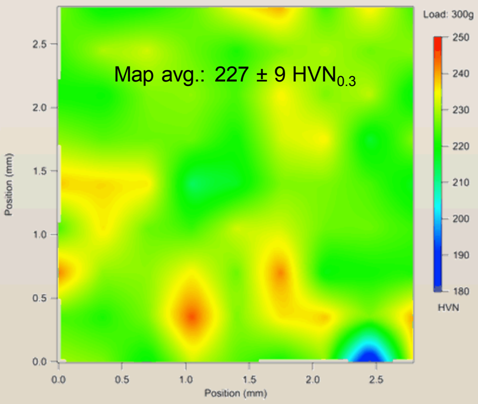
EBSD phase map, SHT+H900, 22% retained austenite

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

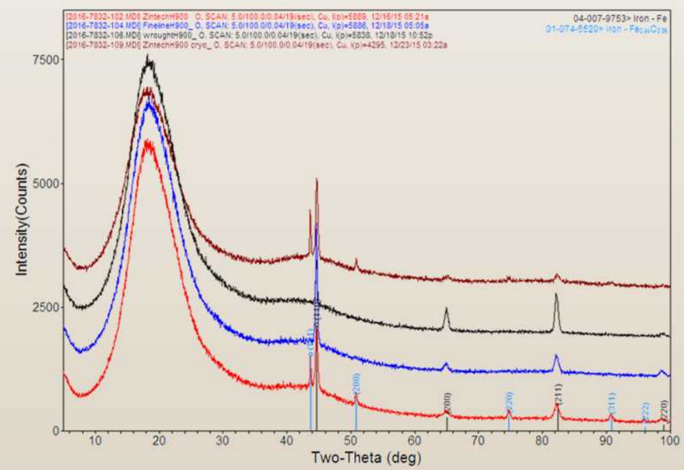
bulk chemical analysis



SHT+H900 microhardness along dogbone length



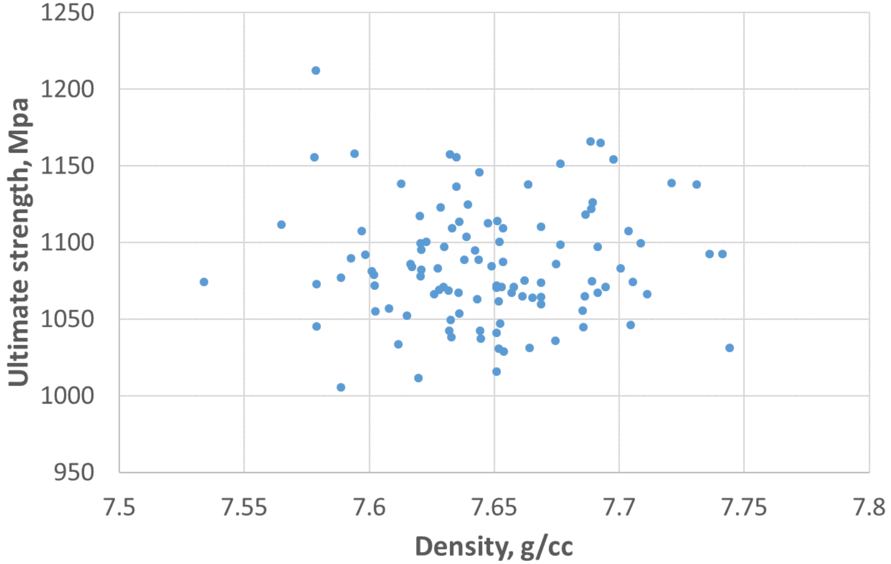
as-printed microhardness on gauge cross section

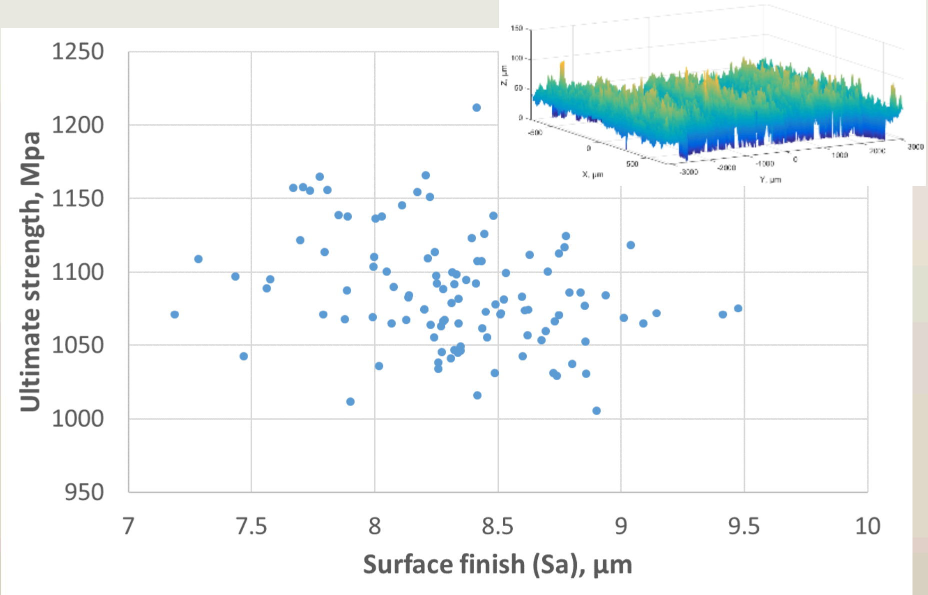


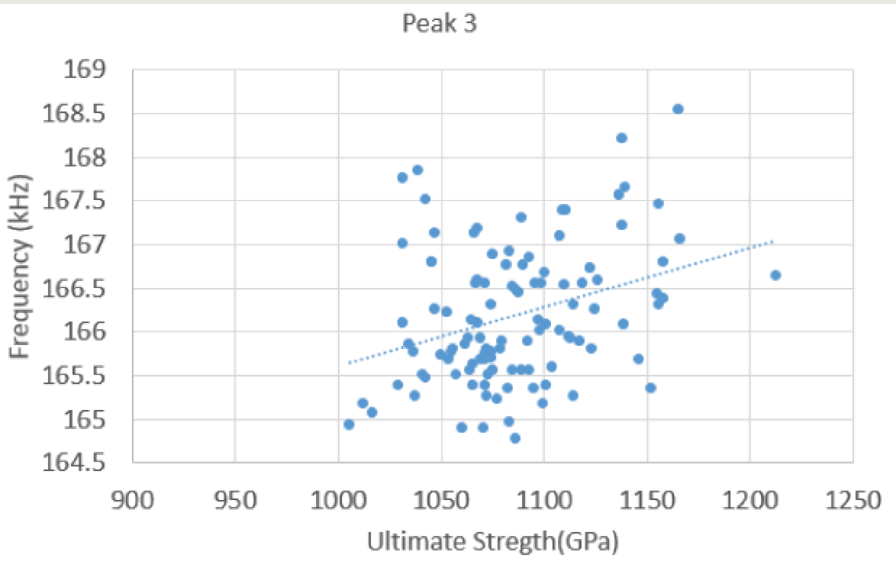
bulk XRD analysis

Implicit Part Correlations

- Archimedes density
- Resonant Ultrasound Spectroscopy
  - swept sine wave input from 2-point transducer (74.2 kHz - 1.6 MHz)
  - 19 resonance peaks
- Surface finish
- No significant trends observed

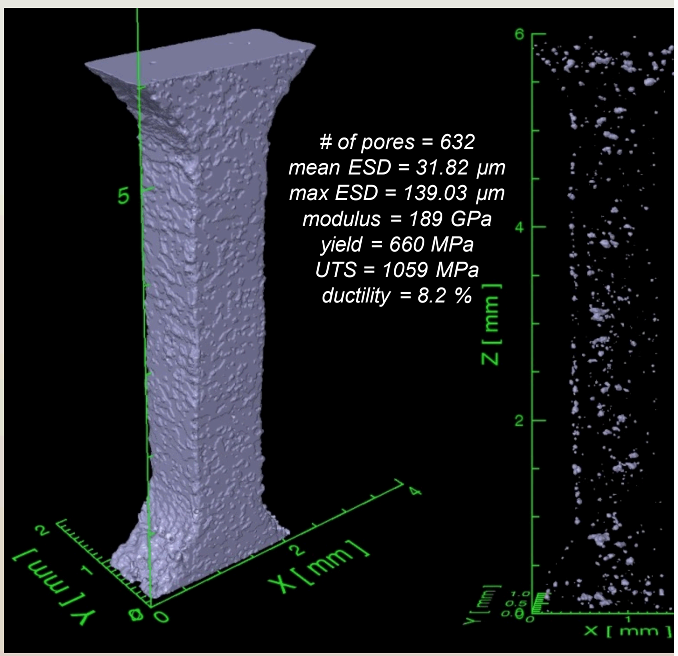




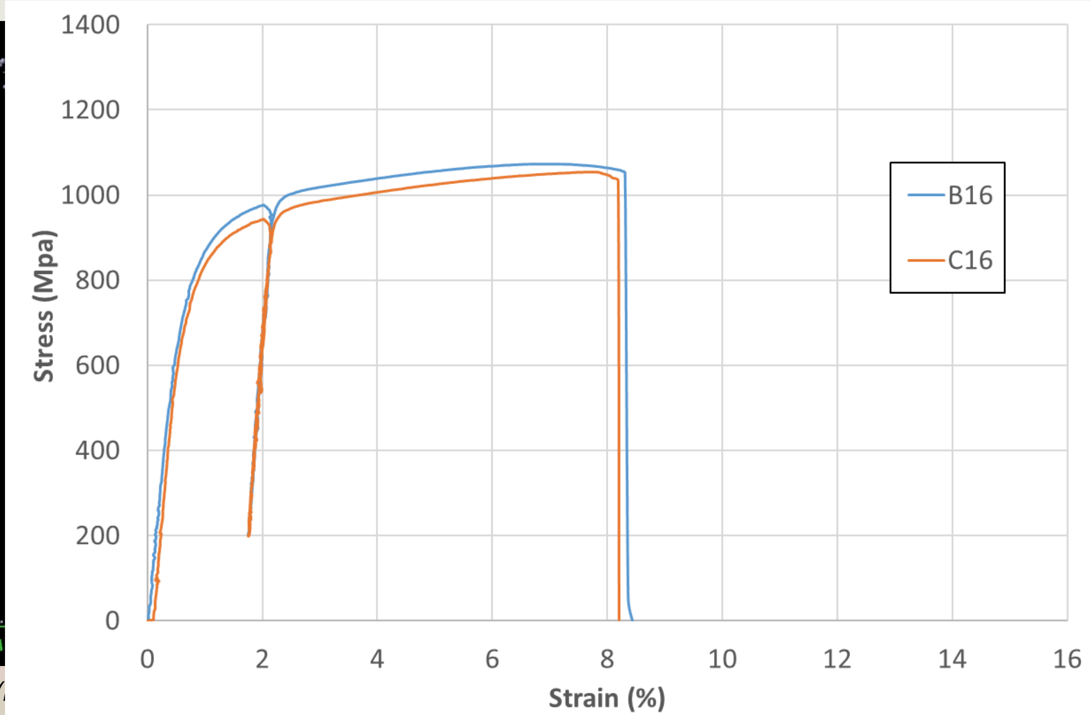


Explicit Porosity Measurements

- 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?

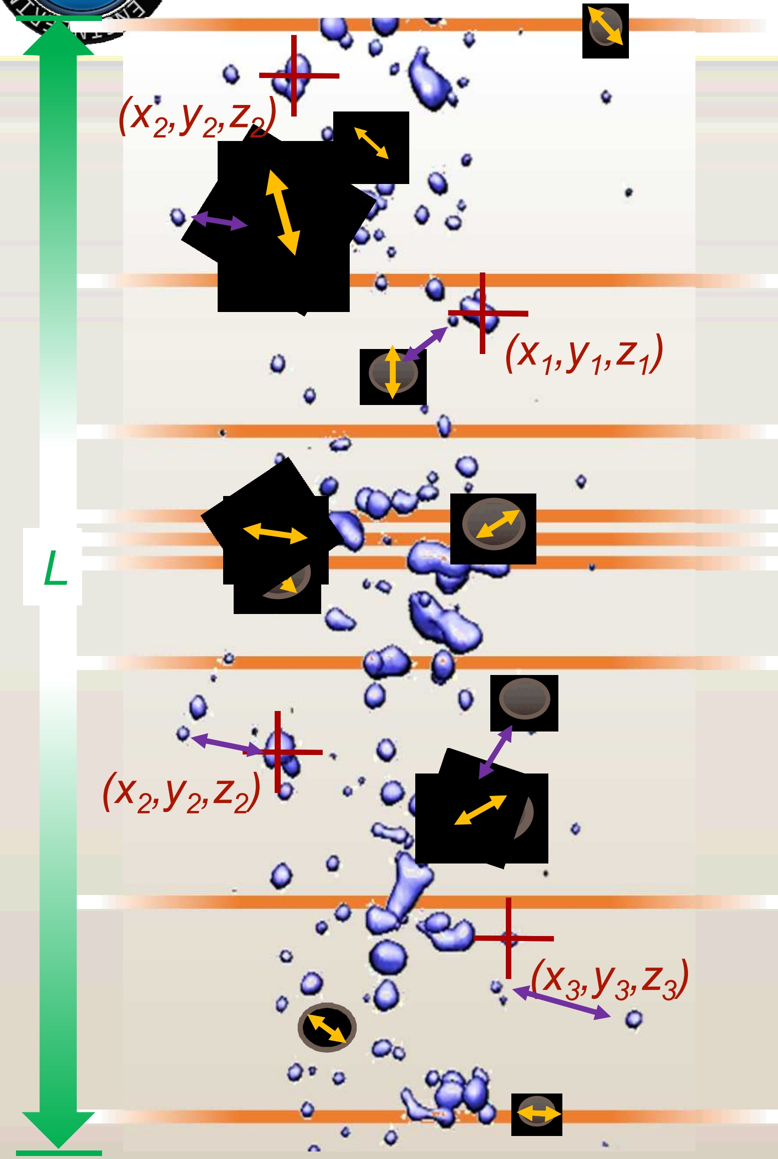


dogbone B,16 CT surface image (left), porosity map (



ESD = equivalent spherical diameter

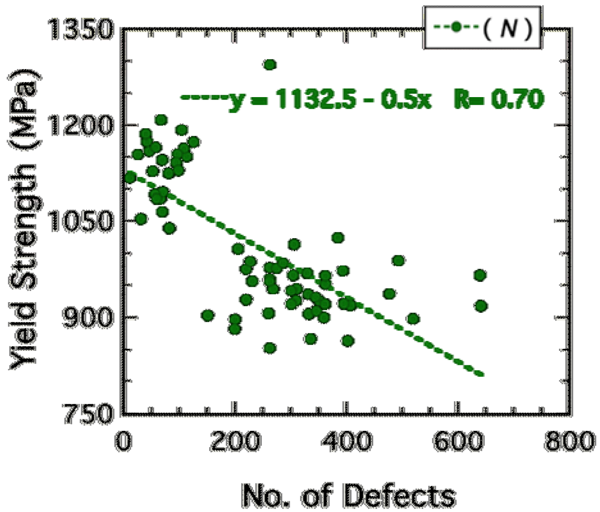
Defect Characterization

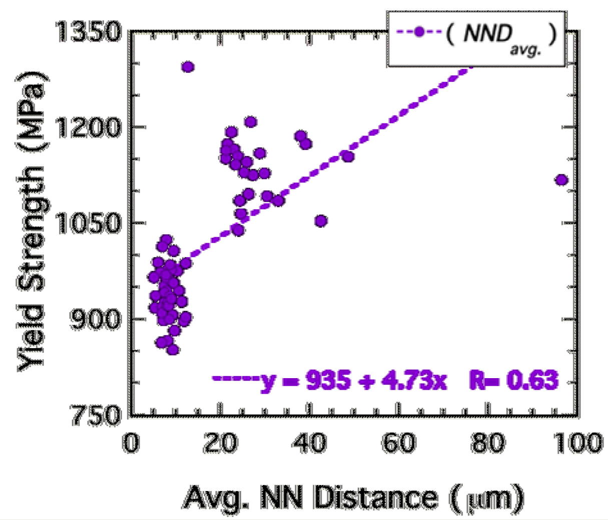


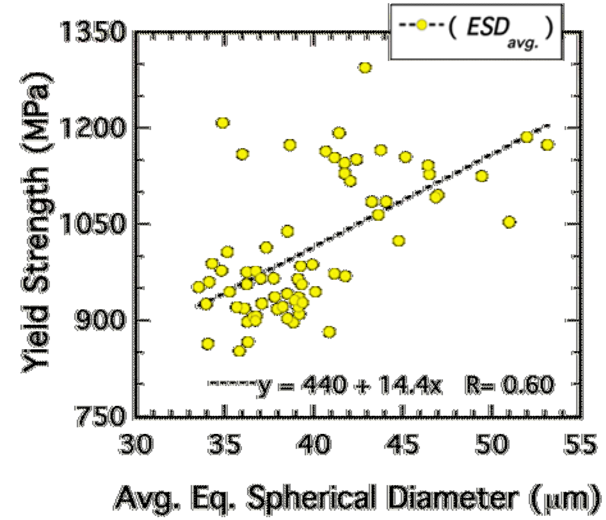
- Total Volume of Defects *(V_{tot})*
- Pore Volume Fraction *(V_{fract})*
- Spatial Location of Pores *(x, y, z)*
- Total Number of Defects *(N)*
- Total Defects/Length *(N/L)*
- Average Defect Volume ($V_{avg.}$)*
- Average Equivalent Spherical Diameter ($ESD_{avg.}$)*
- Average Cross-Sectional Area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

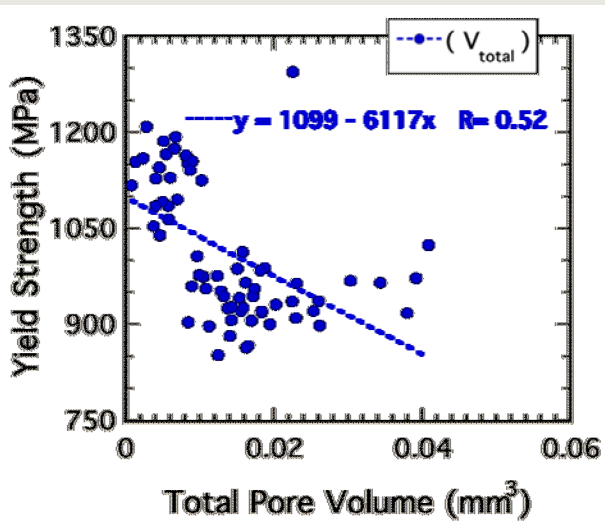
How do we *best* represent the defect populations present?

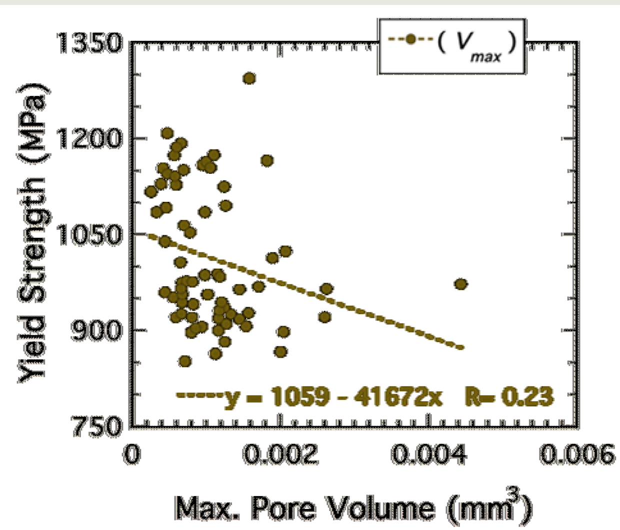
Statistical Correlations Are Elusive







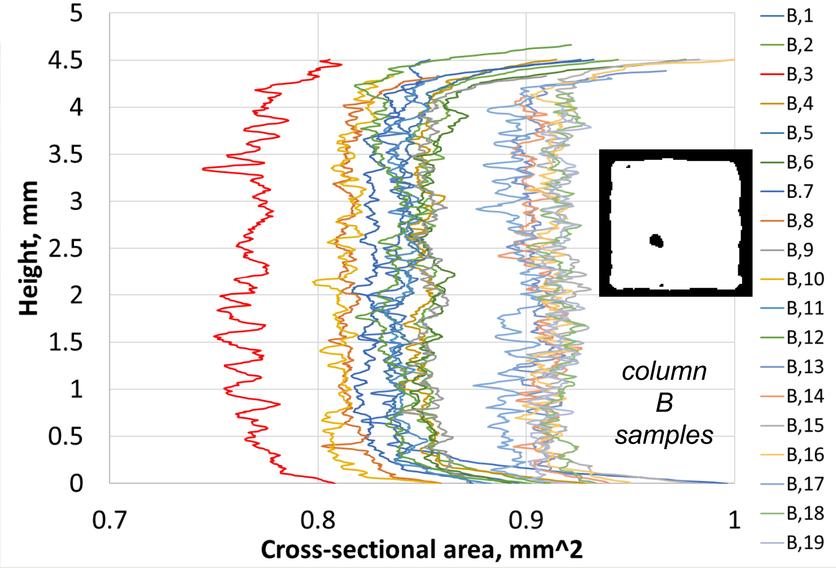


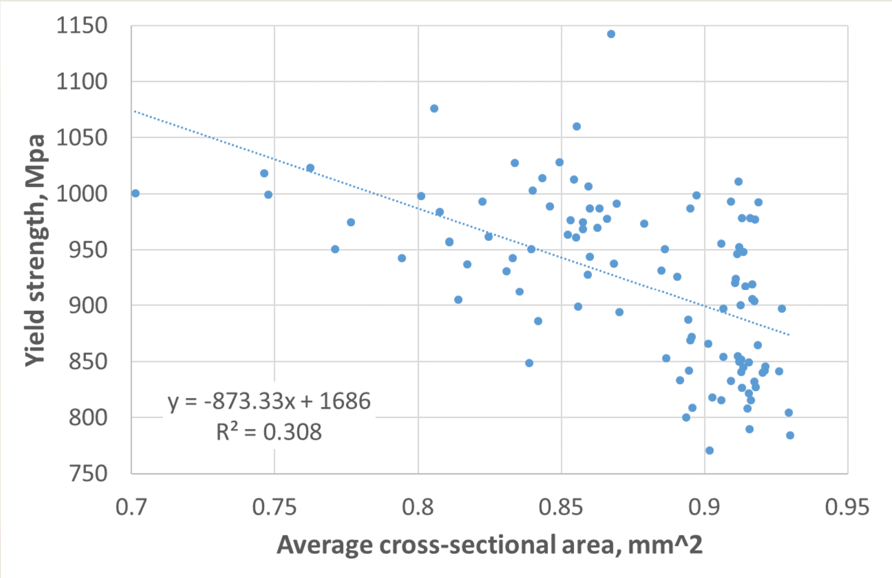


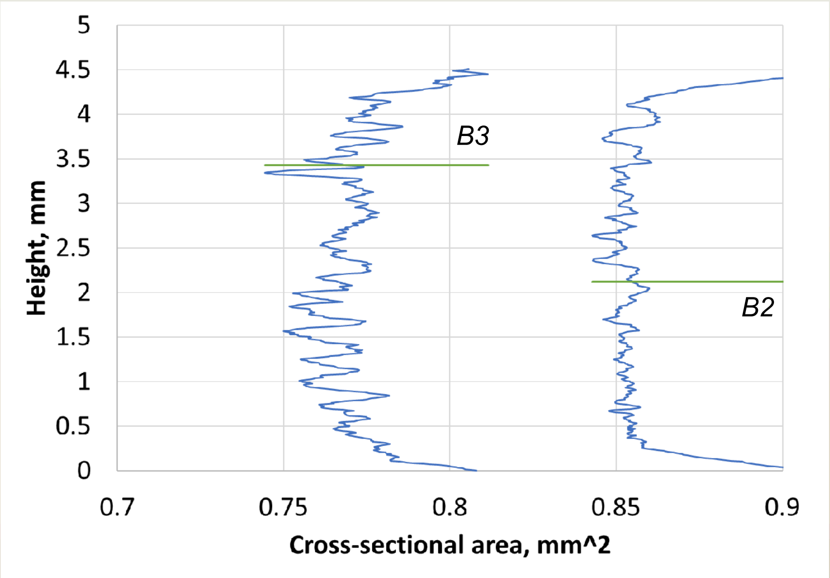
Measure	R^2
No. of Defects	0.50
Avg. NN Distance (mm)	0.40
Avg. ESD (mm)	0.36
Max CSA Redux (mm^2)	0.38
Total Pore Volume (mm^3)	0.27
Avg. Defect Vol. (mm^3)	0.25
Max CSA Redux (%)	0.24
Maximum Pore Size	0.07
Seven factor multivariate regression	0.60

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



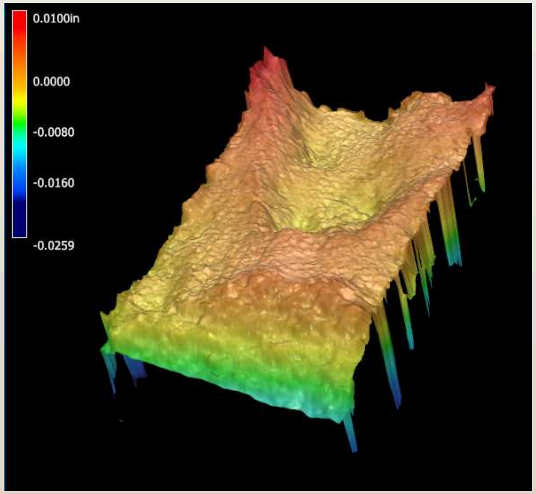


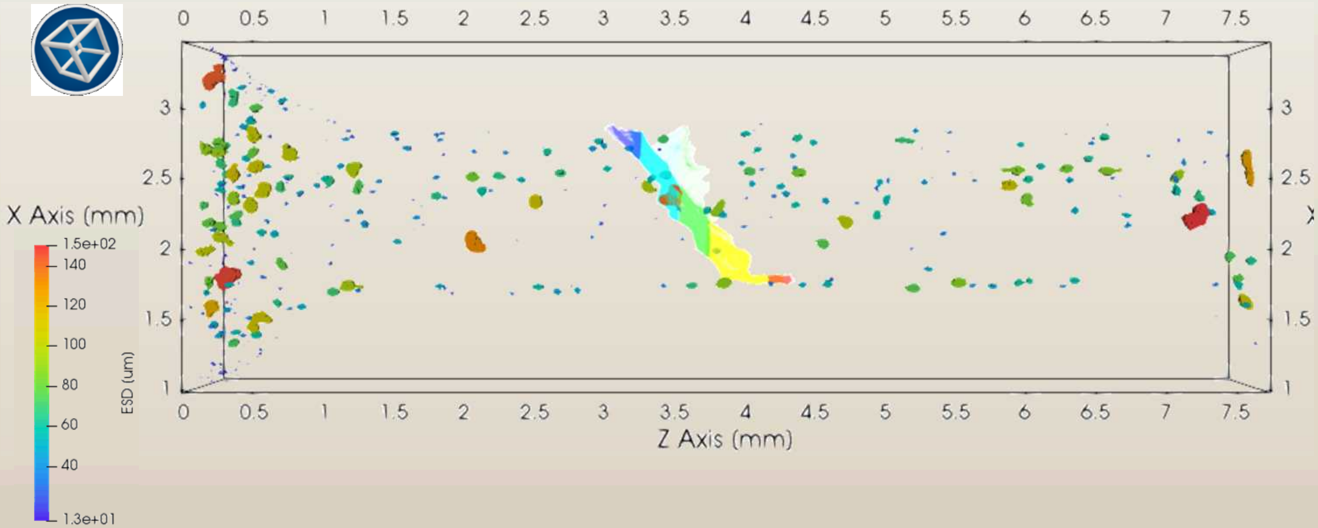


Fractography

- 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

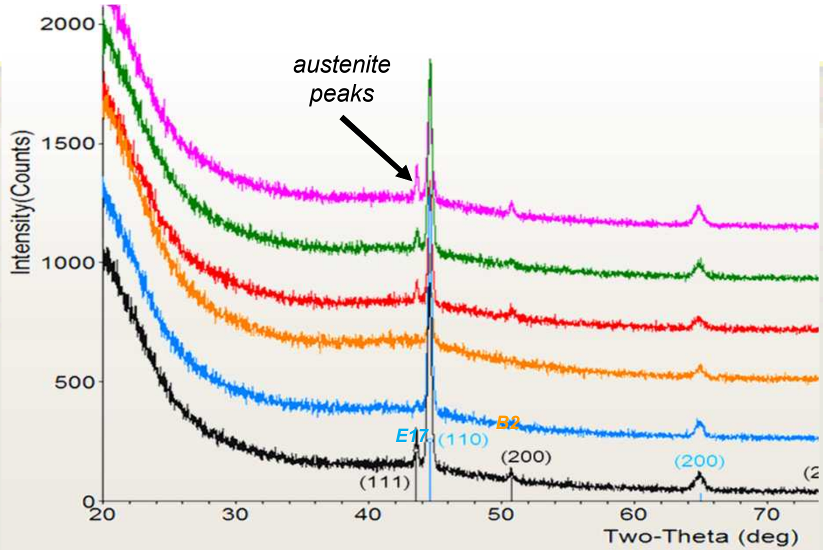
B2, fracture surface optical image by structured light scanning



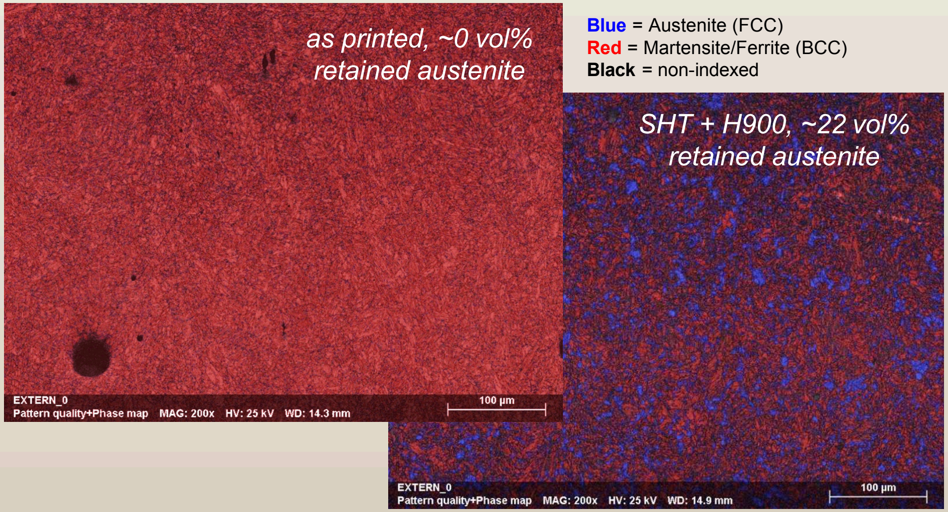


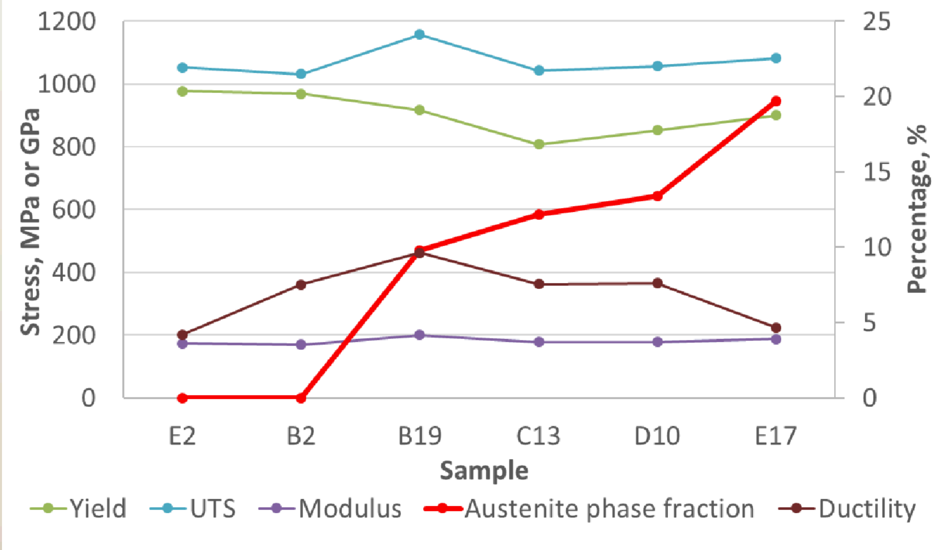
Microstructure Examination

- Compositional analysis identified no anomalies
- XRD revealed unexpected austenite variation in X-Y
  - what about Z?
  - further complication to dogbone performance
  - source = powder, atmosphere?



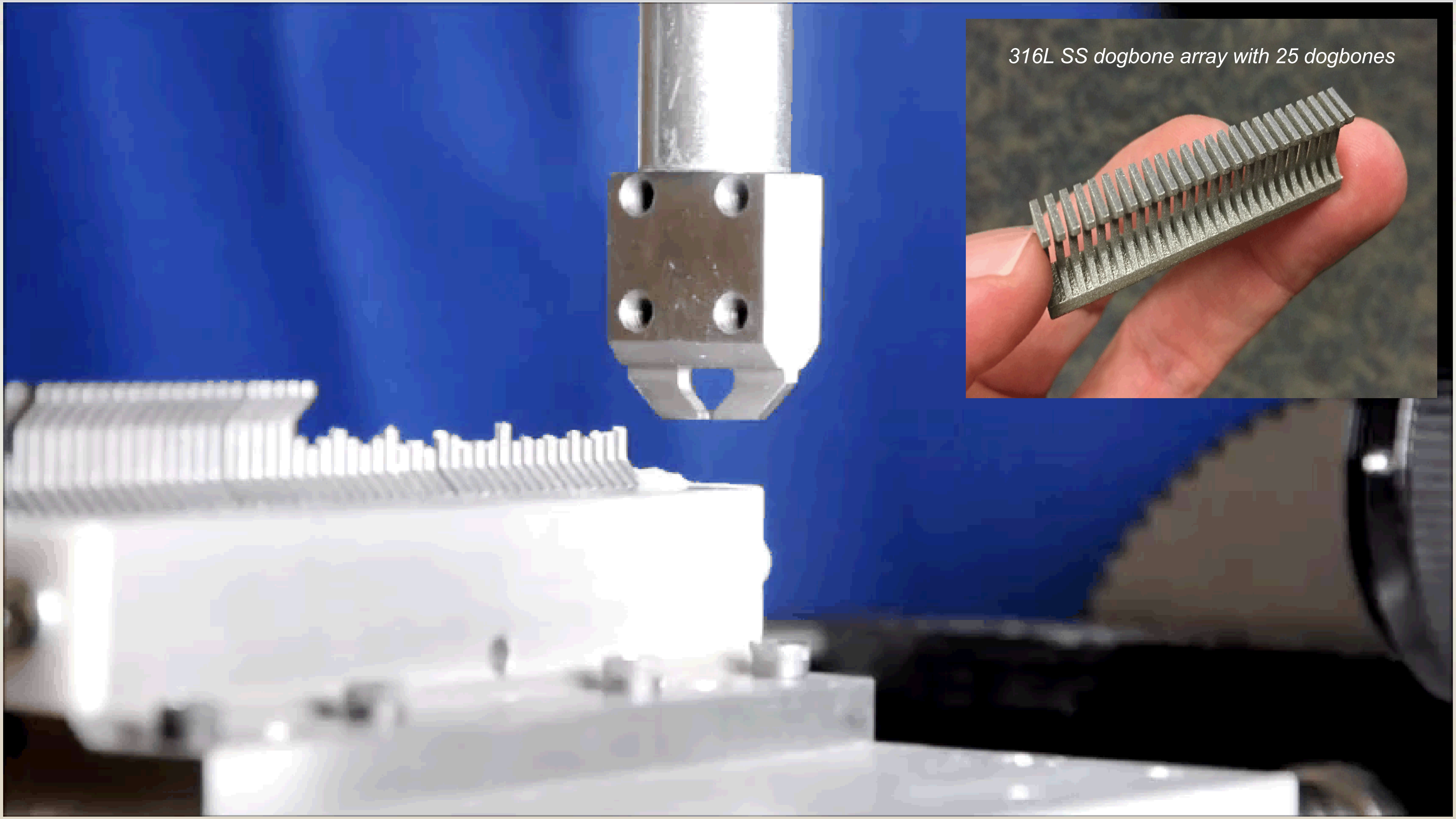
XRD analysis of dogbones across the build sample





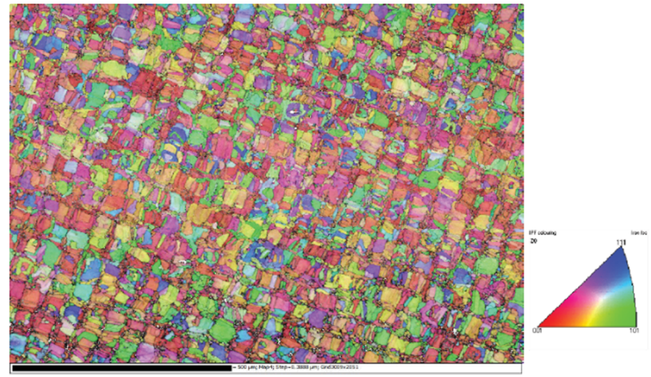
material performance variation w/austenite phase fraction

High Throughput Testing: Gen 2

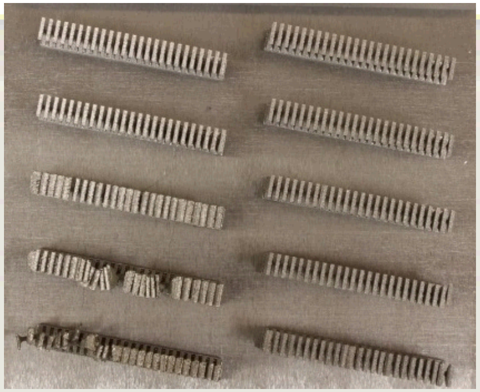


Process Development

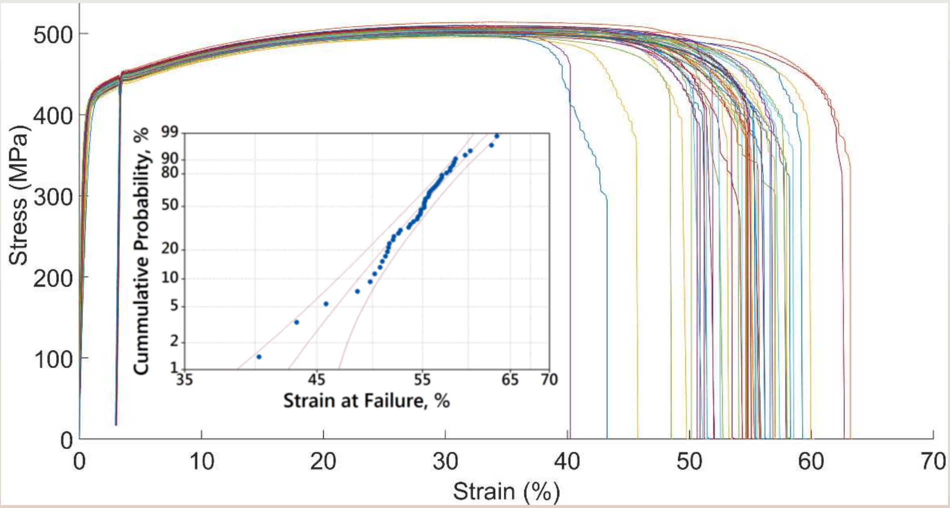
- Laser powder bed fusion
  - 3D Systems ProX 200
    - FEI Aspex
  - process mapping w/CMU
  - process sensitivity study
  - process diagnostics
    - Open Protocol
    - in-situ signatures



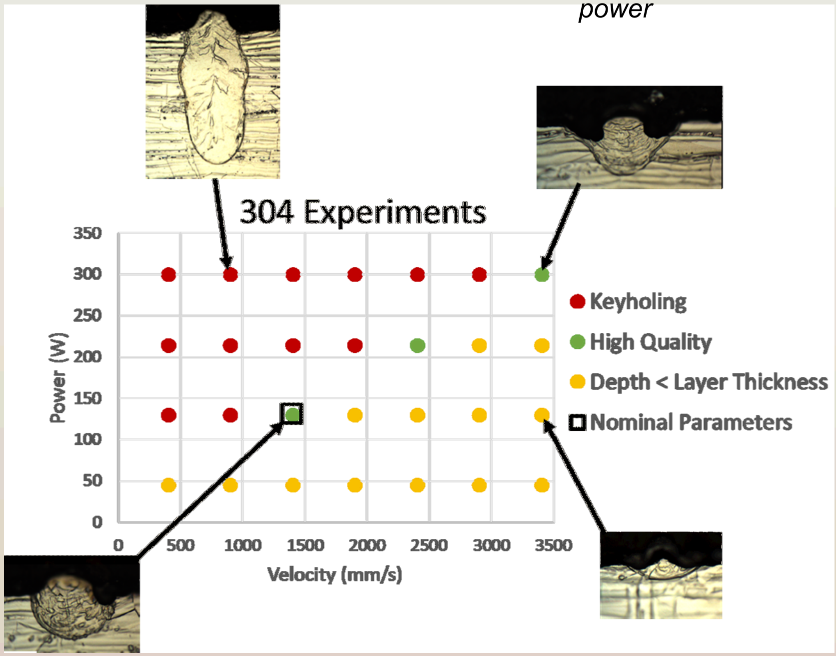
unique EBSD grain structure for 316L SS



Gen 2 samples w/varying laser power

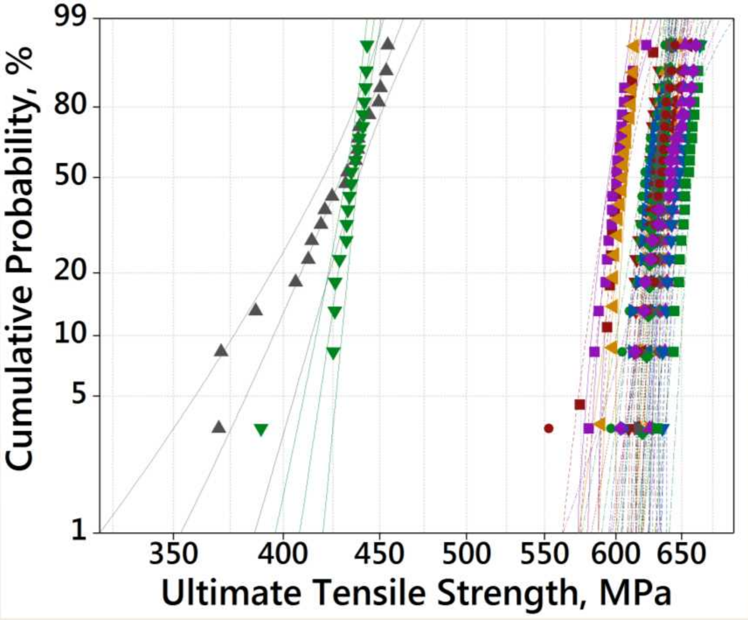


HTT 316L SS data, 50 1x1mm dogbone samples

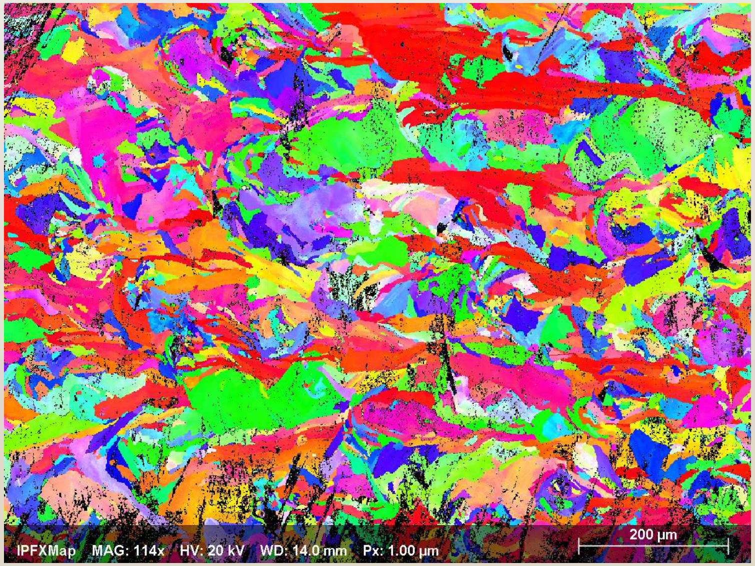


316L SS Study

- Exploring intra-build variations, process sensitivities / margins / optimization
  - leveraging analysis tools developed
- 316L SS printed on 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

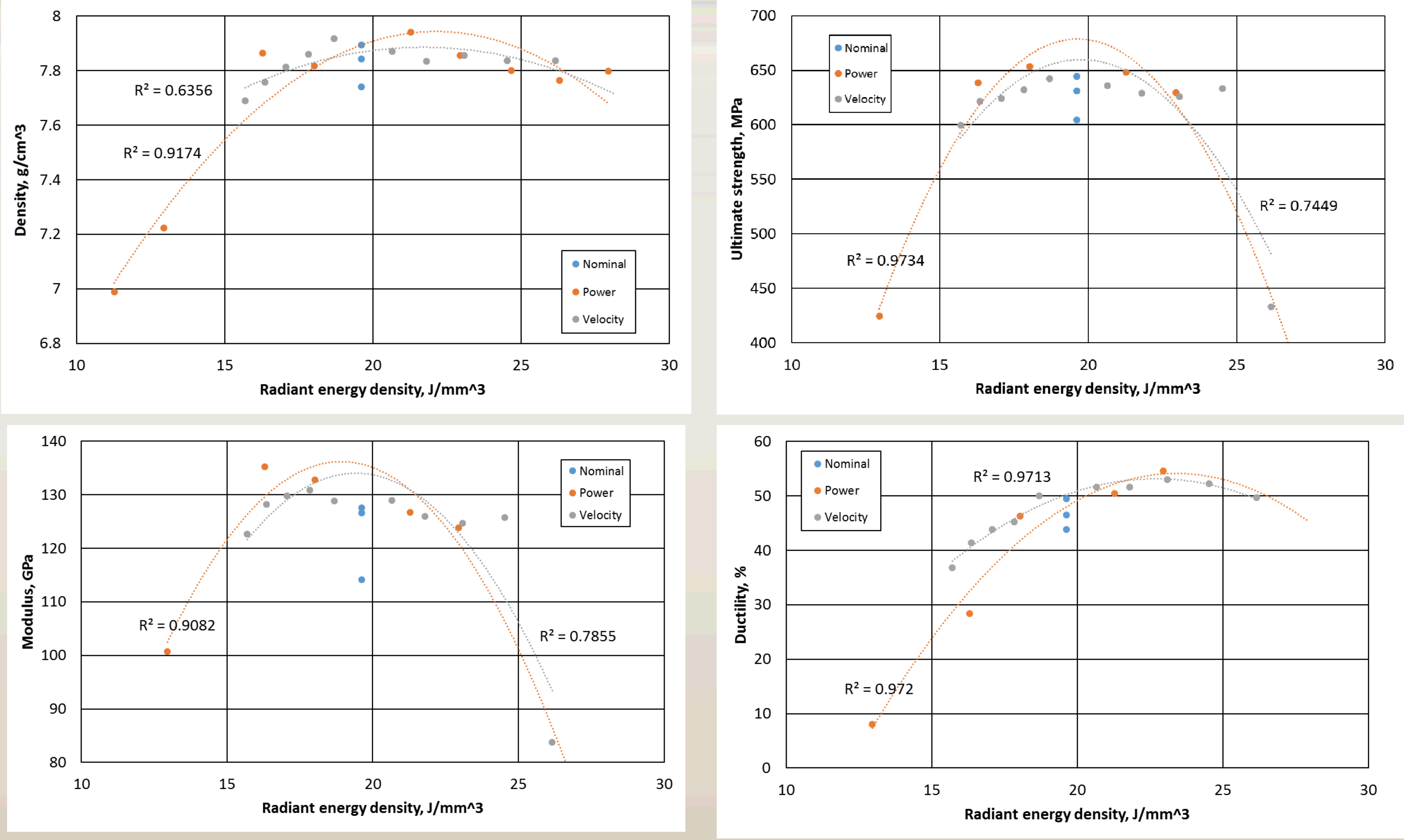


UTS variation w/power, velocity & scan pattern



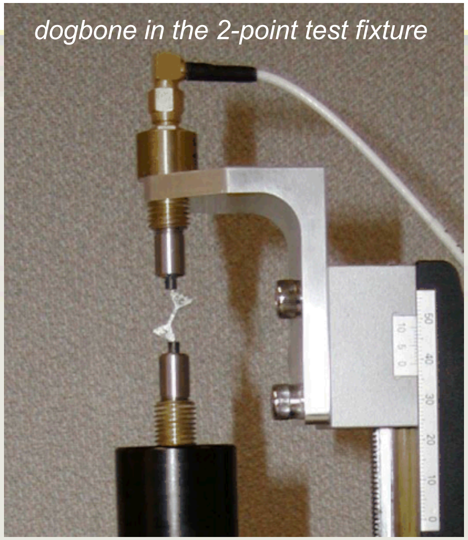
representative texture map via EBSD, phase content has been relatively consistent across process settings

Intra-Build Process Trends

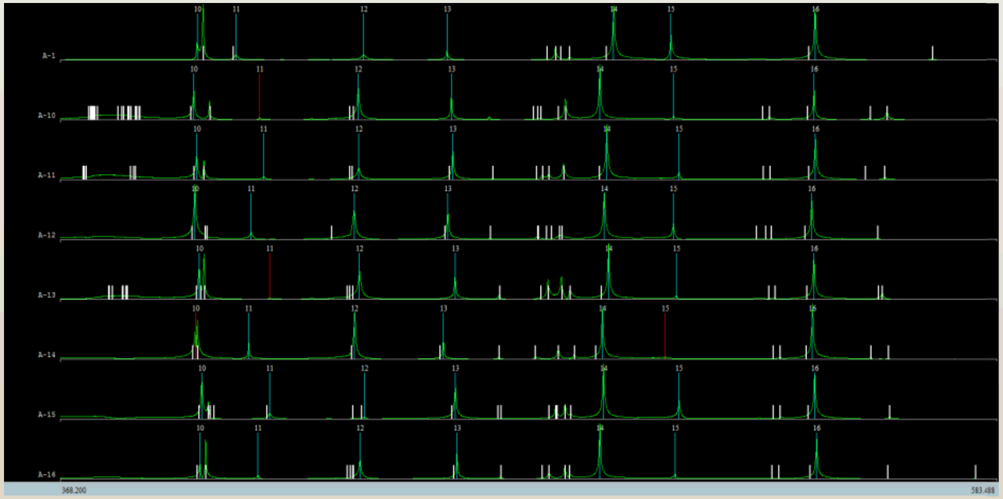


Resonant Ultrasound Spectroscopy

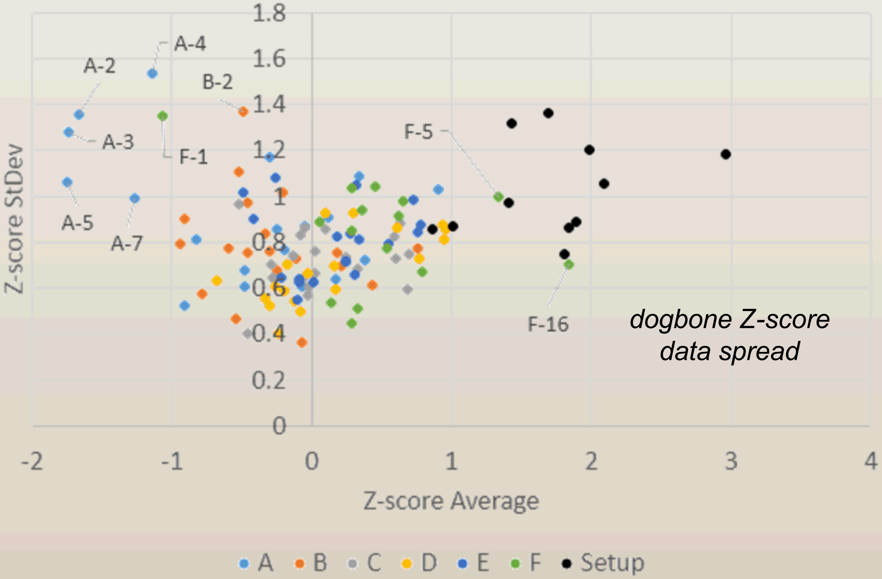
- Swept sine wave input from 2-point transducer
  - spectrum = 74.2 kHz to 1.6 MHz
  - intent is to identify outliers, variations, process limits, defects
- Identified 19 resonance peaks
  - Z-score compares peak frequency w/average & std. dev.
  - no strong trends across 17-4PH dogbone population



dogbone in the 2-point test fixture



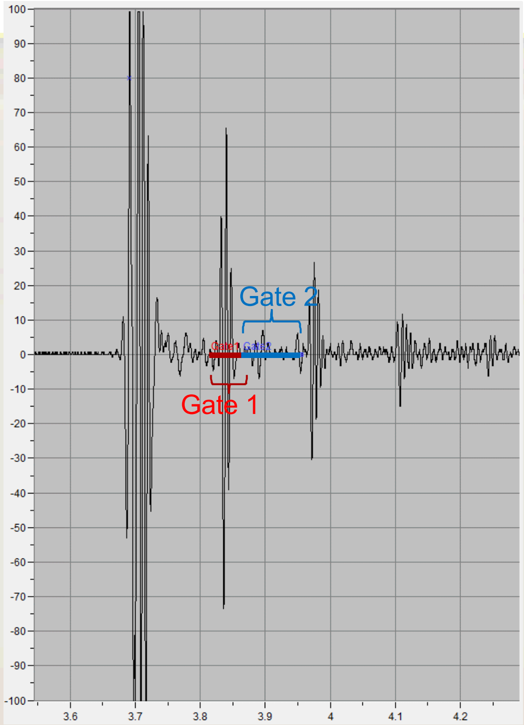
resonance response spectra

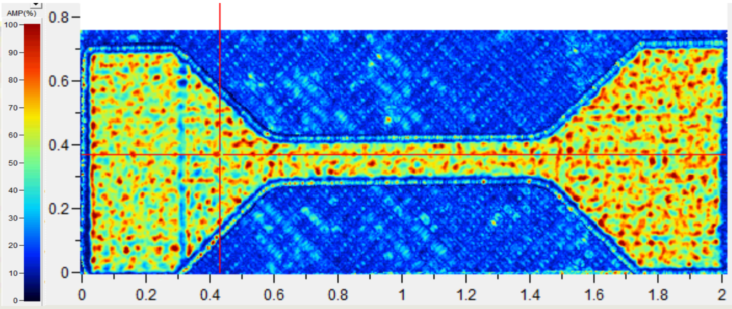


dogbone Z-score data spread

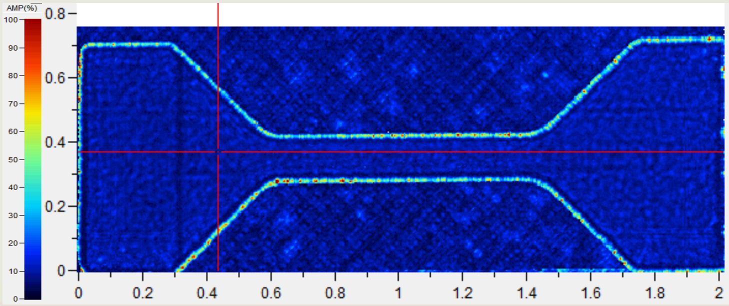
Pulse-Echo Ultrasound Inspection

- Single probe emits incident wave & receives reflected signal
  - gate 1 – backwall surface
  - gate 2 – part thickness
- Material density
  - 17-4PH, Al10SiMg, Ti6Al4V

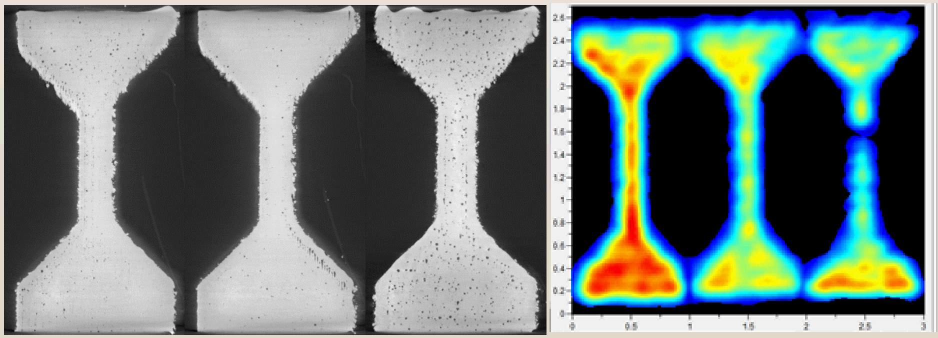




Gate 1 signal



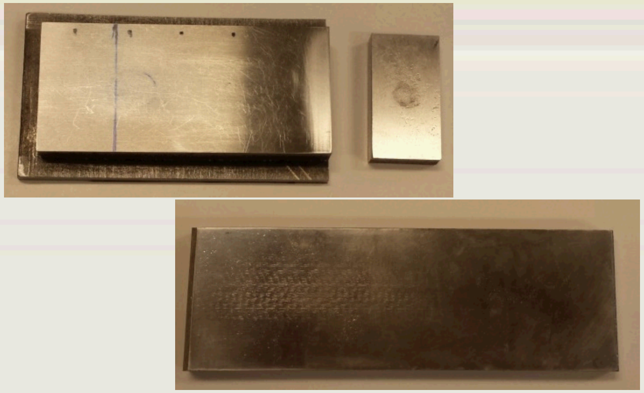
Gate 2 signal



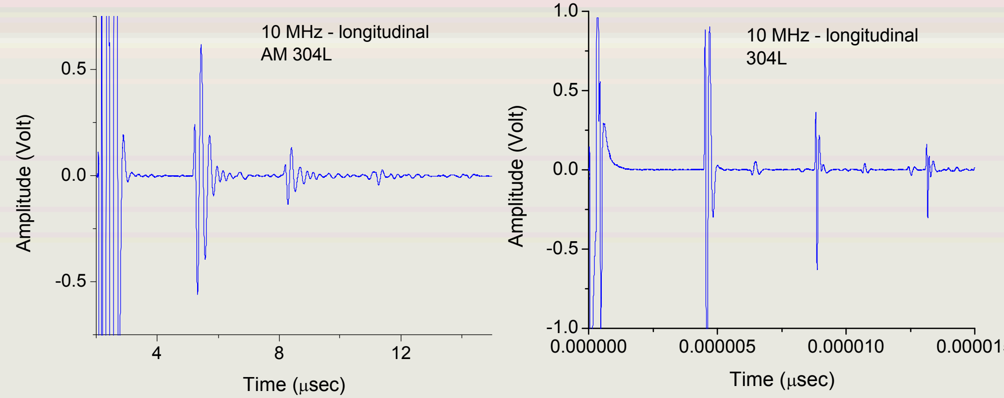
CT images of 98% (left), 96% (center) & 93% (right) dense Al10SiMg dogbones (left) & attenuation of 10MHz ultrasonic backwall reflections (right)

David G. Moore, Ciji Nelson, Sarah L. Stair

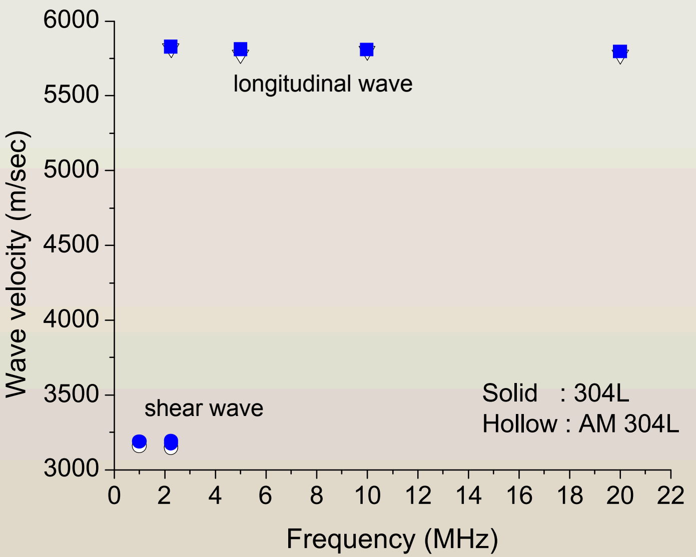
Exploring Wave Propagation to Measure Residual Stress



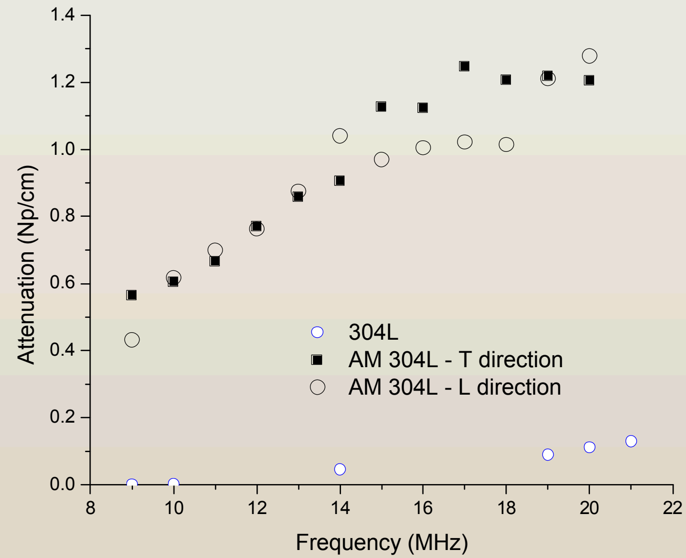
LENS 304L (top) & wrought 304L (bottom) samples



10MHz longitudinal wave time domain signals for AM 304L (left) & wrought 304L (right)



wave velocities of longitudinal & shear waves in AM-304L & 304L specimens



attenuation coefficients of longitudinal wave in AM-304L & 304L specimens, AM-304L acoustic nonlinearity parameter = 3X wrought 304L

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