Sandia National Laboratories

SAND2020-5605C

Addressing Complexity in Additive Manufacturing

PRESENTED BY

Bradley Jared, Materials Engineering & Manufacturing S&T

Complexity is Available

Advanced manufacturing provides ever expanding design freedom & value

- complex freeforms, internal structures, integration

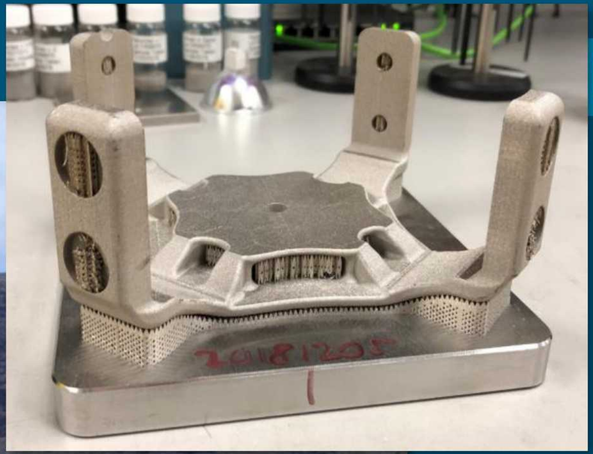
Geometry

Engineered materials

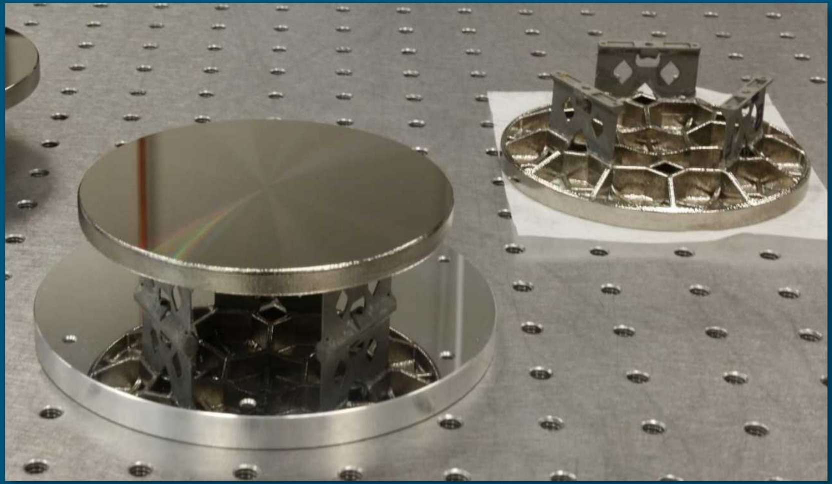
- gradients & microstructure

Sandia HOT SHOT sounding rocket launch from Kauai Test Facility, Hawaii

Photo by Mike Bejarano and Mark Olona, Sandia Lab News

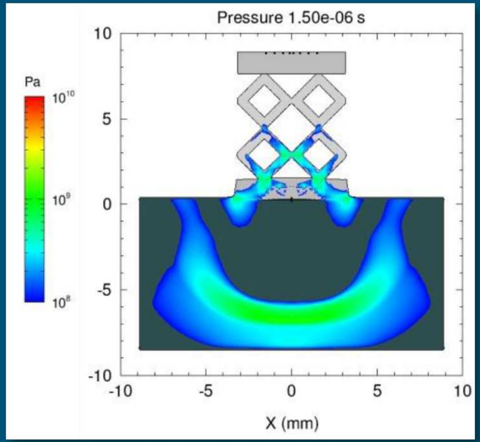


316L SS HOT SHOT top cap on plate



*AM Ti6Al4V mirror w/diamond turned electroless Ni coating, Jared, **ASPE**, 2017*

316L SS test structure for LANL gas gun shot



CTH simulation of 250m/s lattice impact

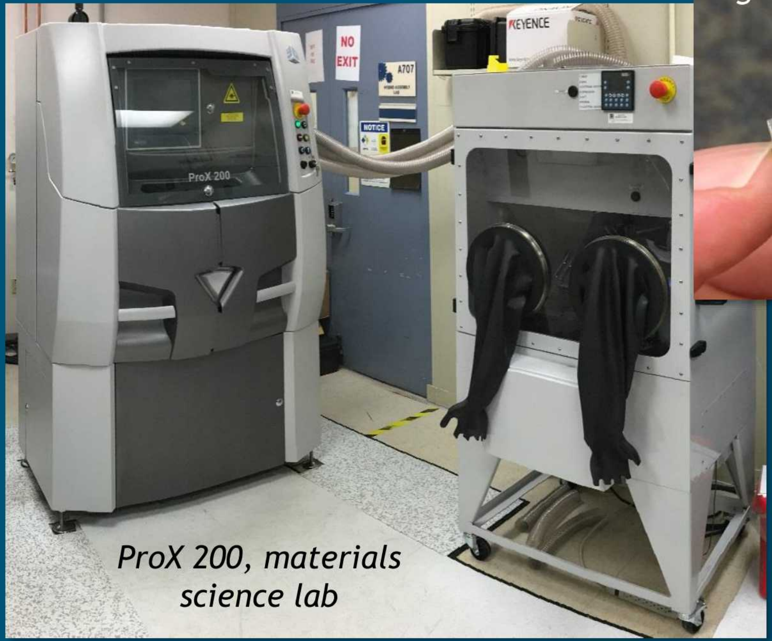
Laser Powder Bed Fusion

3D Systems ProX 200

- CW ytterbium, single mode fiber laser
  - 1070nm, 300W max power, 100µm dia.
  - scan speed = 1.4m/sec
- rotating powder roller
- Ar backfill & cover gas flow

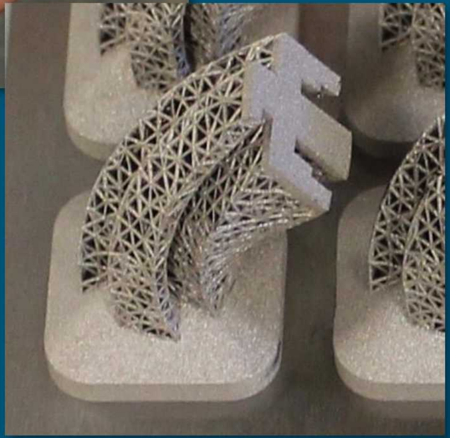
Part capabilities

- 140x140x100mm build volume
- 316L stainless steel
  - 20-30µm diameter powder
- deposition rate ~100mm^3/min
- 10^5-10^6°C/s heating & cooling rates

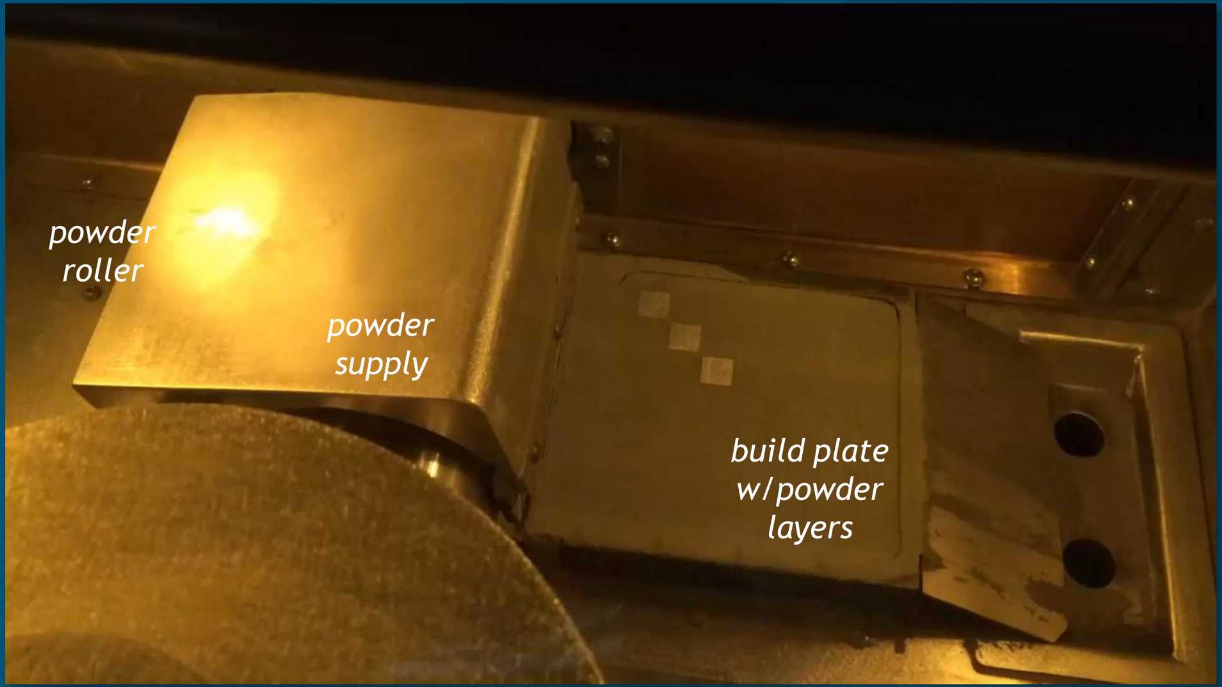


ProX 200, materials science lab

high throughput dogbone sample



Sandia T-bird lattice



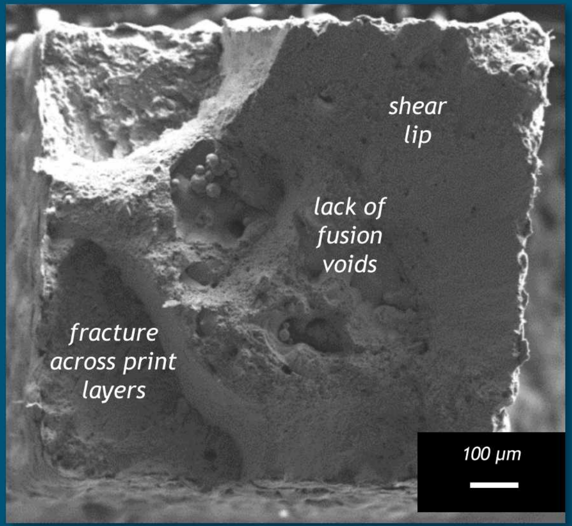
But, Complexity Isn't Free

Features tied to requirements incur costs

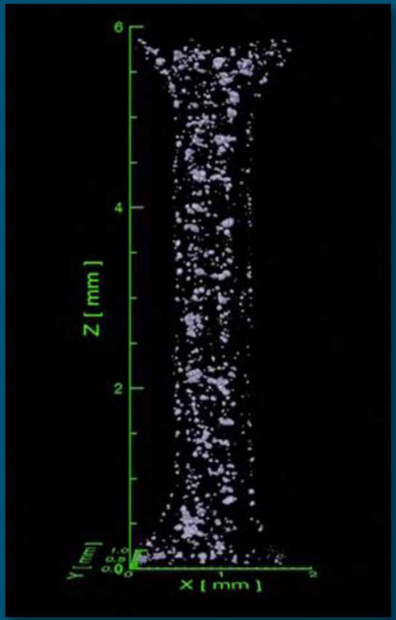
AM material formation concurrent w/geometry
- want to predict part/material performance
- **how to ID a bad part?**
  - significant design margins and/or rigorous post-process inspection / validation

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

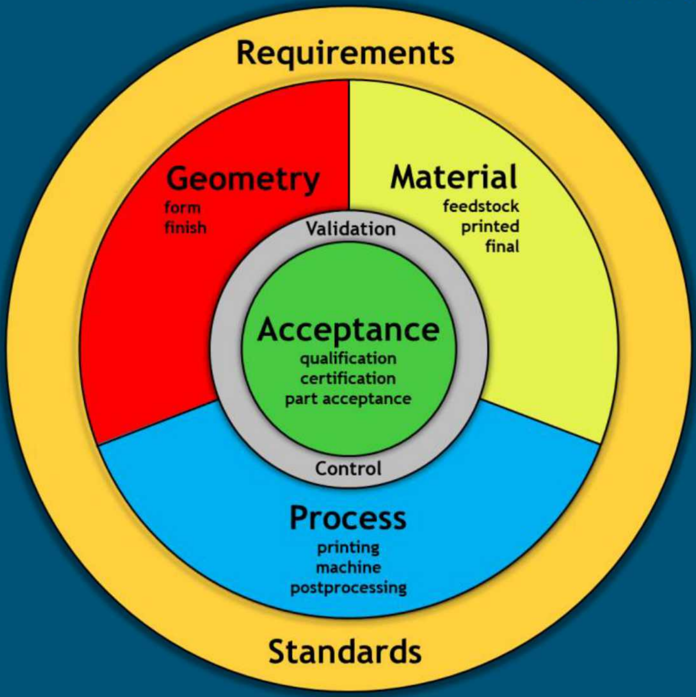
Quantify critical material defects & useful signatures
- D-tests, NDE, process monitoring, mod-sim



17-4PH dogbone fracture surface



17-4PH dogbone porosity



elements of qualification
Jared, Sci Tech and Appl of Metals in AM, 2019

Lack of Process Control Produced Material Uncertainty in Early AM Metals

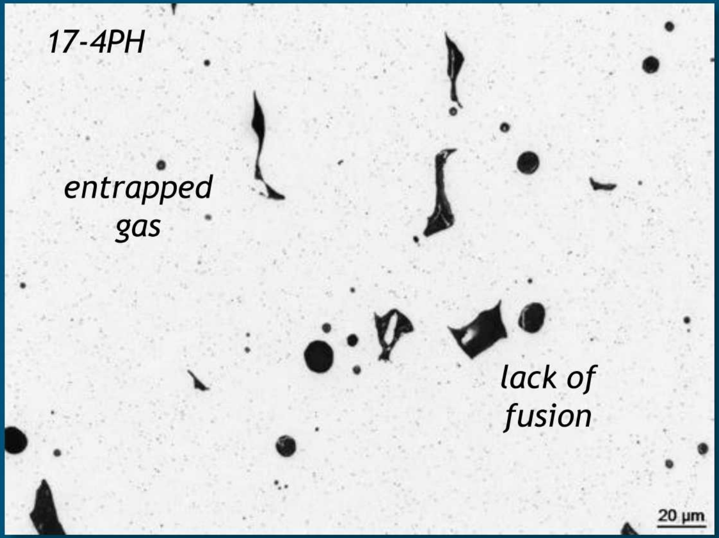
17-4PH parts from external vendor

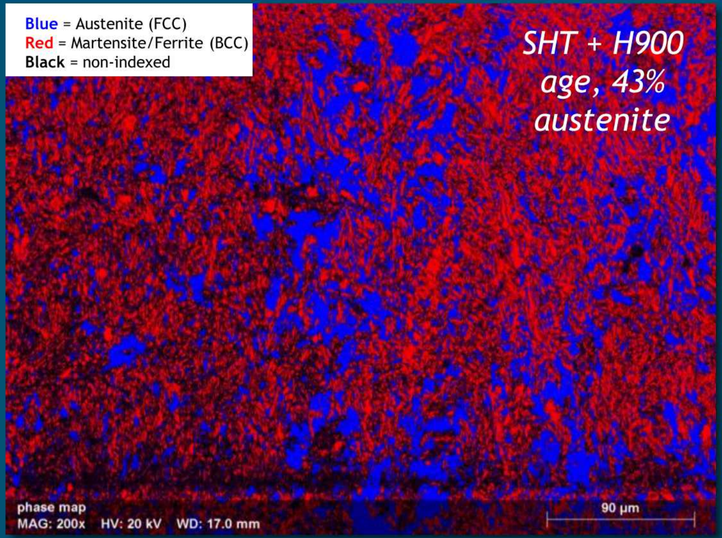
- analysis confirmed 17-4PH composition, but unexpected microstructure

Sandia did not know

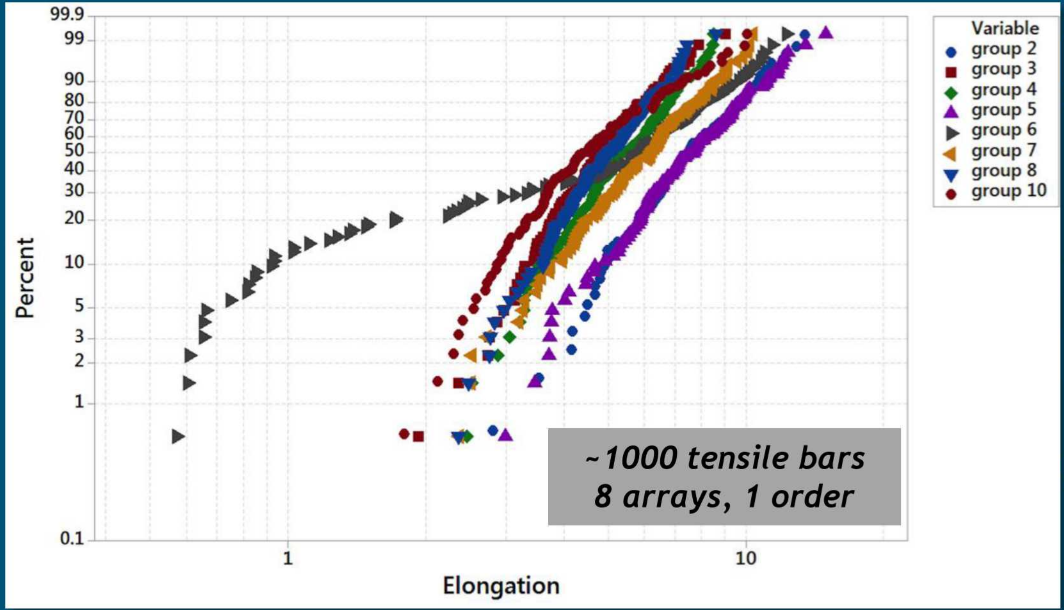
- feedstock pedigree, machine, build environment, process inputs or post-processing steps

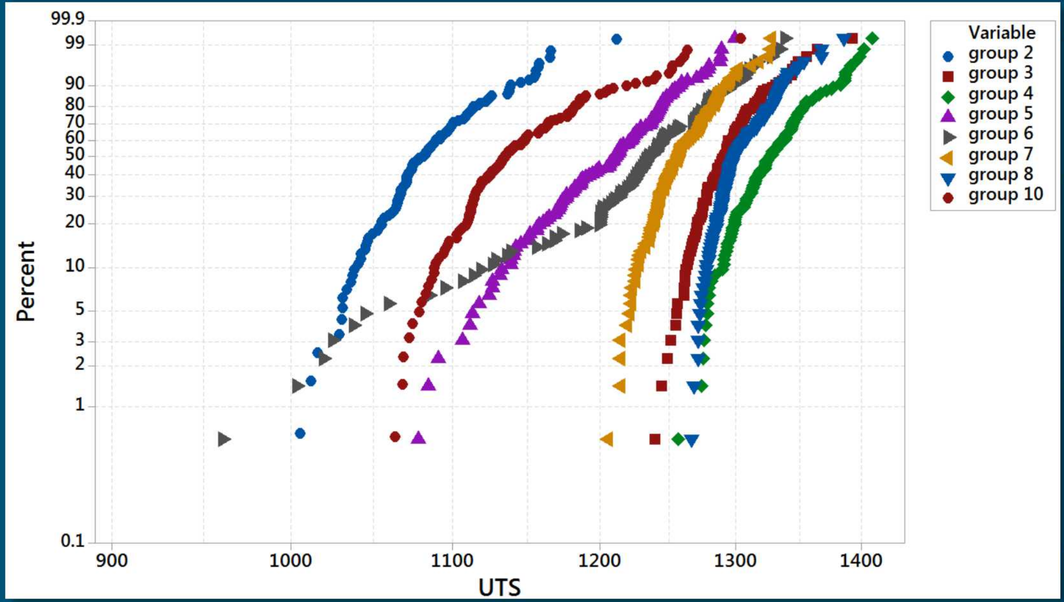
Not-surprisingly, extensive material variability observed





Jared, **SAND2017-13190**





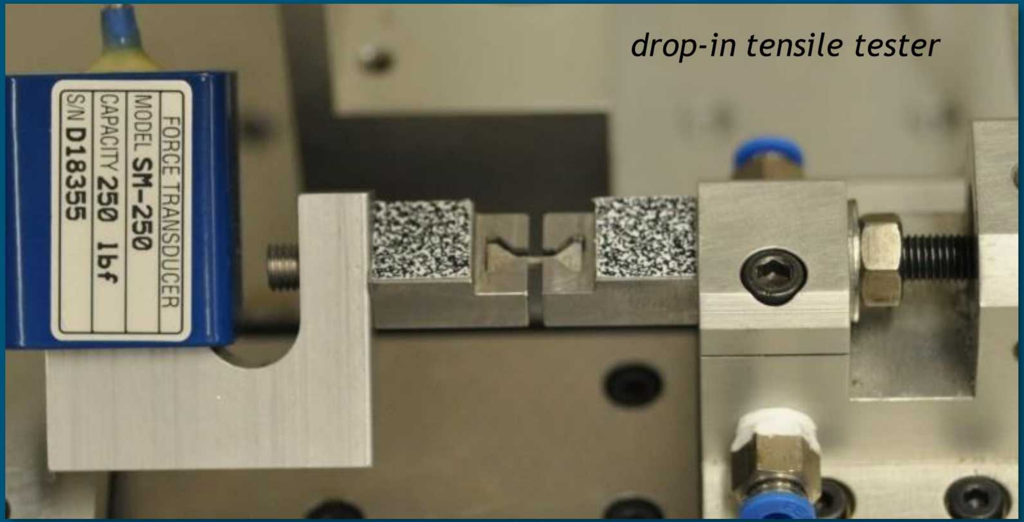
Boyce, ***Adv Eng Mat***, 2017

High Throughput Tensile Testing (Gen 1)

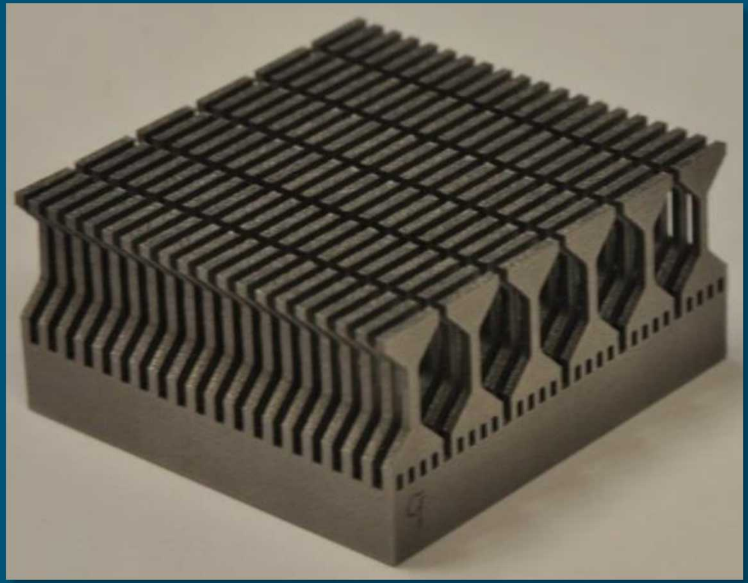
Monolithic build w/110 dogbones
- custom design per ASTM

Digital image correlation (DIC)

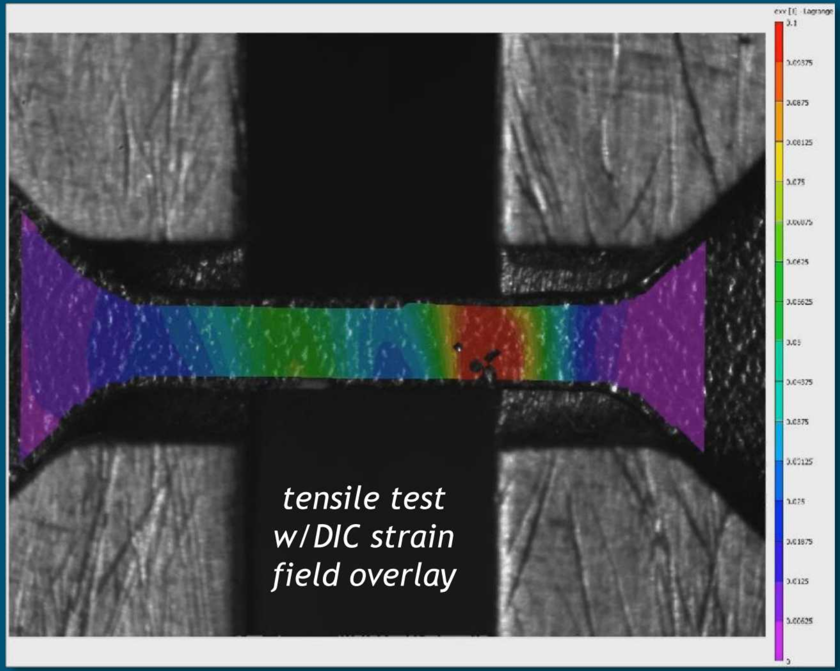
Necessary to rapidly capture material distributions
- applicable for the lab & production



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



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

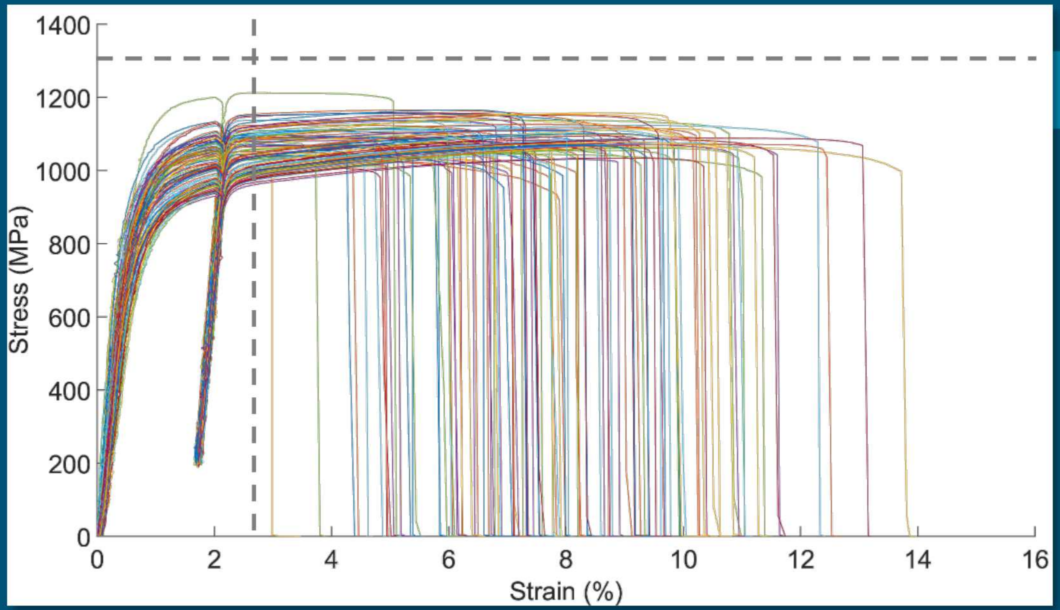


Stochastic Response of AM Metals

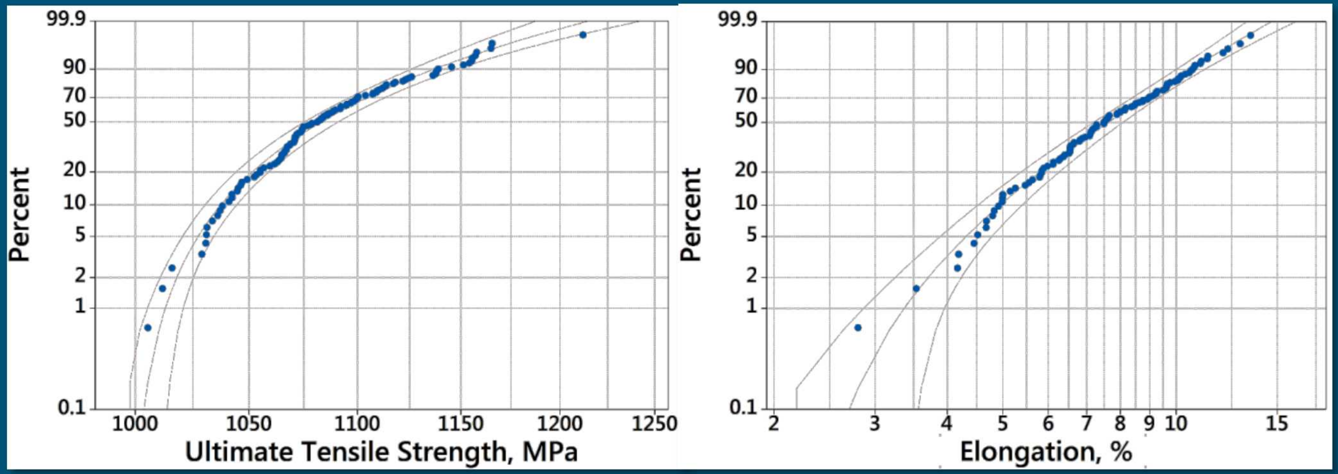
Defect dominated failure

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

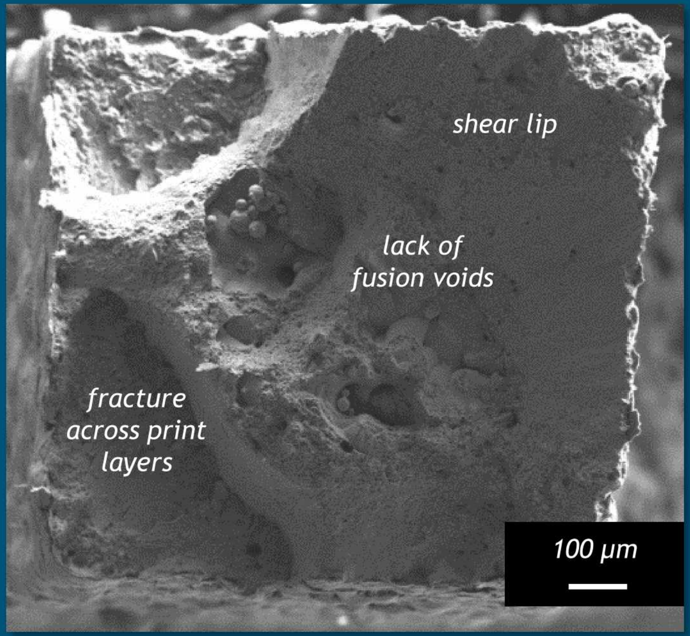
How to capture efficiently & accurately?



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



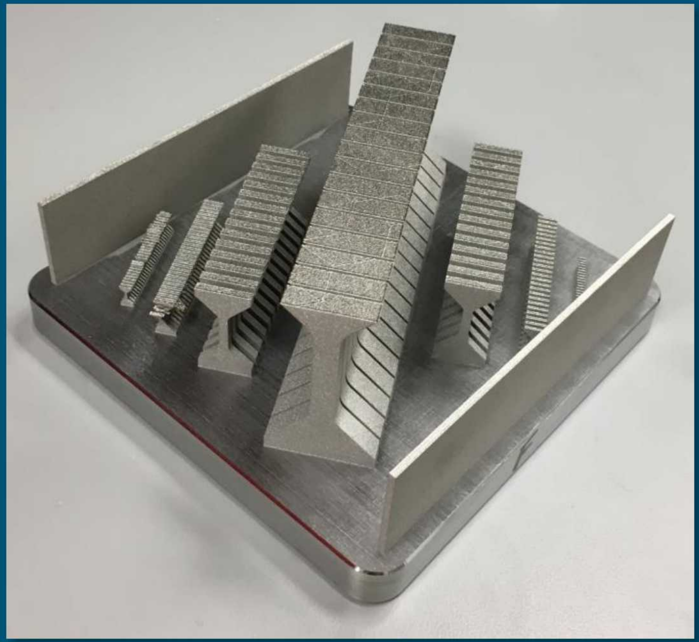
material performance fit to 3-parameter Weibull distributions



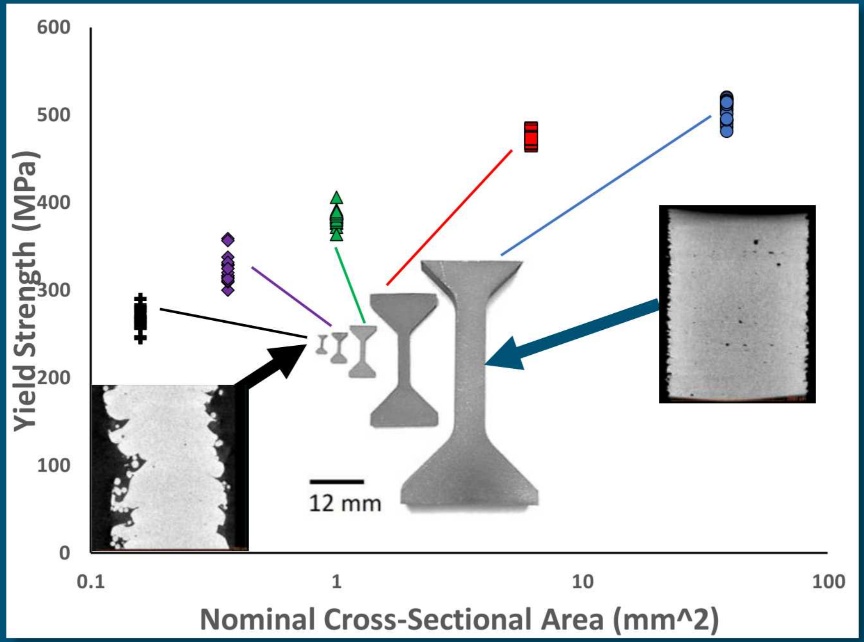
failure at 2% elongation, SHT+H900

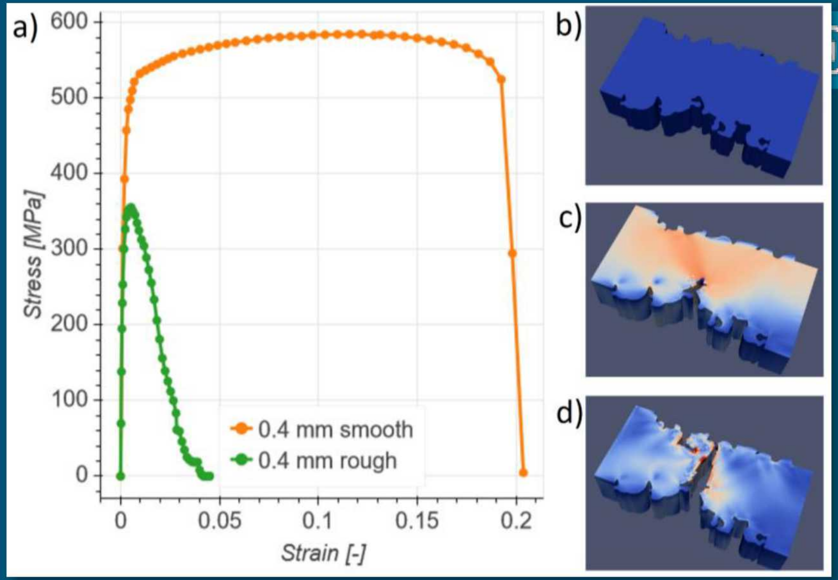
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

Size Effects

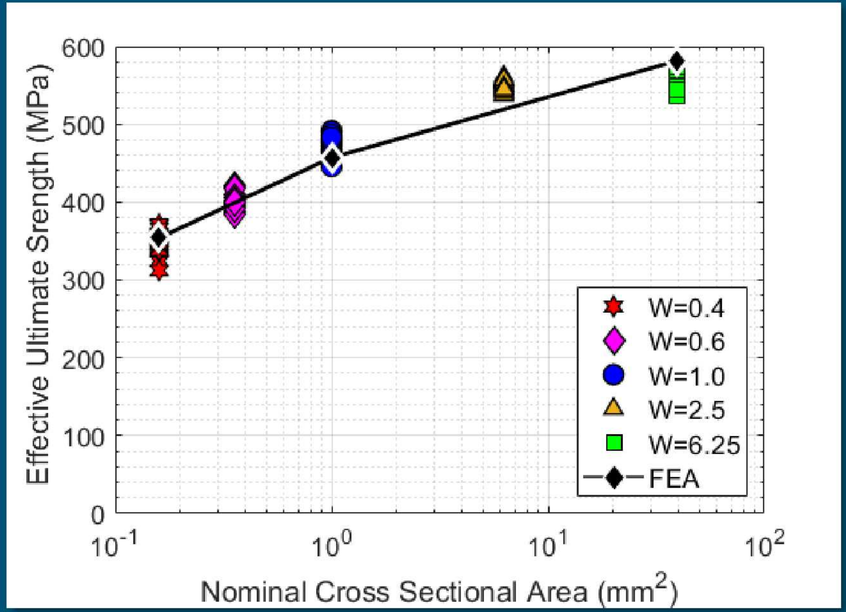


Prox 200 build plate w/ tensile samples

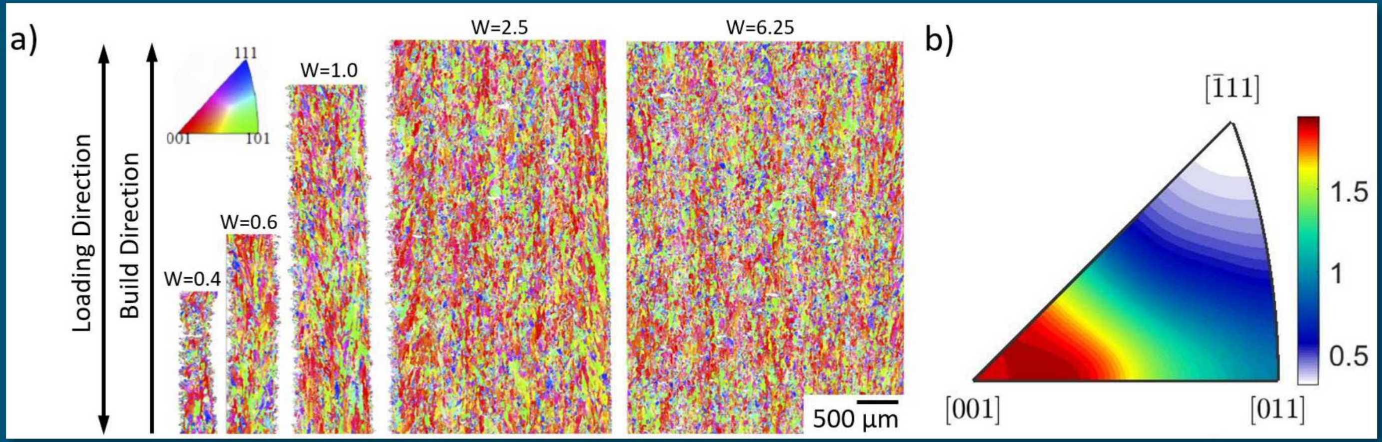




surface roughness dramatically reduces strength of features with similar size scale



FEA model incorporating surface finish correlates well to experiments



microstructure is invariant w/ sample size

A.M. Roach, ***Add Mfg***, 2020

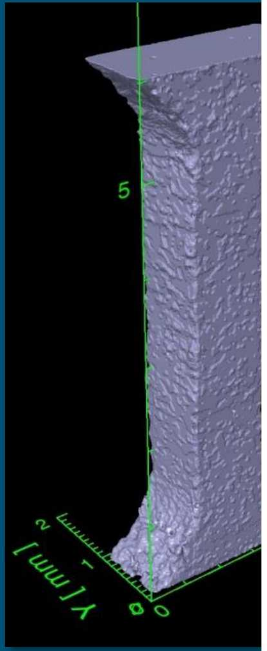
Tying Structure (Porosity) to Properties

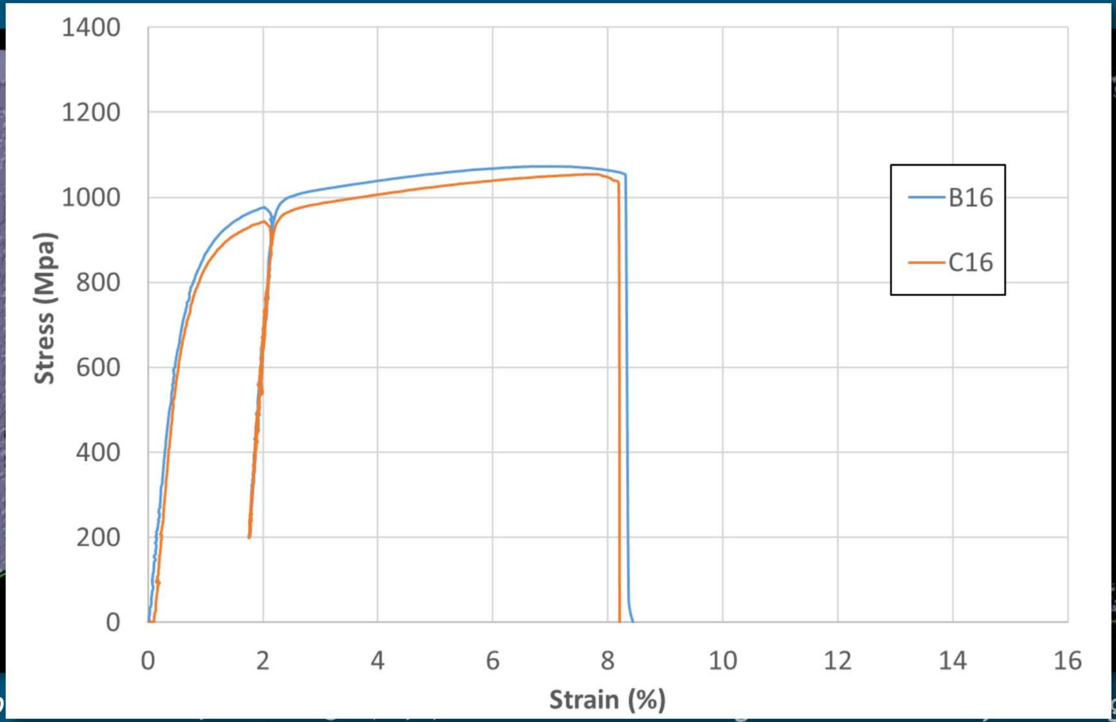
Extensive work using computed tomography (CT)

- multiple potential metrics exist
- correlations are immature

Prediction of uniformly dispersed porosity fields is difficult

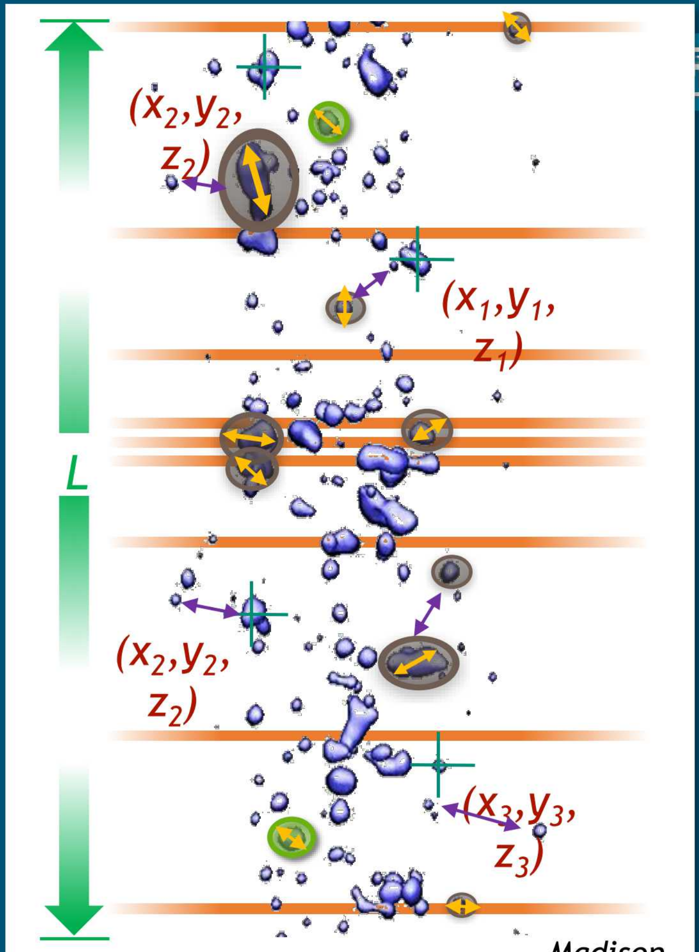
- behavior falls within an expected performance distribution





17-4PH dogbo… porosity map (right)

…ge (left), porosity map (right)



Madison, QNDE, 2018

- 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 ($NND_{avg.}$)*

ESD = equivalent spherical diameter

Gross Defects Drive Performance Outliers

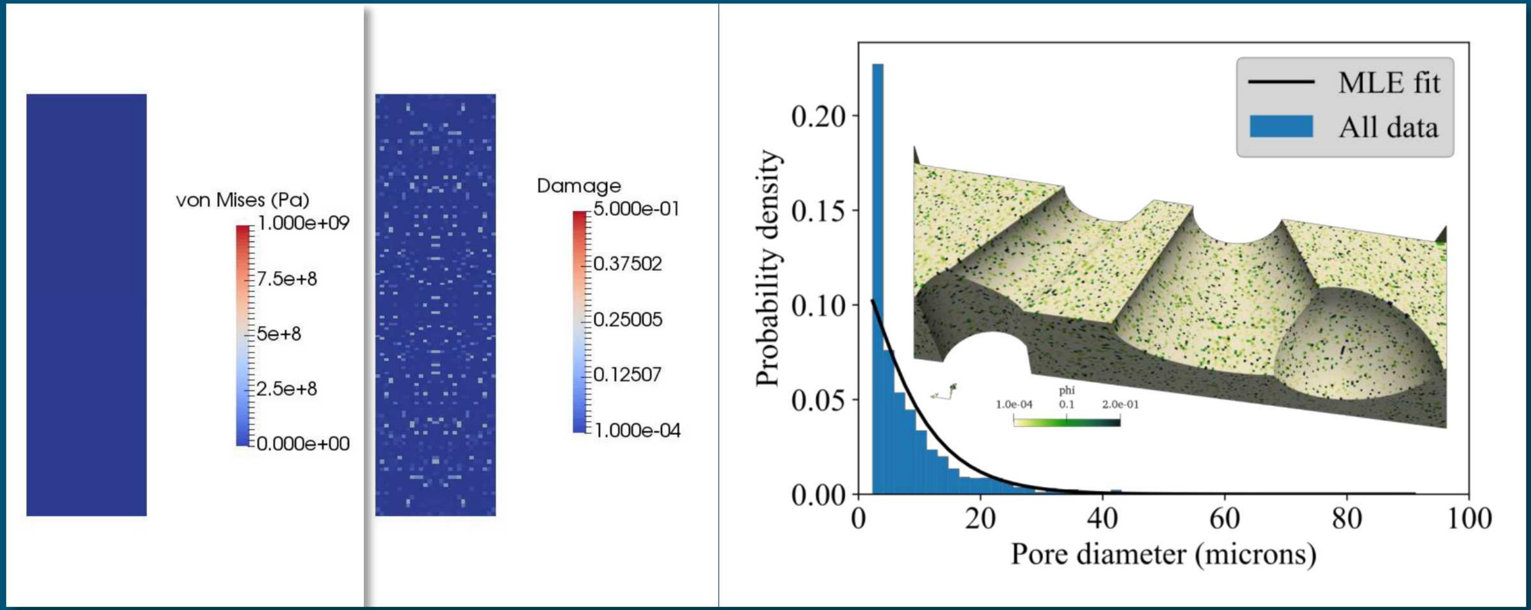
Failure initiates near large pores

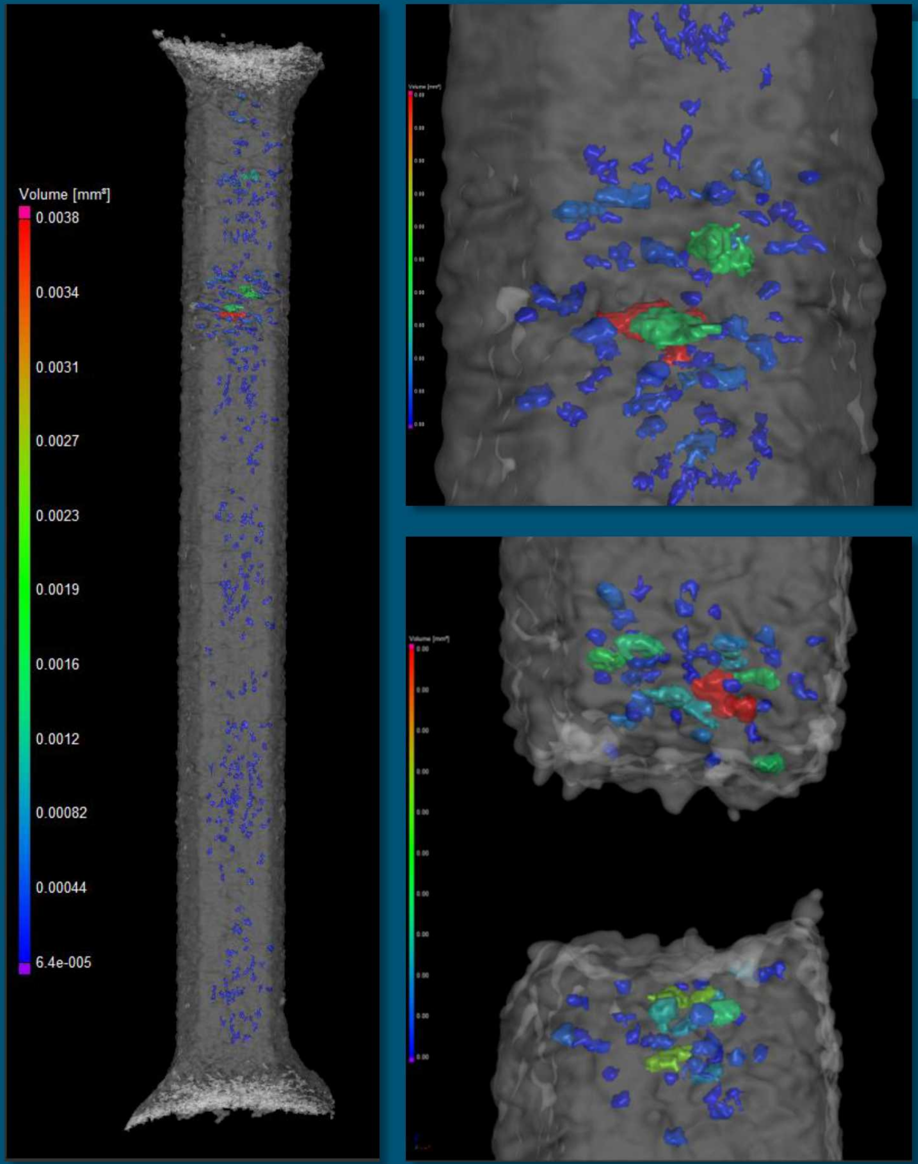
Potential tolerance bound
- design requirements
- CT inspection
- process monitoring

Performance simulation represent power analysis & diagnostics tools

representing porosity as initial damage

*Johnson, **Int J Fract**, 2019*





1x1x10mm 316L SS tensile dogbone (left) from digital volume correlation (DVC), gross porosity region (top right), failure region (bottom right)

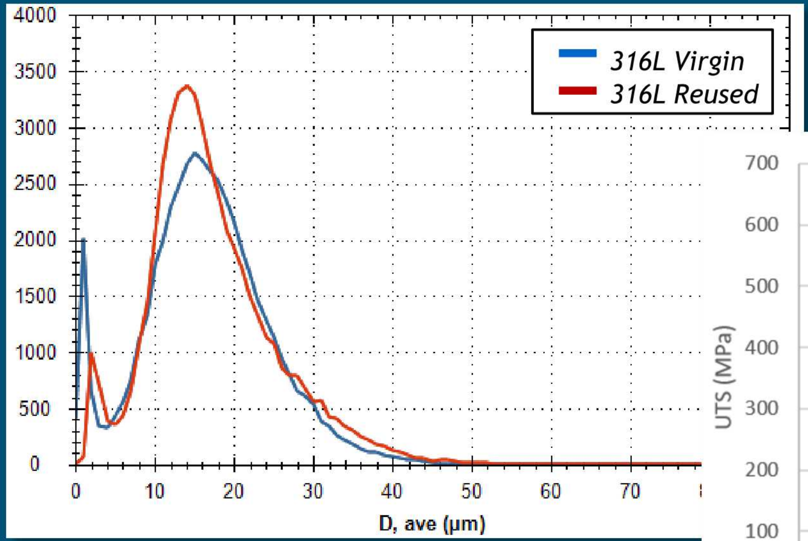
Kyle Johnson, David Moore

Monitoring Powder Reuse

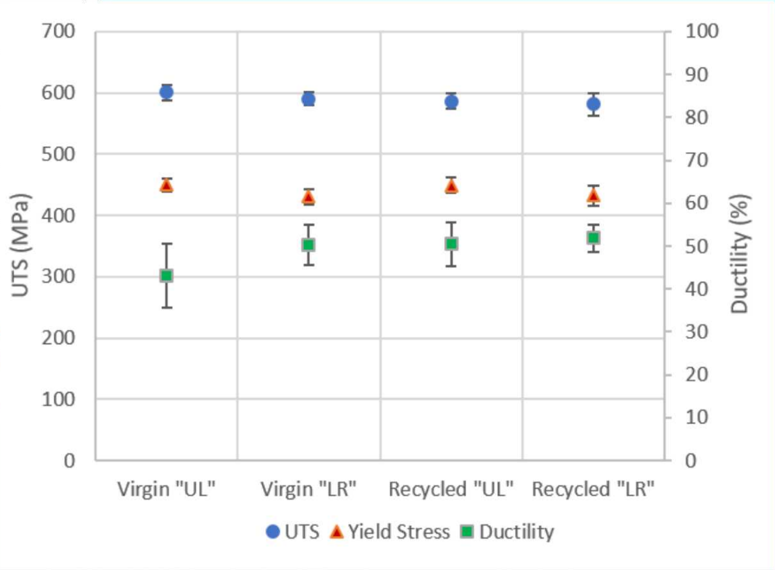
Tracking powder size, morphology & EDS composition w/reuse
- satellites & agglomerates increase
- observe highly spherical, ferrite particles
- increase in fines & reduction in larger particles
- collected over 30 reuses w/powder under Ar

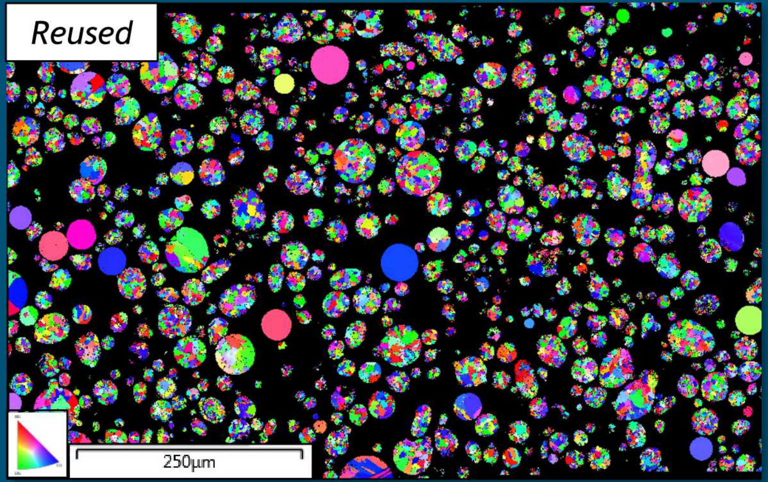
Material properties remain stable

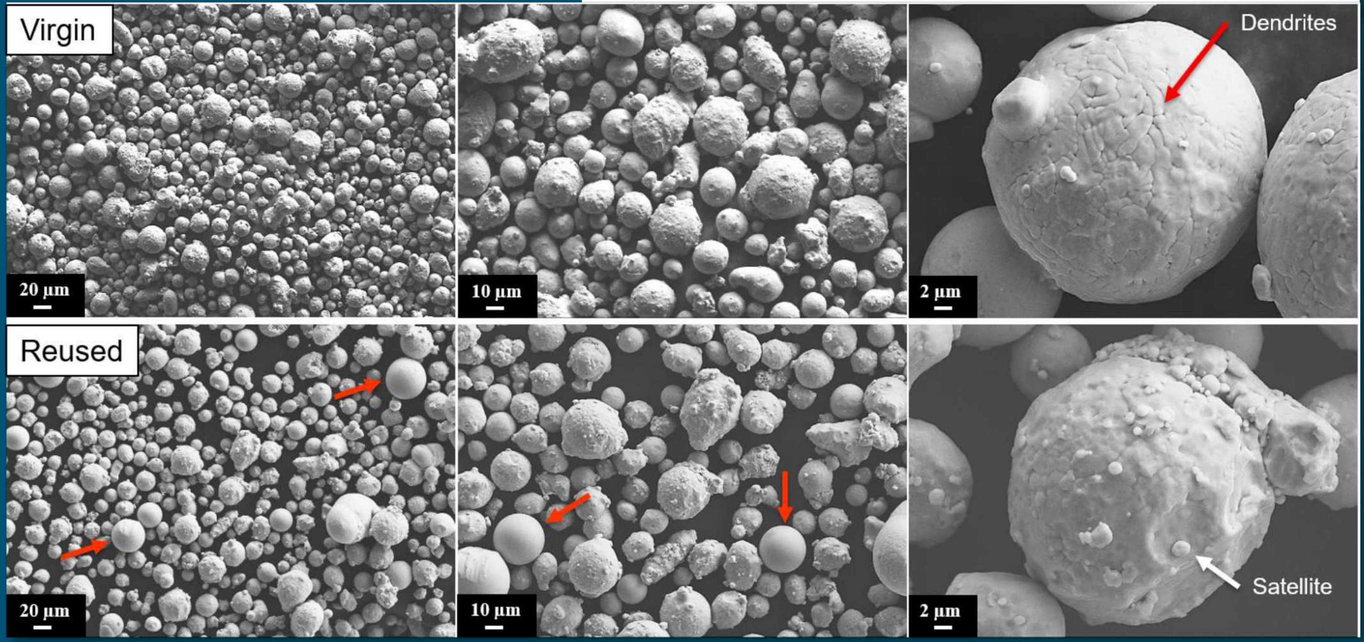
316L SS is a robust material for processing & properties



Virgin: 7.90 g/cm³
Reused: 7.81 g/cm³

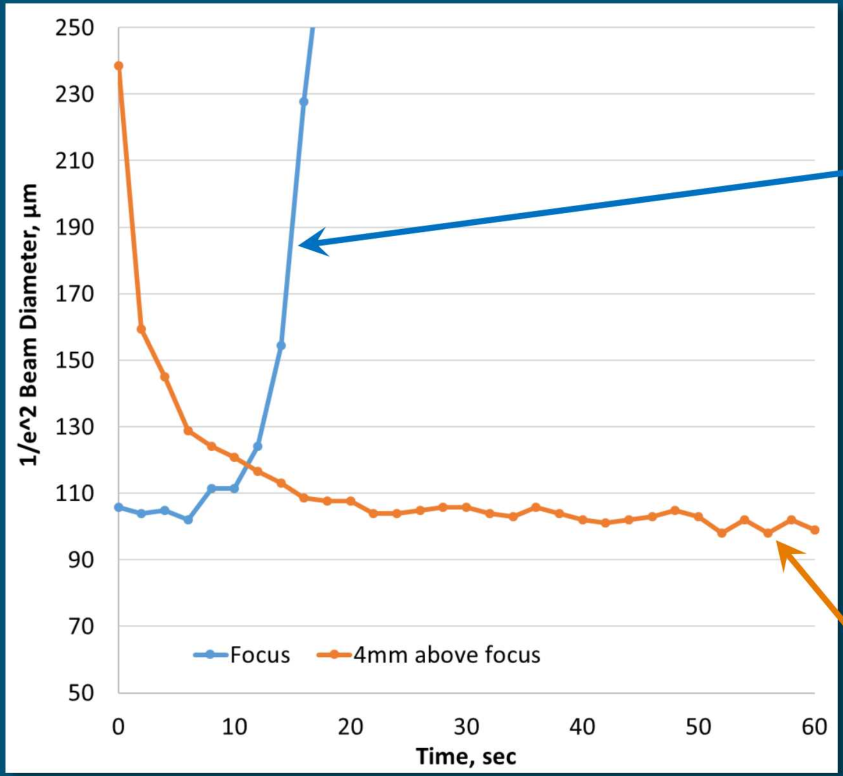




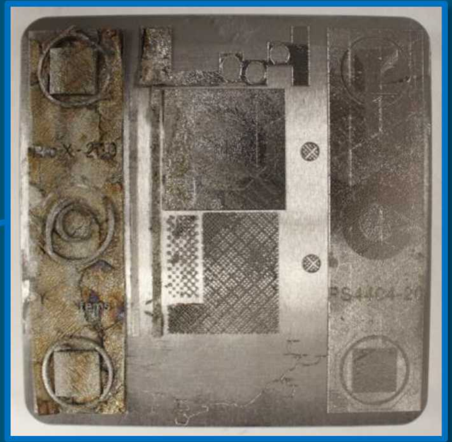


*Heiden, **Add. Mfg.**, 2019*

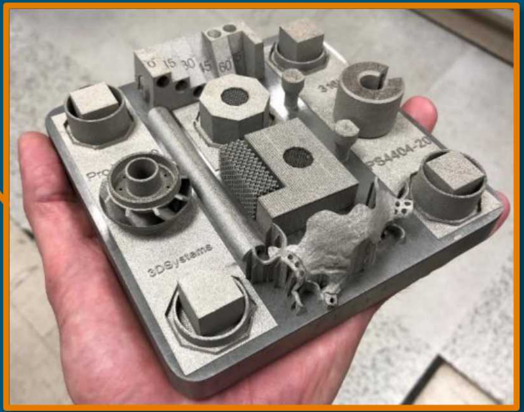
Machine Metrology is Critical to Assure Part Quality



beam diameter variations w/original f-theta lens

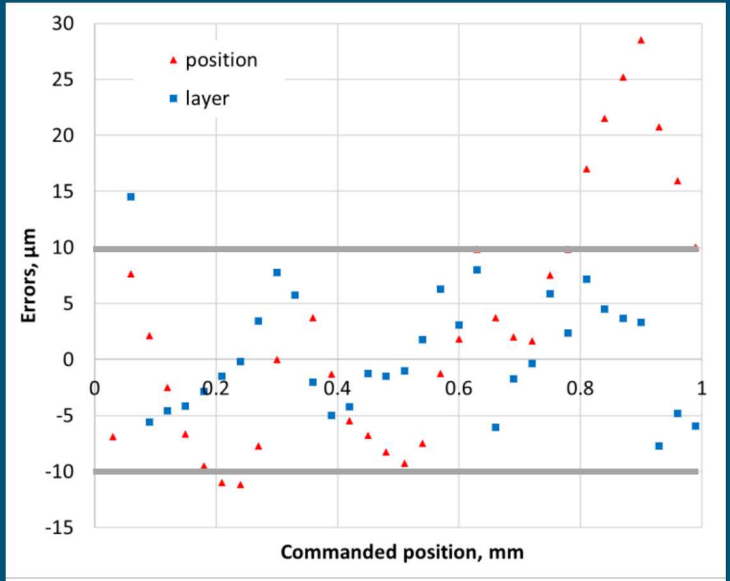


nominal focus offset

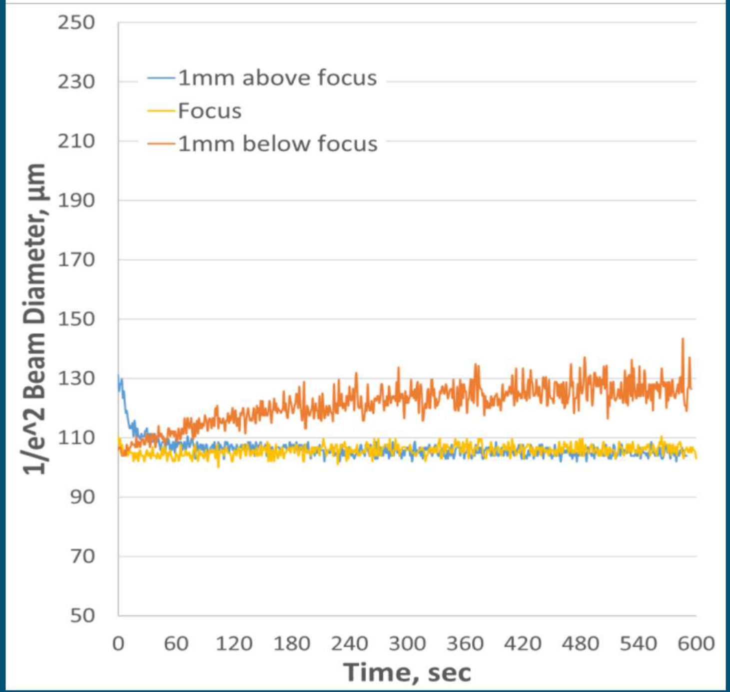


5mm focus offset

layer thickness errors



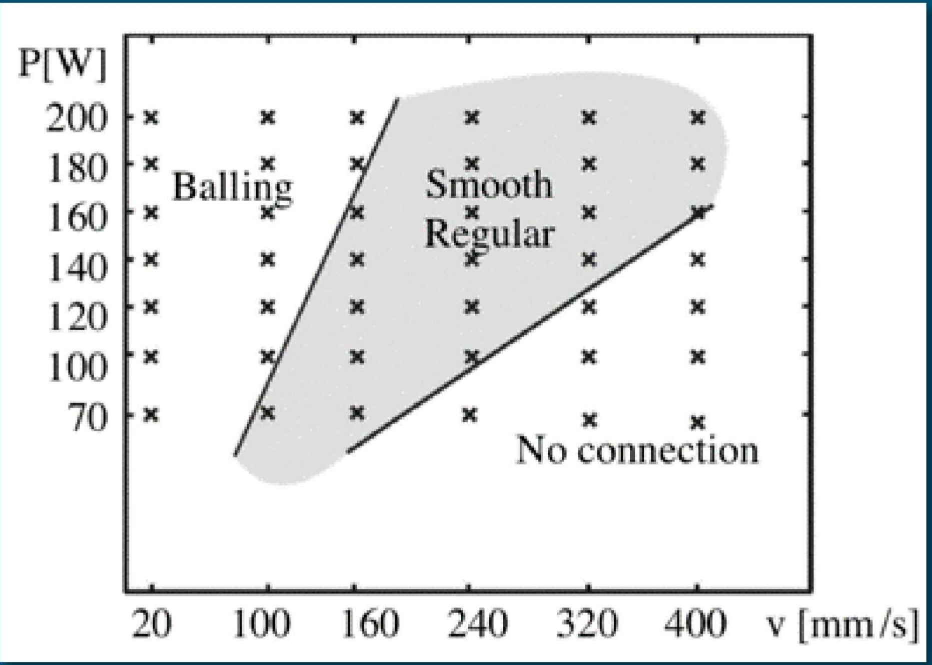
upgraded f-theta lens response



Process-Structure-Property Process Maps

Parameters

- 316L stainless steel
- laser power: 10-240W
- velocity: 50-2800mm/sec
- layer thickness: 30, 40µm
- average powder diameter: 15, 25µm
- laser focus offset: -1.5mm below focus to +3.5mm above



Kruth, ***Rapid Prototyping Journal***, *2008*

Experiment forms

- line scans, area pads, density cubes, HTT tensile, Charpy

Performance metrics

- surface finish, form error, density, tensile properties, Charpy toughness, microstructure
- where are optimal process settings?

The Influence of Process Variables on Physical and Mechanical Properties in Laser Powder Bed Manufacturing

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

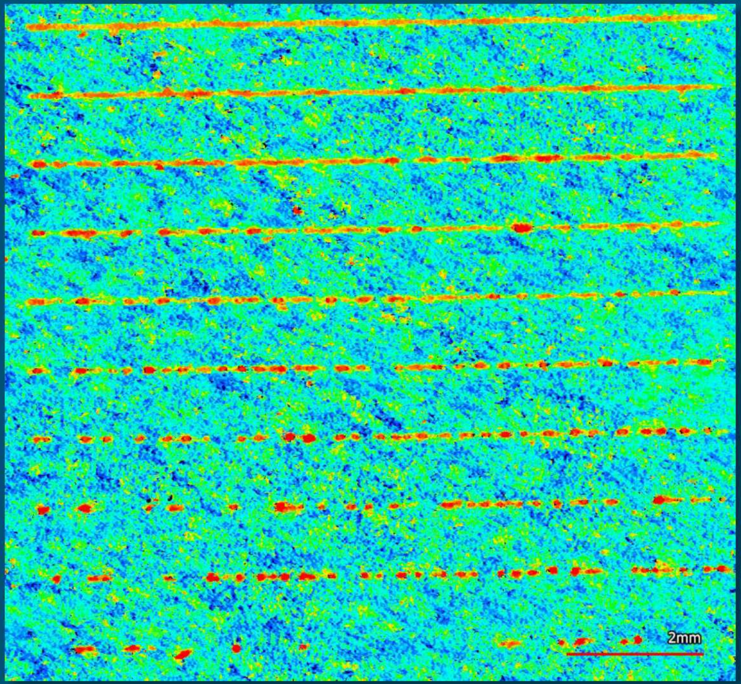
Line Scans

Substrates: bare plate, powder layer on 20 layer AM pad

- 60 lines on each substrate, 1.0 cm long
- power: 25-175W
- velocity: 250-2500mm/sec

Simplistic first step, but quick & informative

- capturing melt pool geometry via metallography
- useful to define nominal process boundaries for any material
- used to establish relevance of simple Rosenthal model

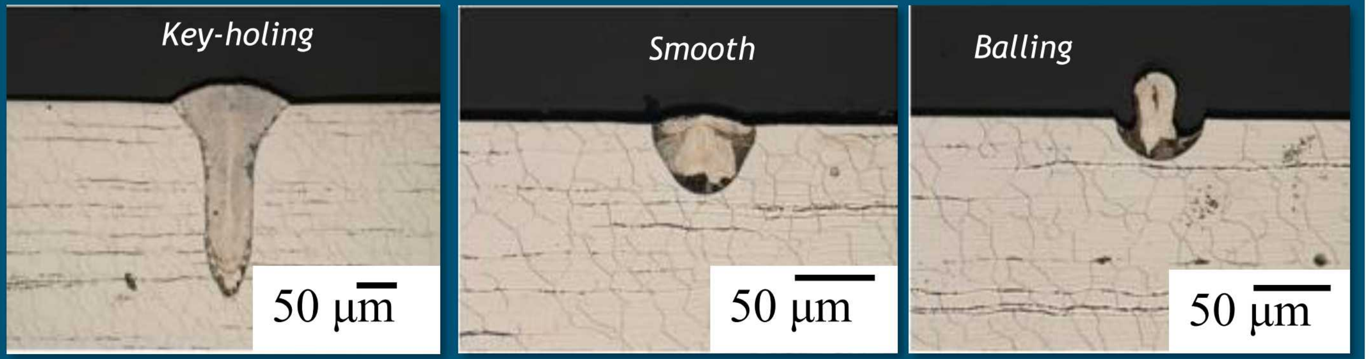


100 W, 250 to 2500 mm/s on pad

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

Line Scans: Plate vs. Powder Layer on Pad

on plate

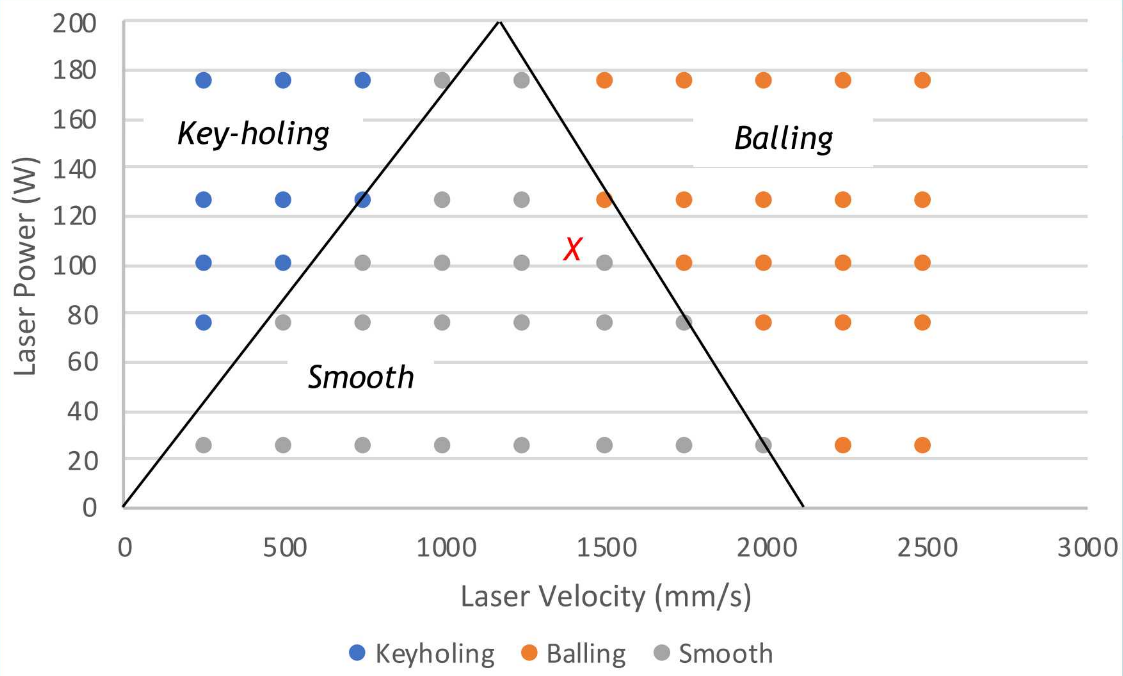


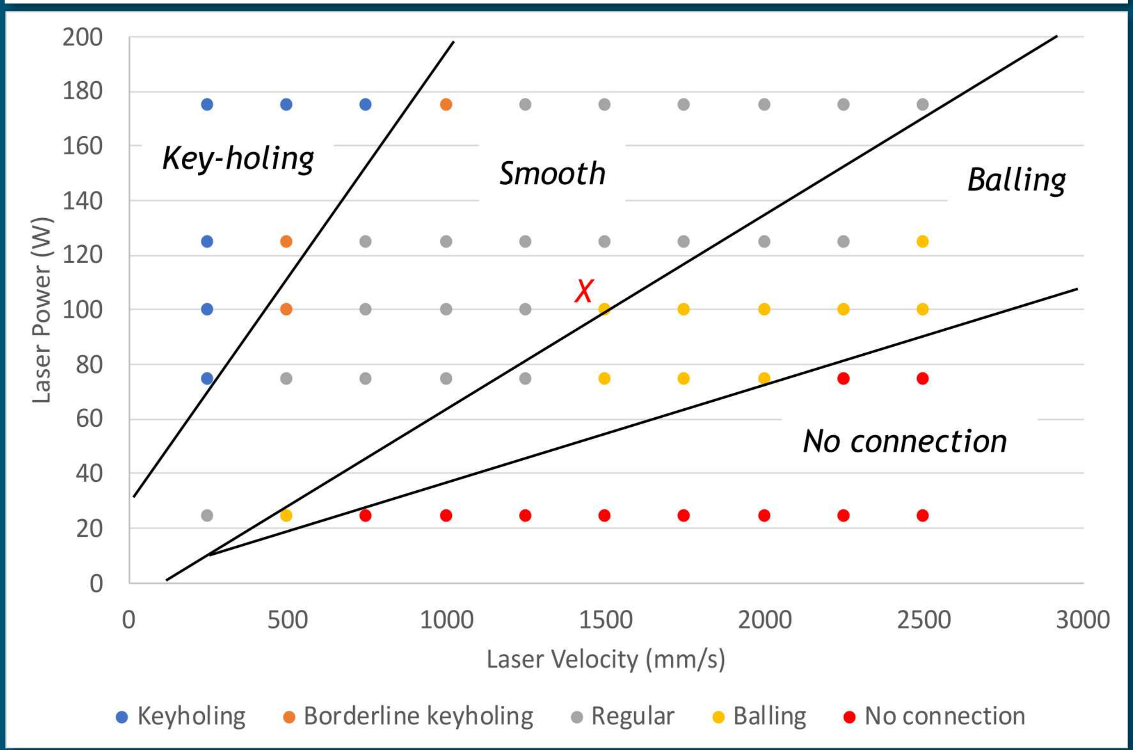
powder layer on pad

Key-holing

Smooth

Balling?





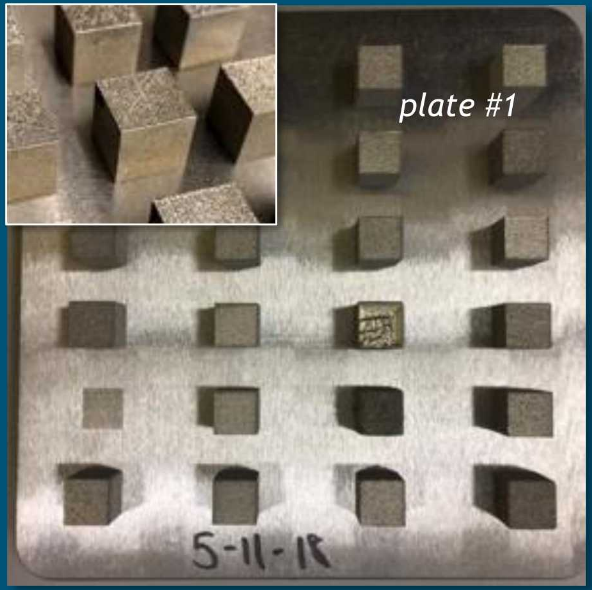
Density Cubes

1cm cubes, 24 per plate

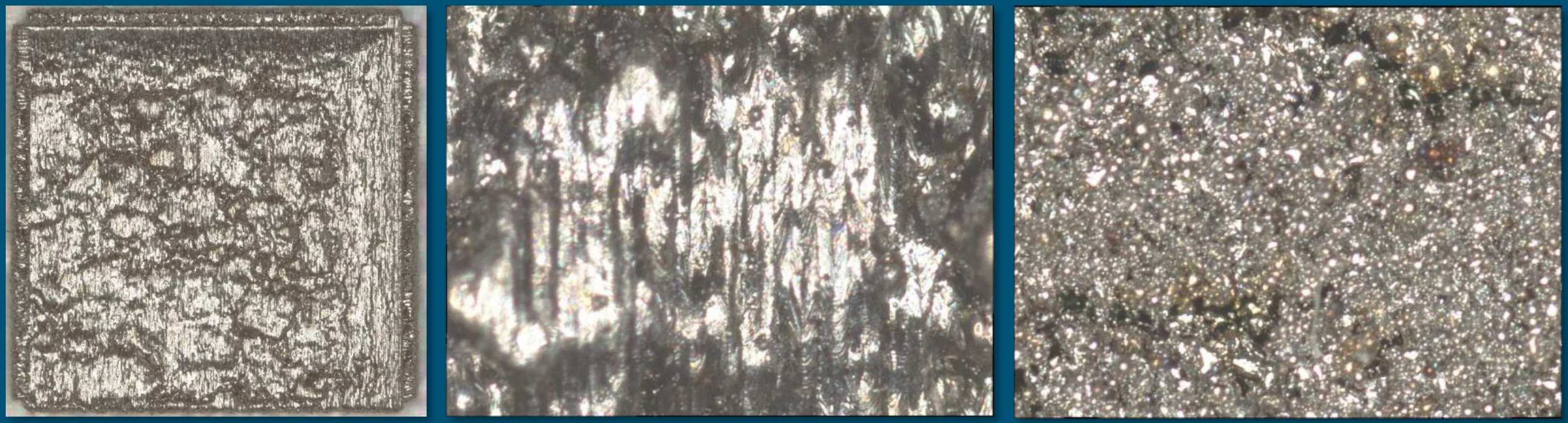
- 10 plates, power, velocity, focus offset, layer thickness, powder size, variation across plate

Bulk material measurements

- density (Archimedes)
- top & side surface form & finish
- microstructure: optical, EBSD

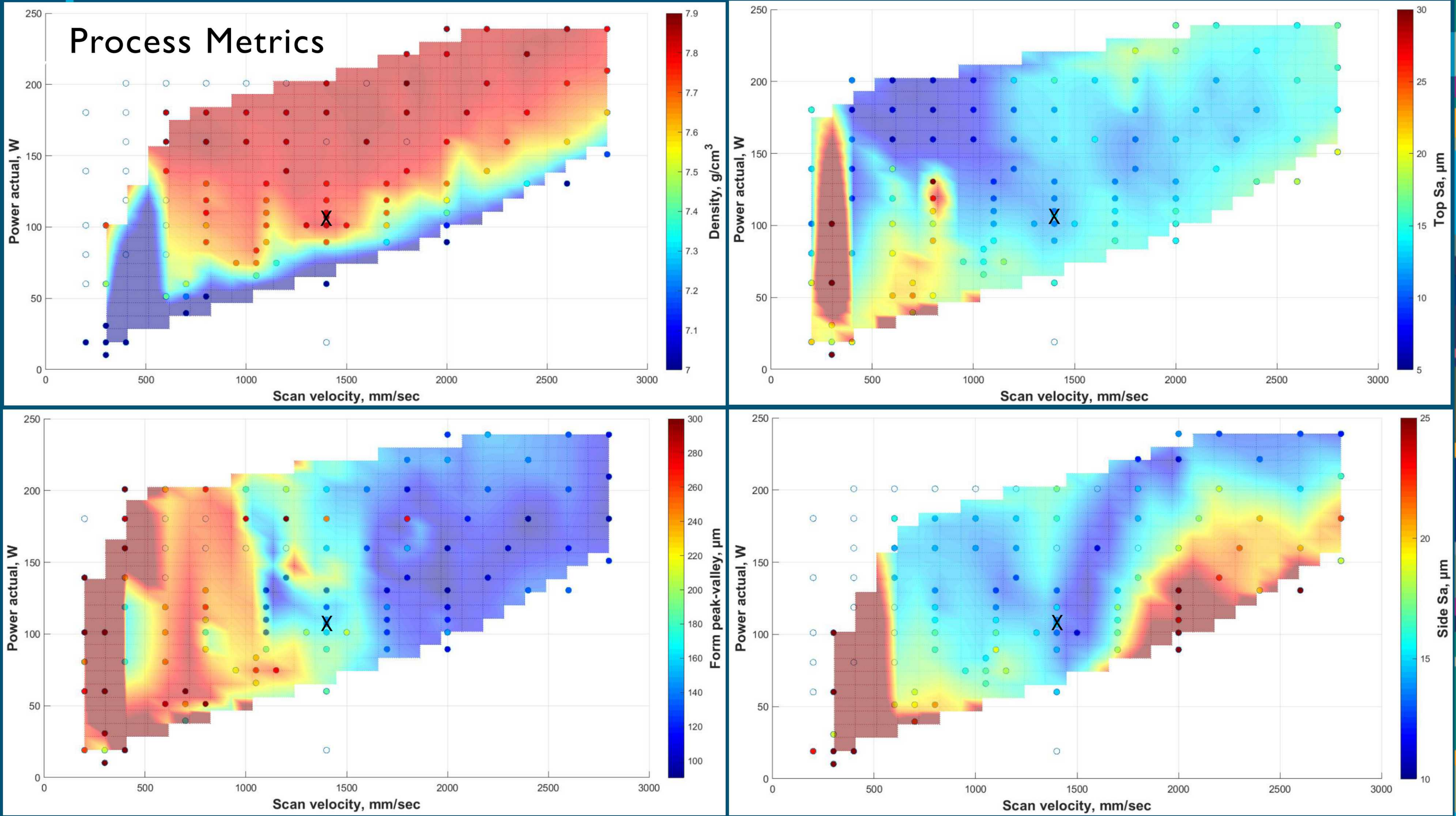


100.2W, 1500mm/sec 209µm PV form (left), top 13.5µm Sa roughness (center), side 9.98µm Sa roughness (right)



60.1W, 300mm/sec 891µm PV form (left), top 73.8µm Sa roughness (center), side 38.1µm Sa roughness (right)

Process Metrics



Material Microstructures, 30µm Layer Thickness

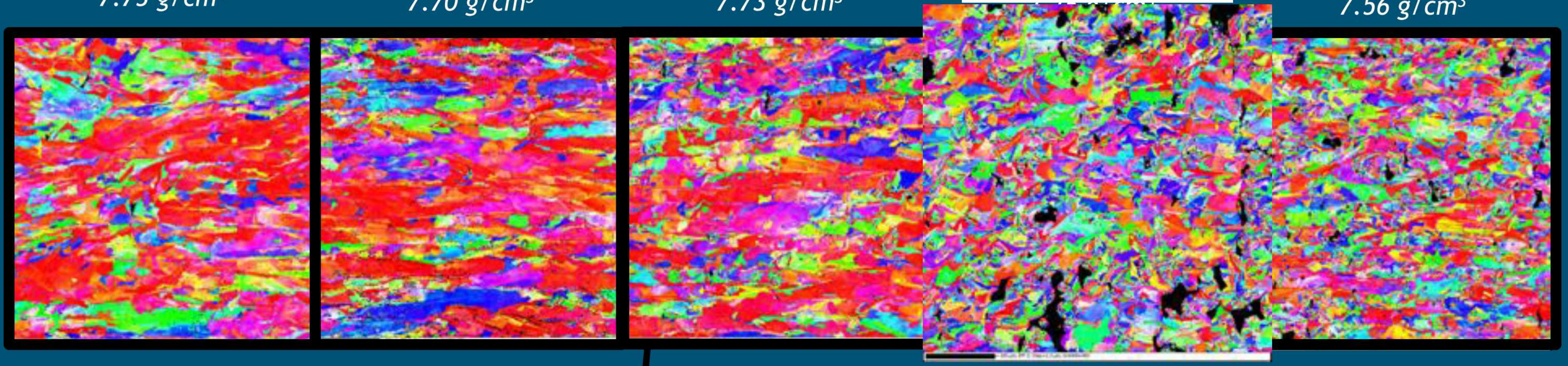
120 W, 800 mm/s
7.75 g/cm^3

120 W, 1100 mm/s
7.70 g/cm^3

120 W, 1400 mm/s
7.73 g/cm^3

120 W, 1700 mm/s
40.0 µm 7.44 g/cm^3

120 W, 2000 mm/s
7.56 g/cm^3



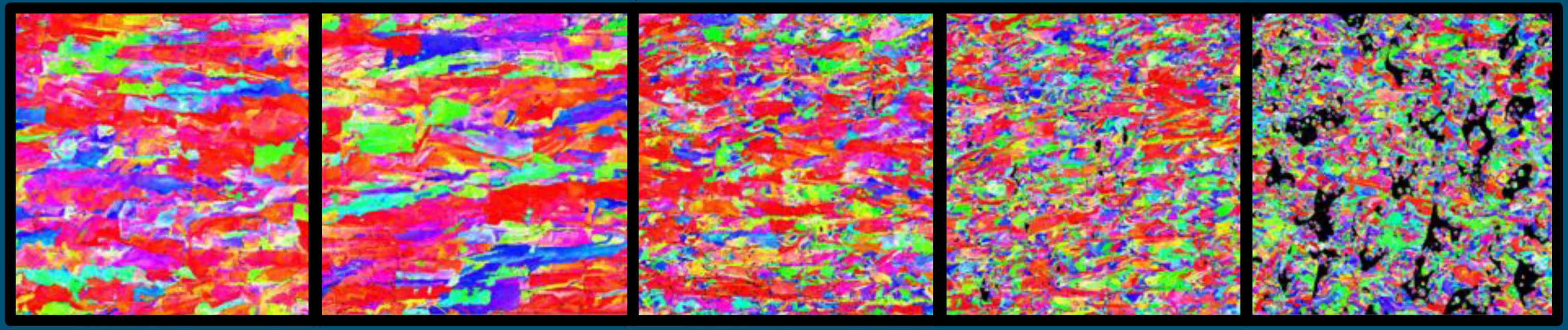
200 W,1400 mm/s
7.84 g/cm^3

180 W, 1400 mm/s
7.85 g/cm^3

107 W, 1400 mm/s
7.87 g/cm^3

90 W, 1400 mm/s
7.70 g/cm^3

60 W, 1400 mm/s
6.63 g/cm^3



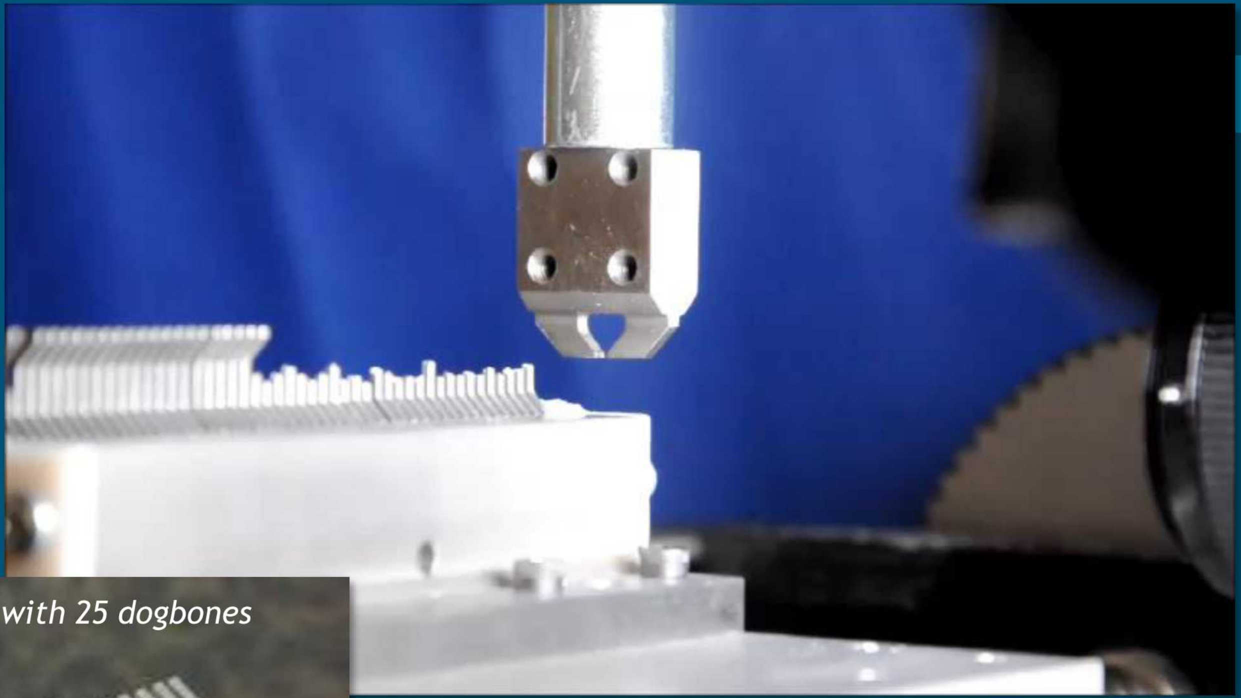
1 mm x 1 mm

decreasing energy density

High-Throughput Tensile Properties

1x1x4mm gauge section, 10 or 25 dogbones/array
- five build plates
- varied power, velocity, powder diameter
- Gen2 HTT system

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

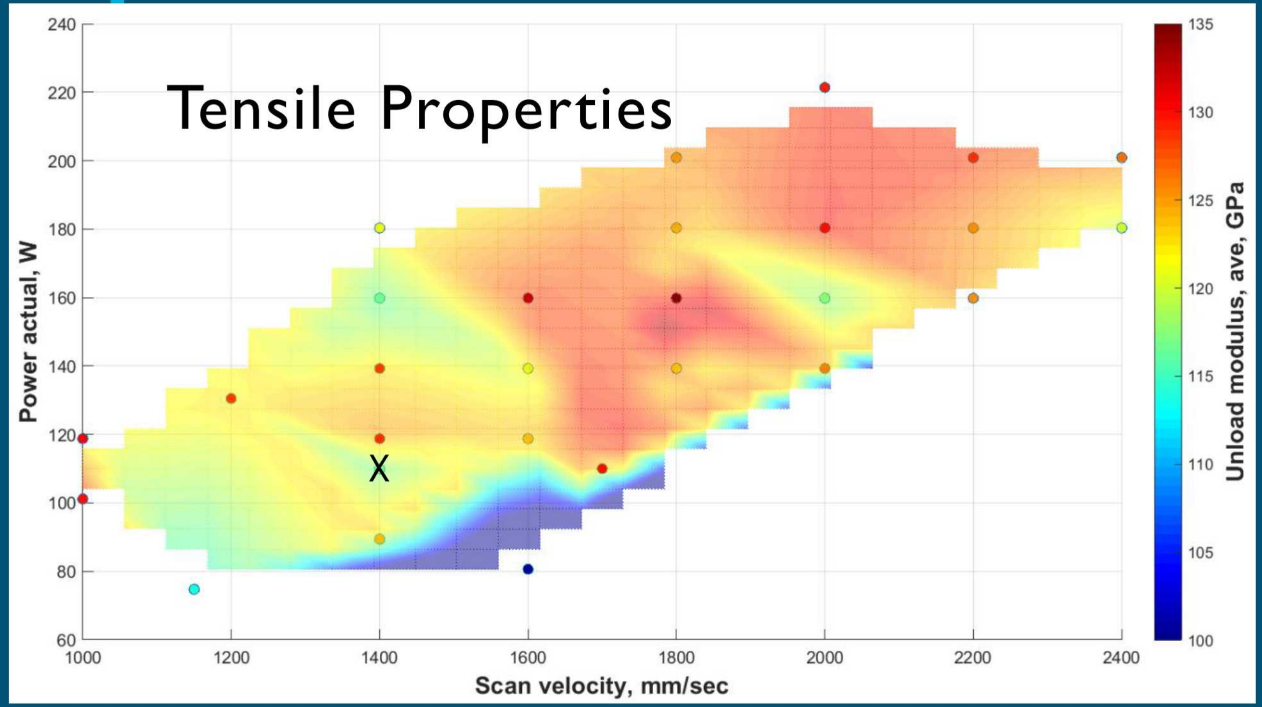


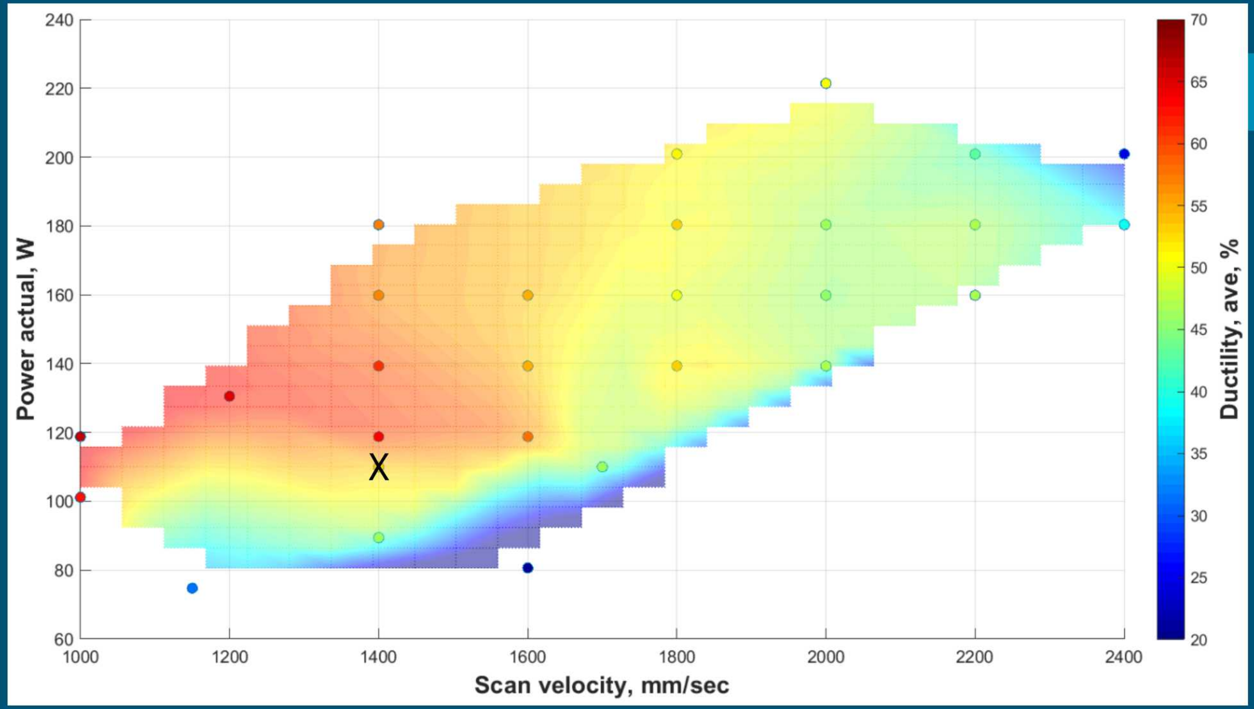
Heckman, ***Mat. Sci. Eng. A***, 2020

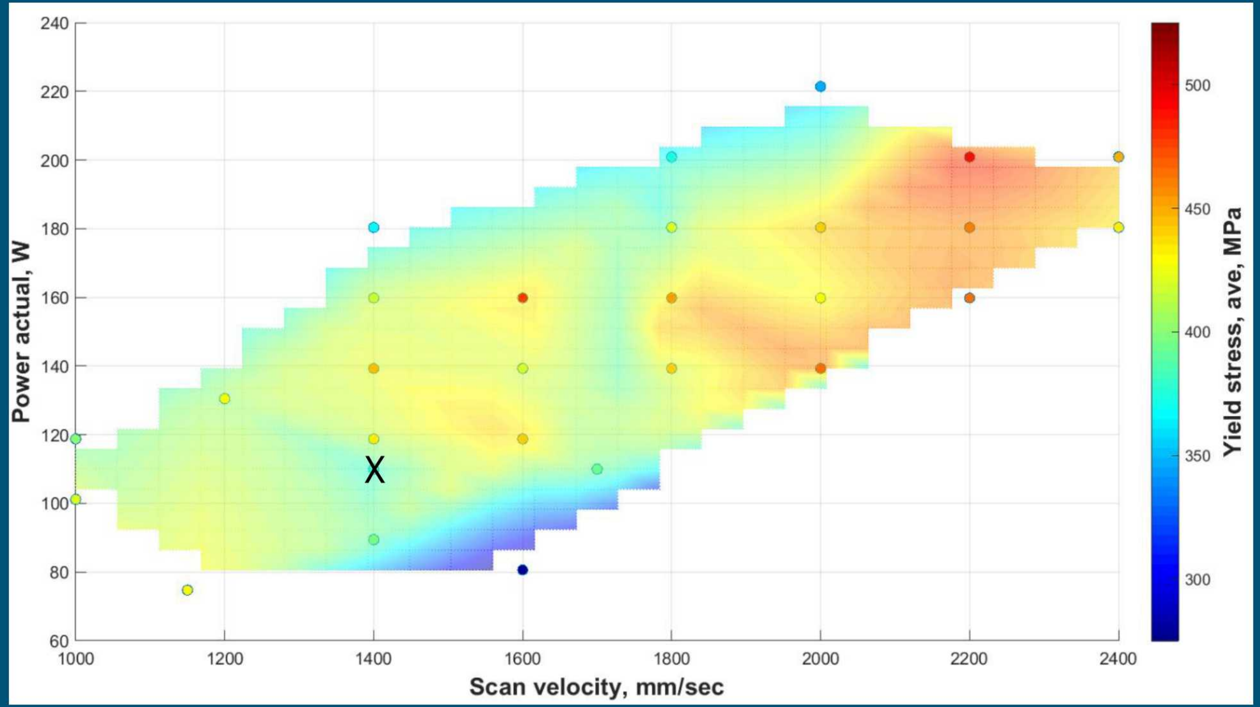
316L SS dogbone array with 25 dogbones

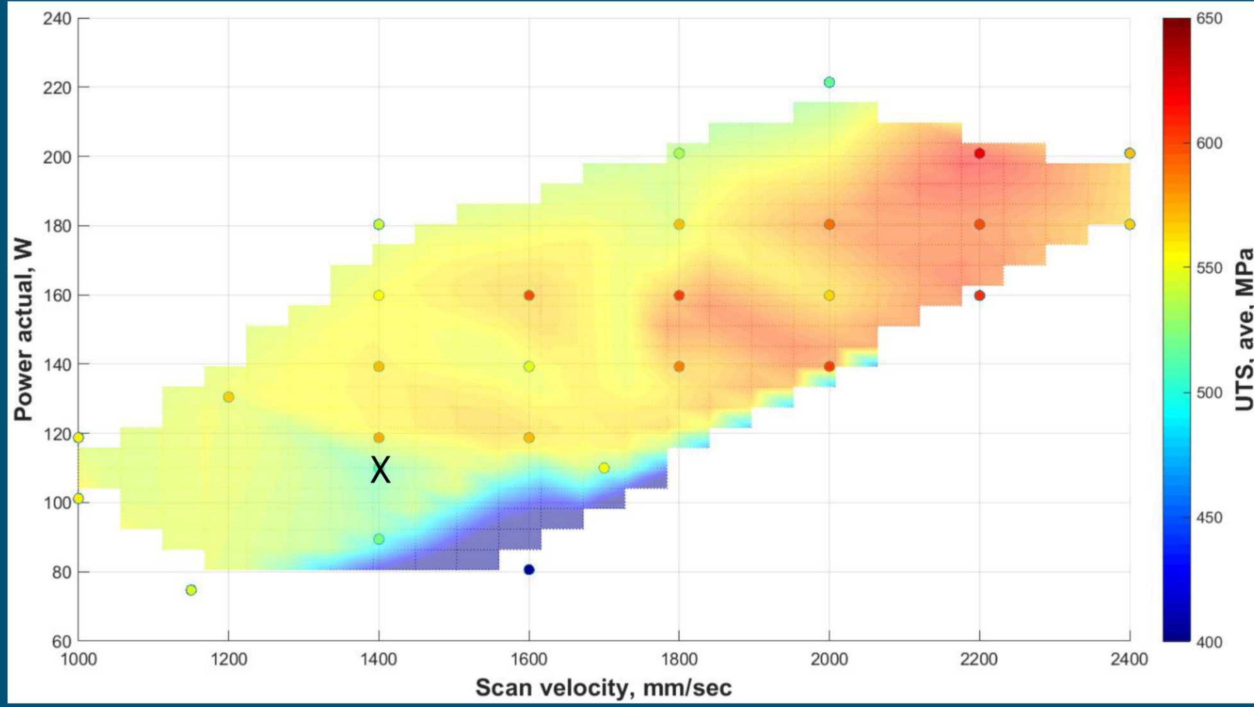
build plate w/20 arrays, 10 dogbones/array

Tensile Properties









Process Understanding & Control Reduced Material Uncertainties

Controlling & logging part, build & powder cycles

- 316L stainless steel
- feedstock pedigree, build environment, process inputs, post-processing, meta data
- print / test artifacts

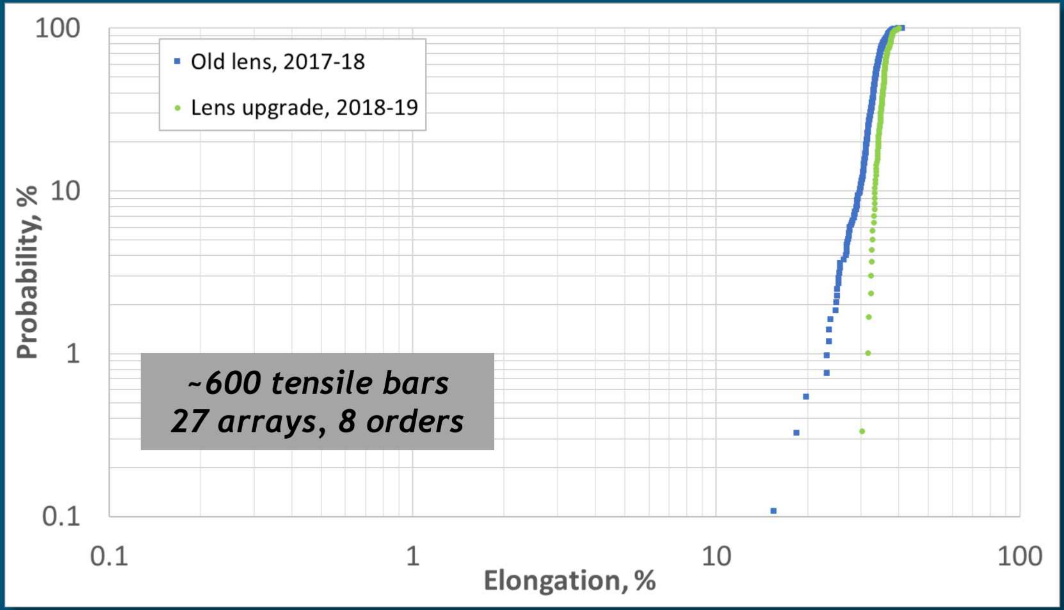
Heuristic dependent

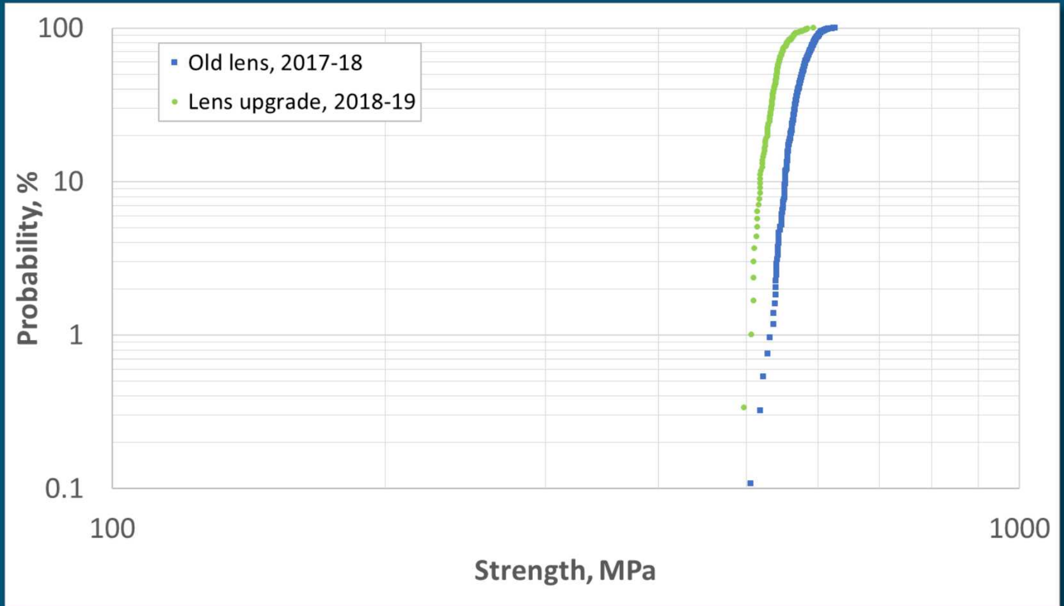
- restrictive
- time consuming
- expensive

Desire accelerated cycles

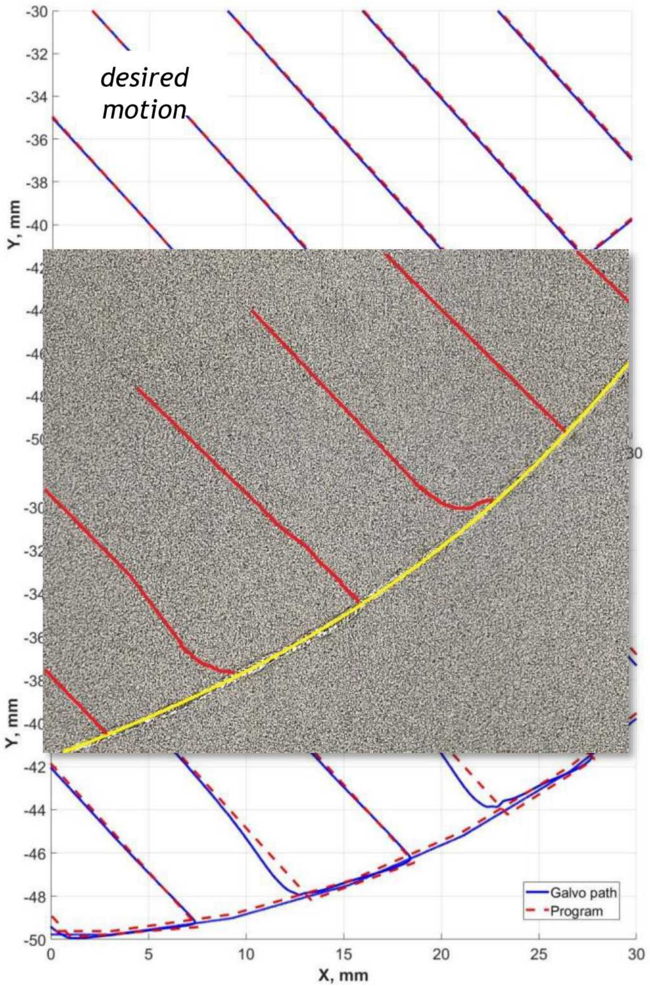
- tolerances & uncertainties

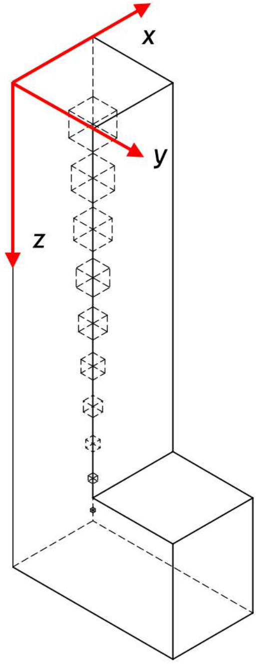
build plate w/process artifacts



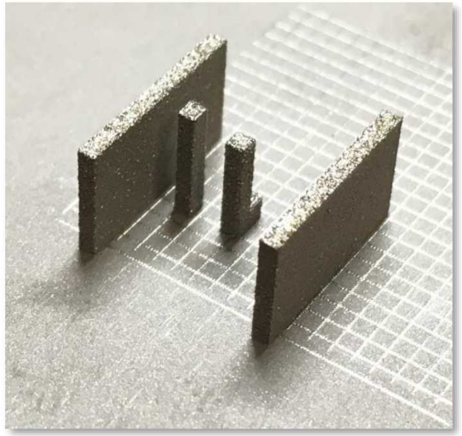


Real-Time Machine Monitoring Reveals Process Perturbations

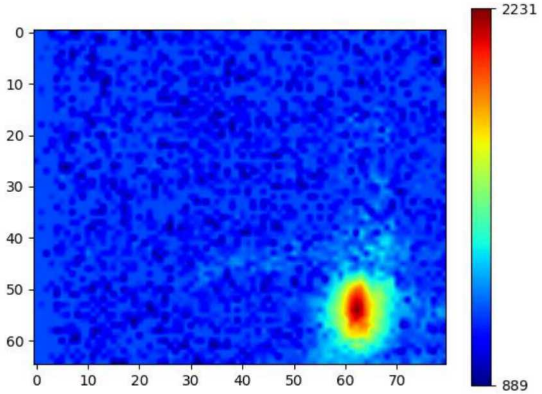




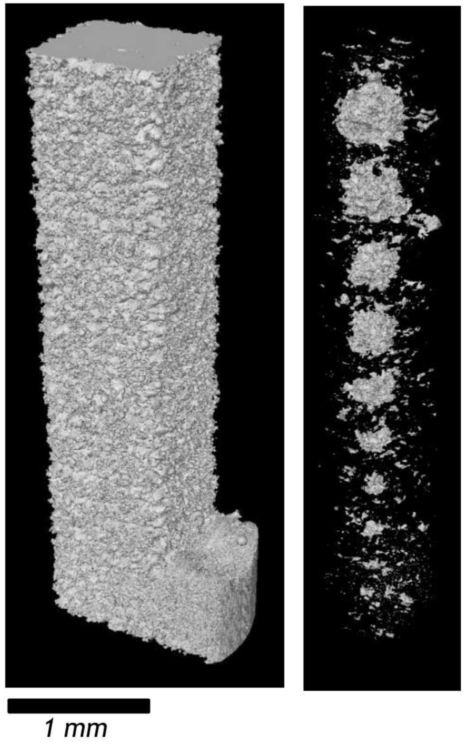
captured hole structure design



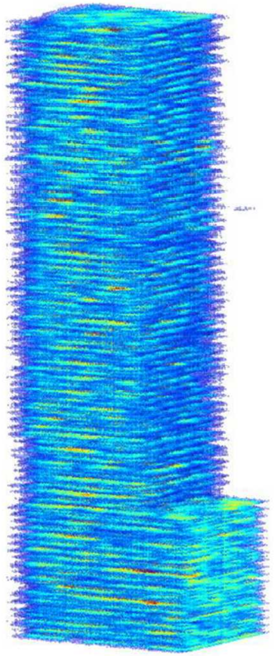
1x1x5mm 316L SS column w/support walls



melt pool motion, nominal settings



μCT reconstruction



two color pyrometer data reconstruction

Archive, Research, Control, Synchronization (ARCS)

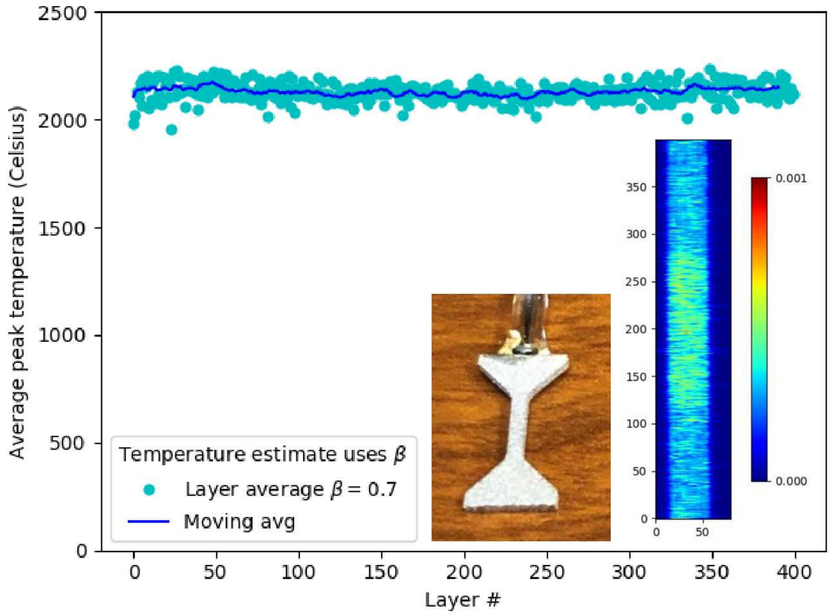
- Penn State, 3D Systems collaboration

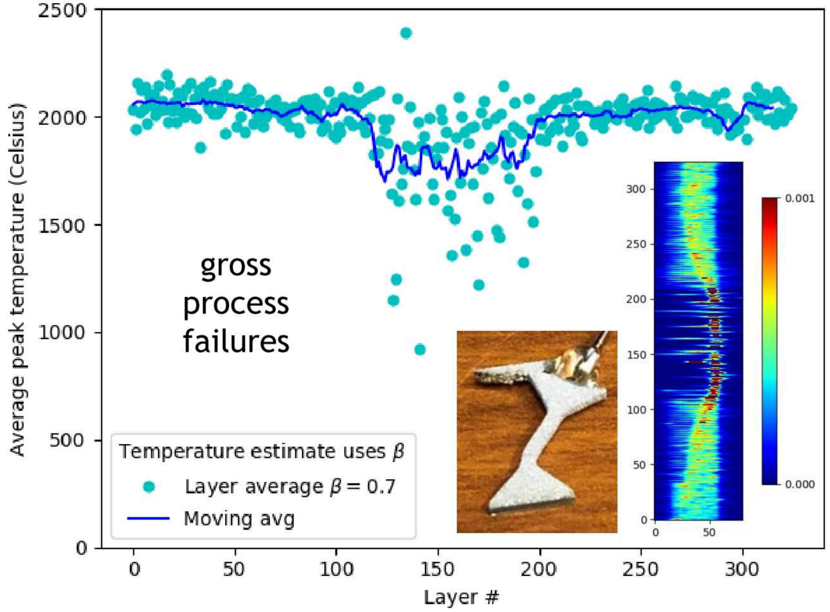
motion @ 100kHz

Exploring multiple sensor signatures

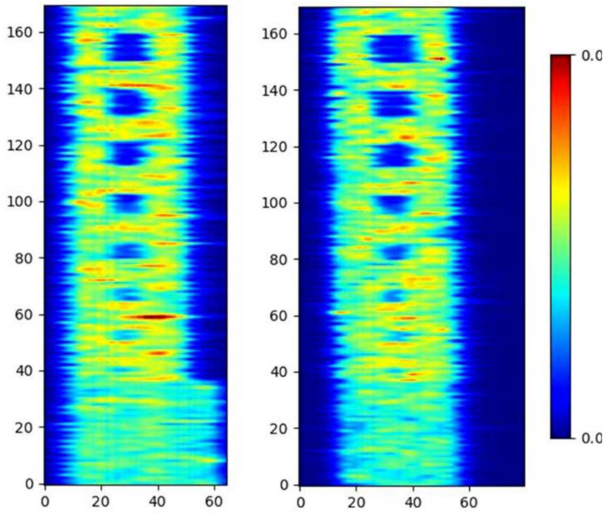
- thermal, optical, acoustic
- two-color pyrometry explored here
- data management & analysis is critical

Correlating Process Signatures w/Material Structures





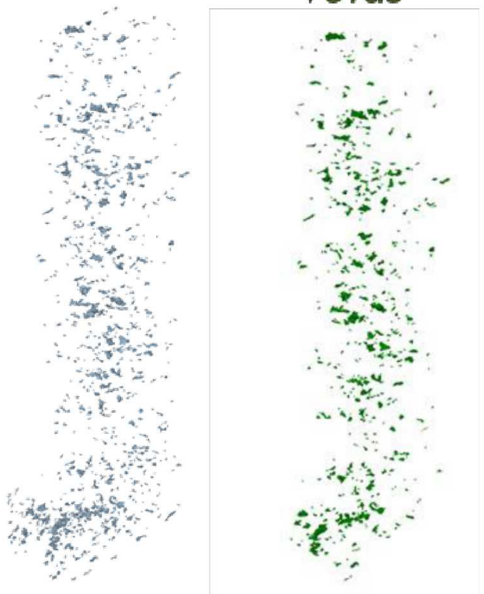
melt pool outliers via ***machine learning*** correlate local void porosity

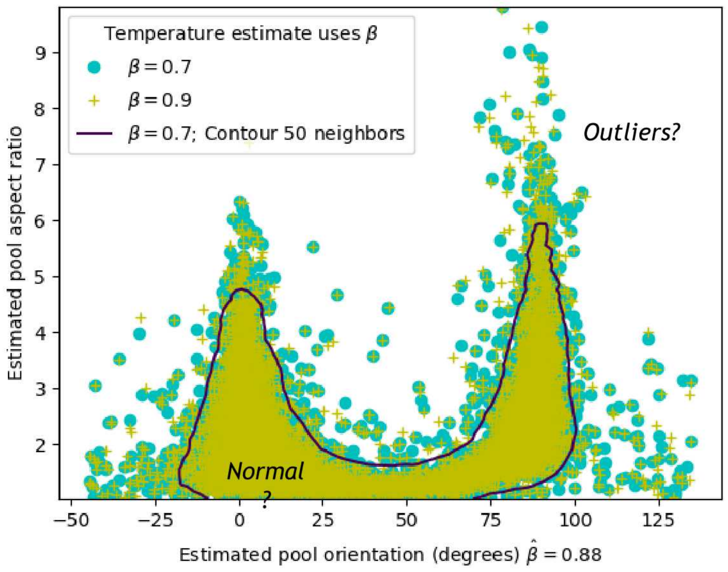


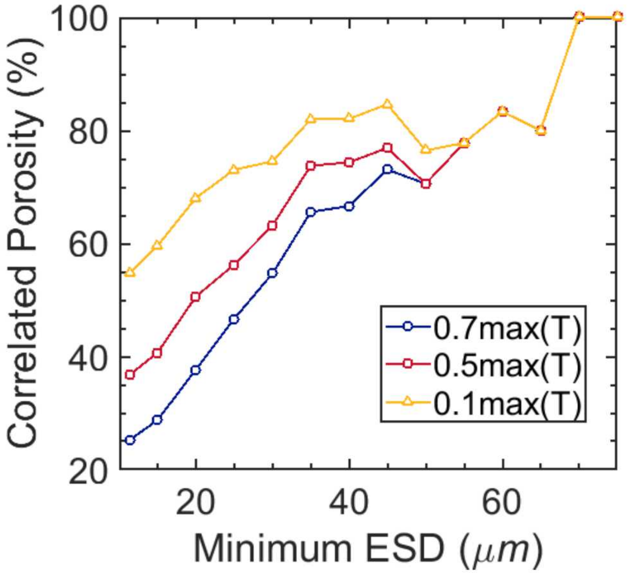
pyrometer data, YZ section (left) & XZ section (right)

All voids

Correlated voids







Mitchell, Add. Mfg, 2020

Material Reconstruction

part side view

VOLUME GRAPHICS

micro-computed tomography

Adobe Photoshop

batch processing
16bit > 8bit conversion
lossless filetype conversion

FIJI

alignment &
registration
cropping
grayscale matching
autoleveling
image filtering
thresholding

MATLAB

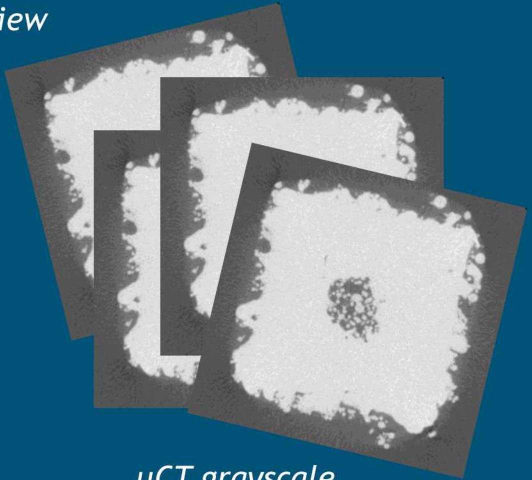
Interactive Data Language

IDL

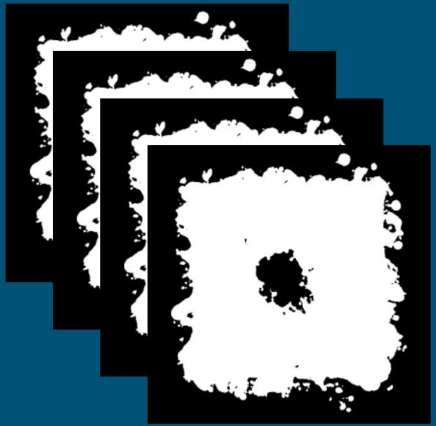
reconstruction
quantification

ParaView
Parallel Visualization Application

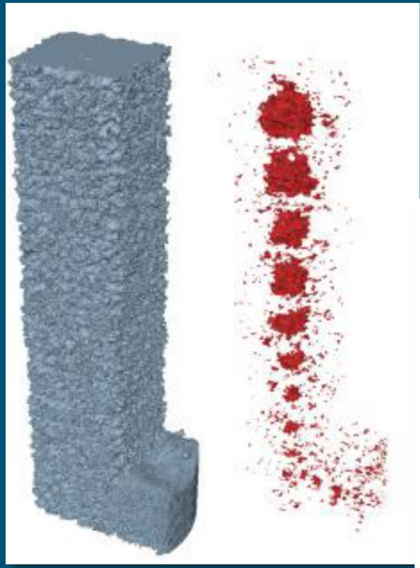
image processing
visualization



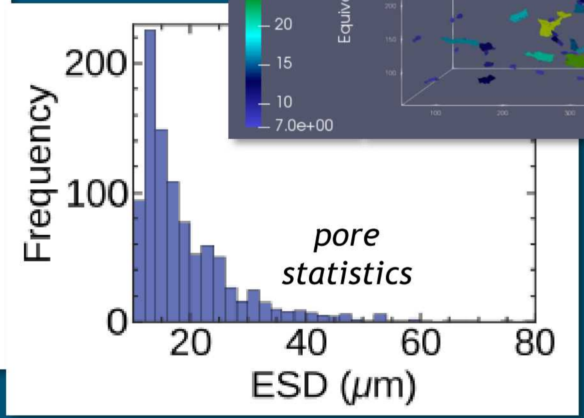
µCT grayscale image stack



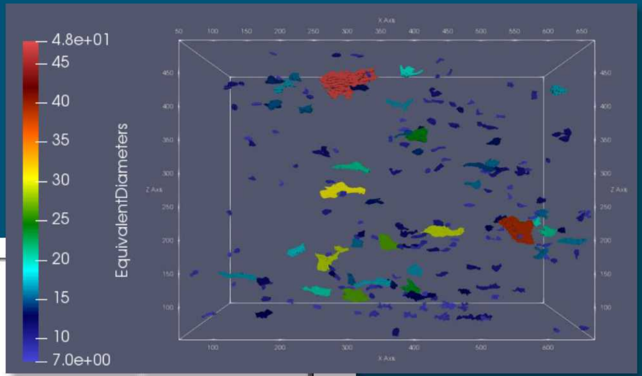
aligned & segmented bitmap stack
white = material, black = air/void



part reconstruction



pore statistics



porosity map generated near the 10 & 20µm pores

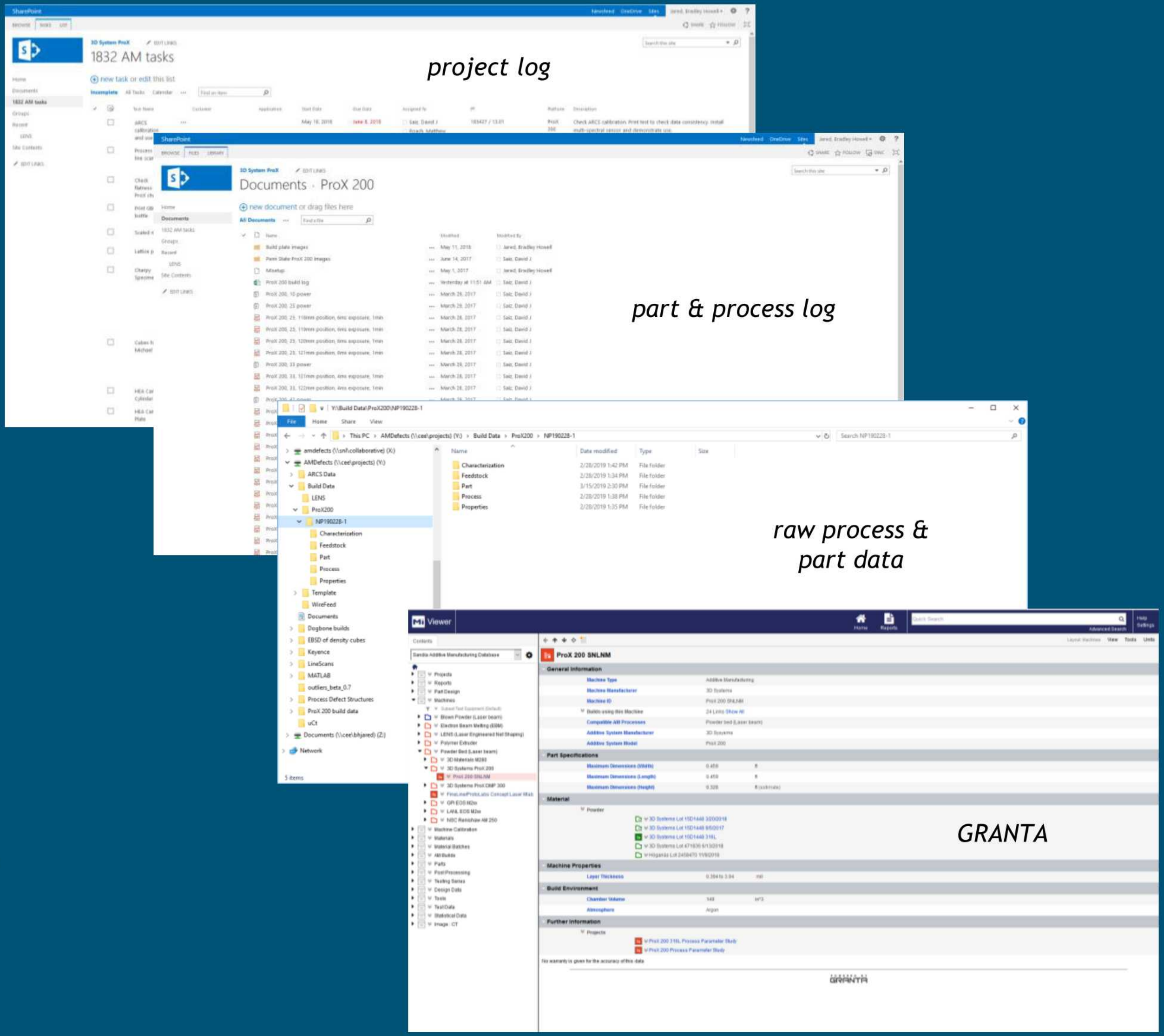
Data Management

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

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

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

GRANTA
- feedstock, machine, process, material data

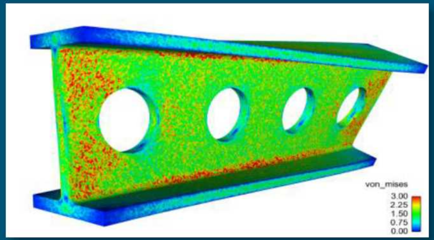


Bradley Jared, Shaun Whetten, Jon Madison, Rick Karnesky

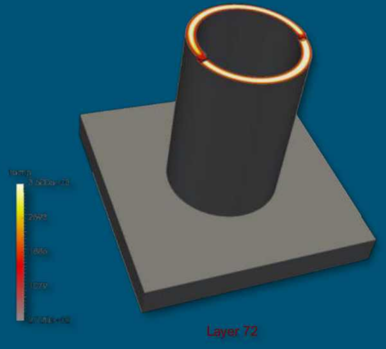
Qualification Tomorrow: Born Qualified

"Changing the Engineering Design & Qualification Paradigm"

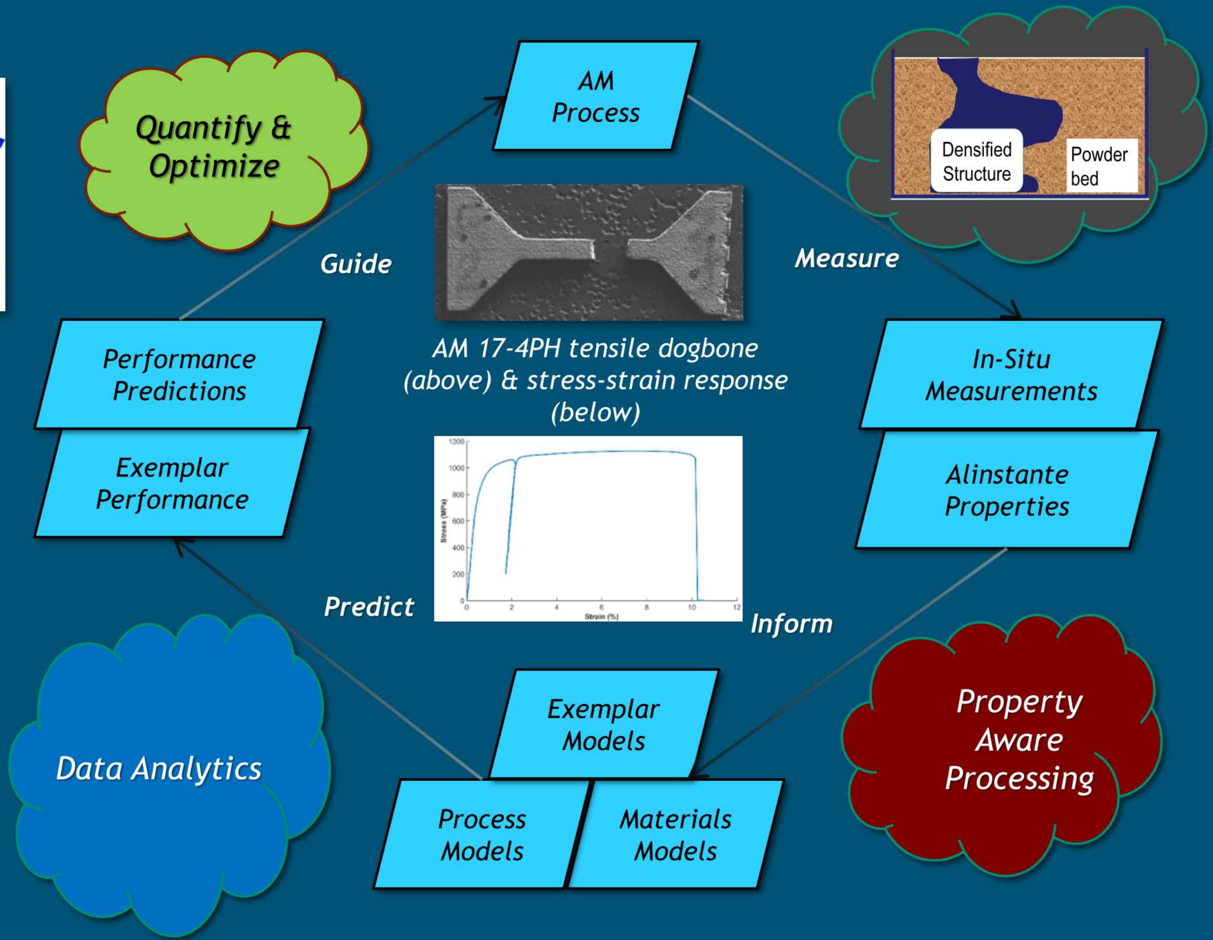
- leverage AM, in-process metrology & HPC to revolutionize product realization
- accelerating design to production



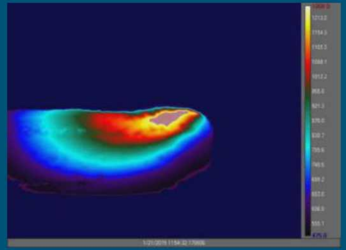
material / part performance simulation



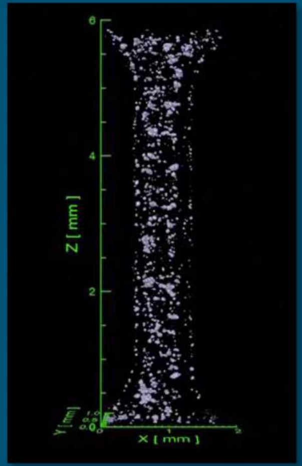
process simulation



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



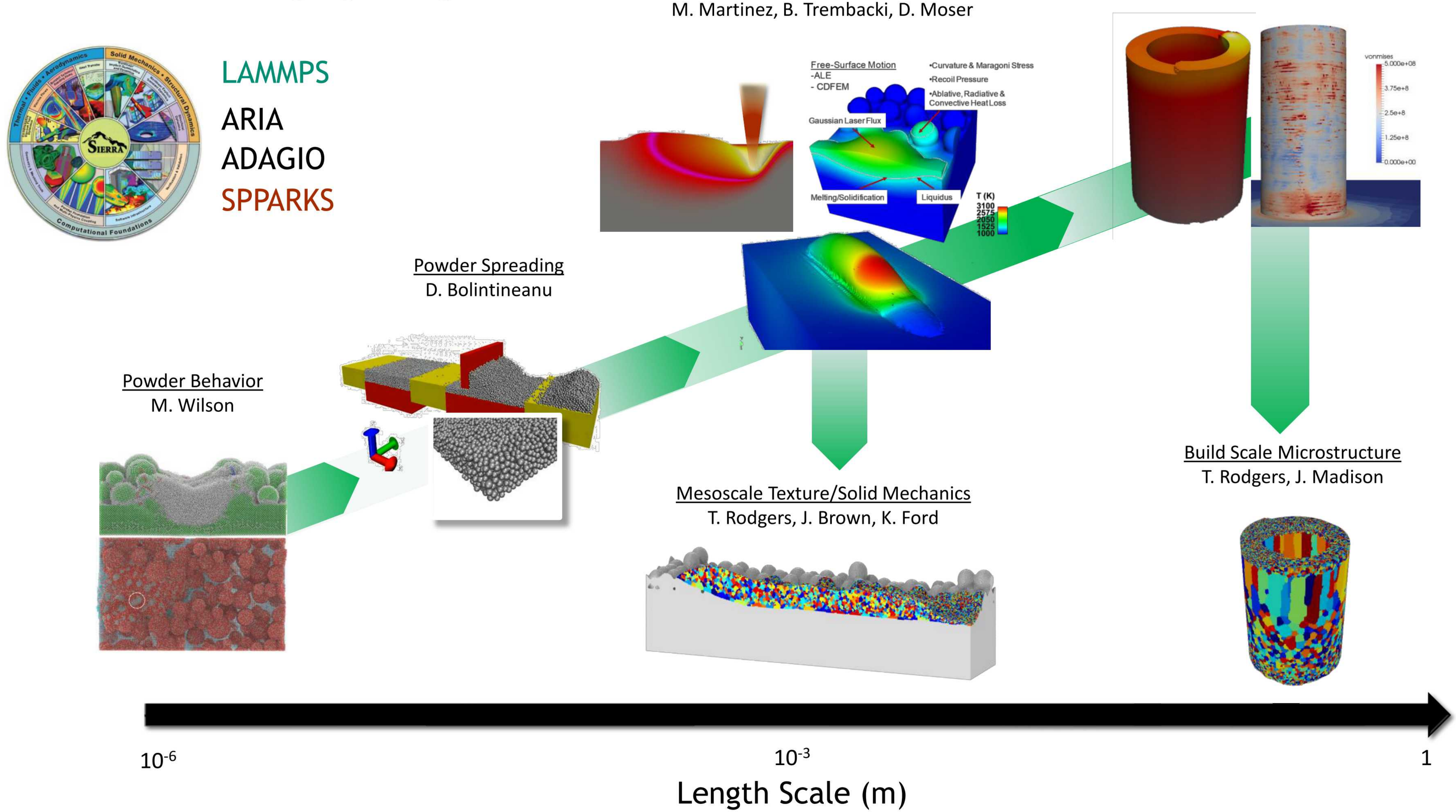
thermal history during bi-directional metal deposition



17-4PH dogbone porosity

Allen Roach

Models Bridging Length Scales



Questions?

Bradley Jared, PhD

Abstract

"Complexity is free" has been an oft-cited refrain during the recent renaissance of manufacturing, typically referencing additive manufacturing (AM). To be sure, however, advanced manufacturing techniques make complexity available as new materials, processes and part topologies are realized enabling performance gains inaccessible through traditional means. Such gains will be discussed in the context of laser-powder bed fusion (L-PBF). The development of physics-based engineered controls and automation methodologies are preferred to satisfy requirements by optimizing process performance, by minimizing output uncertainties, and by increasing product throughput.

Research on L-PBF will be presented to address these process complexities and performance uncertainties. Initial material behavior mimicked an open loop state as properties varied widely and proved difficult to anticipate. Work has since quantified important process-structure-property relationships for powder feedstocks, laser settings and machine components. Machine improvements and metrology procedures have also been developed, producing an increase in process consistency and material confidence. Continued research is examining in-situ melt pool dynamics and exploring advanced data analytic techniques (ex. machine learning) to correlate melt pool outliers to process defects.