SAND2020-3586PE

Addressing Complexity in Advanced Manufacturing

PRESENTED BY

Bradley Jared, Materials Engineering & Manufacturing S&T

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Outline

Background

Complexity is available
- machining
- additive manufacturing

But, complexity isn’t free
- uncertainties
- process-structure-properties
- metrology
- process monitoring & control

Teaching

Sandia National Laboratories

A National Security Science & Engineering Laboratory

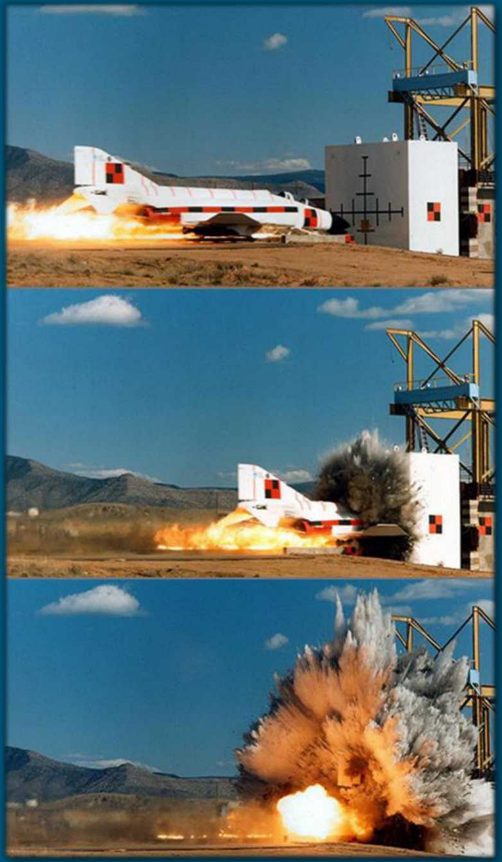
- "Exceptional service in the national interest"

Nuclear Weapons

Defense Systems & Assessments

Energy & Climate

International, Homeland, & Nuclear Security

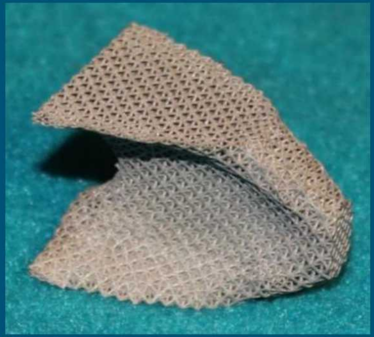


Complexity is Available

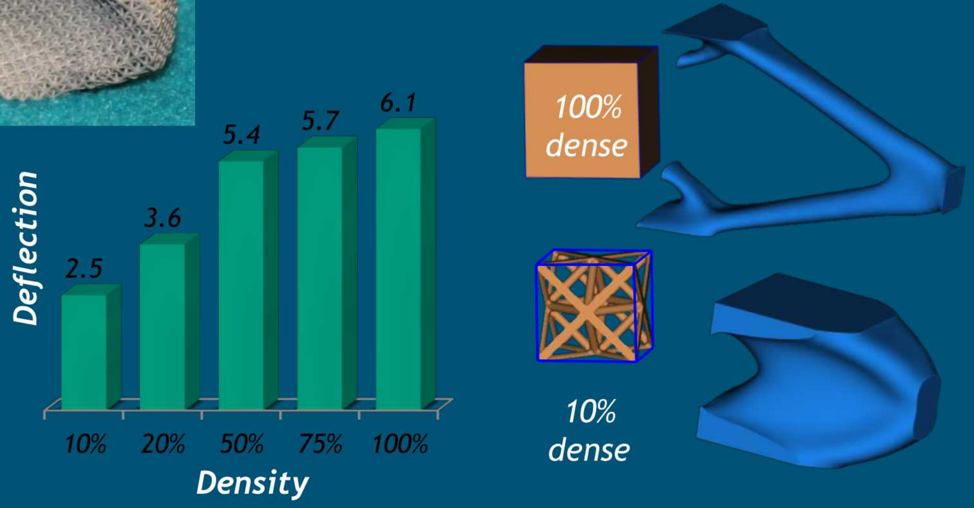
Advanced manufacturing provides ever expanding design freedom & value
- complex freeforms, internal structures, integration

Geometry

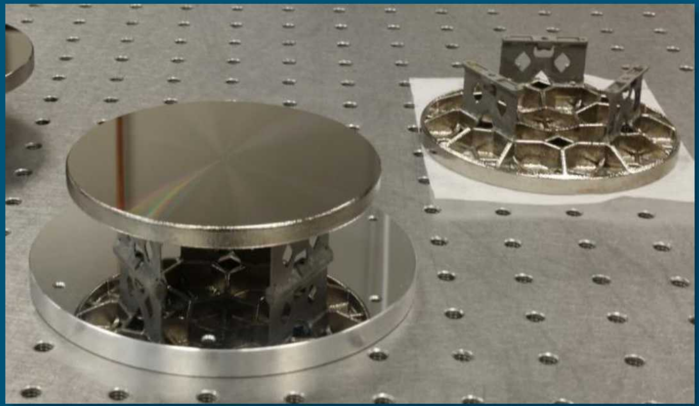
Engineered materials
- gradients & microstructure
- multi-material integration
  - "print everything inside the box, not just the box"



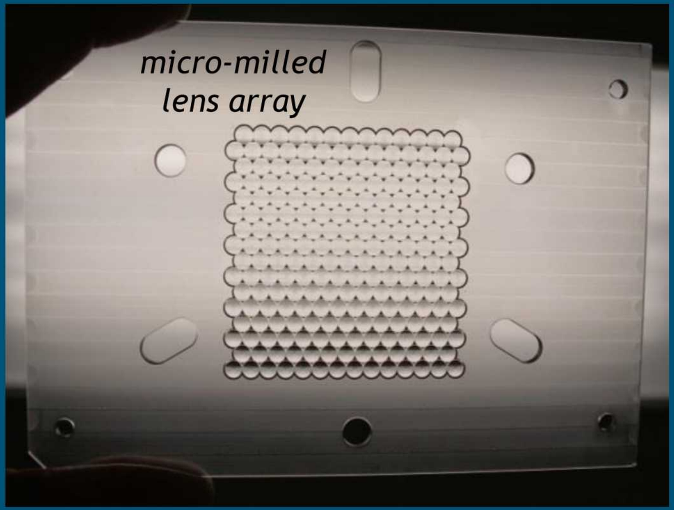
*Jared, B., **Scripta Materialia**, 2017*

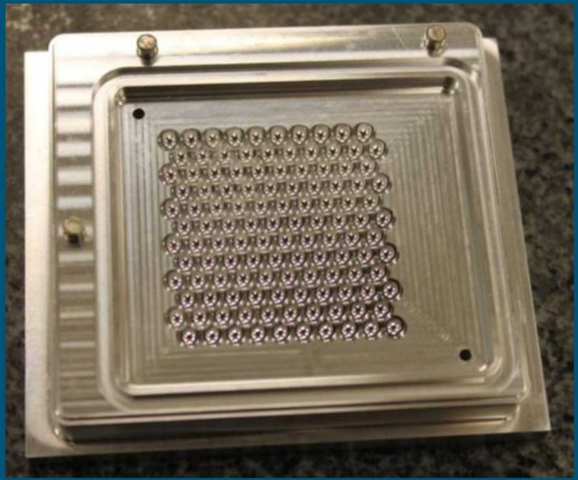


Mitchell structure optimizing stiffness w/mixed mass using PLATO
*Robbins, **Add Mfg**, 2016*



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

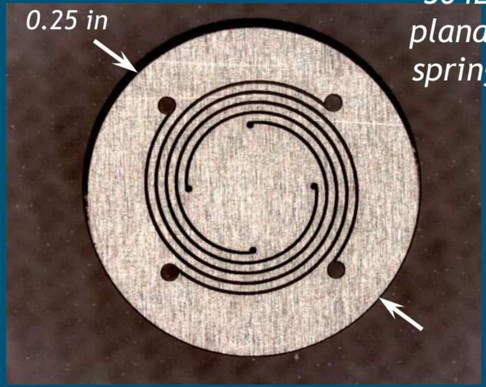


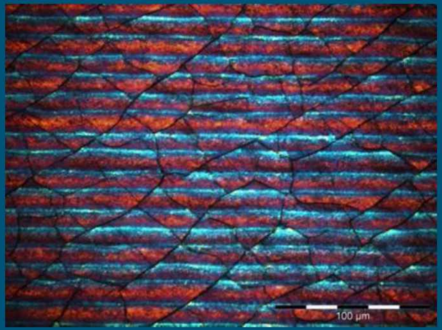


lens mold for casting micro-optic arrays

Ultra-Fast Pulsed Laser Processing

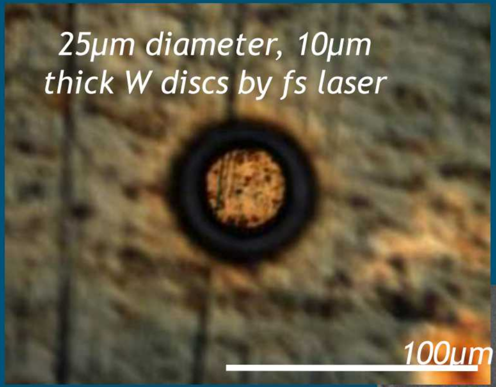
Jared, **Int Con Micro Mfg**, 2012



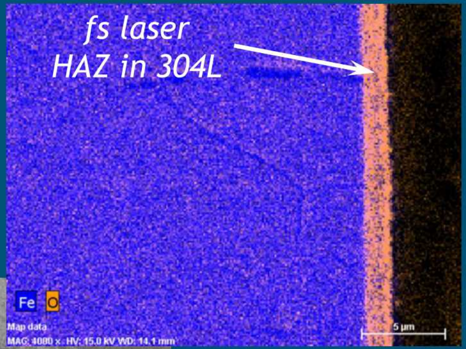


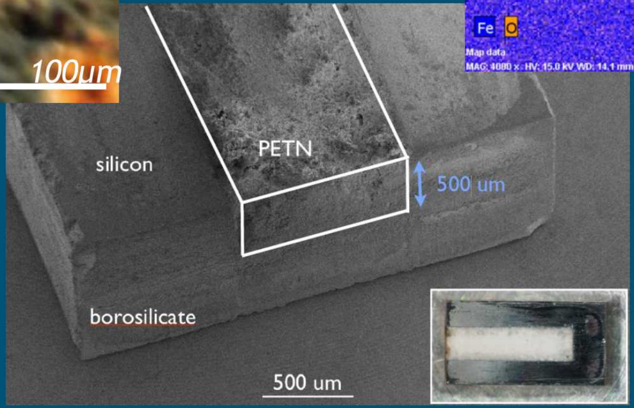
ns titanium oxides
Adams, **Surf & Coat Tech**, 2014

surface modifications

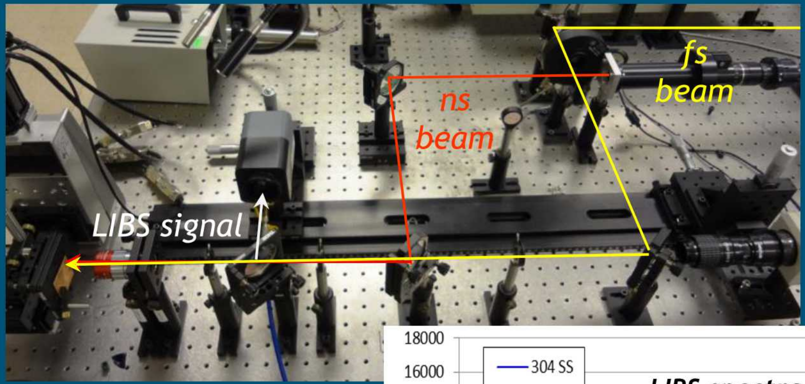


meso scale features



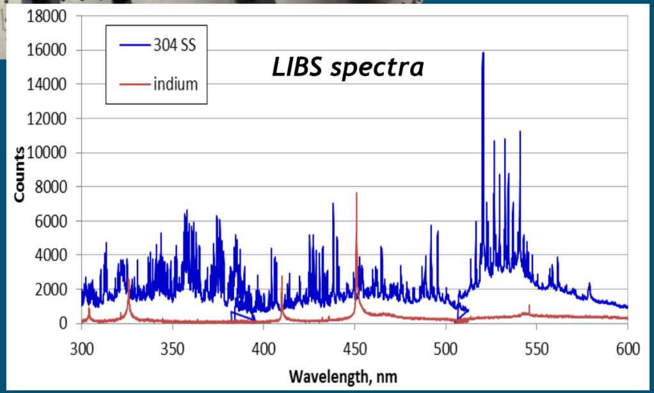


R. Wixom, **Int Pyro Sem & Symp**, 2008.



Jared, **SAND2012-8653**

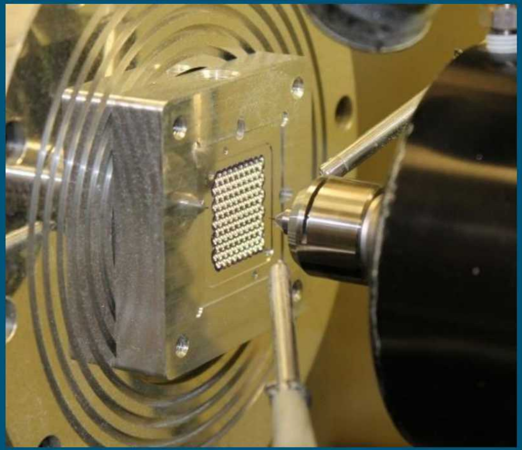
laser induced breakdown spectroscopy (LIBS)



Precision Machining

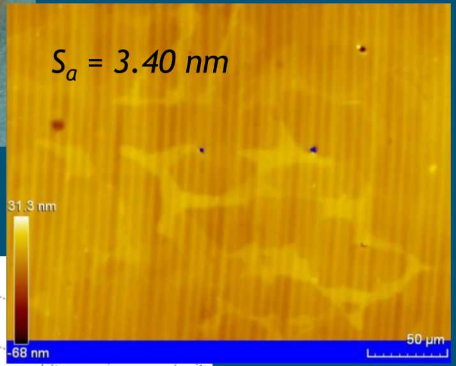
Yasda YMC-430 micro milling

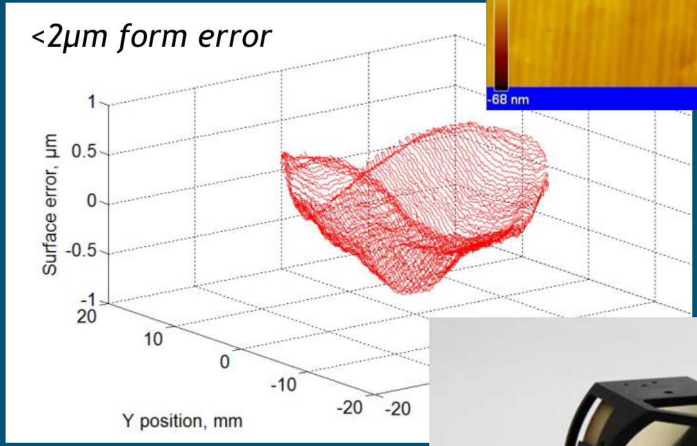
Moore 350FG diamond turning



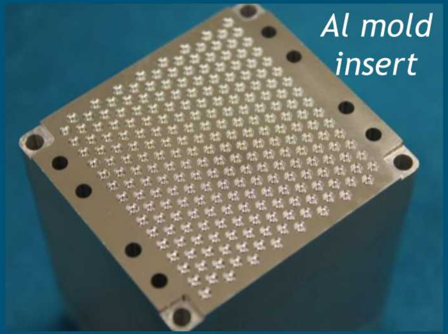
diamond milling Al mold

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

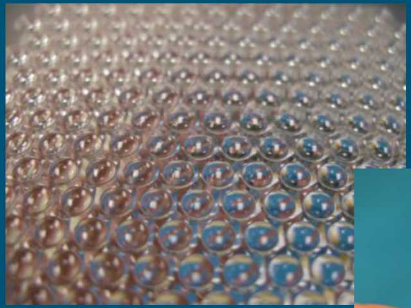




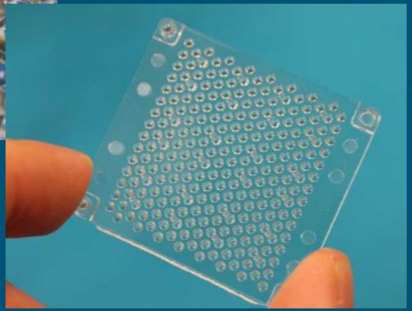
four element monocular telescope



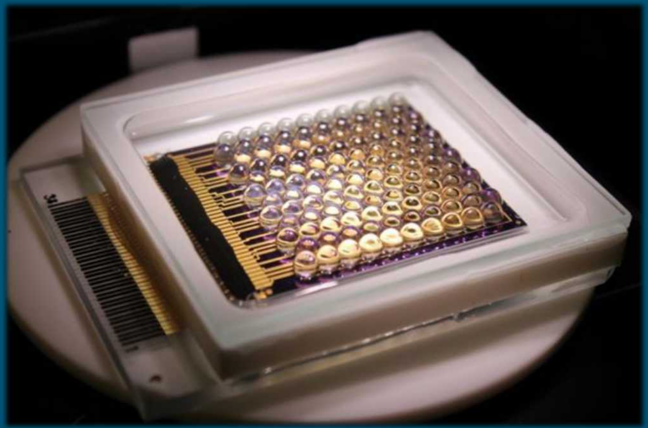
Al mold insert



machined optic array

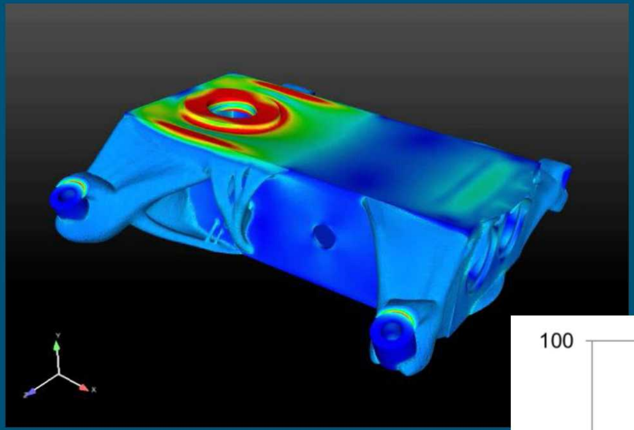


molded optic array

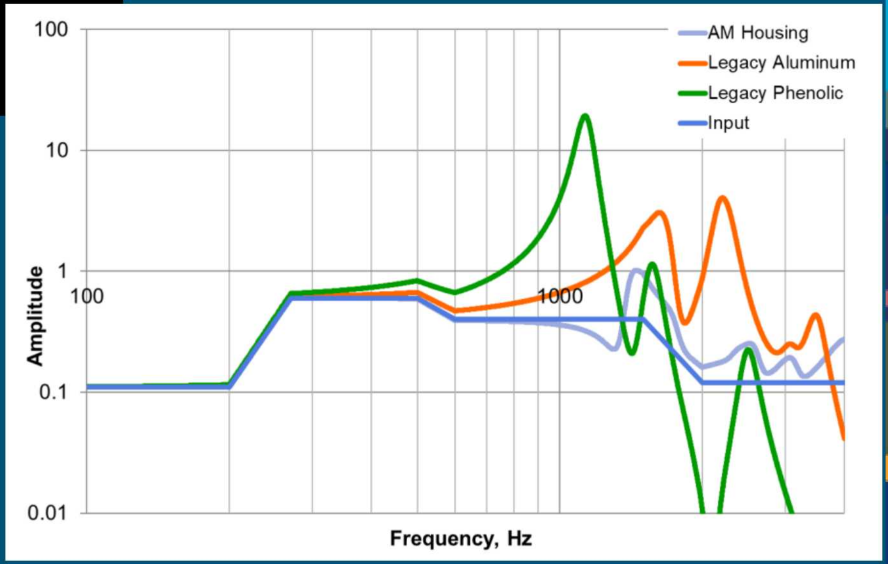


microsystems-enabled photovoltaics (MEPV) module
*Jared, **Opt Exp**, 2014*

Topology Optimization



TO housing significantly reduces vibration amplitudes



Computational synthesis for optimal material use

- design & optimize for performance, not mfg
- design concurrent w/simulation

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

316L SS HOT SHOT top cap on plate

Photo by Mike Bejarano and Mark Olona, Sandia Lab News

integrating TO w/process models

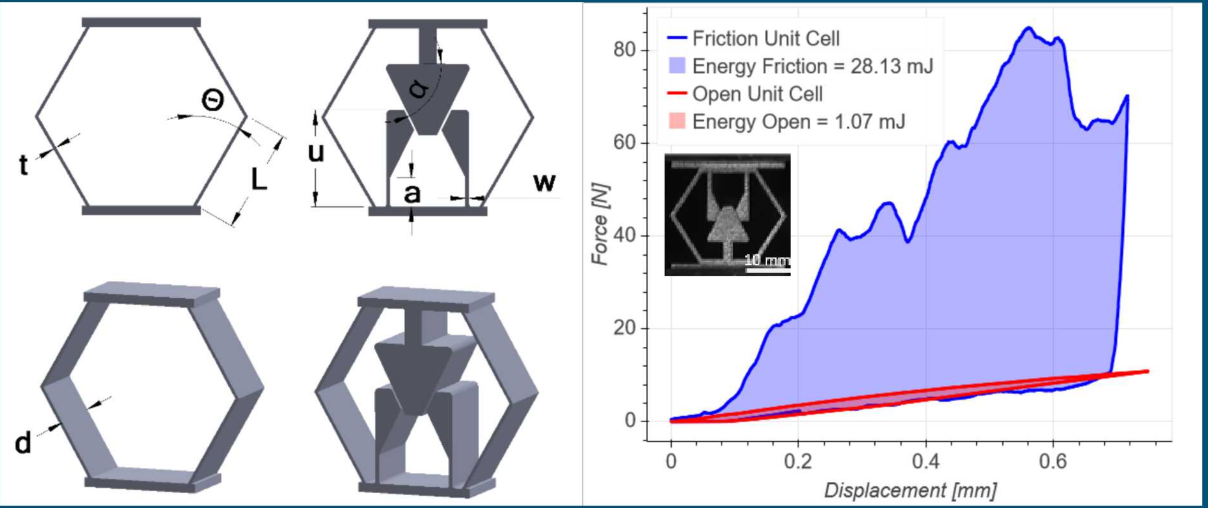
Hierarchical Materials

Compelling design space

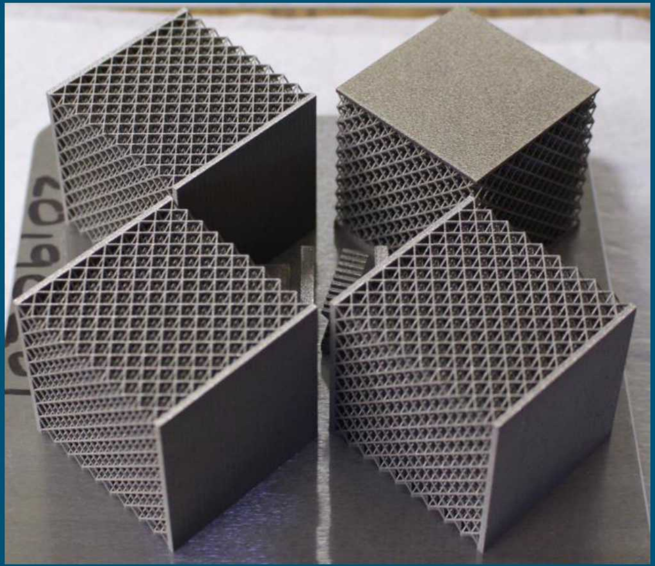
- enables performance regimes inaccessible in homogenous materials
- blurs material & structure boundaries

Current efforts focused on dynamic impacts

- simulation, optimization, inspection & qualification

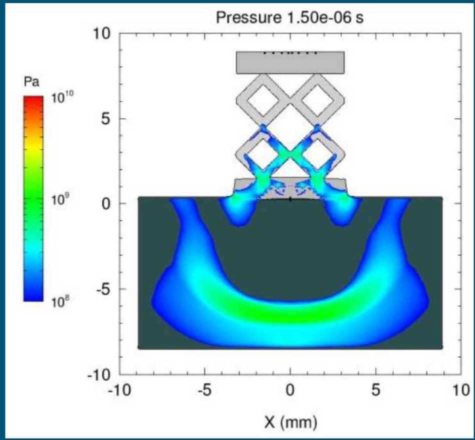


Garland, in process

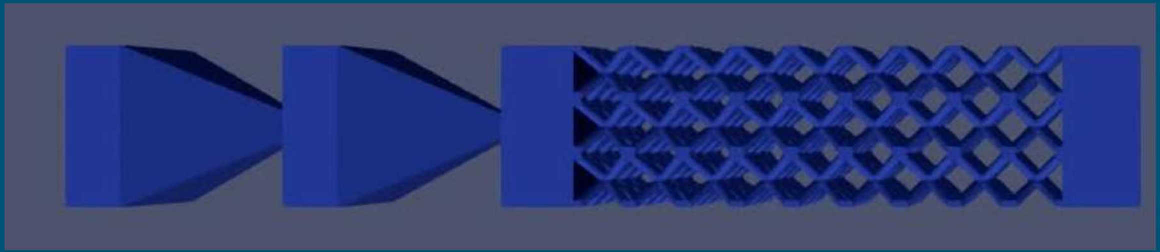


9x9x9 octet samples

316L SS test structure for LANL gas gun shot



CTH simulation of 250m/s lattice impact



dynamic impact, 16.3% dense BCC lattice

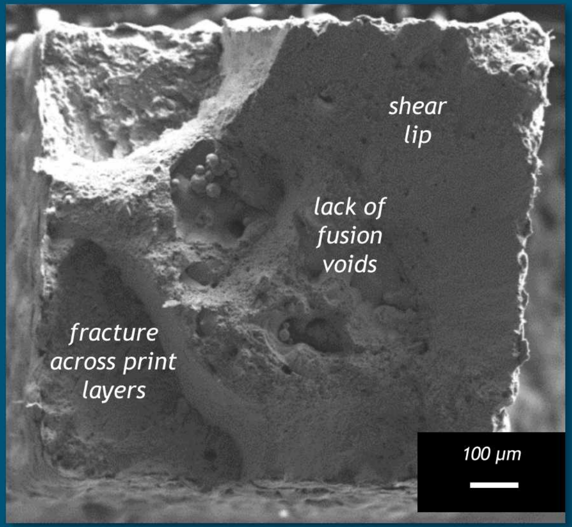
But, Complexity Isn't Free

Features tied to requirements incur costs

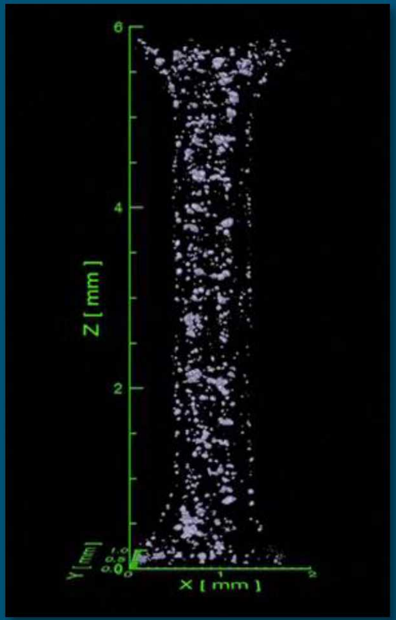
AM material formation concurrent w/geometry
- want to predict part/material performance
- **<u>how to ID a bad part?</u>**
  - significant design margins and/or rigorous post-process inspection / validation

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

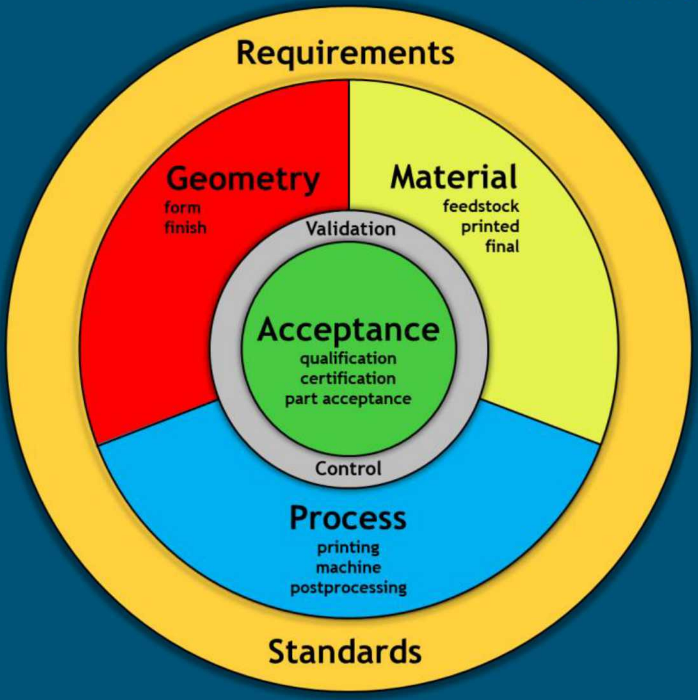
Quantify <u>critical</u> material defects & <u>useful</u> signatures
- D-tests, NDE, process monitoring, mod-sim



17-4PH dogbone fracture surface



17-4PH dogbone porosity



elements of qualification
Jared, <u>Sci Tech and Appl of Metals in AM</u>, 2019

Lack of Process Control Produced Material Uncertainty in Early AM Metals

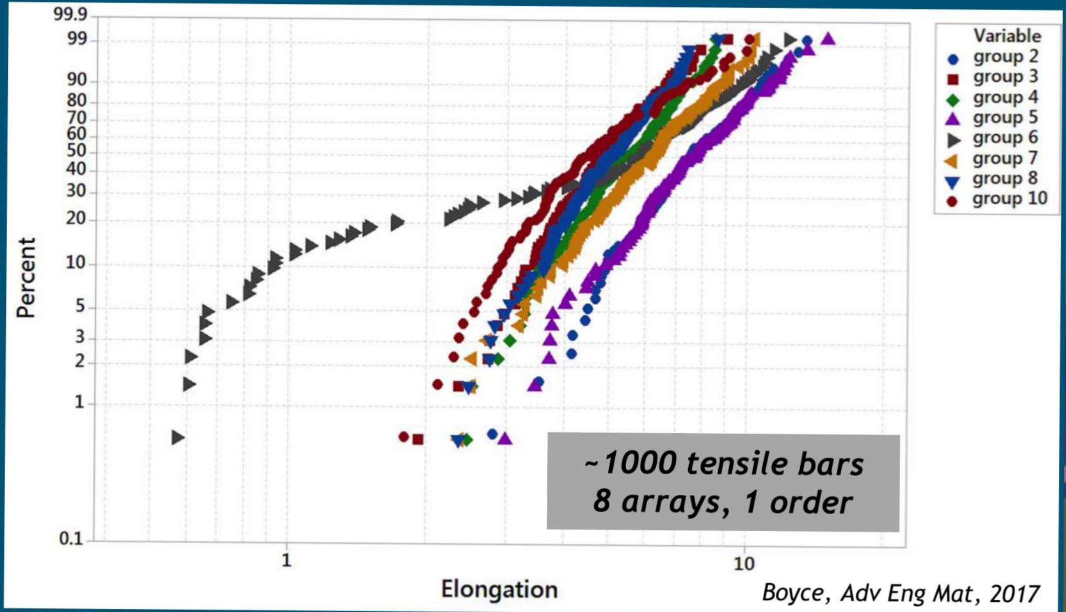
17-4PH parts from external vendor

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

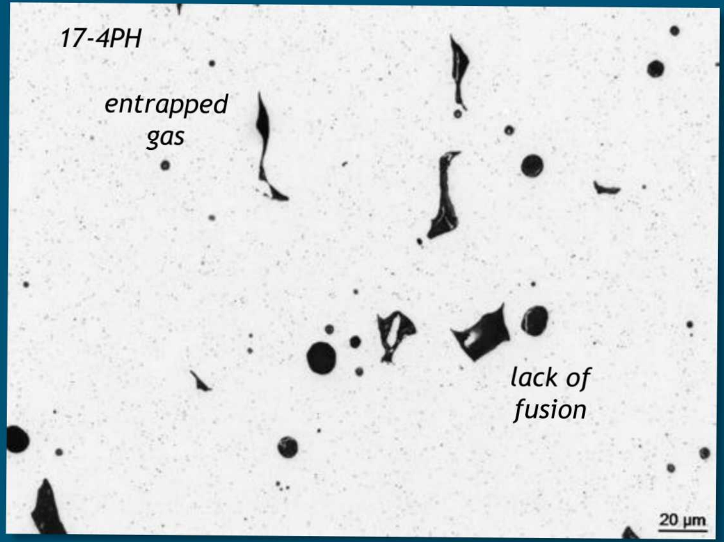
Sandia did not know

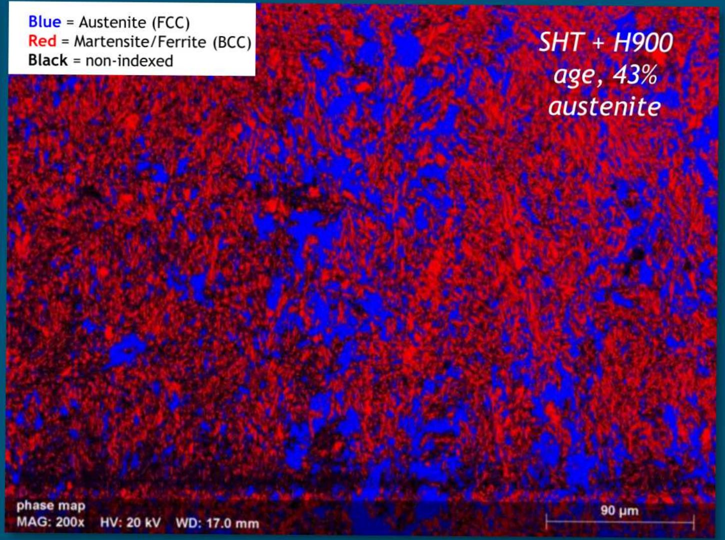
- feedstock pedigree, machine, build environment, process inputs or post-processing steps

Not-surprisingly, extensive material variability observed

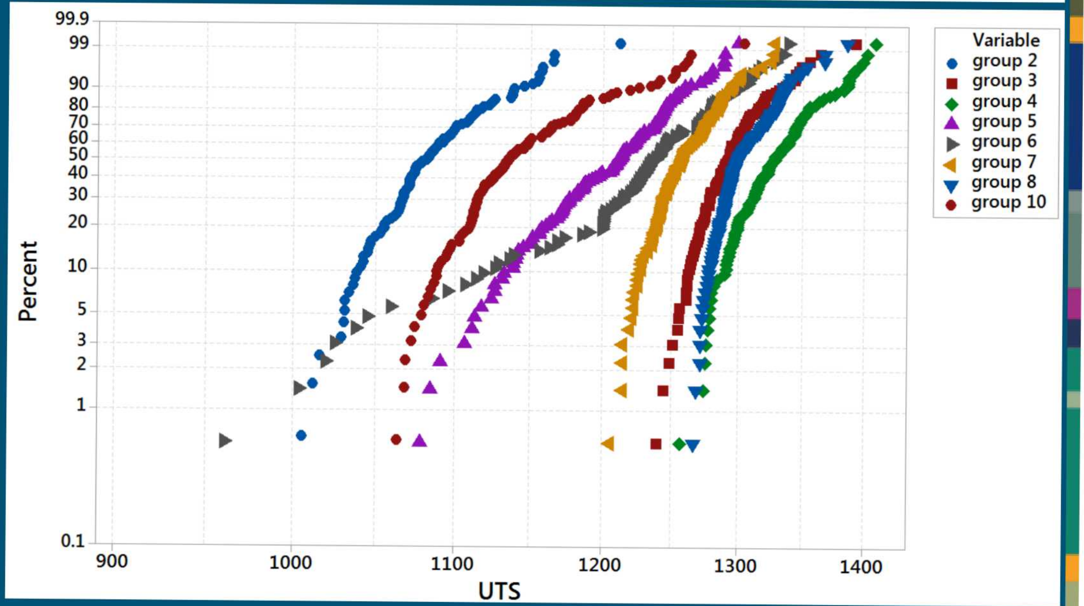


Boyce, *Adv Eng Mat*, 2017





Jared, ***SAND2017-13190***



Boyce, *Adv Eng Mat*, 2017

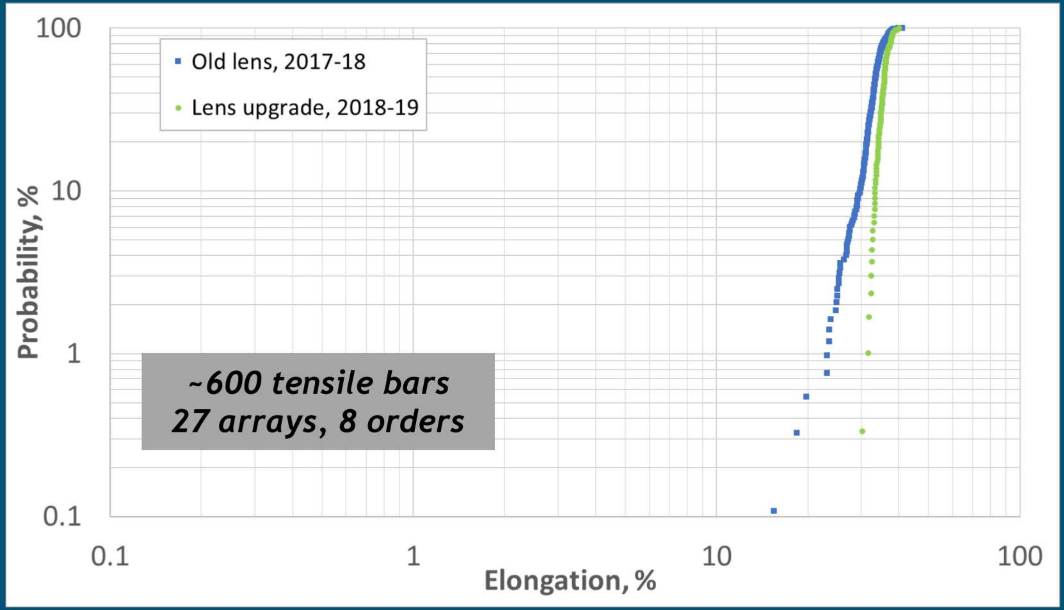
Process Understanding & Control Reduced Material Uncertainties

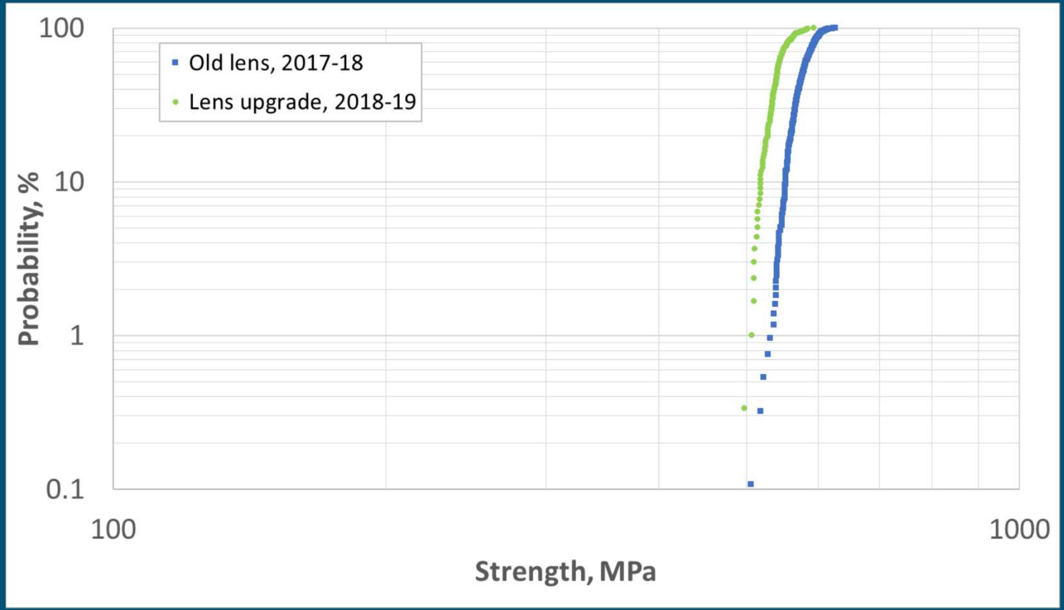
Controlling & logging part, build & powder cycles
- 316L stainless steel
- feedstock pedigree, build environment, process inputs, post-processing, meta data
- print / test artifacts

Heuristic dependent
- restrictive
- time consuming
- expensive

Desire accelerated cycles
- tolerances & uncertainties

build plate w/process artifacts

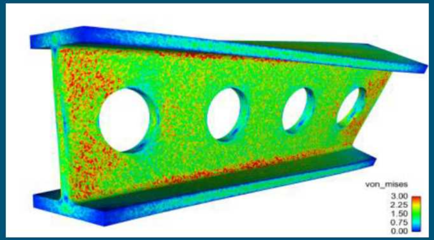




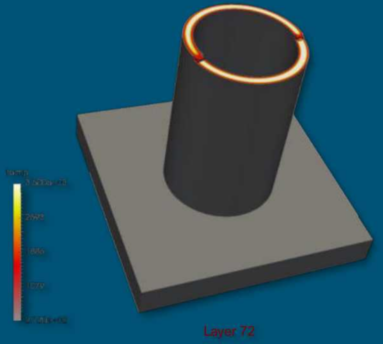
Qualification Tomorrow

"Changing the Engineering Design & Qualification Paradigm"

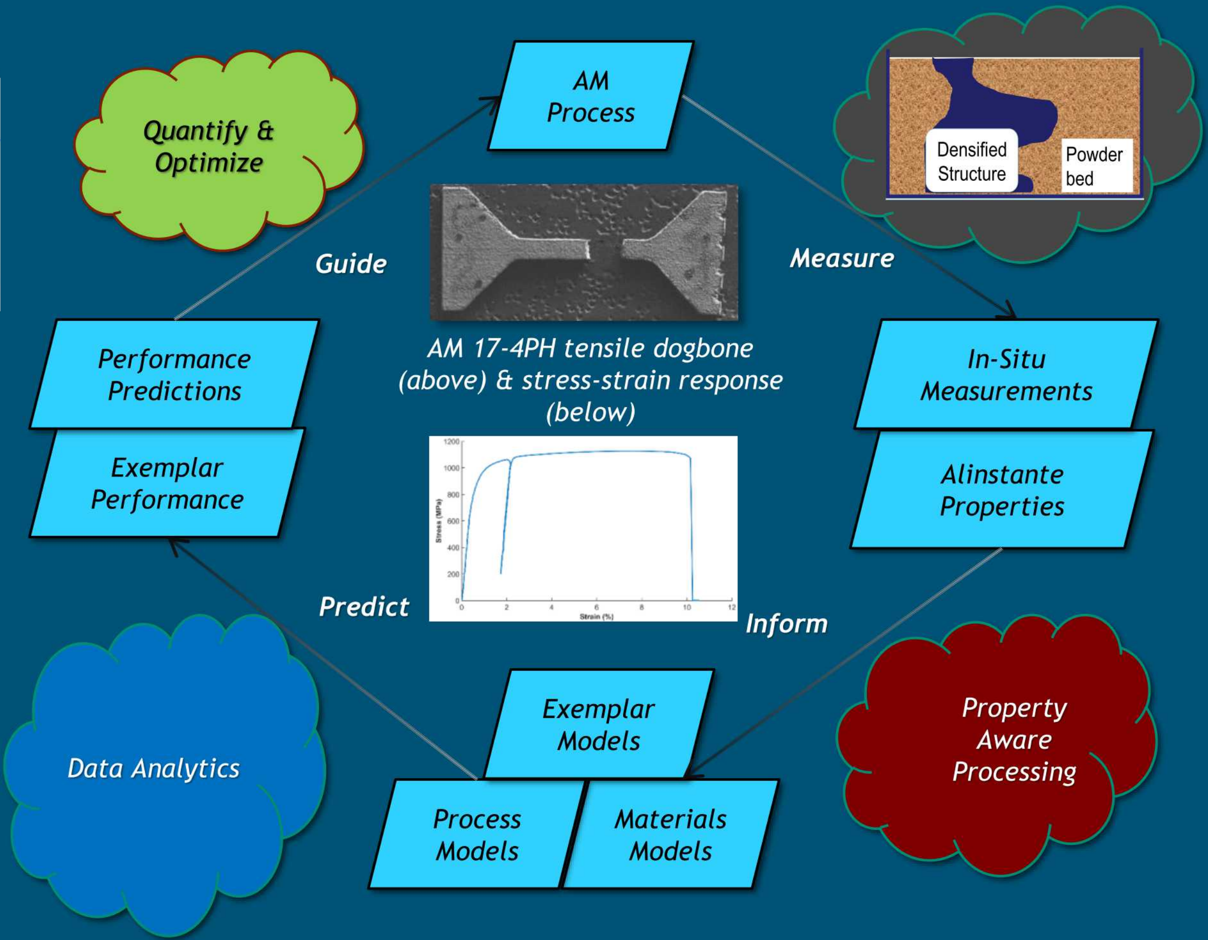
- leverage AM, in-process metrology & HPC to revolutionize product realization
- accelerating design to production

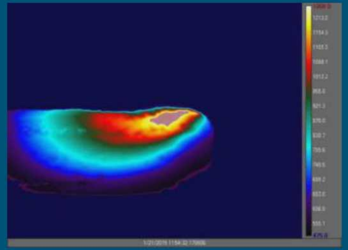


material / part performance simulation

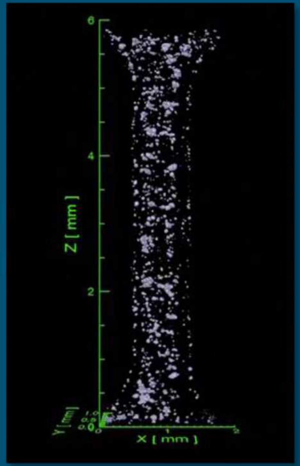


process simulation





thermal history during bi-directional metal deposition



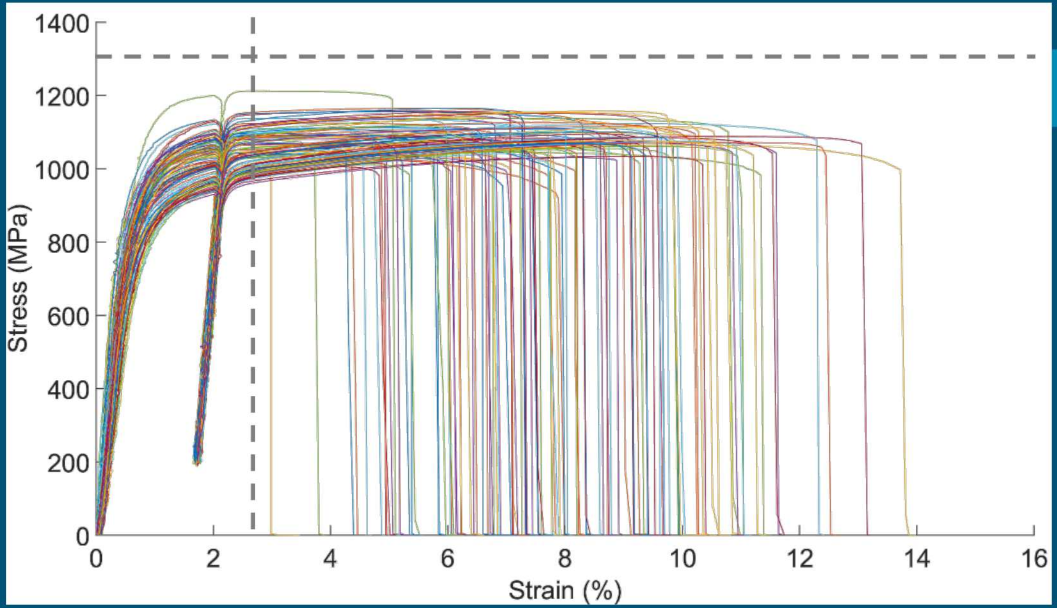
17-4PH dogbone porosity

Stochastic Response of AM Metals

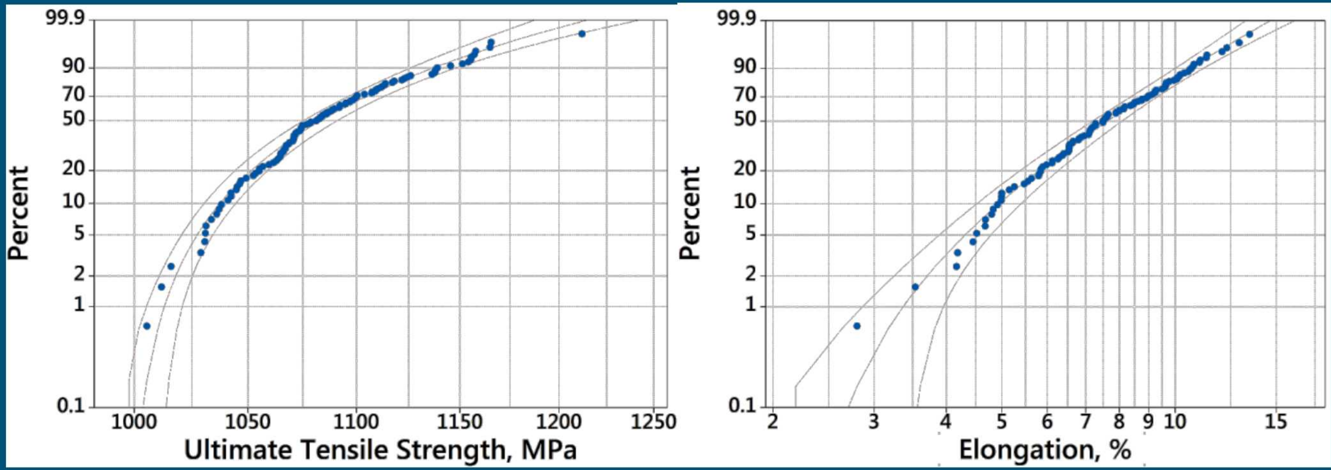
Defect dominated failure

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

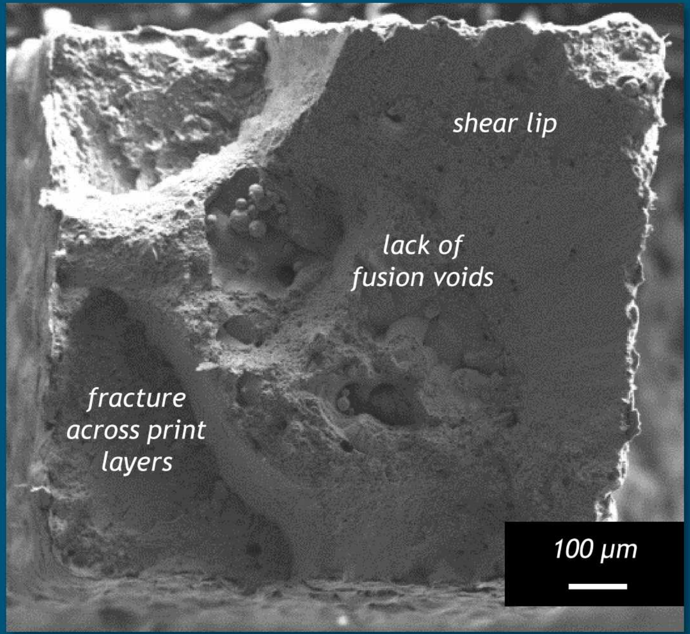
How to capture efficiently & accurately?



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



material performance fit to 3-parameter Weibull distributions

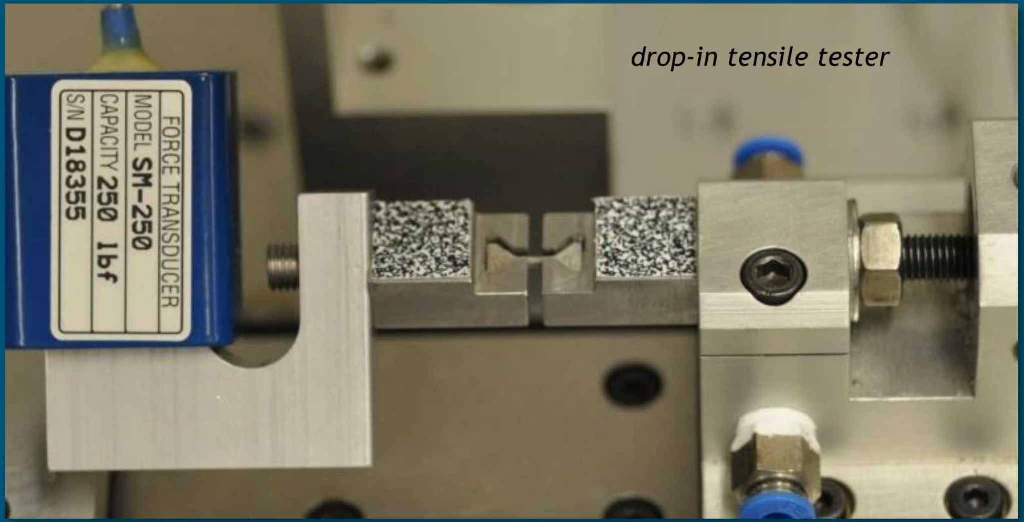


failure at 2% elongation, SHT+H900

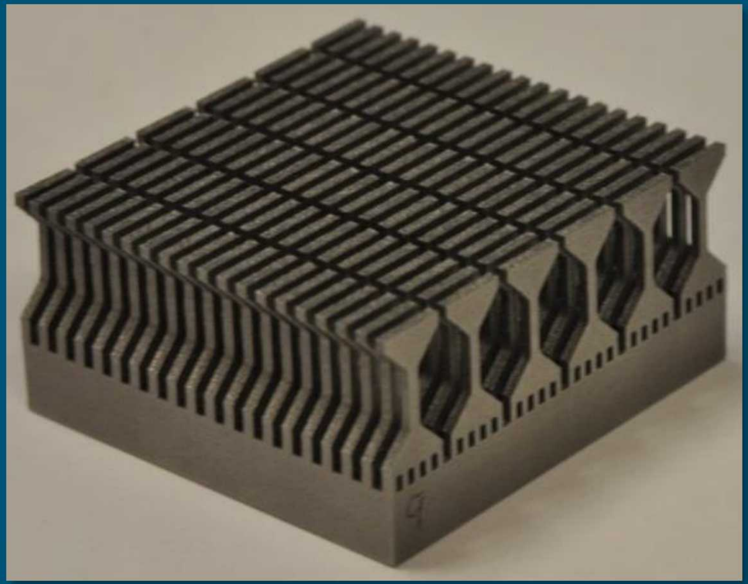
AMS spec for H900: modulus = 197 MPa, yield = 1172 MPa, UTS = 1310 MPa, strain at failure = 5%

High Throughput Tensile Testing (Gen 1)

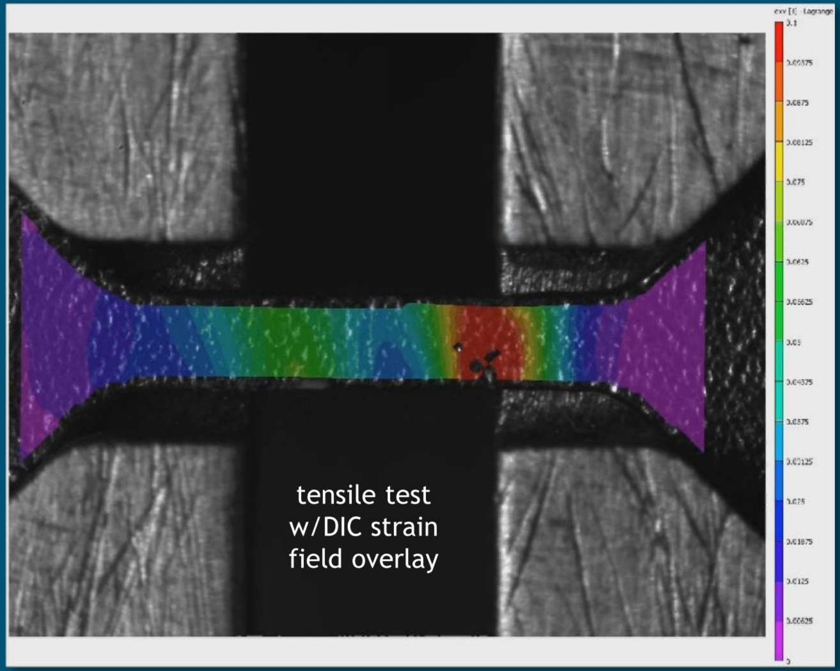
- Monolithic build w/110 dogbones
  - custom design per ASTM
- Digital image correlation (DIC)
- Necessary to rapidly capture material distributions
  - applicable for the lab & production



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



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



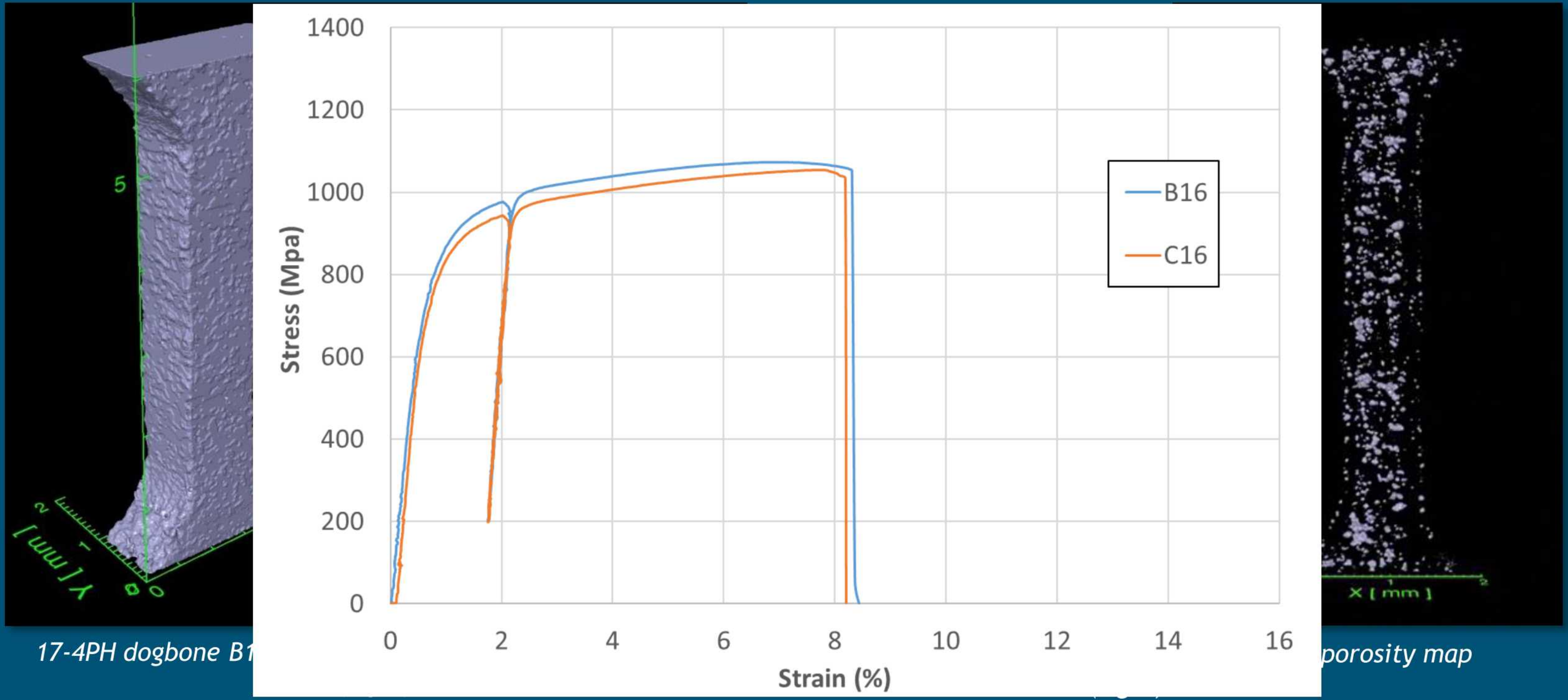
Tying Structure (Porosity) to Properties

Extensive work using computed tomography (CT)

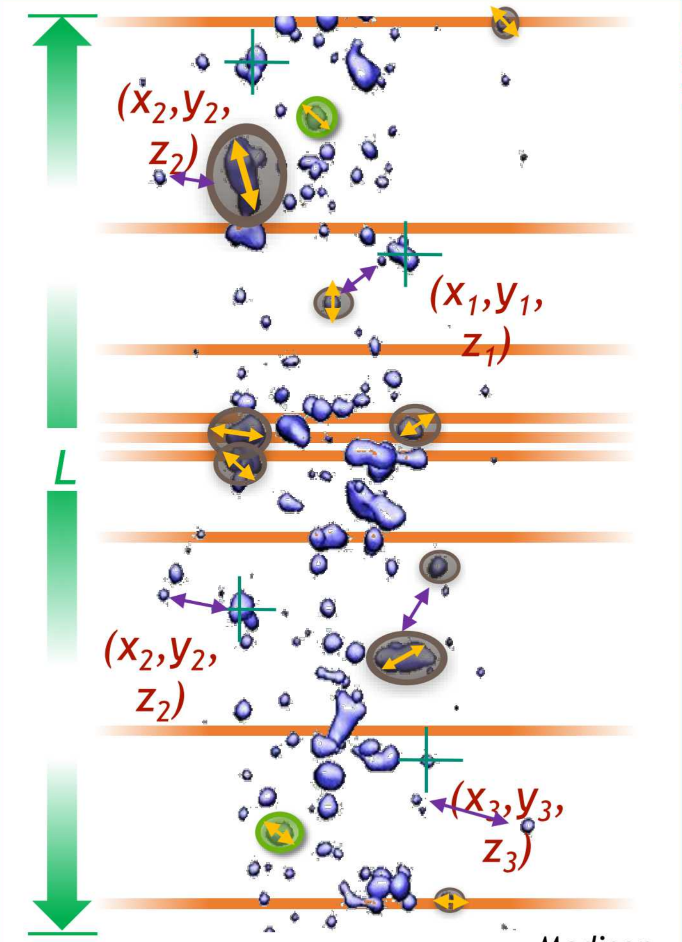
- multiple potential metrics exist
- correlations are immature

Prediction of uniformly dispersed porosity fields is difficult

- behavior falls within an expected performance distribution



17-4PH dogbone B1 … *porosity map*



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

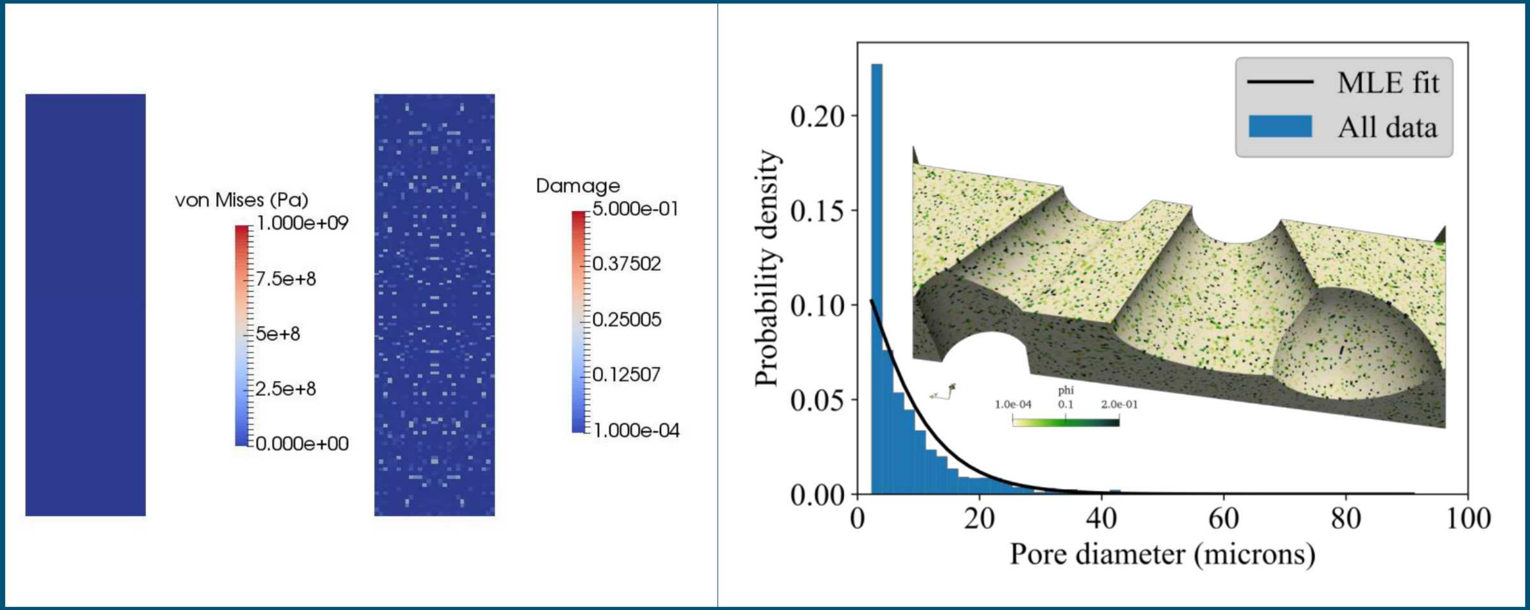
Failure initiates near large pores

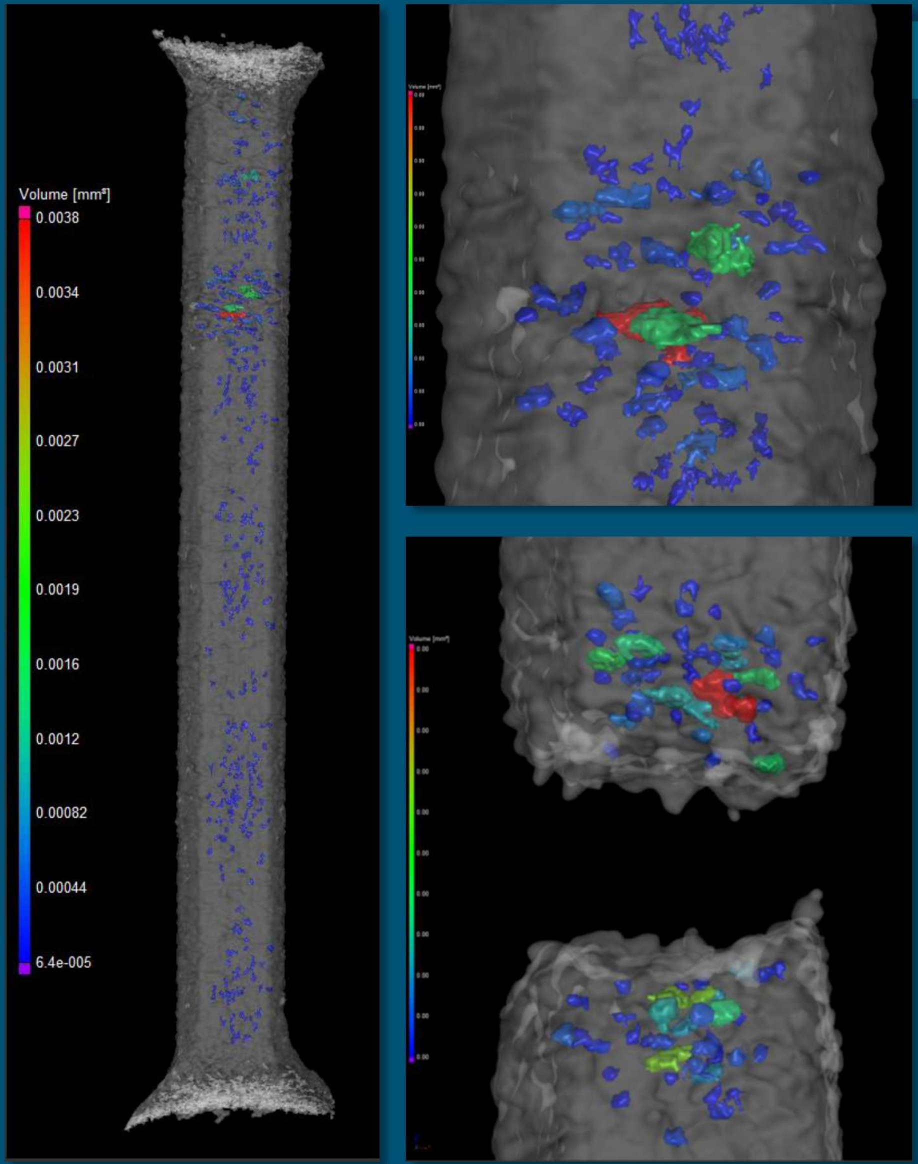
Potential tolerance bound
- design requirements
- CT inspection
- process monitoring

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)

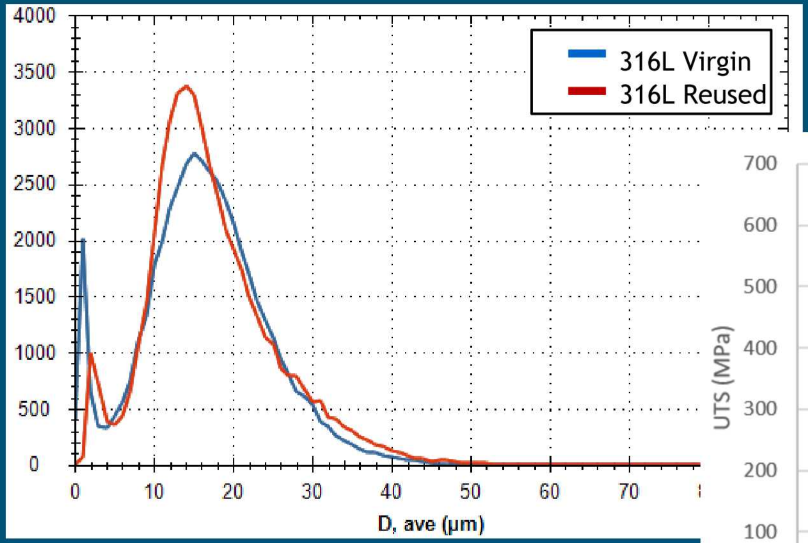
Monitoring Powder Reuse

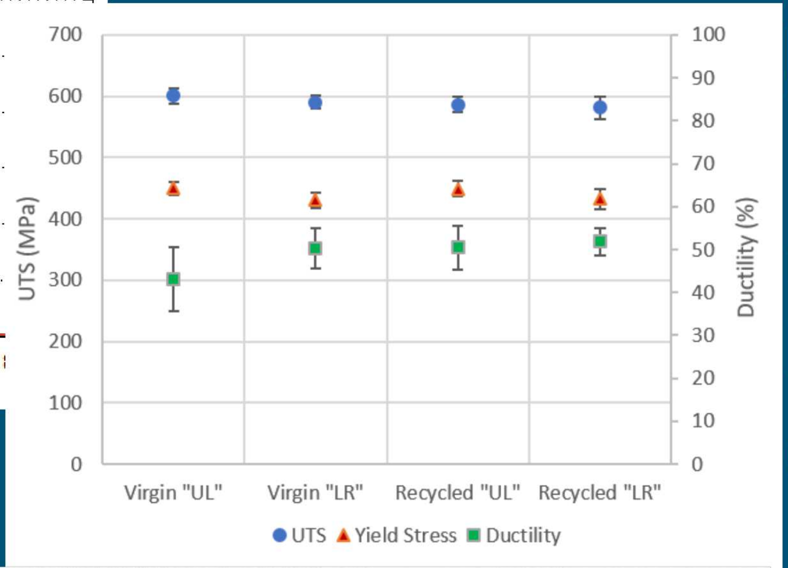
Tracking powder size, morphology & EDS composition w/reuse

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

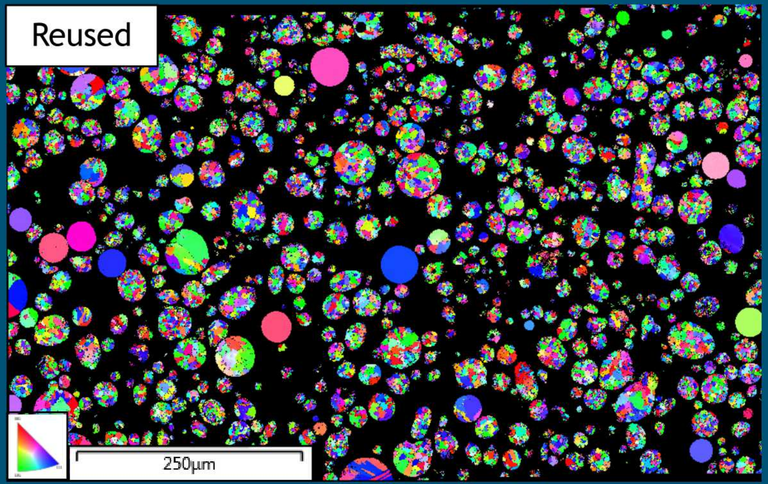
Material properties remain stable

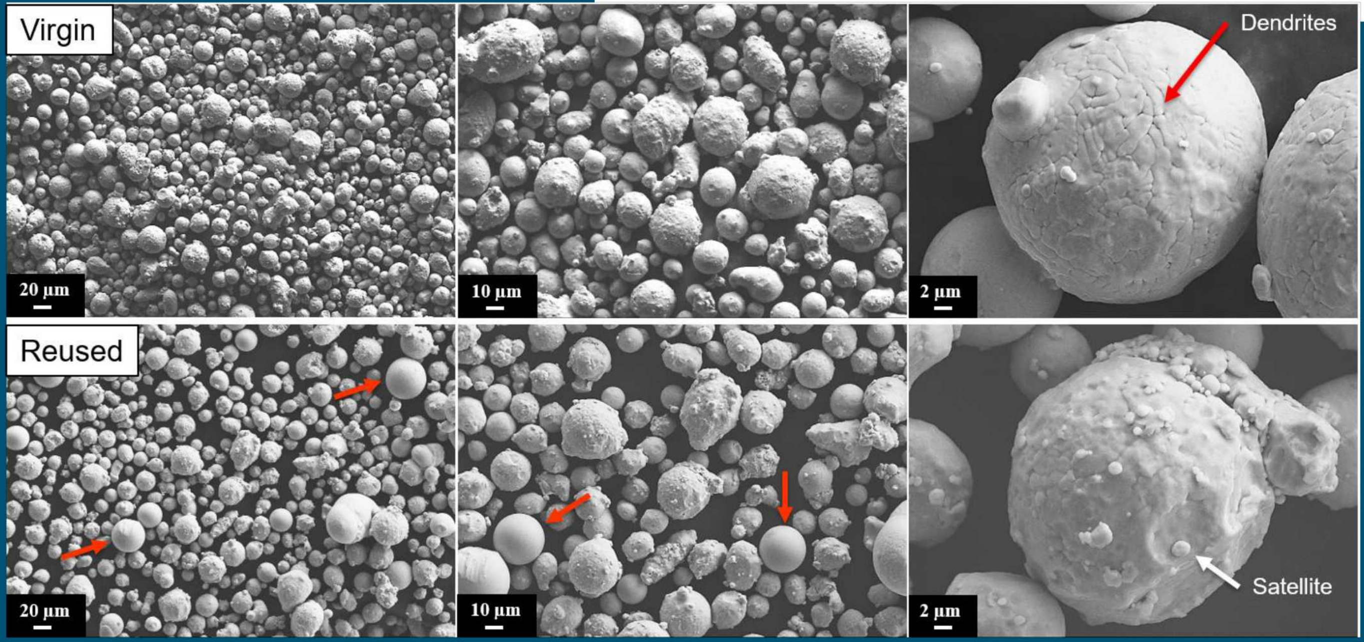
316L SS is a robust material for processing & properties





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

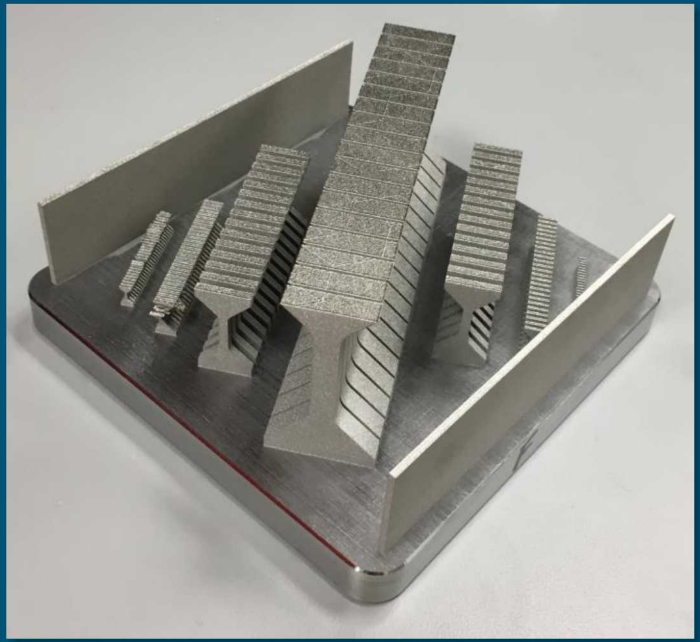




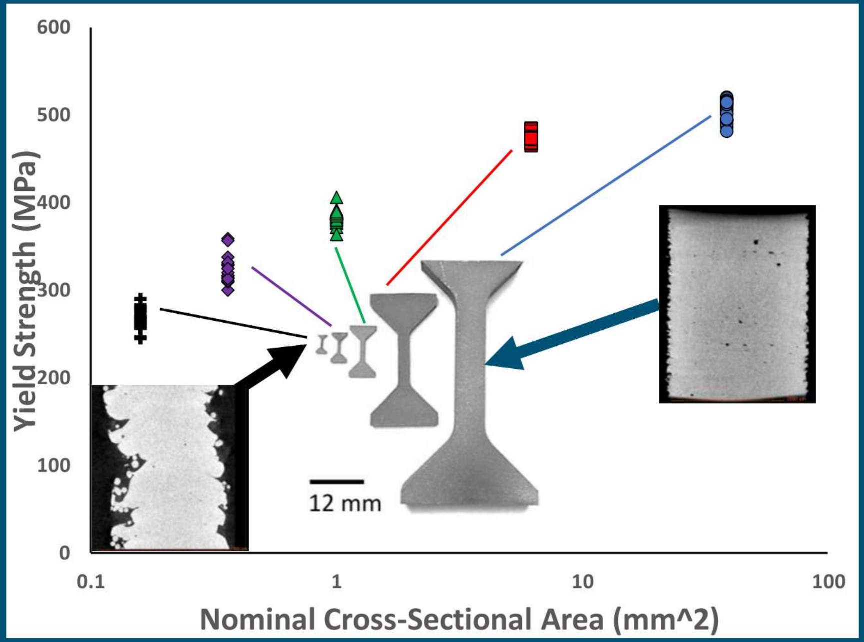
Heiden, Add. Mfg., 2019

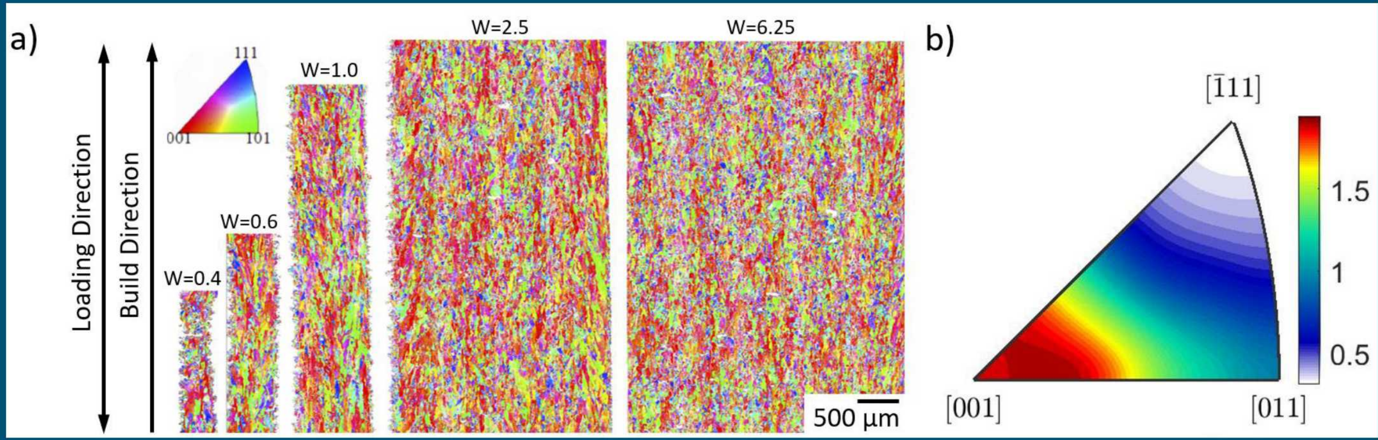
Size Effects

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

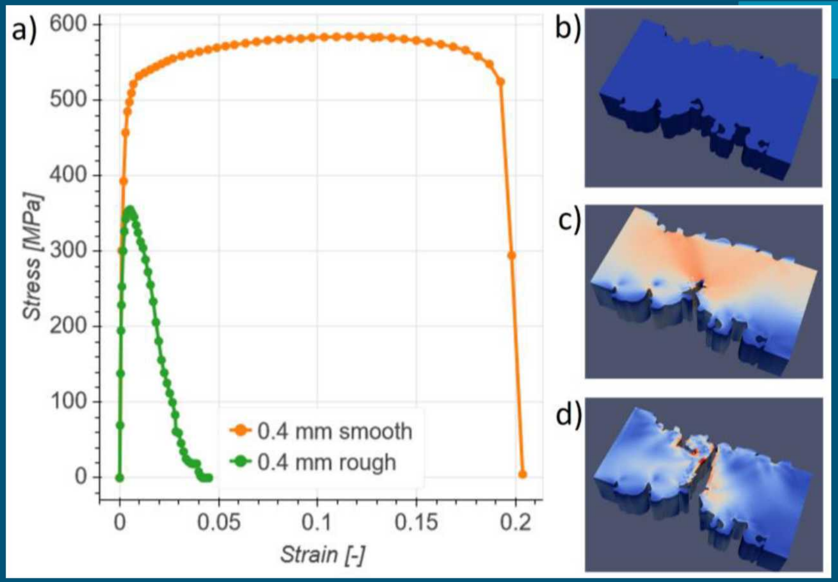


Prox 200 build plate w/tensile samples

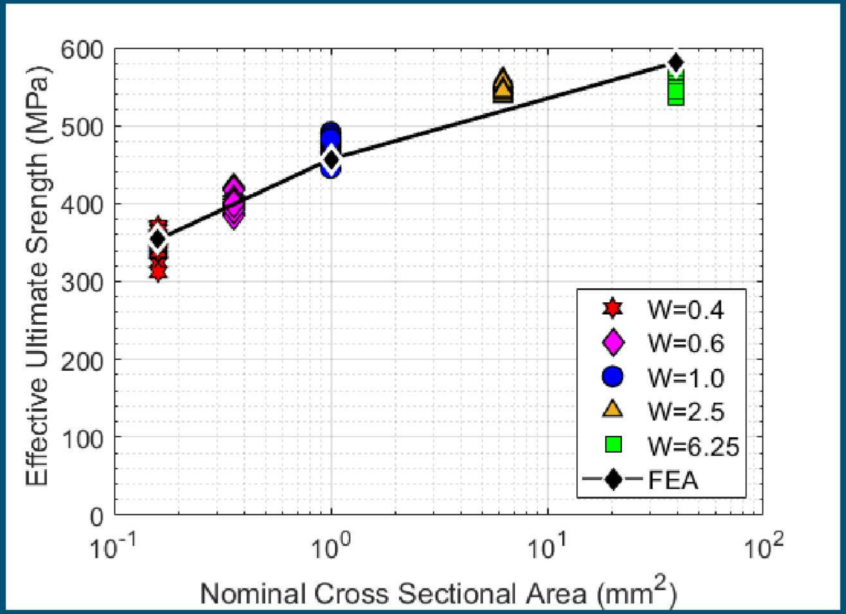




microstructure is invariant w/sample size



surface roughness dramatically reduces strength of features with similar size scale



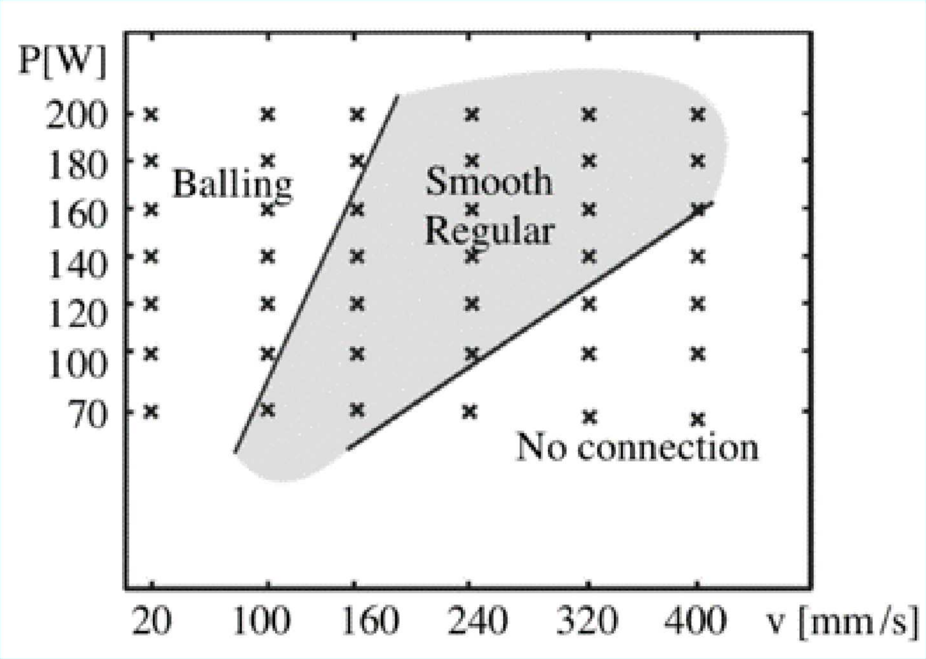
FEA model incorporating surface finish correlates well to experiments

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

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?



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

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

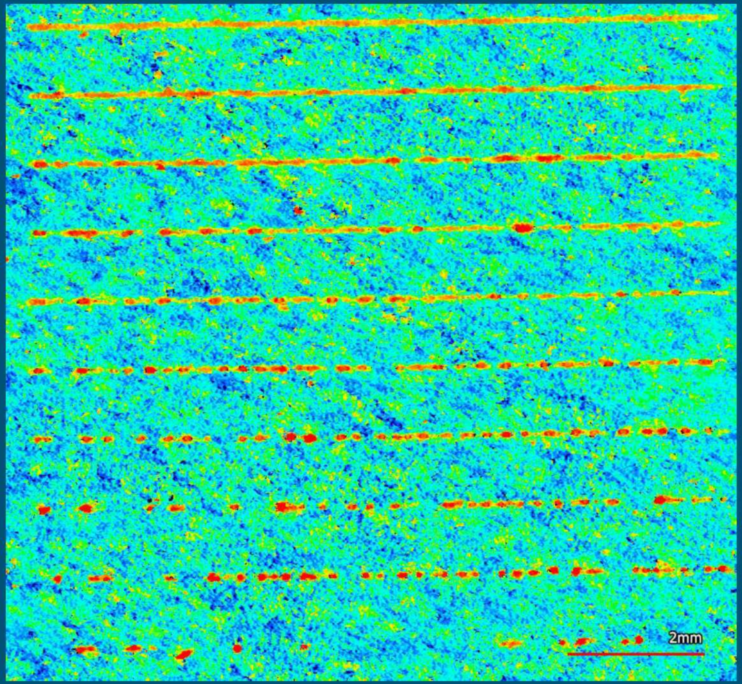
Line Scans

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

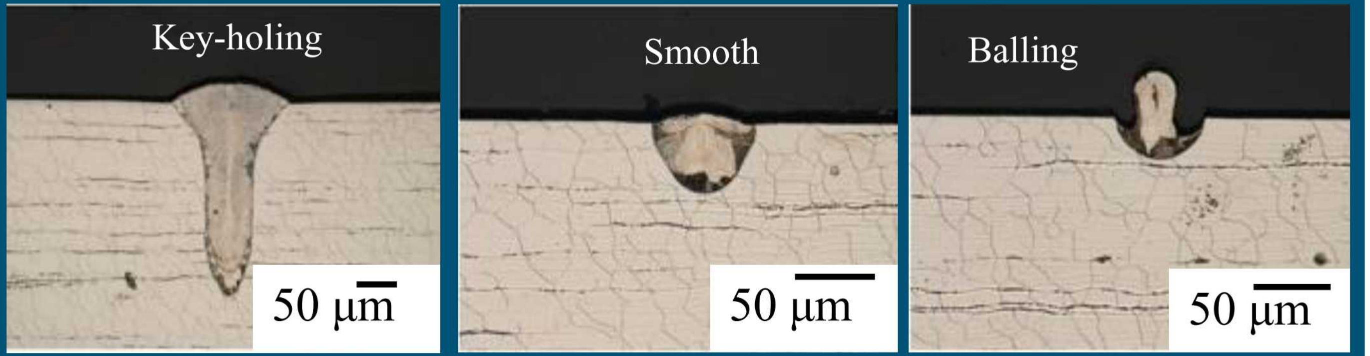


100 W, 250 to 2500 mm/s on pad

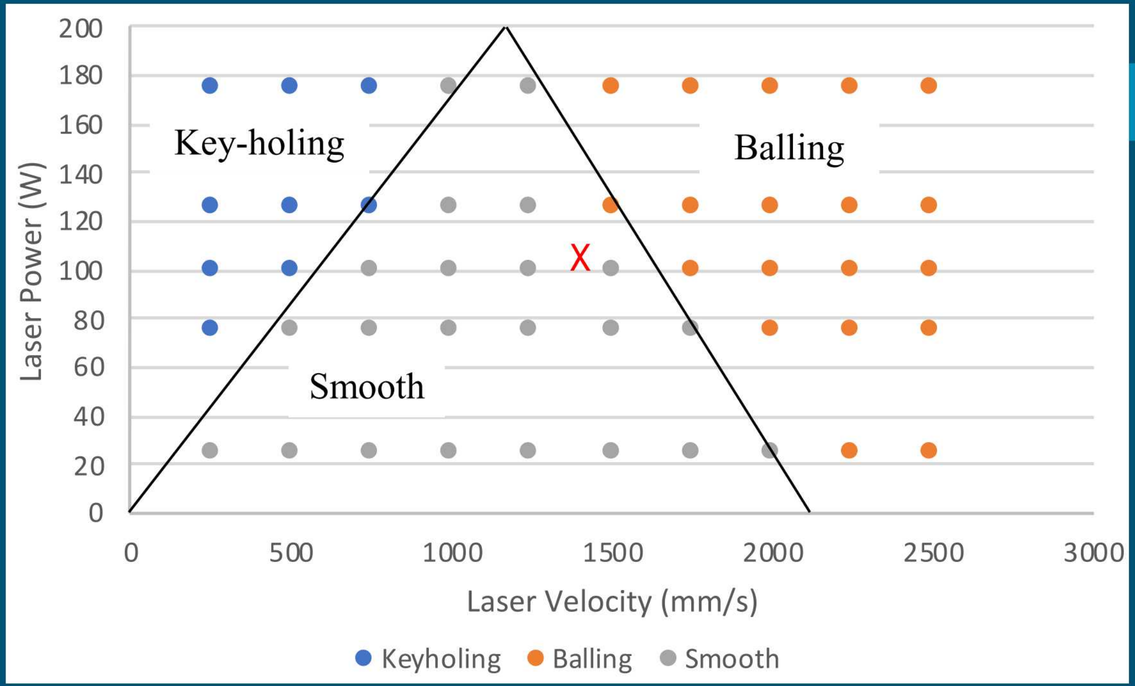
melt pool on plate, 100W, 1500 mm/s

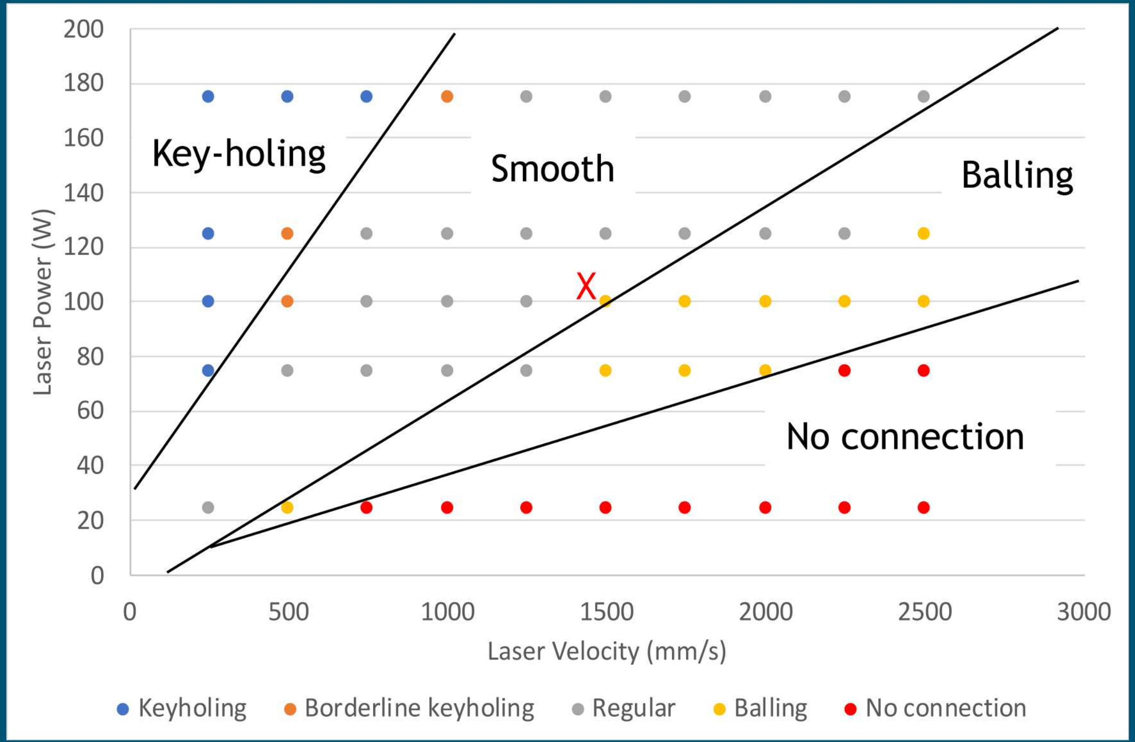
Line Scans: Plate vs. Powder Layer on Pad

on plate



powder layer on pad





Rosenthal Model

Predicts heat distribution from a moving heat source during welding

- Provides an estimated melt geometry

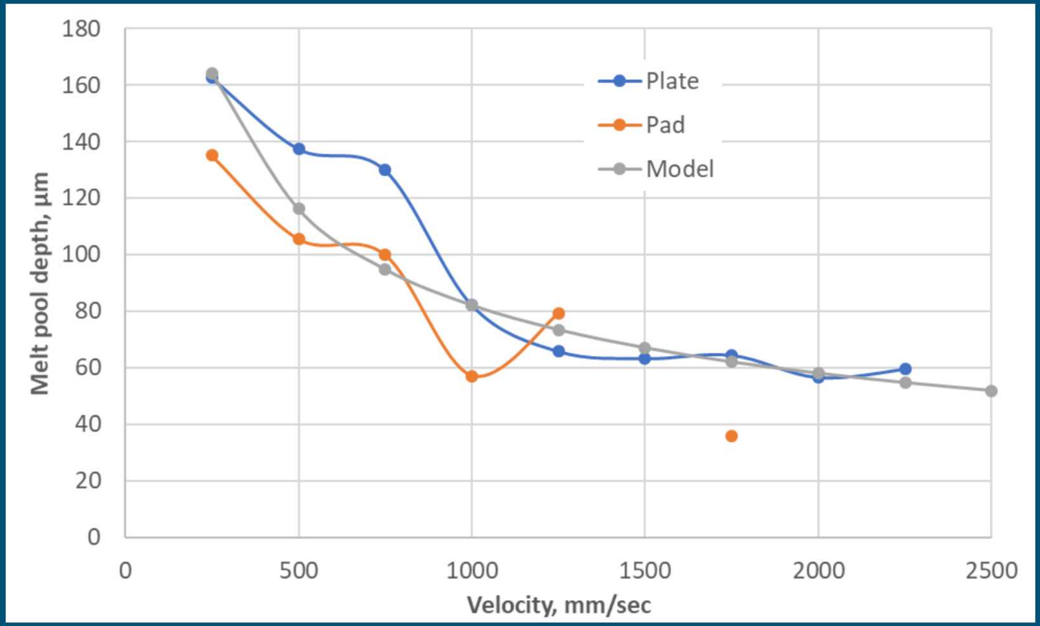
$$T_f - T_0 = \frac{q}{2\pi k R} e^{-\frac{v(w+R)}{2\alpha}}$$

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

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

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

Again, very **simple & easy**



melt pool depth at 100W

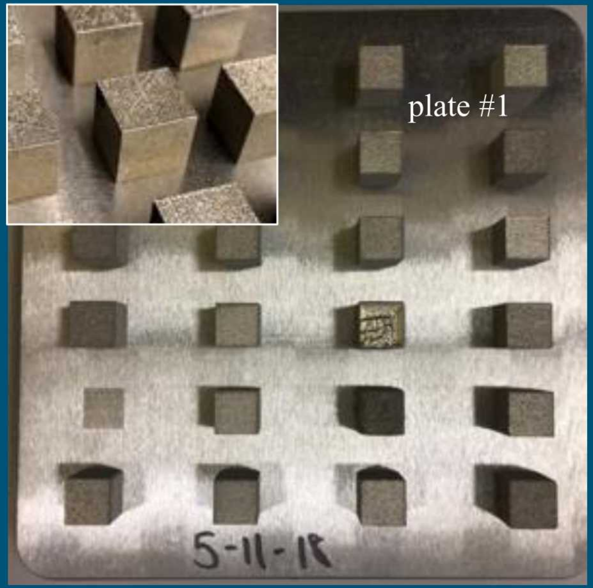
Density Cubes

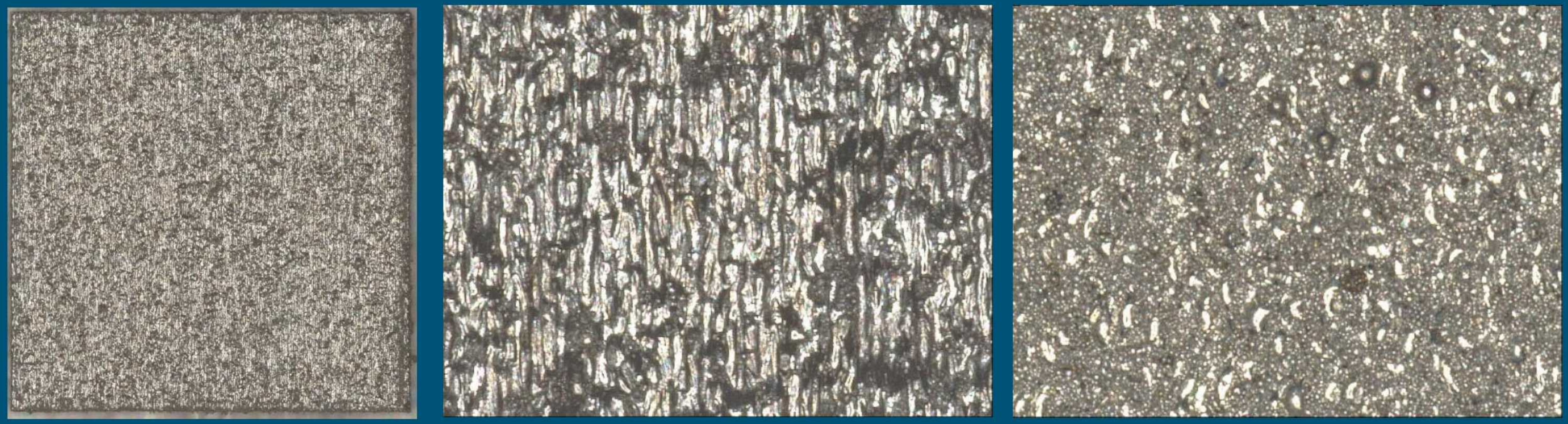
1cm cubes, 24 per plate

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

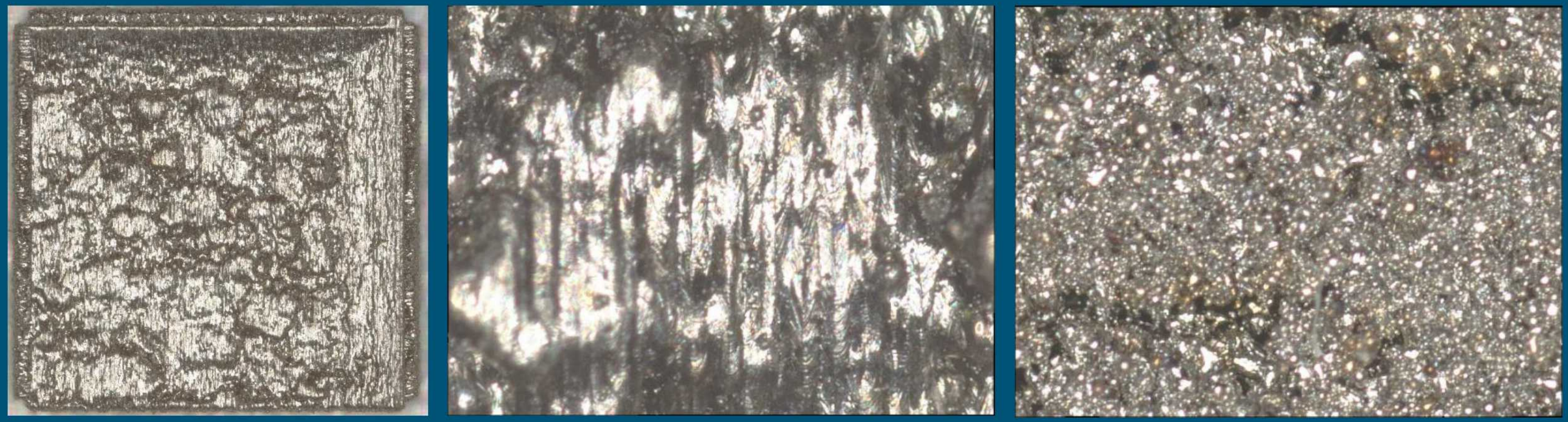
Bulk material measurements

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



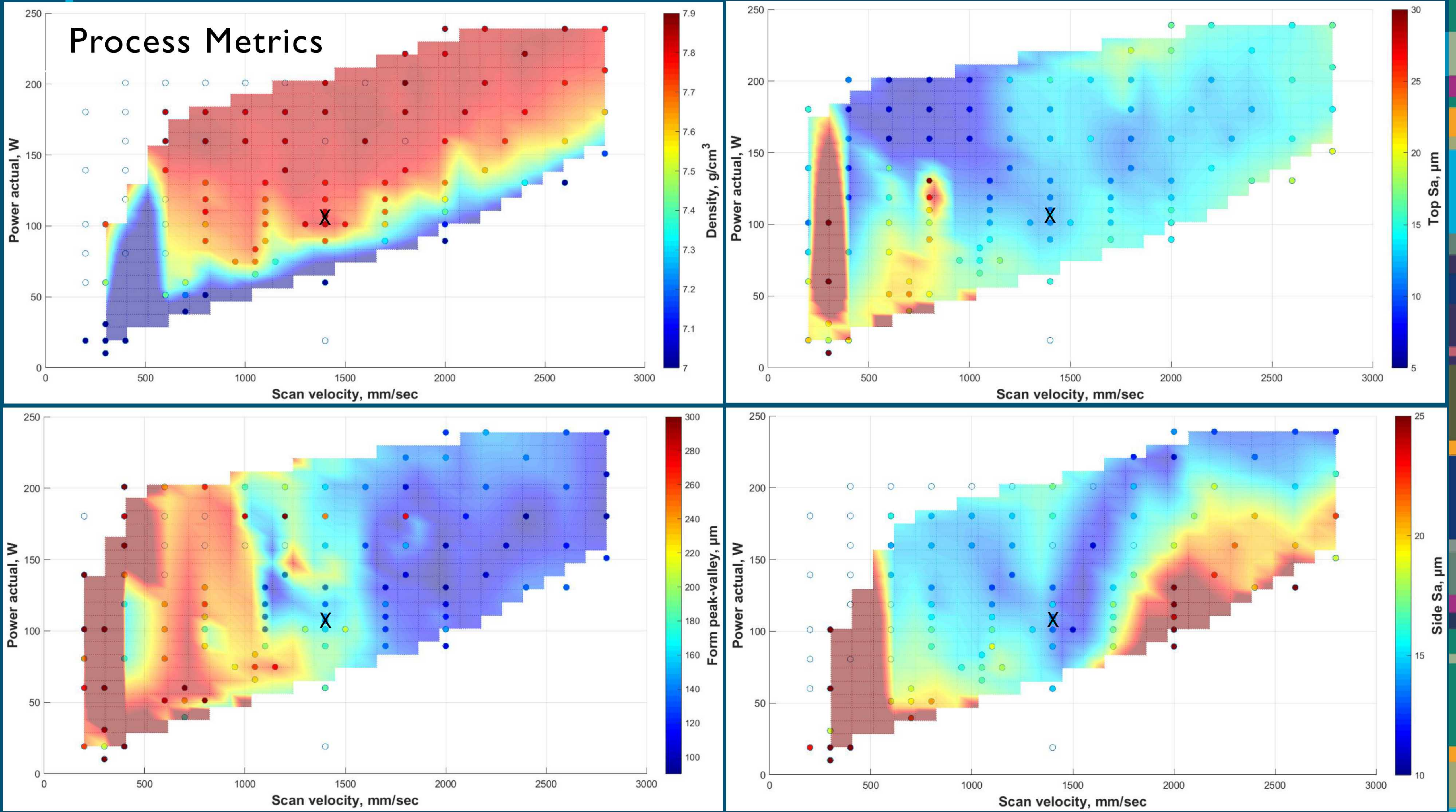


100.2W, 1500mm/sec 209µm PV form (left), top 13.5µm Sa roughness (center), side 9.98µm Sa roughness (right)

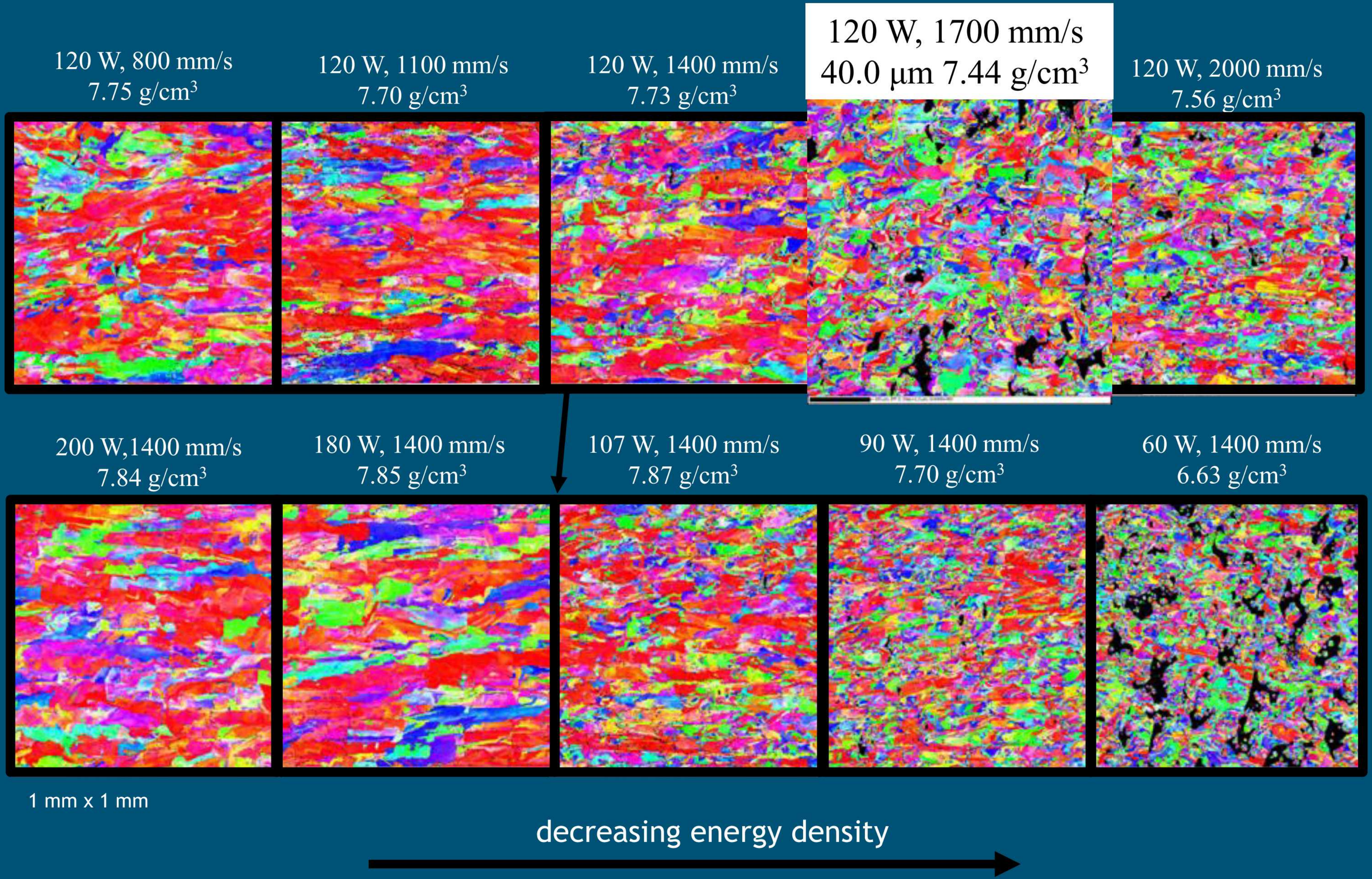


60.1W, 300mm/sec 891µm PV form (left), top 73.8µm Sa roughness (center), side 38.1µm Sa roughness (right)

Process Metrics



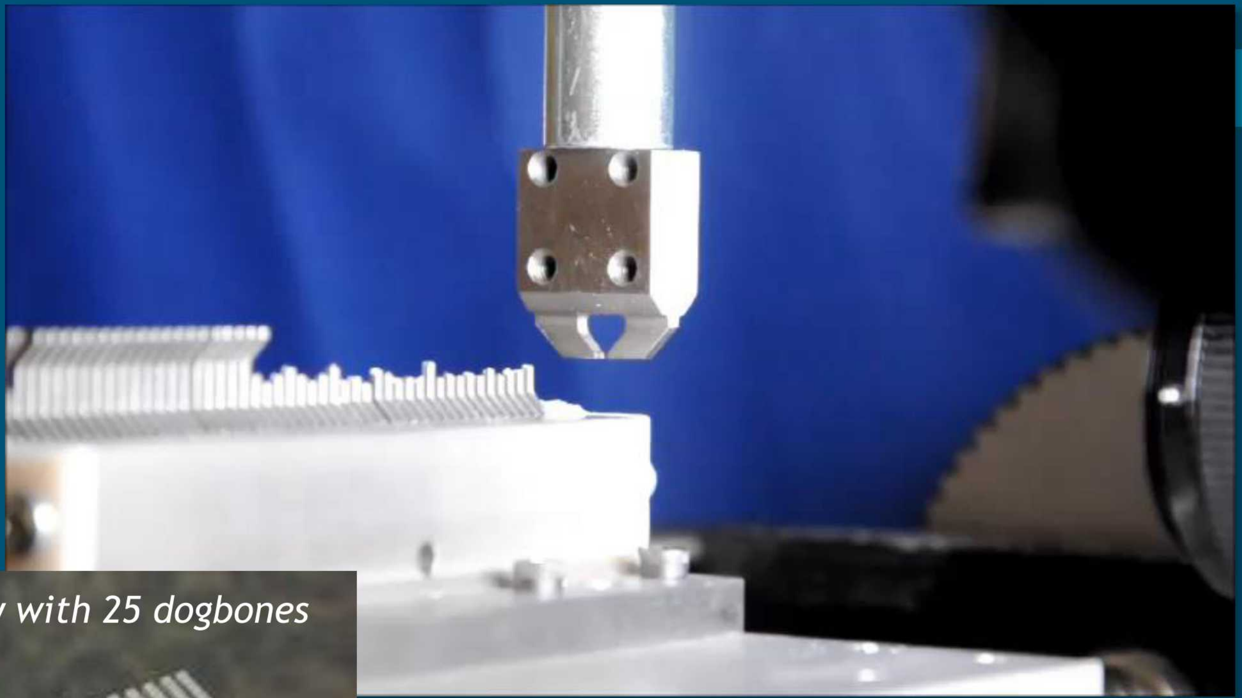
Material Microstructures, 30μm Layer Thickness



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

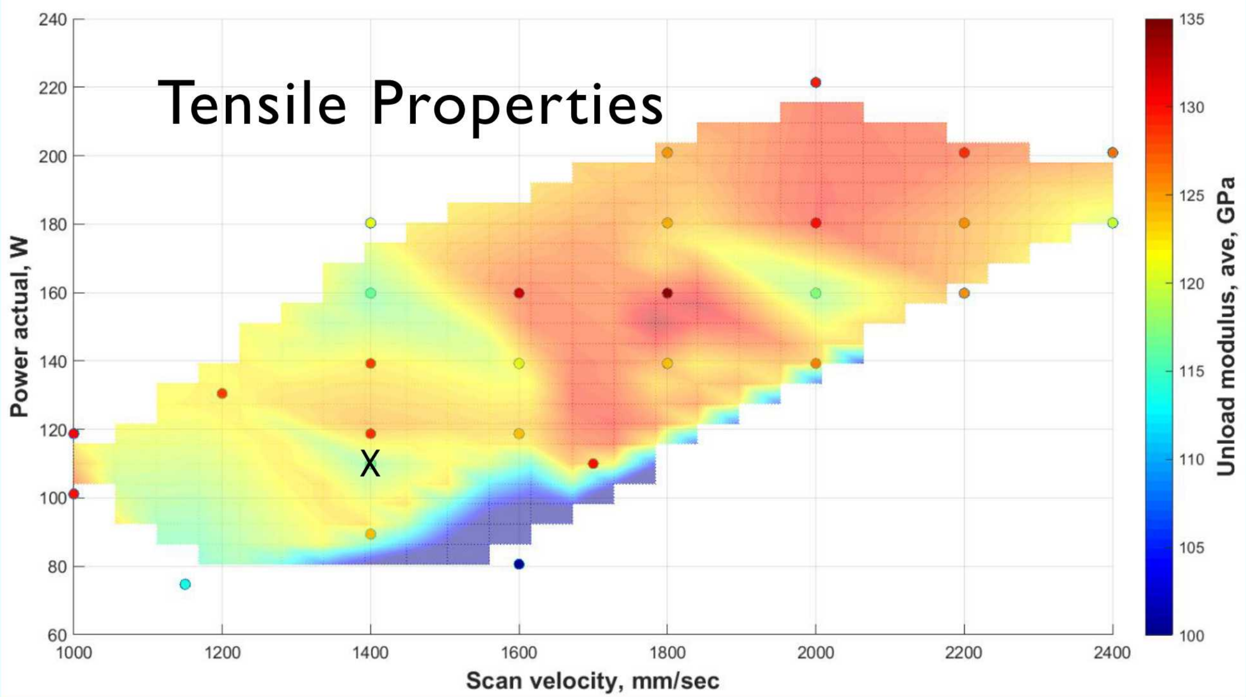


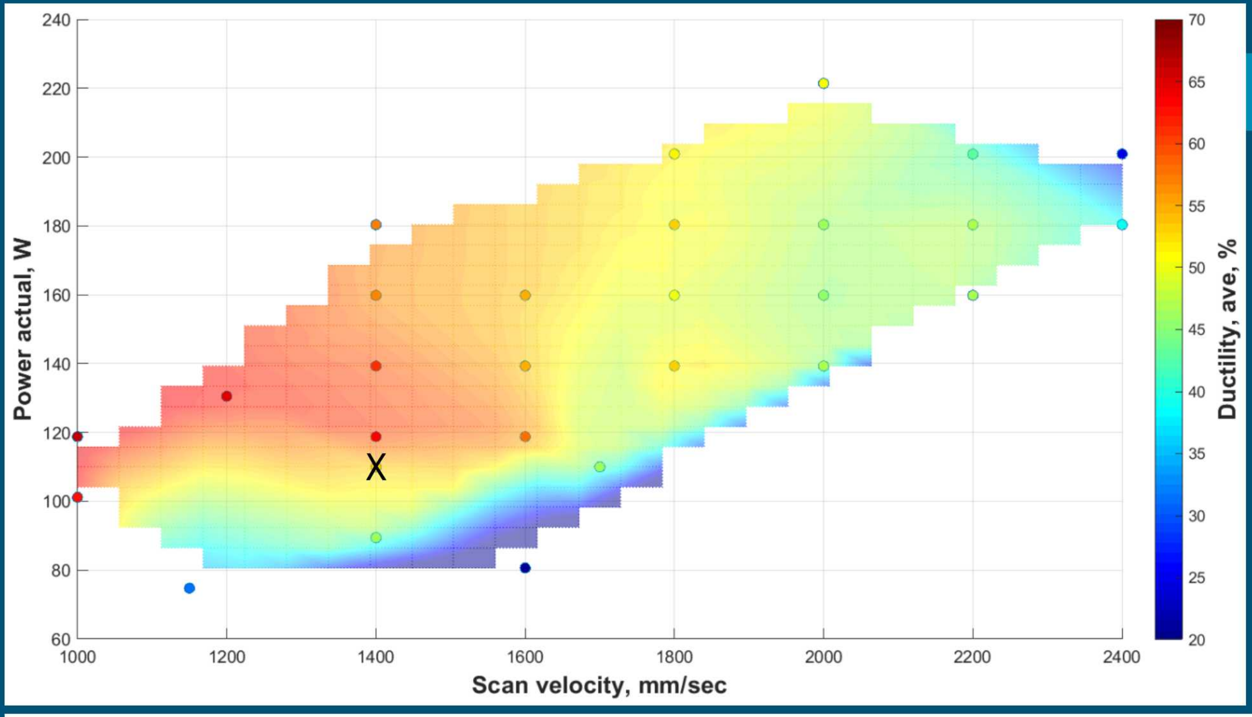
Heckman, **Mat. Sci. Eng. A**, 2020

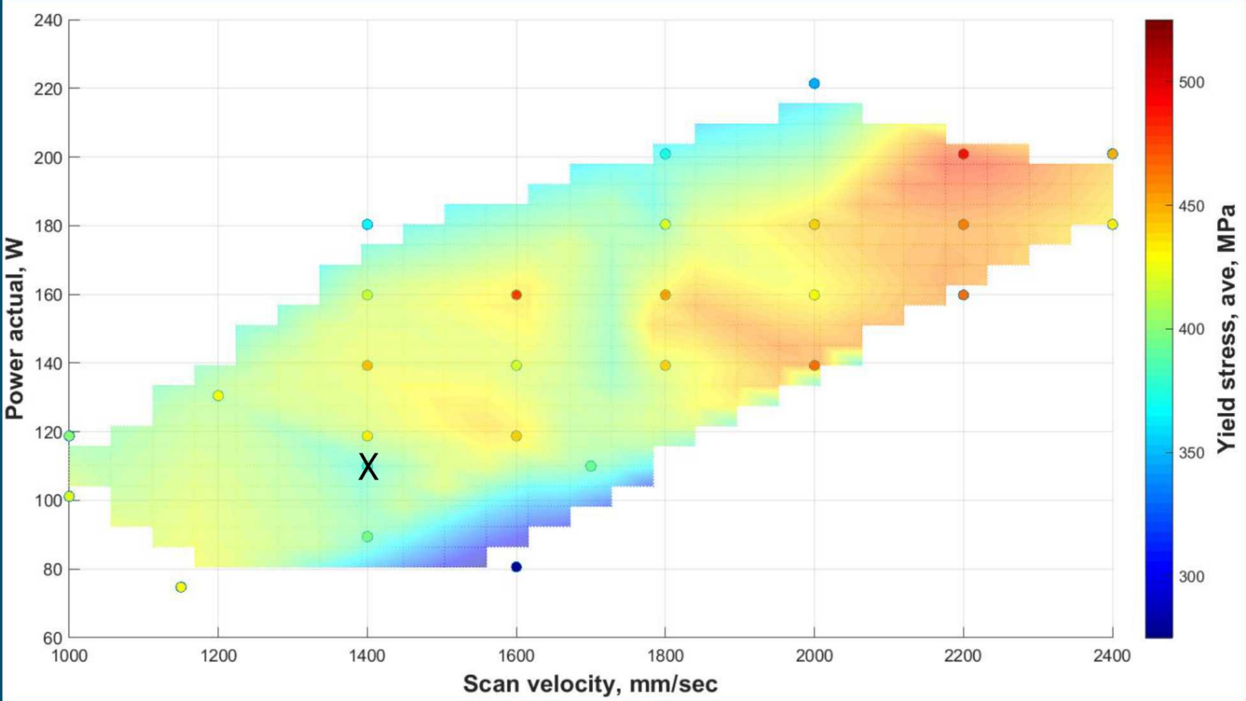
316L SS dogbone array with 25 dogbones

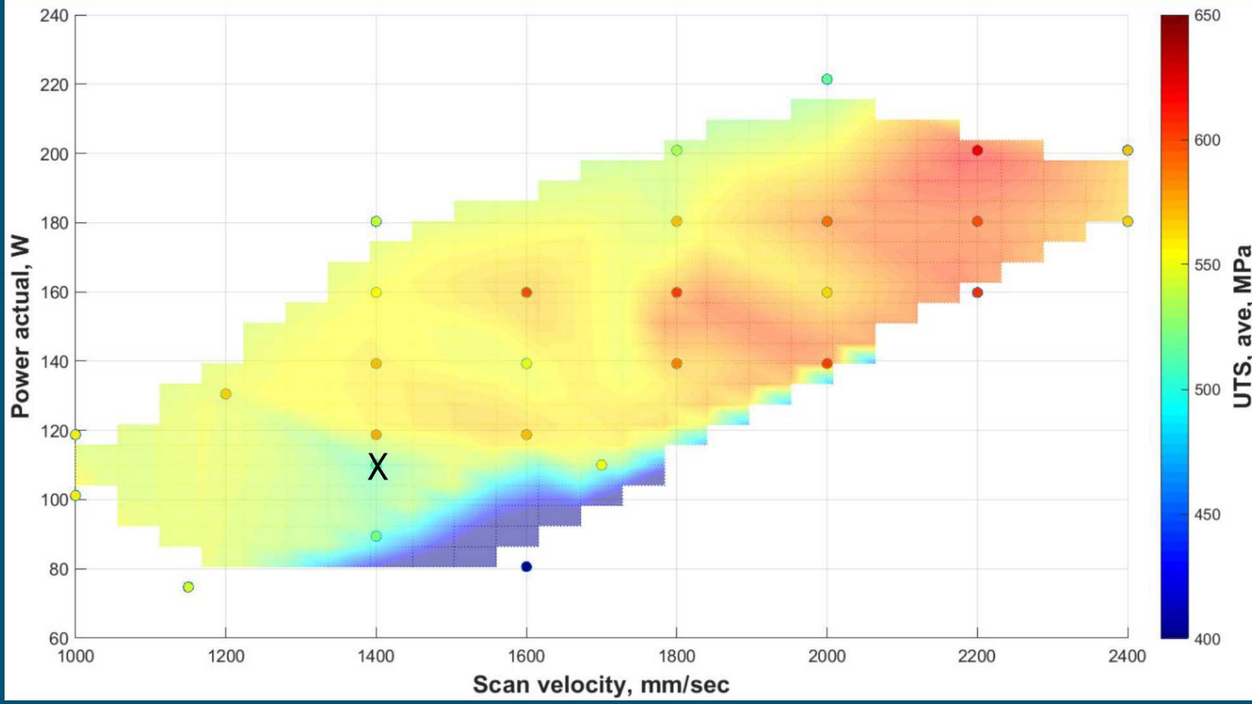
build plate w/20 arrays, 10 dogbones/array

Tensile Properties









Lattice Process-Structure-Properties

Motivation

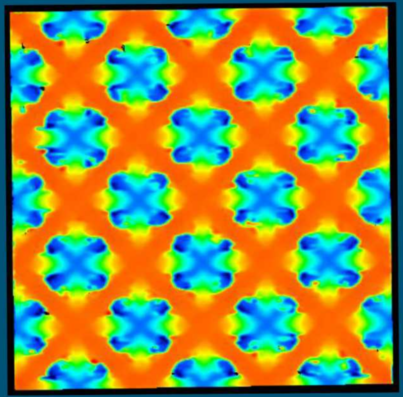
- qualification
- process / performance tolerances

Developing process maps

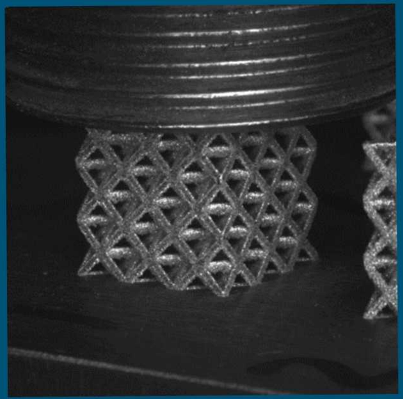
- represents additional design freedom

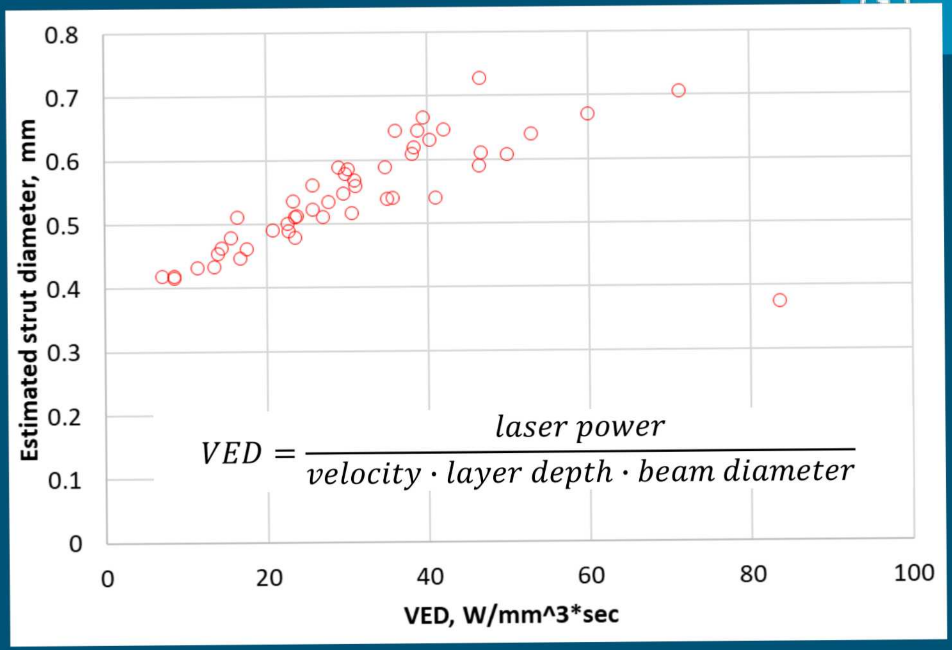
top surface image

topography

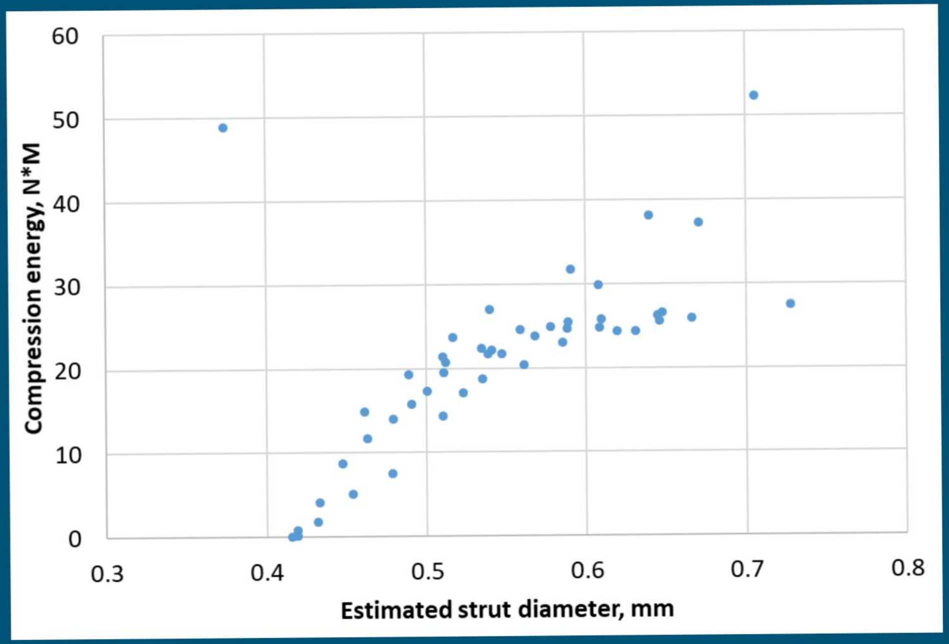


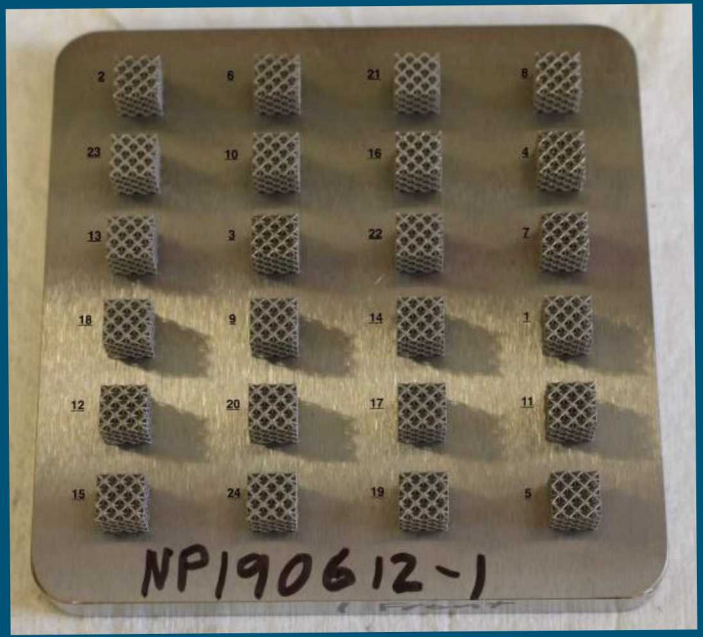
compression testing





$$VED = \frac{laser\ power}{velocity \cdot layer\ depth \cdot beam\ diameter}$$





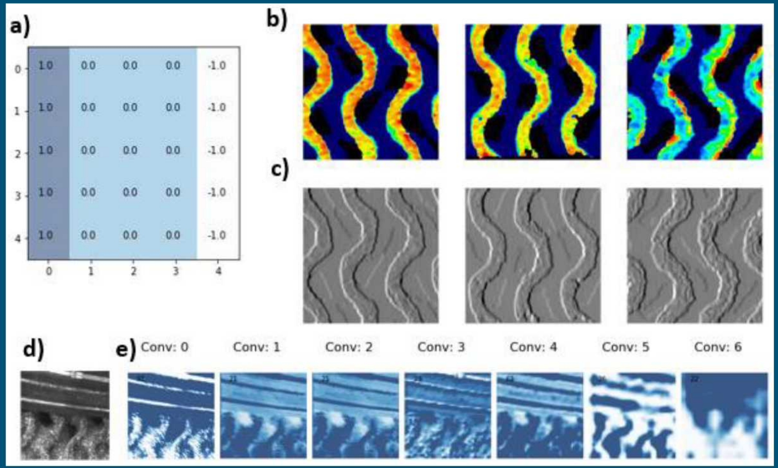
1cm³ octet cubes build plate

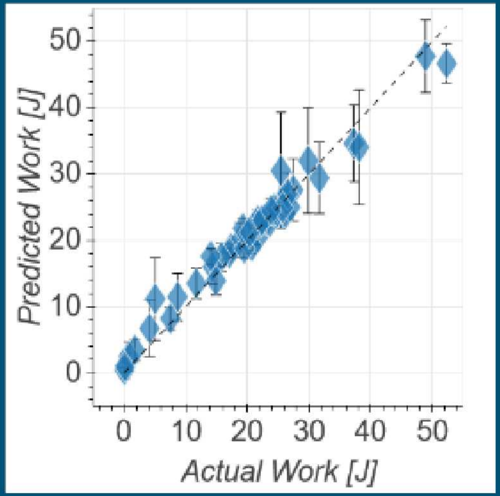
Lattice Process-Structure-Properties

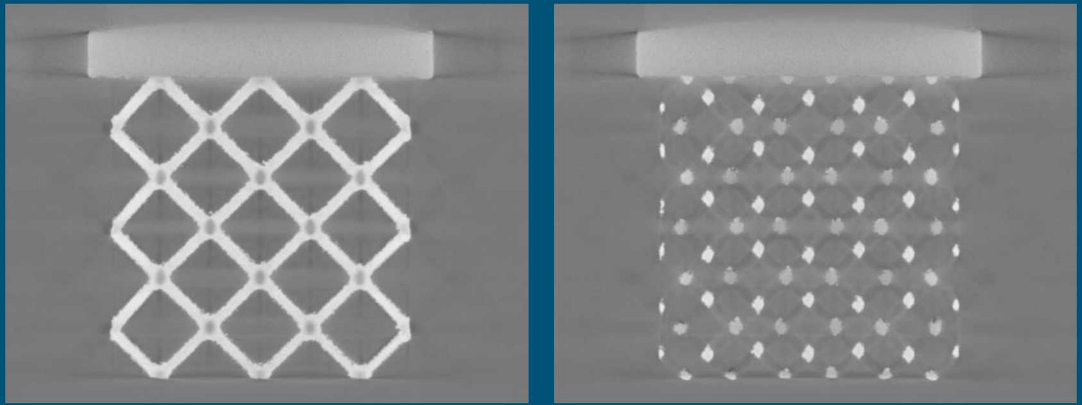
Motivation
- qualification
- process / performance tolerances

Developing process maps
- represents additional design freedom

Inspection
- machine learning
  - addresses “feature engineering” challenges
- high throughput computed tomography







CT images from 10min scan of octet with struts (left) & nodes (right), 12μm voxels

*A. Garland, **Add Mfg**, in review*

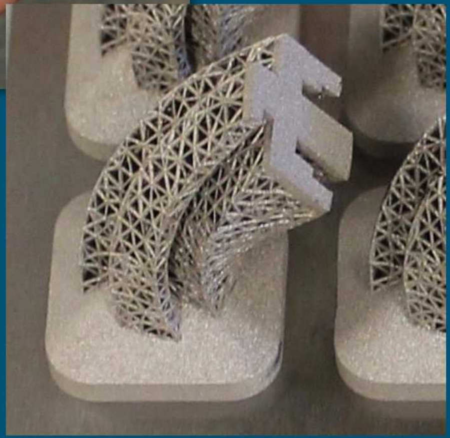
Laser Powder Bed Fusion

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

Motion Stage Errors

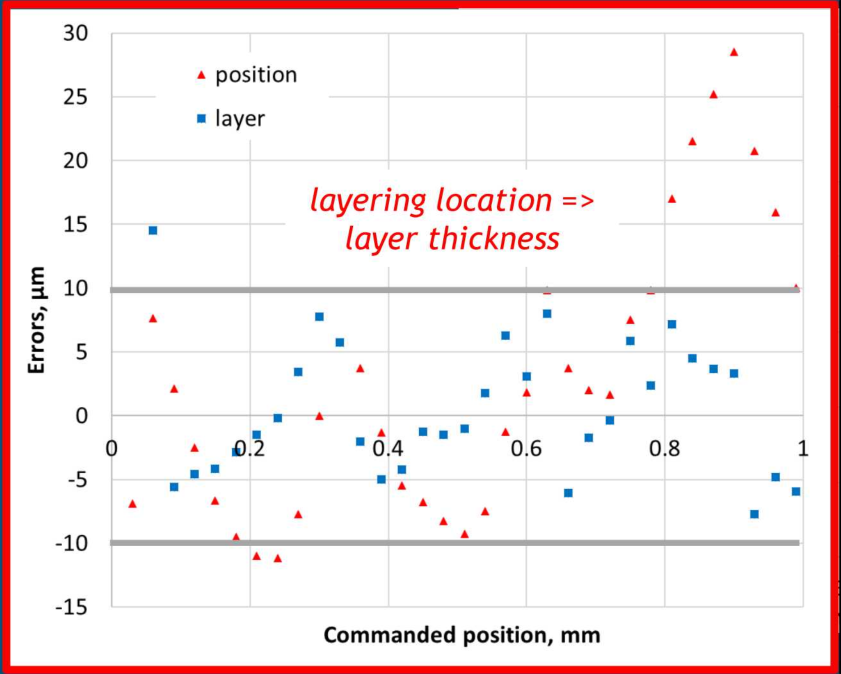
100mm ball screw drives
- supply piston – controls powder dosage
- build piston – controls layer thickness

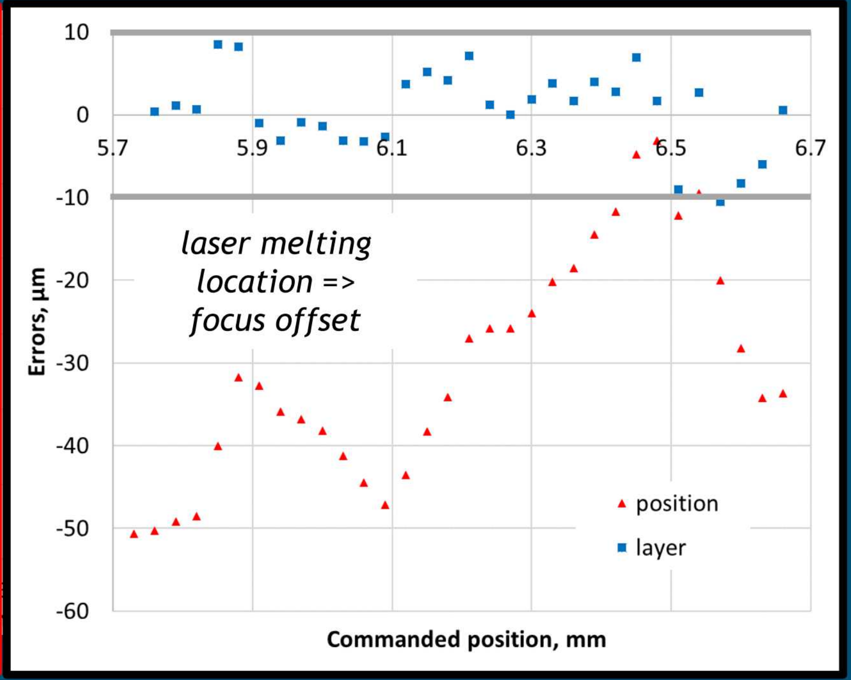
Measurements
- LJ-V7200 laser profiler
  - range: ±48mm
  - Z repeatability: 1µm

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

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

Keyence LJ-V7200 focused onto build plate





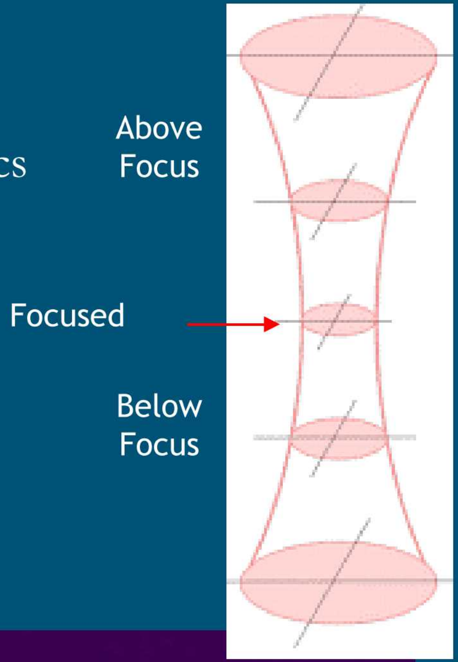
Laser Characterization

Power @ powder layer, not machine setting

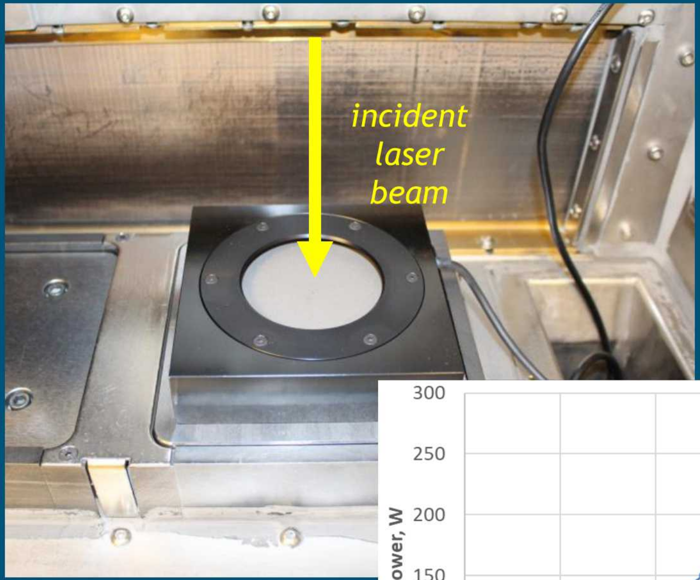
- required for accurate & repeatable process optimization

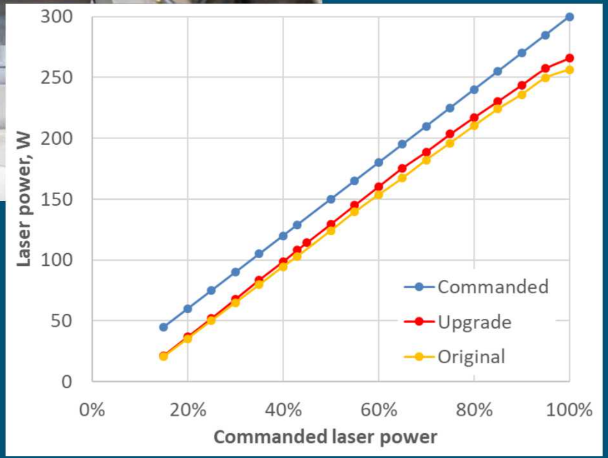
Beam profiling

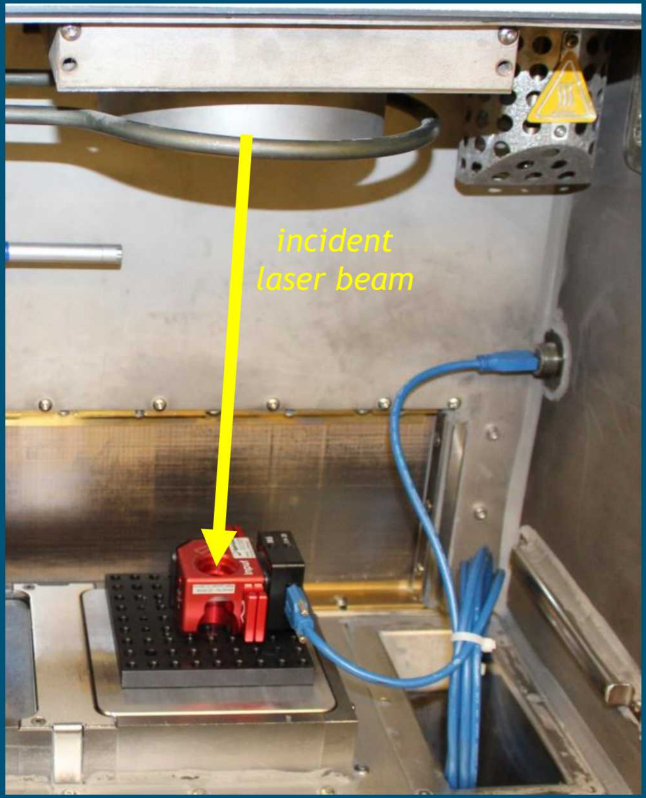
- diameter along optical axis
  - variation w/laser power
- temporal response
  - heating & cooling
- original & upgraded f-theta optics



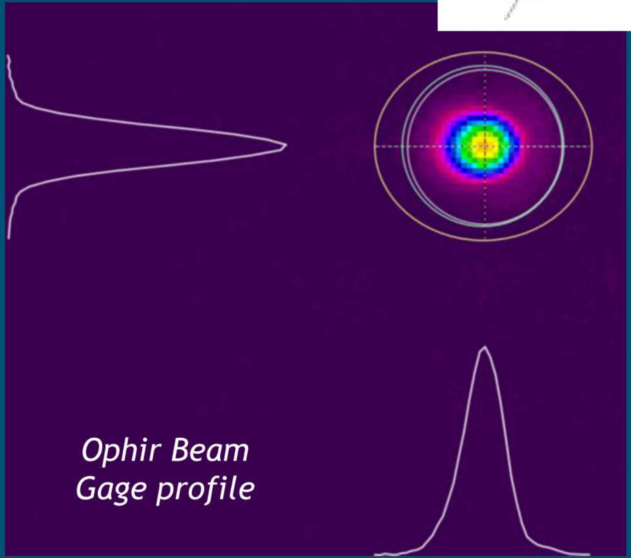
Ophir L50(300)A-LP1 power meter on the build plate







Ophir SP 928 profiler on the build plate

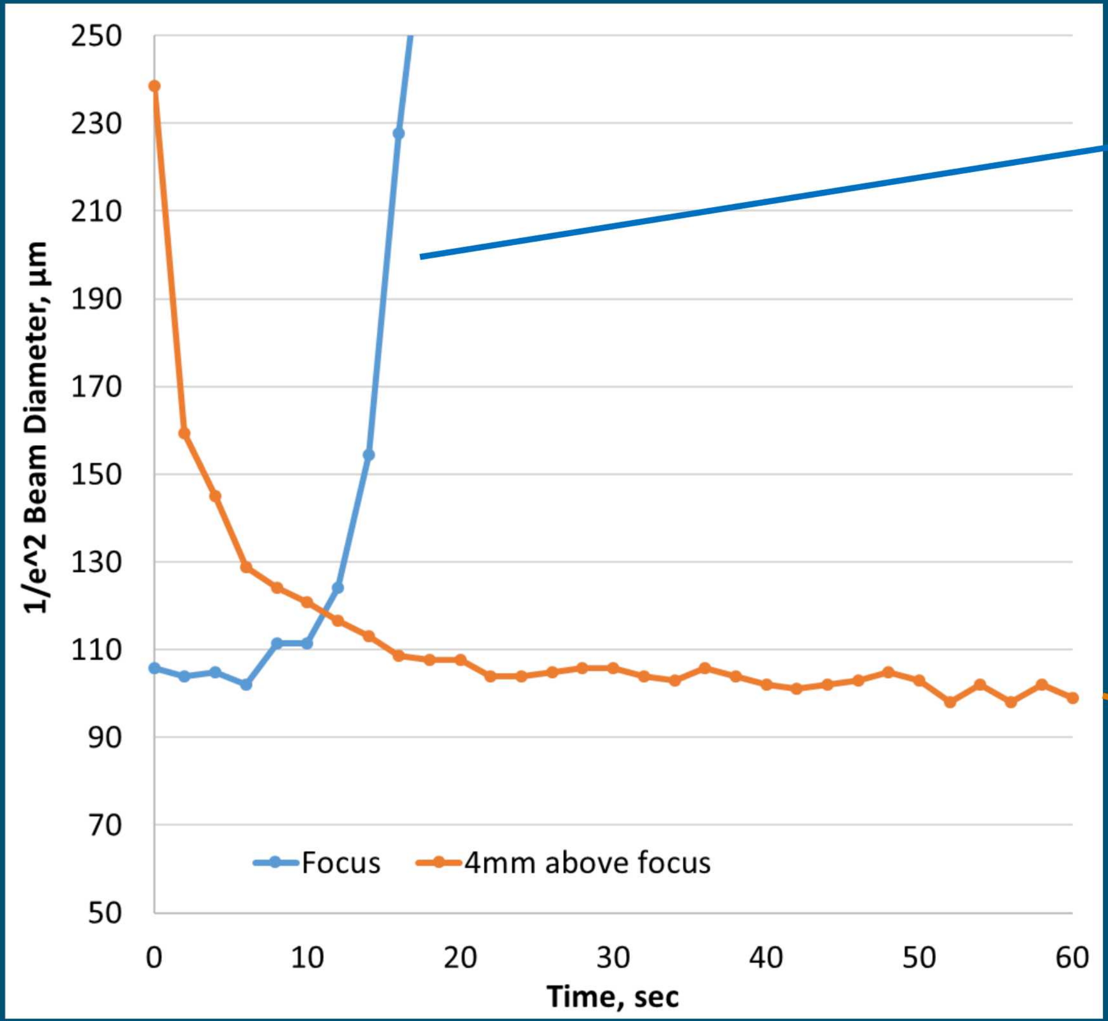


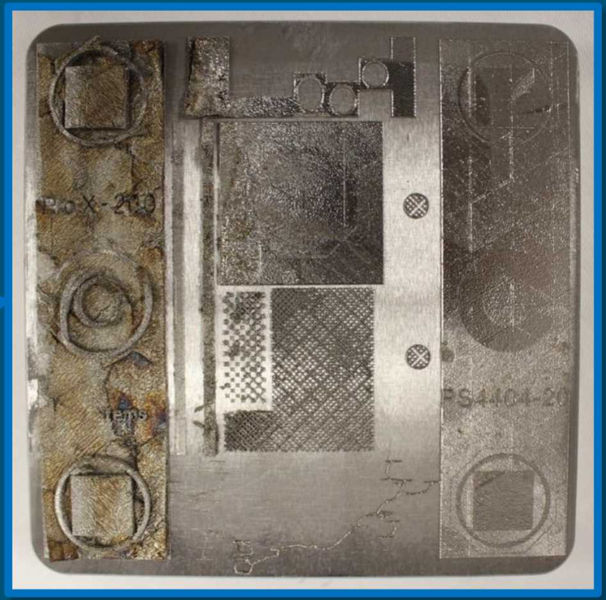
Ophir Beam Gage profile

Original F-Theta Diameter Variation

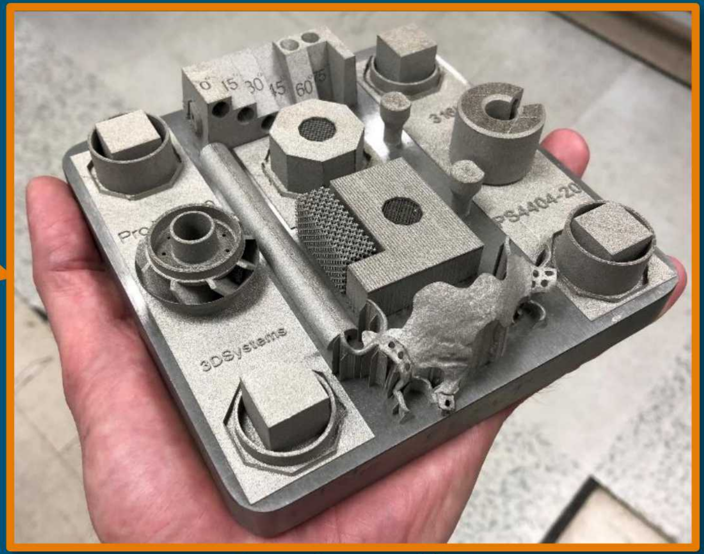
Thermal lensing obscures optimal focus for a realistic build cycle

- introduces challenges & uncertainties to part & material generation





nominal focus offset

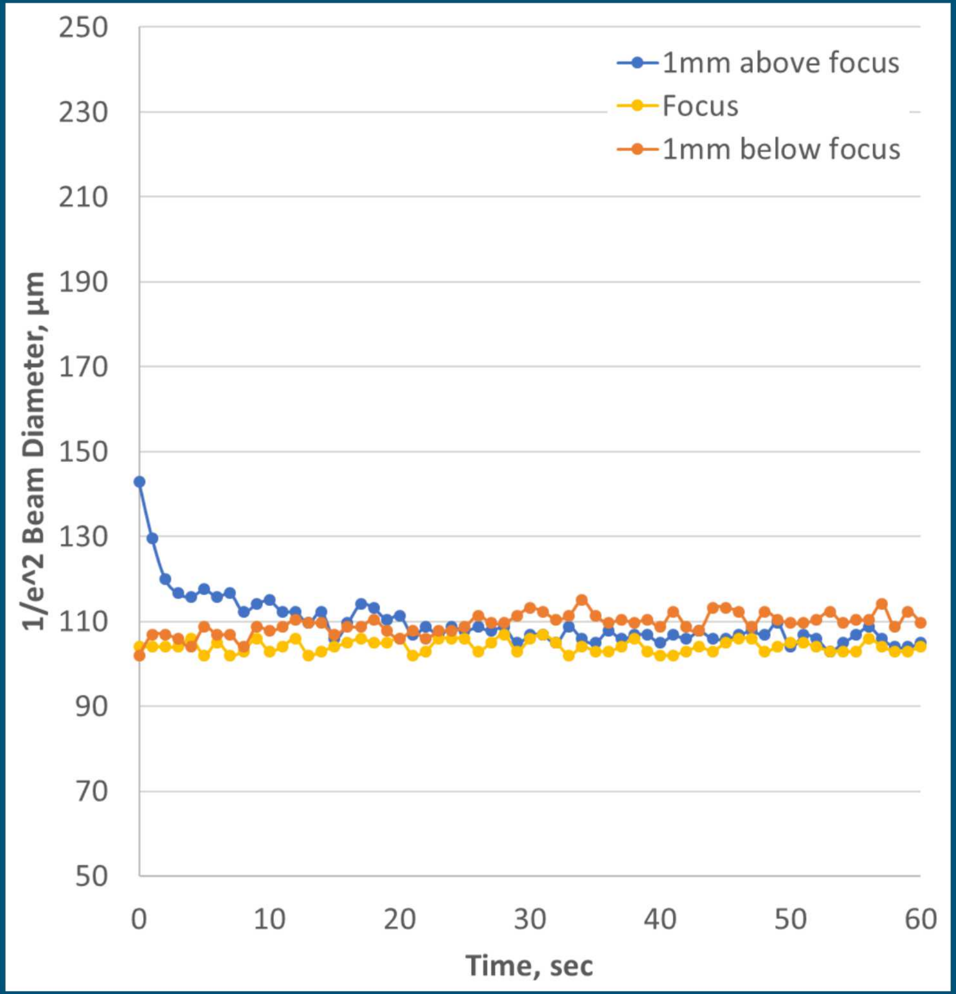


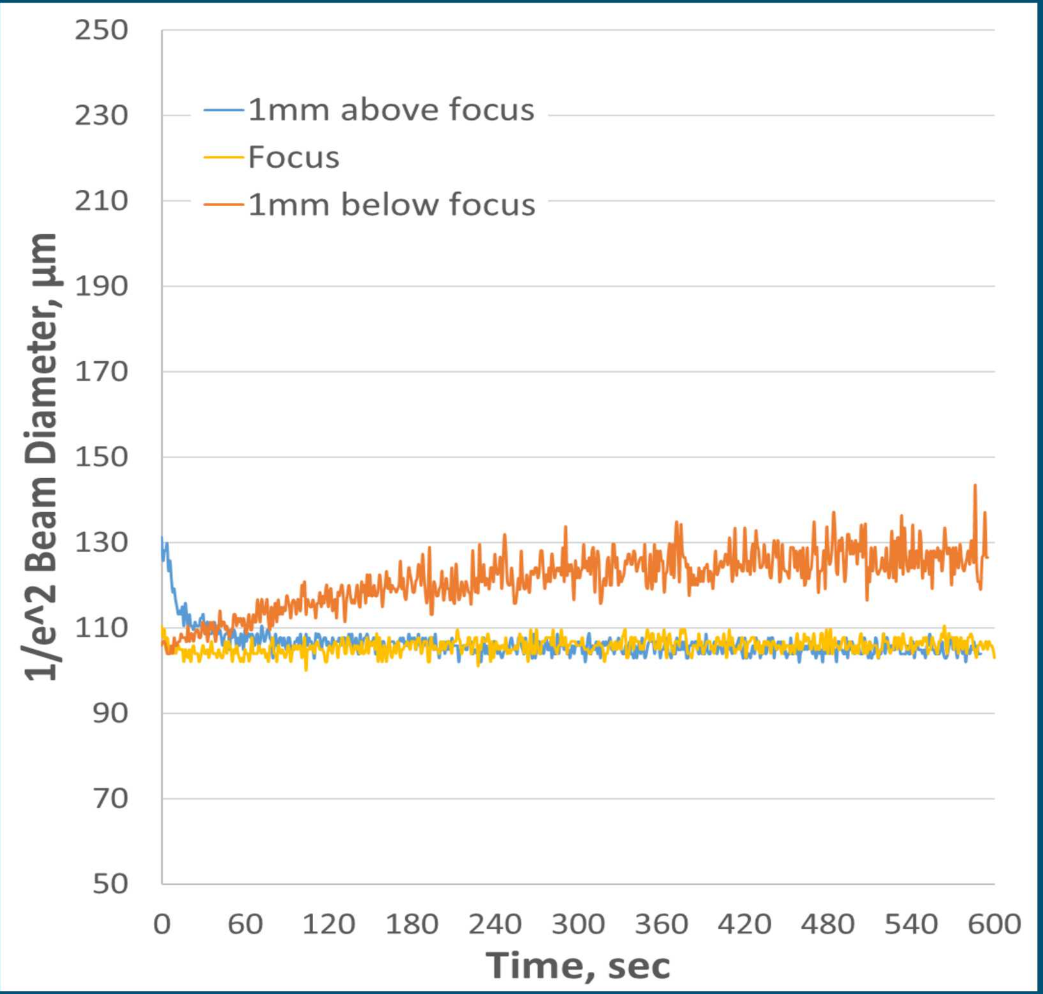
4mm focus offset

Upgraded F-Theta Diameter Variation

Dramatic reduction in thermal lensing & improved repeatability / consistency

Critical to process optimization efforts

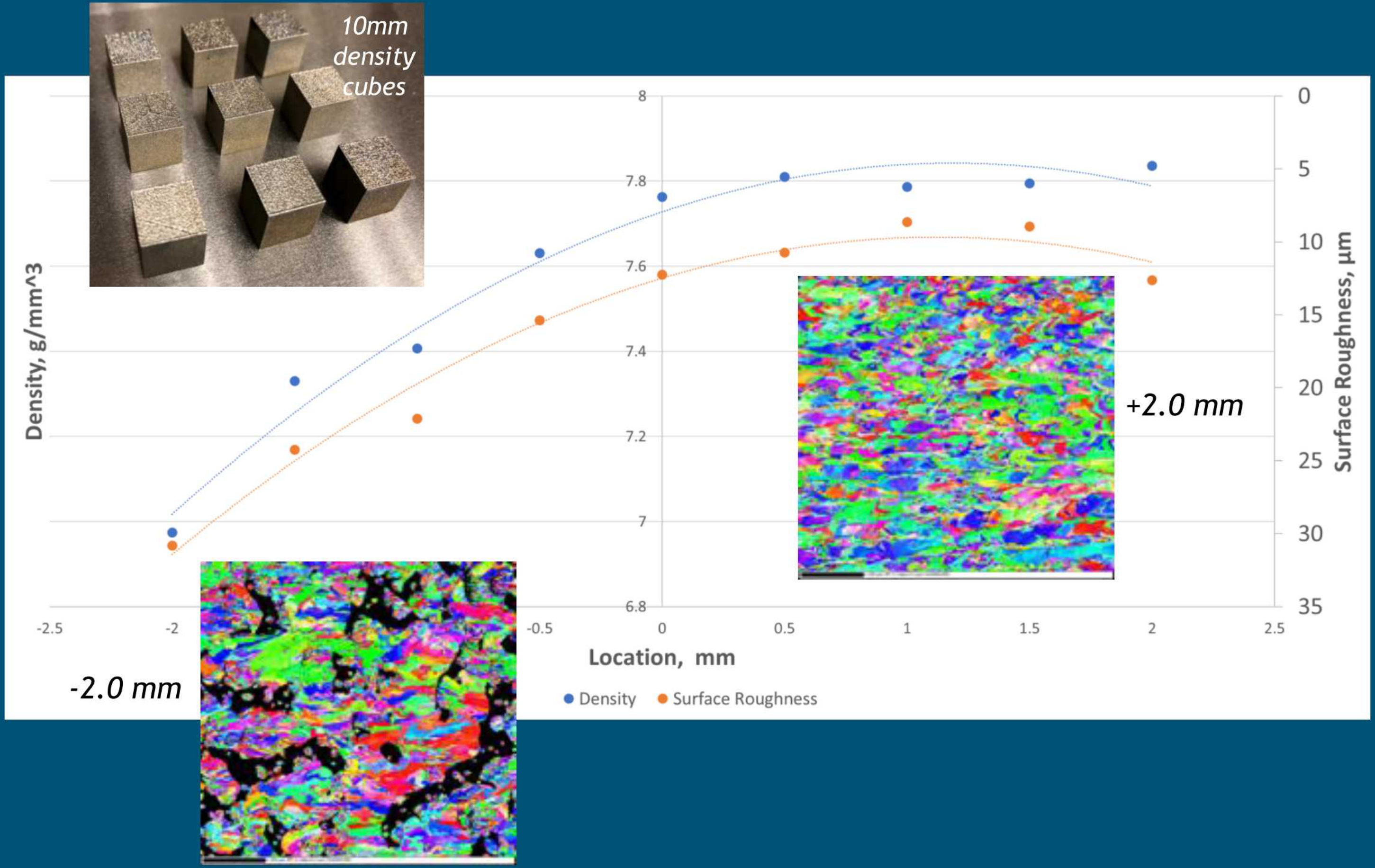


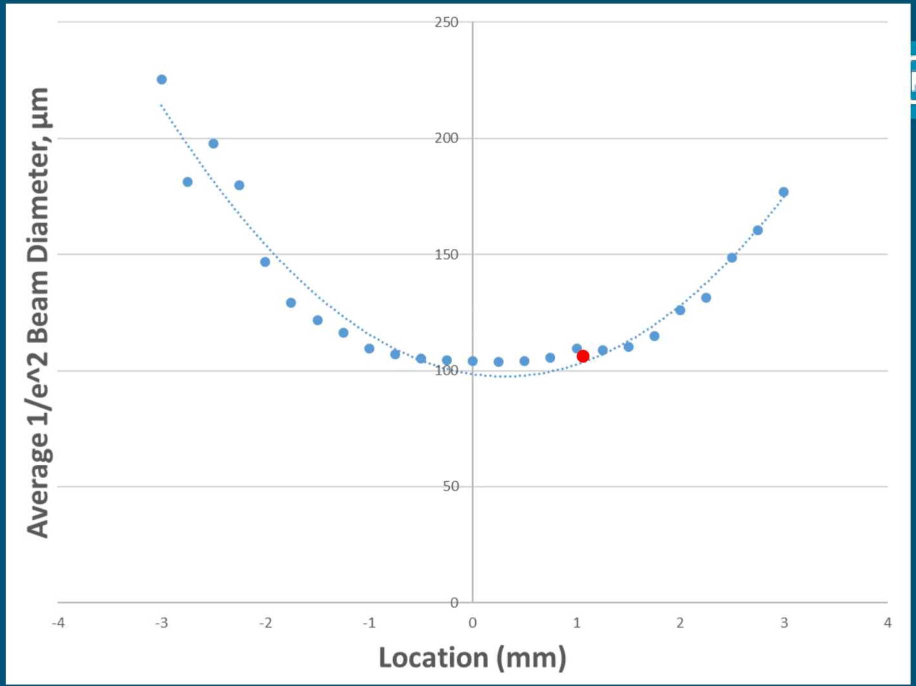


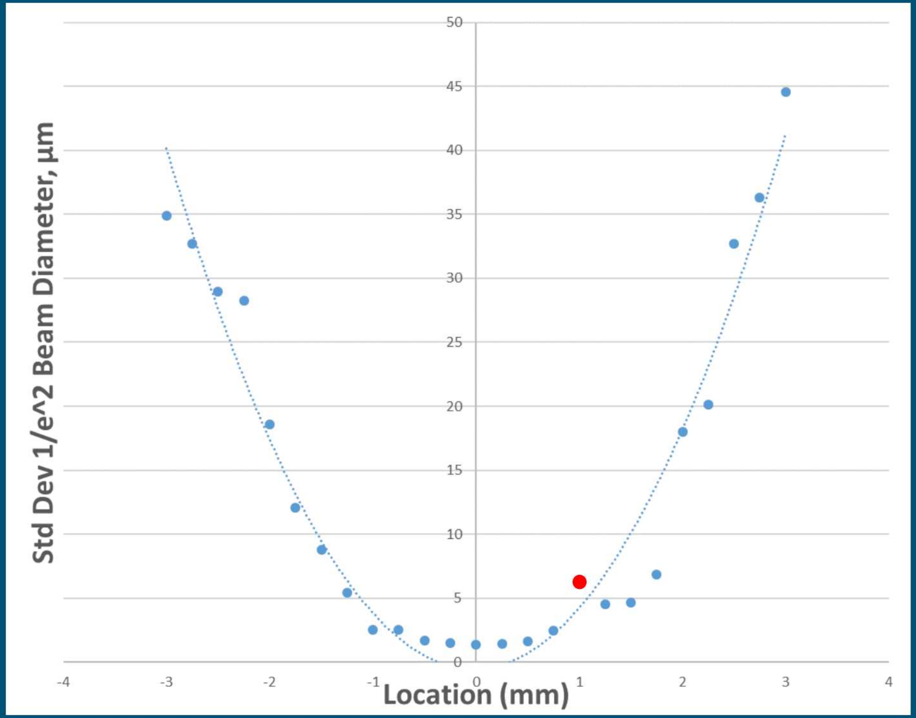
Upgraded F-Theta Focal Distance

How critical is build plate location relative to laser focus?

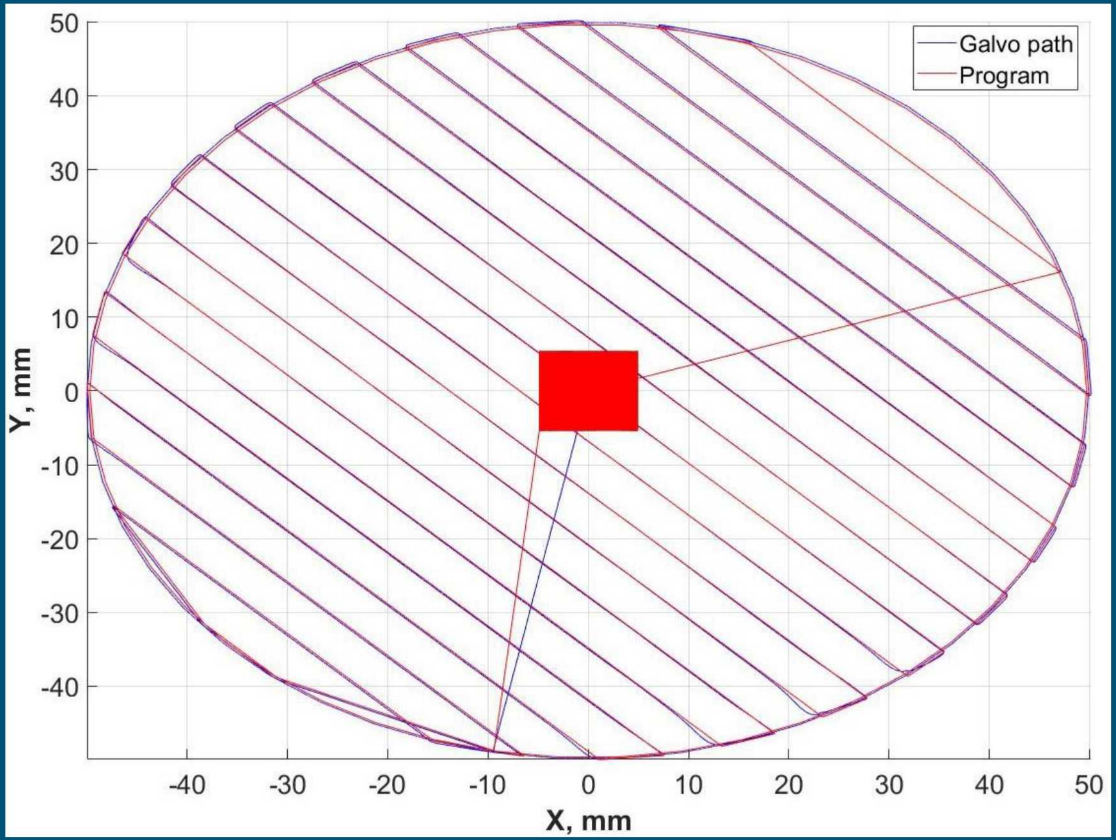
- "optimal" process appears to be +1mm from "focus"
- presumably plasma plume impacts optimal offset







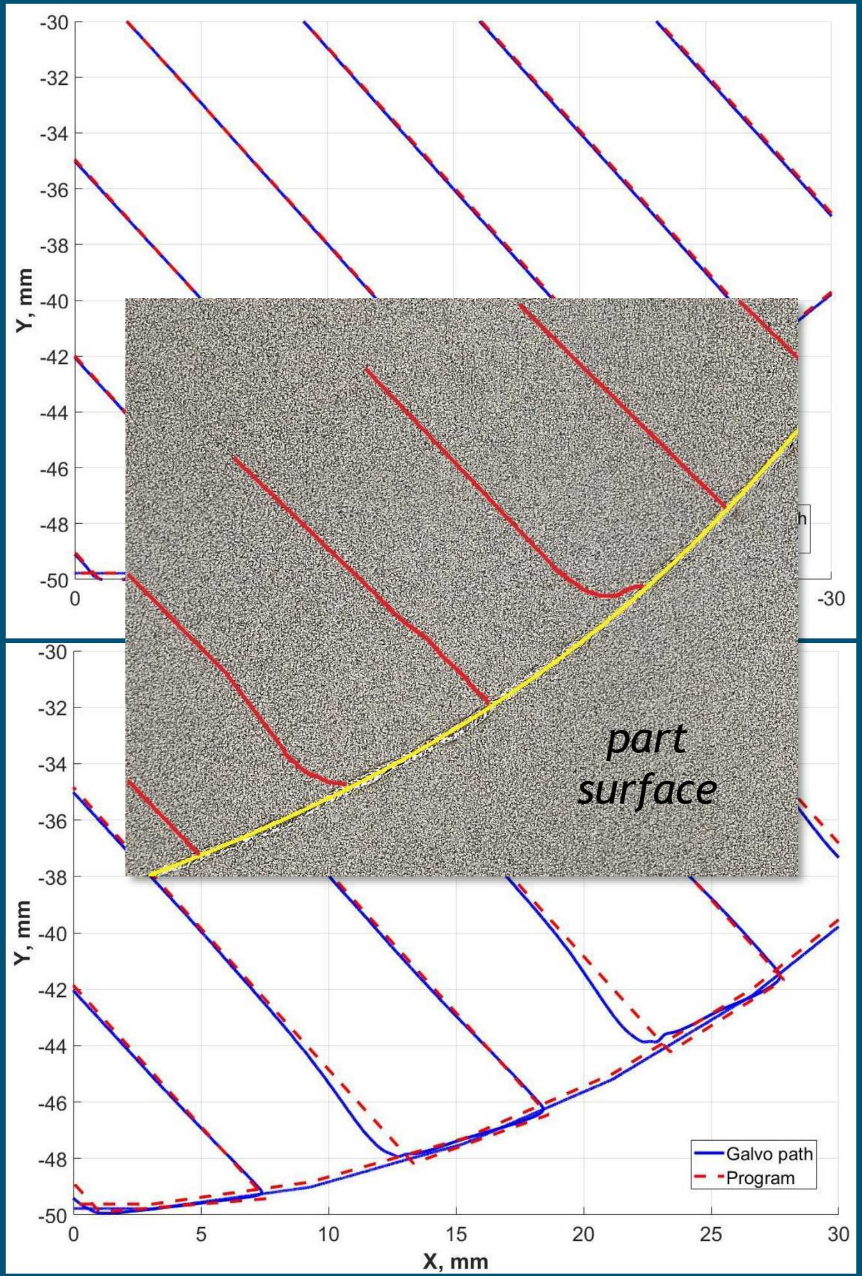
Real-Time Machine Monitoring Reveals Process Perturbations



ARCS output for a simple test pattern

desired motion

galvo errors



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

Process Monitoring

Material formation concurrent w/geometry

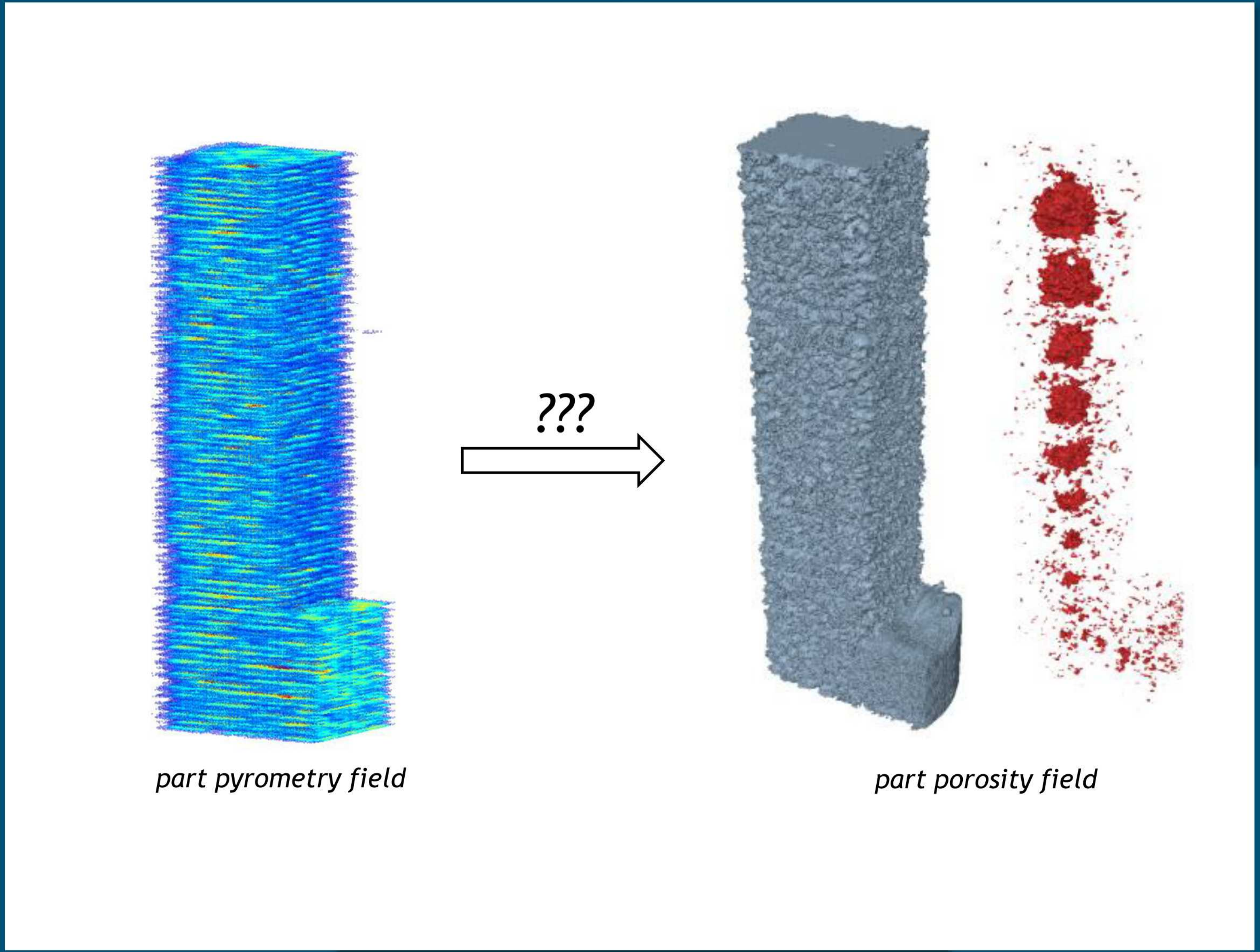
- want to predict part/material performance
- qualification / acceptance requires
  - significant design margins
  - understanding defect impacts on performance

How to ID a bad part?

- proof testing
- non-destructive inspection
- *process monitoring*

Objective

- correlate sensor data (X,Y,Z,time) to spatial material porosity (X,Y,Z)



There are Multiple Potential Melt Pool Signatures for Interrogation

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

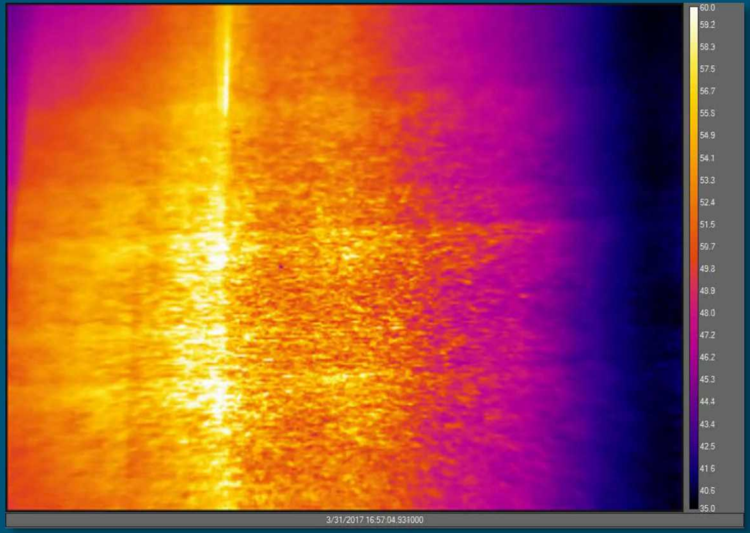
Optical
- Photron PhotoCam Speeder V2 high speed cameras
- blue light illumination
- Ocean Optics LIBS2500plus spectrometer
- Keyence LJ-V7020 & LJ-V7200 laser line scanners

Acoustic
- audio microphone, acoustic emission

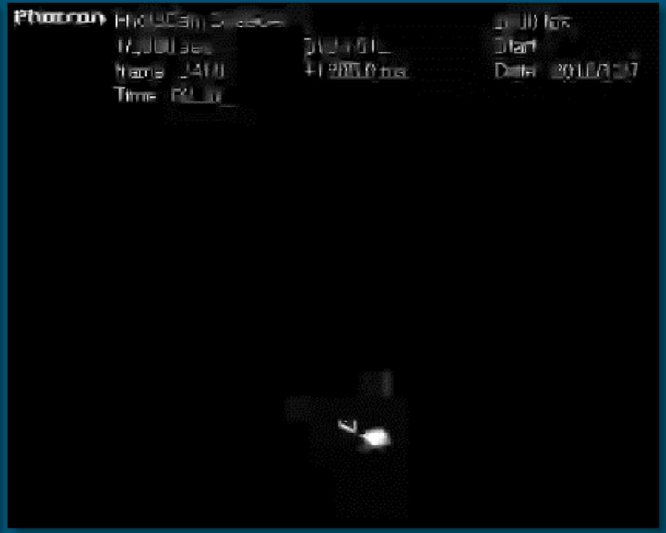
3D Systems Open Protocol platform
- PSU multi-spectral sensor

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

ThermaViz installed in the ProX 200



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

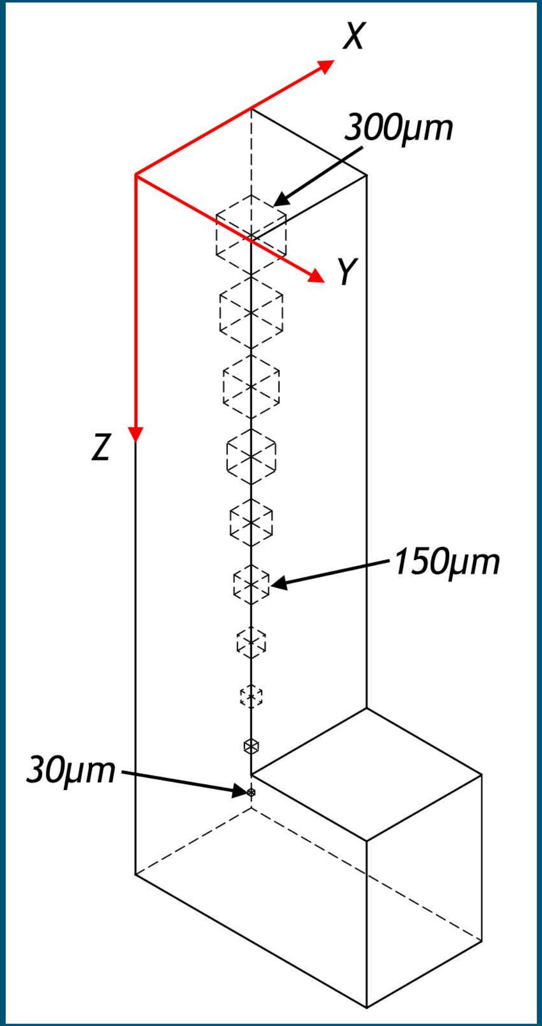


Photron high speed optical melt pool video

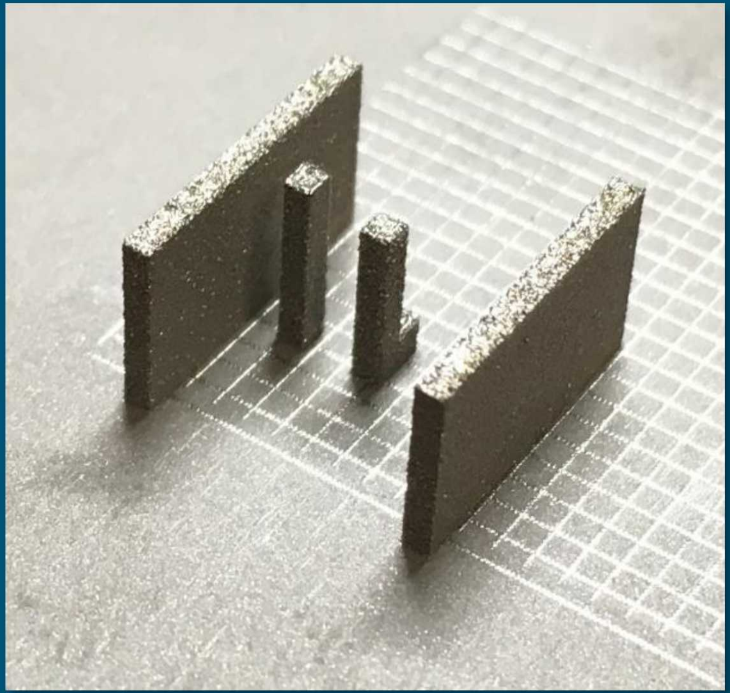
Captured Holes Structure

Design
- 1x1x5.25mm column, 175 layers
- holes
  - 1-10 layer thickness (30-300μm cubes)
- 316L stainless steel

Material characterization
- Zeiss Xradia 520 Versa μCT
- voxel resolution: ***1.98μm***



captured holes design


captured holes part printed in 316LSS

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

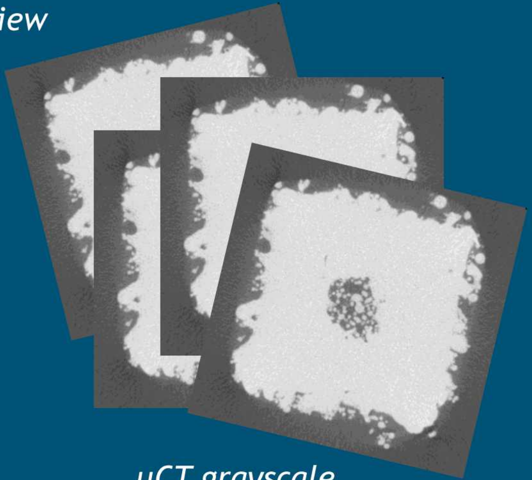
Interactive Data Language

IDL

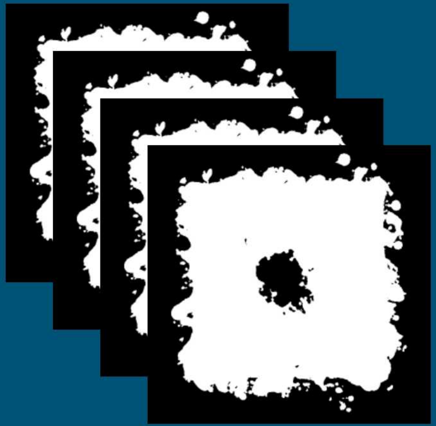
reconstruction
quantification

ParaView
Parallel Visualization Application

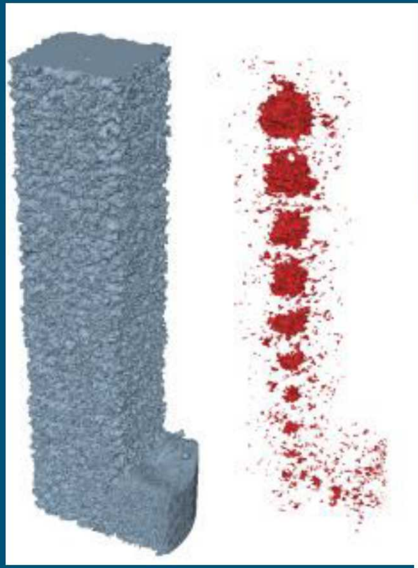
image processing
visualization



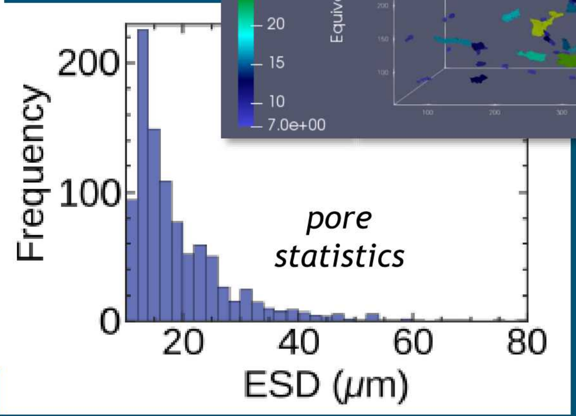
μCT grayscale image stack



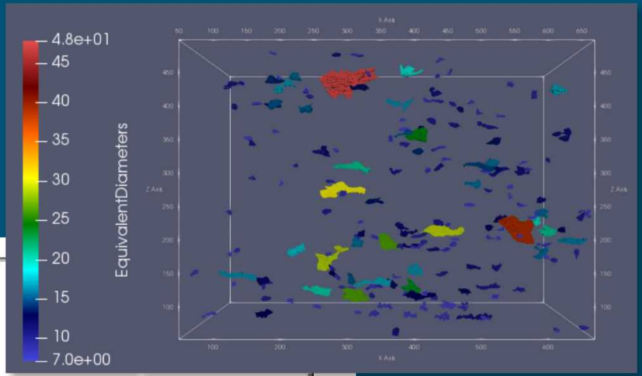
aligned & segmented bitmap stack
white = material, black = air/void



part reconstruction



pore statistics



porosity map generated near the 10 & 20μm pores

Melt Pool Monitoring

Stratonics Therma-Viz 2-color pyrometer

- CMOS imagers: ~20µm/pixel
- 750 & 900nm filters
  - 50nm bandpass
- $Temp_{pixel} \cong func(I_{750nm}/I_{900nm})$

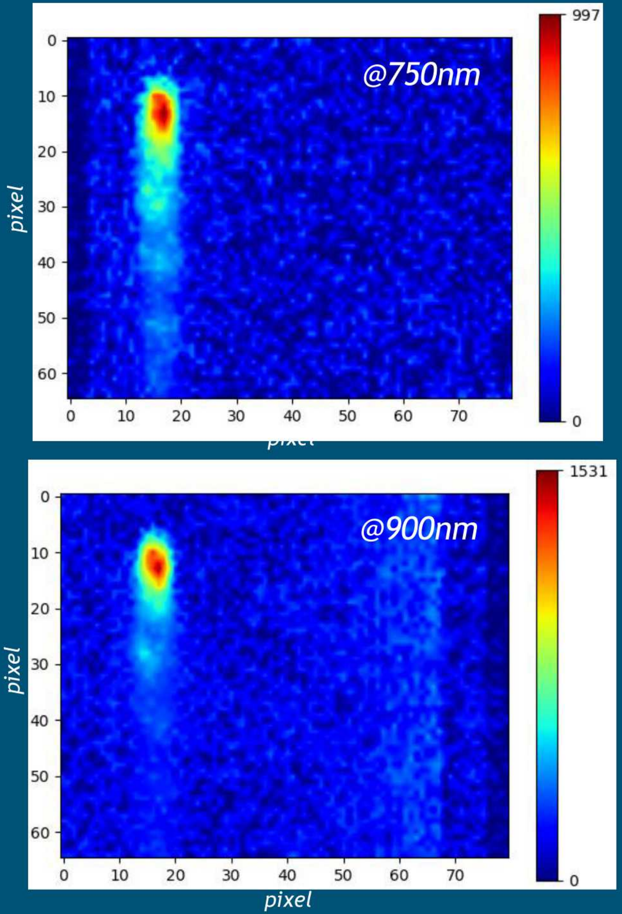
Fixed field, angled viewing

- FOV: 80 x 65 pixels (1.6 x 1.3mm)
- frame rate: 6-7kHz
  - desire >10kHz based on scan velocity

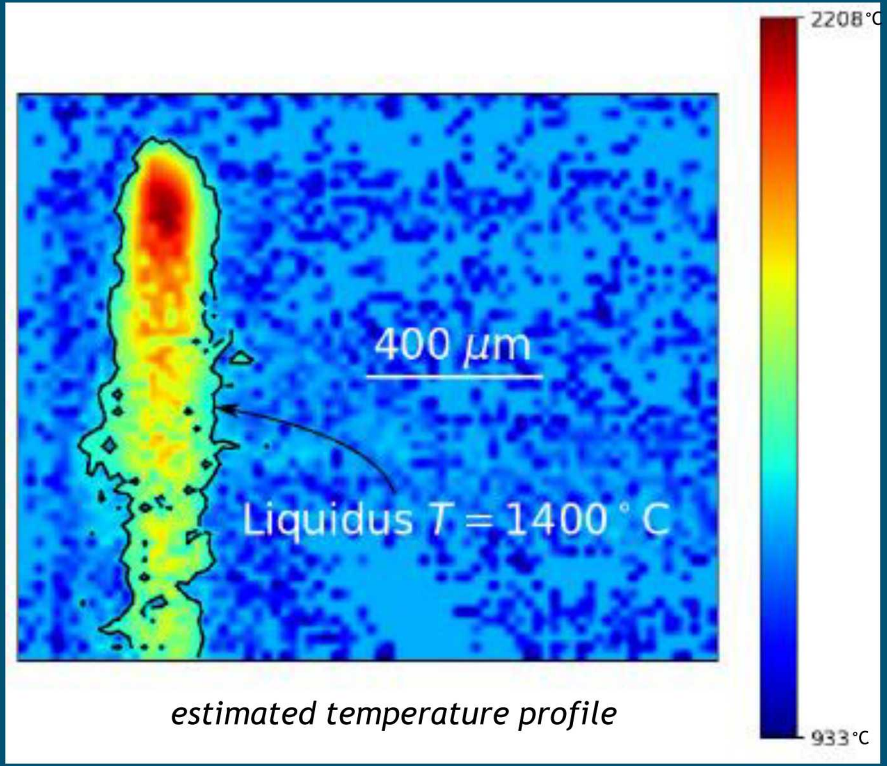
Data analysis

- 87,500 image frames per part
- custom scripts to estimate temperature & melt pool characteristics

raw camera intensity

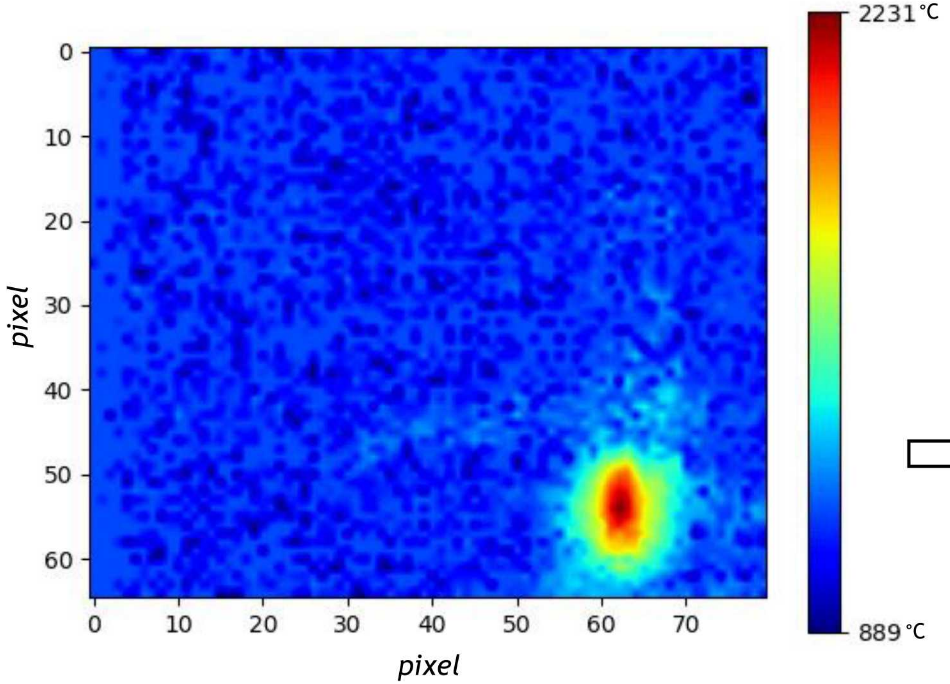


ThermaViz installed in the 3D Systems ProX 200

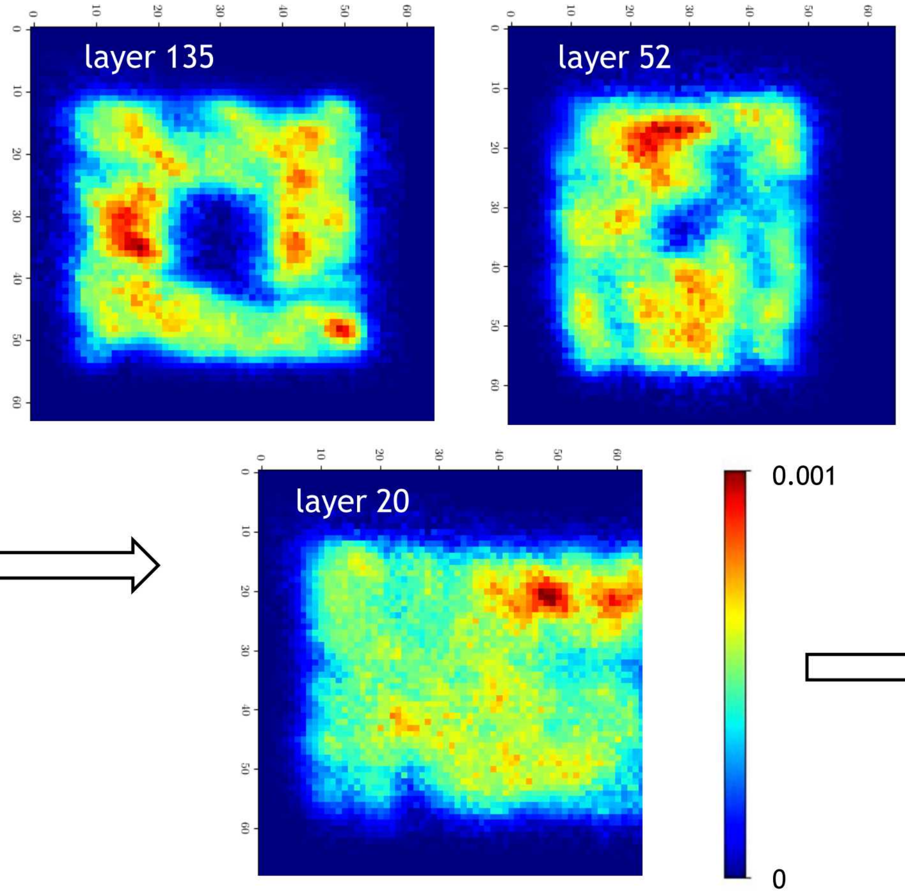


estimated temperature profile

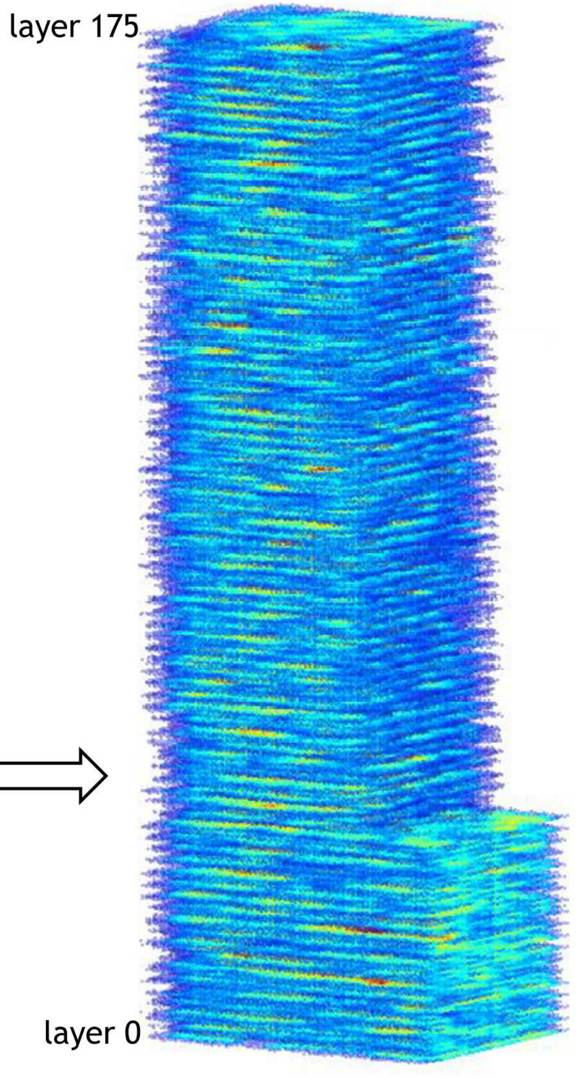
Mapping Volumetric Thermal Inputs



1) Sum temperature at every pixel in every image in an entire layer



2) Layer temperature maps are normalized to their maximum temperature sum



3) Assemble layers to generate volumetric part map

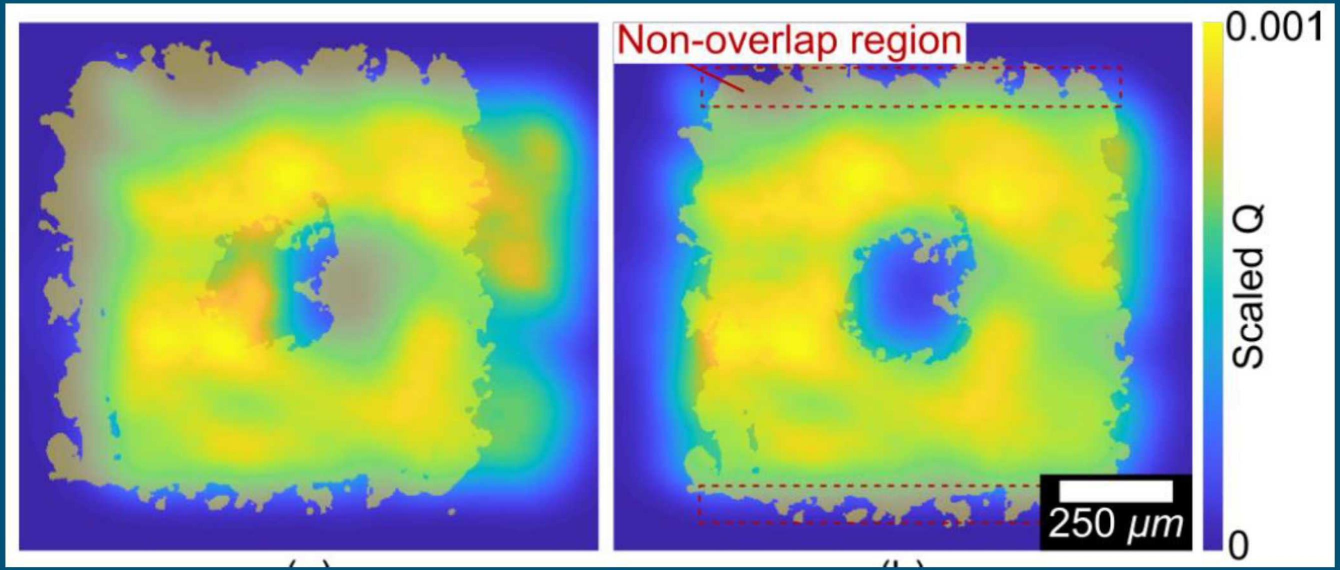
Data Registration

Disparate spatial resolutions & aspect ratios

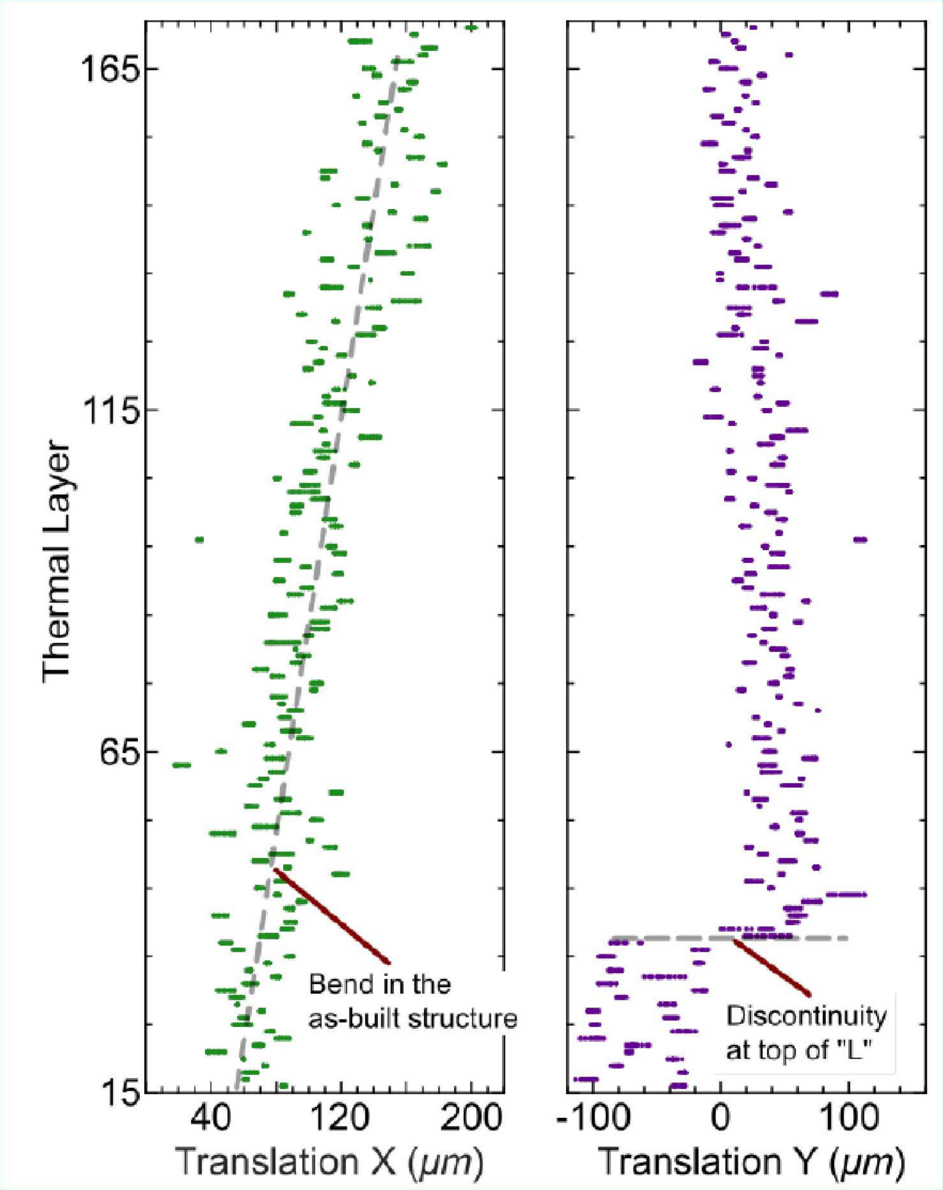
- layerwise pyrometer data scaled to μCT using bilinear interpolation

Part distortion

- requires linear translations in X & Y of pyrometer data
- top surface is Z = 0 since EDM removes bottom geometry



overlap error near part top (left) improved after registration (right)



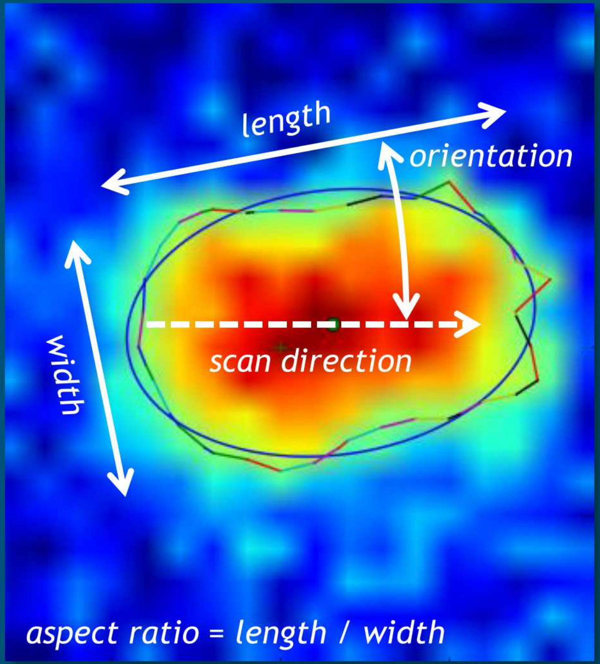
Identifying Melt Pool Outliers

Calculate melt pool characteristics (length, width, orientation, …)

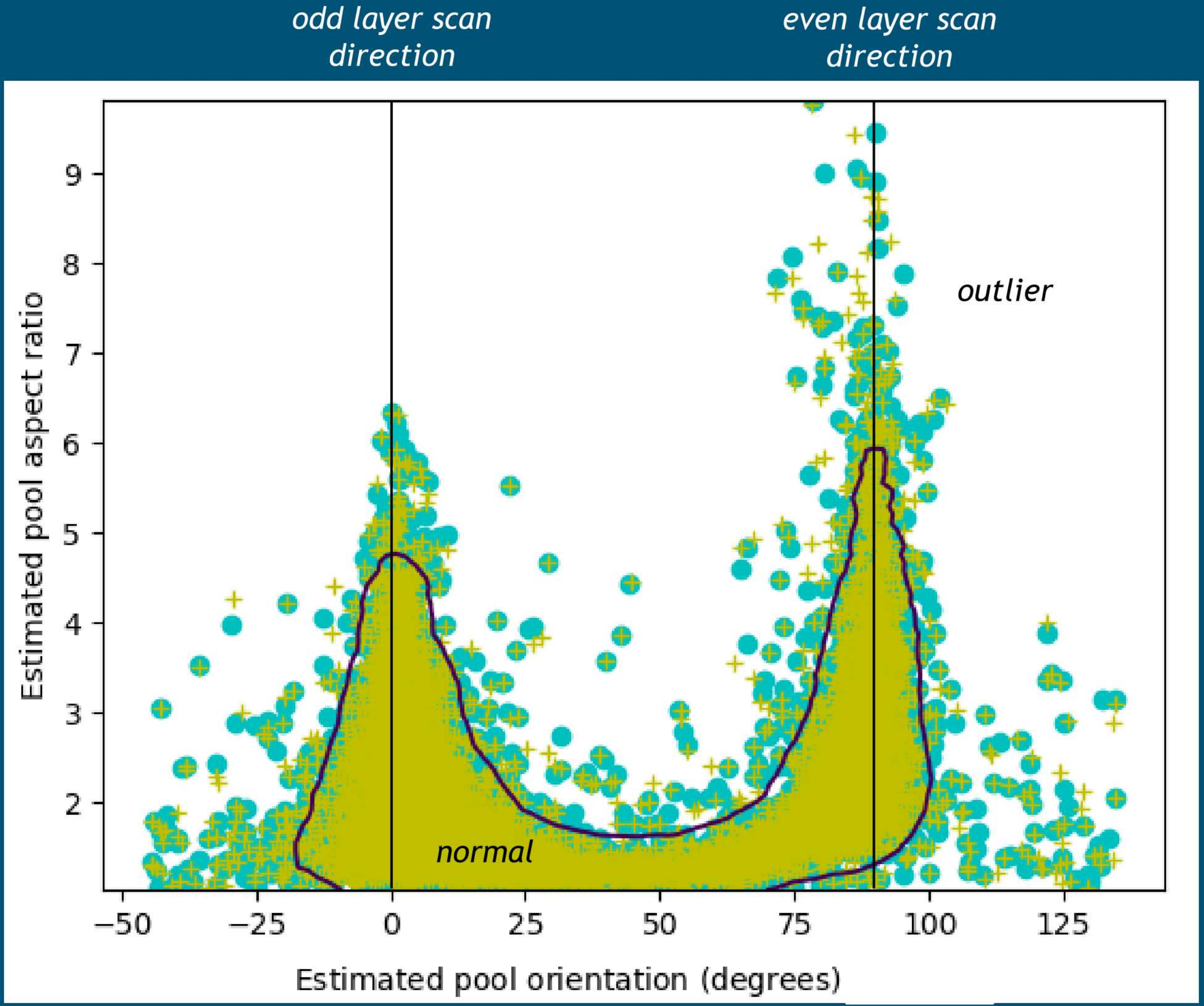
- aspect ratio vs. orientation determined valuable

Classify normal & outlier melt pools by neighbors

- outliers had <50 neighbors within a search region
- 457 outliers identified



melt pool characteristics

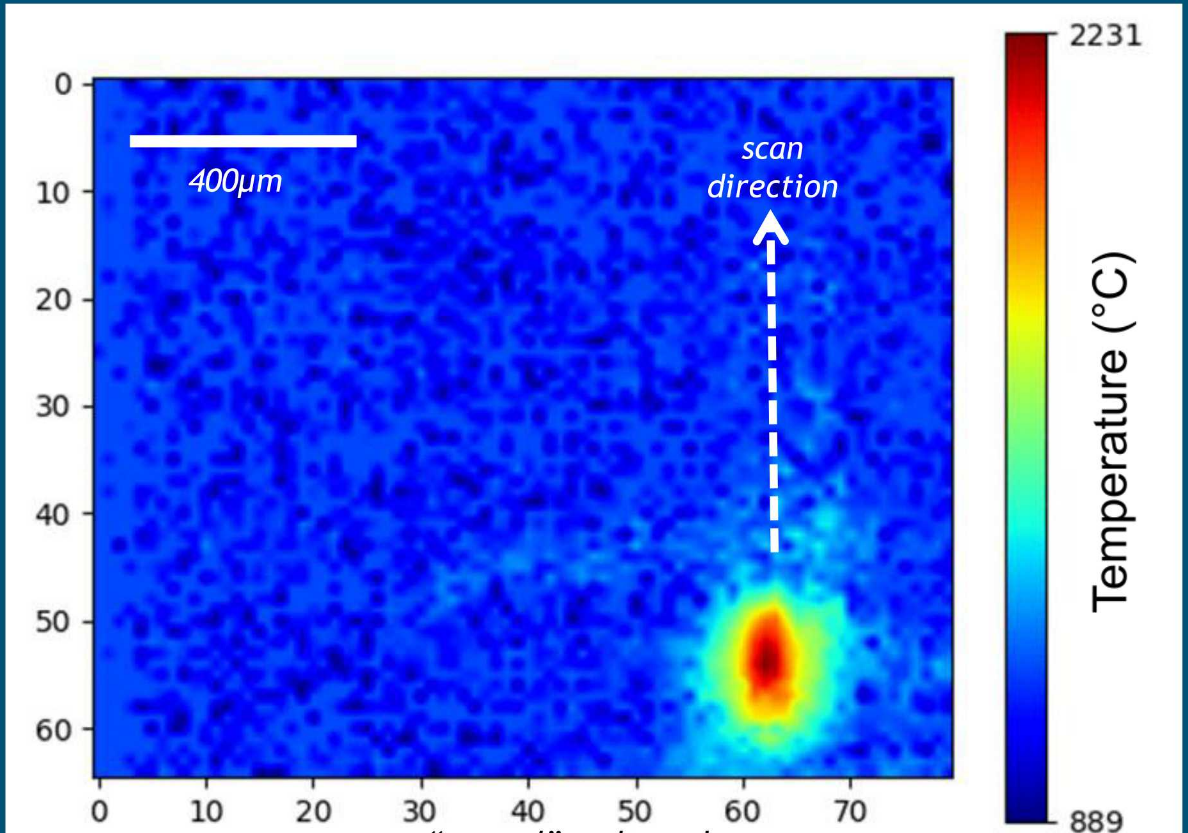


Melt Pool Outliers

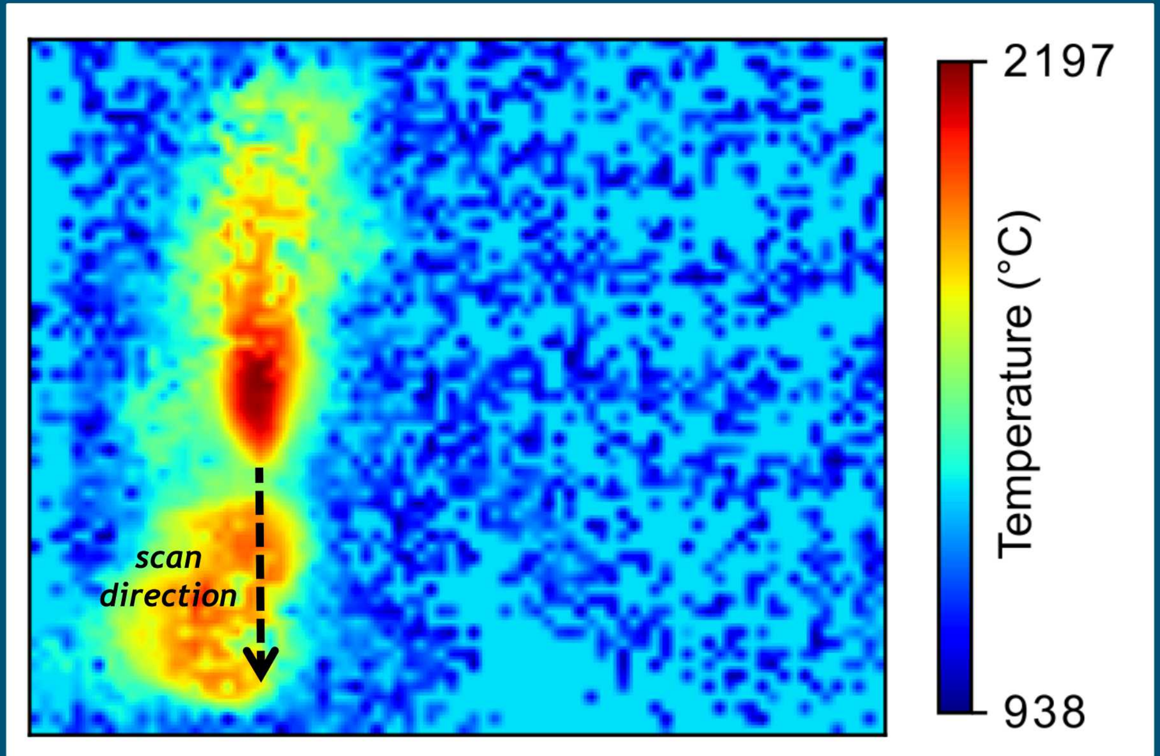
Normal pools are elliptical, symmetrical & aligned to scan direction

Outliers are not

- orientation angle outliers most likely signify spatter
- aspect ratio outliers may signify overheating / keyholing

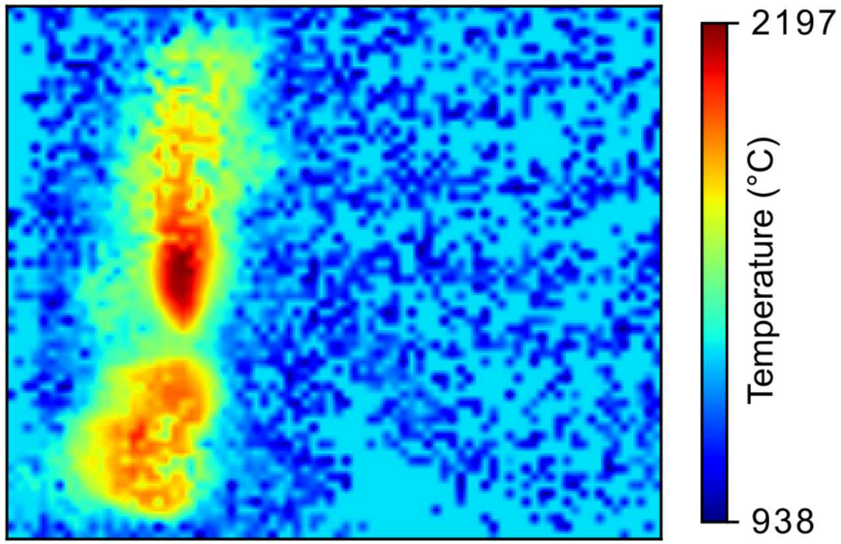


“normal” melt pool

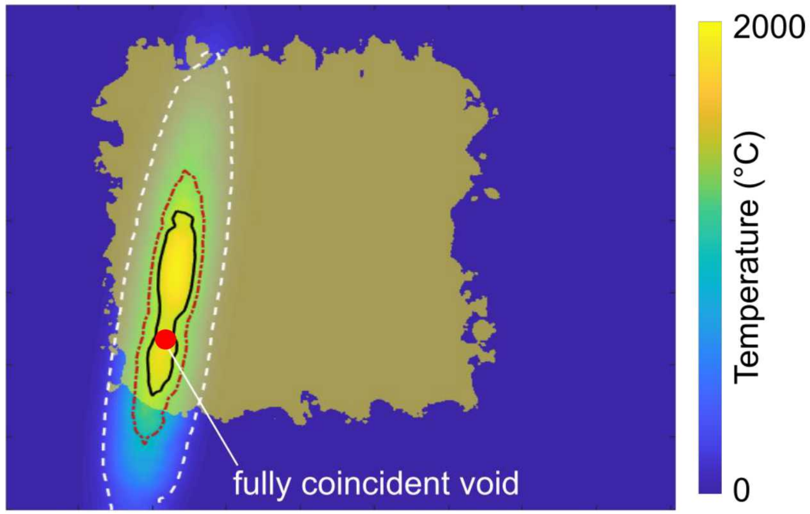


“outlier” melt pool

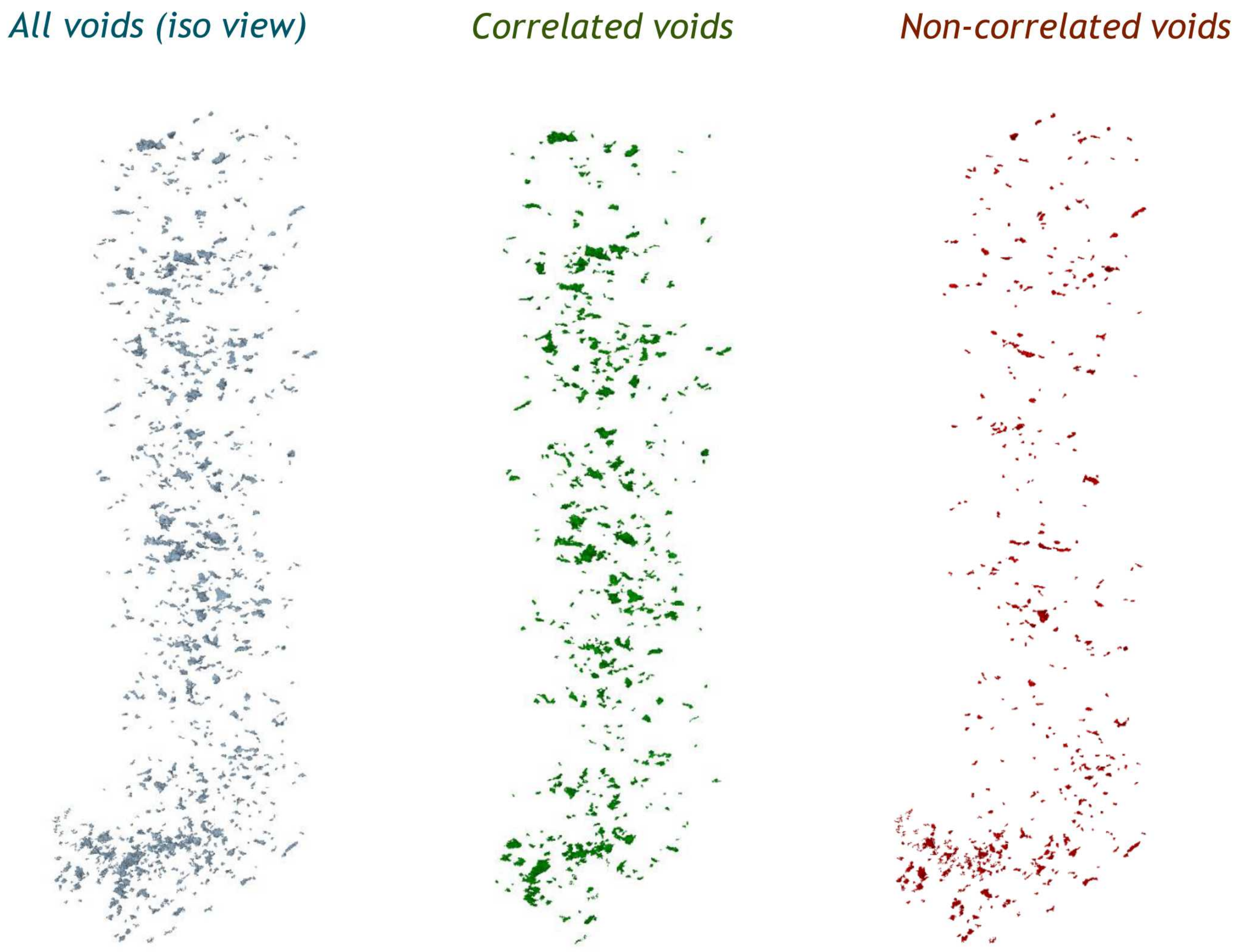
Correlating Pores w/Outlier Melt Pools



"outlier" melt pool

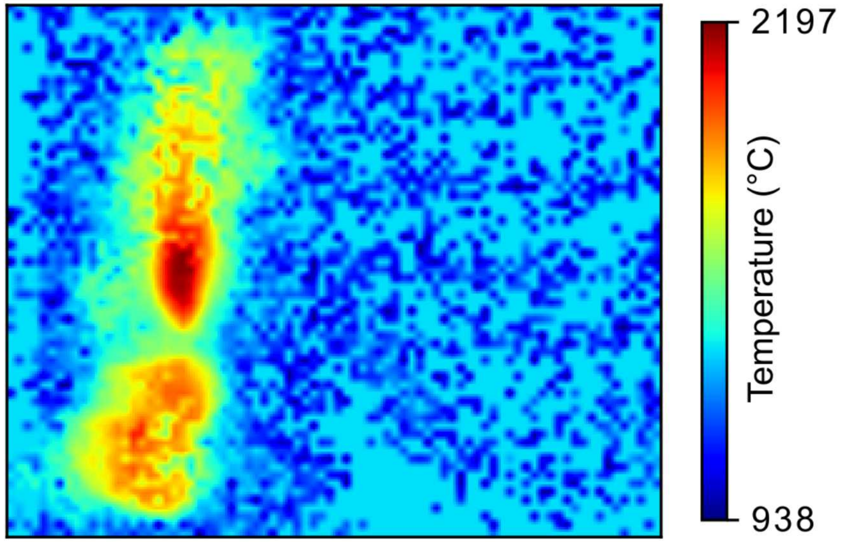


overlay of melt pool contour with pore location

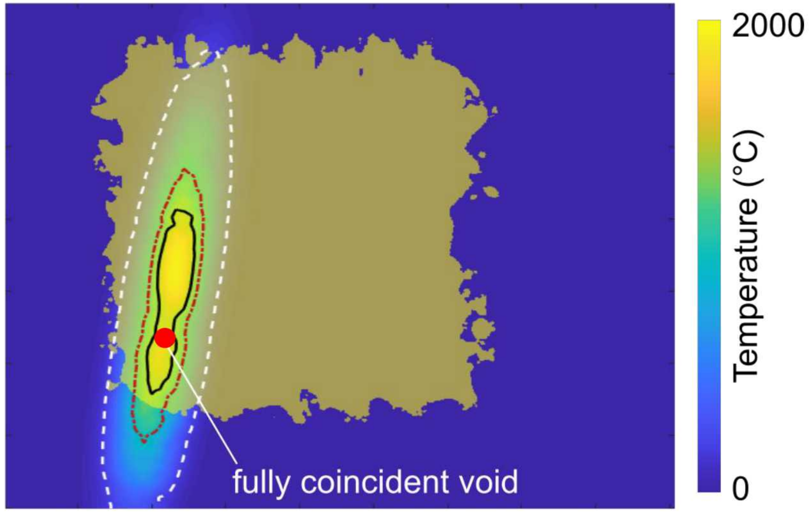


Correlation established if pore(s) is located within search region surrounding outlier melt pool

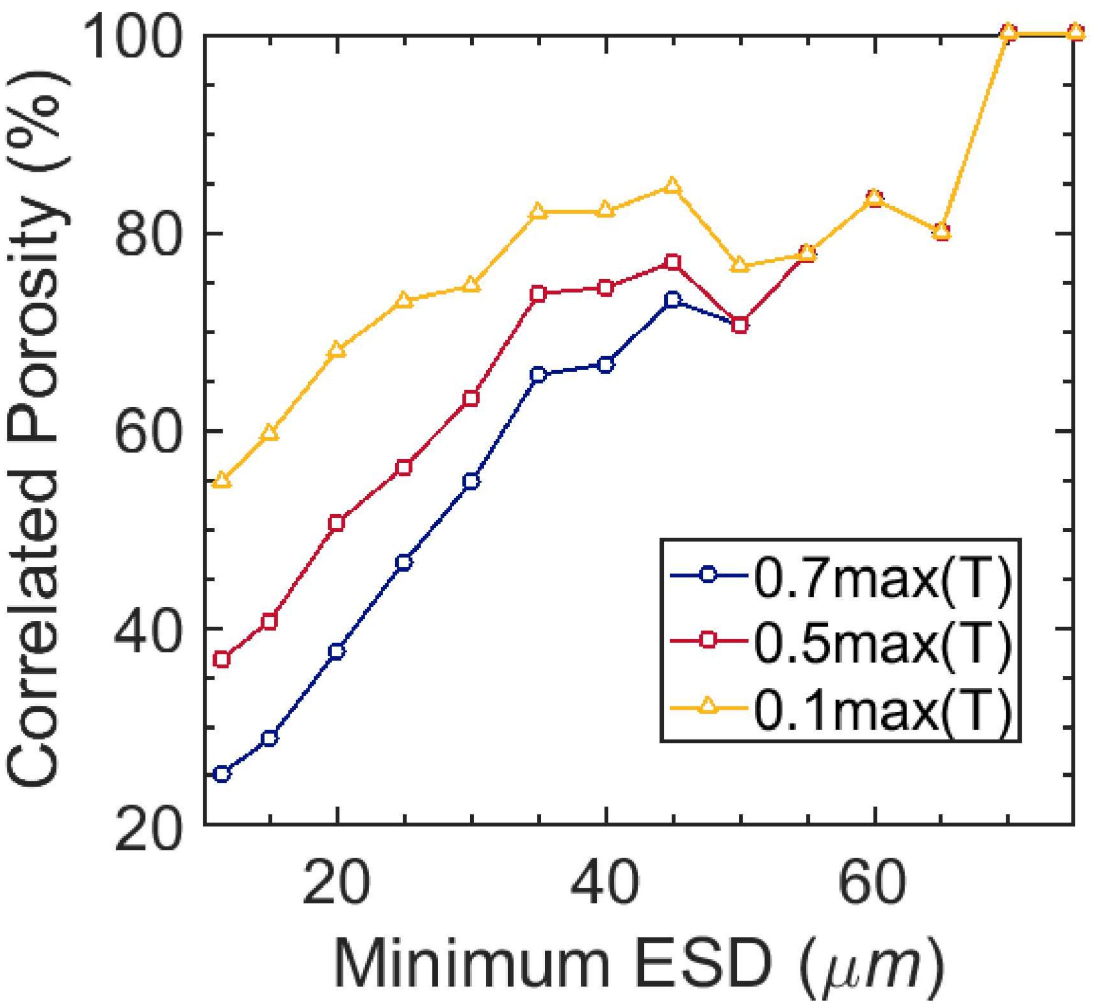
Correlating Pores w/Outlier Melt Pools



"outlier" melt pool



overlay of melt pool contour with pore location



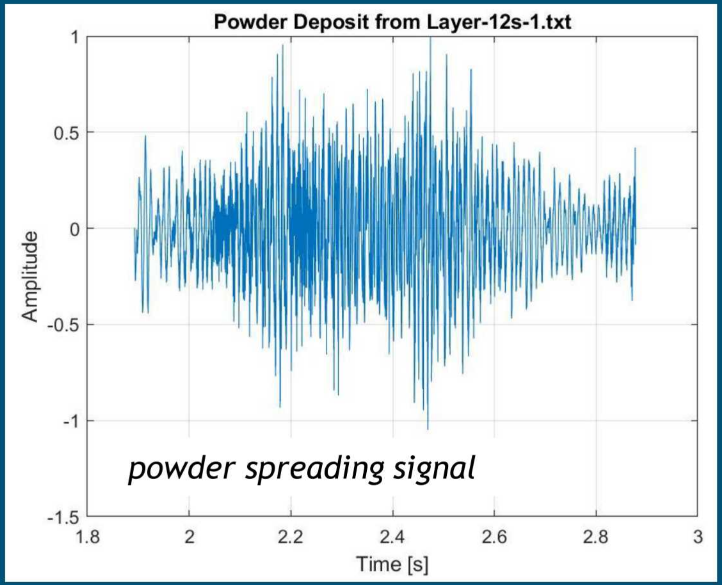
Correlation success increases with increasing pore size

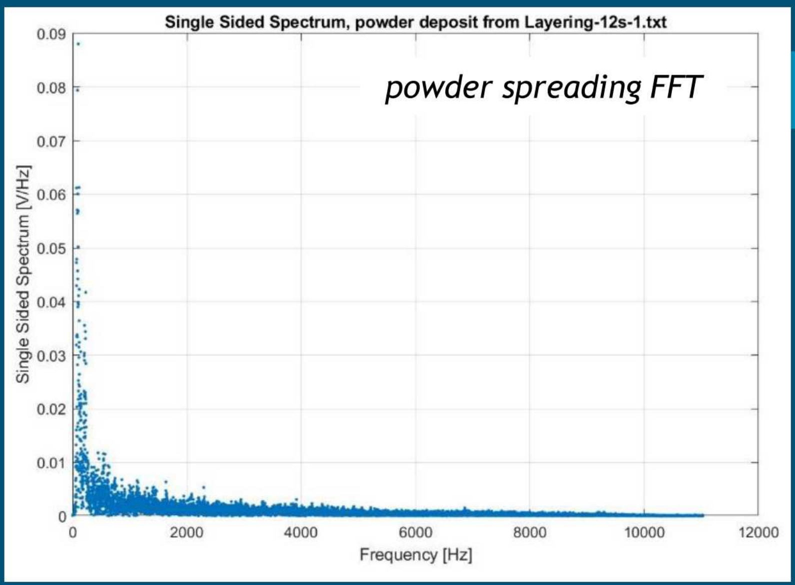
Acoustics

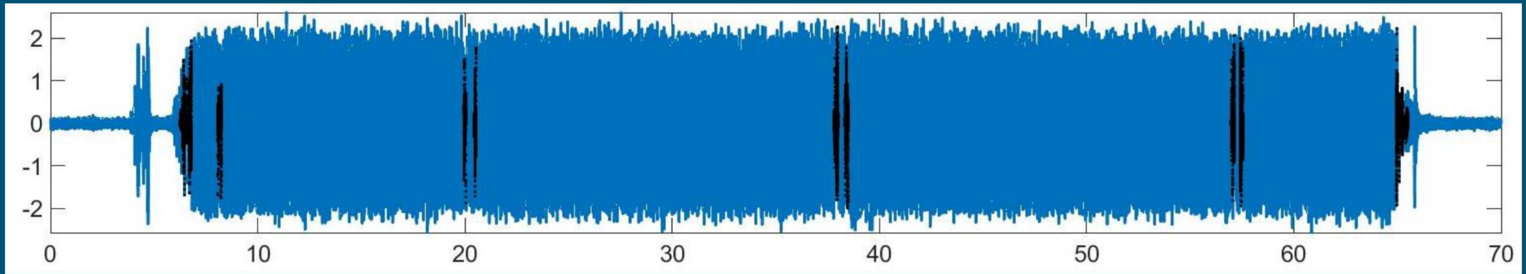
Simple, inexpensive sensors

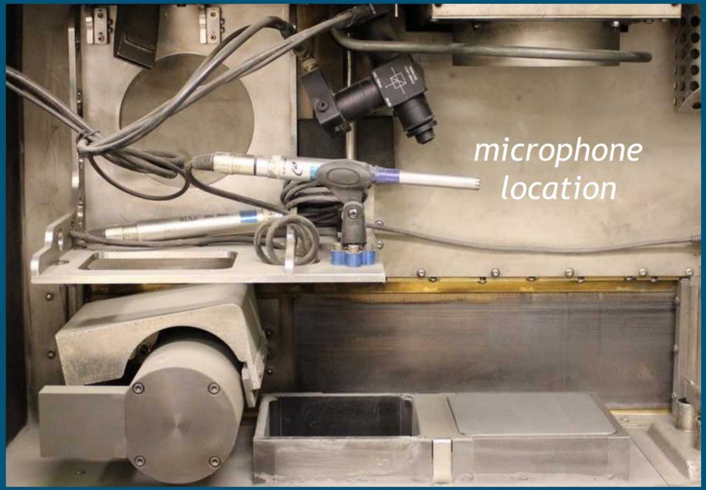
Interrogation potential
- welding prior art
- melt pool, powder spreading, part damage, environment disturbances

Challenging signal deconvolution

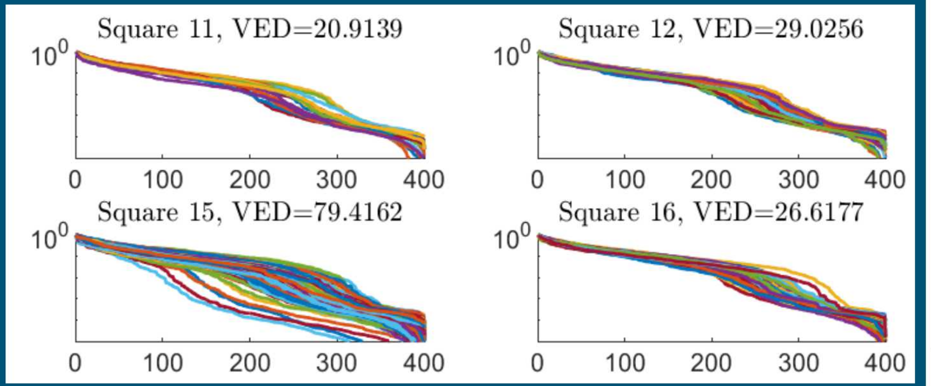


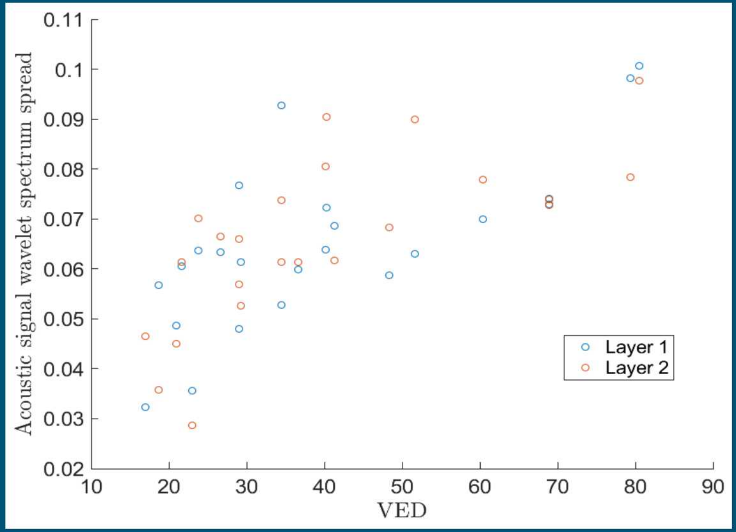






wavelet analysis of varying laser power & velocity



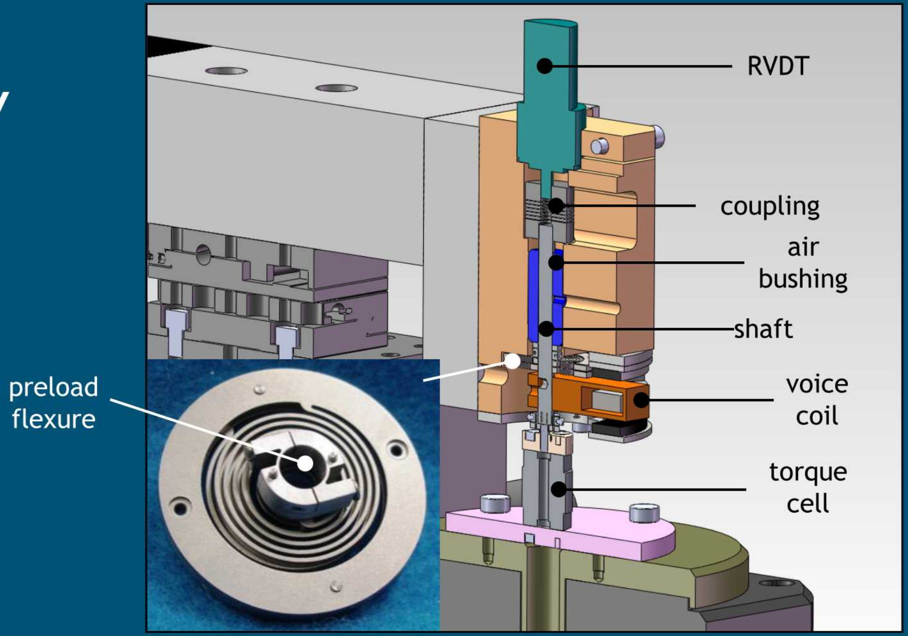


Questions?

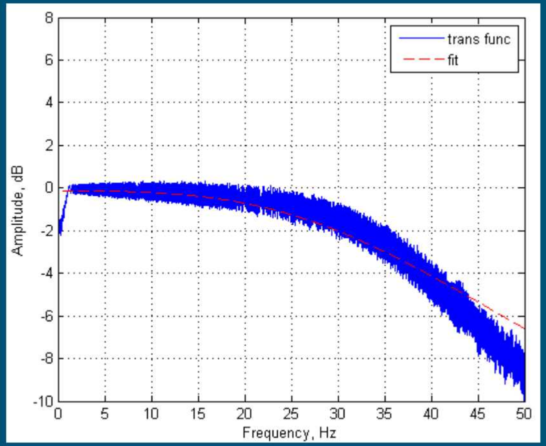
Bradley Jared, PhD

Dynamic Meso-Scale Torsion Spring Metrology

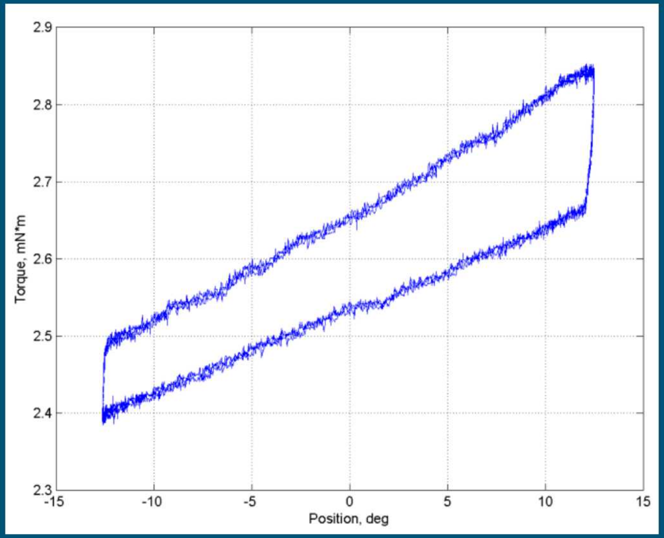
A representative meso-scale torsion spring. The wire diameter is 0.175mm, the spring length is 3.8mm, the coil diameter is 2.5mm, and the wire material is Elgiloy.



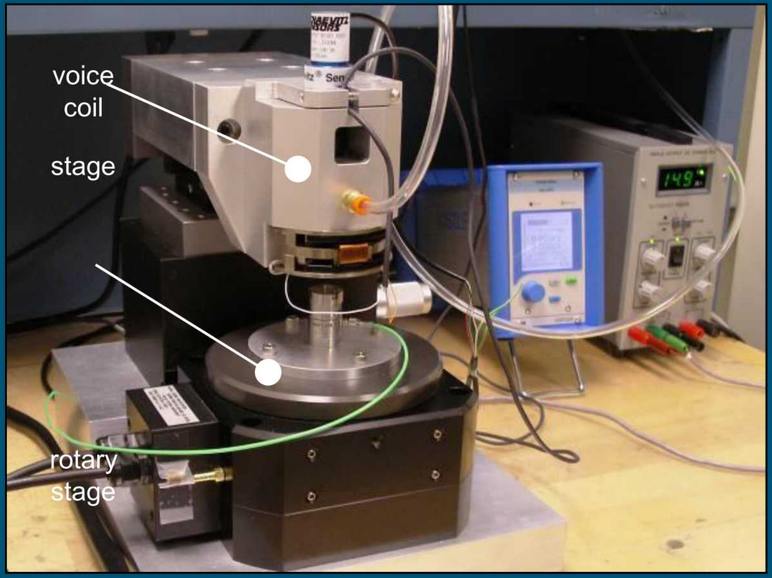
A cross-sectional view identifying critical elements of the actuation mechanism.



Voice coil actuator PID closed loop transfer function.



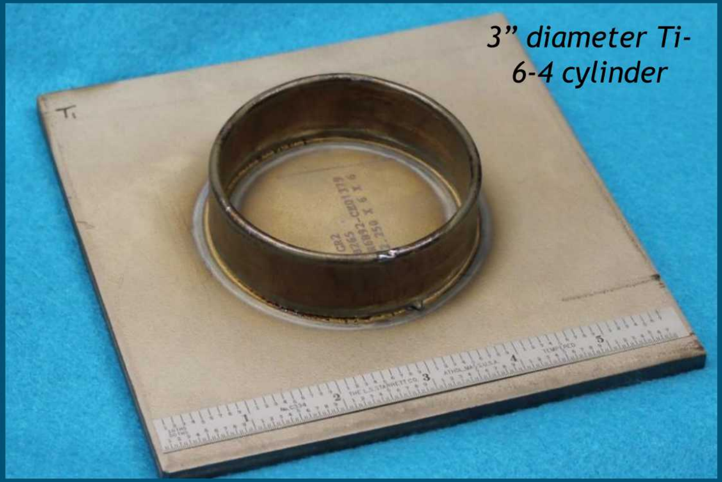
Torsion spring data from a 1Hz, ±12.5° sine wave with a 82.5° preload.



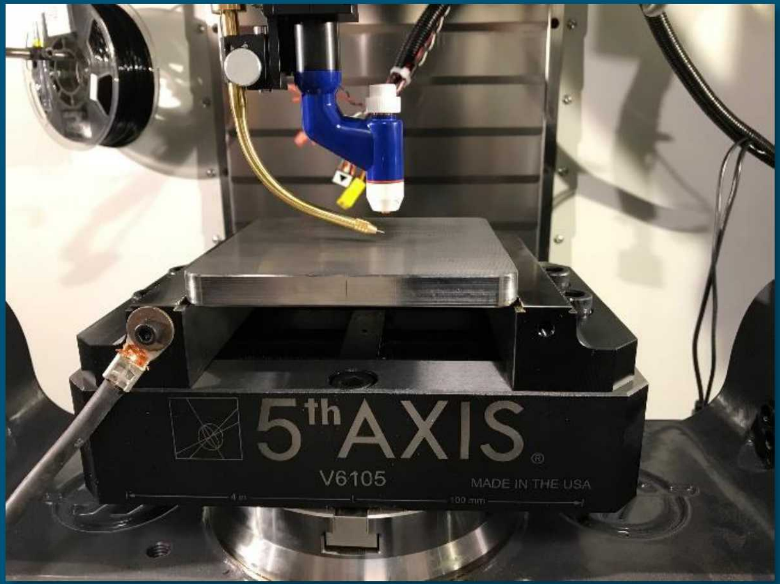
The prototype system for the measurement of meso-scale torsion springs.

Wire Feed

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




HAAS VF2 mill-turn

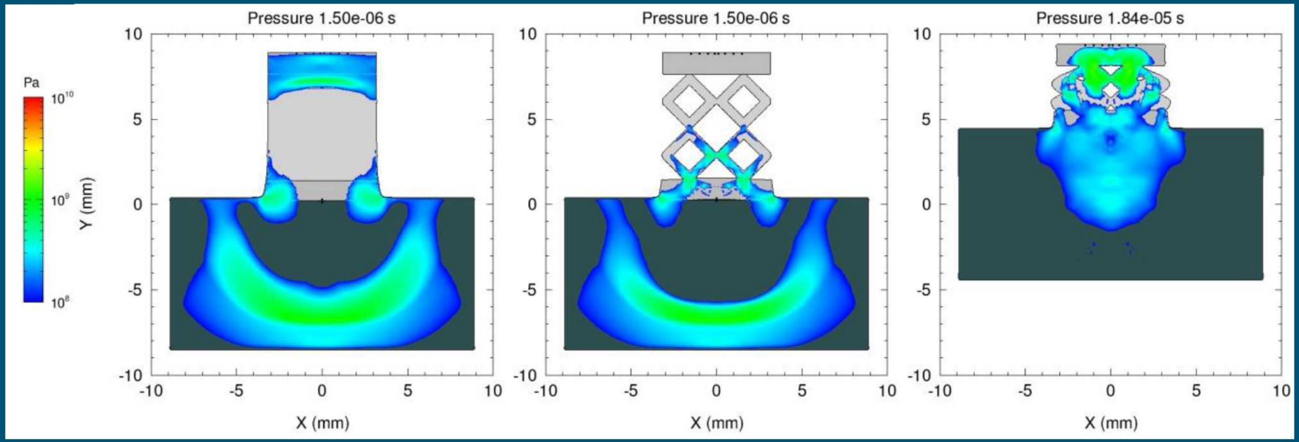


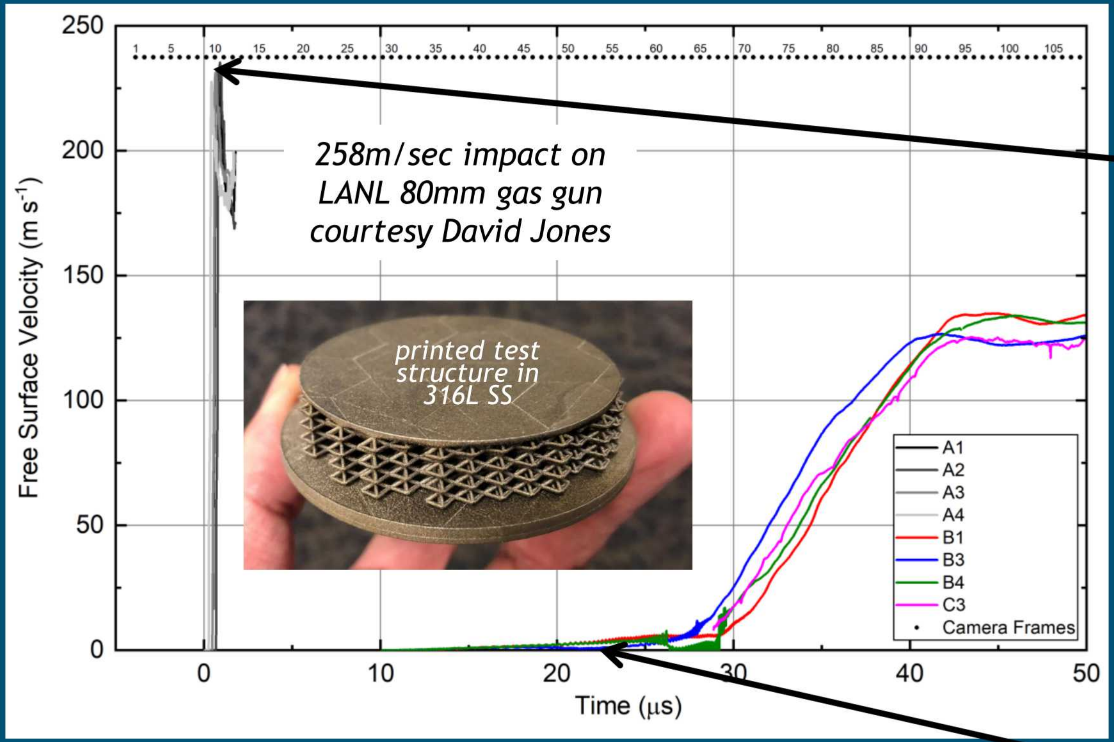
Ti-6Al-4V printing

Shaun Whetten, Ray Puckett

Dynamic Impact

baseline: shock arrives 1.5μs after impact (left)
lattice: no shock @ 1.5μs (center), shock arrives @ 18.4μs (right)





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 ultra-fast laser processing, precision machining and laser-powder bed fusion (L-PBF). Application exemples include meso-scale springs, freeform optics, topology optimized structures and hierarchical materials for impact mitigation.

While complexity may be available and desired in component material and geometry, complexity introduces costs that are inevitably accrued during development, qualification and inspection activities. Immature industries and processes routinely address this complexity using heuristics, human expertise, administrative controls, experimental validation and/or ex-situ inspection. Such approaches can be expensive and prohibitive in terms of time and resource commitments. Instead, 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.

L-PBF is one of the most popular forms of metal AM as it affords designers the ability to fabricate complex structures such as lattices and topologically optimized structures. The adoption of L-PBF in high consequence applications, however, has been relatively slow due to process complexities and uncertainties in resultant material properties. 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. A desired future state is real-time control of L-PBF melt pools to continue process improvements and to reduce defects. A further goal is to inform and support an accelerated qualification paradigm for high consequence parts whereby development and production cycles are reduced dramatically over current timescales and resource allocations.