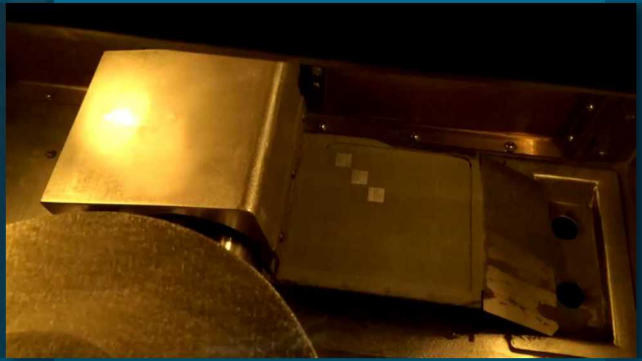
Sandia National Laboratories

SAND2020-0734PE

Process Plateaus, Not Peaks, in Laser-Powder Bed Fusion



PRESENTED BY

Bradley Jared

Josh Koepke, Jarett Tigges, David Saiz, Michael Heiden

U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Motivation

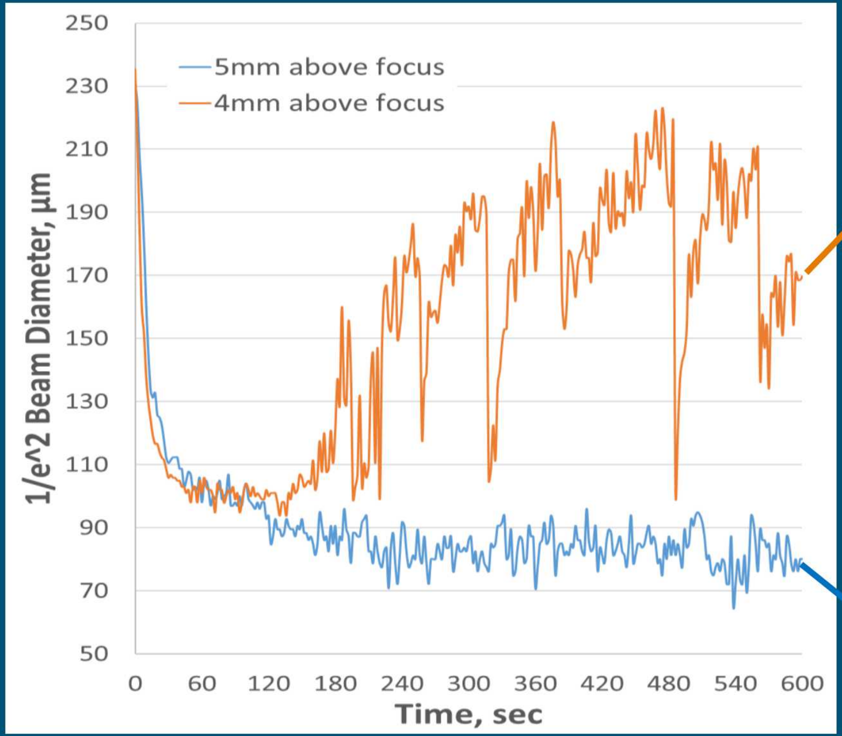
AM metal qualification for NW remains a challenge…

Machine metrology is a critical

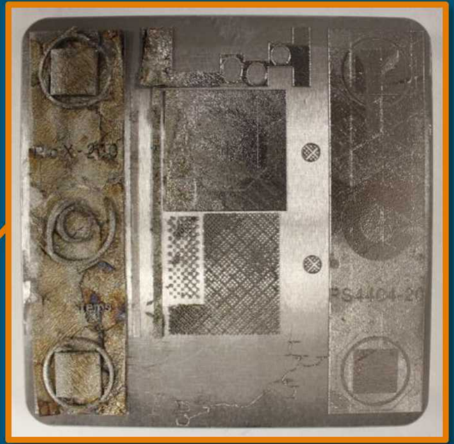
What are process tolerances & margins?

Does a truly optimal process state exist?

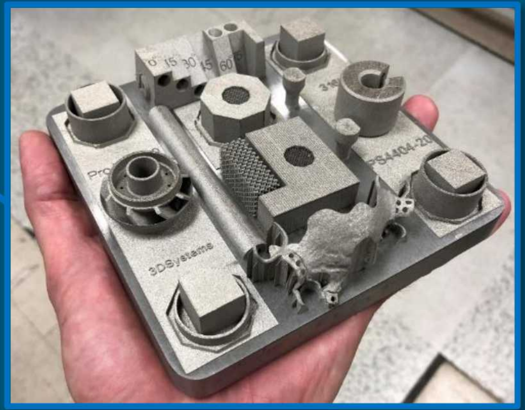
Can optimization be performed faster & cheaper?



beam diameter variations w/original f-theta lens



nominal focus offset



5mm focus offset

Our Approach: Explore Process Space

Parameters

- 316L stainless steel
- laser power: 10-240W
- velocity: 50-2800mm/sec
- layer thickness: 30, 40µm
- average powder diameter: 15.0, 25.0µm
- laser focus offset: -1.5mm below focus to +3.5mm above

Experiment forms

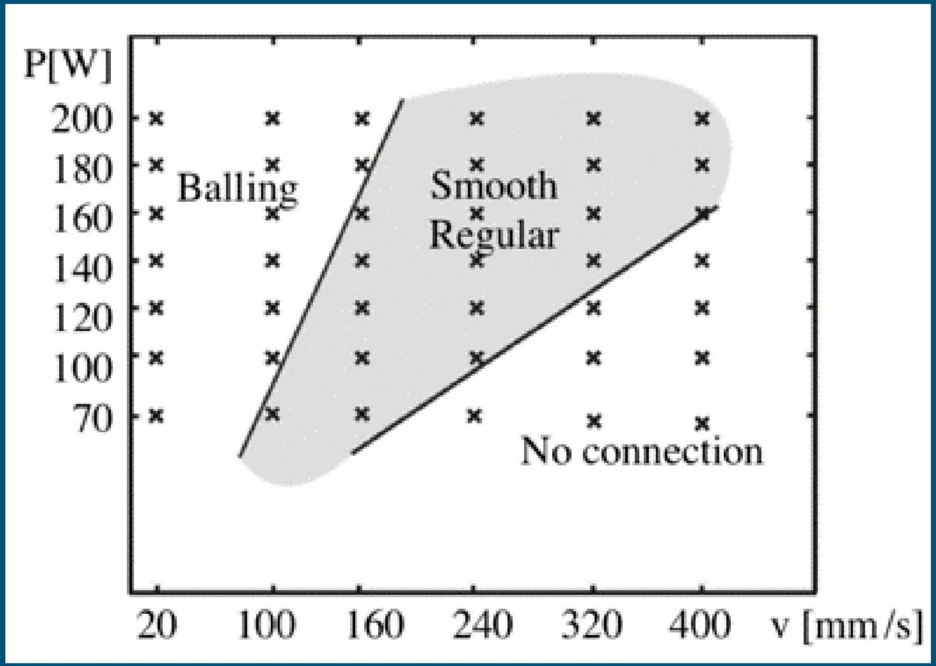
- line scans, area pads, density cubes, HTT tensile, Charpy

Performance metrics

- surface finish, form error, density, tensile properties, Charpy toughness, microstructure

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

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



*Kruth et al, (2008), **Rapid Prototyping Journal***

Line Scans

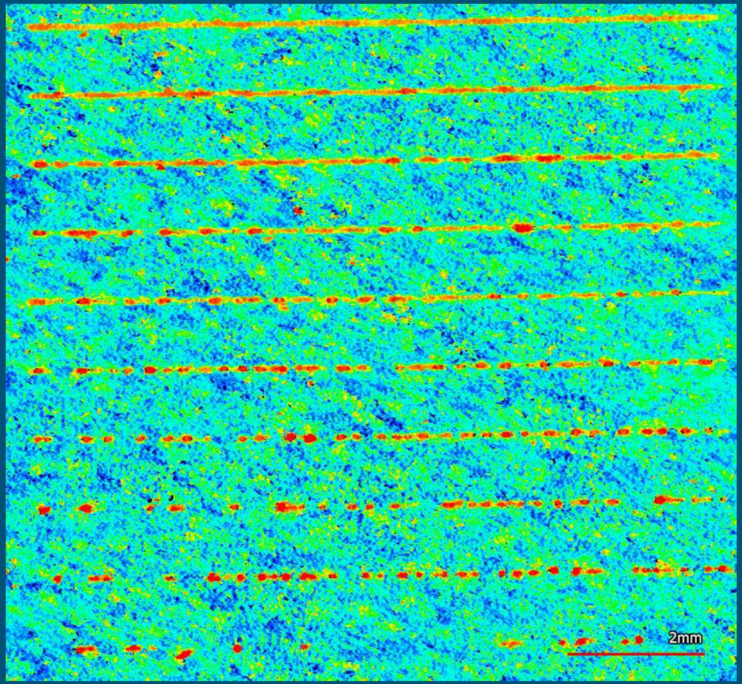
Substrates: bare plate, powder layer on 20 layer AM pad

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

Establish relevance of simple Rosenthal model

Simplistic first step, but quick & informative

- capturing melt pool geometry via metallography
- useful to define nominal process boundaries for any material

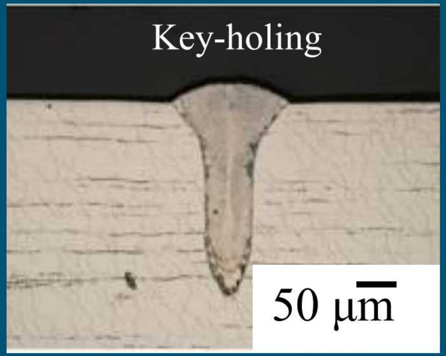


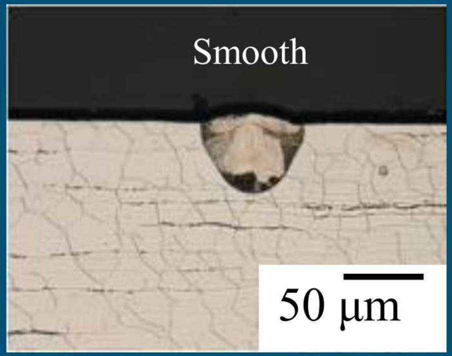
100 W, 250 to 2500 mm/s on pad

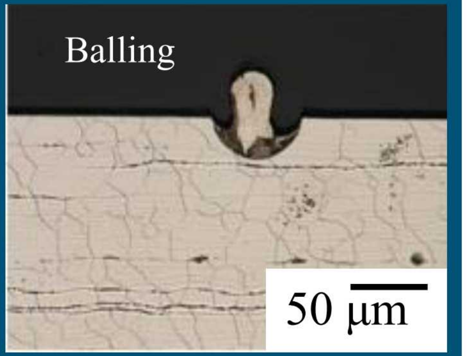
melt pool on plate, 100W, 1500 mm/s

Line Scans: Plate vs. Powder Layer on Pad

on plate



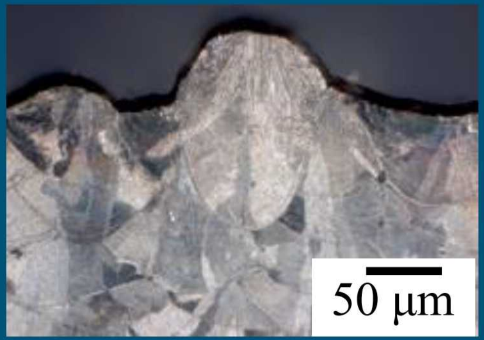




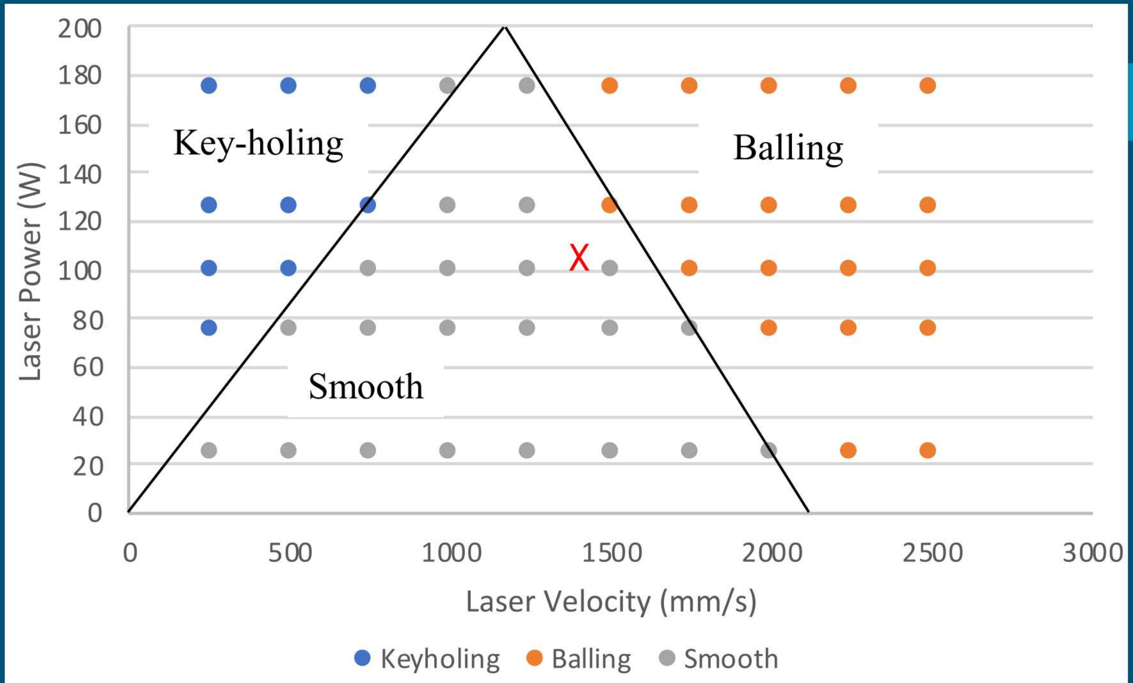
powder layer on pad

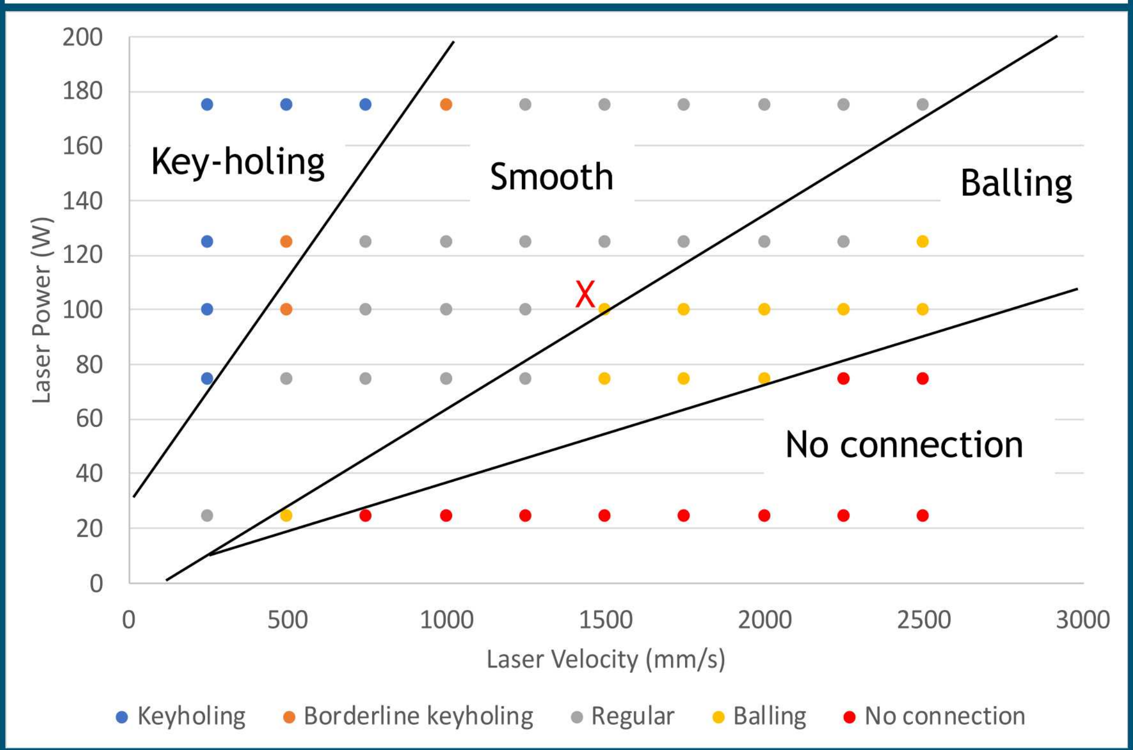
Key-holing

Smooth



Balling?





Rosenthal Model

Predicts heat distribution from a moving heat source during welding

- Provides an estimated melt geometry

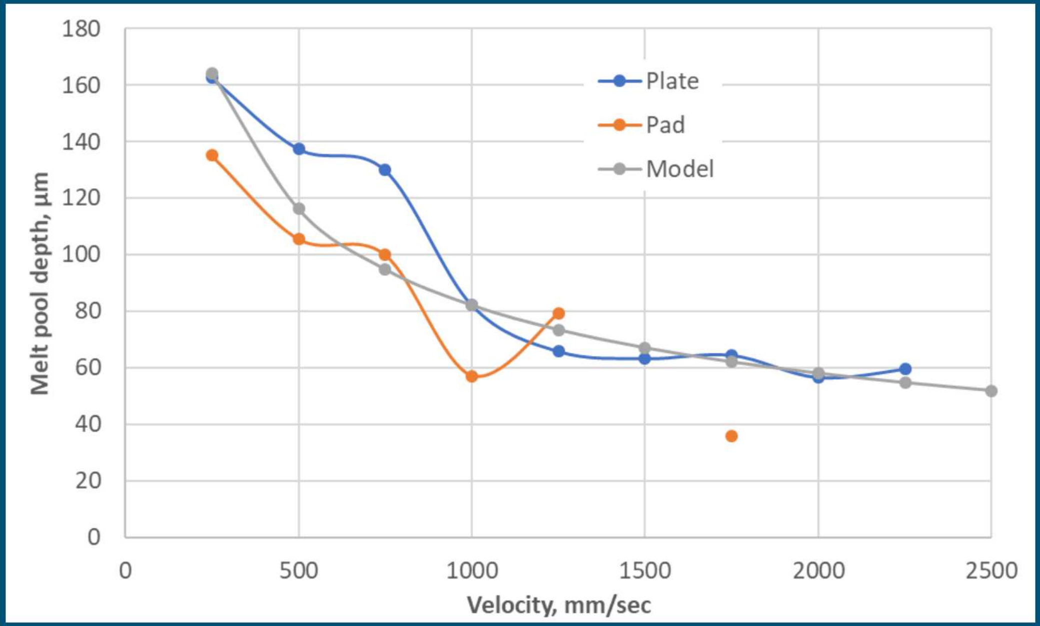
$$T_f - T_0 = \frac{q}{2\pi k R} e^{-\frac{v(w+R)}{2\alpha}}$$

- 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

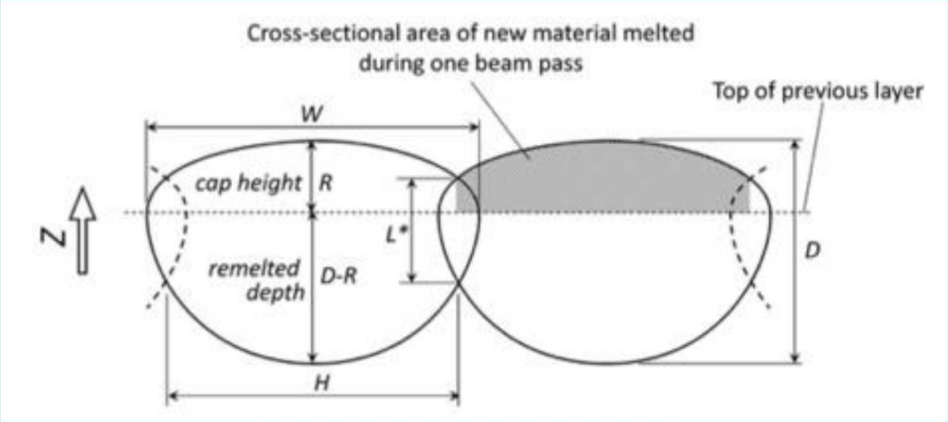
Predicting Density

Criterion for full melting (Tang, et al)

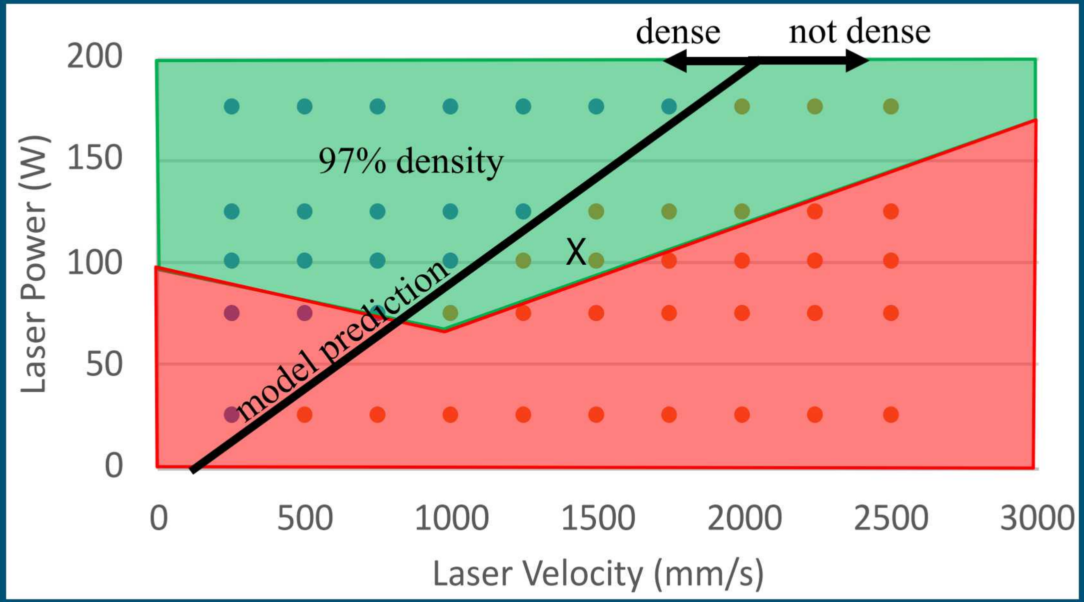
$$(\frac{H}{W})^2+(\frac{L}{D})^2 \leq 1$$

- H – hatch spacing
- W – width (Rosenthal / experiment)
- L – layer thickness
- D – depth (Rosenthal / experiment)

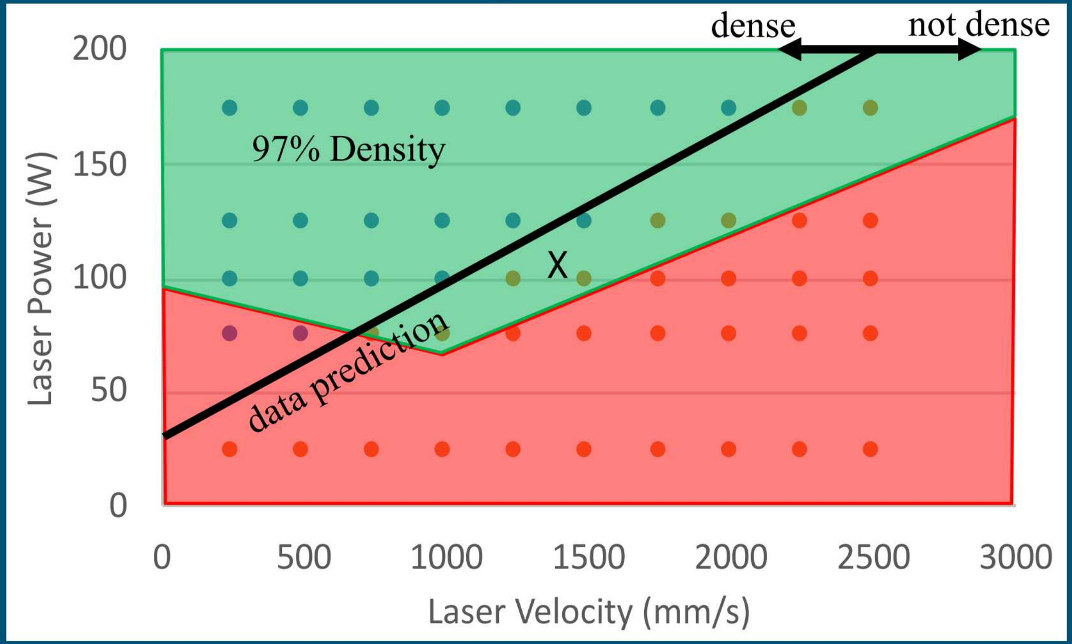
Simple model to explore alternative layer thickness or cross-feed spacing



Tang et al, **Additive Manufacturing**



Material density, cubes vs. Rosenthal model, 30μm layer, 50μm cross-feed



Material density, cubes vs. melt pool on plate data , 30μm layer, 50μm cross-feed

Area Pads

1x1cm pad, 1mm thick, 24 per plate

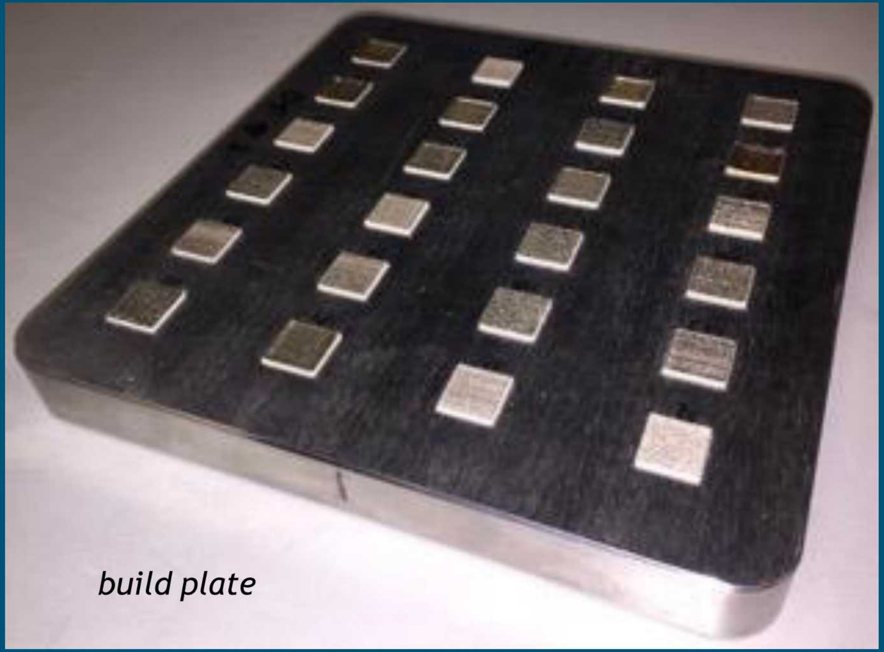
- 7 plates, power, velocity, focus offset, variation across plate

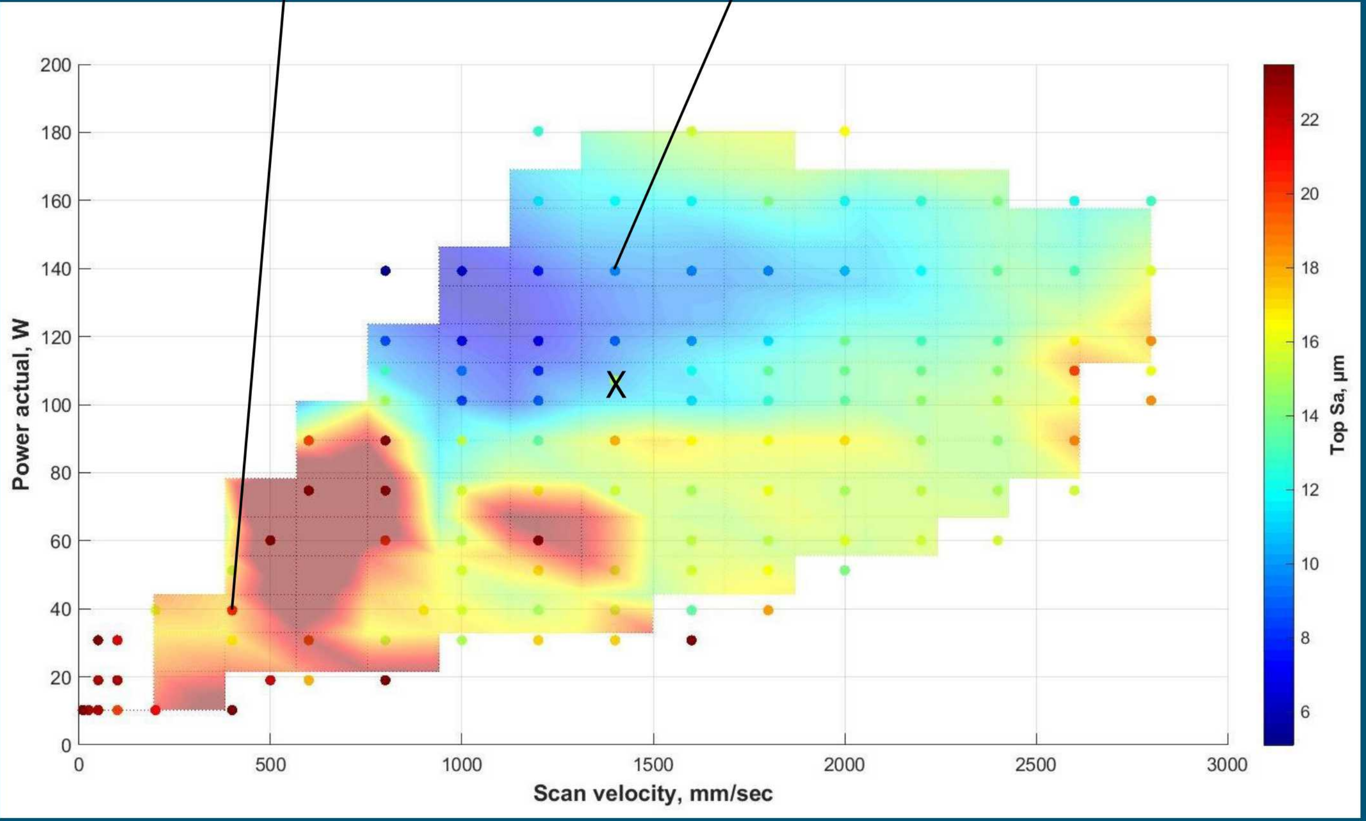
Very simple & fast to process & measure

- form (flatness), low mag, 9x9mm area
- finish, high mag, 2x2mm area

Sa: 40.772µm, 60.1W, 500mm/sec

Sa: 9.506µm, 139.3W, 1400mm/sec





material density, cubes vs. Rosenthal model

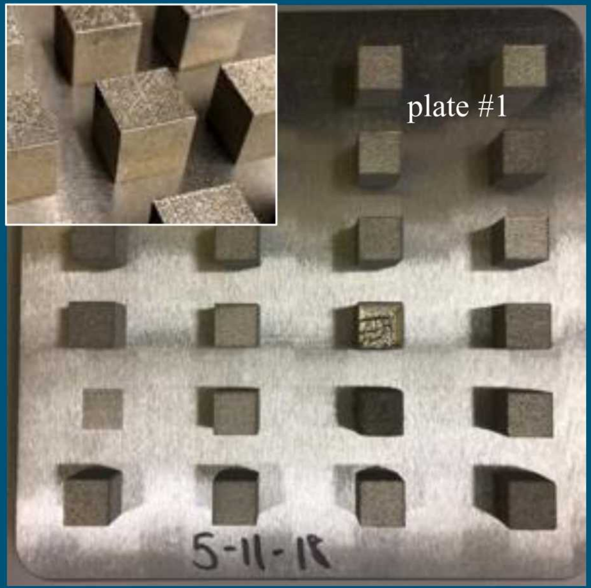
Density Cubes

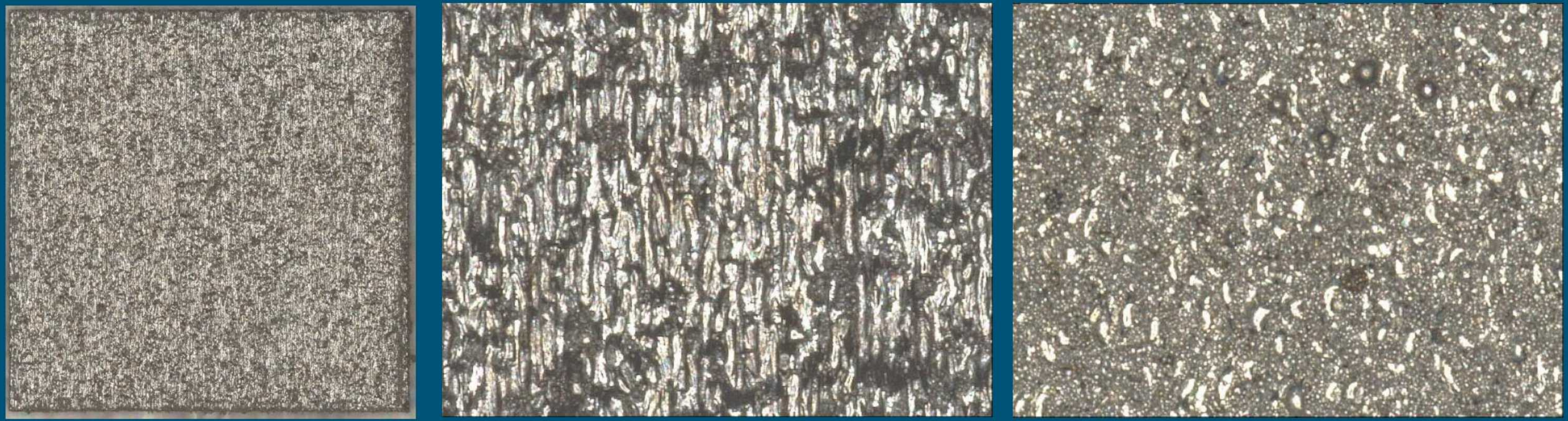
1cm cubes, 24 per plate

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

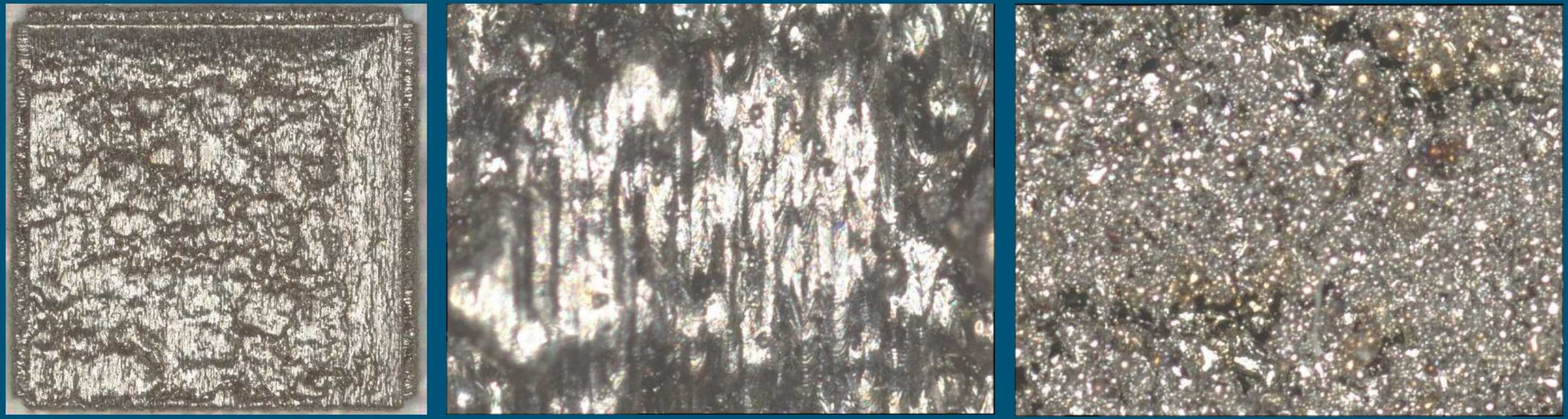
Bulk material measurements

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



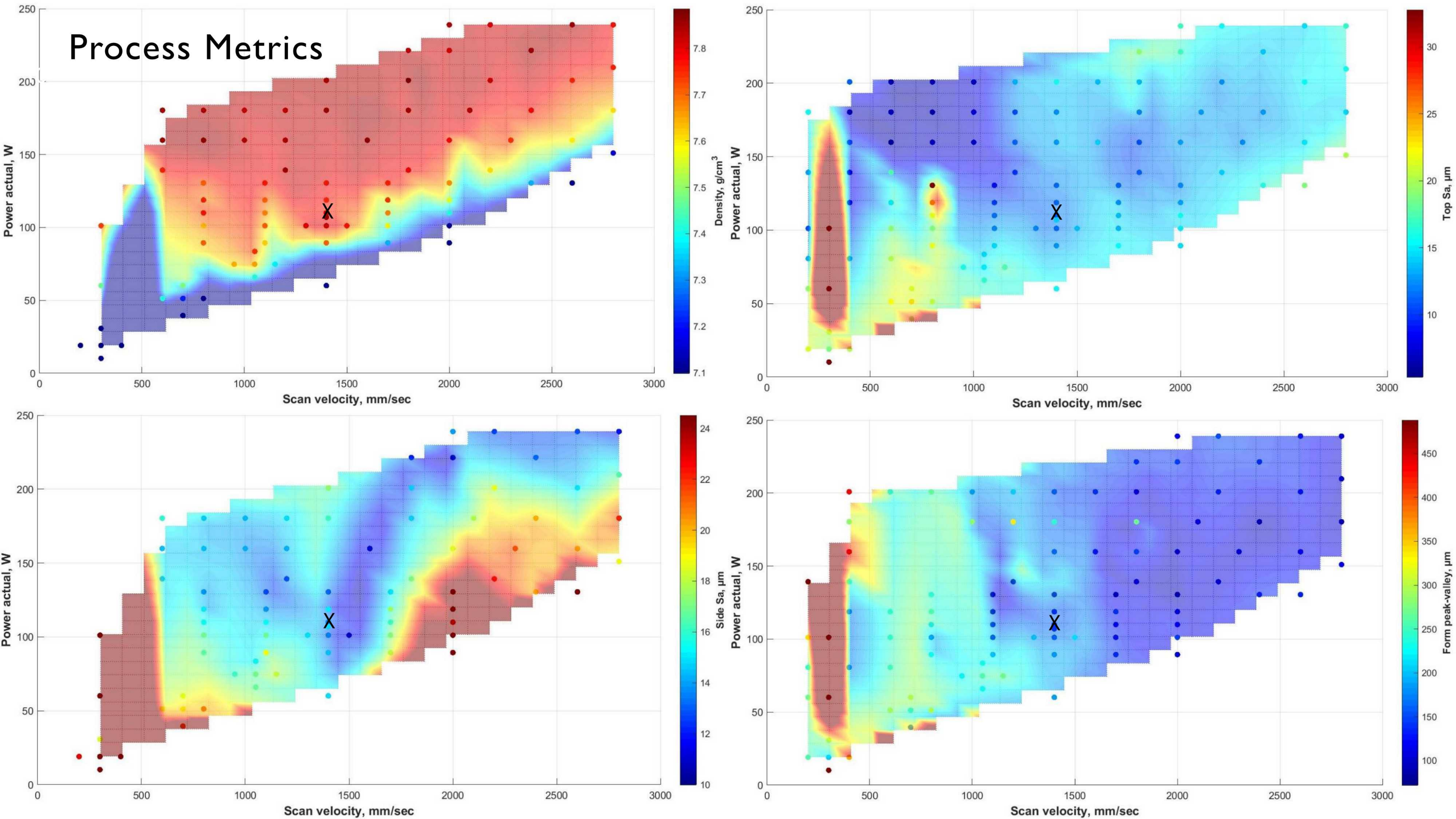


100.2W, 1500mm/sec 209µm Pkk form (left), top 13.5µm Sa roughness (center), side 9.98µm Sa roughness (right)



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

Process Metrics



Material Microstructures, 30µm Layer Thickness

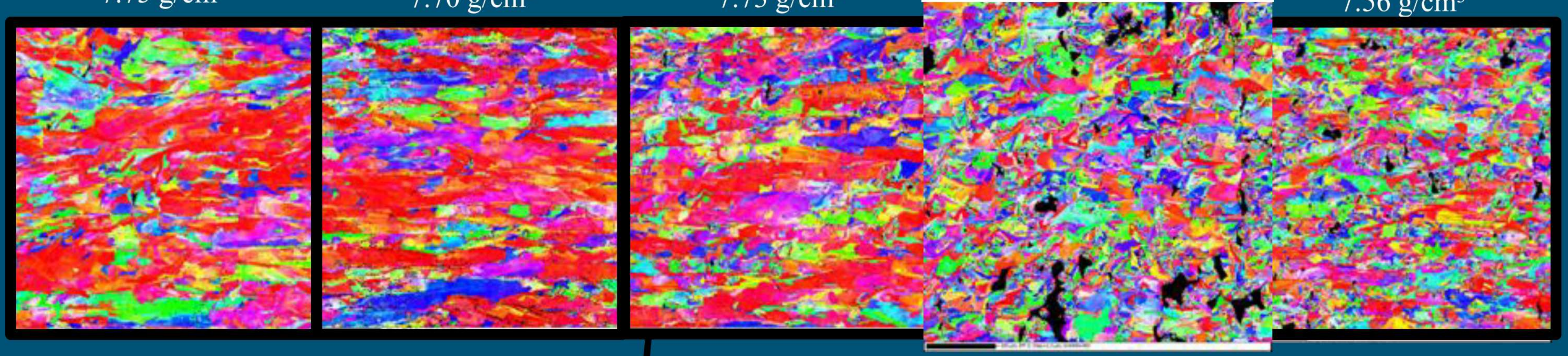
120 W, 800 mm/s
7.75 g/cm^3

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



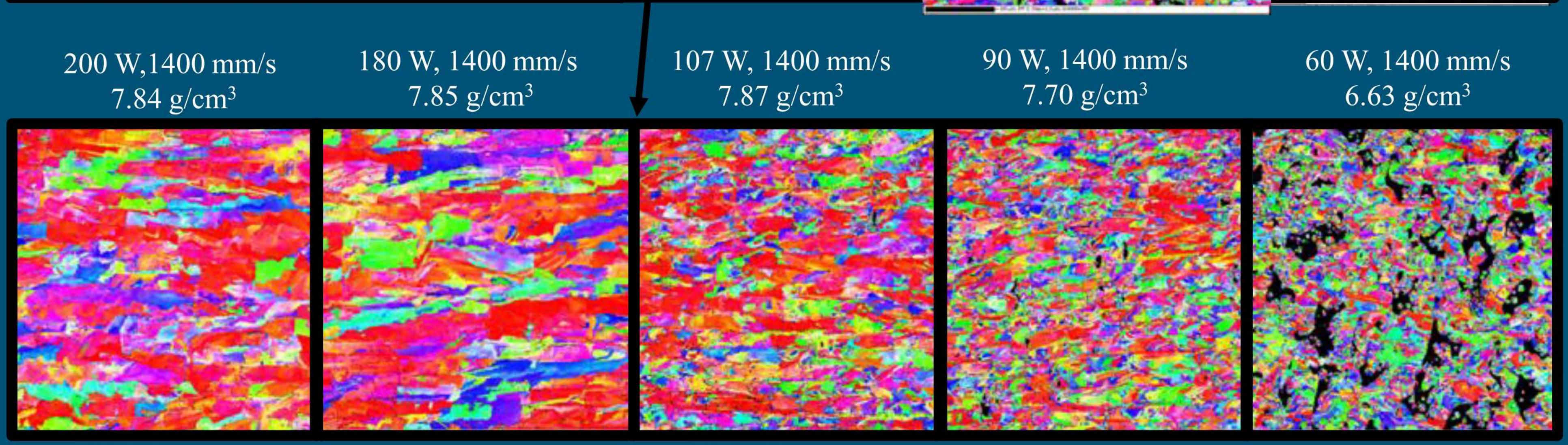
200 W,1400 mm/s
7.84 g/cm^3

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



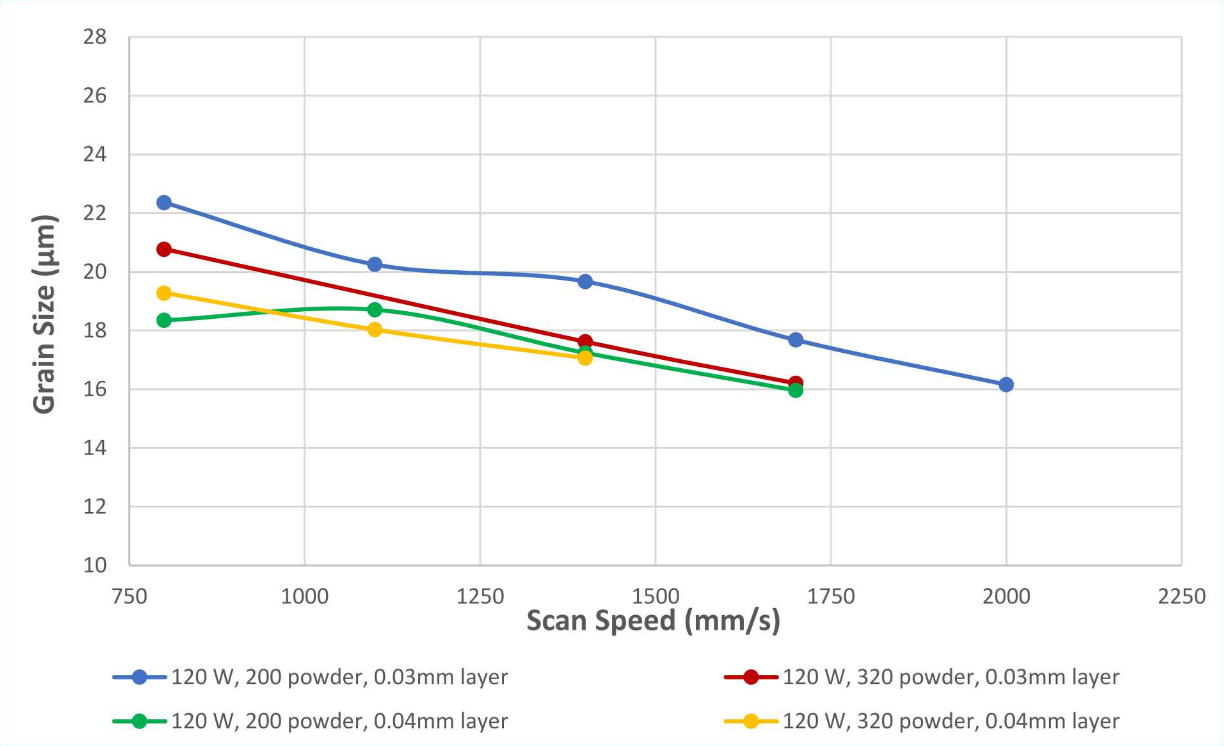
1 mm x 1 mm

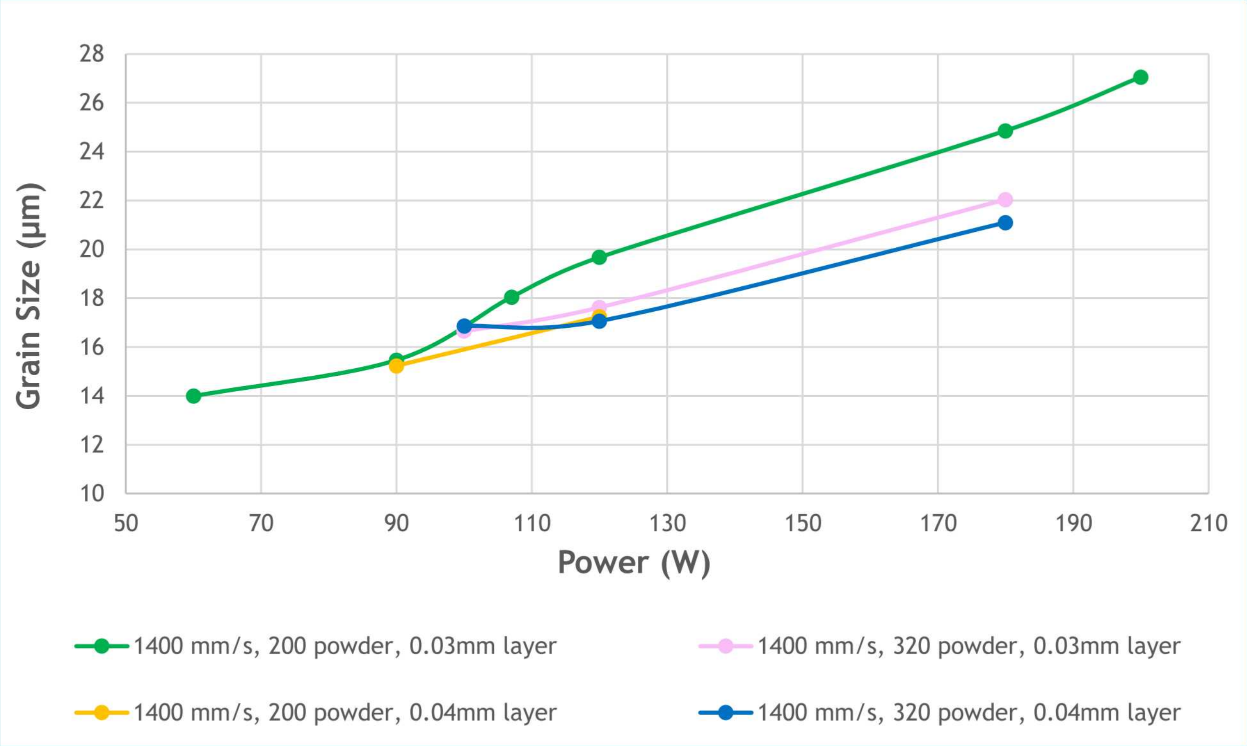
decreasing energy density

Grain Size Varies as Expected with Laser Energy Density

Decreases with increasing velocity

Increases with increasing power



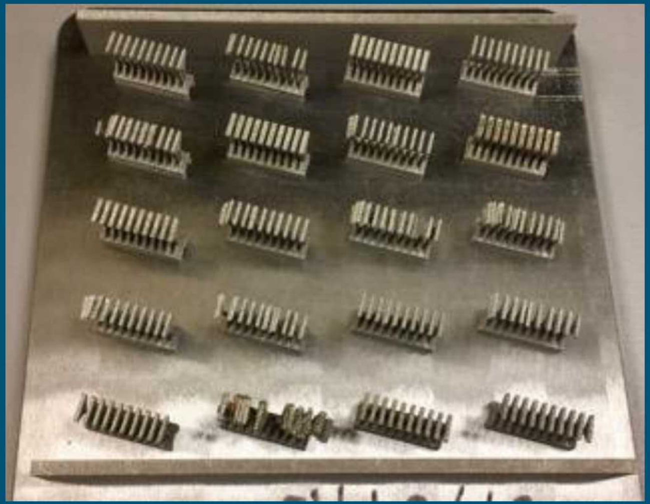


High-Throughput Tensile

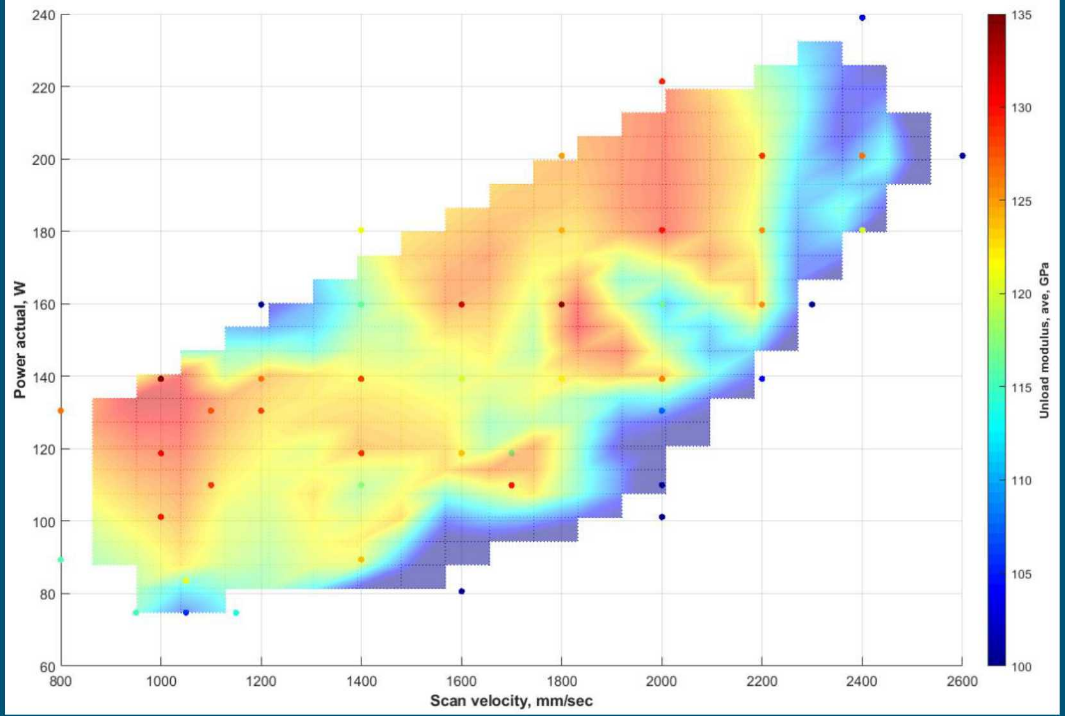
1x1x4mm gauge section, 10 or 25 dogbones/array
- five build plates
- varied power, velocity, powder diameter

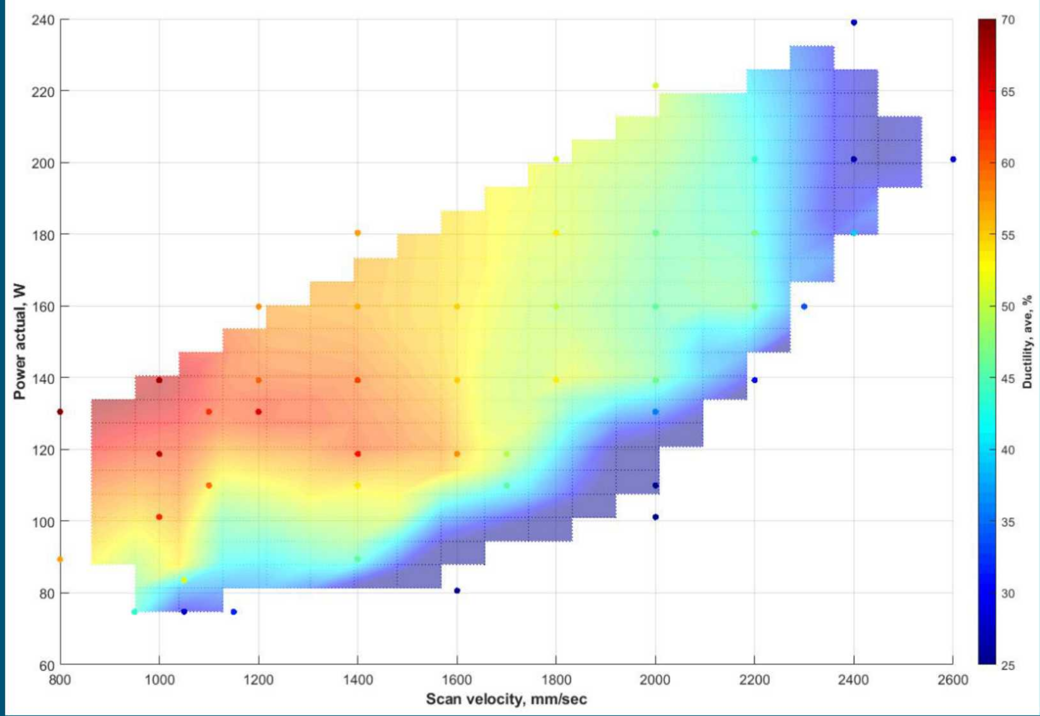
>500 dogbones tested
- density (Archimedes)
- surface roughness
- mechanical properties
  - UTS, YS, modulus, ductility

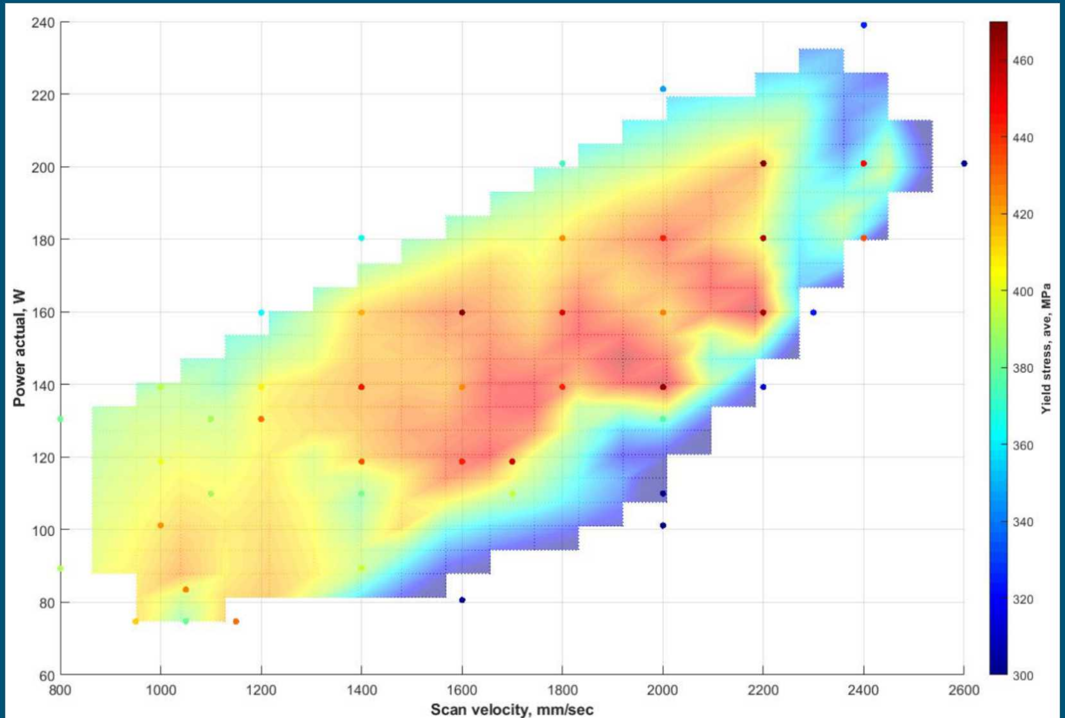
process “plateau” depends on requirements
- density isn’t a definitive process metric
- properties & manufacturability trades
  - how do properties scale w/feature & geometry?

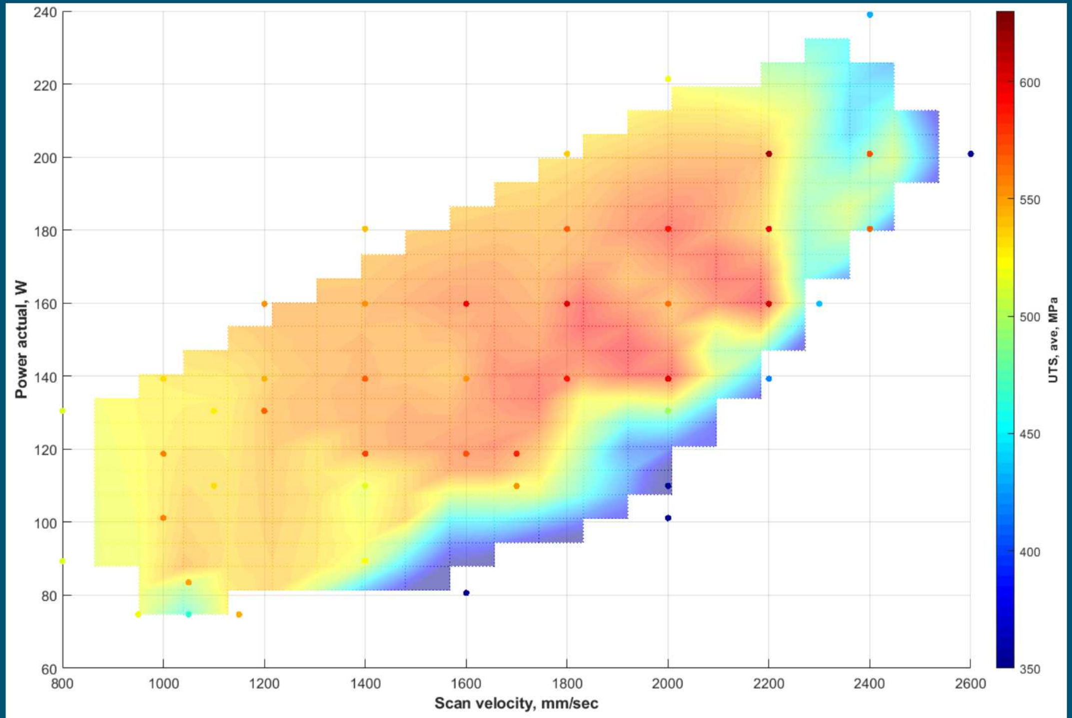


build plate w/20 arrays, 10 dogbones/array

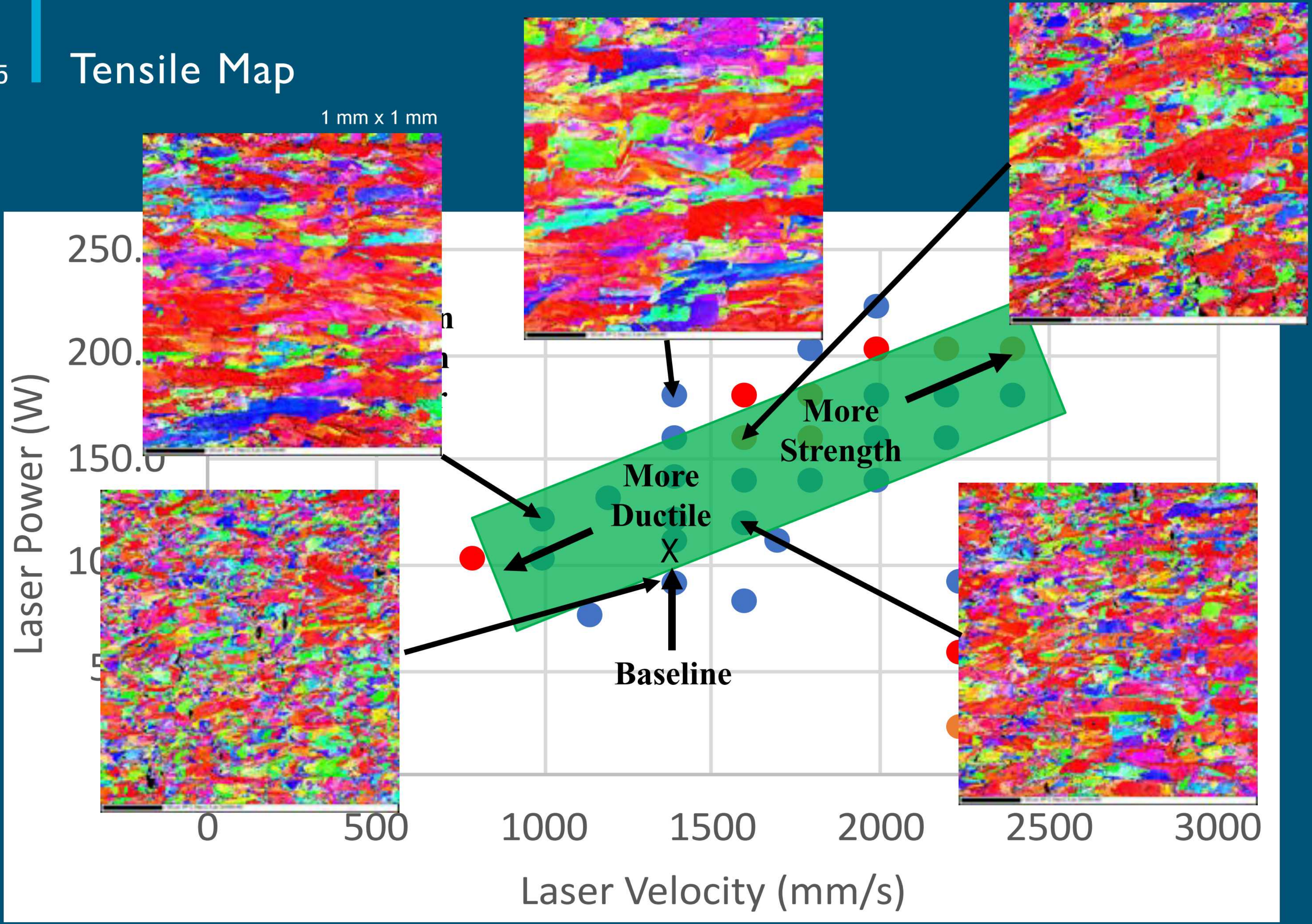

Power actual, W
Scan velocity, mm/sec
Unload modulus, ave, GPa


Power actual, W
Scan velocity, mm/sec
Ductility, ave, %


Power actual, W
Scan velocity, mm/sec
Yield stress, ave, MPa


Power actual, W
Scan velocity, mm/sec
UTS, ave, MPa

Tensile Map



max YS: 489 Mpa

- @ 200 W, 2200 mm/s

max UTS: 621 Mpa

- 200 W, 2000 mm/s

max ductility: 66%

- 120 W, 1000 mm/s

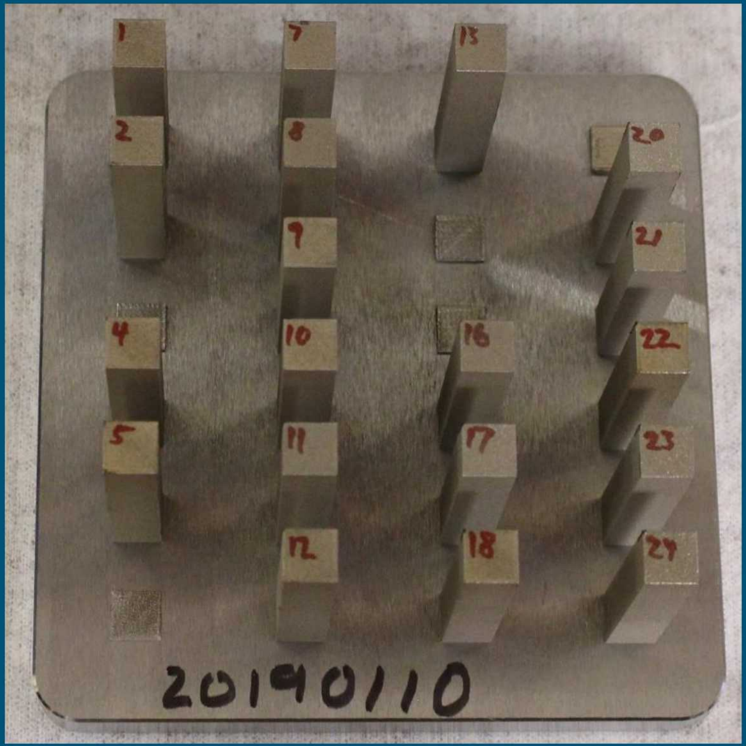
Vertical Charpy Process Map

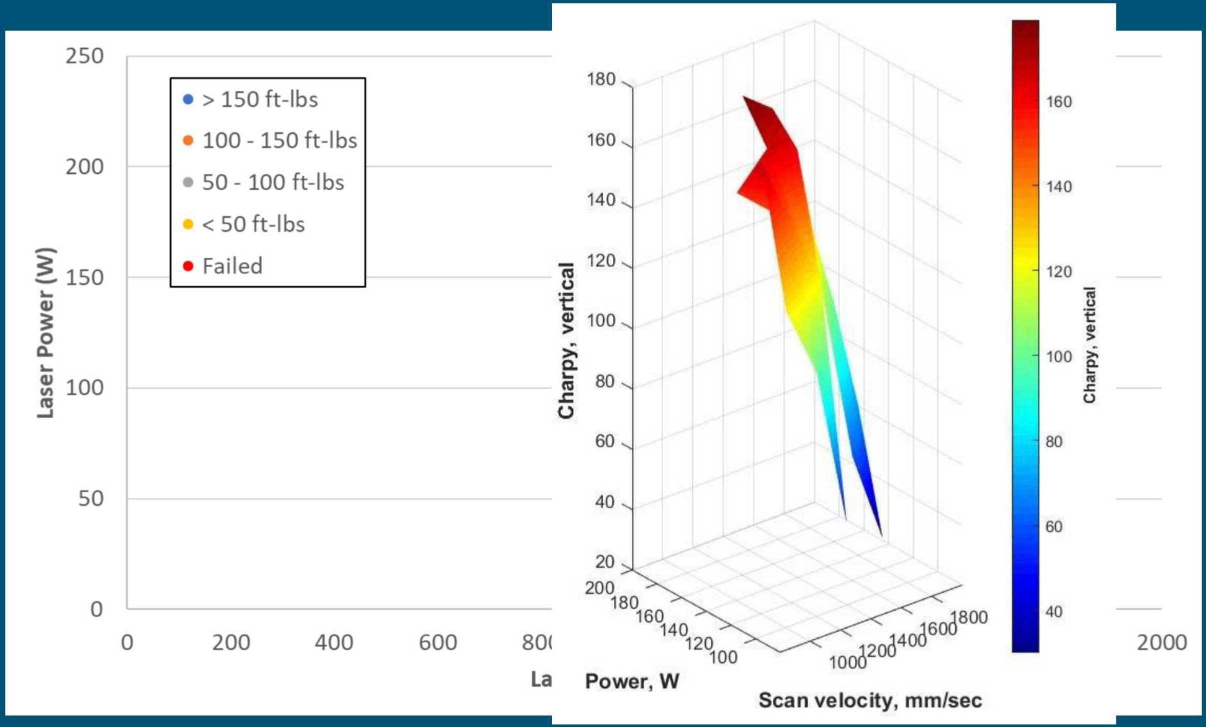
10x10x55mm Charpy impact samples

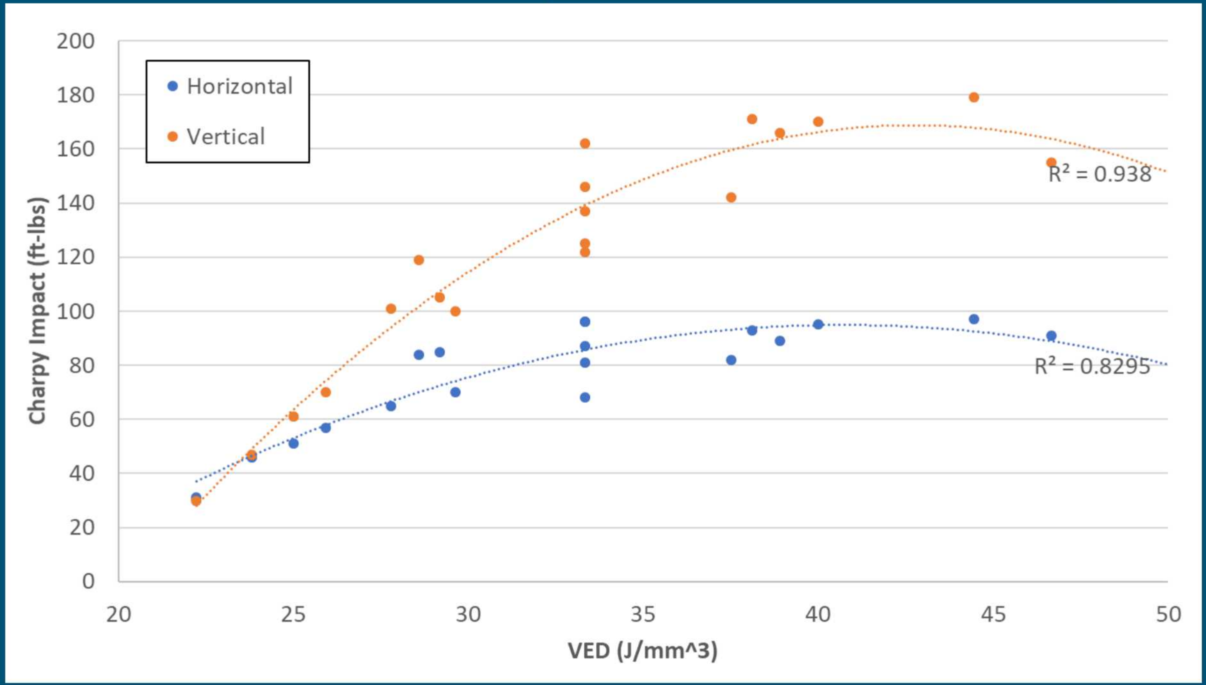
- density, hardness, impact toughness
- quick to print & test

exhibit greater process sensitivity than HTT

faster process development?







Summary

Simple line scans provide good point for initial process understanding

- estimate starting point for eliminating lack-of-fusion
- simplistic Rosenthal model worked better than expected
- melt pool understanding can be applied to other layer thickness & hatch spacing
- area pads represent another quick test, possibly quicker to characterize

Density cubes, metallurgy & tensile testing are required for better, detailed material / process understanding

- Charpy samples can be a quick mechanical strength indicator

Process performance is a plateau (mesa?), not a point

- properties & manufacturability trades
  - density isn't a great defining metric by itself
  - finish, form, density, mechanical strength
  - how do properties scale w/feature & geometry?
- observe microstructure changes w/process settings

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

QUESTIONS?

Cubes

NP180511-1, *1: focus offsets w/ baseline settings, powder lot #1

NP180531-1 , *2: power, velocity settings, powder lot #1, 30µm layer

NP180605-1 , *3: baseline settings, powder lot #1, 30 µm layer

NP180607-1 , 4: power, velocity settings, powder lot #1, 40 µm layer

NP180619-1 , 5: power, velocity settings, powder lot #2, 30 µm layer

NP180620-1 , 6: power, velocity settings, powder lot #2, 40 µm layer

NP180622-1 , 7 : power, velocity settings, powder lot #?, 30 µm layer

NP180622-2 , 8: ???, powder lot #1, 30 µm layer

NP180625-1 , 9: power, velocity settings, powder lot #1, 40 µm layer

NP180628-1 , 10: power, velocity settings, powder lot #1, 30 µm layer

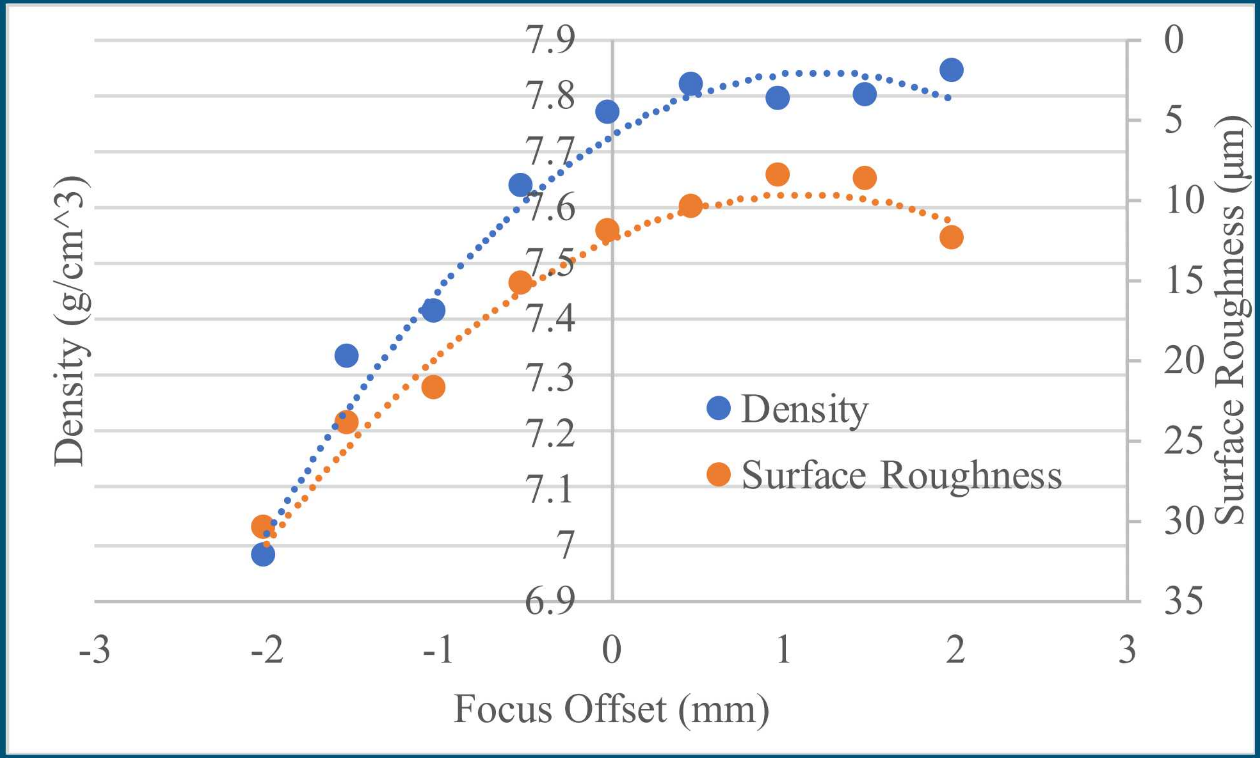
NP181112-1 , 11: power, velocity settings, powder lot #1, 40 µm layer

NP180510-1 , focal build 1

NP181204-1 , focal build 2

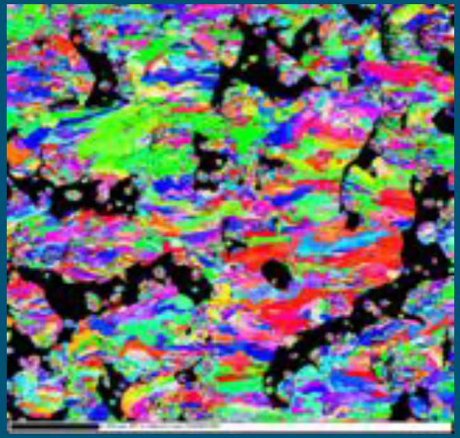
Plate (#)	Power (W)	Velocity (mm/s)	Focus offset (mm)	Layer thickness (µm)	Powder lot (#)
FDC	107	1400	Varied	30	1
1	10 to 110	200 to 1500	+1	30	1
2	90 to 140	800 to 2000	+1	30	1
3	140 to 180	600 to 1400	+1	30	1
4	75 to 160	300 to 2000	+1	40	1
5	85 to 180	600 to 1800	+1	30	2
6	100 to 180	300 to 1800	+1	40	2
7	failed				
8	107	1400	+1	30	1
9	85 to 175	225 to 1800	+1	40	1
10	130 to 240	1400 to 2800	+1	30	1

Variation with Laser Focus Offset

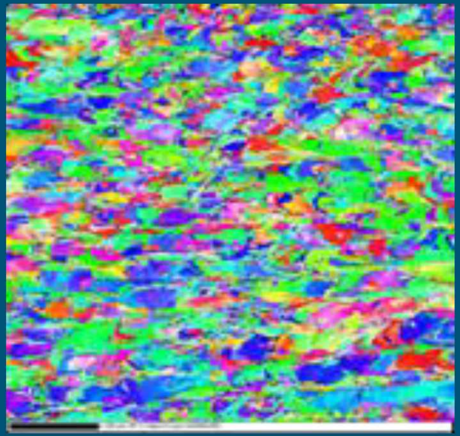


focus offsets w/ baseline settings, powder lot #1

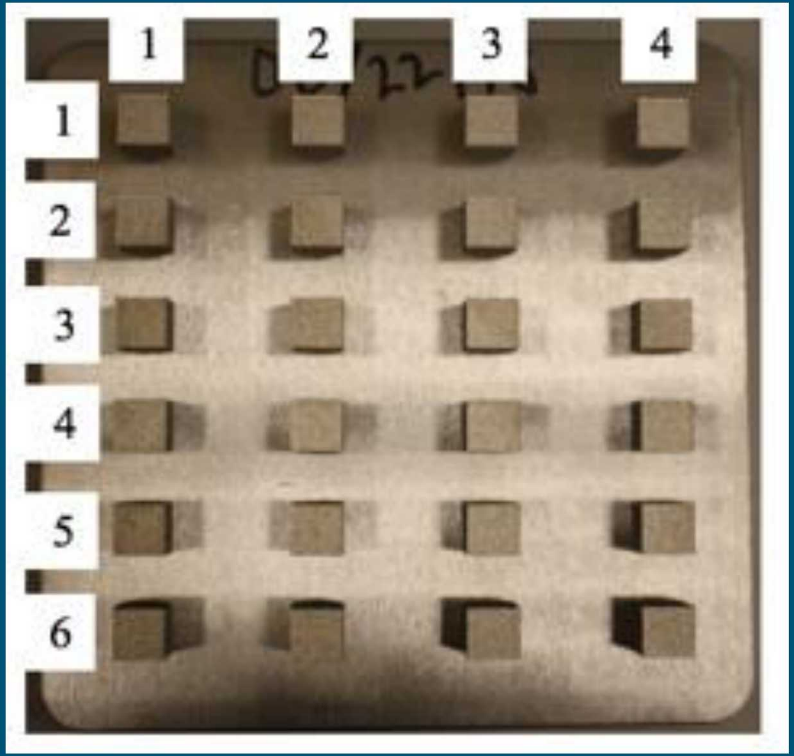
-2.0 mm



+2.0 mm



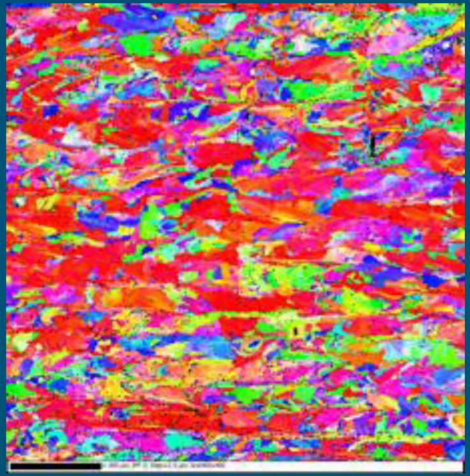
Cube Density Variation Across Build Plate



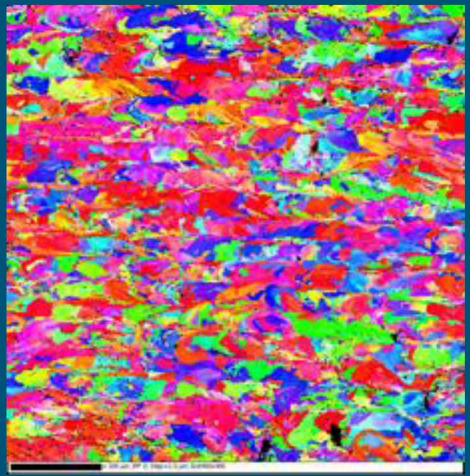
baseline settings, powder lot #1, and 30 µm layer thickness

		Surface Roughness (µm)	Density (g/cm^3)
Column	1	11.443	7.818
	2	11.030	7.803
	3	11.090	7.822
	4	12.947	7.777
Row	1	11.802	7.757
	2	11.905	7.773
	3	10.870	7.807
	4	11.947	7.836
	5	11.136	7.839
	6	12.105	7.819
Average			7.80±0.04

7.87 g/cm^3

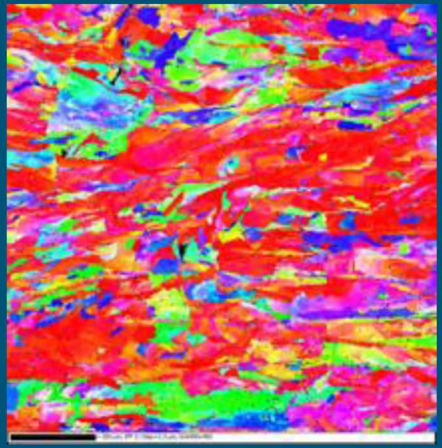


7.68 g/cm^3

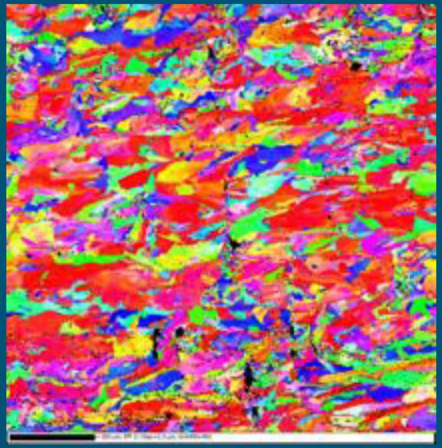


Cube EBSD Across Laser Power, Velocity & Layer Thickness

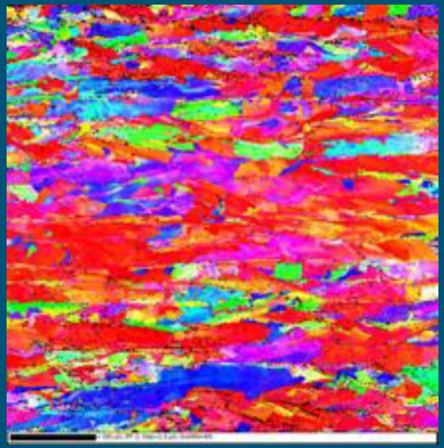
120 W, 800 mm/s
30.0 µm 7.75 g/cm³



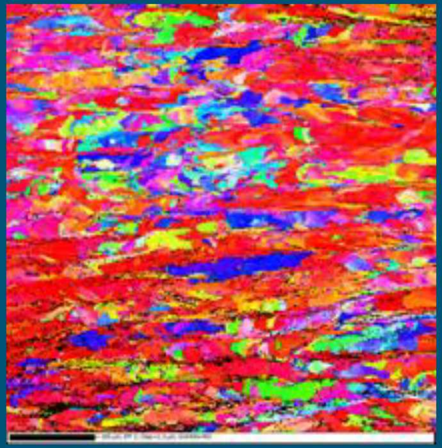
120 W, 800 mm/s
40.0 µm 7.78 g/cm³



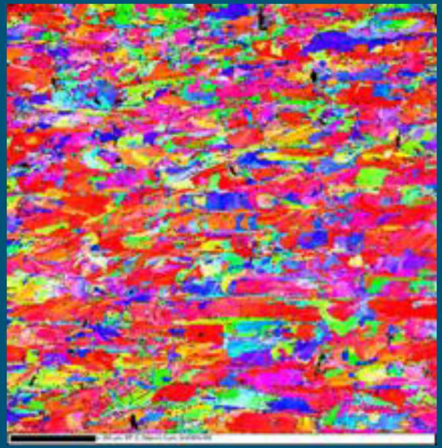
120 W, 1100 mm/s
30.0 µm 7.70 g/cm³



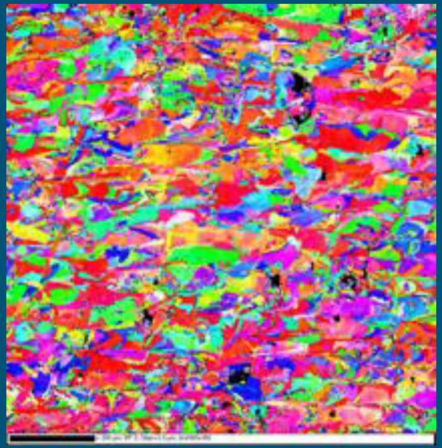
120 W, 1100 mm/s
40.0 µm 7.83 g/cm³



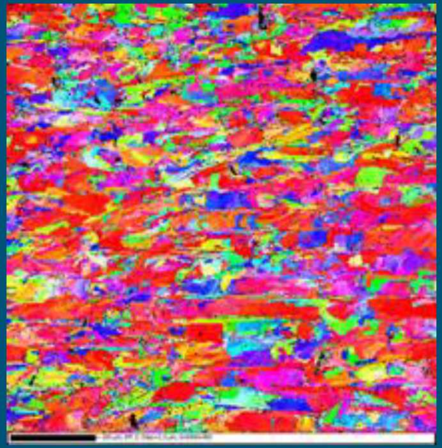
120 W, 1400 mm/s
30.0 µm 7.73 g/cm³



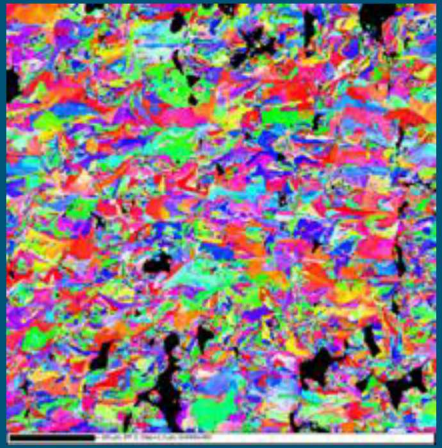
120 W, 1400 mm/s
40.0 µm 7.77 g/cm³



120 W, 1700 mm/s
30.0 µm 7.75 g/cm³



120 W, 1700 mm/s
40.0 µm 7.44 g/cm³



Abstract

Metal laser-powder bed fusion (L-PBF) involves numerous process inputs which must be established to insure the reliable fabrication of part material and geometry. Work has been performed on 316L stainless steel to quantify its parameter space relative to laser power, laser scan velocity and powder layer thickness. Multiple performance metrics were evaluated including surface roughness, geometrical form error, material density, microstructure, tensile mechanical properties and Charpy impact toughness. It has been discovered that the process space for L-PBF 316L involves a viable process window that is much more of a plateau area than an optimized peak. It has also been determined that establishing process settings based solely on material density, a common practice in the industry, is likely not truly optimal. These results, and their potential impact on part performance will be discussed.