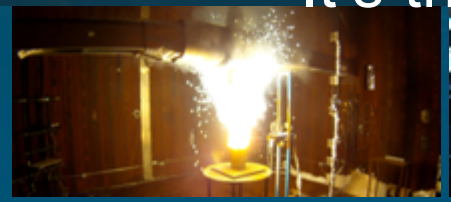
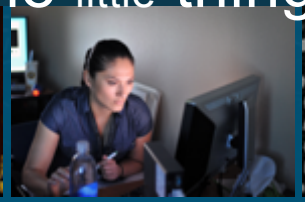
SAND2021-12175PE

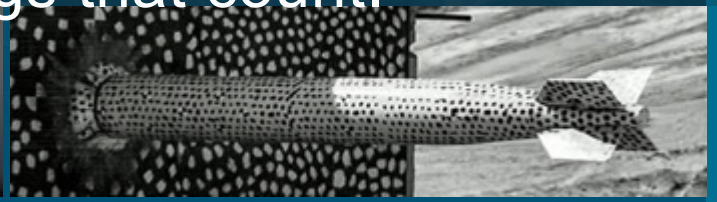
Sandia National Laboratories

Process optimization and statistical process control of small features in metal additive manufacturing:

It's the little things that count.







Presented by

Scott C. Jensen

Sandia Postdoctoral Seminar Series
9/30/2021

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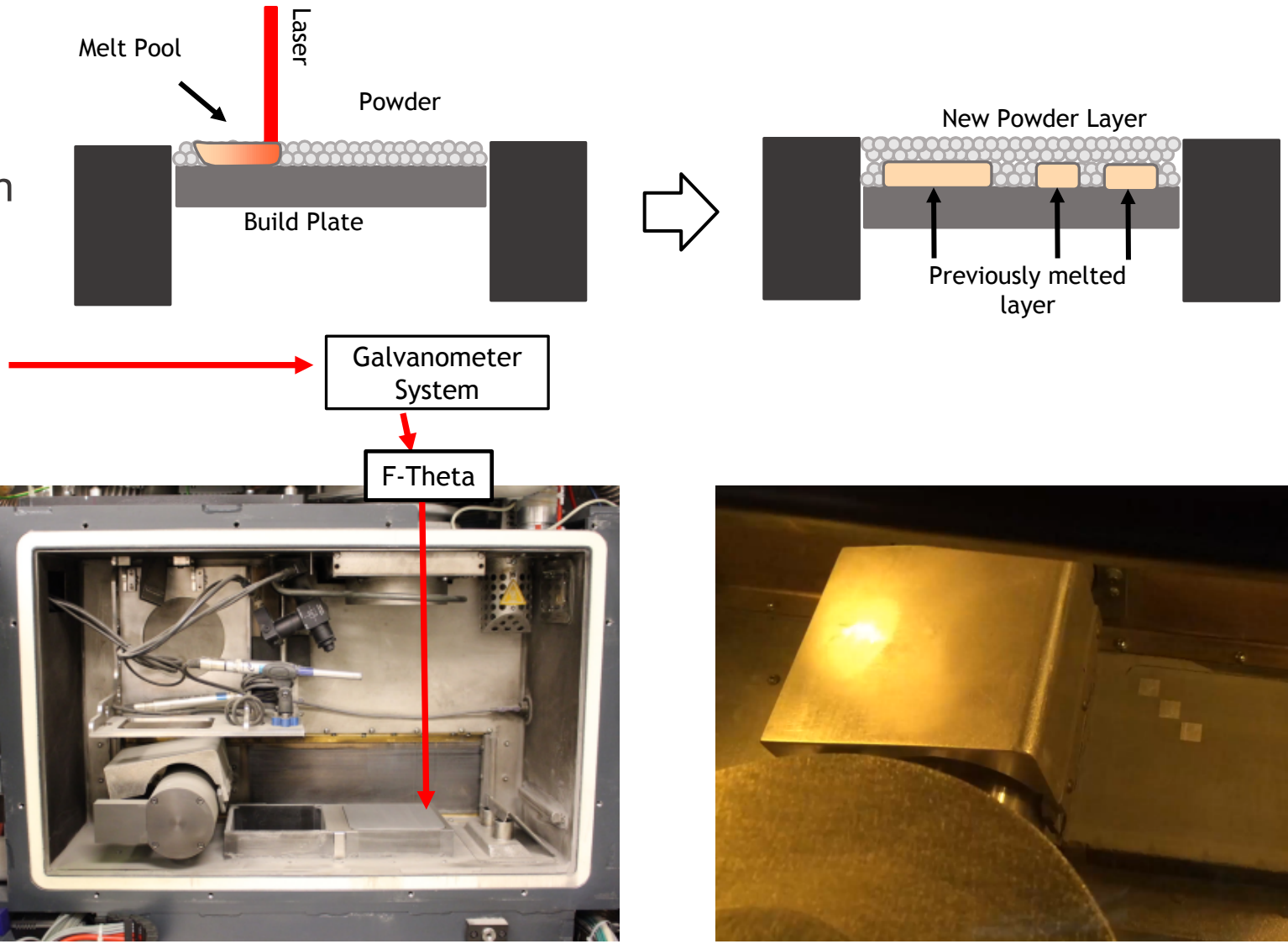
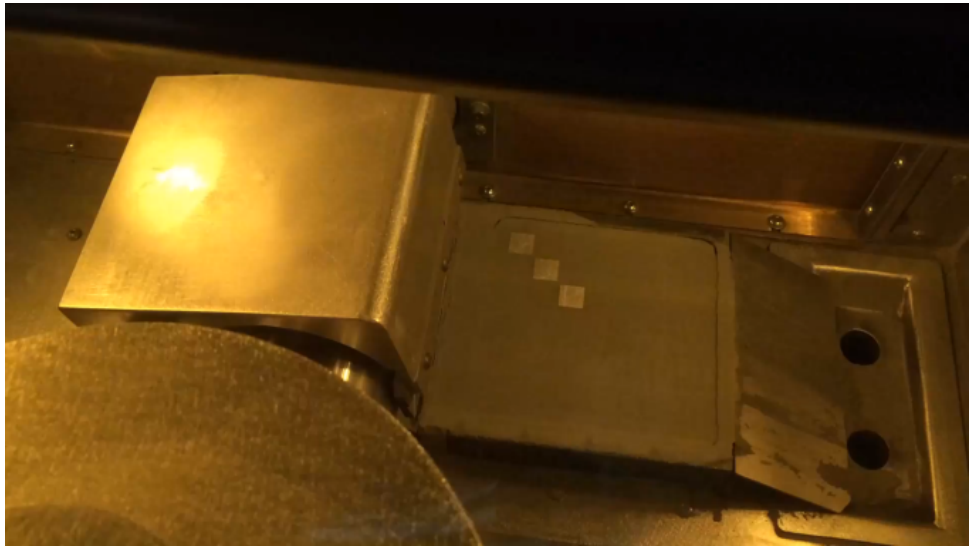
Additive Manufacturing: An Overview

Additive Manufacturing (AM) Process

Laser Powder Bed Fusion

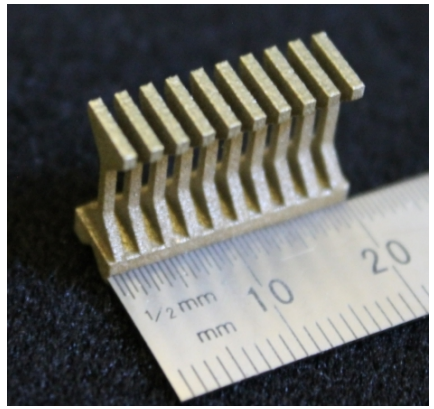
Stainless Steel 316L

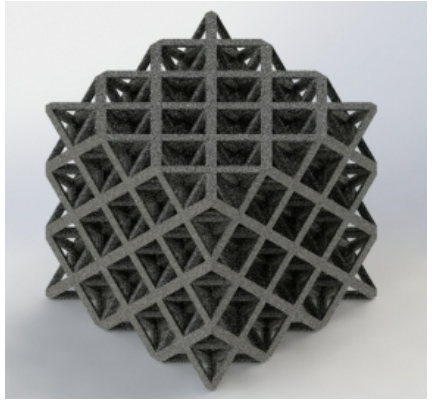




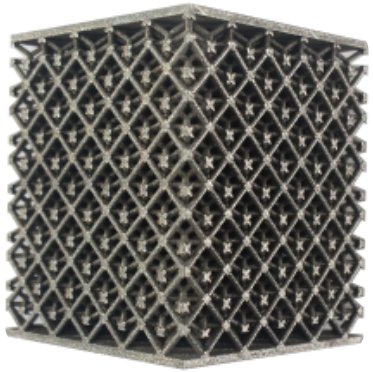
AM Parts

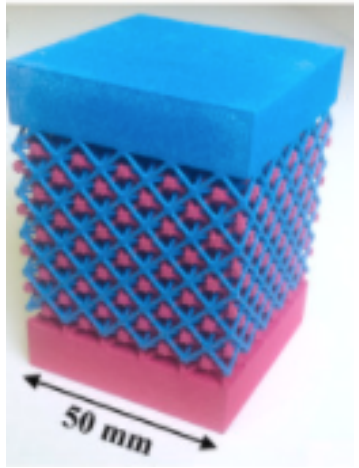
Small Features / Lattices





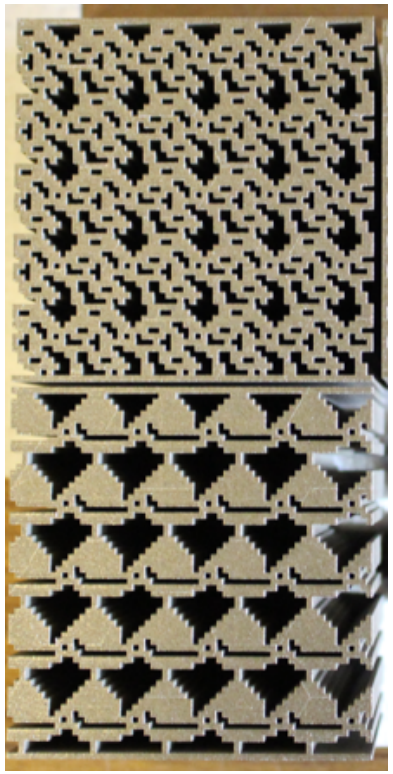
Interpenetrating Lattices

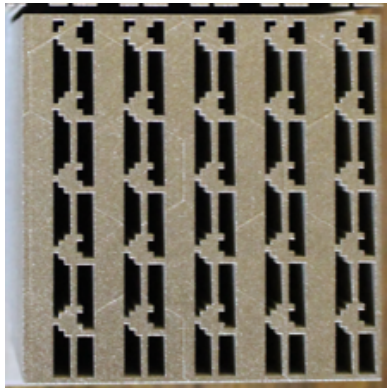




White, B. C., Garland, A., Alberdi, R., & Boyce, B. L. (2021). *Additive Manufacturing*, *38*, 101741.

2-D Optimized Design (Stiffness vs Elastic Wave Delay)

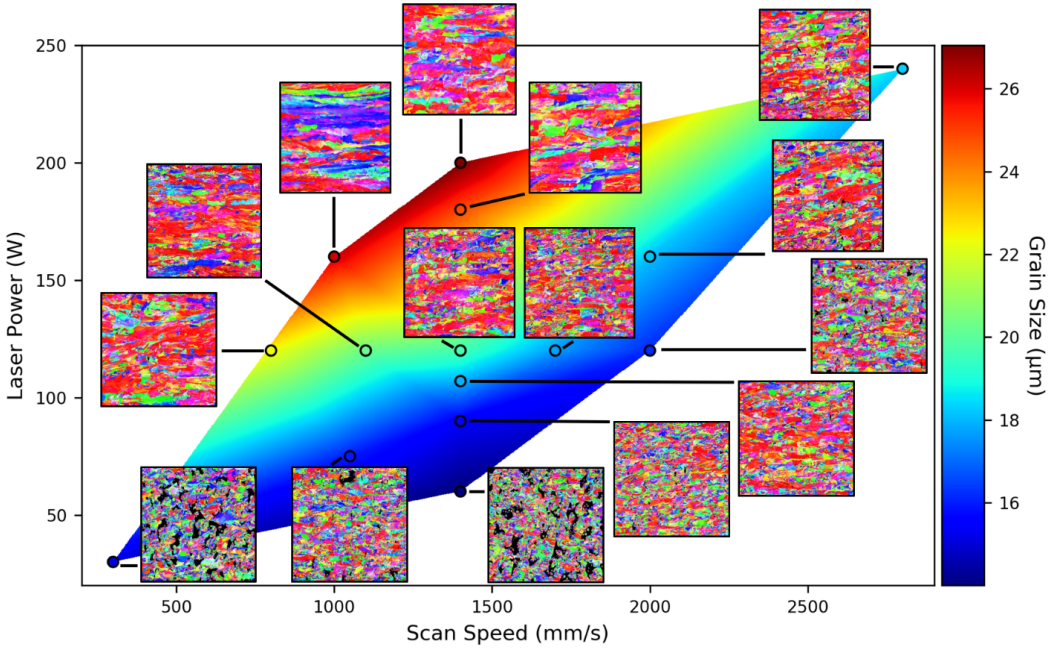




Garland, A. P., White, B. C., Jensen, S. C., & Boyce, B. L. (2021). *Materials & Design*, *203*, 109632.

Challenges

Laser powder bed fusion creates microstructure, surface quality, porosity, and geometry at the same time



Thermal history for small features is different, so microstructure can be different too!

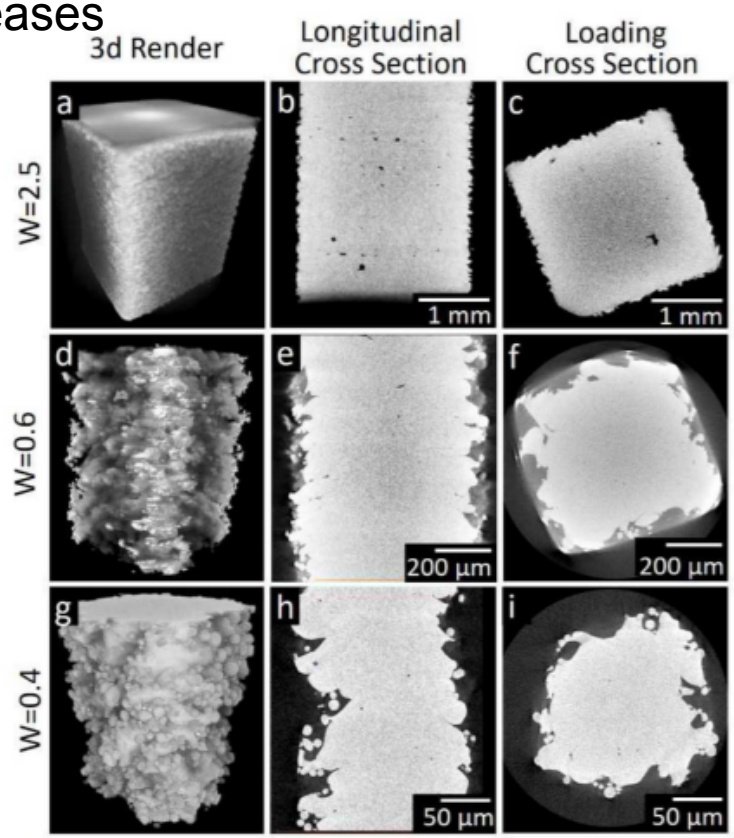
Average Particle Diameter (16 µm)

Melt-pool Width (50 µm)

Surface Roughness (~15 µm)

Width (mm)	Surface to Area Ratio
2.5	2%
1	6%
0.6	10%
0.4	14%

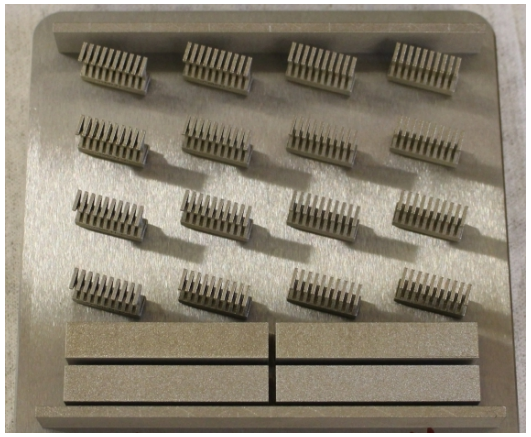
The load bearing area becomes less defined and possible effects of stress concentrators increases

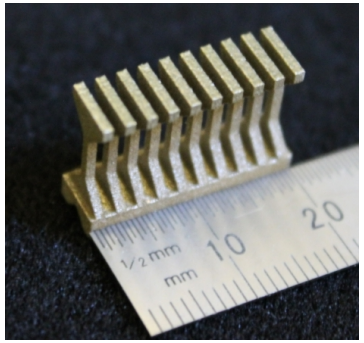


Roach, A. M., White, B. C., Garland, A., Jared, B. H., Carroll, J. D., & Boyce, B. L. (2020). *Additive Manufacturing*, *32*, 101090.

Process to Performance

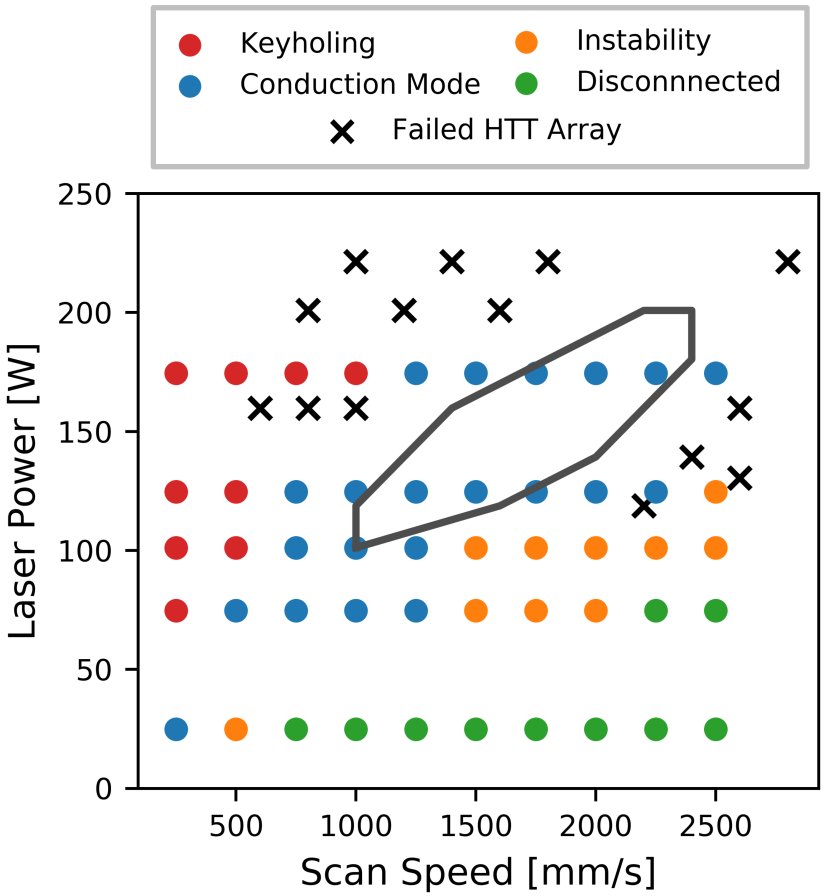
Finding the Sweet Spot for Small Features

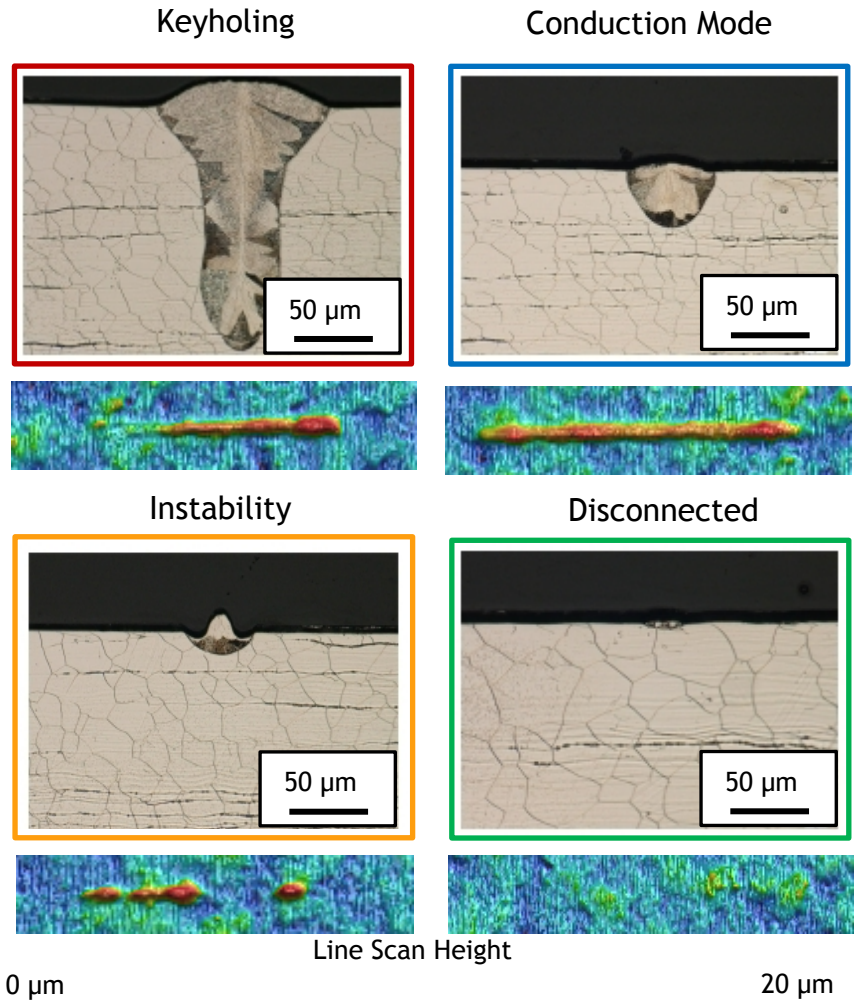




Establishing the Printable Process Window for Laser Powder Bed Fusion

Line Scan Geometry

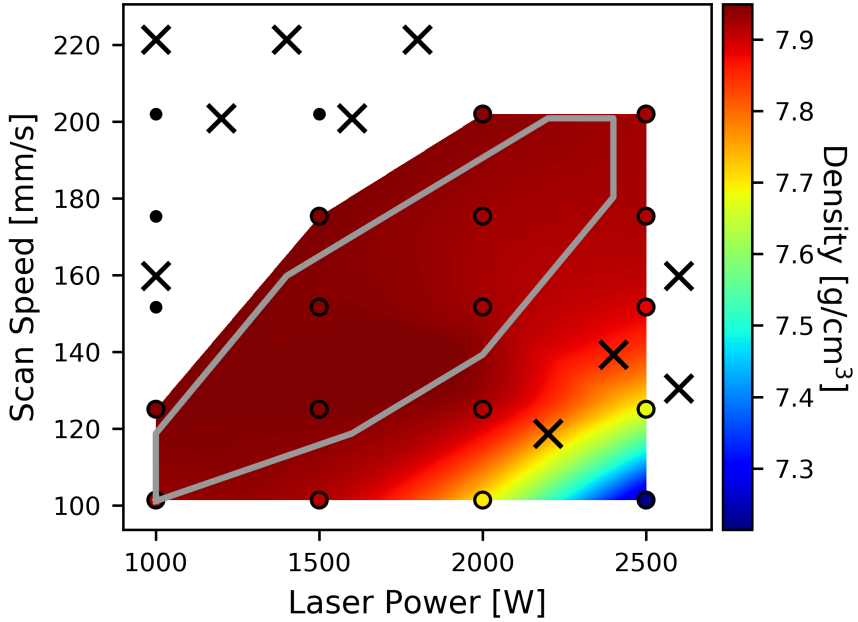


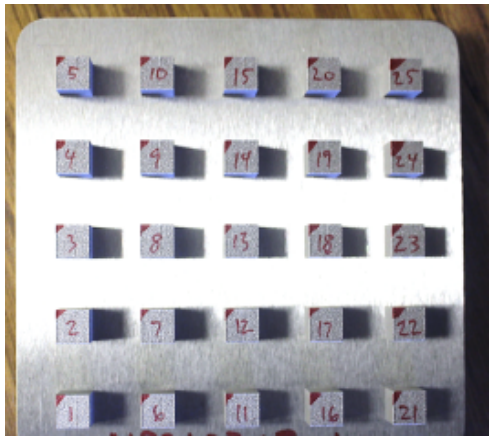


Density

Density Across the Process Space

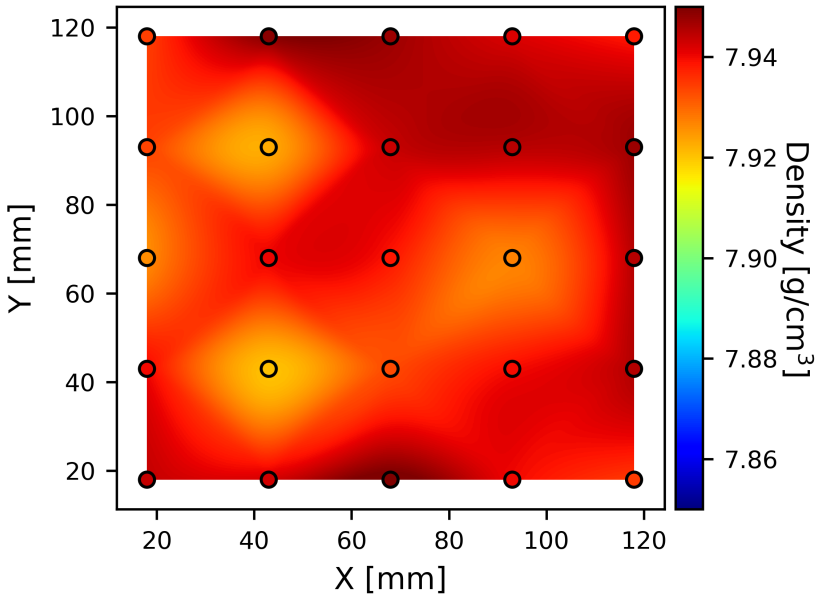
The density varies from 7.92 to 7.95 g/cm^3
(0.4 % Change Across the Range)





Density Across the Build Plate

The density varies from 7.92 to 7.95 g/cm^3
(0.4 % Change Across the Range)



Practical Approach: Performance Changes Across the Printable Window

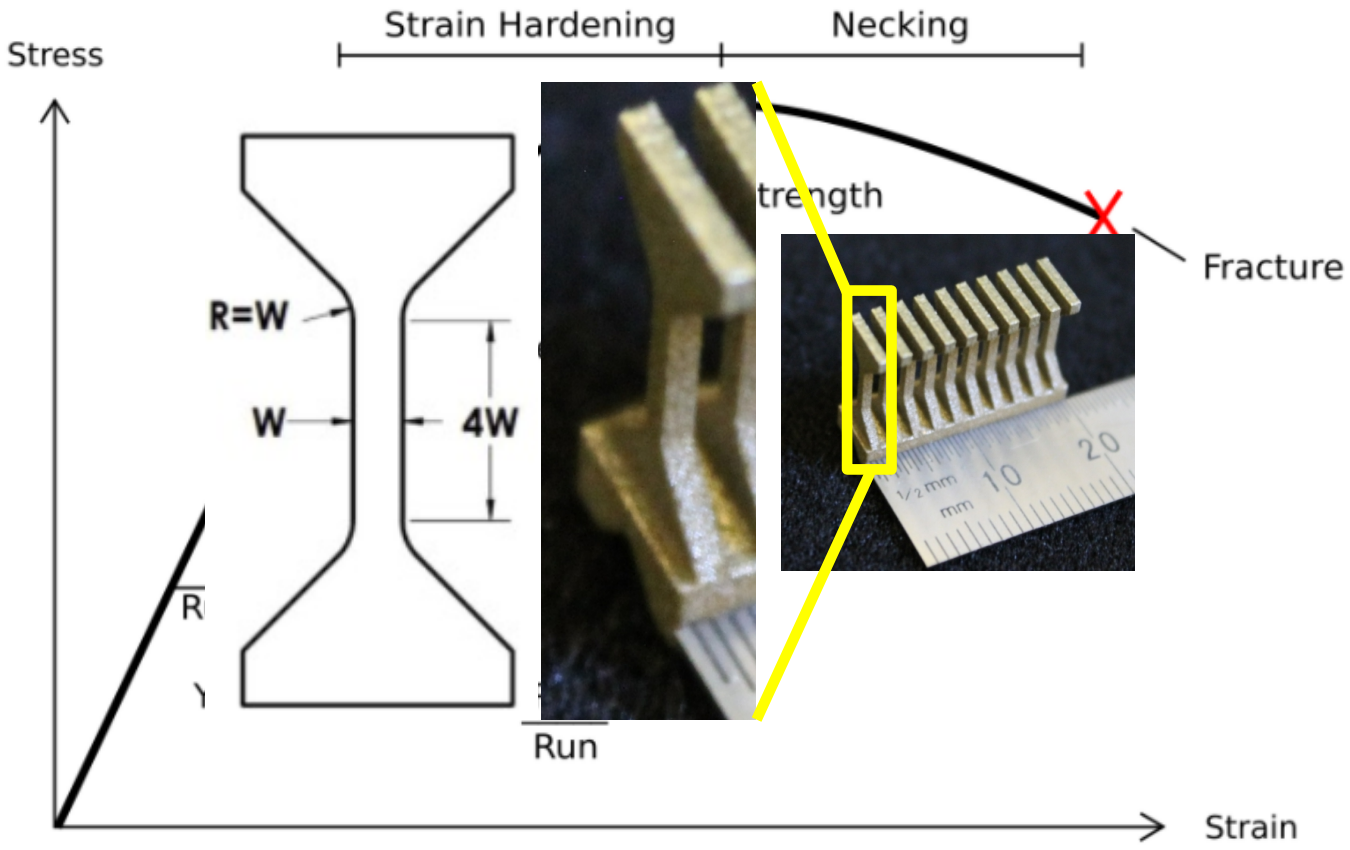
High-Throughput Tensile Tests

Stress = F/(Load Bearing Gage Area)

Effective Stress = F/(Measured Gage Area)

High Throughput Tensile Bar Samples

- 1 mm^2 nominal gage area
- One array per laser power/scan speed set
- 10 dogbones printed per array
- Randomly positioned across the plate
- Dimension ratios as indicated in ASTM E8

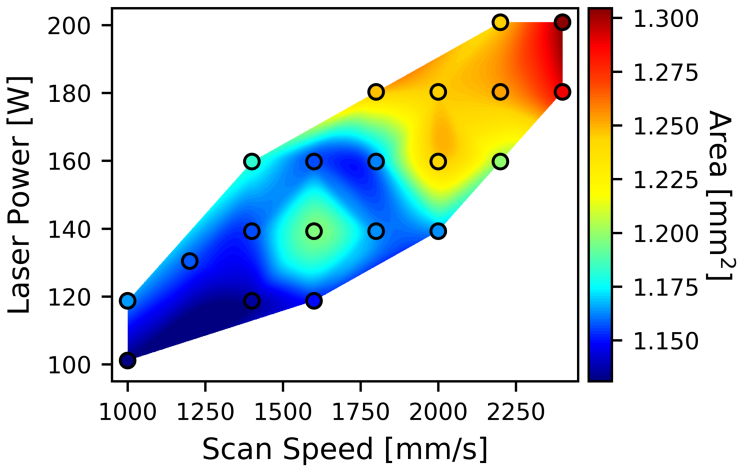


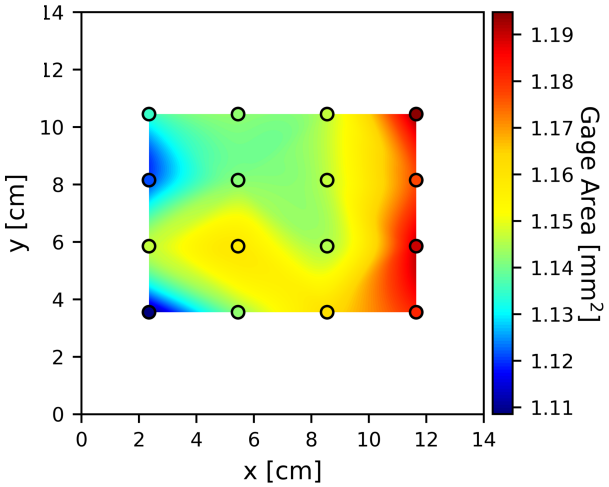
Strain = L/L_0

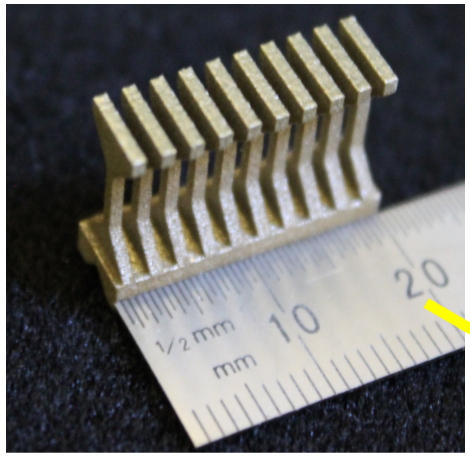
Tensile properties ("engineering")

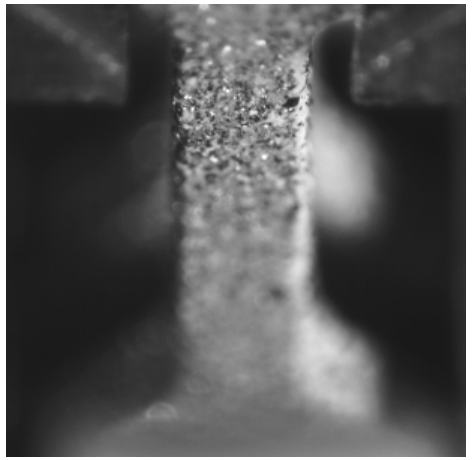
Yield Strength	Stress at 0.2% plastic strain
UTS	Max stress
Ductility	Strain at failure
Unloading Modulus	Unloading to 100 MPa after reaching 2% strain

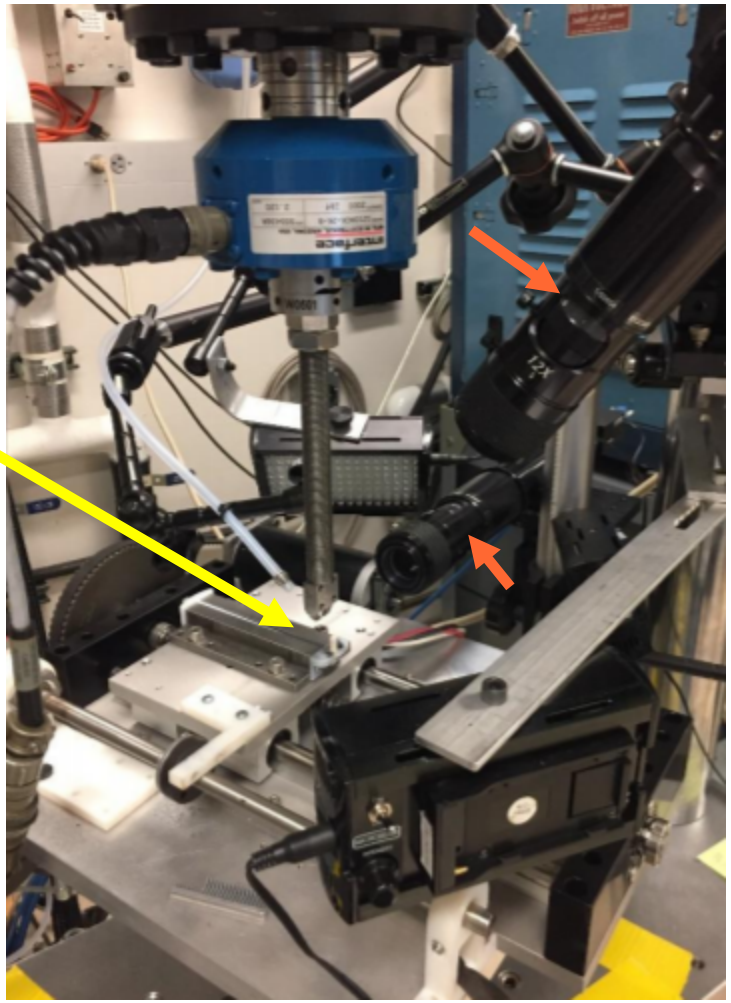
Area Measurements



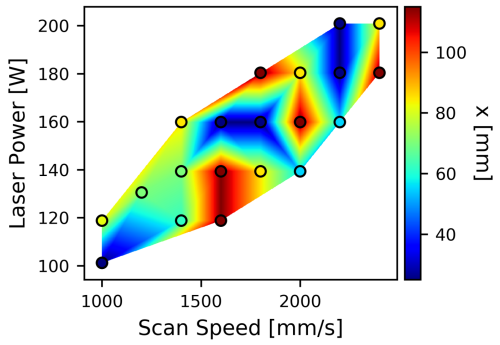


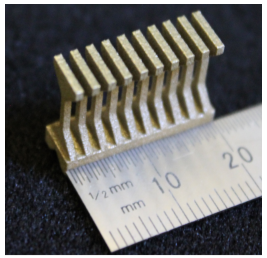






Effective Properties

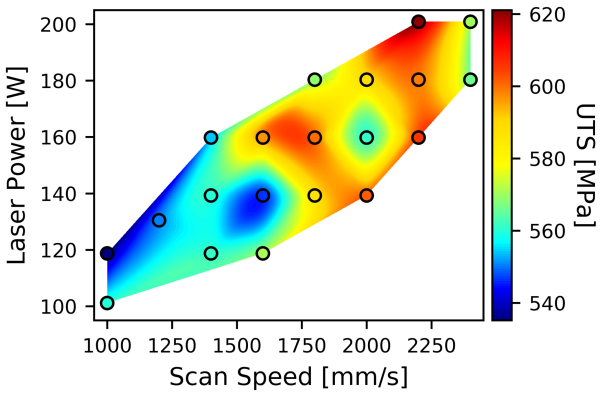


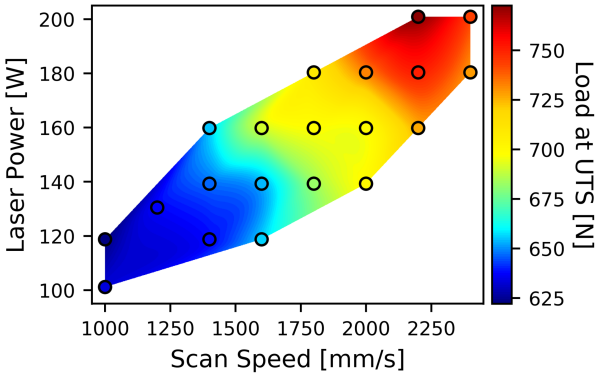


Normalized by Area

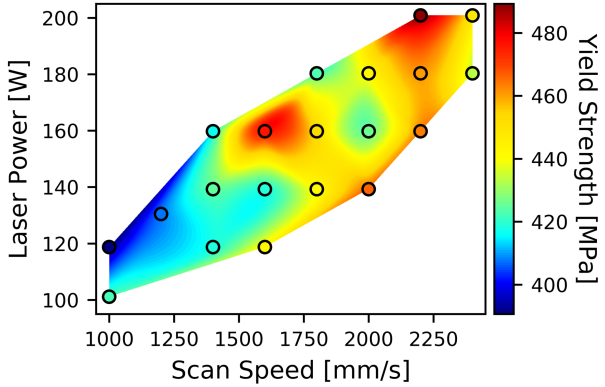
Directly Measured

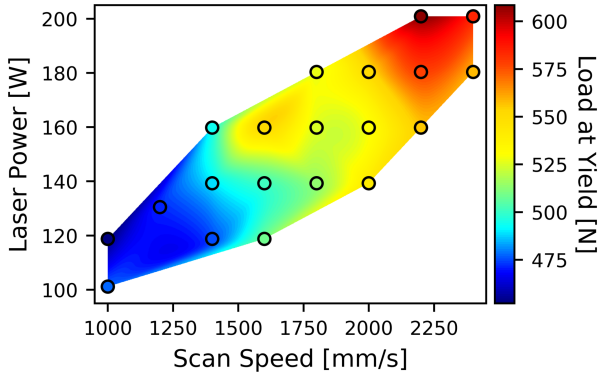
Ultimate Tensile Strength



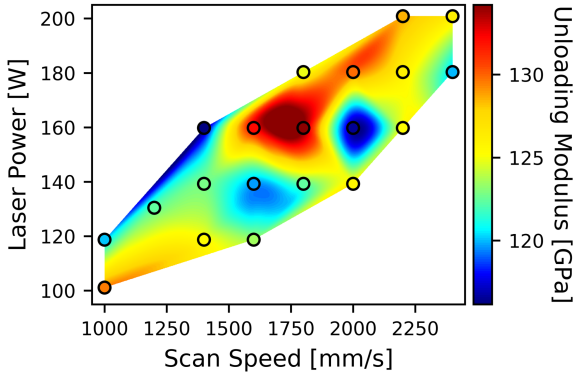


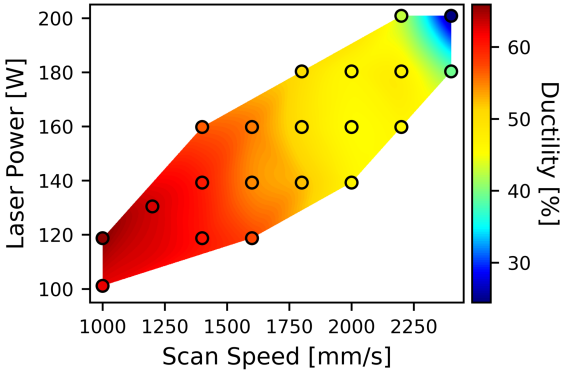
Yield Strength





Modulus/Ductility





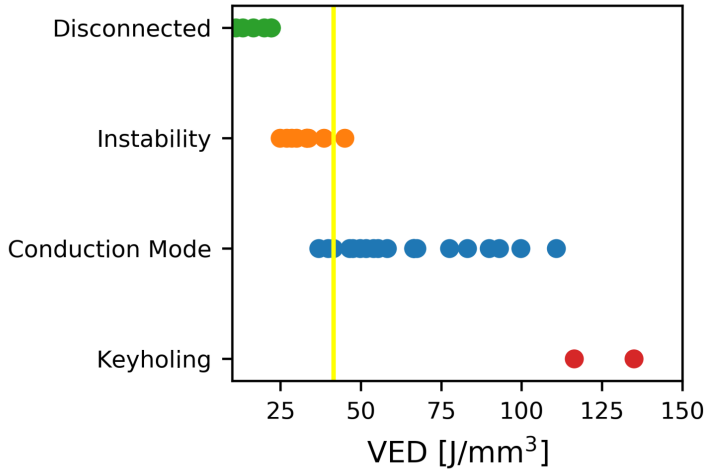
Mechanical Properties

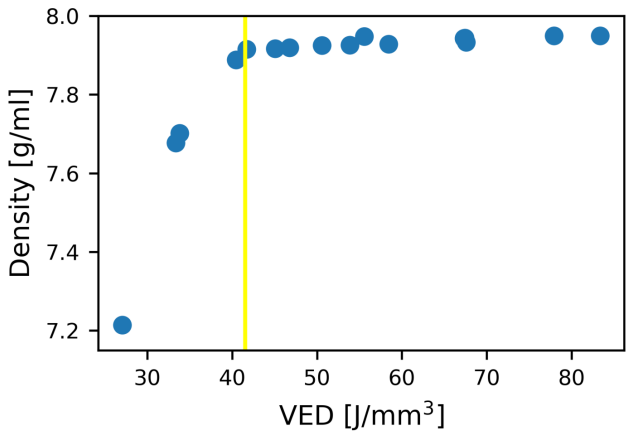
	Nominal Area (mm^2)	Laser Power (W)	Scan Speed (mm/s)	Area (mm^2)	UTS (MPa)	Yield Strength (MPa)	Ductility (%)	Unloading Modulus (GPa)
AM	1	120	1000	1.16 (0.04)	535 (19)	391 (15)	66 (4)	120 (8)
AM	1	200	2200	1.24 (0.05)	621 (9)	489 (20)	43 (3)	129 (2)
AM Standard (ASTM F3184-16)					515	205	30[1]	
Wrought Samples (Machined Surface)				1.11 (0.01)	627 (6)	308 (3)	71 (2)	159 (13)
Wrought Standard (ASTM A240/A240M-20)					485	170	40[1]	

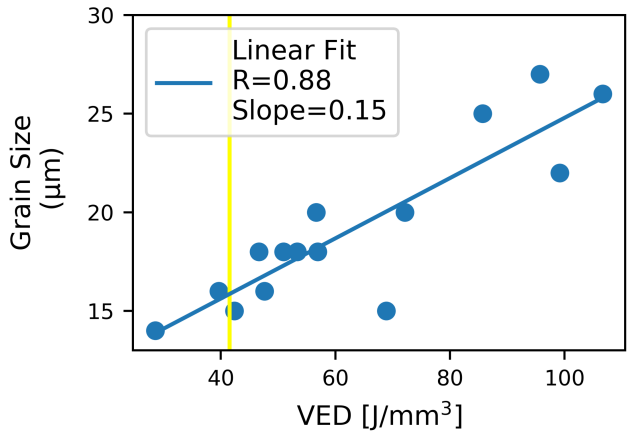
[1] Elongation % in 50 mm minimum.

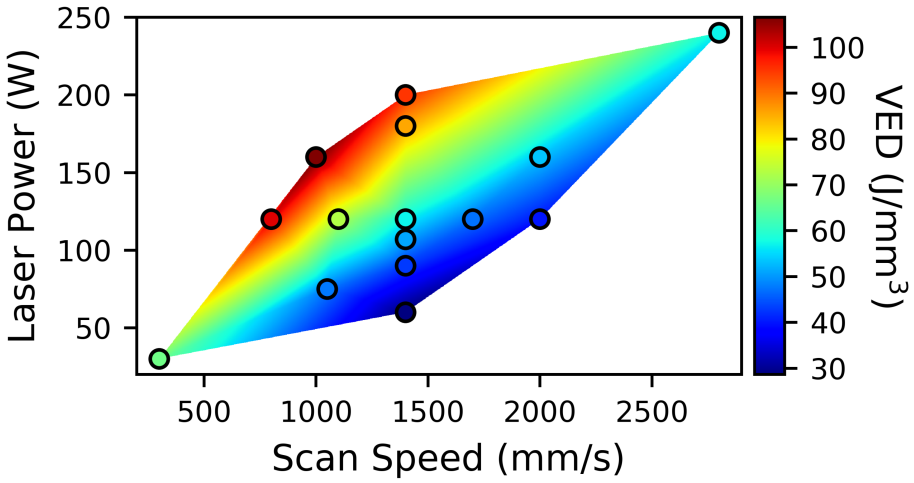
Volumetric Energy Density (VED)

$$VED = \frac{(Laser\ Power)}{(Scan\ Speed)(Beam\ Diameter)(Layer\ Thickness)}$$

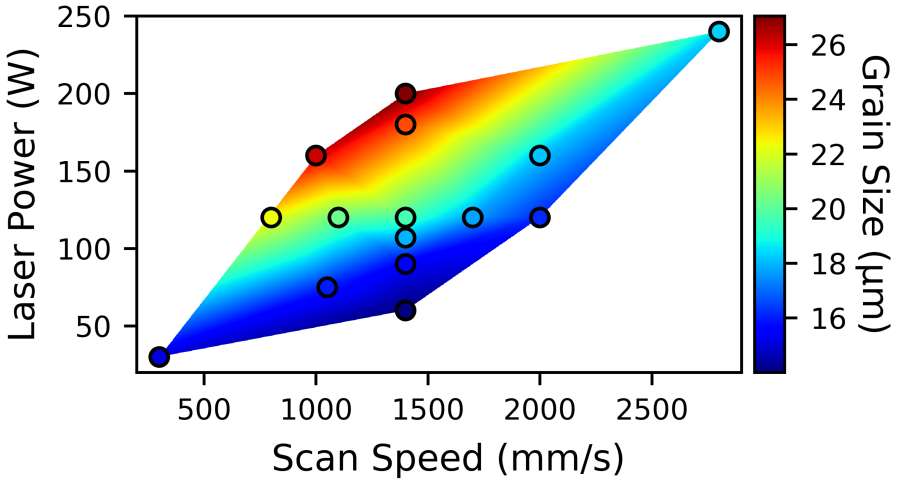




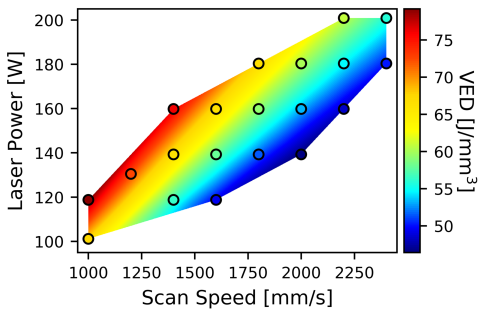


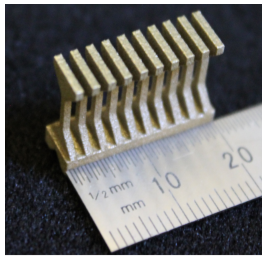


Melt-pool Size



Effective Properties

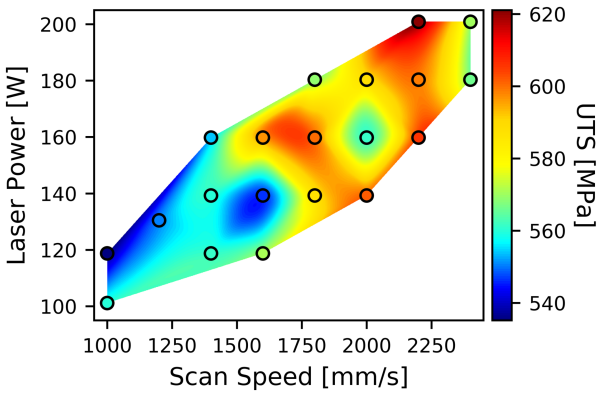


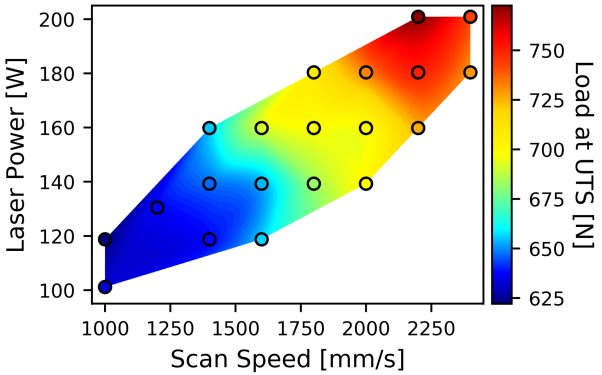


Normalized by Area

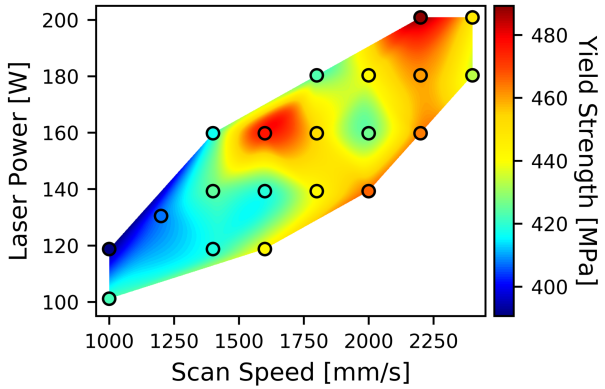
Directly Measured

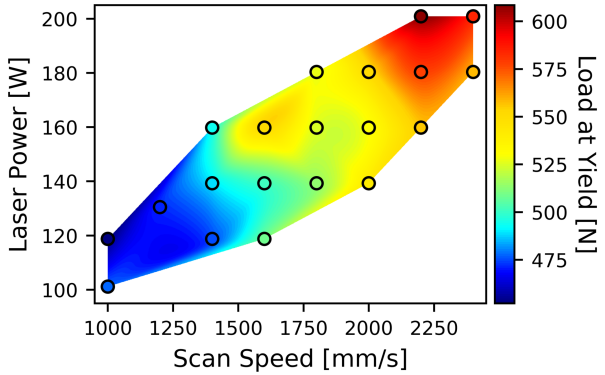
Ultimate Tensile Strength



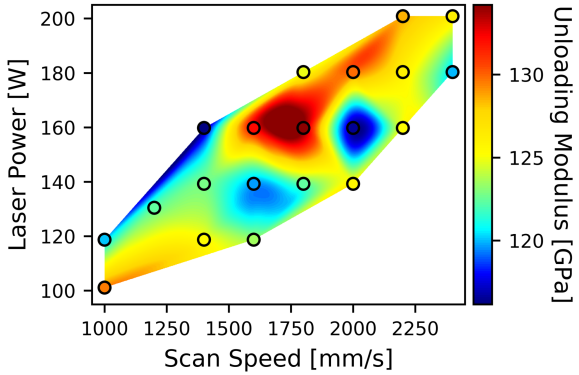


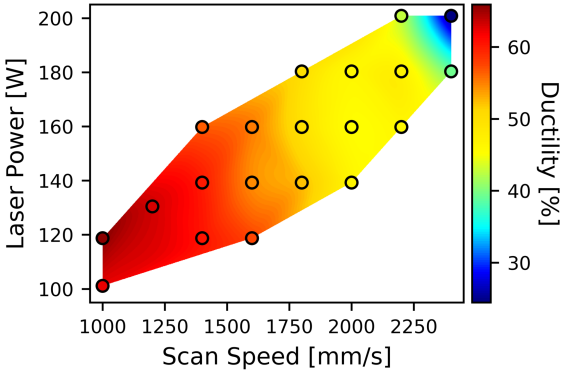
Yield Strength



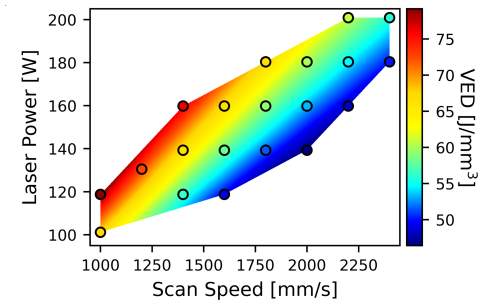


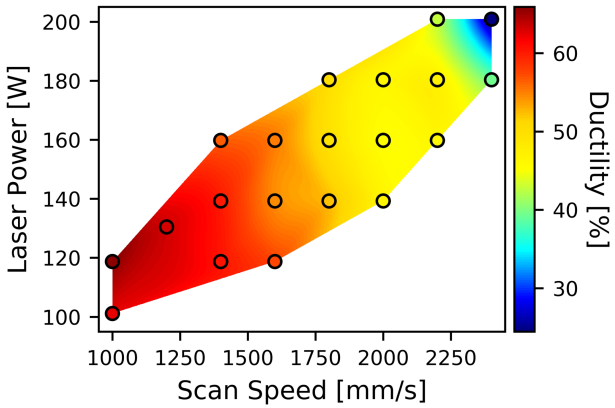
Modulus/Ductility



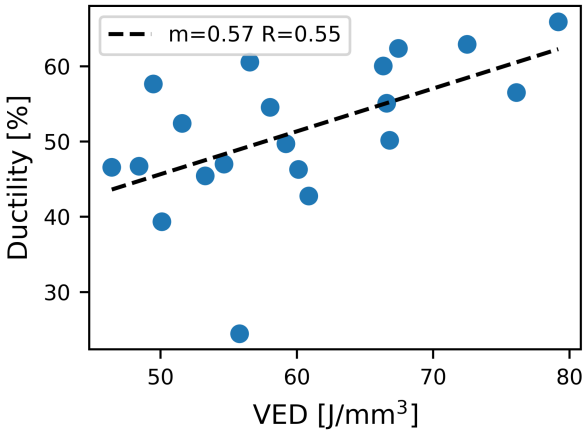


Volumetric Energy Density (VED)

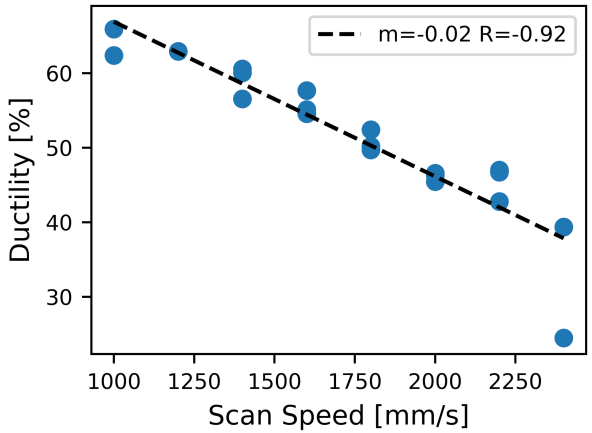




VED



Scan Speed

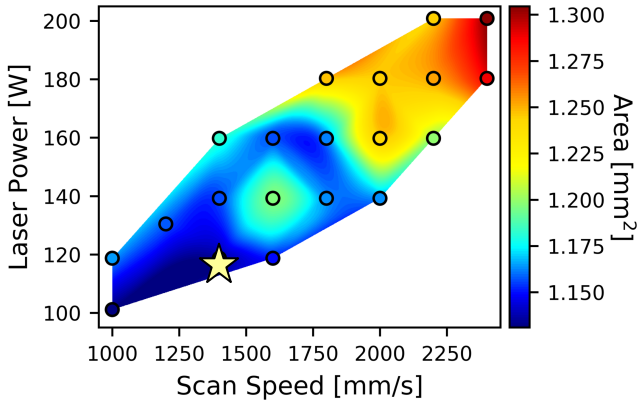


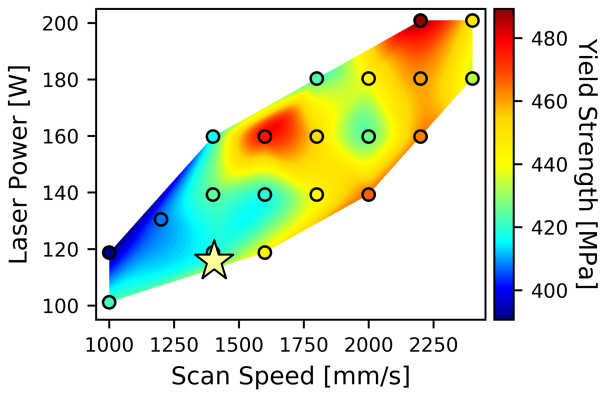
- This behavior is more linearly dependent with scan speed and laser power than VED.
- Miniature Tensile bars can extract properties across the process space which can allow for small feature optimization.

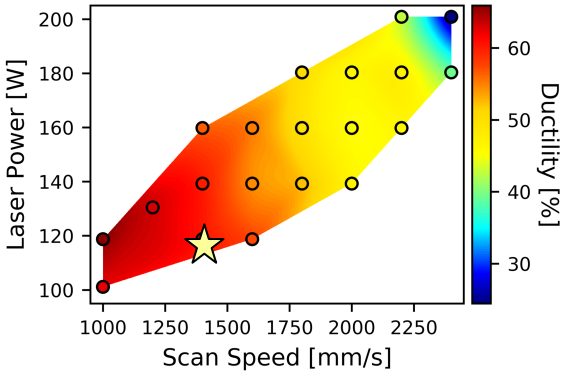
Optimization Considerations

Once you've accepted your flaws, no one can use them against you.

1. Extreme Values
2. Ductility vs Strength
3. Build Rate
4. Compensation for area changes







Process monitoring and sensitivity

Those who do not track the past are condemned not to repeat it...

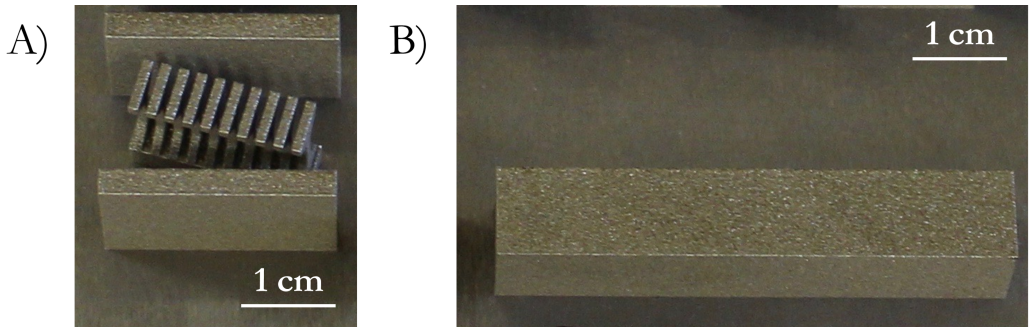
Witness Samples

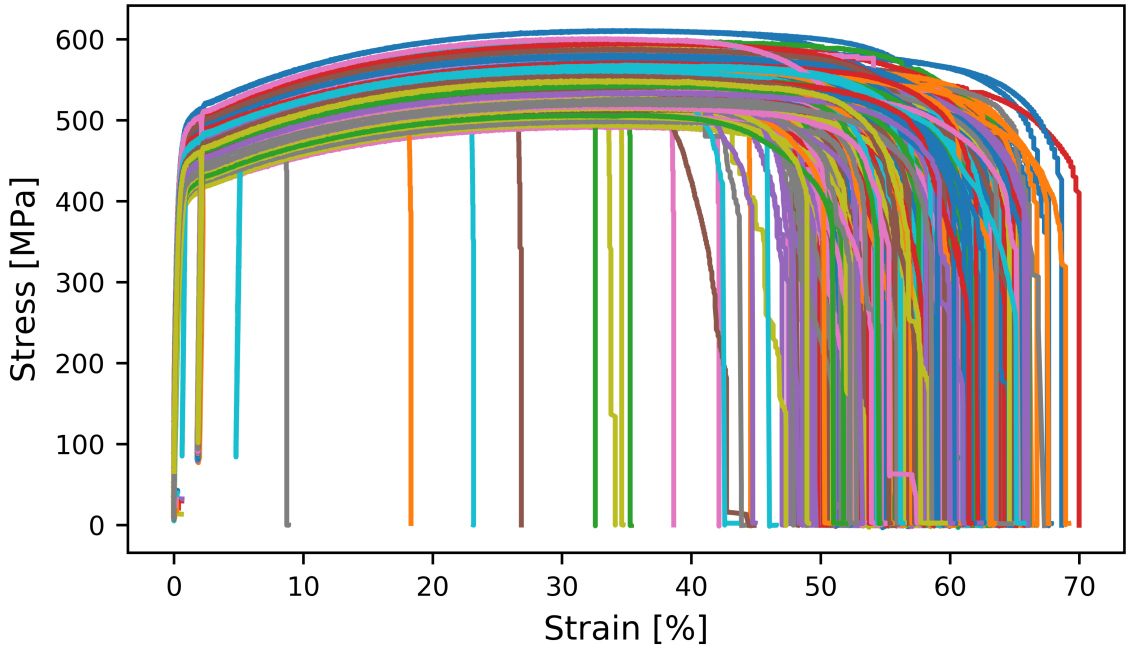
Scan Settings:

- 113 W laser power (45%)
- 1400 mm/s scan speed
- 50 µm hatch
- 50 µm laser spot size
- 30 µm layer thickness
- Hexagonal scan strategy

Charpy impact test

- High strain-rate test to determine the energy absorbed during fracture

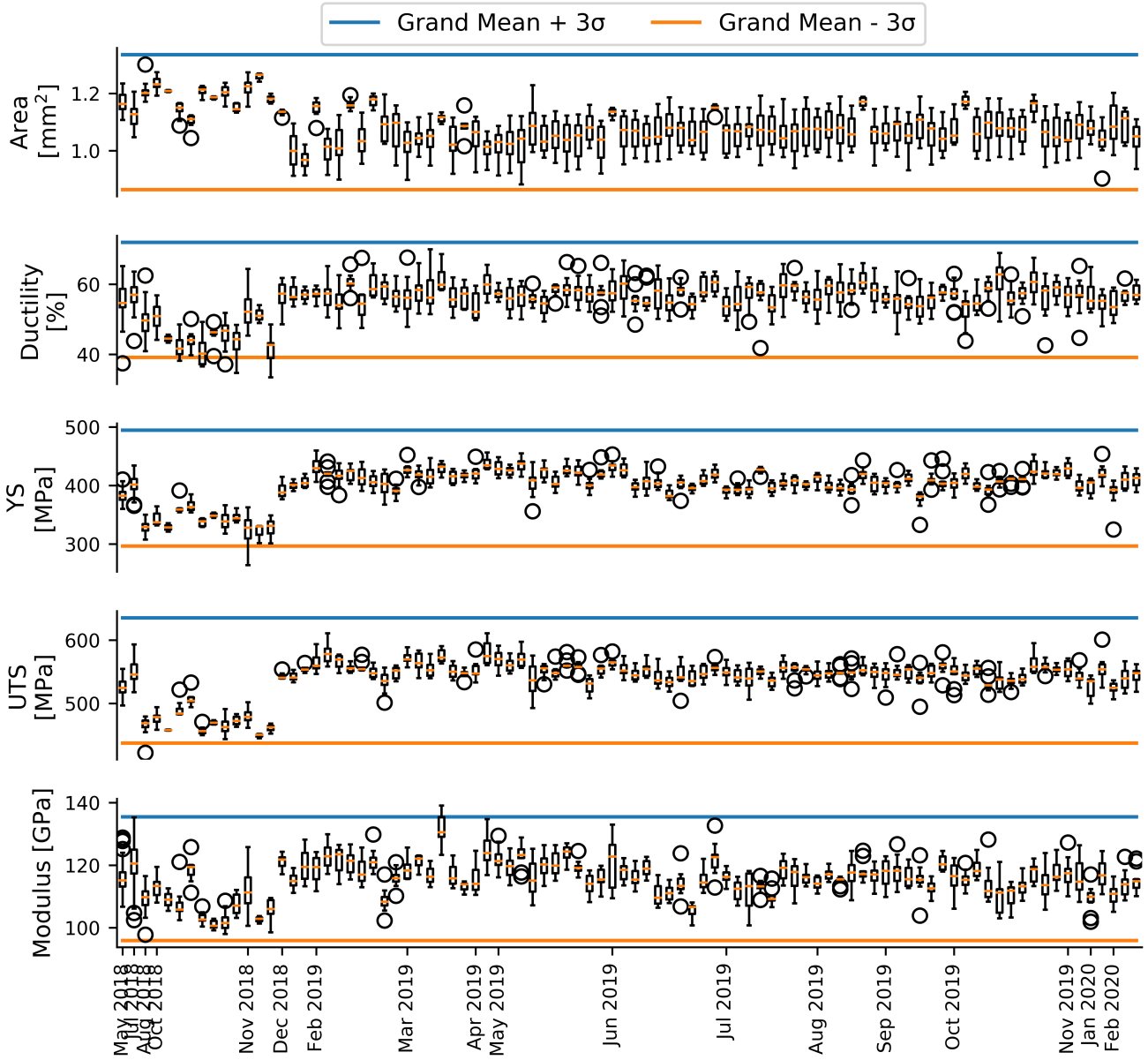




A journey of a thousand tensile bars…

Each boxplot represents data from one day (at least an array of 10 tensile bars)

Three standard deviations above and below the grand mean are shown (ie sample standard deviation of combined individual bars)

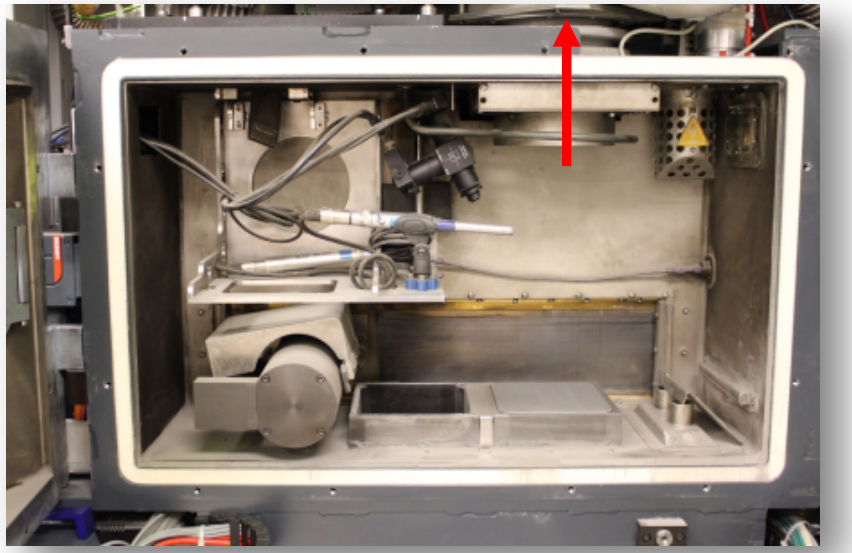


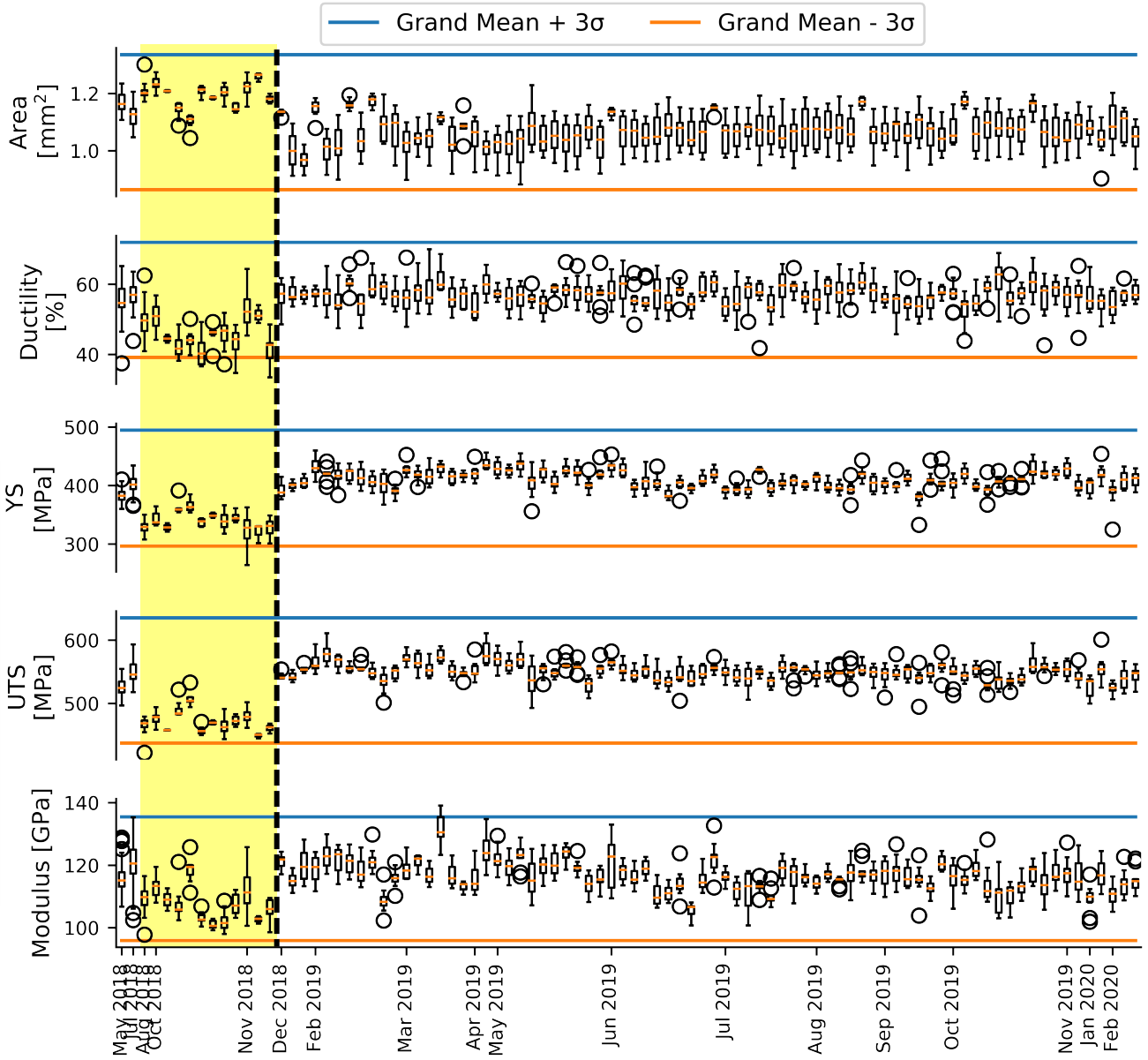
All Data

Powder size change

Lens upgrade

Lens height adjustment





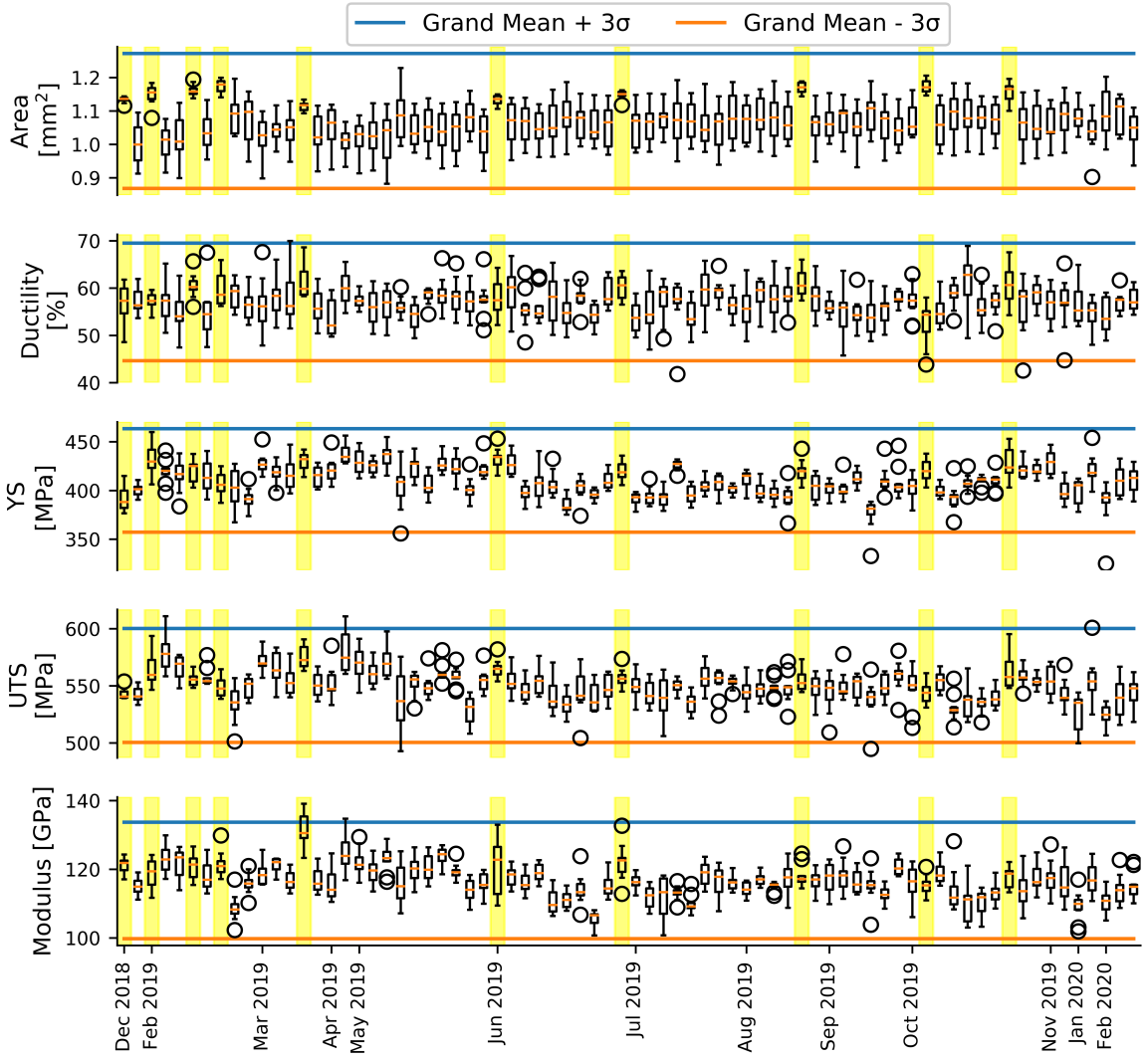
Software Change

Two slicer software's from 3D systems were used:

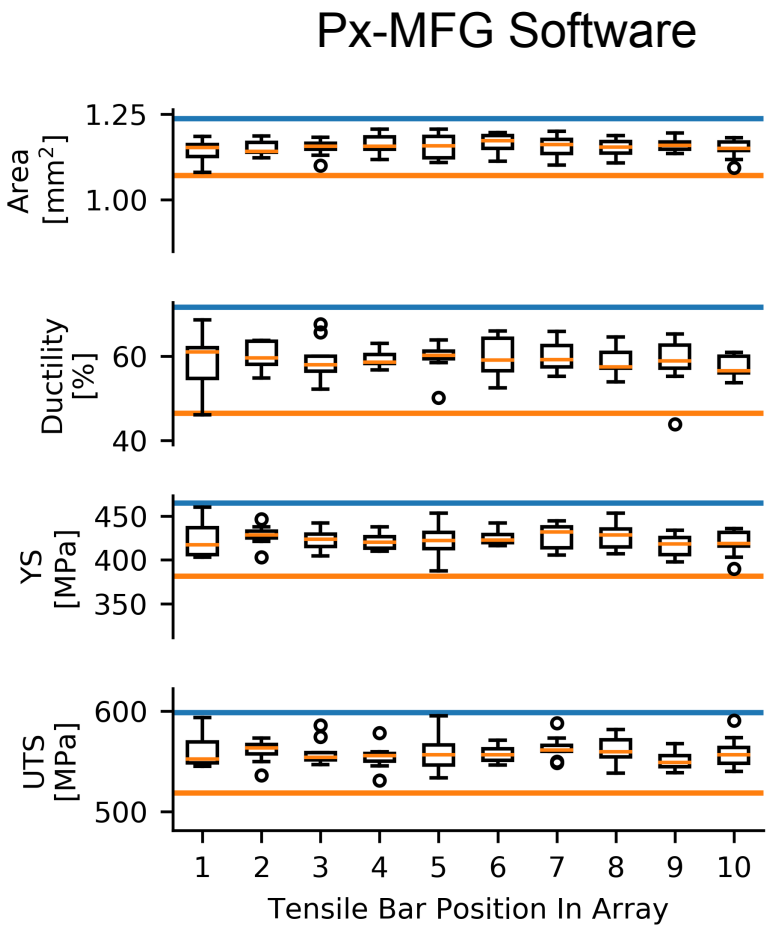
- Px-MFG (Highlighted)
- 3DXpert (Old Version)

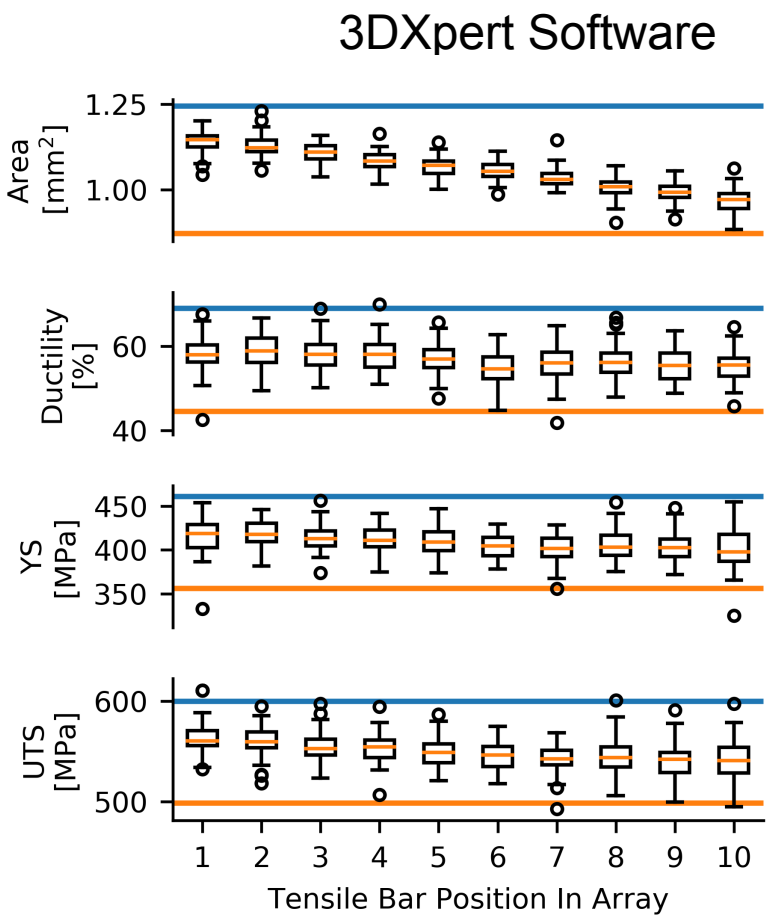
Px-MFG is the legacy software

- Used to compare to historical data
- Easily use multiple process settings



Tensile Bar in Rack





Wait, does this mean AM is scary?

- ~70 µm change in thickness
  - Meltpool is 50 µm
- Changing slicer software IS a process change
  - Guilty until proven innocent
- Early version of 3DXpert software
  - This has since been fixed

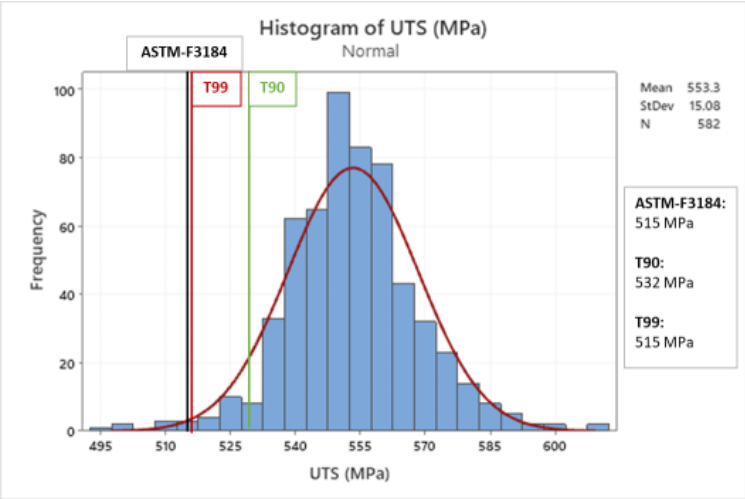
Baseline Properties

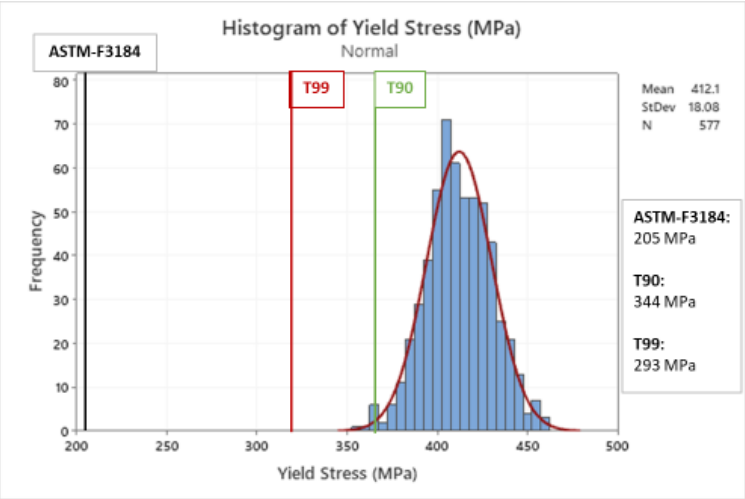
T99 value gives the value where 99% of samples should be higher than with a 95% confidence.

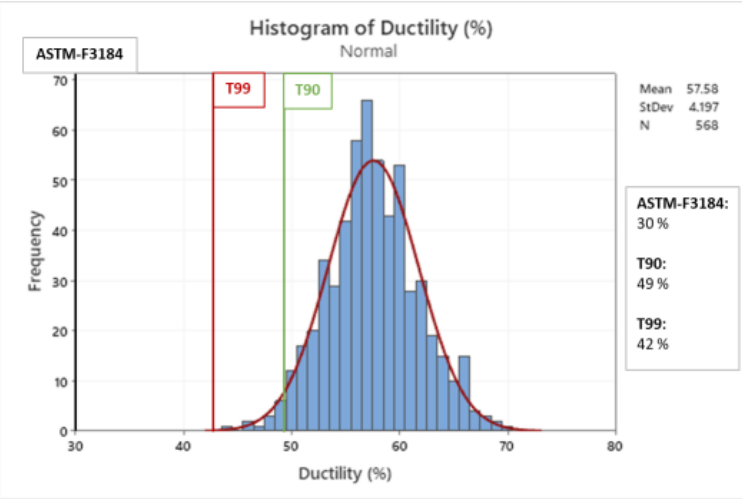
Meet or exceed AM standards (ASTM F3184-16)

Tensile Properties – T99

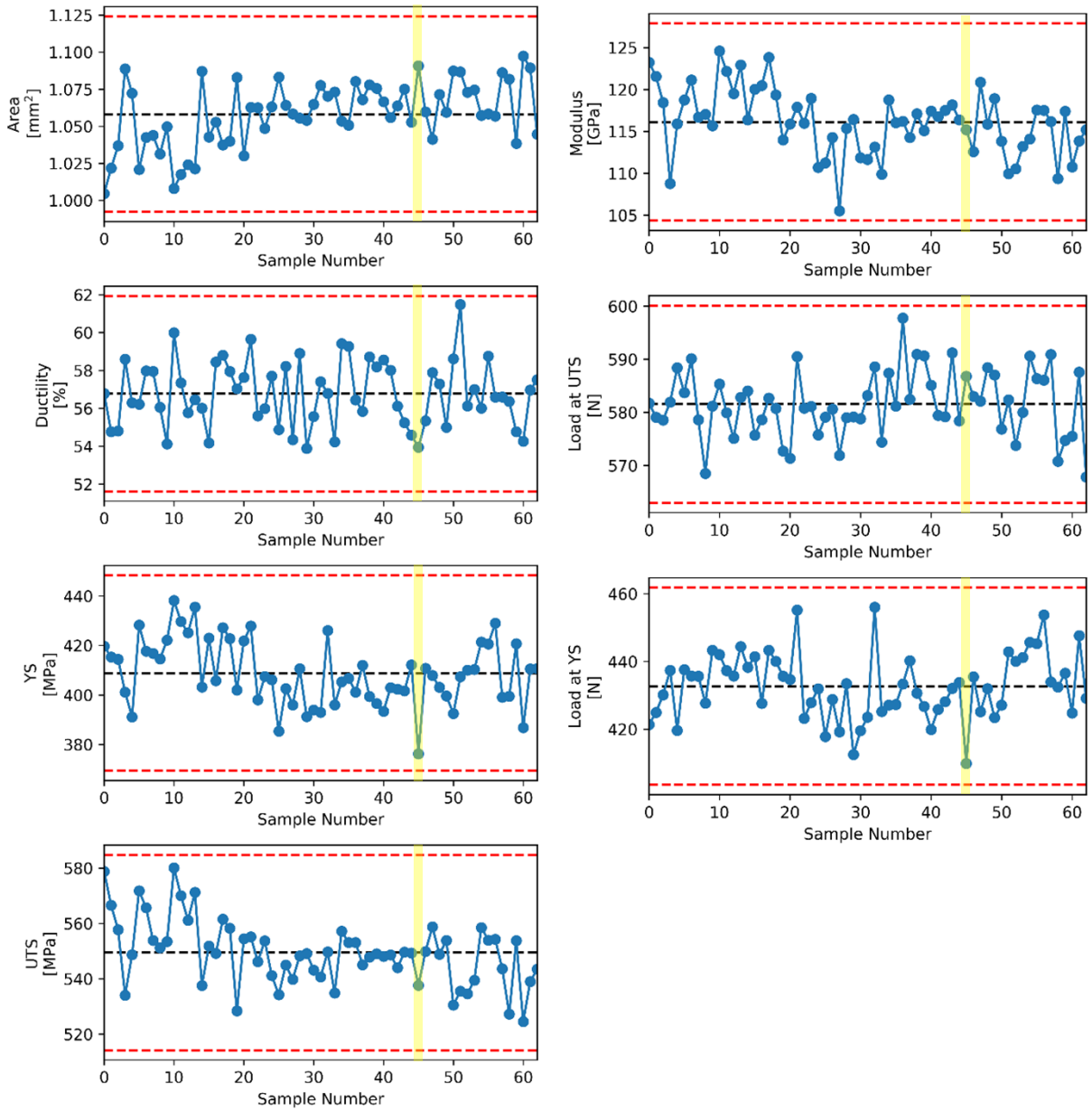
Yield Strength [MPa]	293
UTS [MPa]	515
Ductility [%]	42
Unloading Modulus [GPa]	95





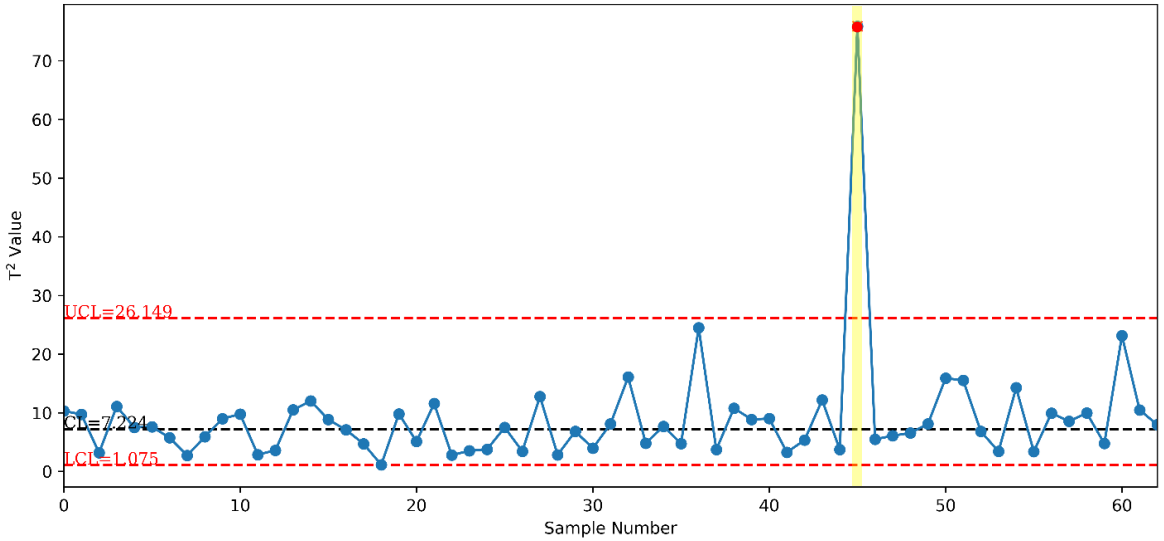


Individual's Chart (3 SD Control Limits)



Multivariate Control Chart

Hotelling T^2 Chart (α=0.01)



Variance Control Chart

Multiple sources of variability

- Within a batch (Array)
  - R-chart (Range of spread)
- Variability
  - MR-Chart (Moving range)

Detecting Process Changes

A great witness coupon is always willing to be little…

	Baseline Values			Number of Standard Deviations from Baseline Mean									
				Average Powder Diameter 16 to 26 µm	Software (Area)	Laser Power [W] (Scan Speed - 1400 mm/s)				Scan Speed [mm/s] (Laser Power - 120 W)			
	Mean	σ[1]	CV			100	120	140	160	1000	1200	1400	1600
Area [mm]	1.15	0.021	0.018	1.4	-4.6	-	-0.7	0.2	1.4	0.4	-	-0.7	-0.2
Ductility [%]	59.1	2.9	0.048	-4.7	-0.8	-	0.5	0.3	-0.9	2.4	-	0.5	-0.5
UTS [MPa]	558.8	9.7	0.017	-8.7	-0.8	-	0.1	0.0	-0.5	-2.4	-	0.1	1.3
Yield Stress [MPa]	423.4	8.5	0.020	-9.5	-1.7	-	-0.8	0.0	-0.7	-4.0	-	-0.8	2.3
Modulus [Gpa]	120.8	4.8	0.039	-2.7	-0.9	-	0.9	0.3	-1.0	-0.1	-	0.9	0.6
Load UTS [N]	644.3	4.6	0.007	-17.9	-13.4	-	-1.3	0.5	2.3	-4.8	-	-1.3	2.6
Load YS [N]	488.2	7.0	0.014	-11.9	-7.9	-	-1.9	0.2	0.7	-5.1	-	-1.9	3.0
Density [g/cm3]	7.9	0.0054	0.0007	-27.3	0.2	-3.8	0.4	1.6	0.8	1.8	1.5	0.4	-2.5
Hardness [HRB]	92.5	0.56	0.006	-9.7	0.4	0.3	2.3	0.1	-2.0	-1.2	0.2	2.3	0.3
Charpy [J]	63.4	4.9	0.077	-9.3	0.0	-6.1	-0.3	1.5	1.1	1.4	1.5	-0.3	-5.3

[1] Unbiased estimator for the standard deviation of individual samples (Charpy) or for the means (HTT arrays)

Tensile bars are great for small features:

- Capture area changes
- Sensitive to small feature properties (surfaces)
- Result in multiple properties in one test – Great for multivariate analysis

Conclusions

Process Optimization

- Effective tensile properties do not follow typical volumetric energy dependence of bulk material
- Wide range of ductility and strength across the printable window
- Extreme values indicate poor process settings
- Area changes across the process space

Process Monitoring

- Demonstrate process monitoring for laser powder bed fusion
- Identify sources of variability in the AM process and how they can affect properties
- High Throughput Tensile bars are better witness coupons for small features than density/hardness/Charpy because:
  - They capture area changes
  - Performance have similar dependence on process to other small features
  - Capture multiple variables in one measurement that can be used in a multivariate analysis

Questions?

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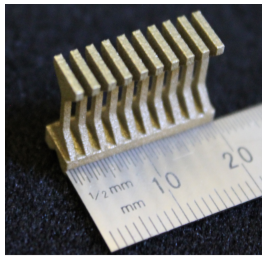
Back-Up Slides



Area Changes Across Process Space

F=(UTS)(Load Bearing Area)

	Laser Power [W]	Scan Speed [mm/s]	Volumetric Energy Density [J/mm³]
Blue	120	1000	79
Green	130	1200	72
Orange	140	1400	66
Red	120	1400	57