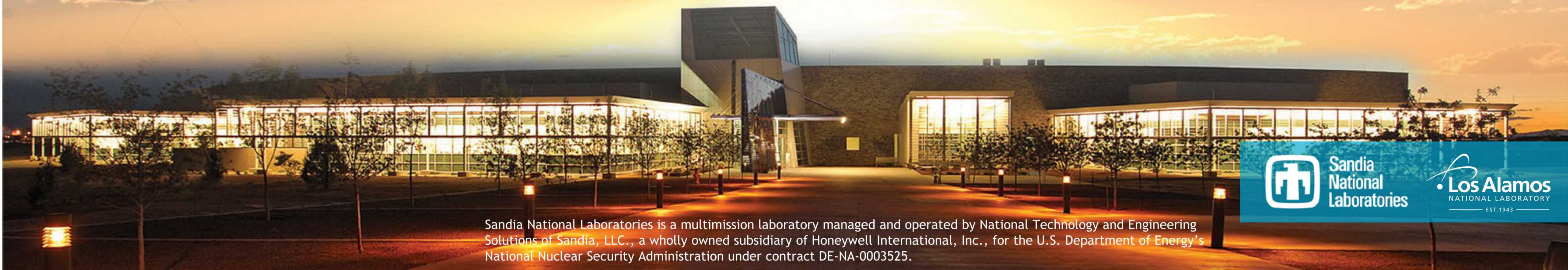
SAND2019-15492C

Improving performance and reliability of additively manufactured metals by linking experiments, models, and analytics

Brad L. Boyce

Materials, Chemical, and Physical Sciences Center

Sandia National Laboratories



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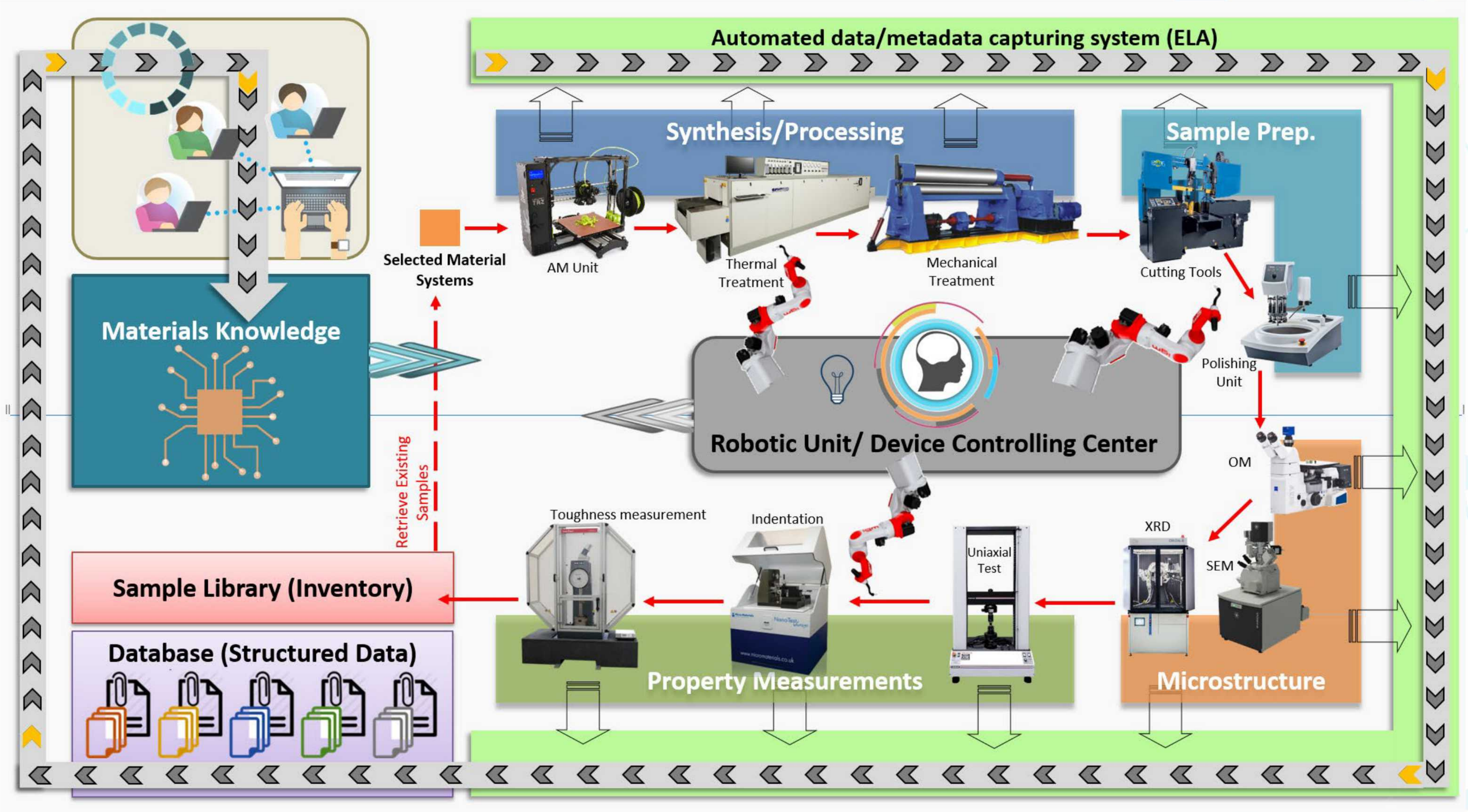
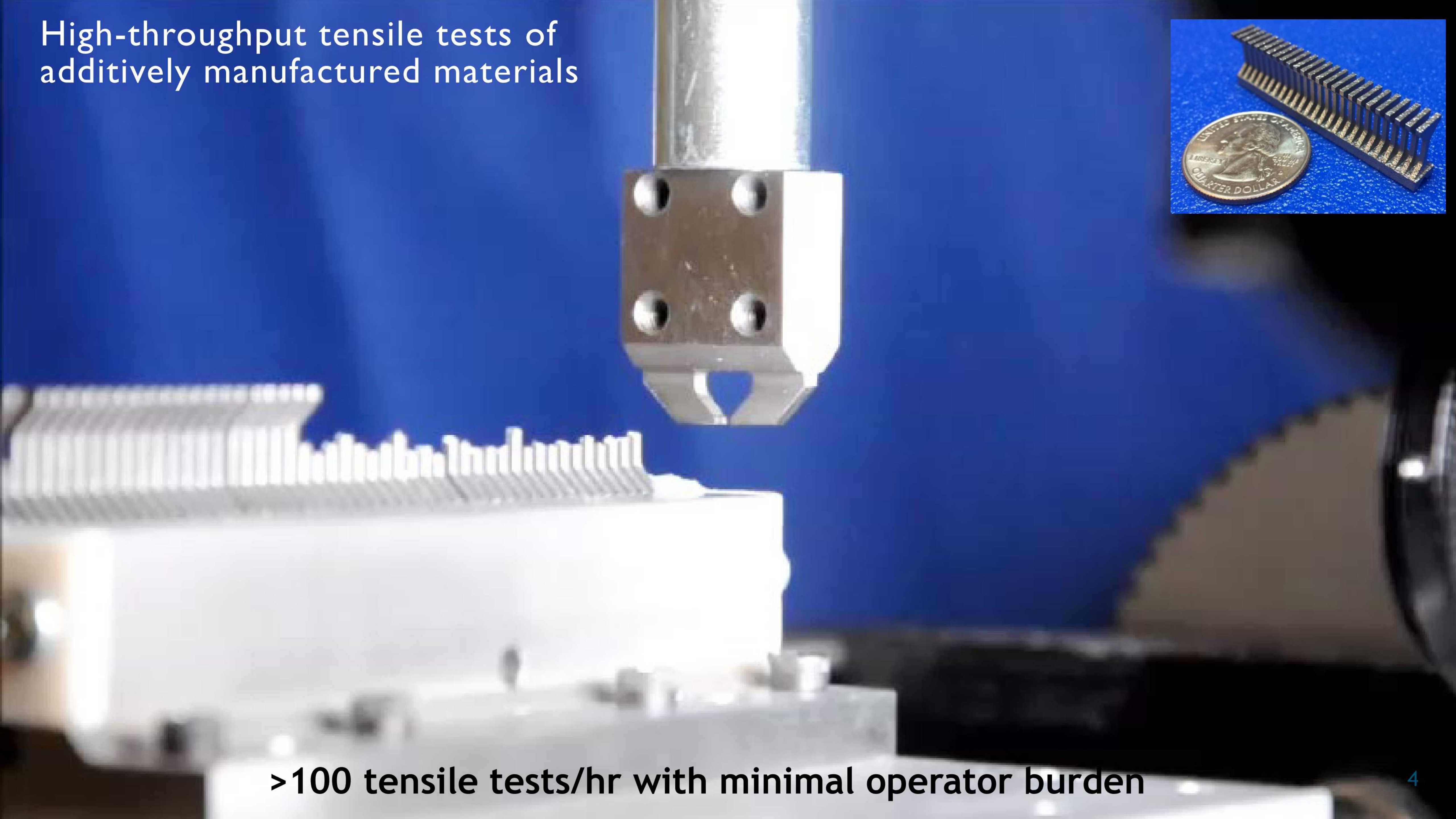
Kalidindi’s vision for automated data-driven discovery



https://matin.gatech.edu/groups/mined_sg9_automation_autonomy_experiments

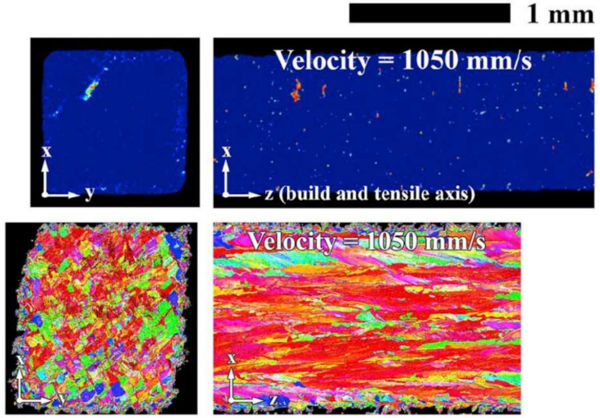
High-throughput tensile tests of additively manufactured materials



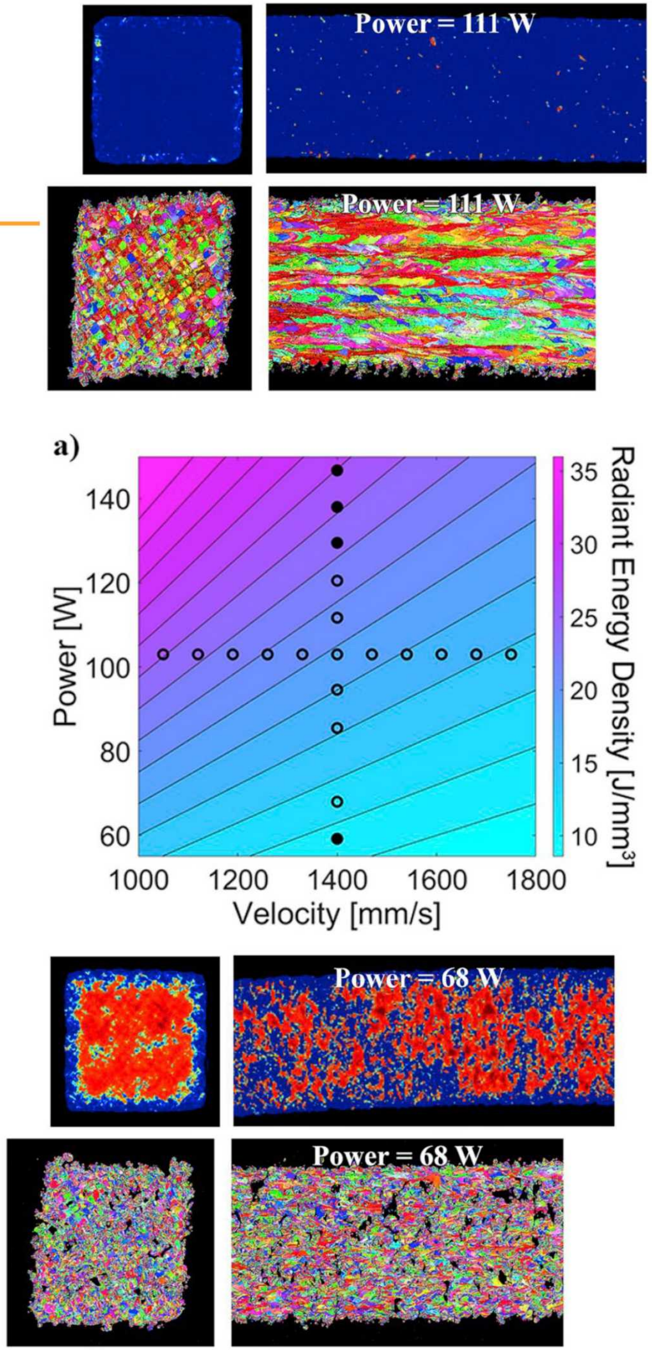
>100 tensile tests/hr with minimal operator burden

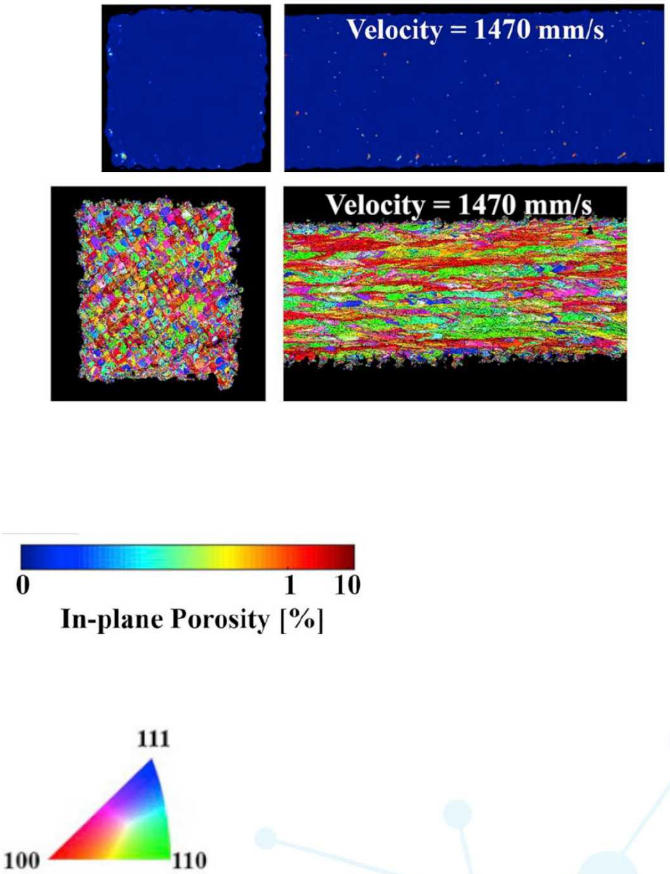
Process parameter study

X-ray computed tomography



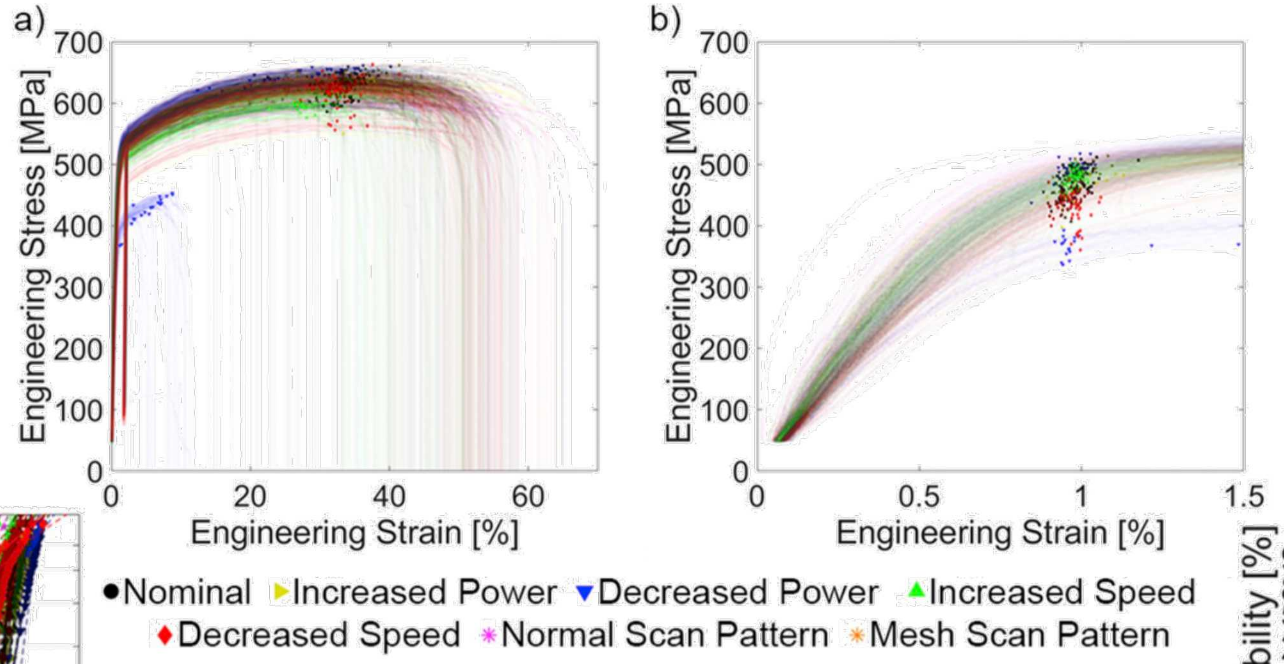
High-speed electron backscatter diffraction

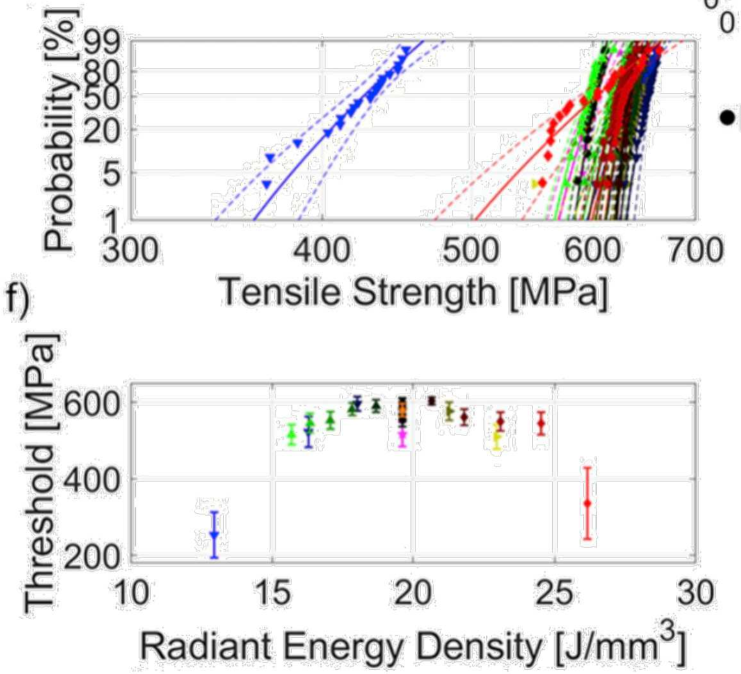


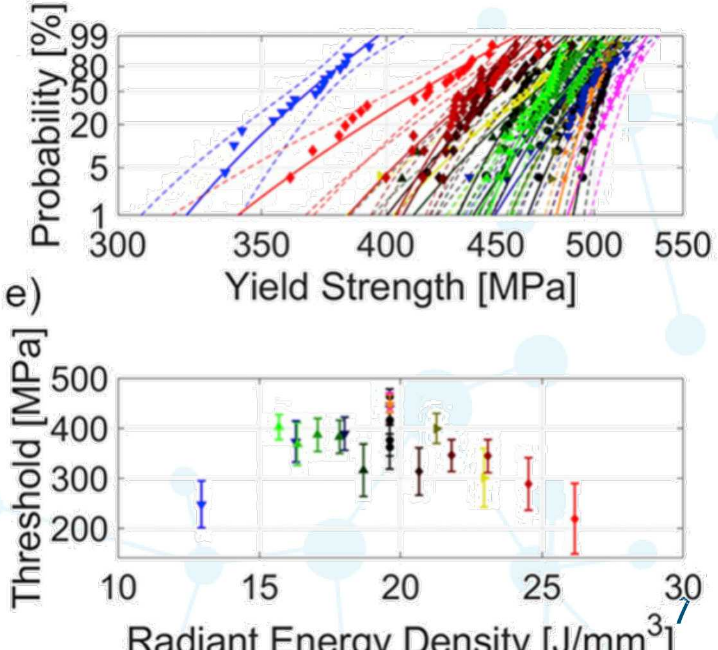


Heckman…Boyce, *Mater. Sci. Eng. A.*, 2020

High-throughput data → a Weibull minimum allowable threshold



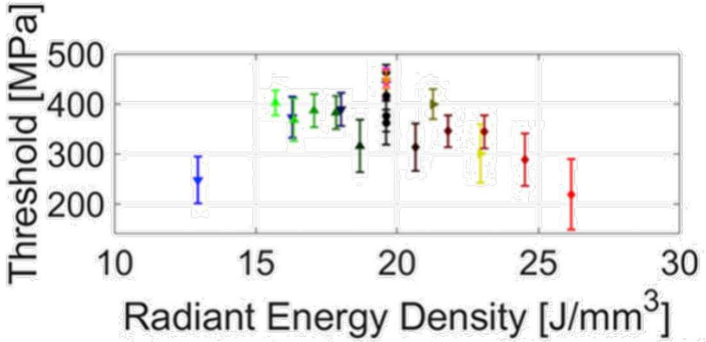


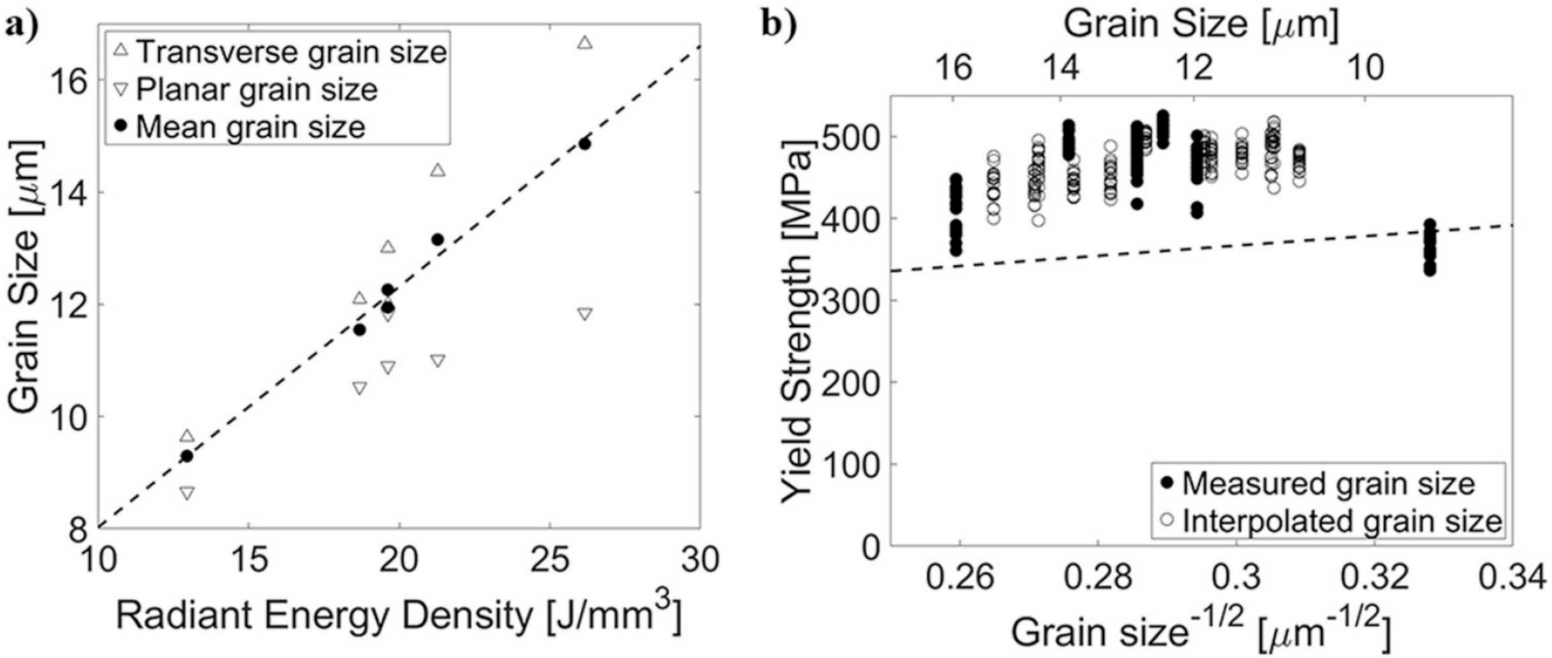


Heckman…Boyce, *Mater. Sci. Eng. A.*, 2020

Connecting the dots… the old fashioned way…

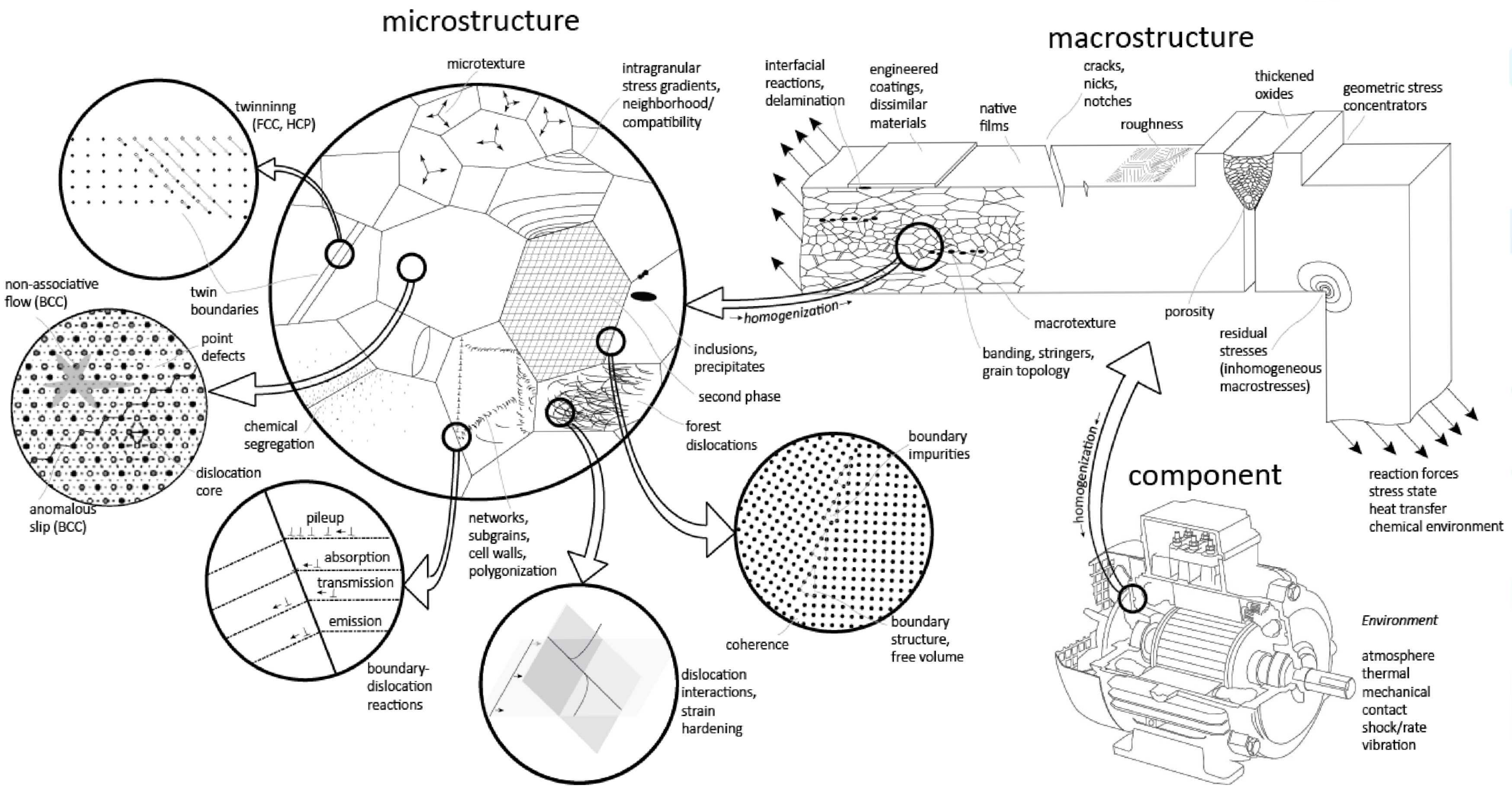
Weibull threshold
Yield Strength (MPa)





Heckman…Boyce, *Mater. Sci. Eng. A.*, 2020

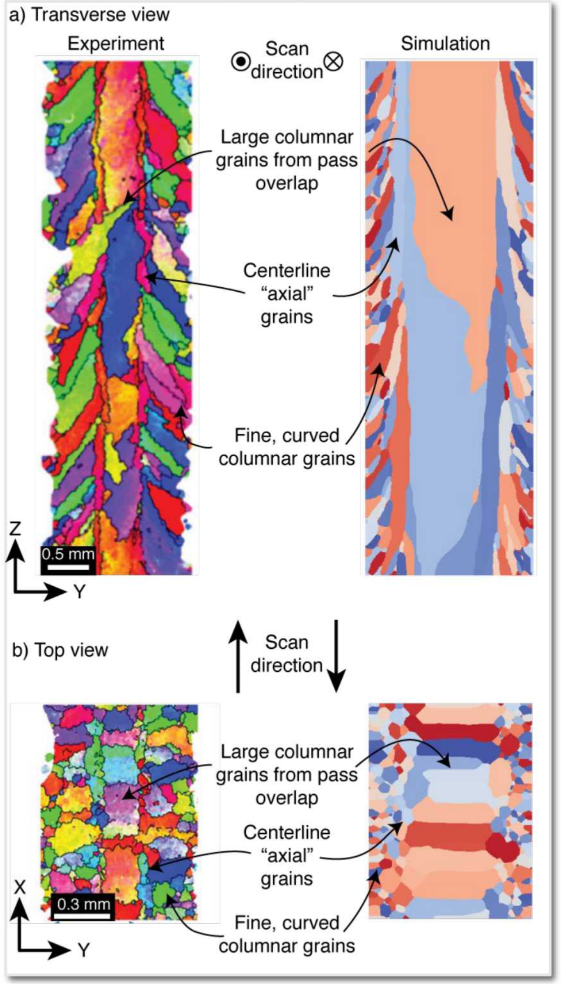
Grain size is not the only factor affecting mechanical response…



Predicting the microstructure is even more difficult!

Examples of solidification modeling

Grain shape predictions



This is a **herculean** challenge

Powder packing
Laser/plume interactions
Plasma fluid mechanics
Radiation heat transfer
Laser energy adsorption, radiation
Thermal expansion
Non-equilibrium vapor pressure
Evaporation with latent heat
Pressure-temperature relations
T-dependent heat capacity
Incompressible fluid dynamics
Convective/conductive heat transfer
Capillary forces
Marangoni forces
Hydrodynamic mixing
Multicomponent liquid-solid diffusion
Solidification macrosegregation
Solidification shrinkage
CTE thermal contraction
Thermomechanical deformation
Residual Stress
Solid-state diffusion
Anisotropic crystallization
Solid-state phase transformation

Collaboration with M. Martinez, T. Rodgers, et al.

The intractability of complete process-structure-property mastery?

Process
100+ variables

Structure
100+ variables

Properties
Dozens relevant

Powder packing
Laser/plume interactions
Plasma fluid mechanics
Radiation heat transfer
Laser energy adsorption, radiation
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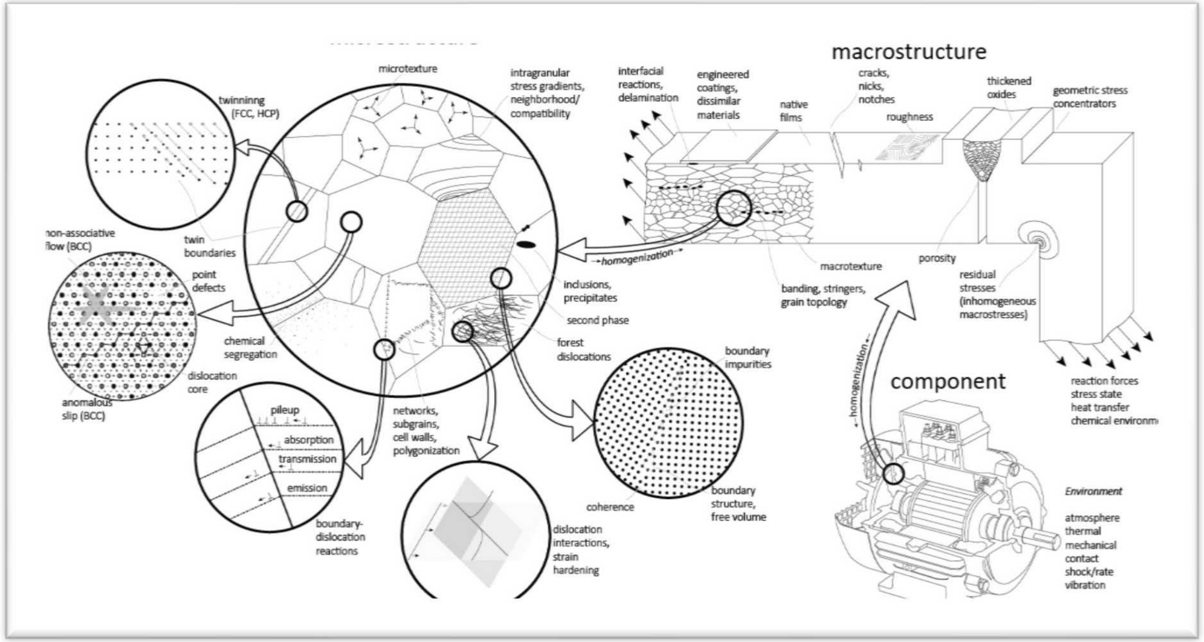
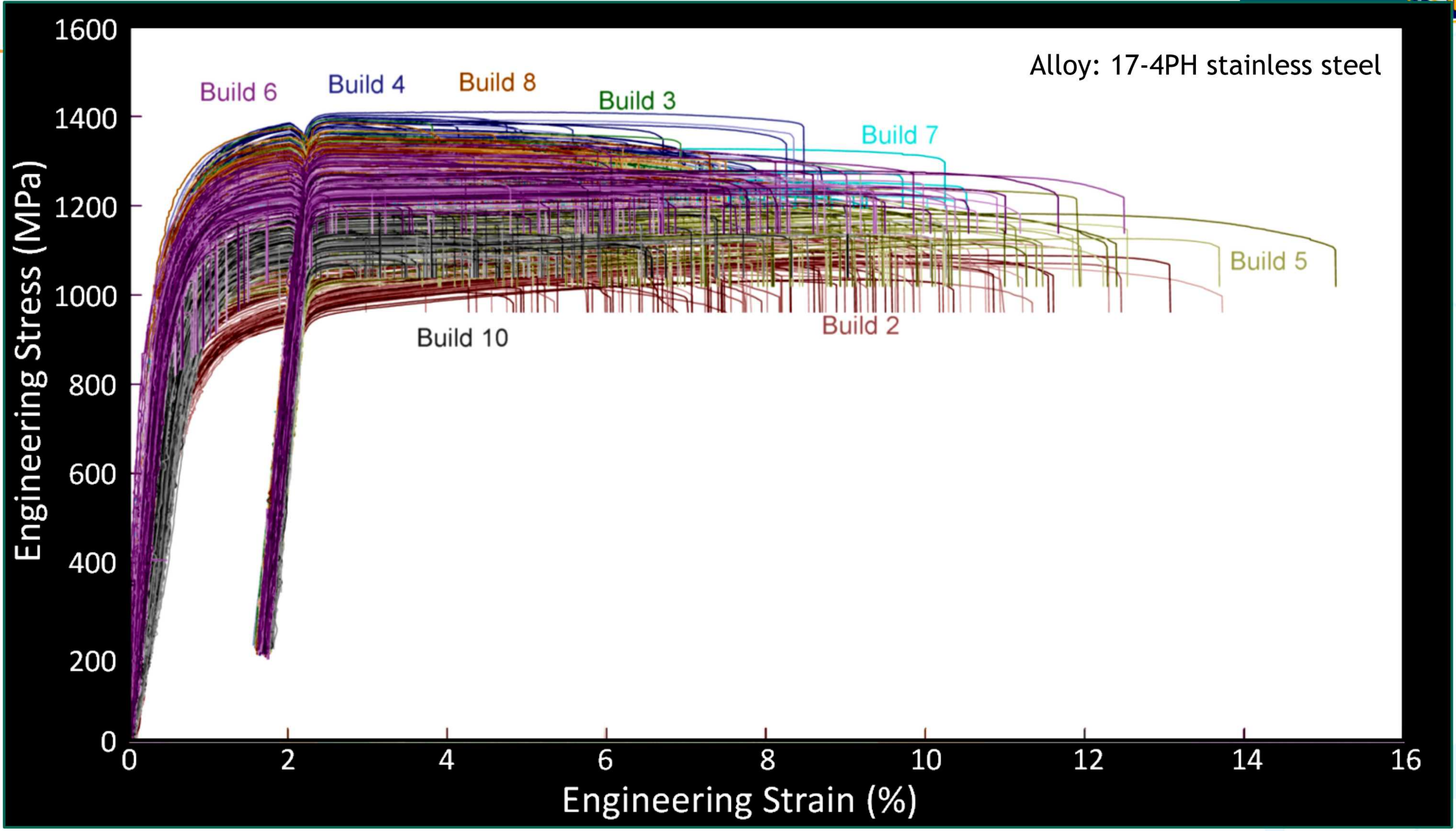


Modulus
Yield-strength
Work Hardening
Fracture Toughness
Ductility
Fatigue life
Wear resistance
Temp-dependence / Creep
Strain-rate dependence
Corrosion resistance

Materials Science Mad Libs:

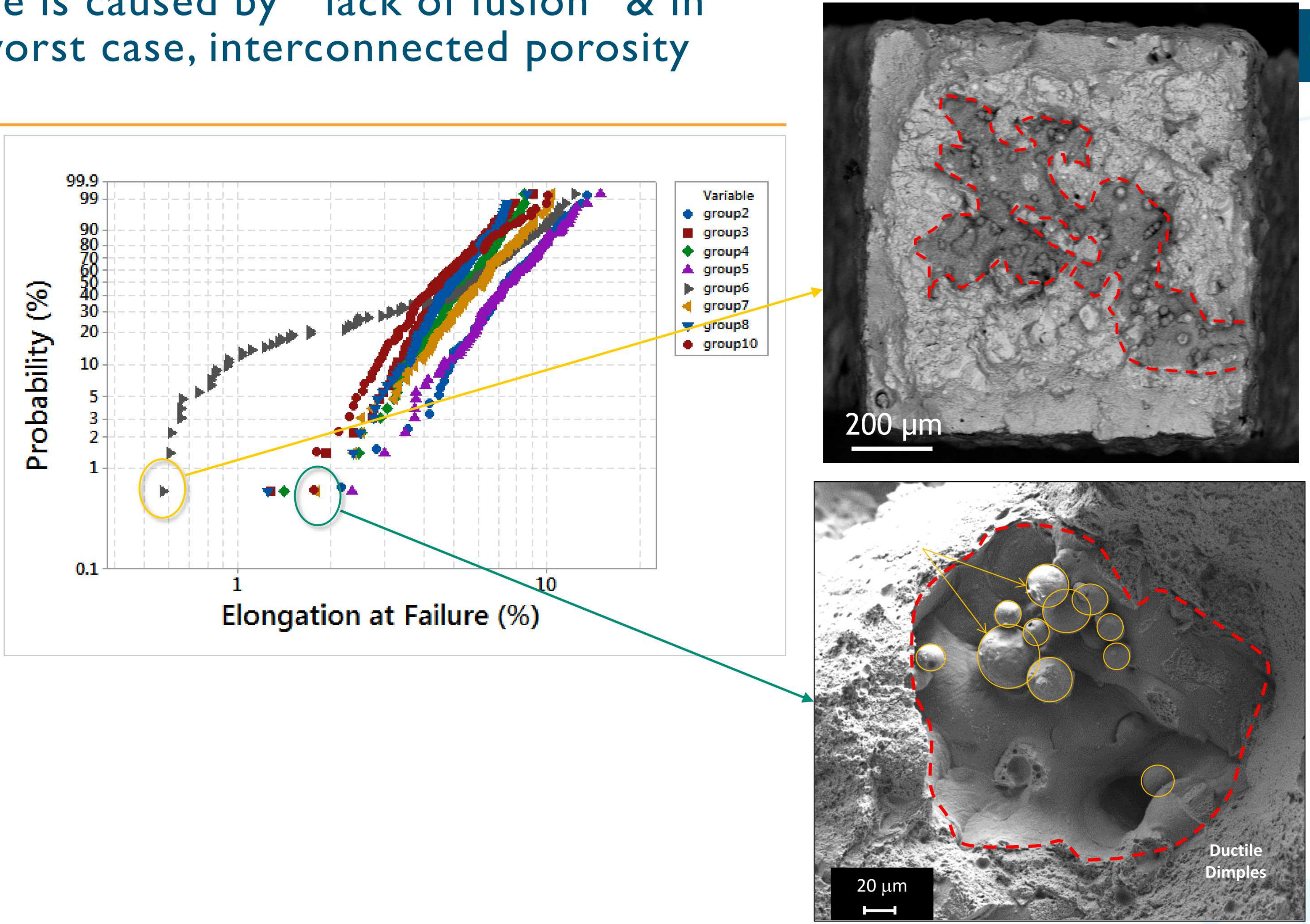
How does the ___*process*___ affect the ___*structure*___ and ultimately control ___*property*___

Over 1000 tensile tests on nominally identical additive material



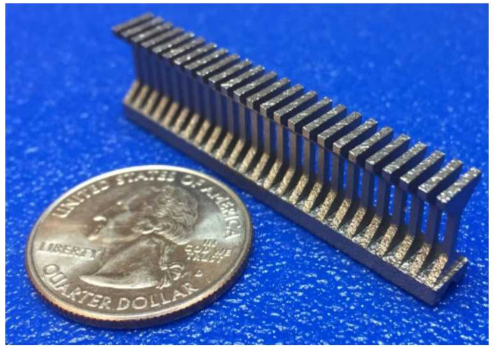
Boyce, Salzbrenner, Rodelas, Swiler, Madison, Jared, Shen, *Advanced Engineering Materials*, 2017

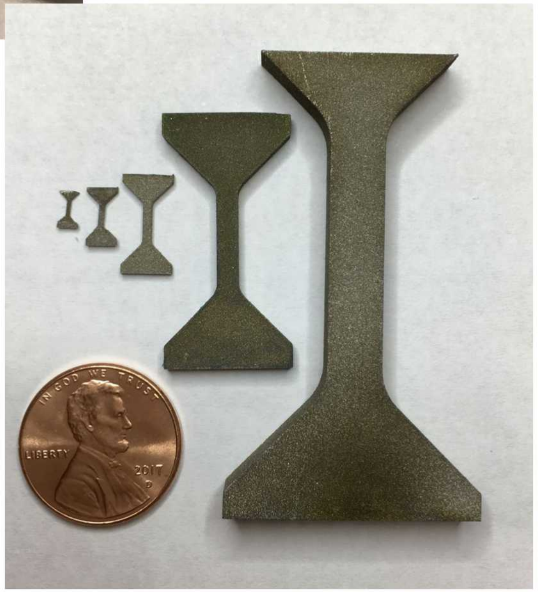
Failure is caused by "lack of fusion" & in the worst case, interconnected porosity

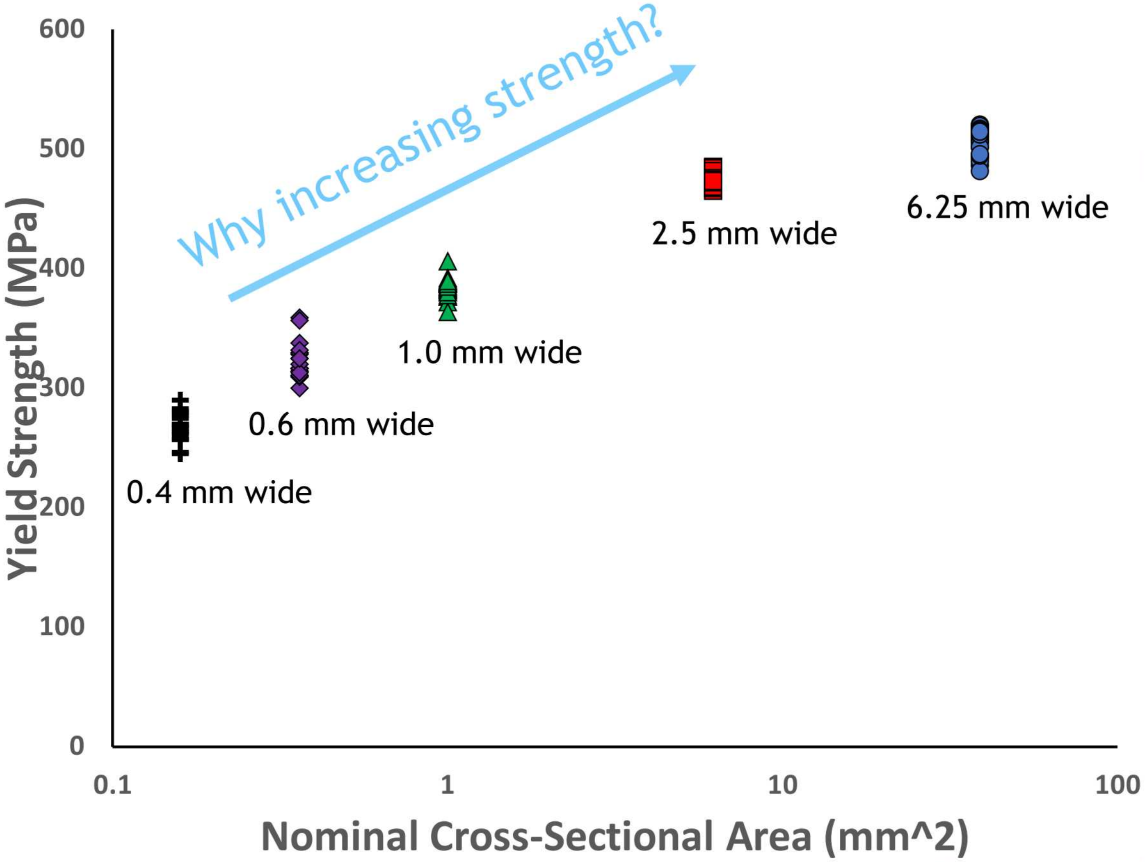


Boyce, Salzbrenner, Rodelas, Swiler, Madison, Jared, Shen, *Advanced Engineering Materials*, 2017

Representative volume consideration???
Size dependence of effective mechanical properties…

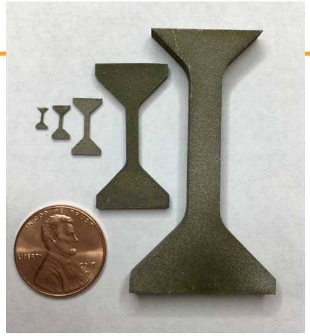


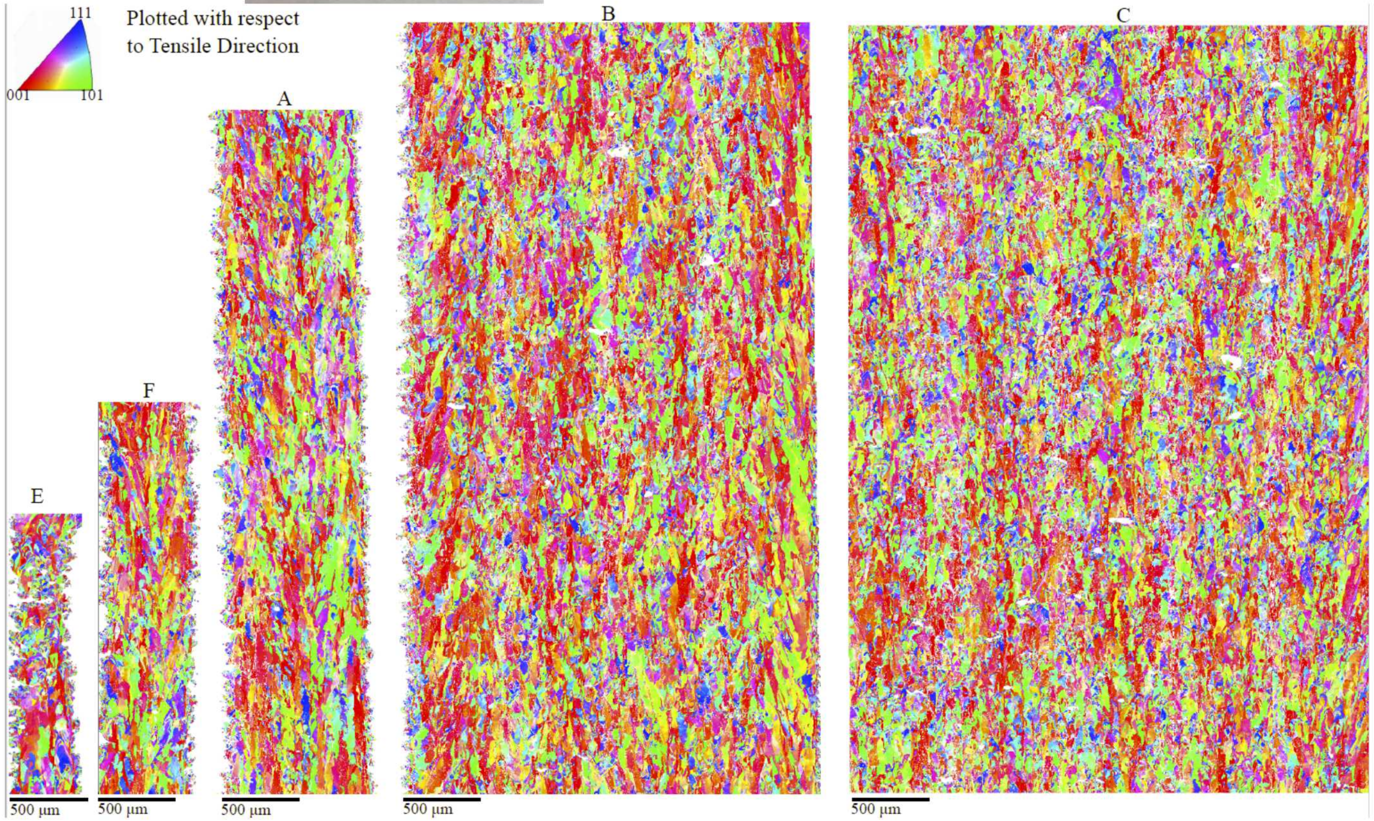


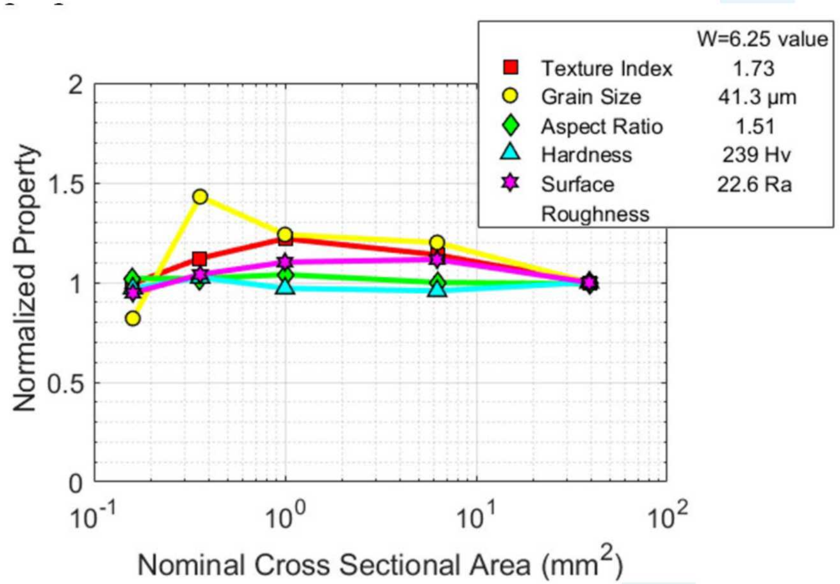


Roach…Boyce, *in review*

No microstructural source of size dependent properties…!

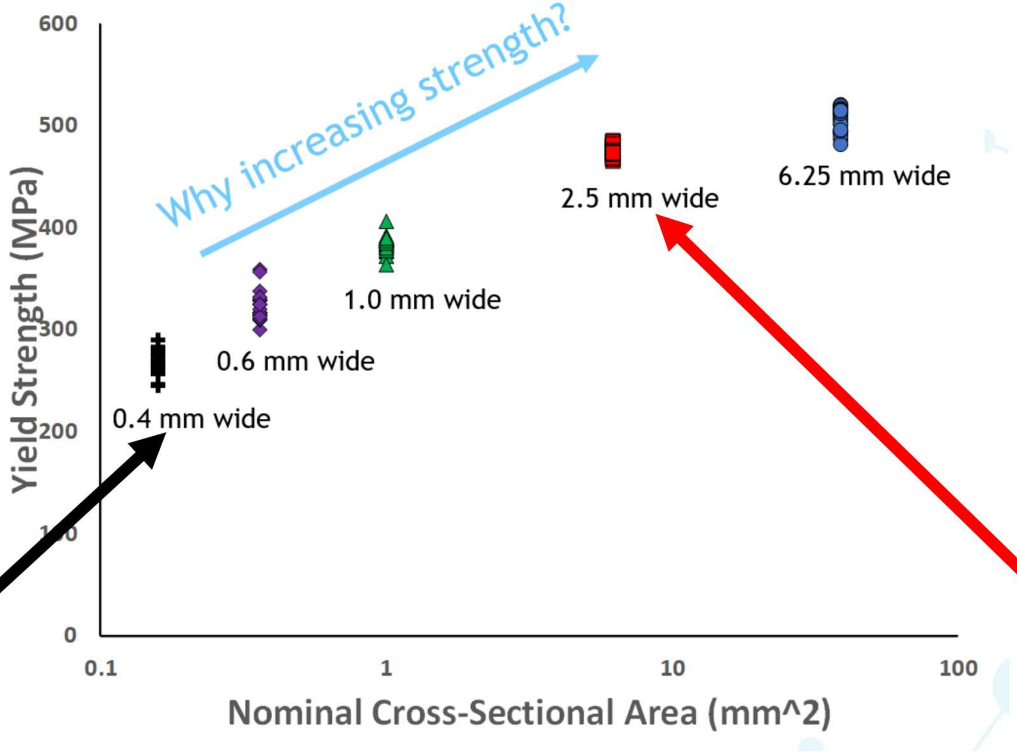


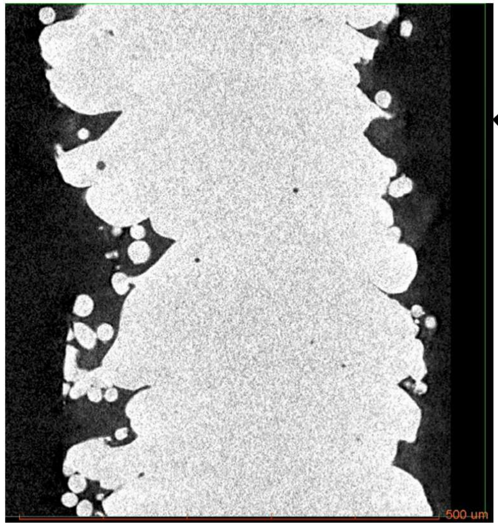


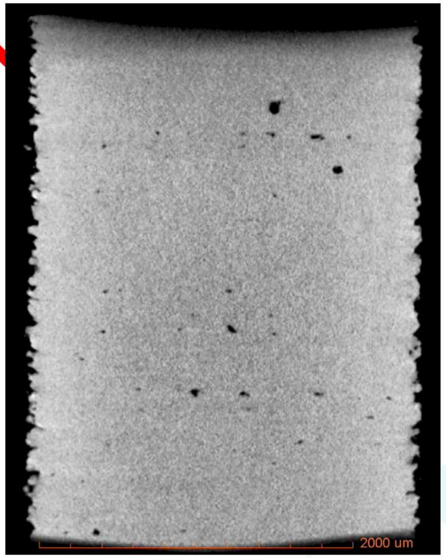


Roach…Boyce, *in review*

Surface topography dominates when features are <2.5 mm!



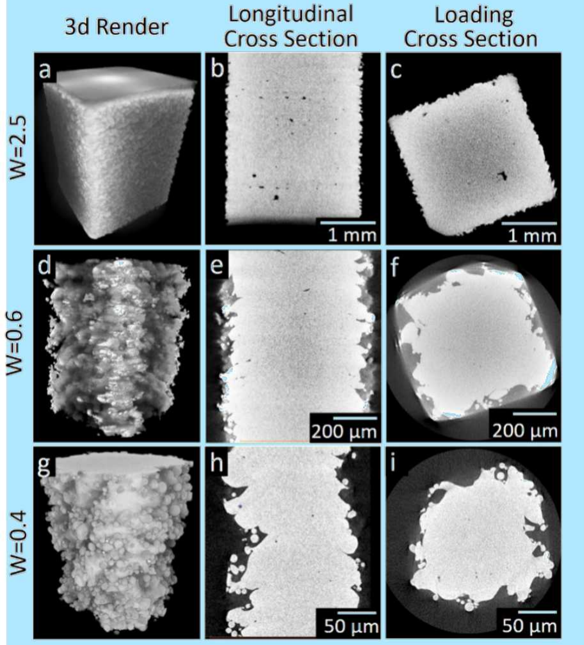




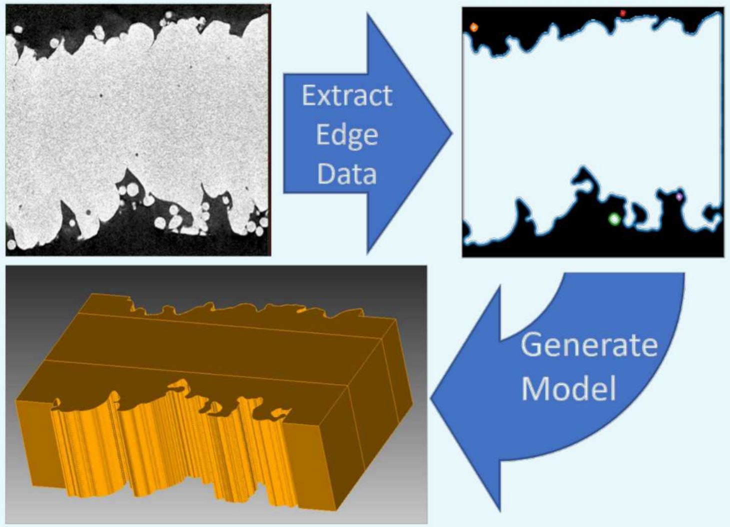
Roach…Boyce, *in review*

Finite element modeling of roughness effect

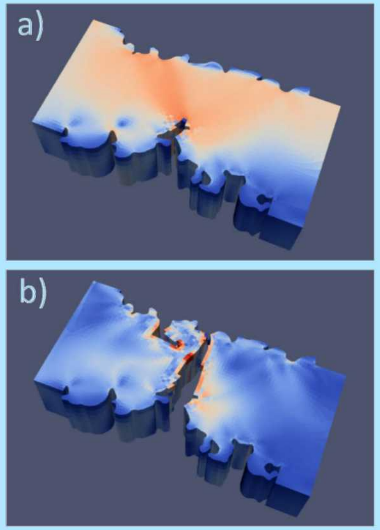
1) Collect CT scans



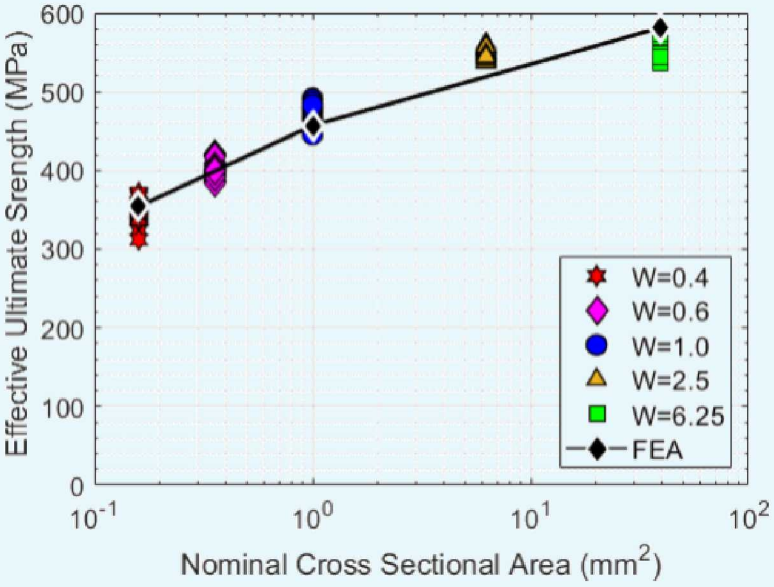
2) Digitize geometry



3) FEA



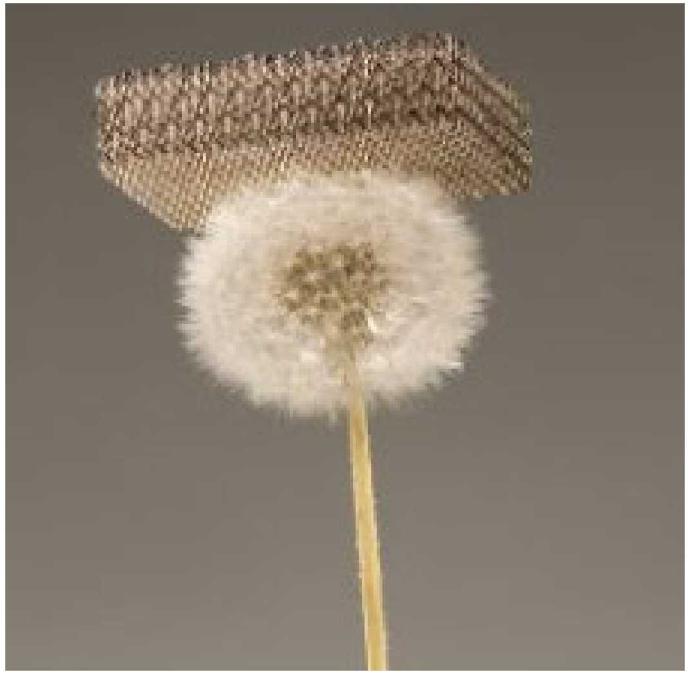
4) Confirm experimental trends



Roach…Boyce, *in review*

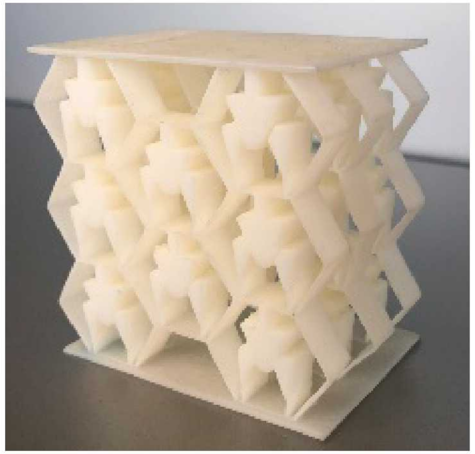
AM lattice metamaterials will maximize surface topography effects

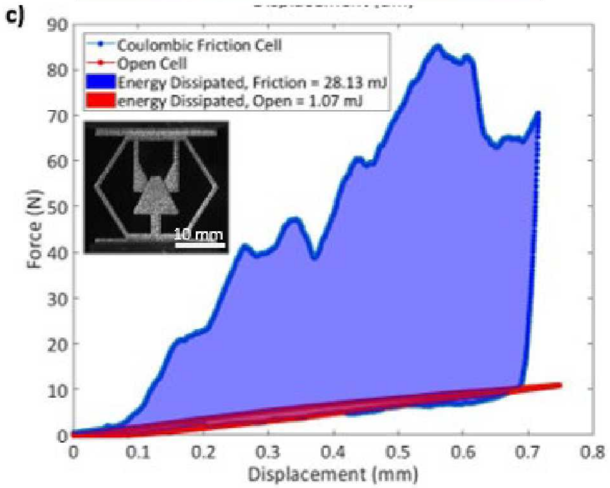
Lightweight, stiff structures



Schaedler…Carter, *Science*, 2011

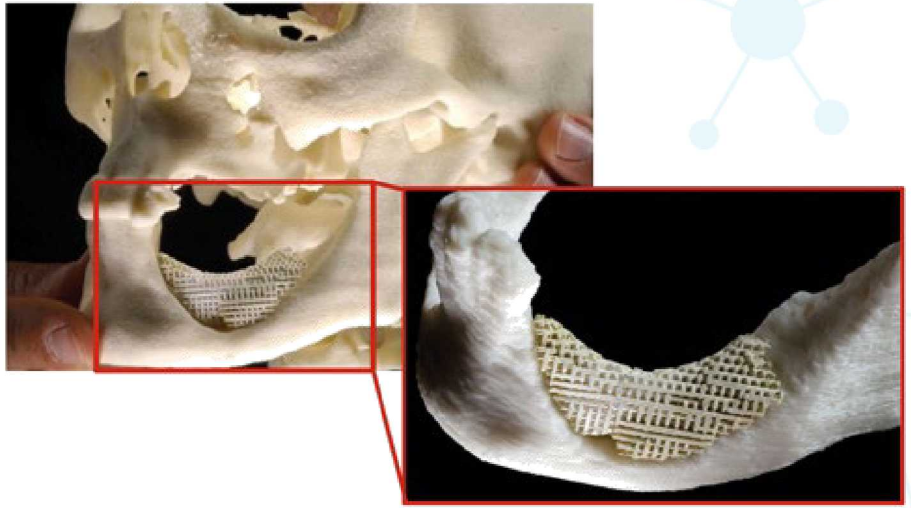
Energy-dissipating structures

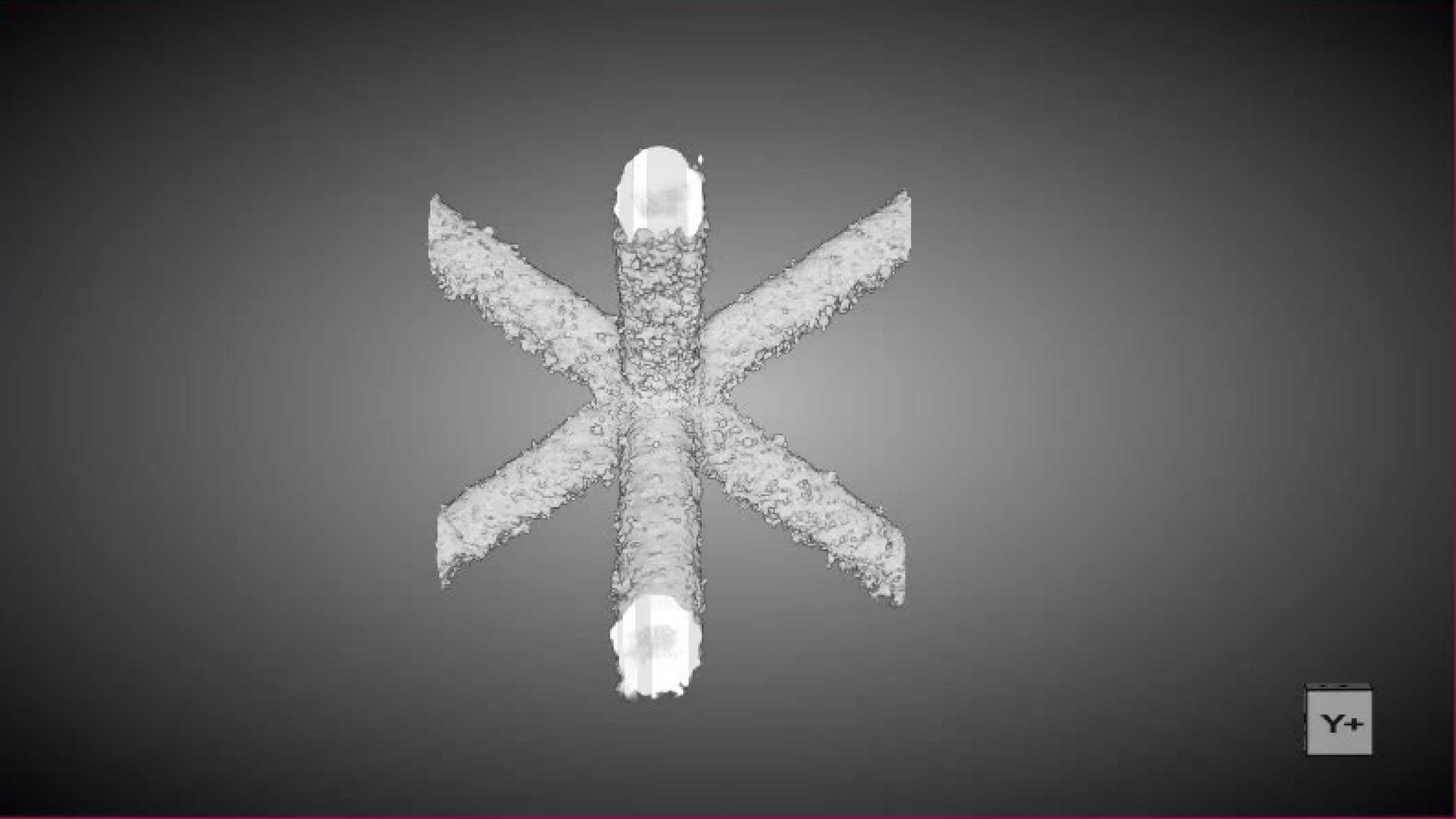




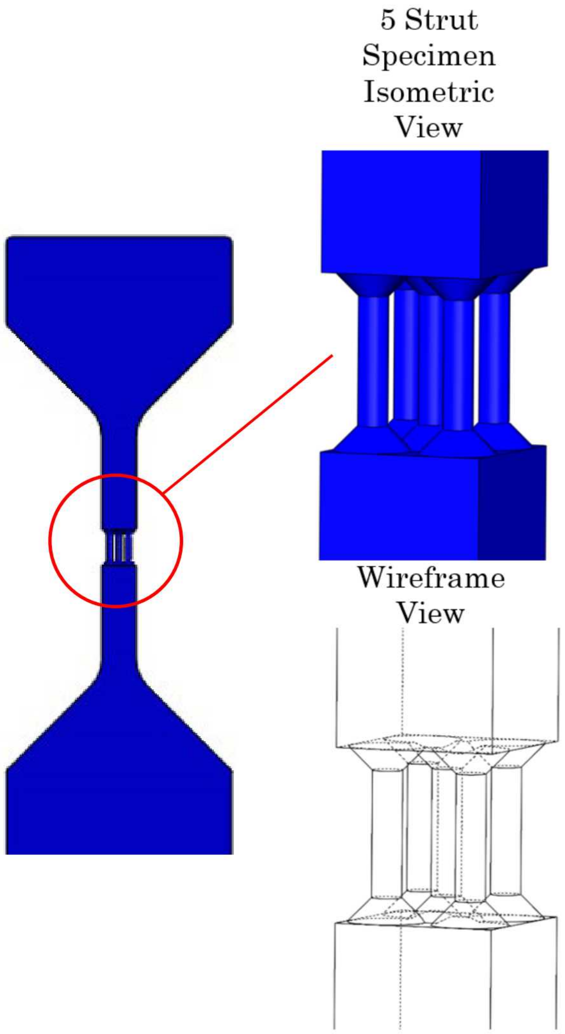
Boyce, patent filed

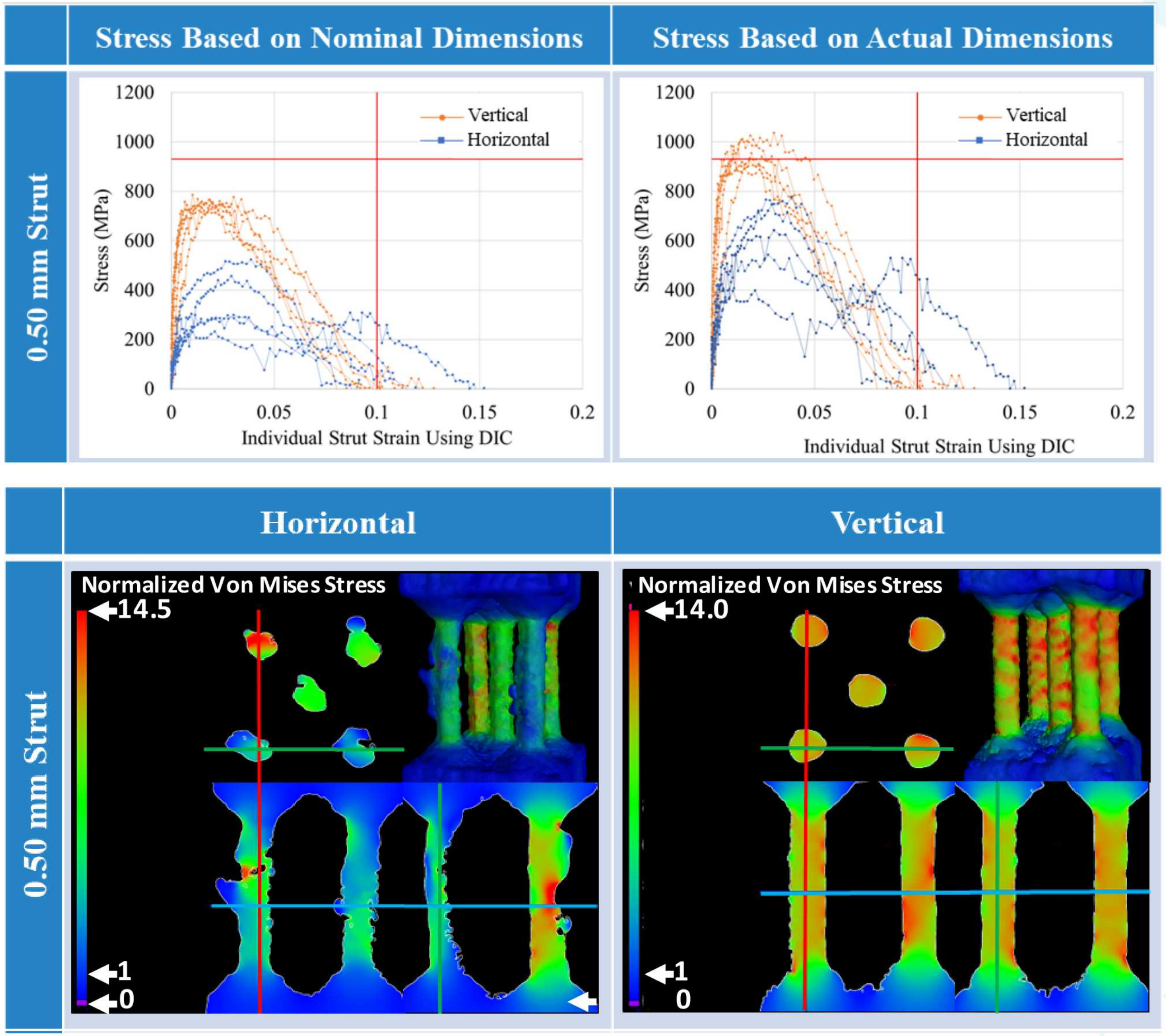
Custom-fit scaffolds




Y+

Indeed, the effective strength of struts can be <50% of the 'material' strength

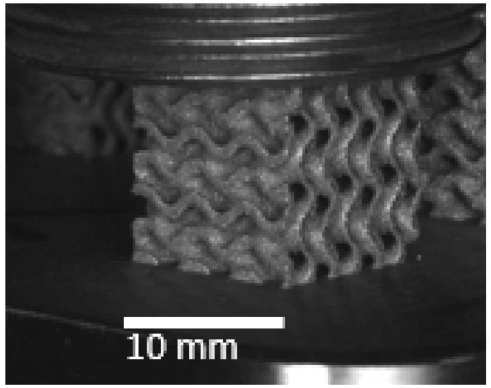


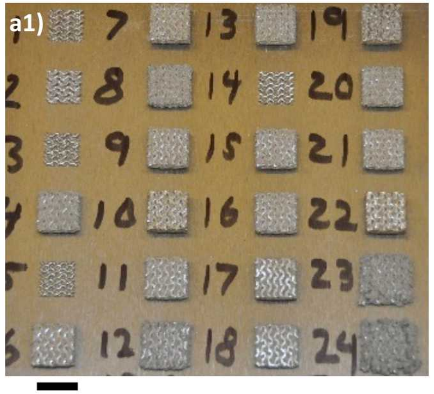


Dressler…Boyce, *Additive Manufacturing*, 2019

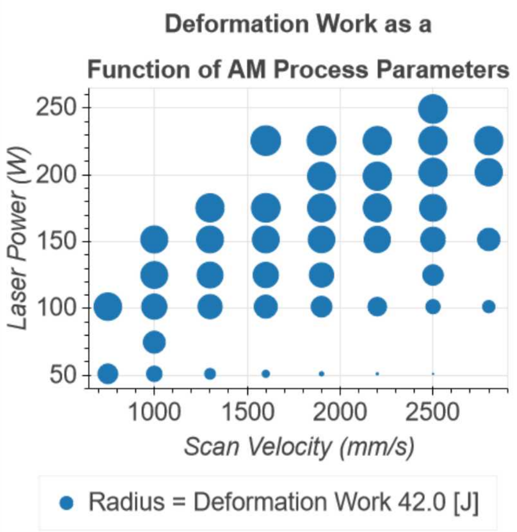
Process parameter study for a lattice…

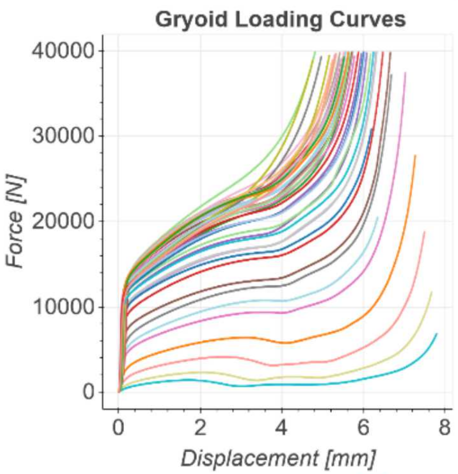
gyroid



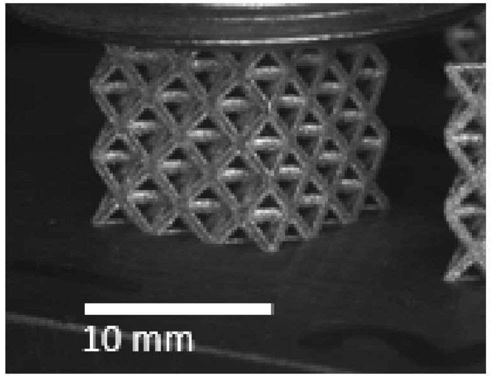


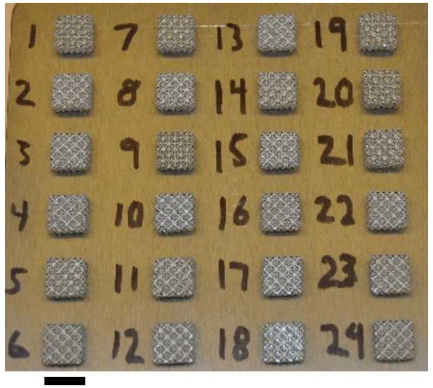
10 mm



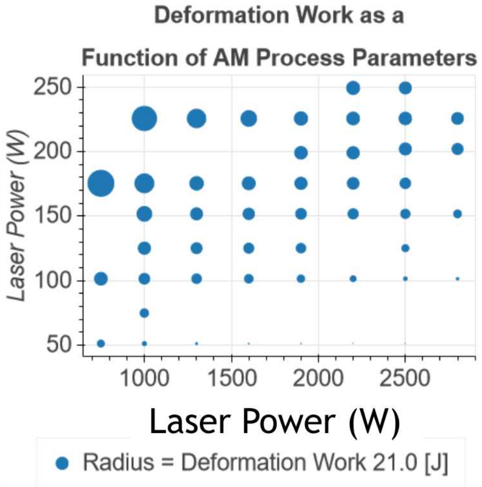


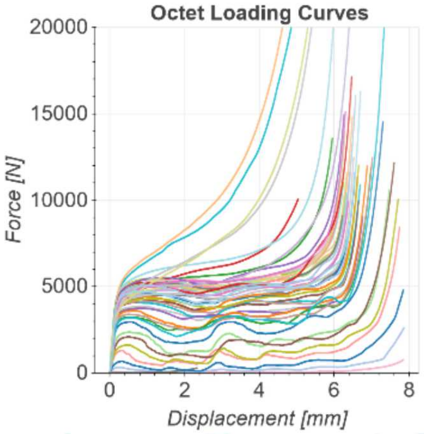
Octet truss





10 mm

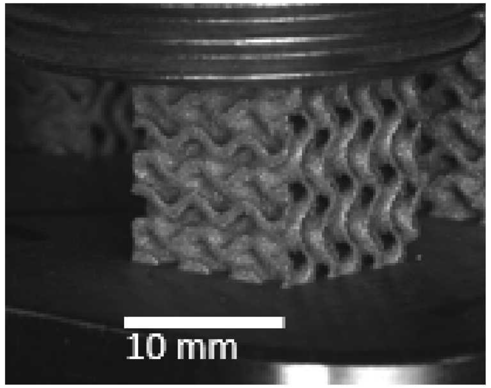


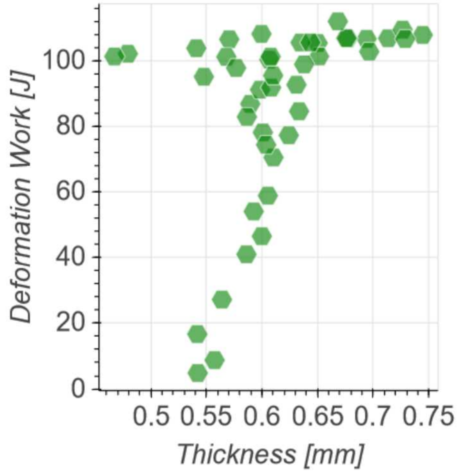


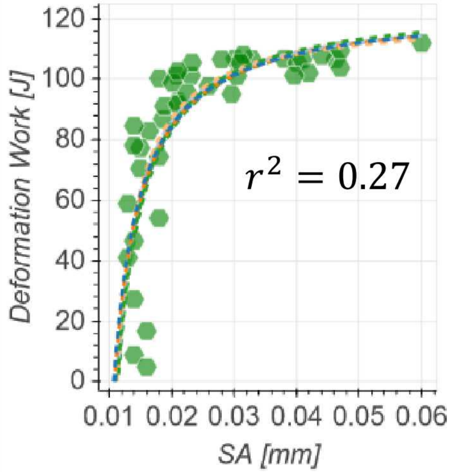
Garland…Boyce, *submitted*

Can we ‘predict’ mechanical properties with just scalar measures

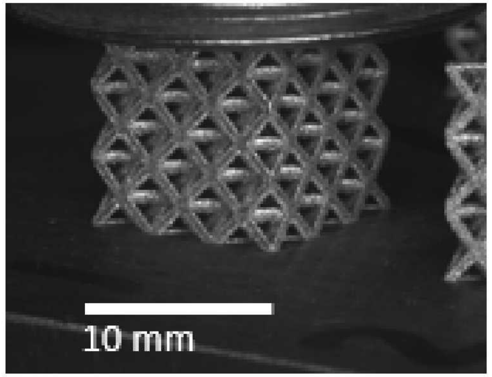
gyroid

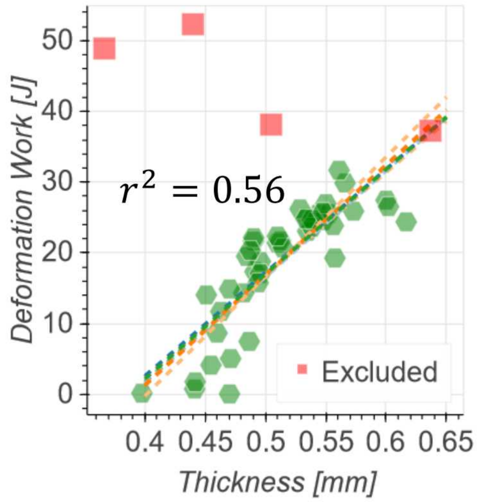


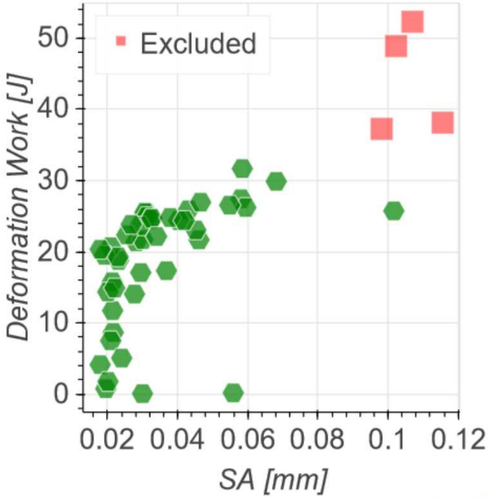




Octet truss





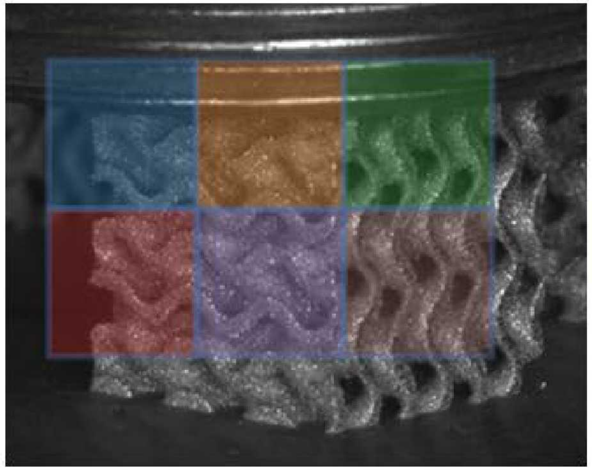


Garland…Boyce, *submitted*

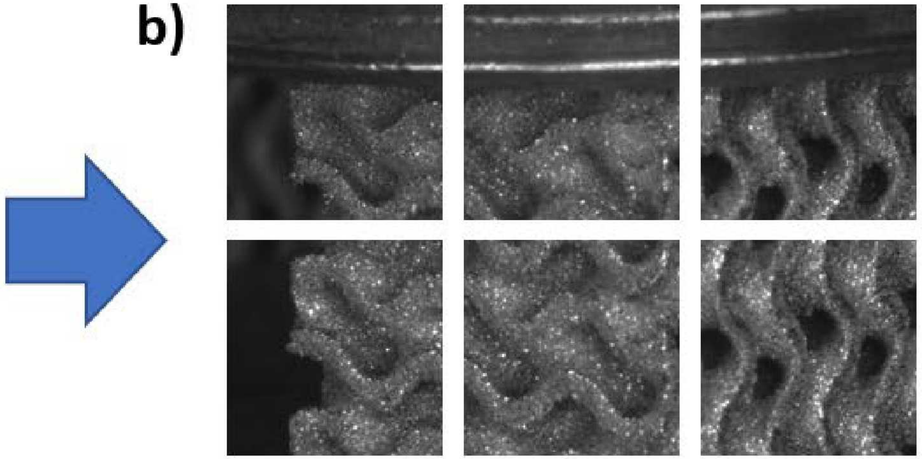
Can machine learning do any better?

Convolutional neural network; 16 layers (resnet16 in fastai library);
stratified k-fold training (8 folds / 11% of data held for testing); enriched data by subwindowing

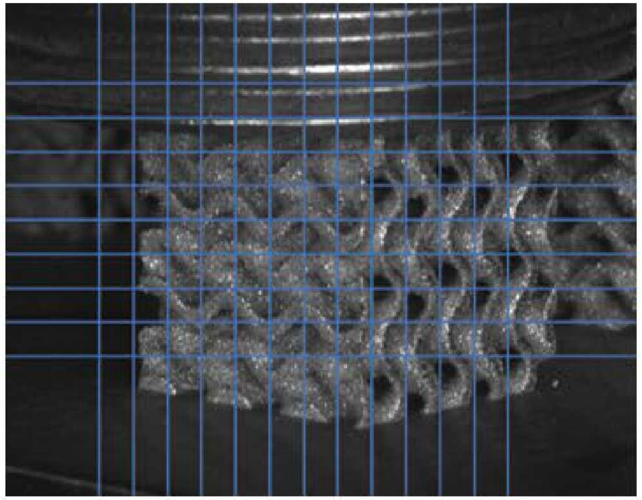
a)



b)



c)



To ‘enrich’ the available data, rather than training on the entire image, we trained on 45 sub-images (windows) of each original image. This takes advantage of the repetitive nature of the lattice.

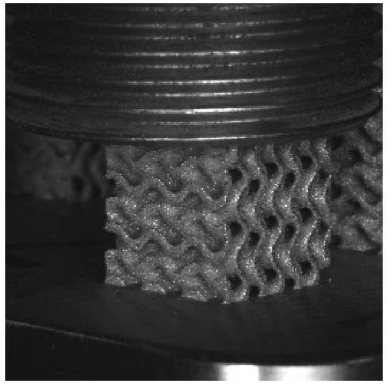
Garland…Boyce, *submitted*

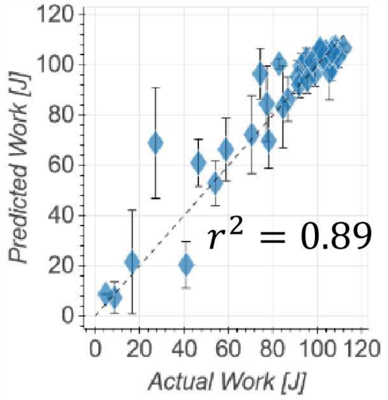
Can machine learning do any better?

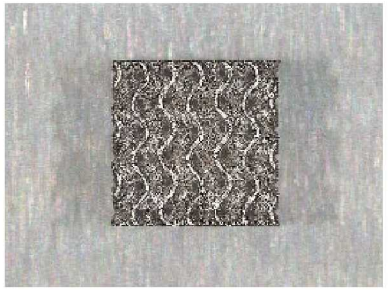
Oblique view

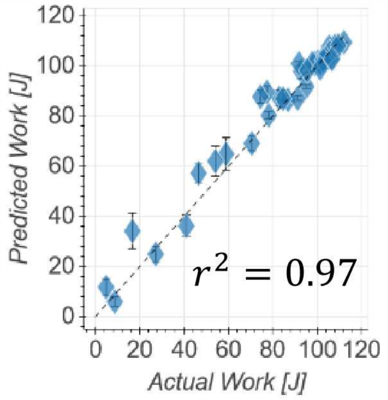
Top-down view

gyroid

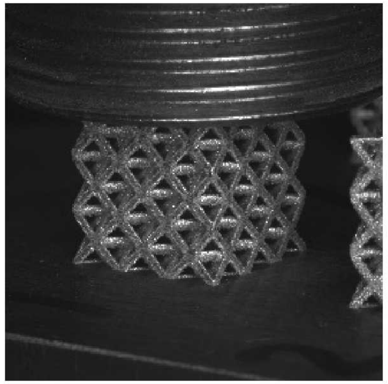


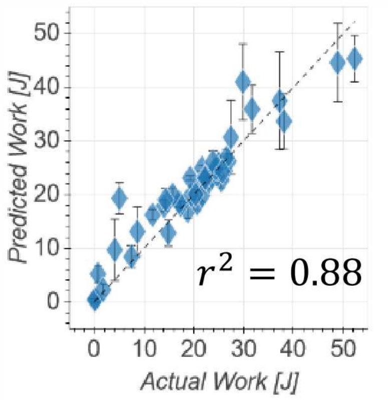


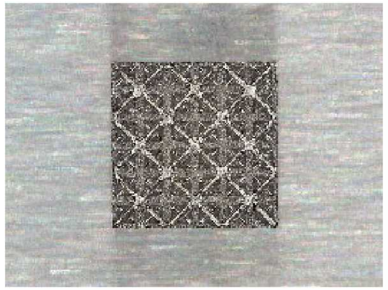


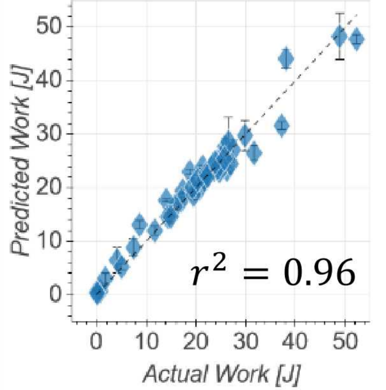


Octet truss



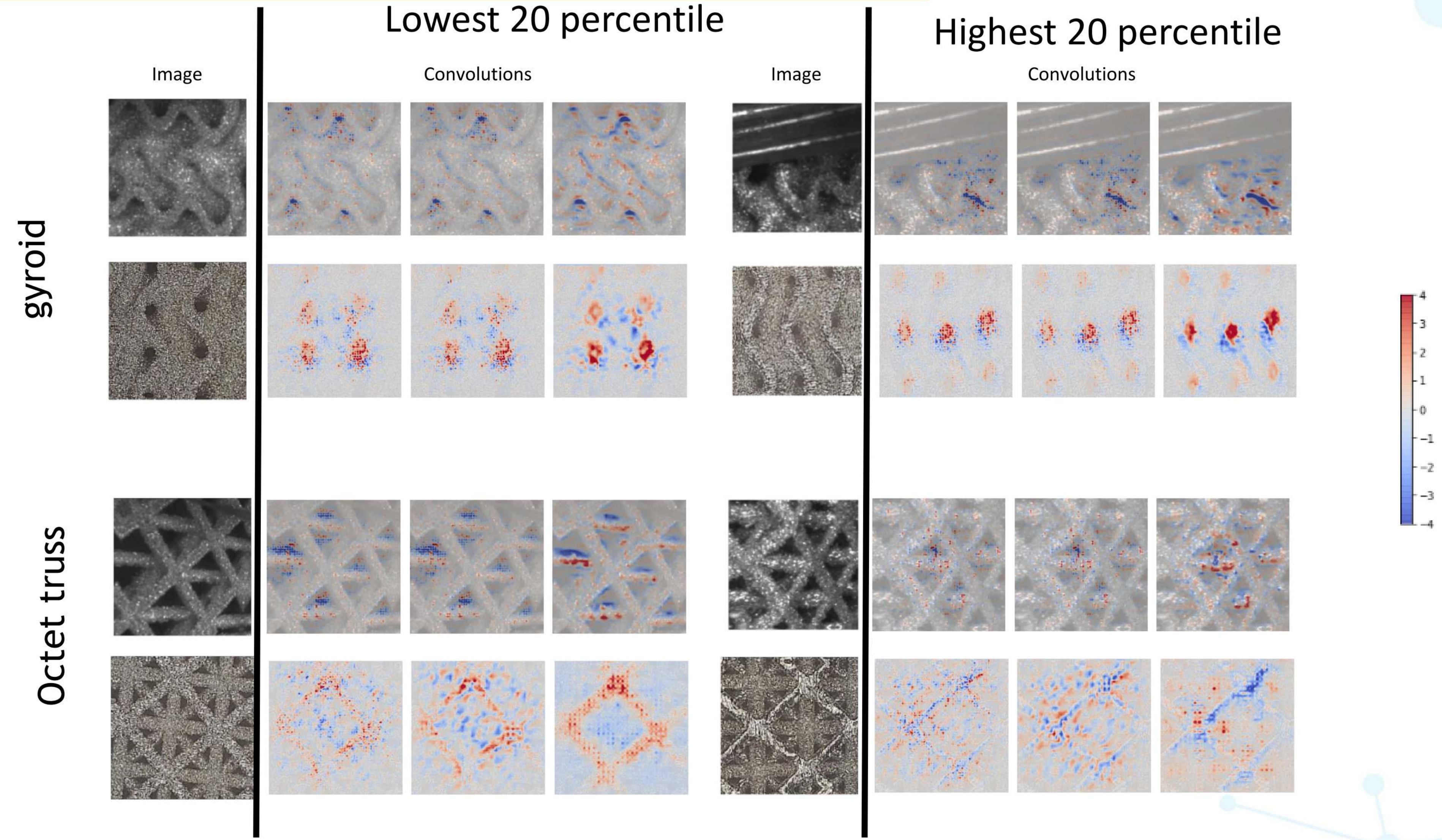






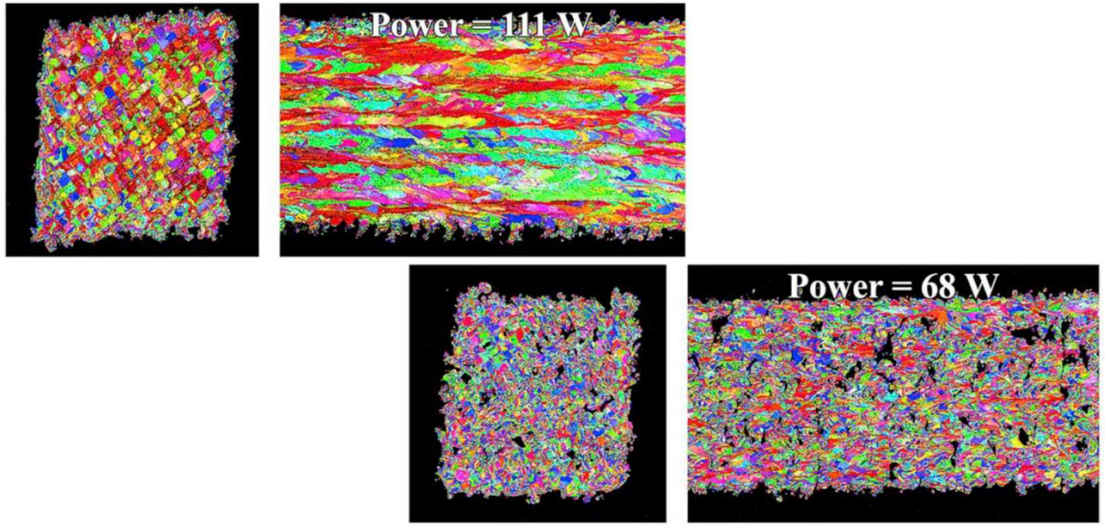
Garland…Boyce, *submitted*

Machine learning's weakness: '*explainability*' and *extrapolation*

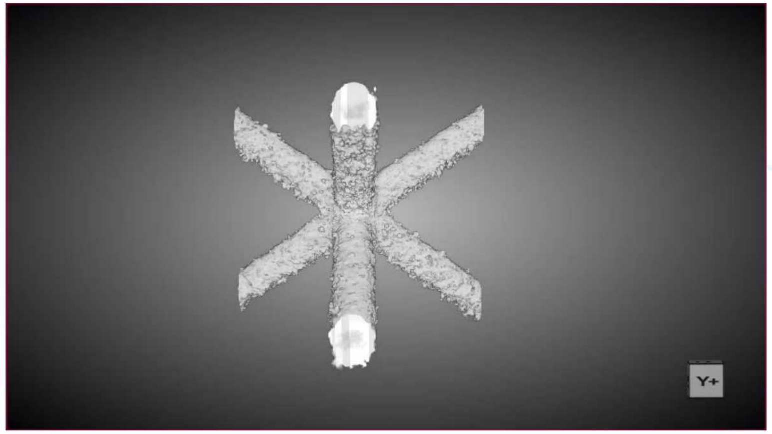


Summary

Monolithic AM



Feature-rich AM



First order influence: microstructure & porosity

Complex pathway to prediction

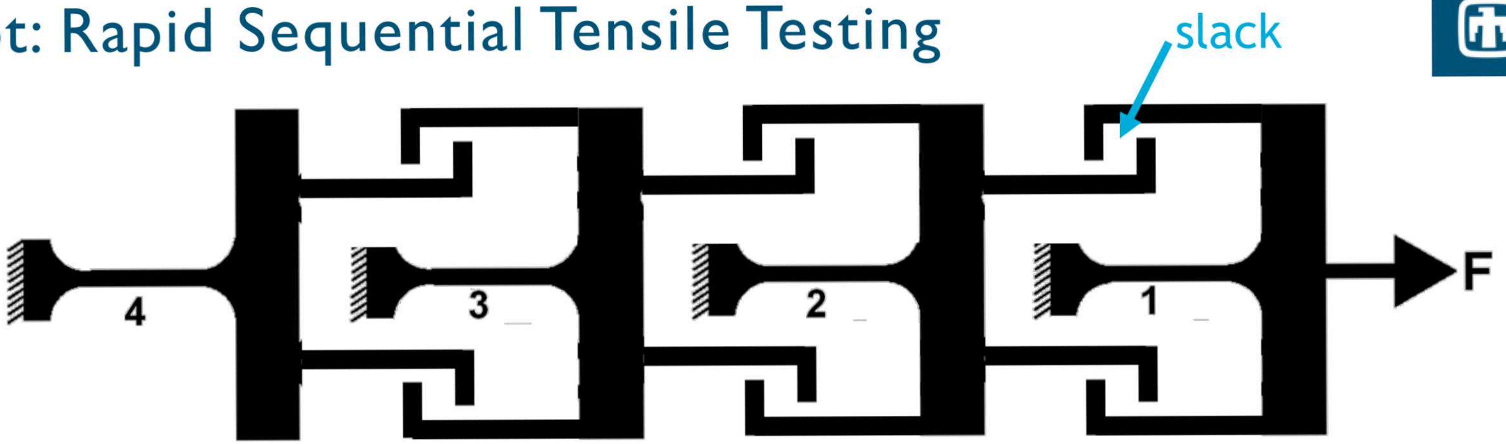
First order influence: dimensions & surface topography

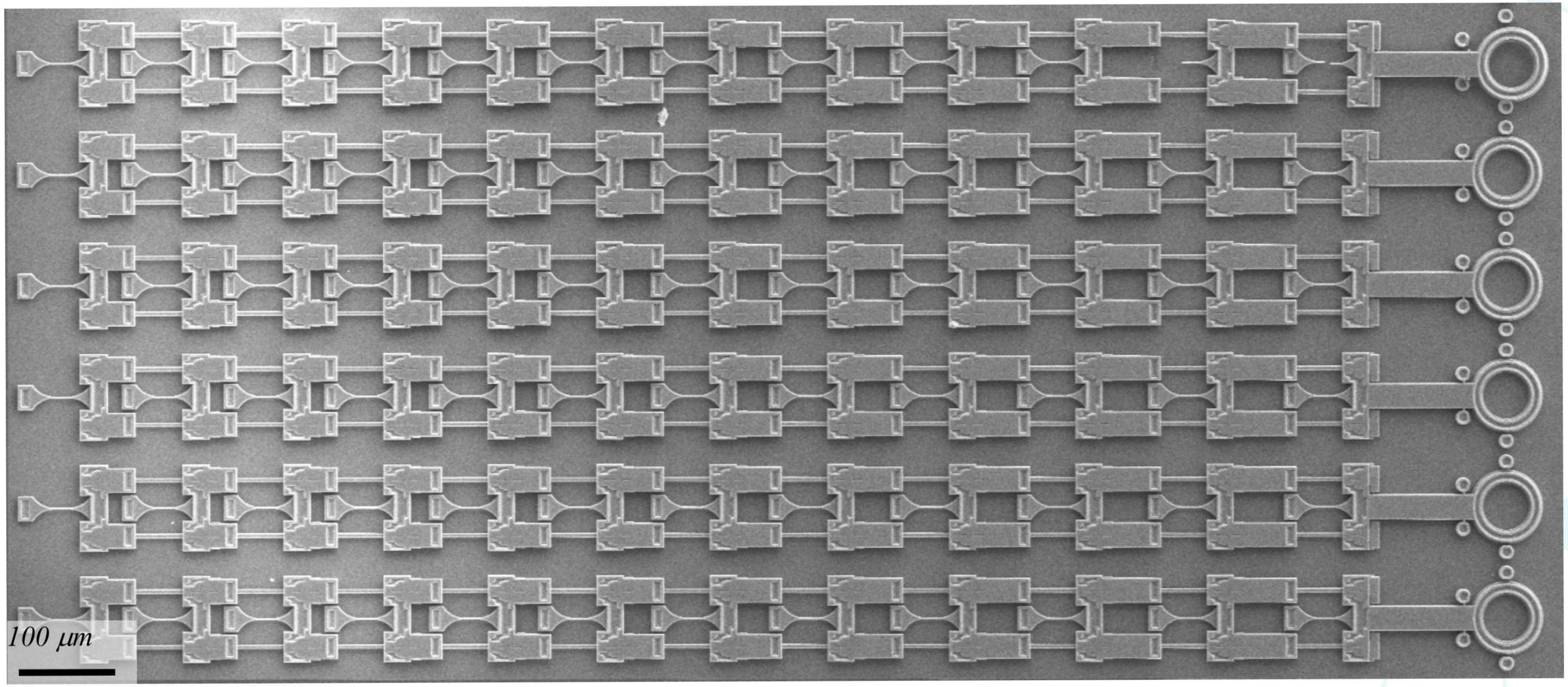
Potentially easier to predict

In this presentation, I drew data from ~2000 mechanical tests. High-throughput testing and machine learning enable us to develop process-structure-property relationships that were otherwise elusive.

backup

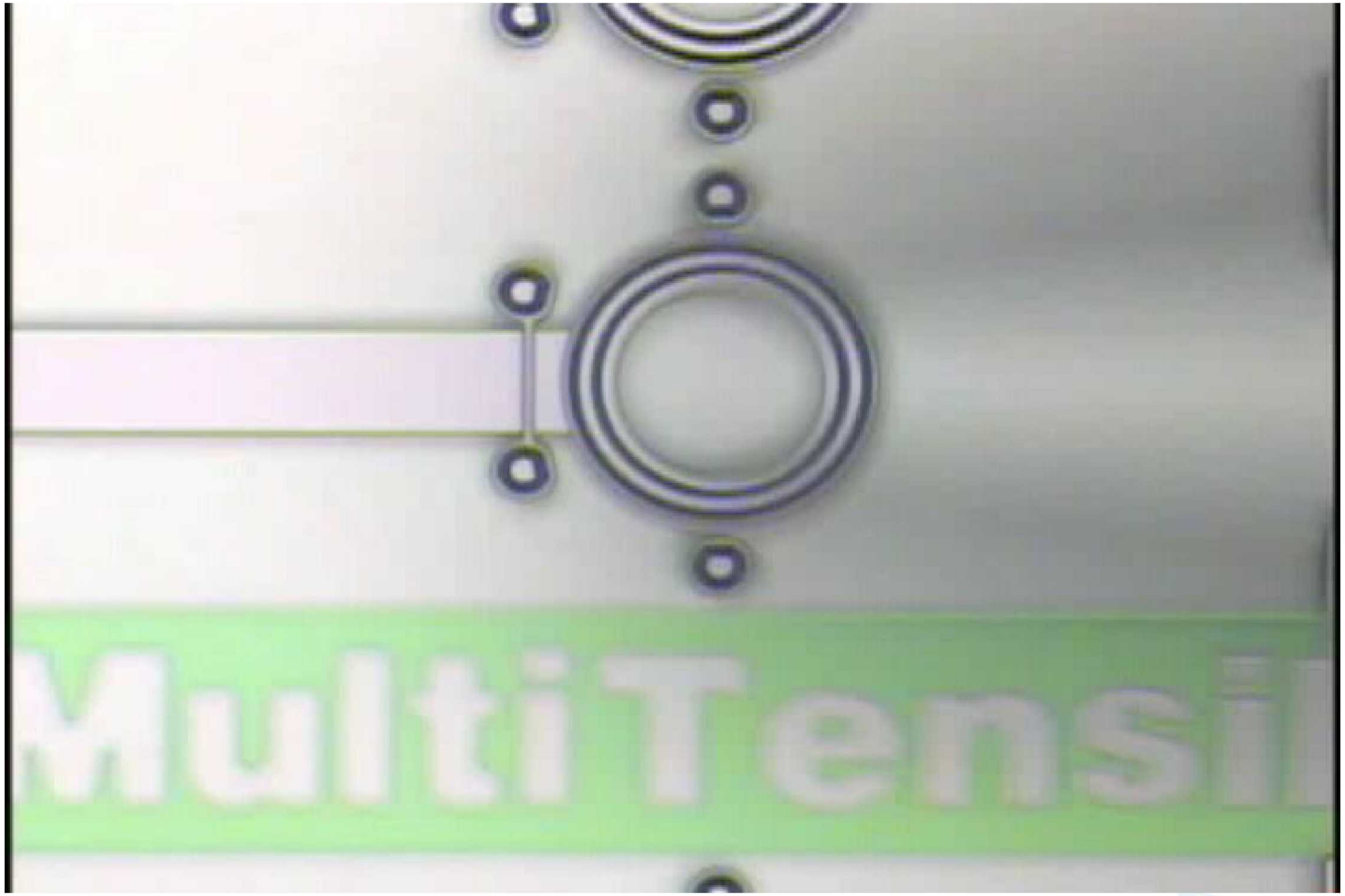
Slack Concept: Rapid Sequential Tensile Testing



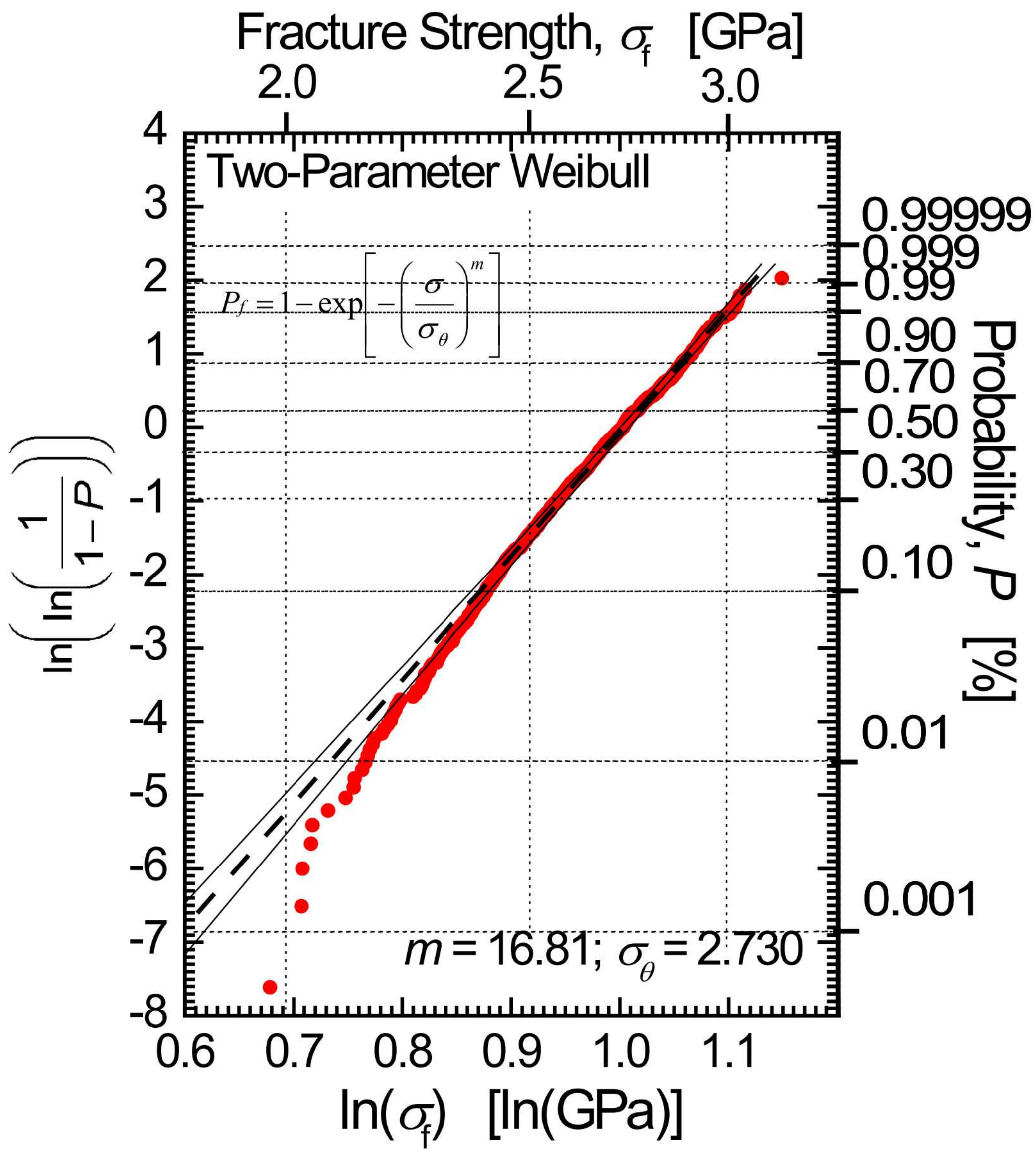


Boyce, *Experimental Mechanics,* 2010

The Slack Chain Concept: Rapid Sequential Tensile Testing



Weibull Fit to 1,008 Nominally Identical Tests



Boyce, *Experimental Mechanics,* 2010

Properties 'Alinstante'

Sandia National Laboratories

An Aspirational Goal:

Can we reduce materials science evaluation from months to hours?

(design-build-test loop in a day?)

Geometric metrology probe

Surface roughness probe

Mechanical properties probe

Compositional probe

Phase probe

Thermal probe

Electrical probe

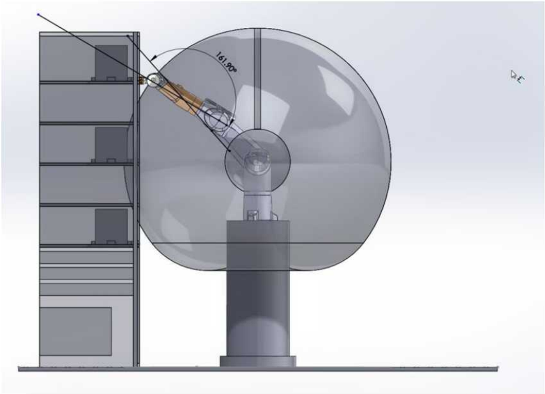
Tribology probe

Resonance probe

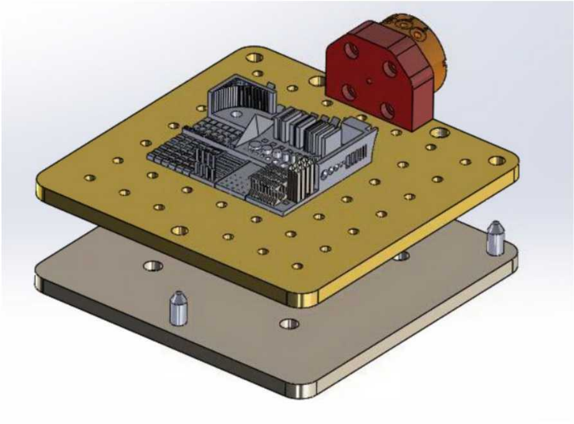
…

The development of “Alinstante”

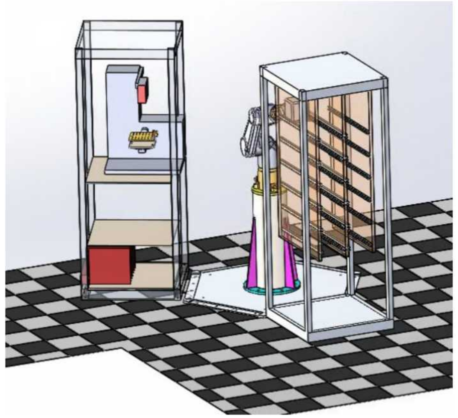
Reachability Analysis



Sample handling tray



Workcell with part handling



Modules such as the GOM Atos Core 3D Scanner

CHARACTERIZE

PRINT

POST-PROCESS