Rapid, High-Throughput Mechanical Properties Measurements of Additively Manufactured Metals

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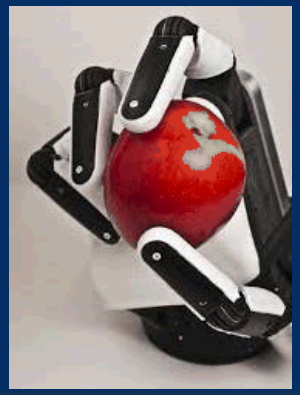

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration
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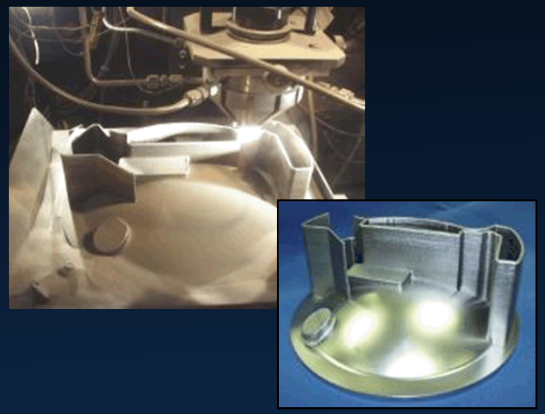
Sandia has a rich heritage in Additive Manufacturing

FastCast*
prototype test unit

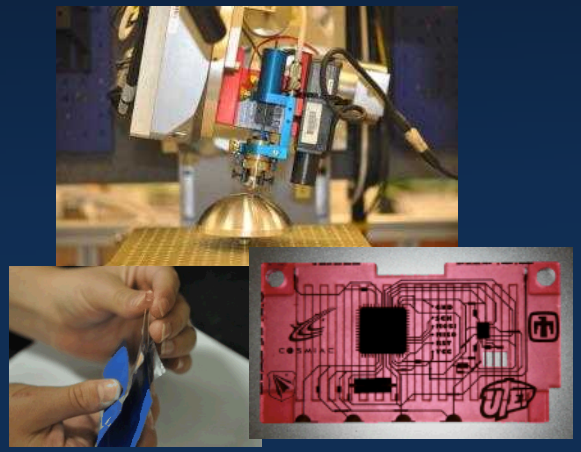
LENS®*
fireset housing



RoboCast*
ceramic parts

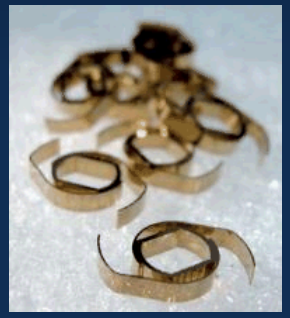
energetic materials

Direct Write
conformal electronics



MEMS SUMMIT™*
micro gear assembly

LIGA
"Hurricane" spring



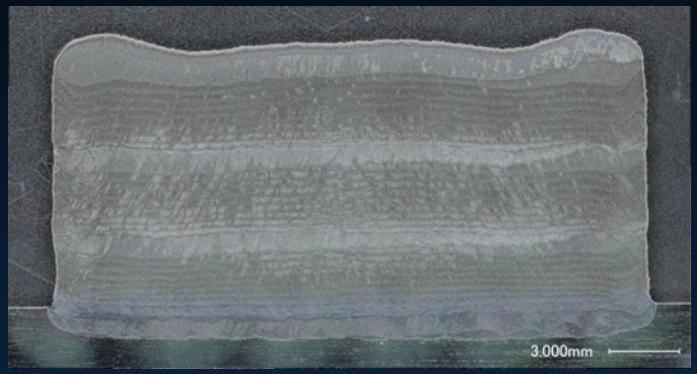
Spray Forming
rocket nozzle

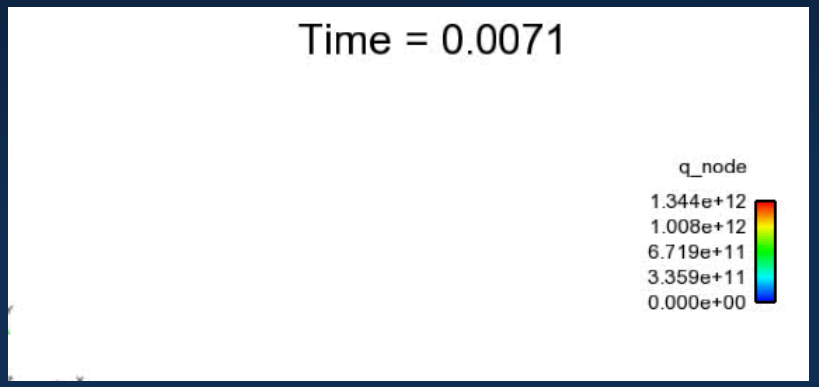
* Sandia licensed/commercialized technology

Additive manufacturing offers rapid production of custom, geometrically complex parts

How do we rapidly qualify the materials produced by additive manufacturing?

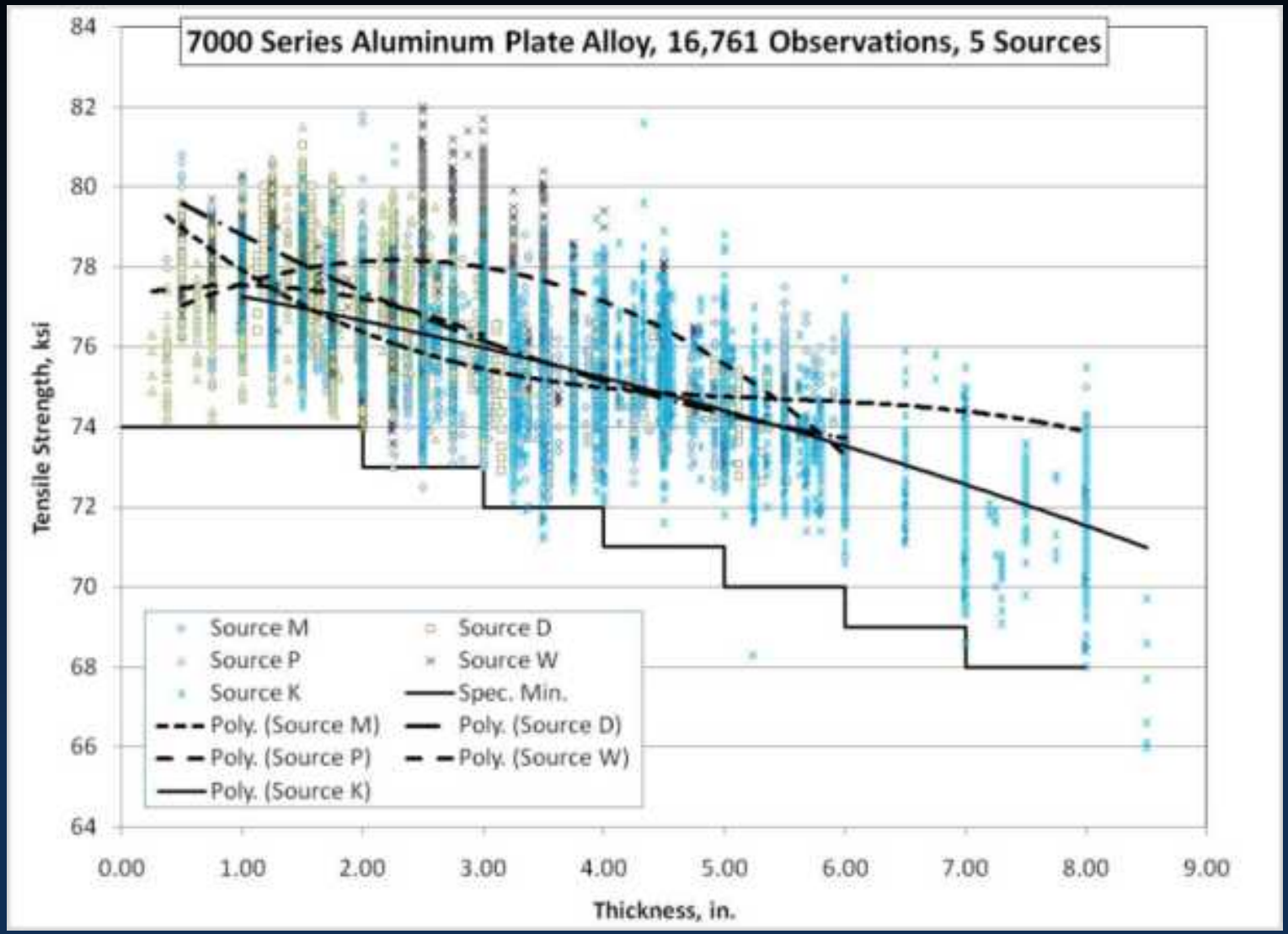
The holy grail of 'born qualified': model-informed process monitoring and control



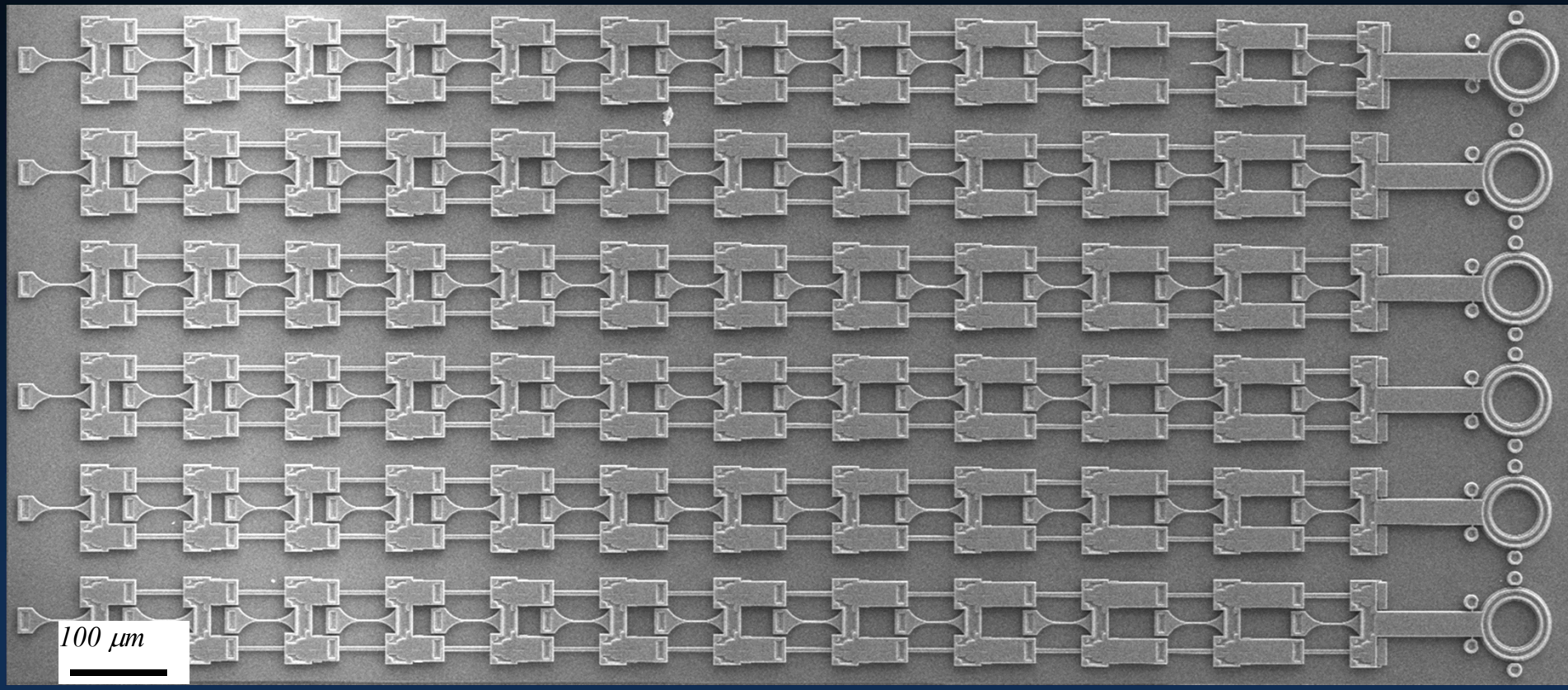


Courtesy of Josh Sugar

How conventional materials are qualified…

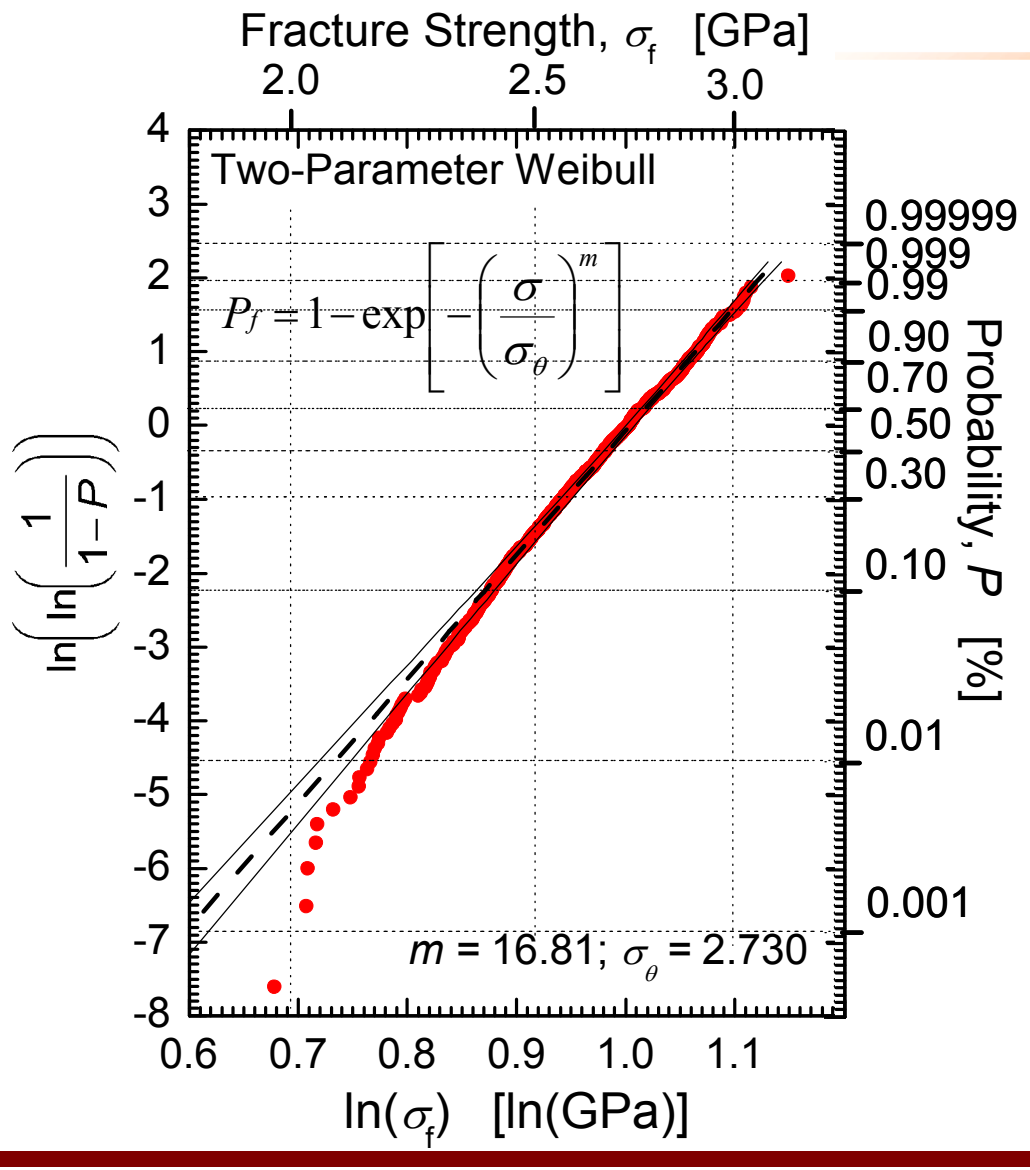


The Slack Chain Concept: Rapid Sequential Tensile Testing for Large Statistical Datasets



Boyce, *Experimental Mechanics,* 2010

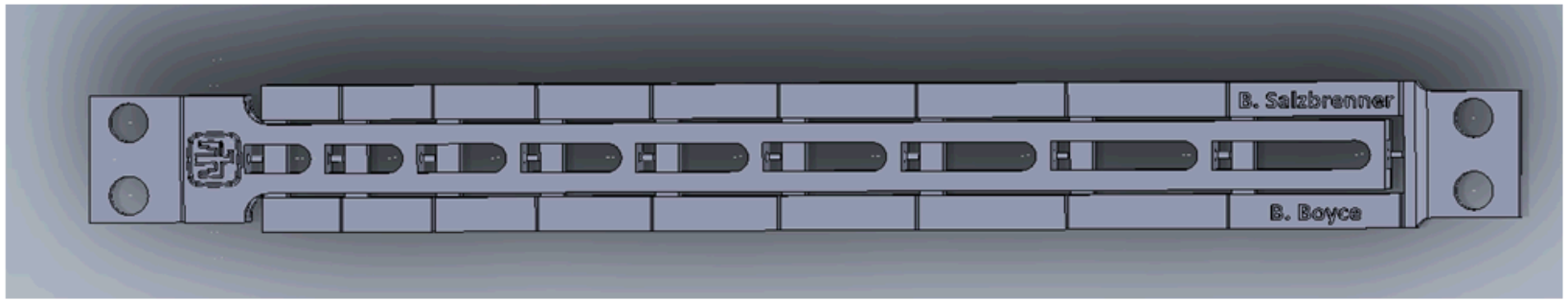
Weibull Fit to 1,008 Test Repeats

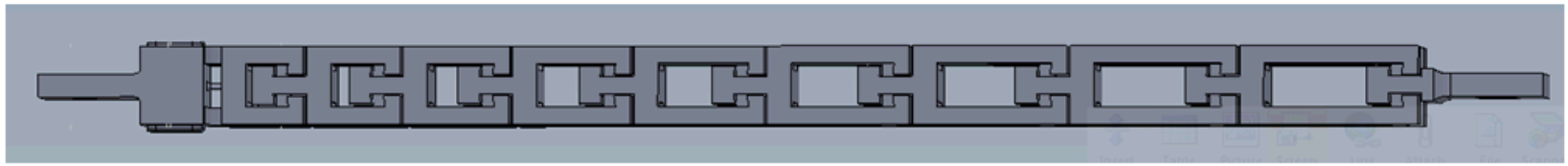


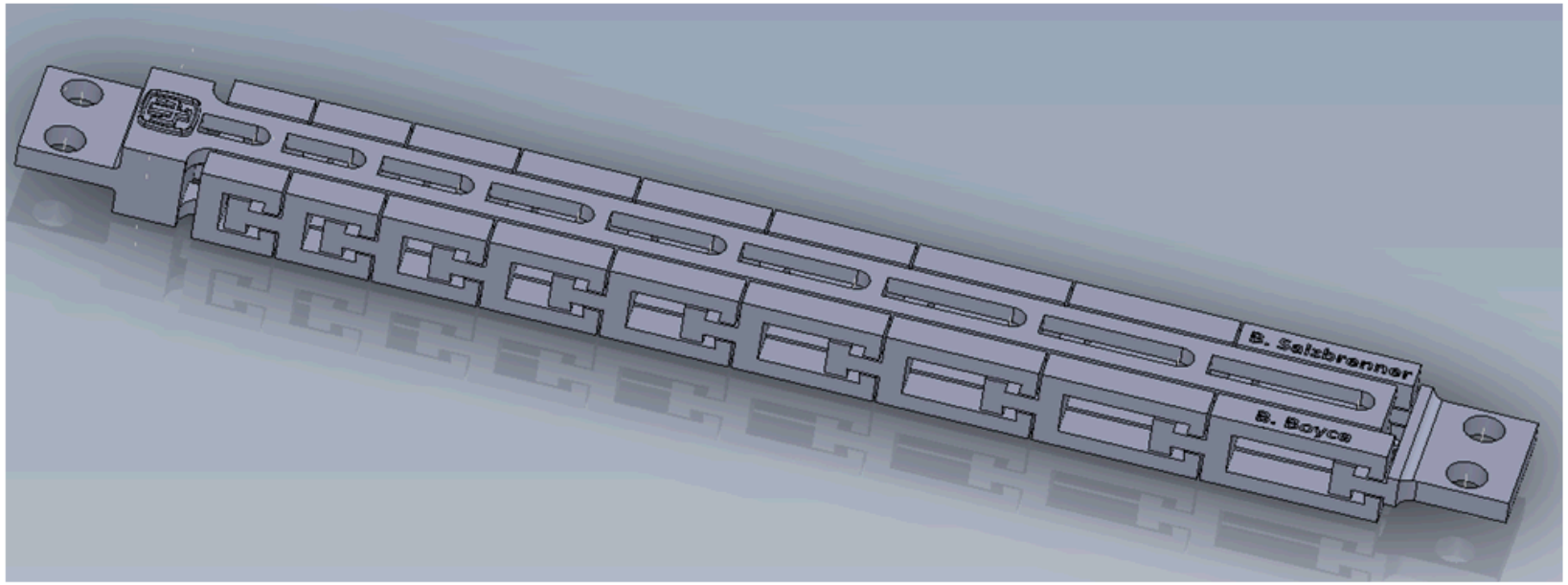
Boyce, *Experimental Mechanics,* 2010

Can we apply principles of rapid, streamlined mechanical testing to additive manufacturing?

Sequential concept for additive manufacturing

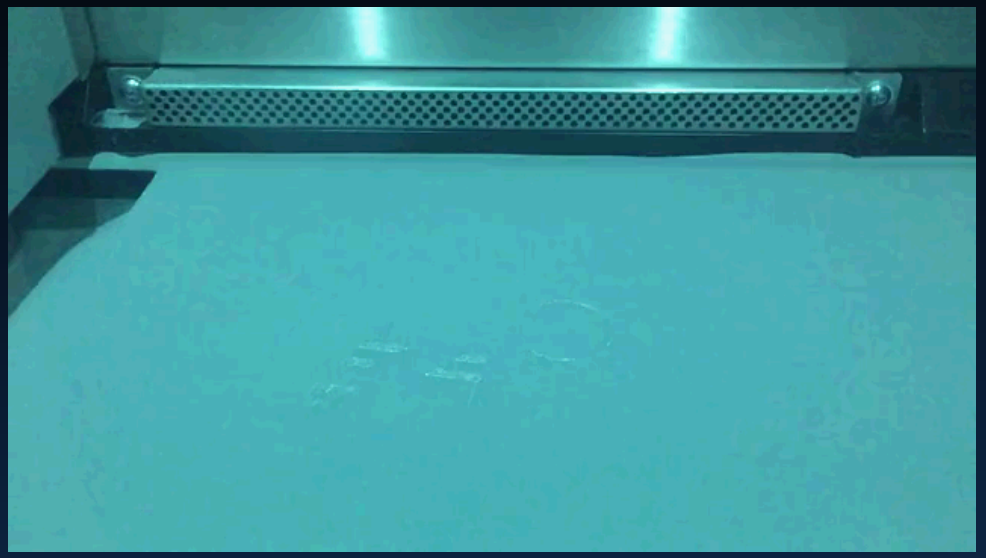


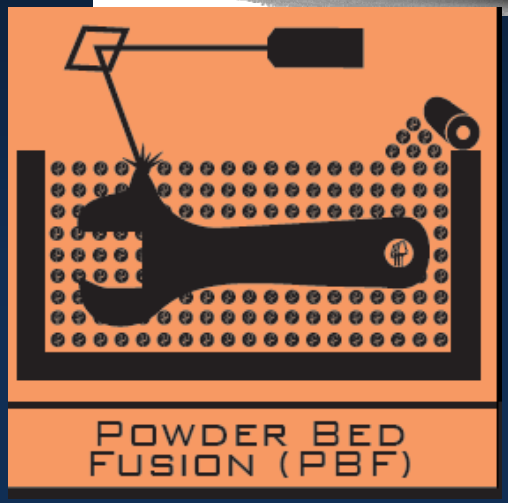




Laser Powder Bed Fusion (L-PBF)

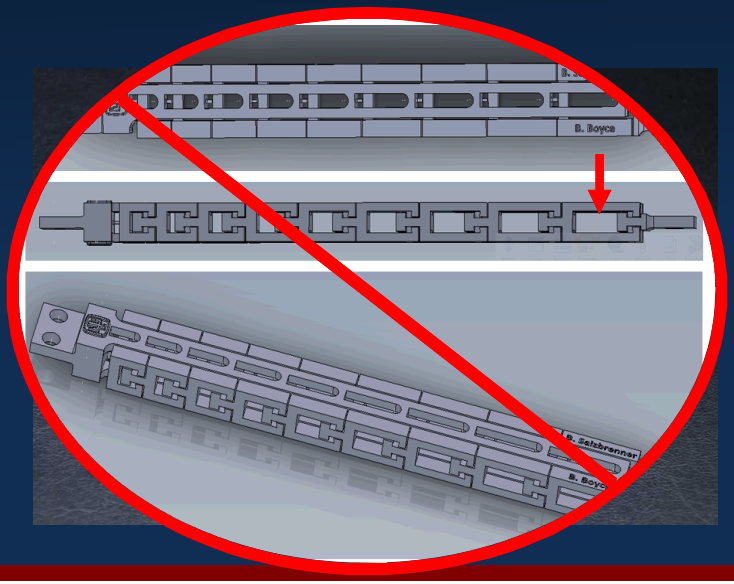
...ting)



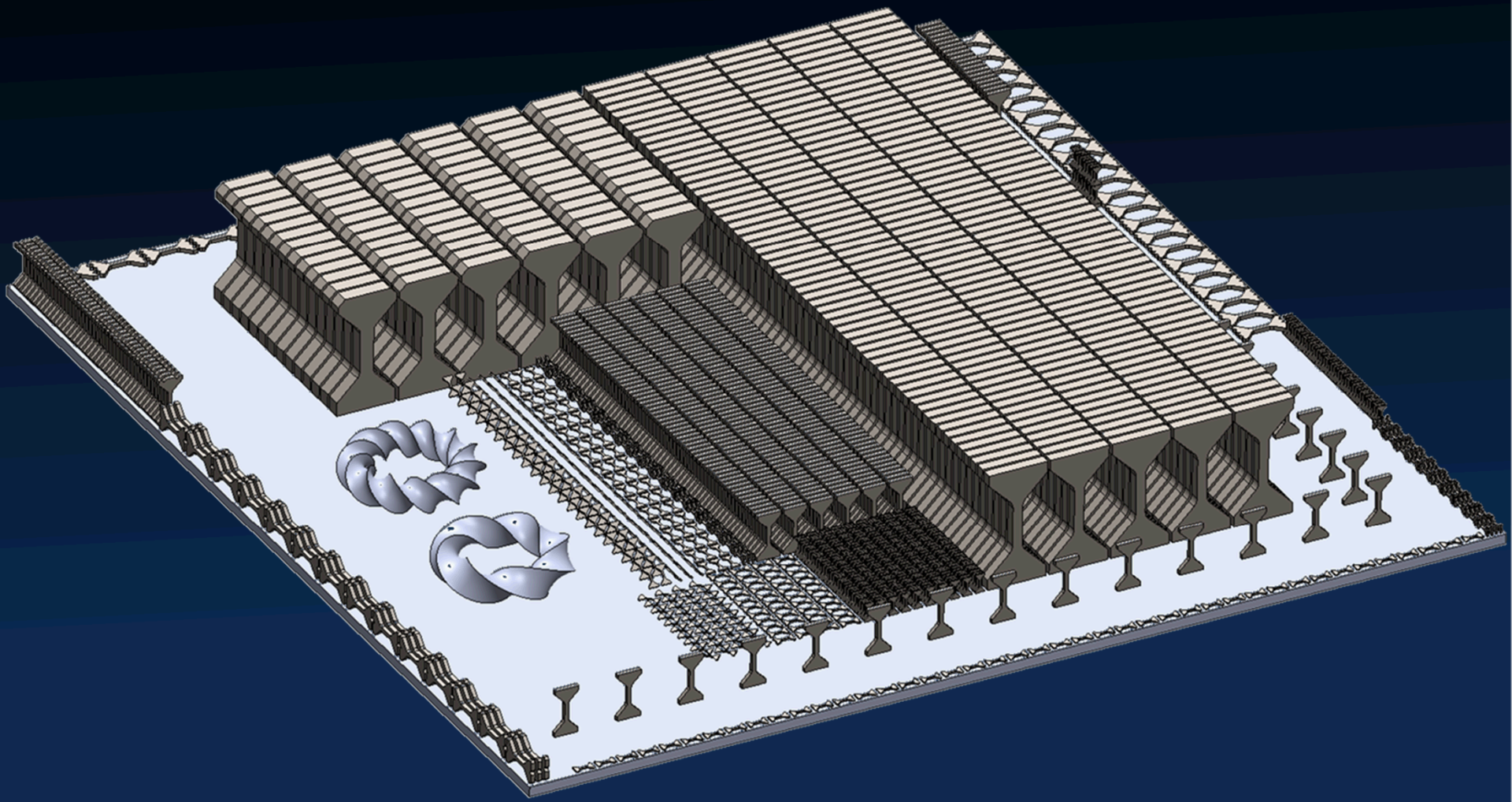


Key process variables:

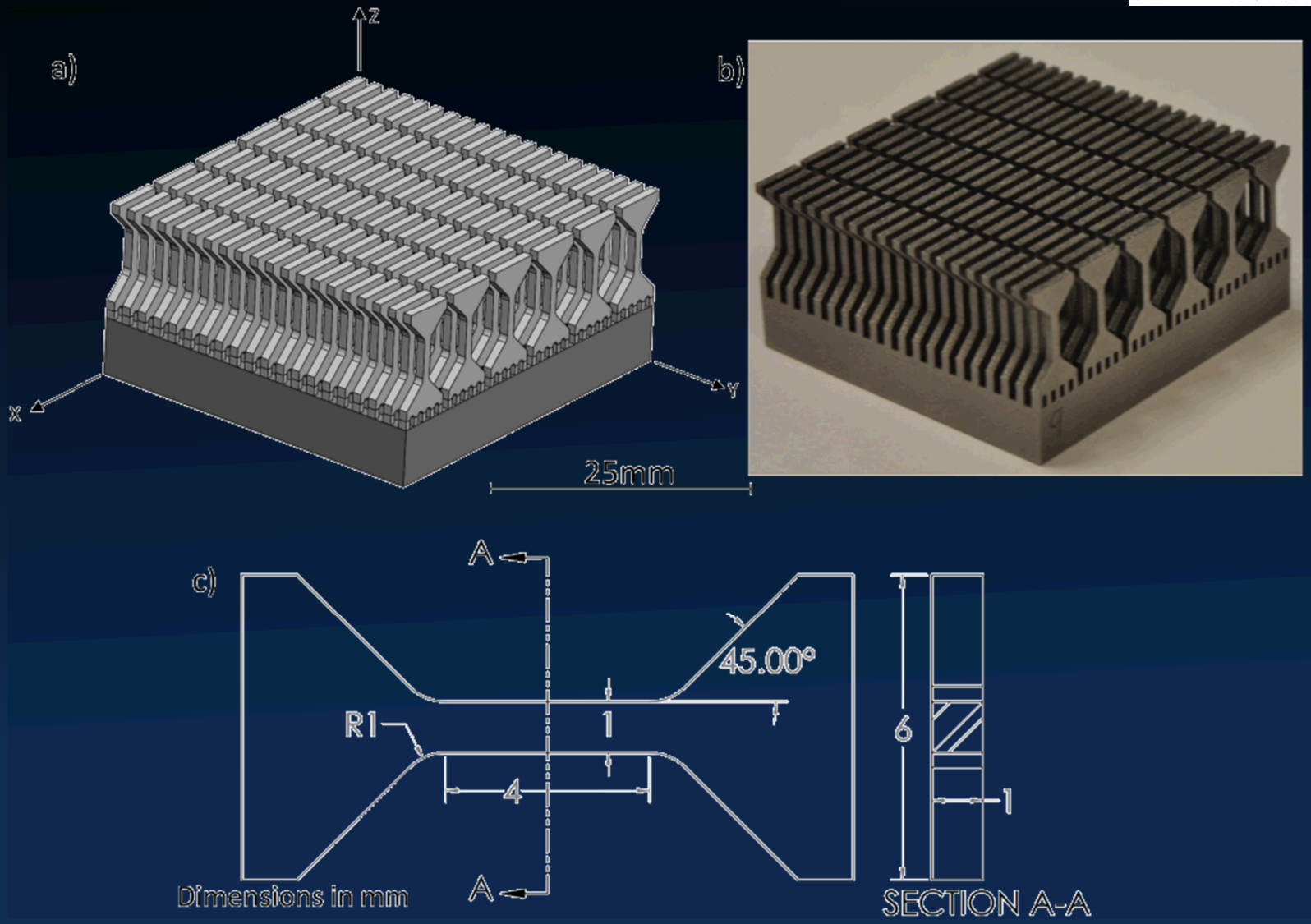
* Powder feedstock
* Laser power
* Raster speed
* Hatch & layer spacing



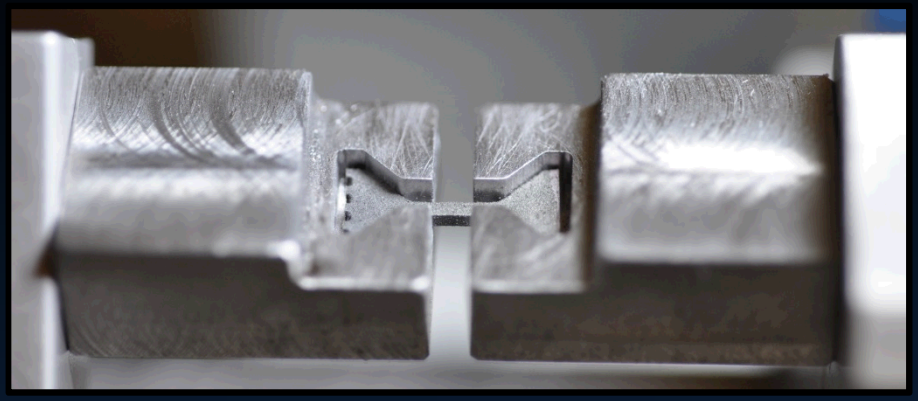
AM offers opportunities to print extensive mechanical test coupons



Starting simple: 'cooling fin design'

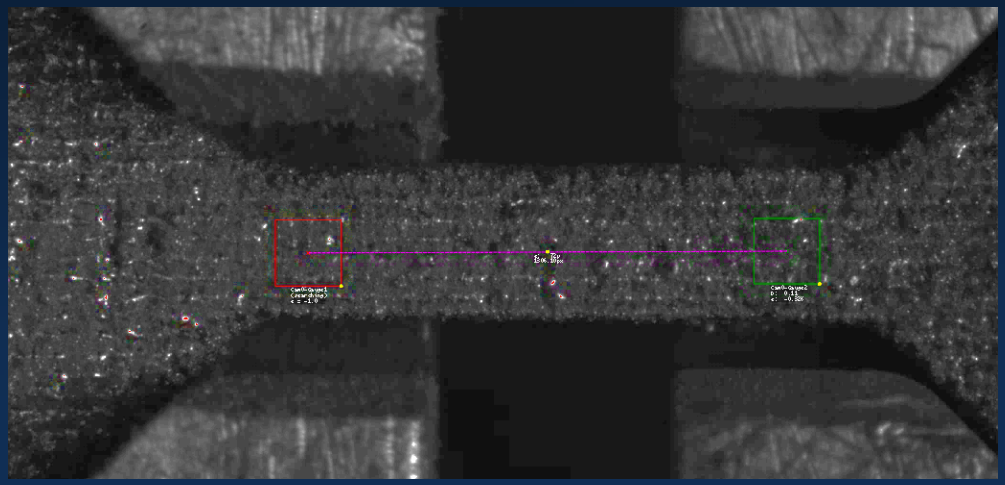


Streamline the testing process



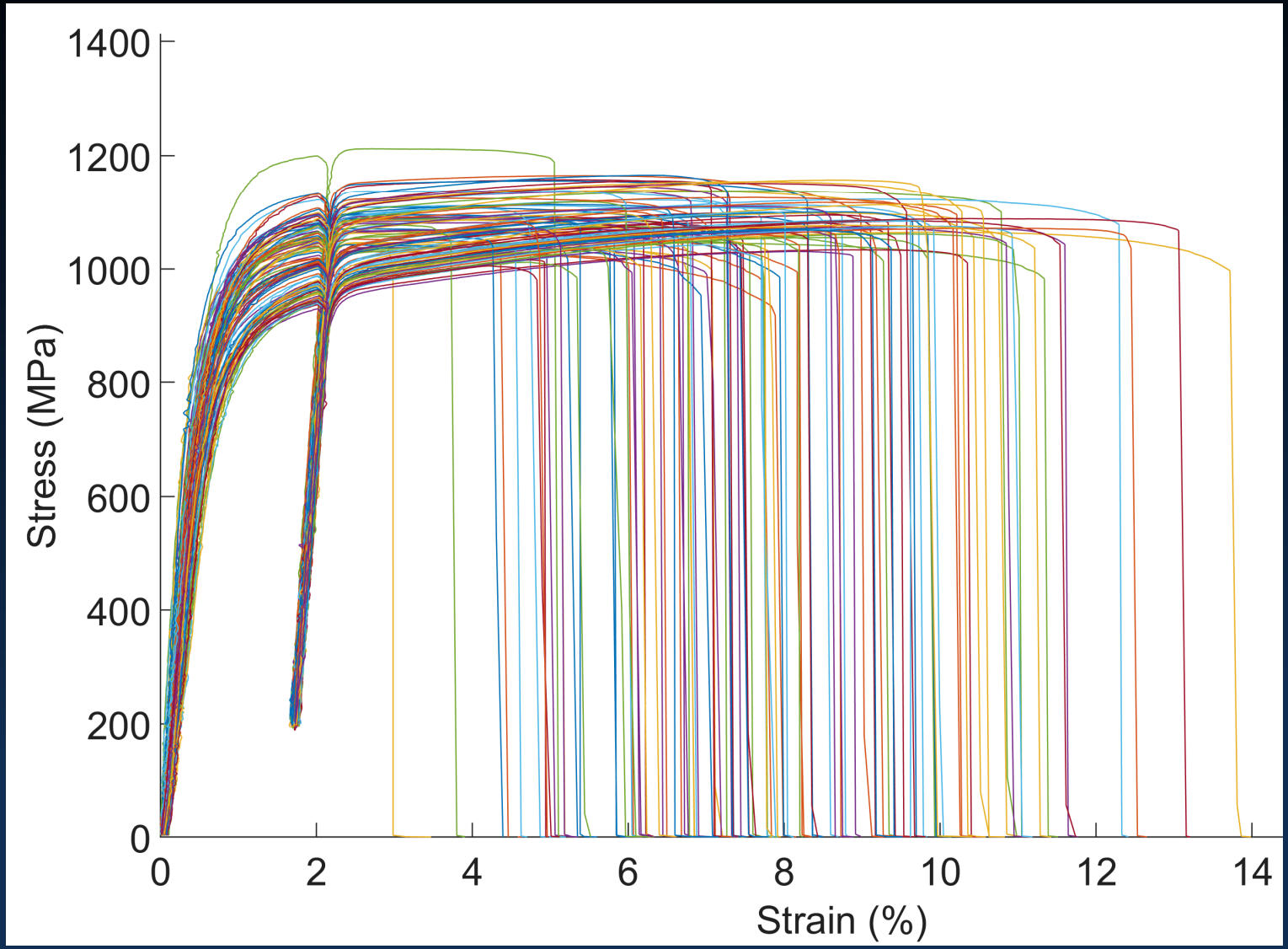
1. Adopt self-aligning ‘drop-in’ grips

3. Maximize software automation to reduce burden on operator



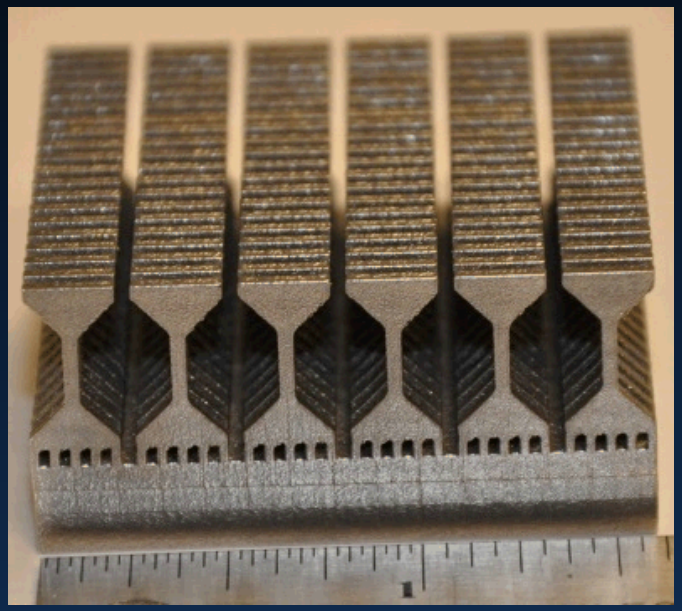
2. Measure strain with non-contact “live” digital image correlation

100 tensile tests in 4 hours…



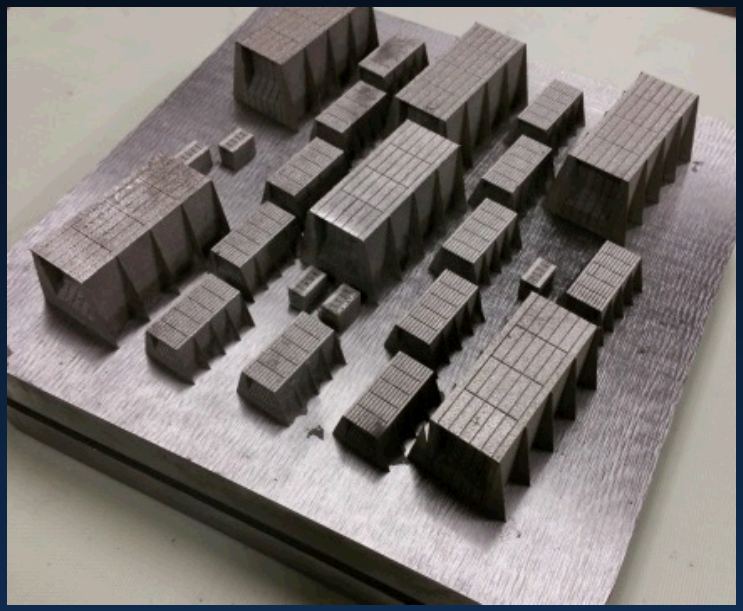
A comparison of 2 major commercial vendors

ConceptLaser Mlab



Vendor 1

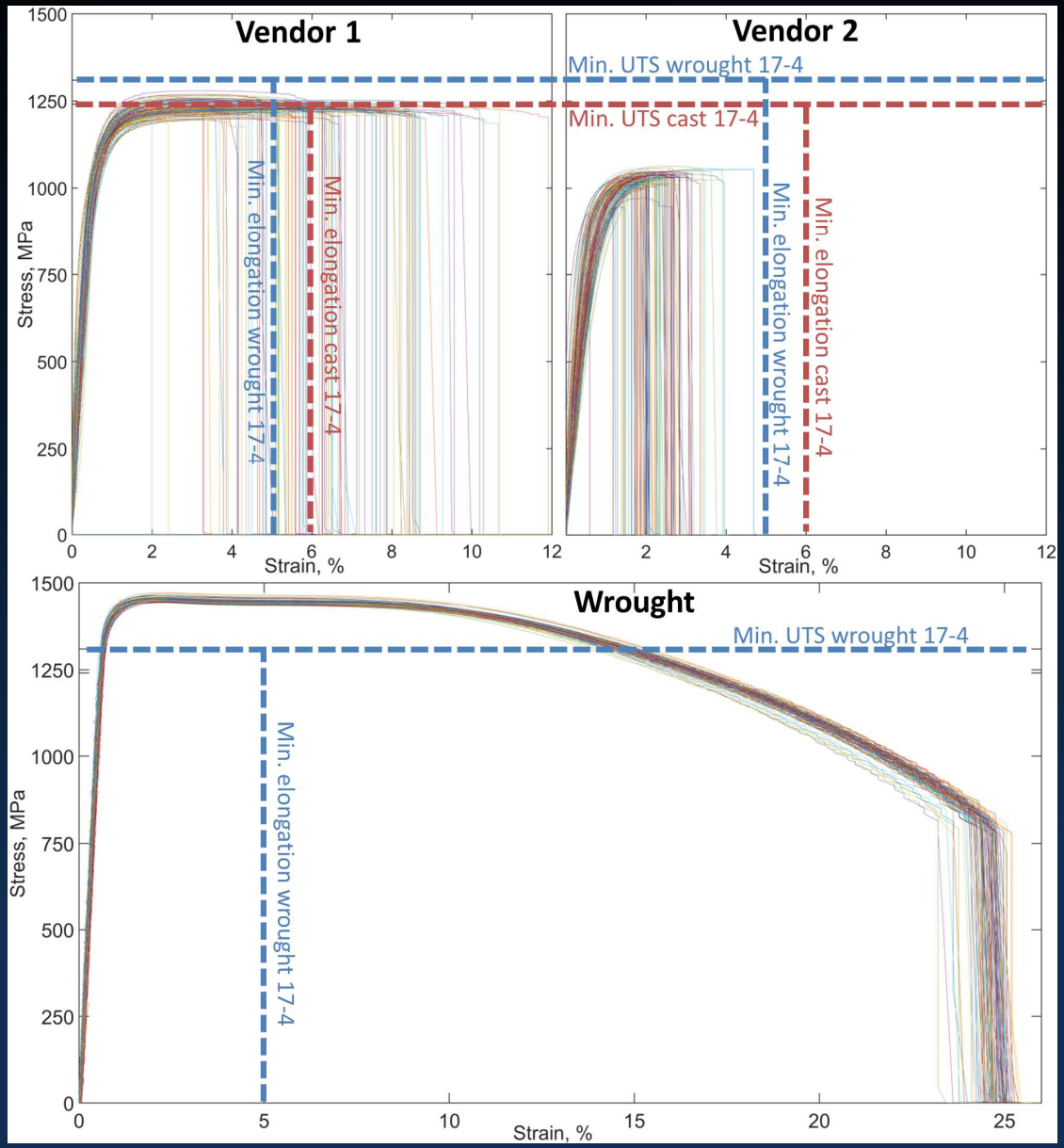
3D Systems ProX300



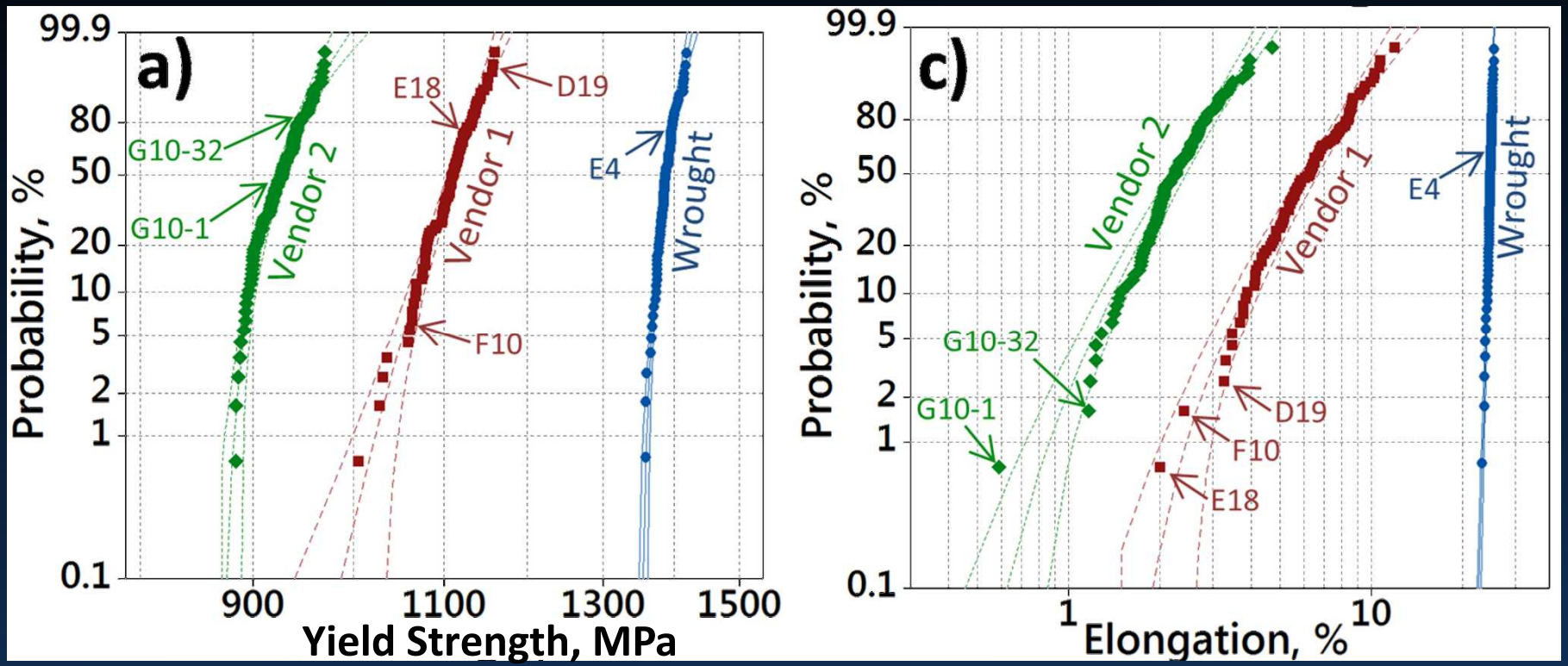
Vendor 2

Alloy: PH17-4 H900 (preciptation hardenable martensitic stainless steel)

Comparing 100 tests from 3 sources



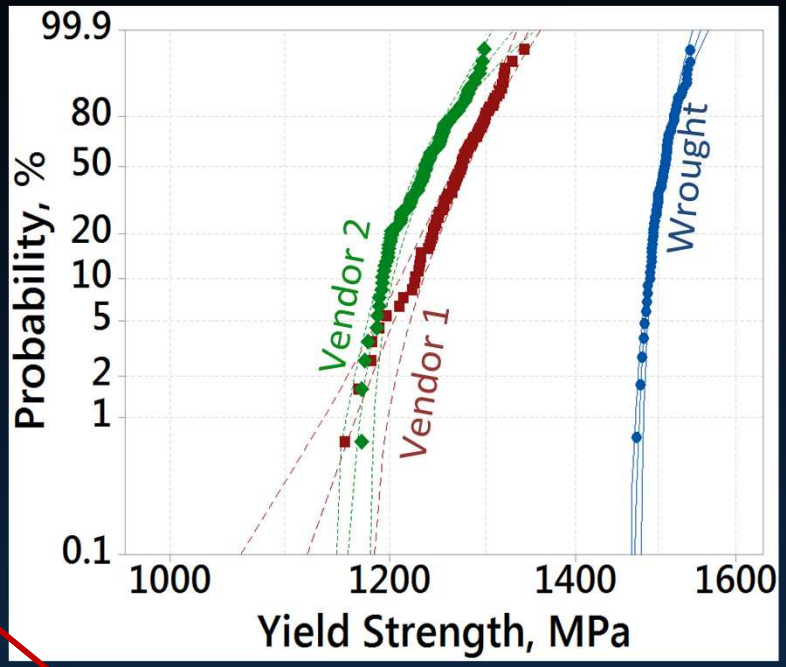
3-Parameter Weibull Fits to Distributions



What is the origin of different properties???

Effect #1: Surface roughness

Cross-sectional area inferred from digital micrometer measurements (measurement method was biased by the highest asperity)



b) Vendor 2

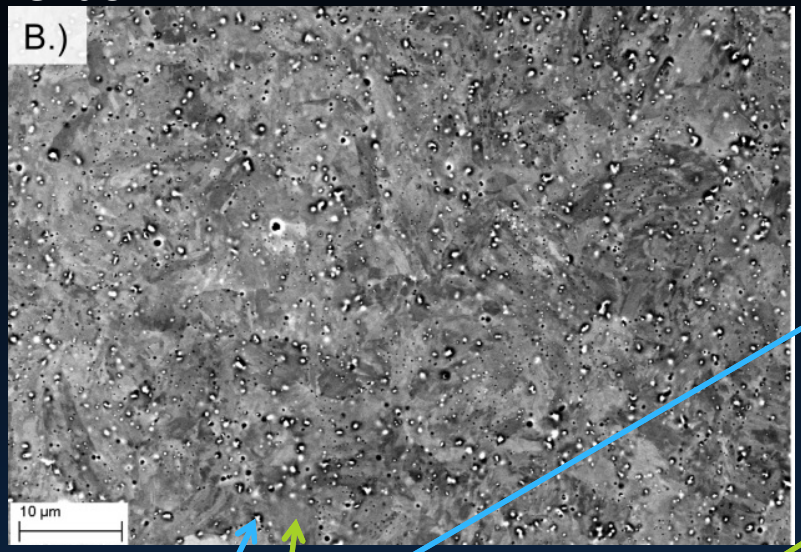
a) Vendor 1

c) Wrought

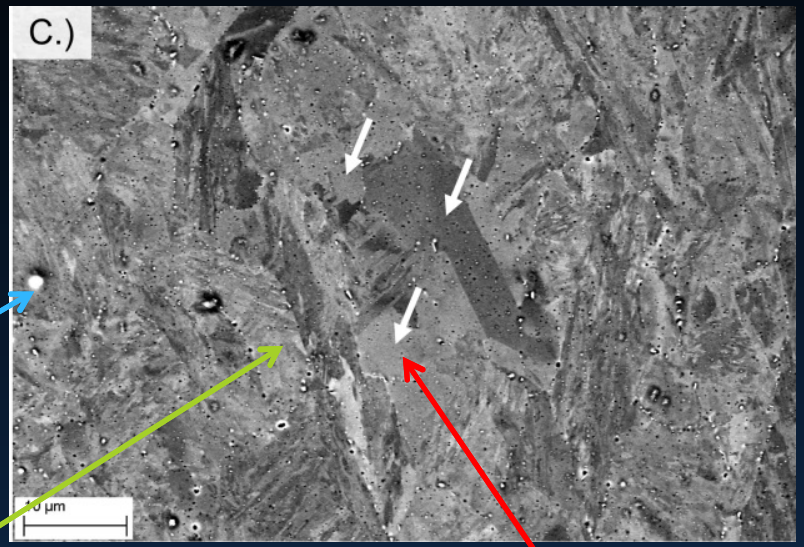
500μm

Effect #2: Phase content

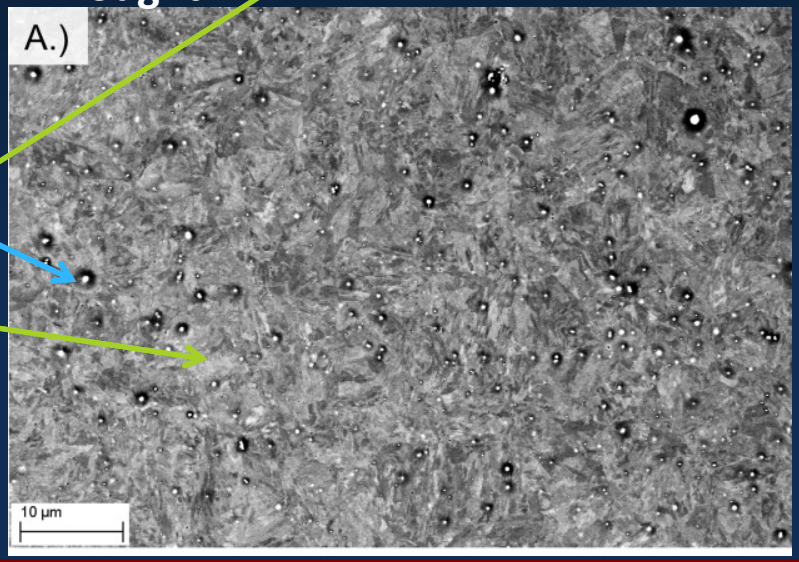
Vendor 1



Vendor 2



Wrought



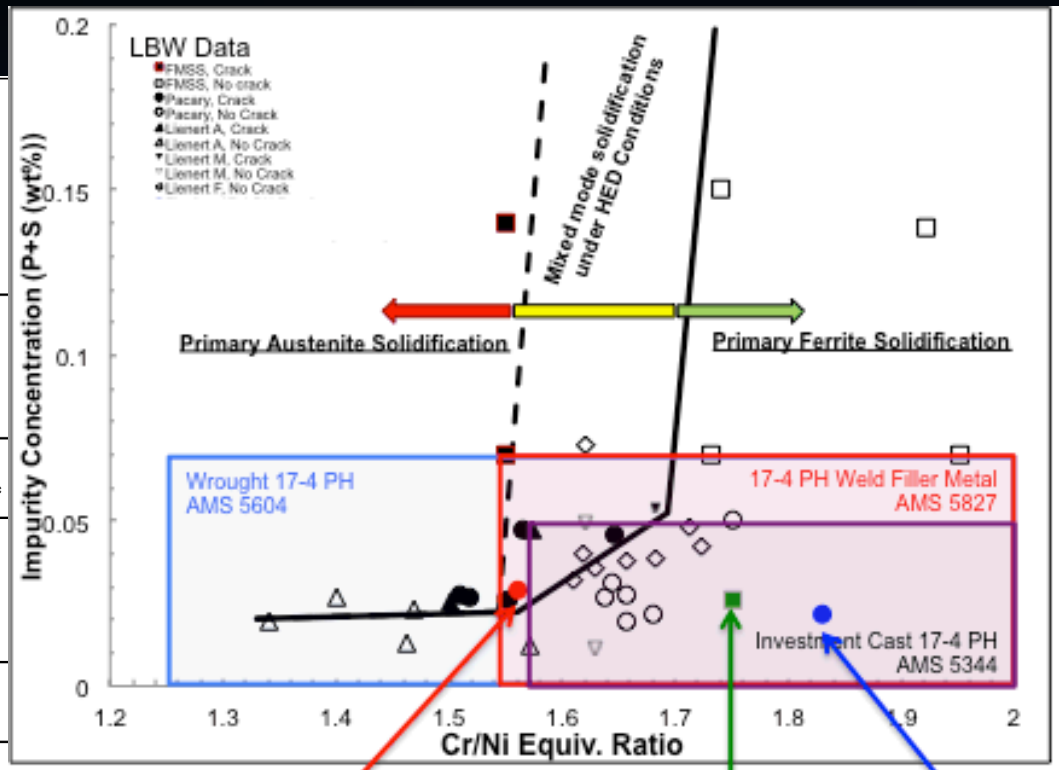
Nb carbides

Lath Martensite

Retained austenite!

In collaboration with Jeff Rodelas

Why Austenite in Vendor 2 material???



Vendor #2
M_s: -10°C

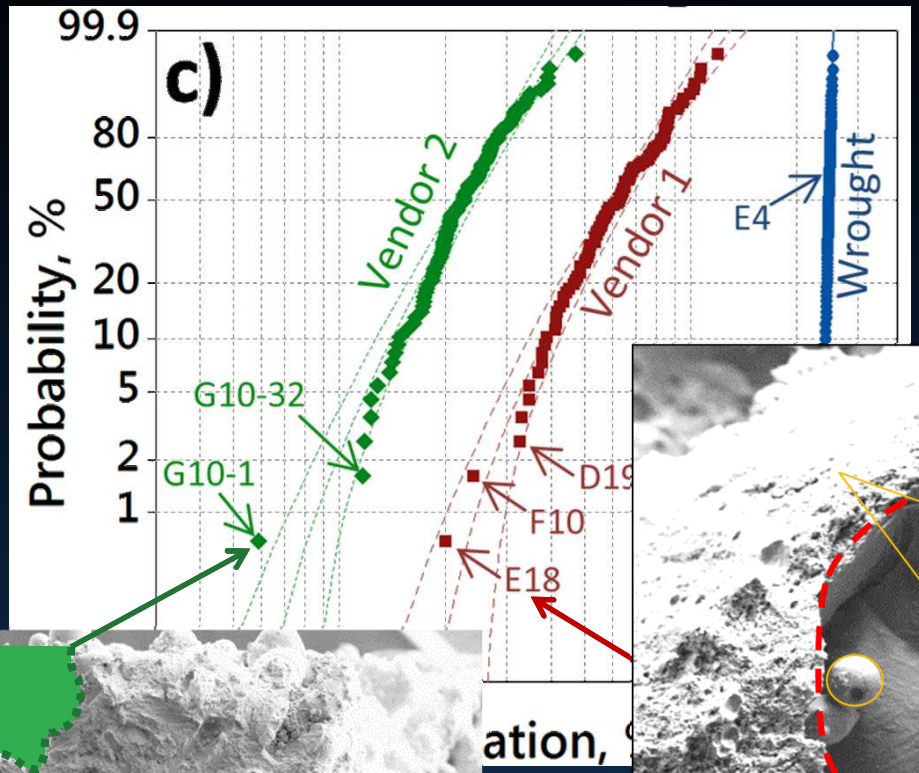
17-4 PH sheet
M_s: 109°C

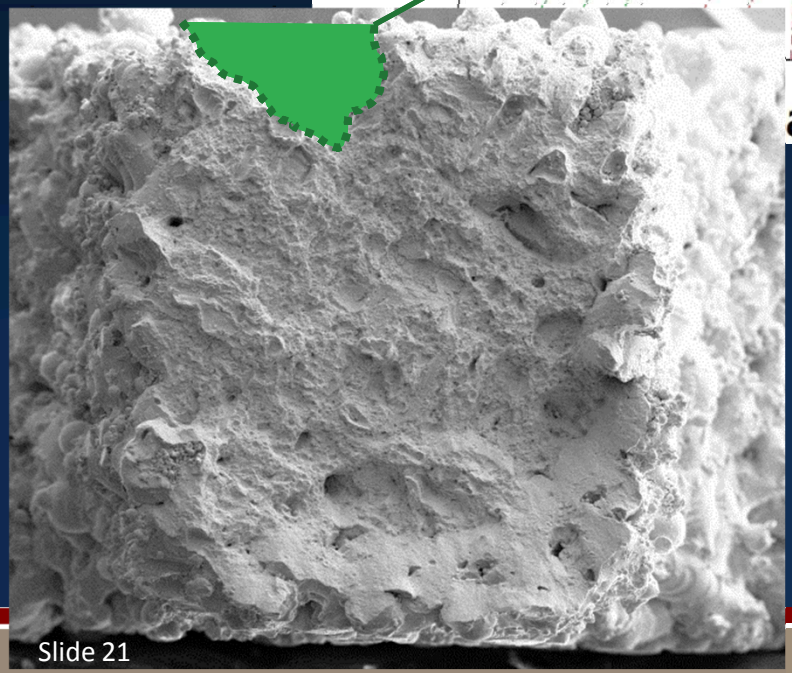
Vendor #1
M_s: 100°C

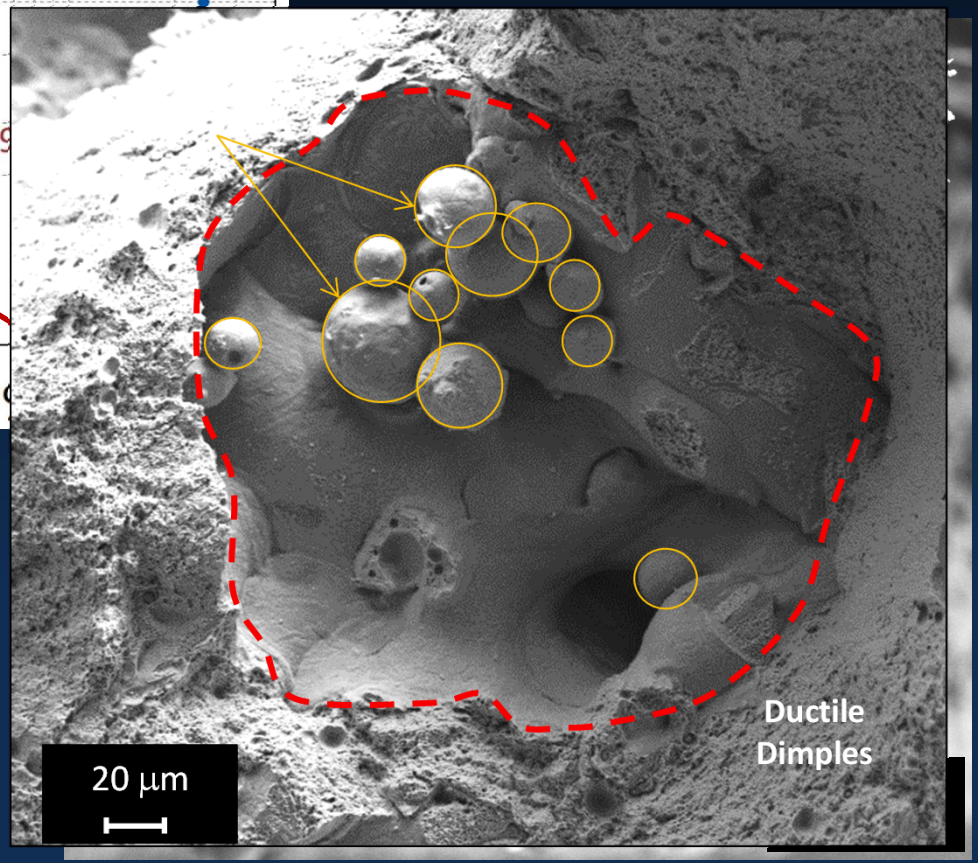
	Tin	Nitrogen	Molybdenum	Iron
Nominal Wrought Composition (AMS5604)	NS	NS	0.05 Max.	Remainder
Wrought Composition**	0	0.023	0.28	
Nominal Invest. Cast Composition (AMS5344)	0.02 Max.	0.05 Max.	NS	
Vendor 1 Composition*	0	0.056	0.045	
Vendor 2 Composition*	0	0.15	0.17	

NS=none speci
*compared to
**compared to

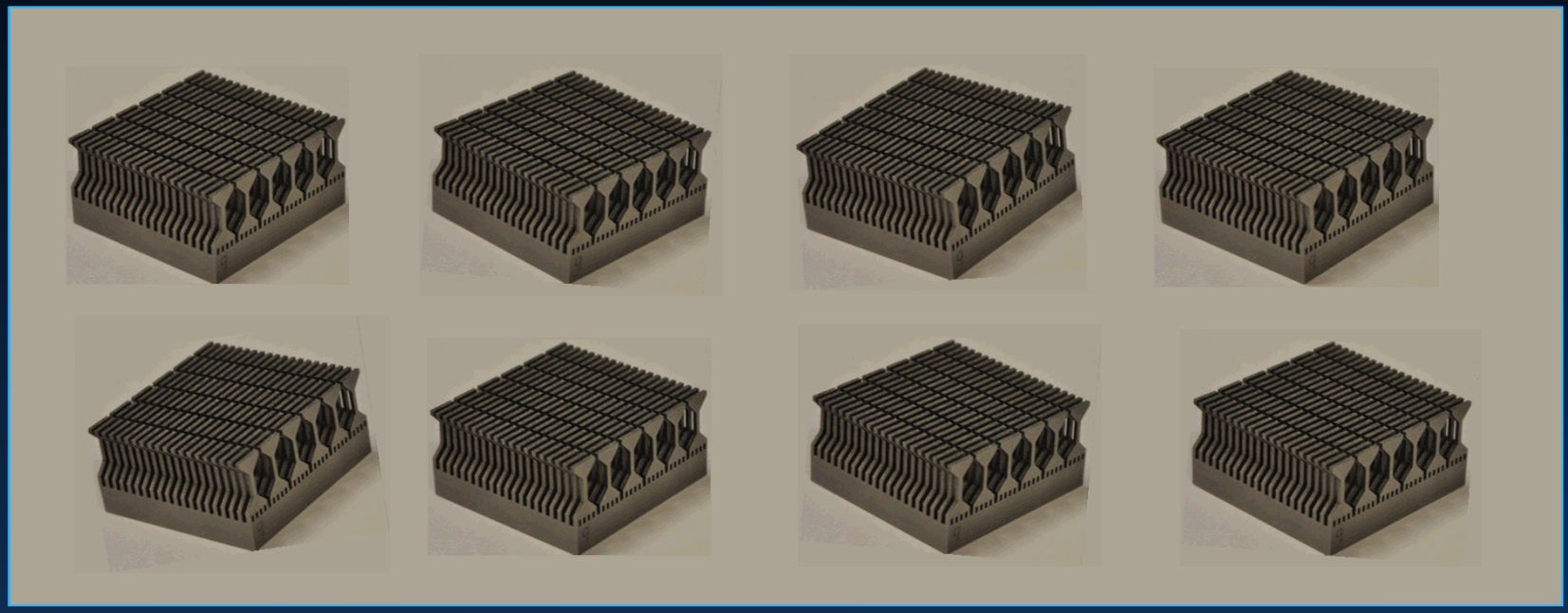
Why such large differences in ductility?





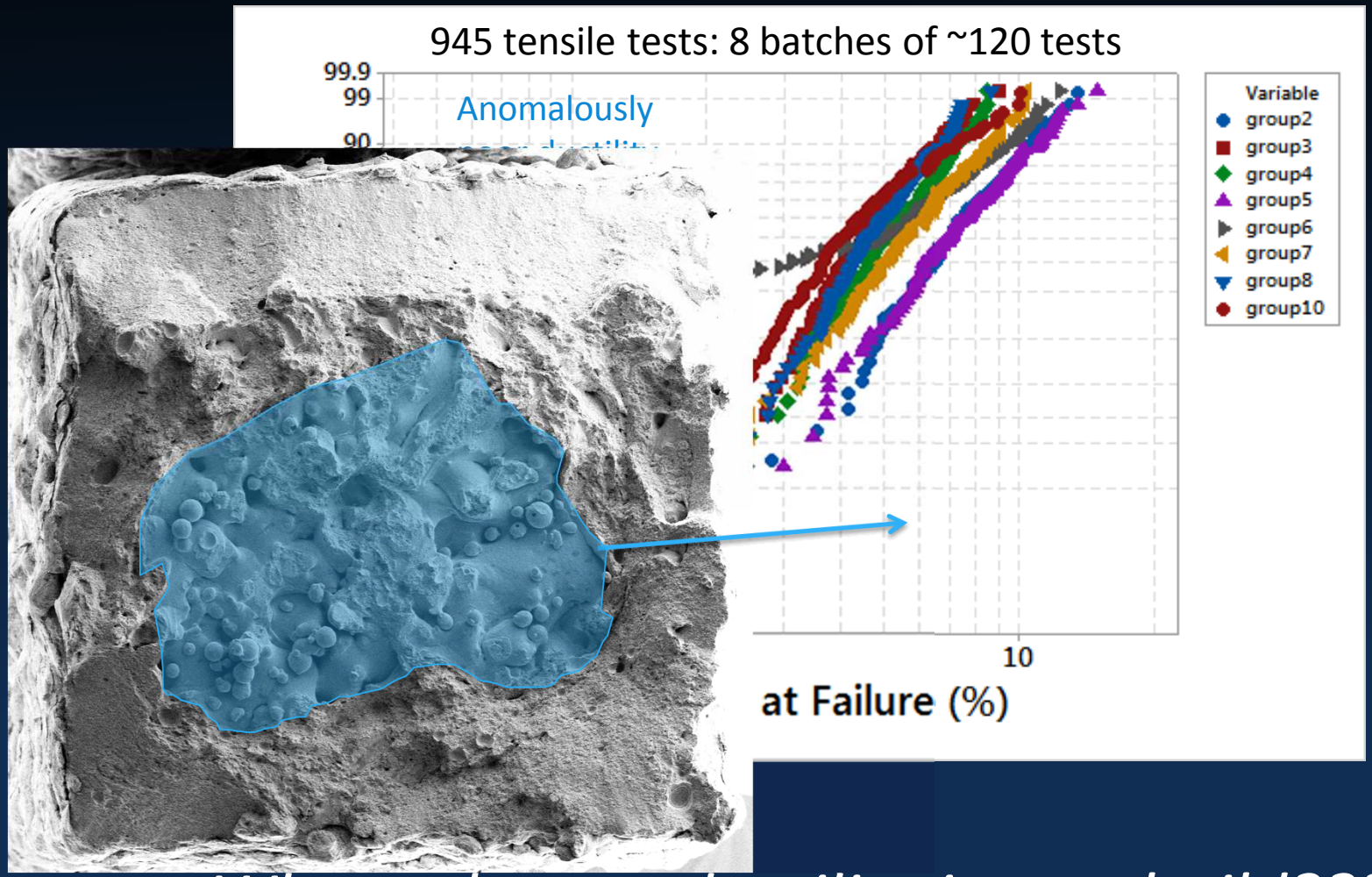


How consistent are 8 separate builds of the same 'cooling fin' from the same vendor?



(960 tensile bars!)

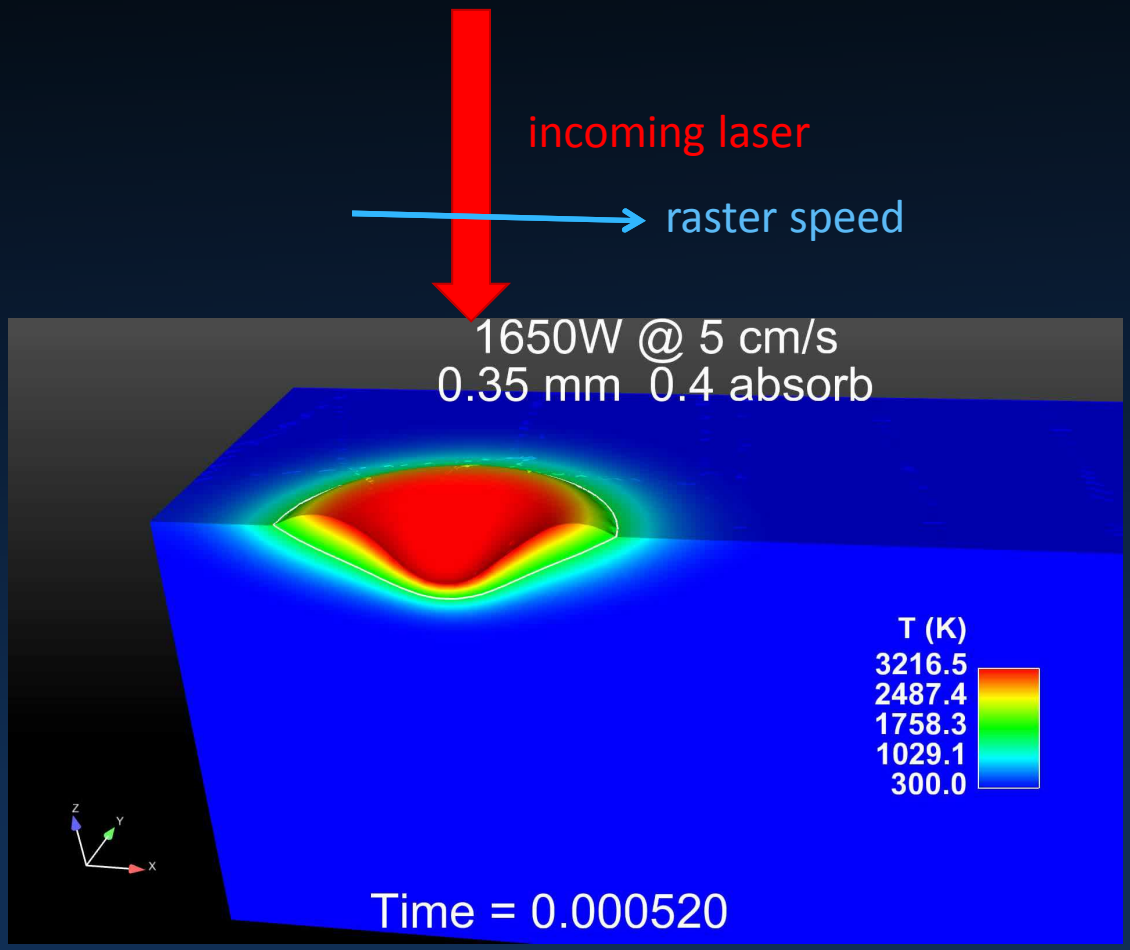
Distributions from 8 nominally identical cooling fins (Vendor 1)



Why such poor ductility in one build???

How do we fix this?

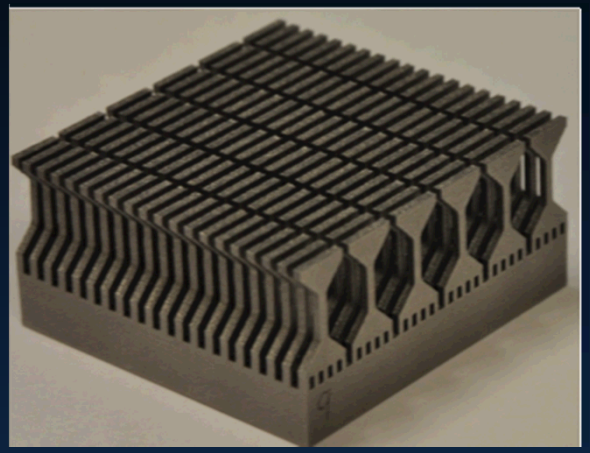
→ Understand and control the sources of flaw formation



Laser/plume interactions, raytracing
Plasma fluid mechanics
Radiation heat transfer
Laser energy adsorption
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 residual stress
Solid-state diffusion
Anisotropic crystallization
Solid-state phase transformation

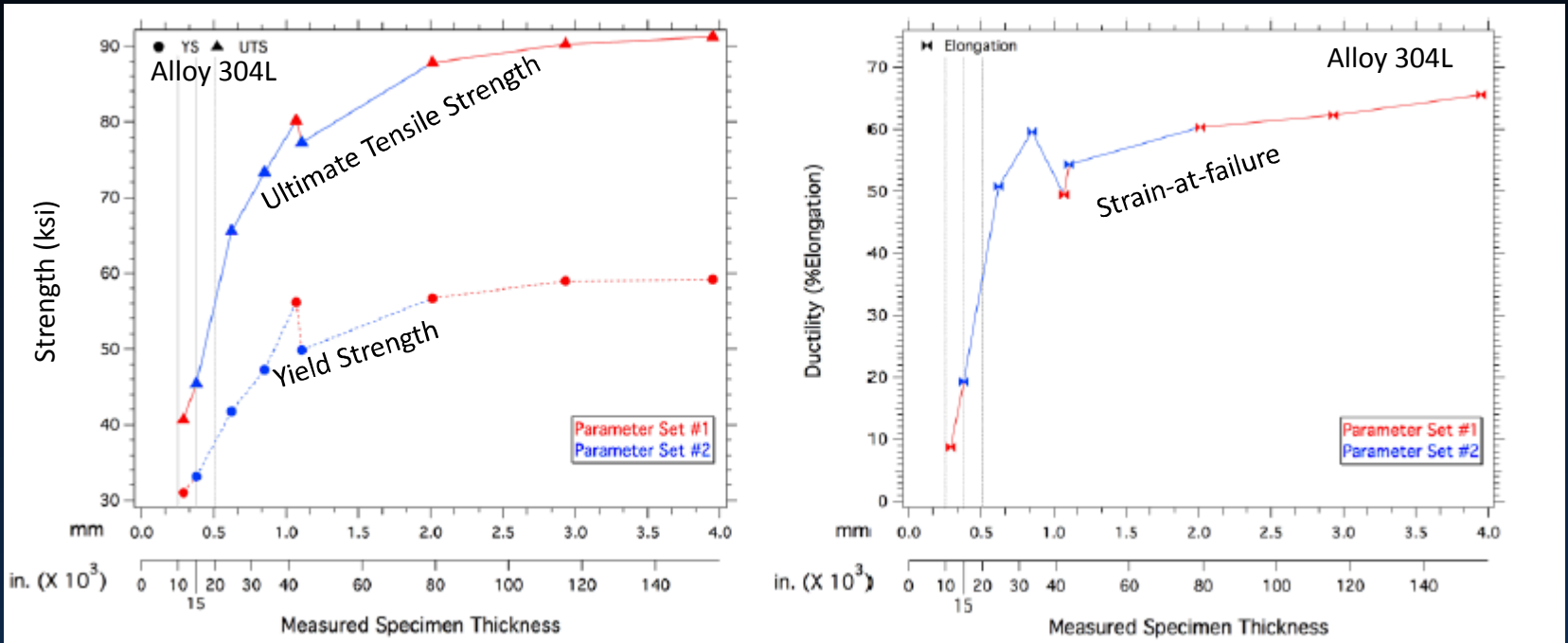
Summary…

High-throughput measurements of additively manufactured materials provides a rapid method for screening performance anomalies and diagnosing sources of poor reliability.



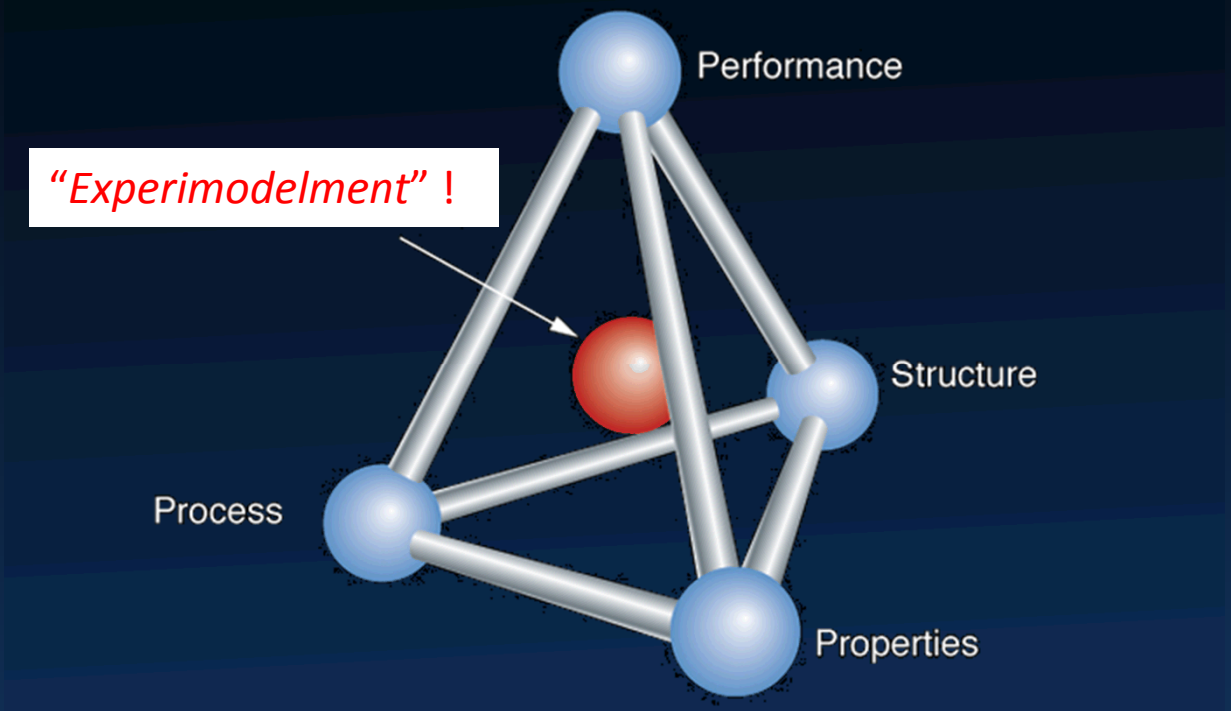
Eventually, we would like to screen using in-process monitoring/control. Rapid materials characterization will enable the development of needed process-structure-property correlations.

Future work…

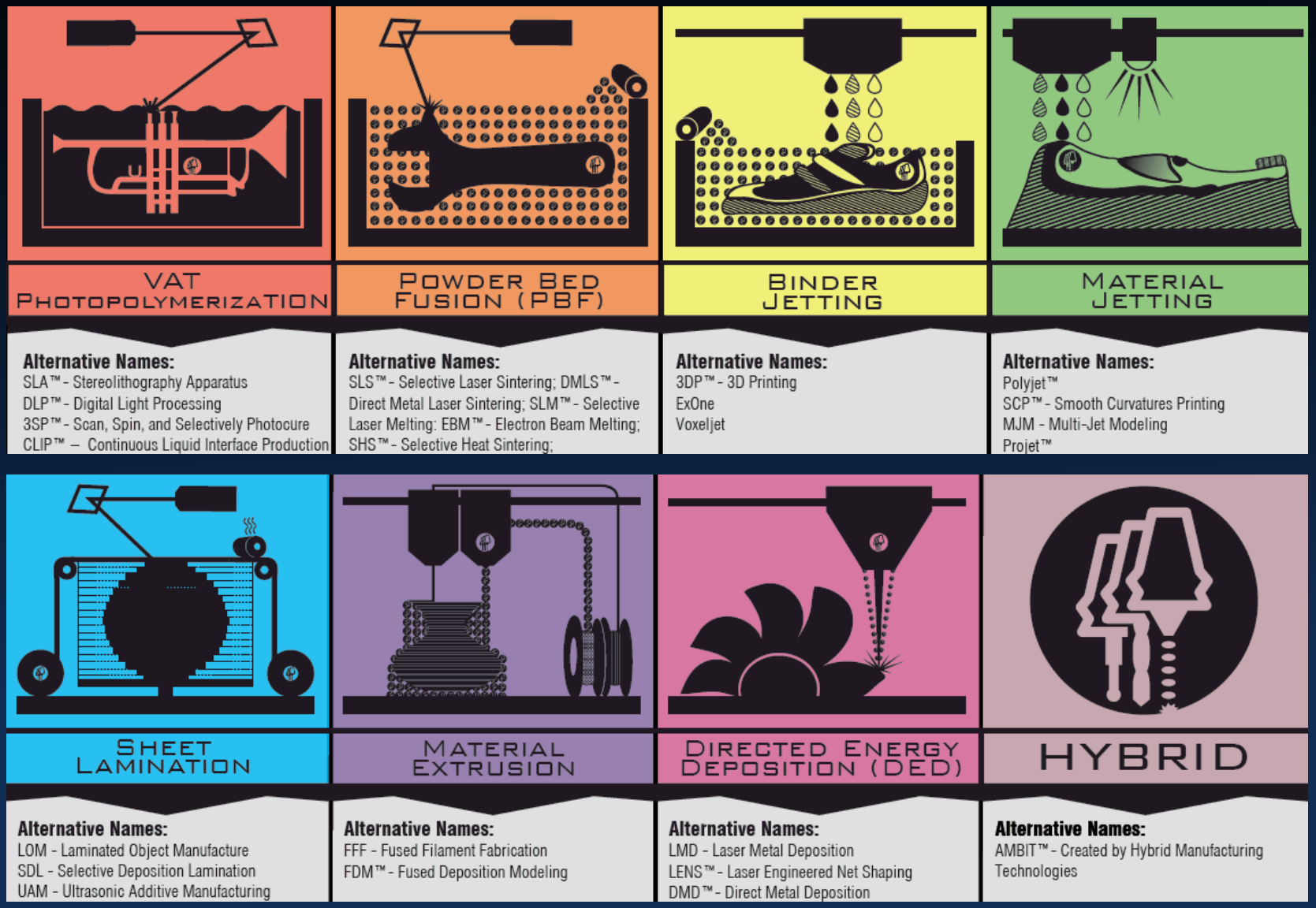


How does sample thickness affect defect populations and resulting property distributions?

What is the origin of different properties?

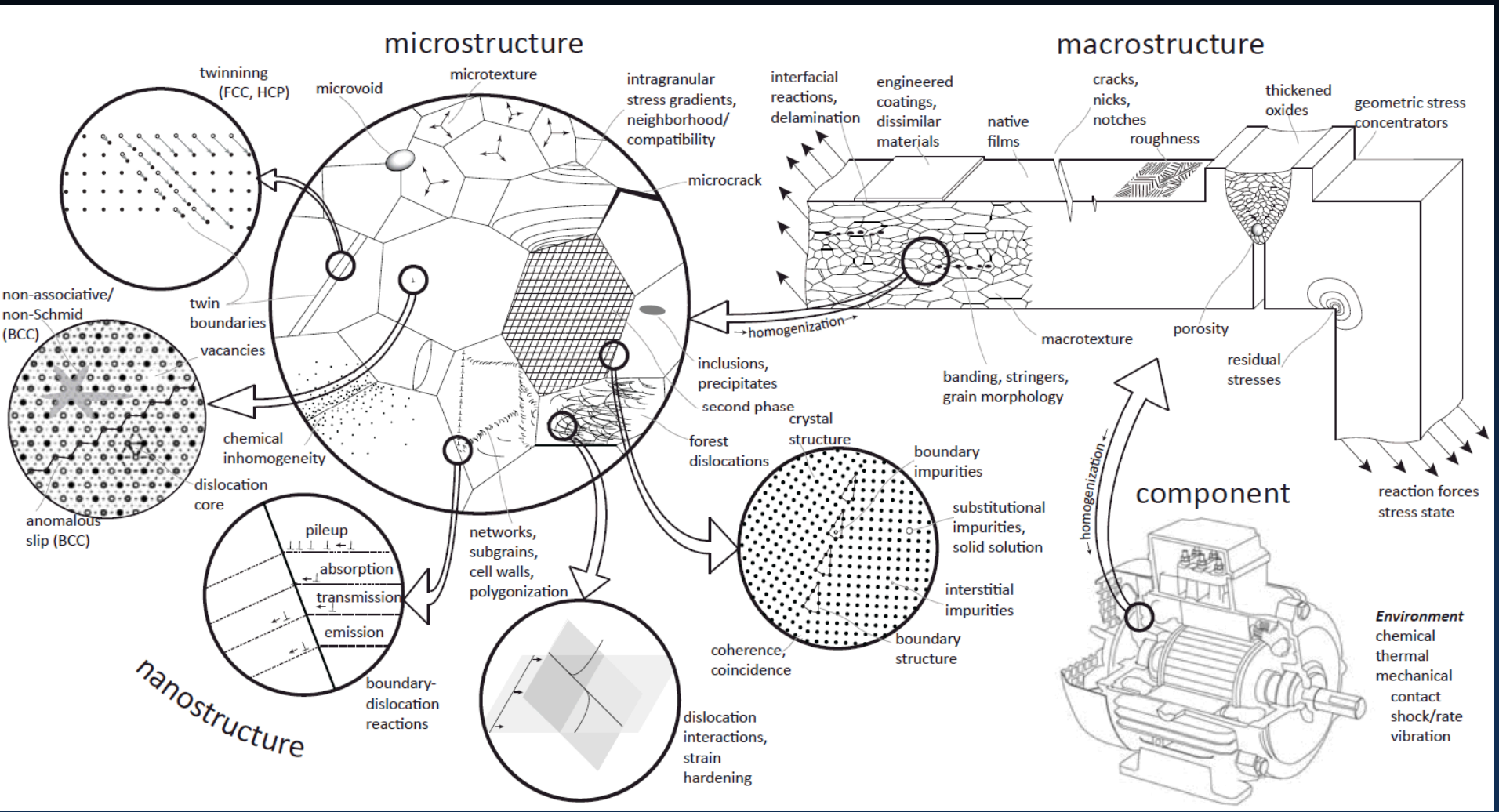


8 Families of AM Processes (ASTM F2794)

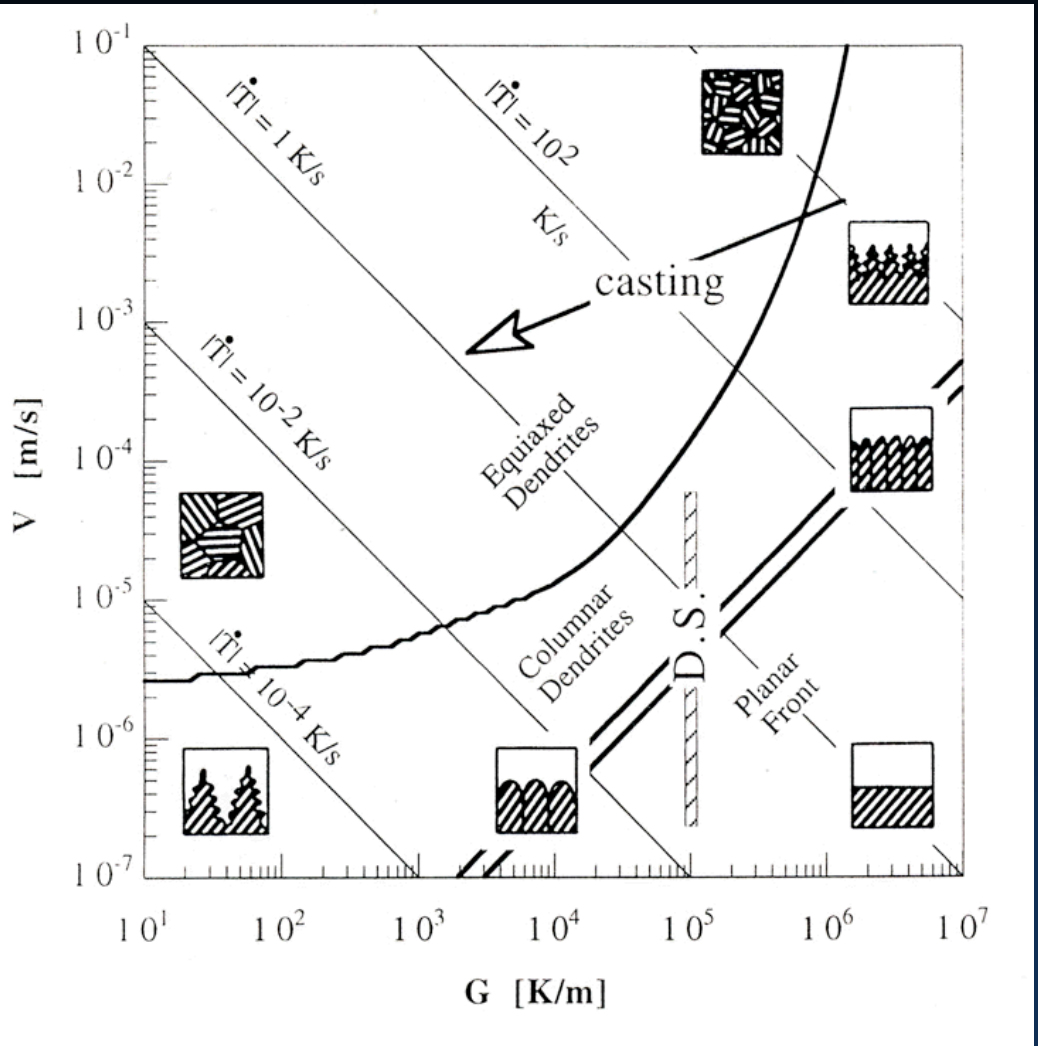


Graphic created by Hybrid Manufacturing Technologies based on ASTM F2794 definitions

What is the origin of different properties?



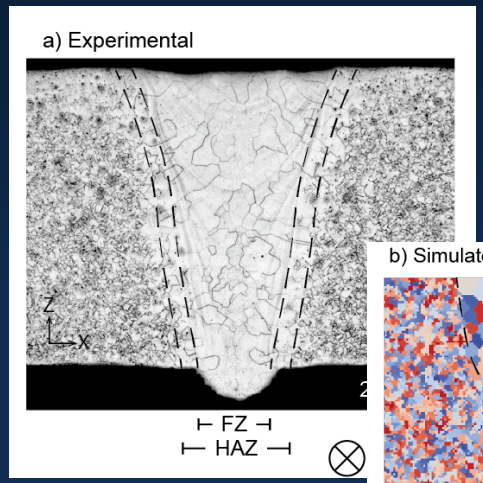
Ultimate goal: Predict solidification microstructure

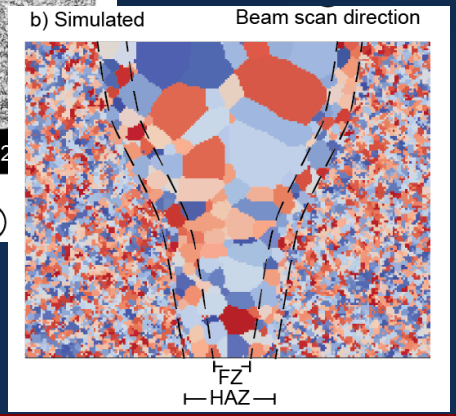


Potts Kinetic Montre Carlo

$$P = \begin{cases} \exp\left(\frac{-\Delta E}{k_B T_S}\right) & if\ \Delta E > 0 \\ 1 & if\ \Delta E \le 0 \end{cases}$$

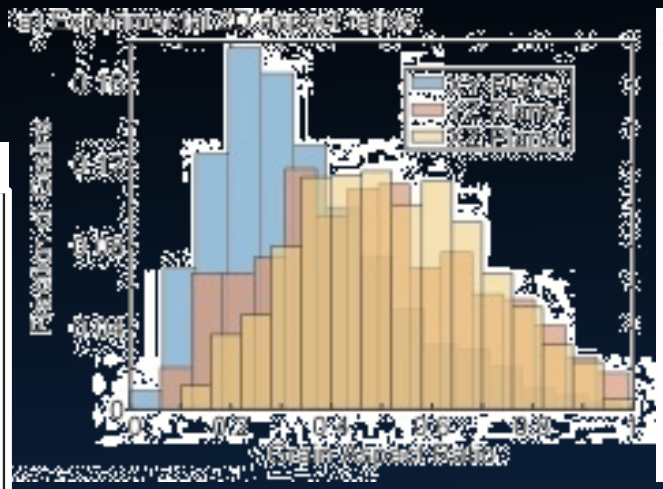
$$E = \frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{26}\left(1-\delta\left(q_i, q_j\right)\right)$$

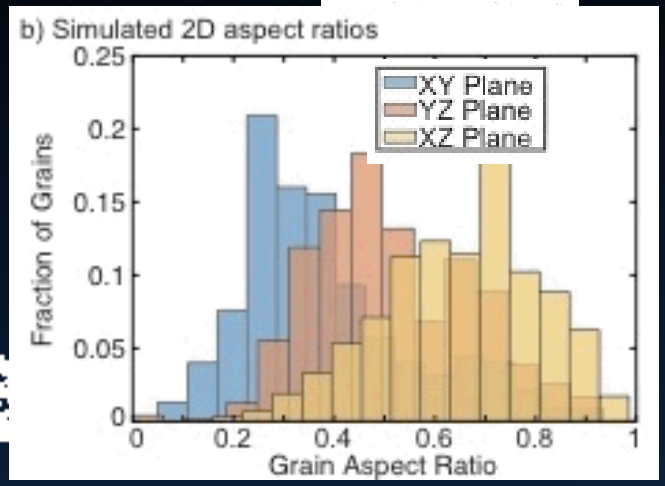


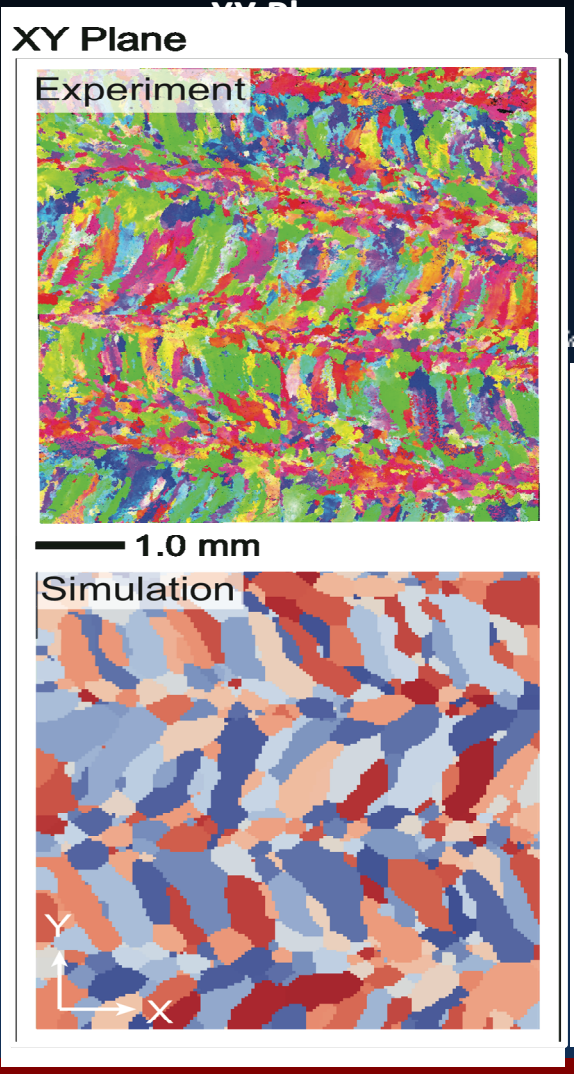


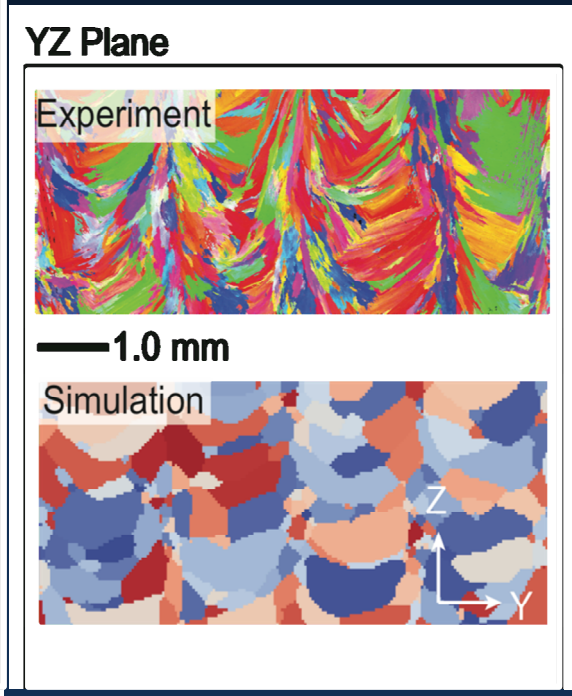
Kurz, W. and Fisher, D. J., Fundamentals of Solidification, Chapter 4: Solidification Microstructure, Trans Tech Publications (Enfield, NH, 1998)
Rodgers, Madsion, and Tikare, JOM, 2016

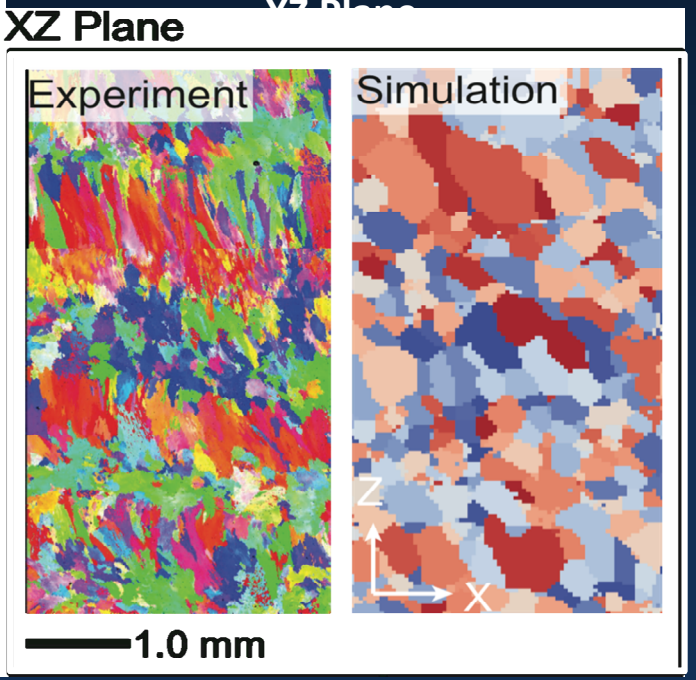
Capturing complex solidification microstructure



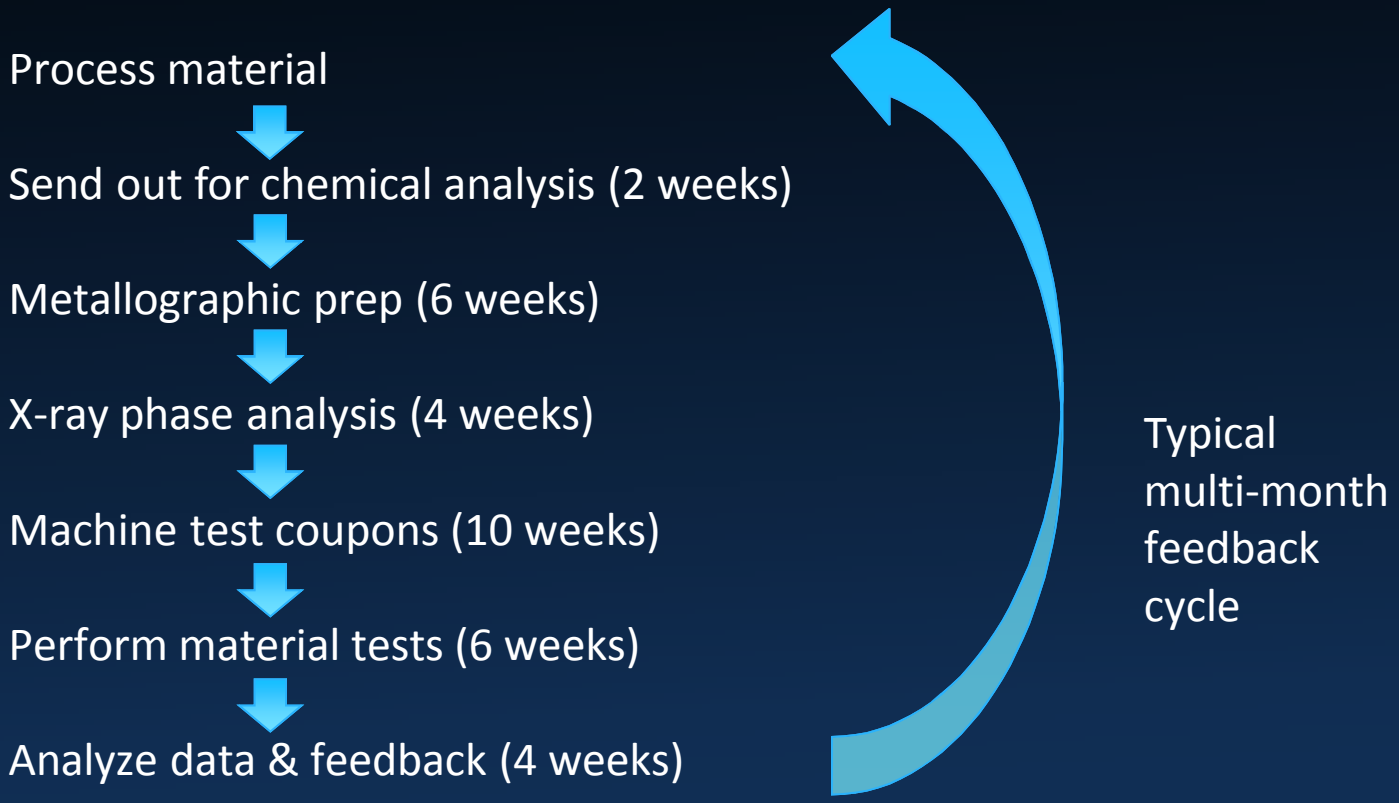




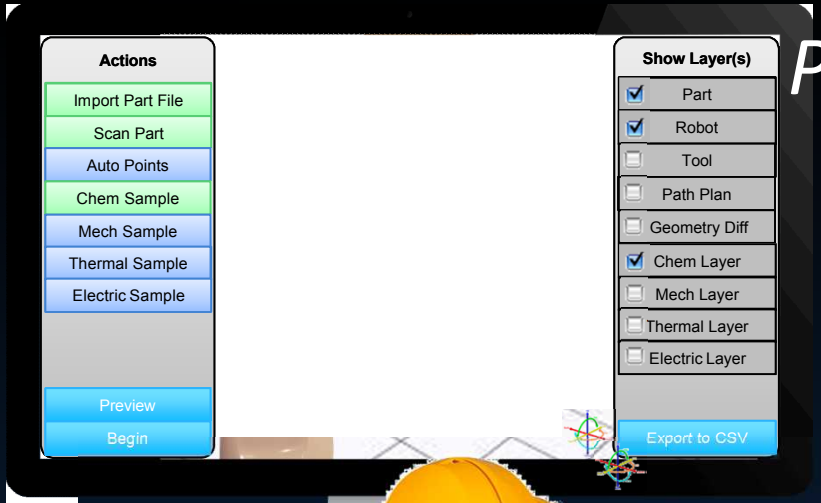




The conventional materials science cycle is not commensurate with the speed of AM



Properties 'Alinstante'



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

…