

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

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Sandia has a rich heritage in Additive Manufacturing



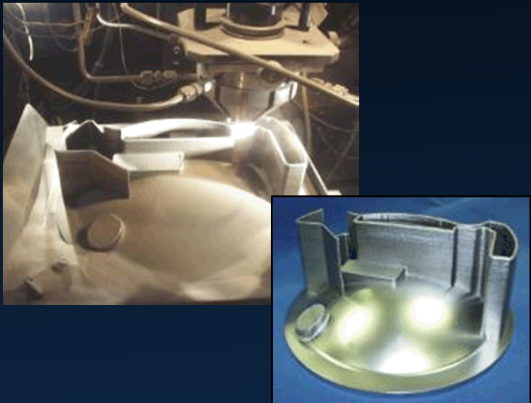
FastCast*

prototype test unit



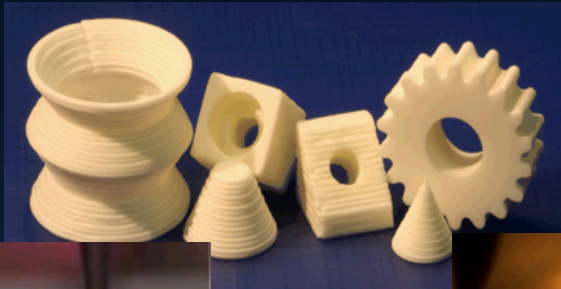
LENS®*

fireset housing



RoboCast*

ceramic parts

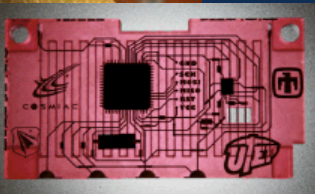
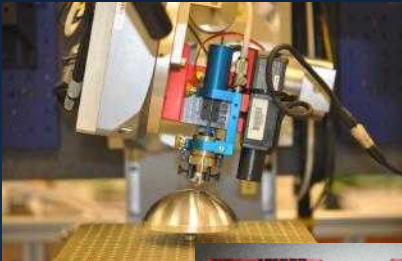


energetic materials



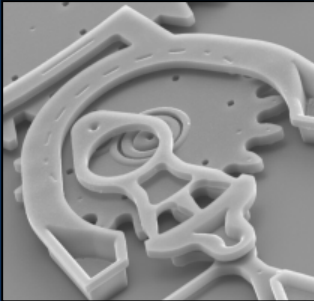
Direct Write

conformal electronics



MEMS SUMMIT™*

micro gear assembly



LIGA

“Hurricane” spring



Spray Forming

rocket nozzle

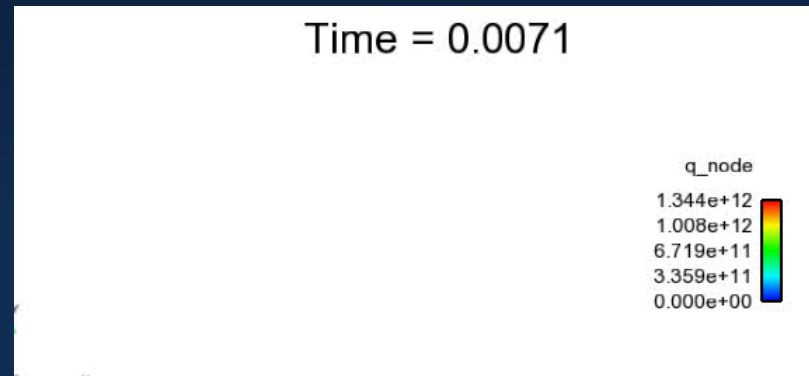
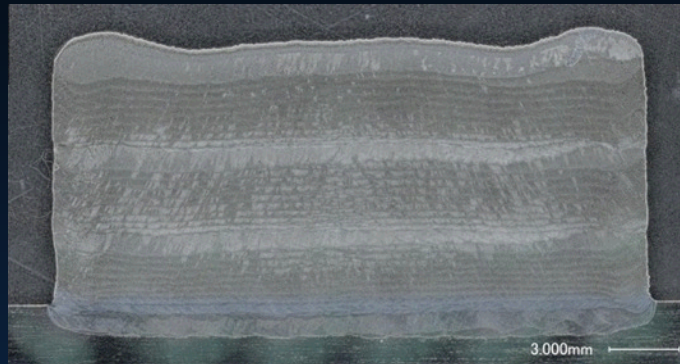




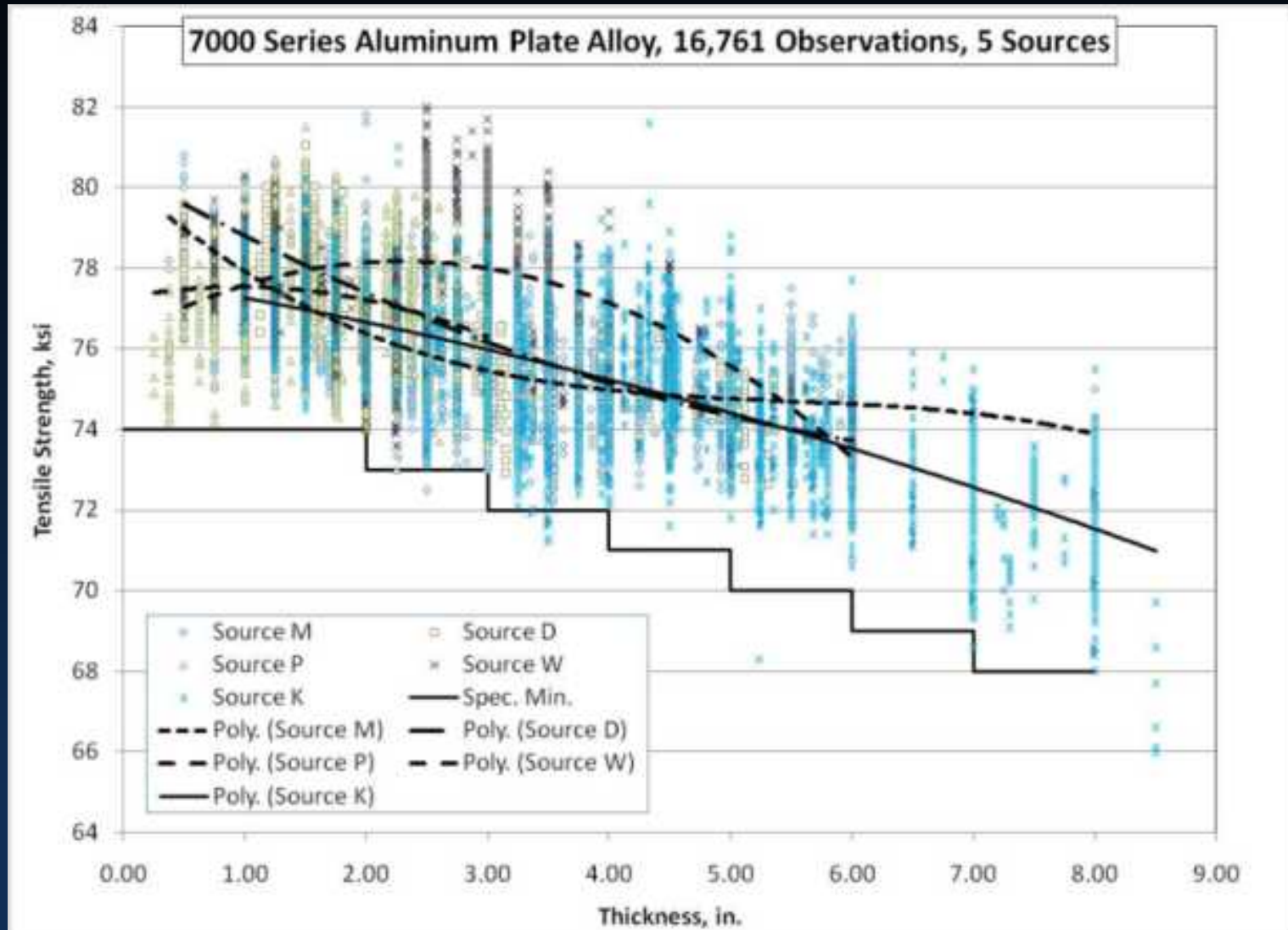
Additive manufacturing offers rapid production of custom, geometrically complex parts

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

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

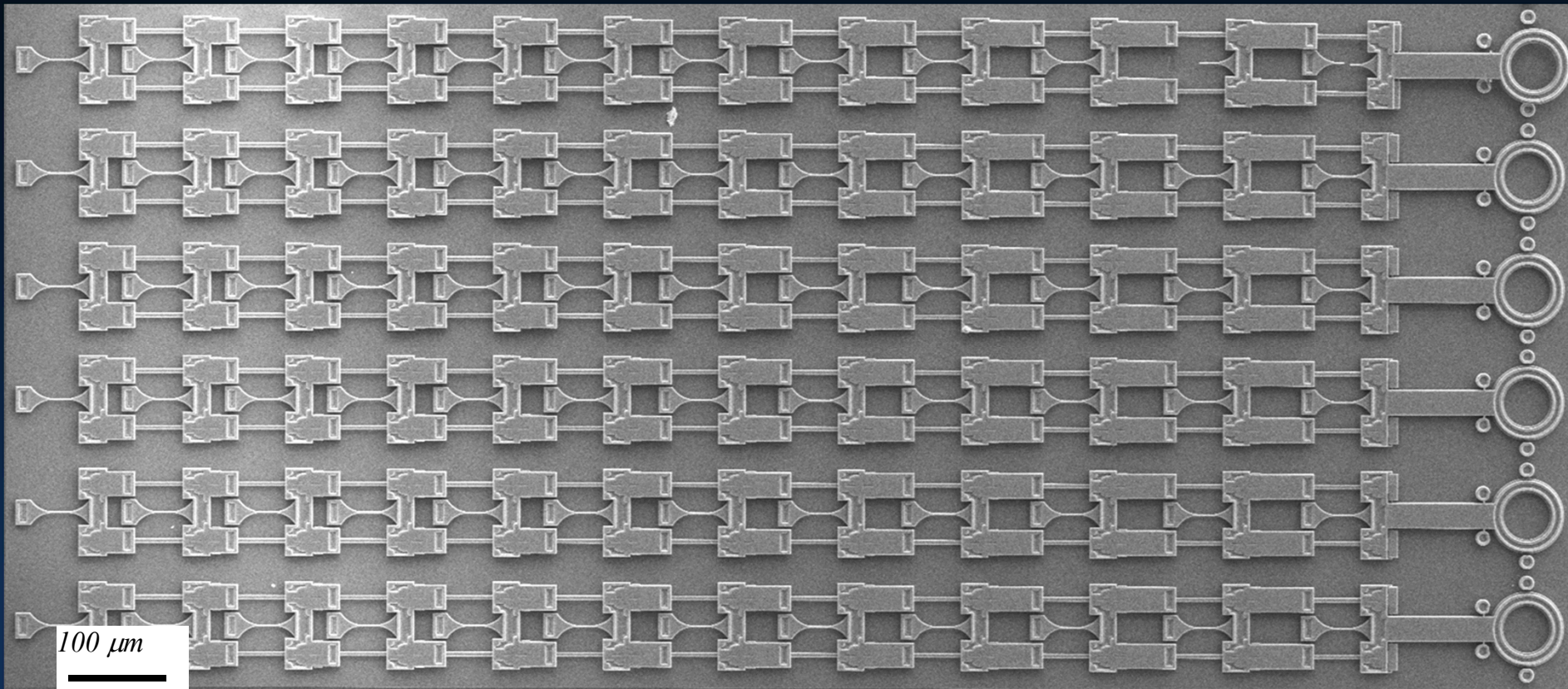


How conventional materials are qualified...

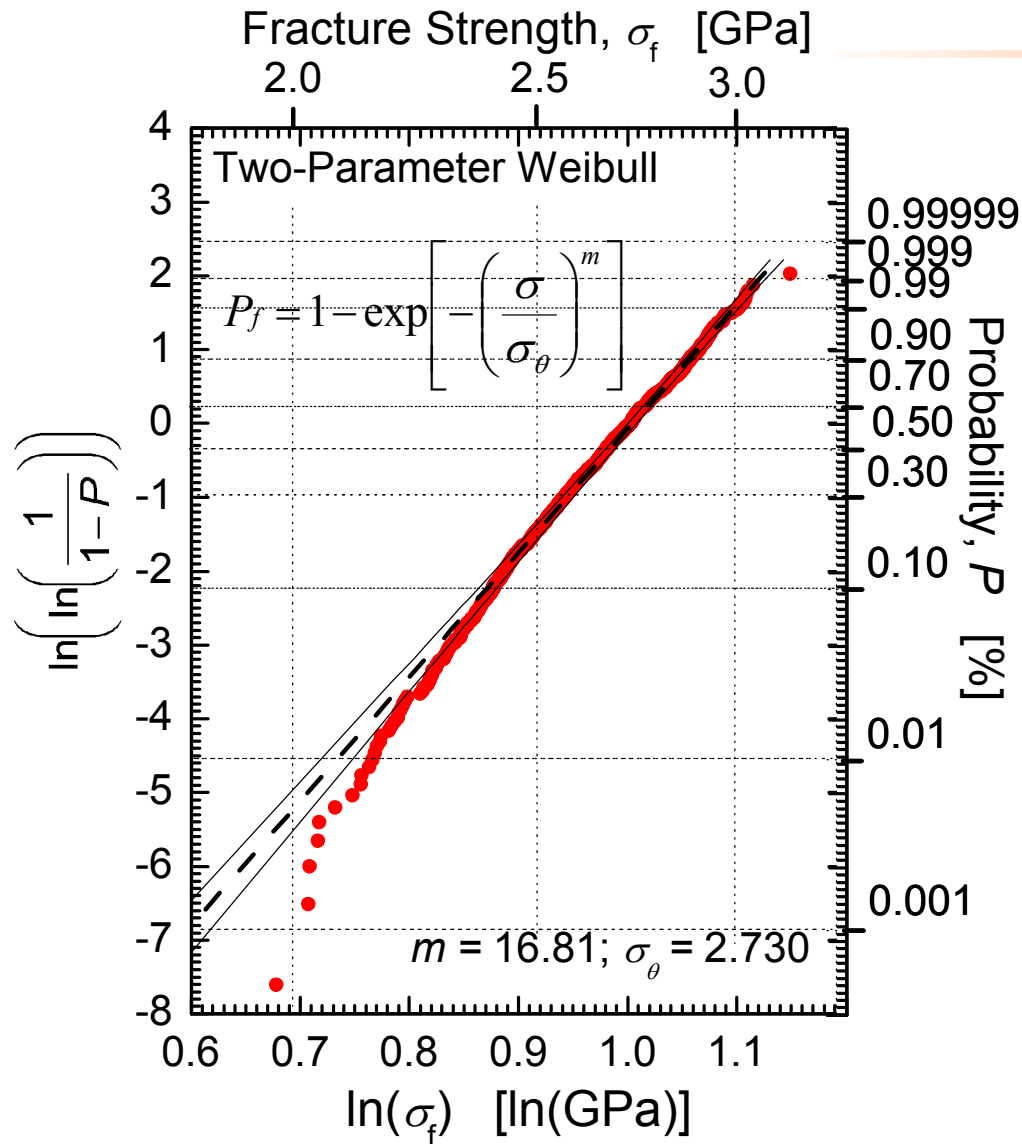


The Slack Chain Concept: Rapid Sequential Tensile Testing for Large Statistical Datasets

10/24/2010
10:00:00
10/24/2010



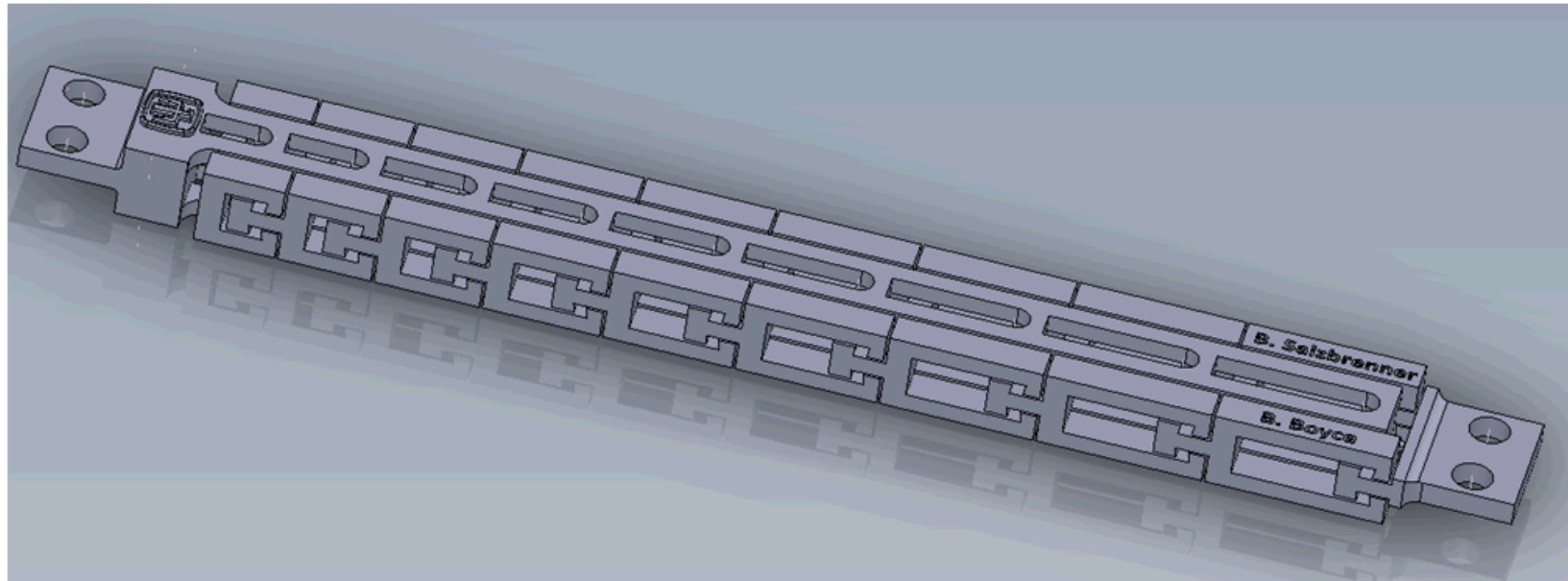
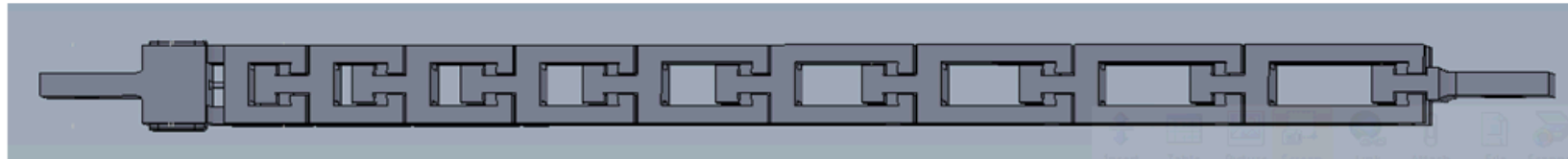
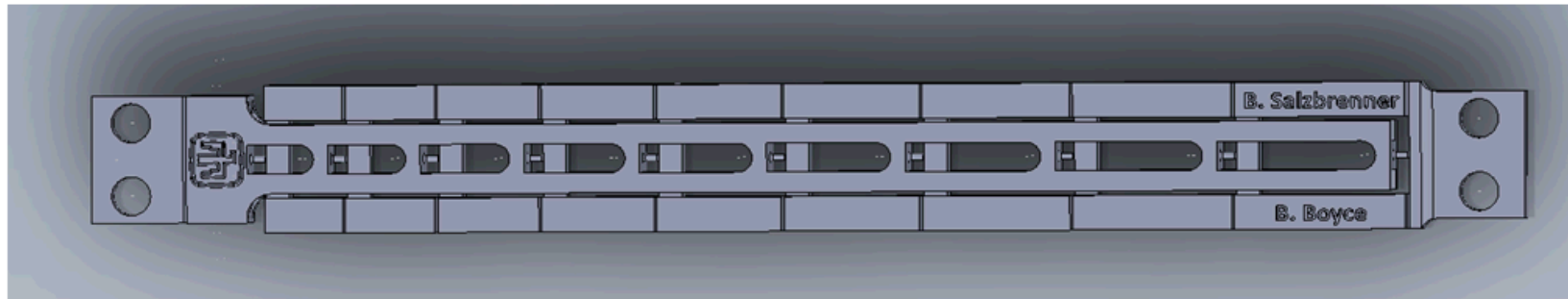
Weibull Fit to 1,008 Test Repeats



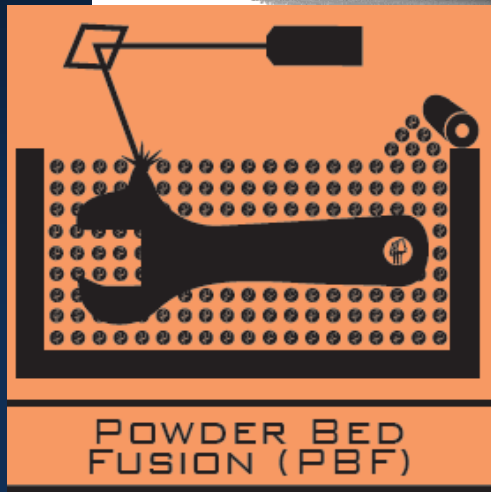


Can we apply principles of rapid, streamlined mechanical testing to additive manufacturing?

Sequential concept for additive manufacturing

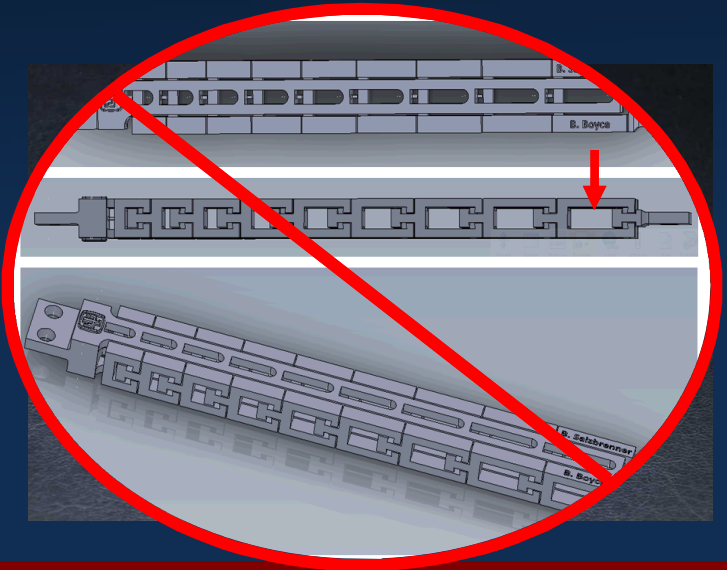


Laser Powder Bed Fusion (L-PBF)

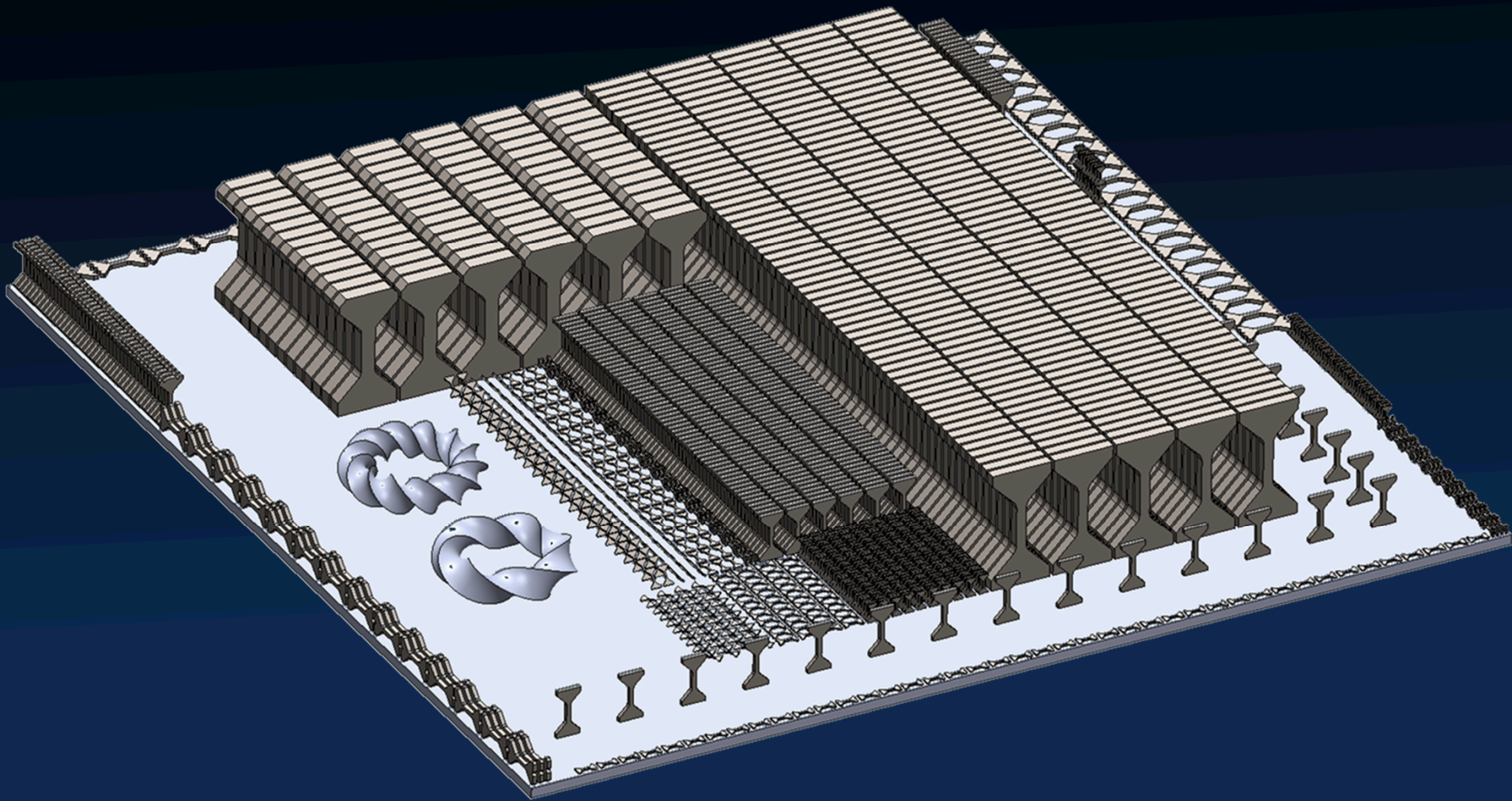


Key process variables:

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

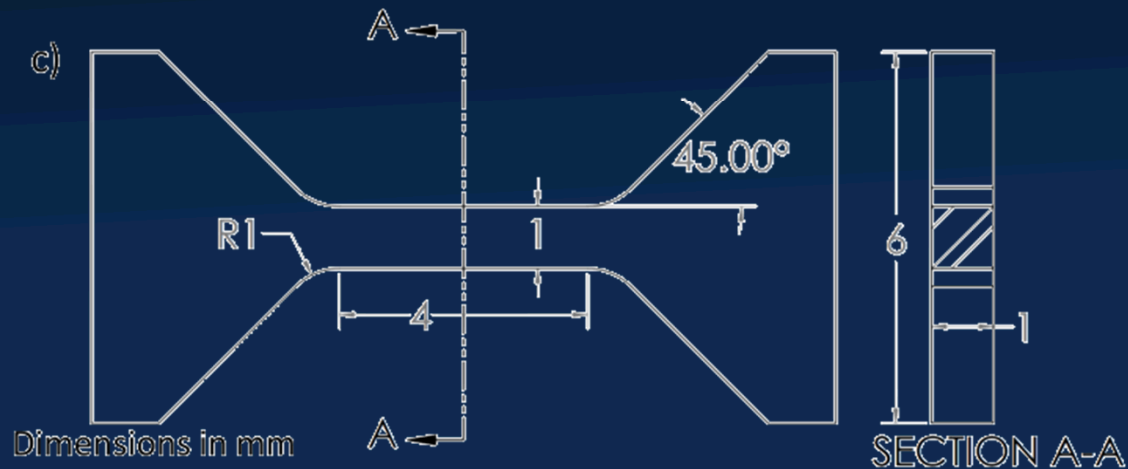
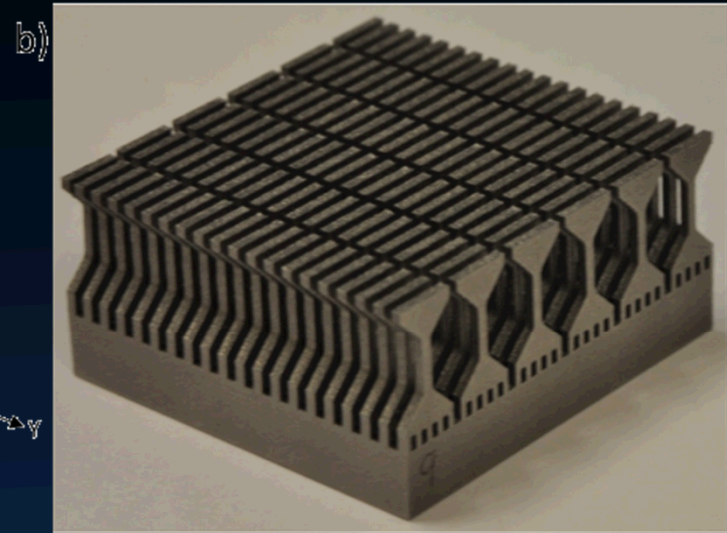
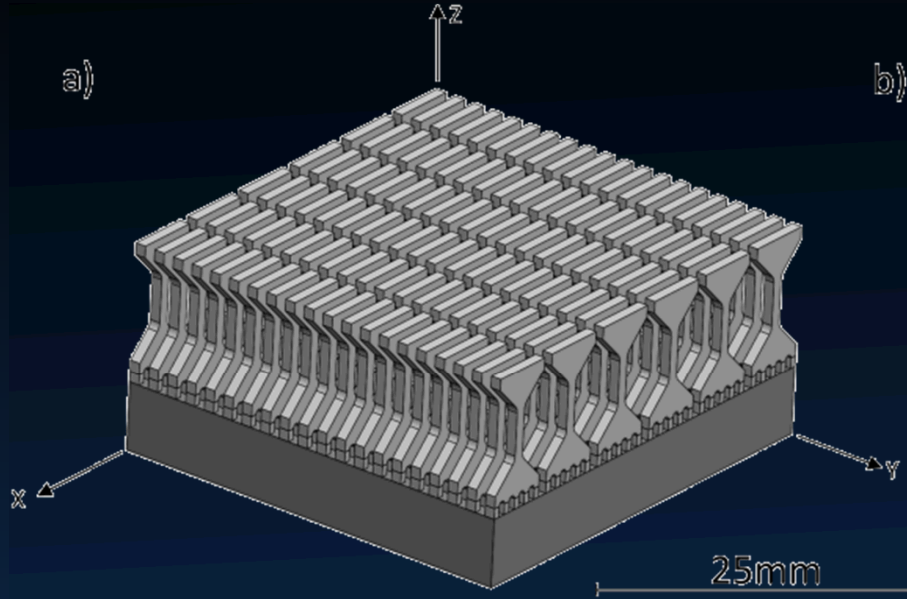


*AM offers opportunities to print
extensive mechanical test coupons*

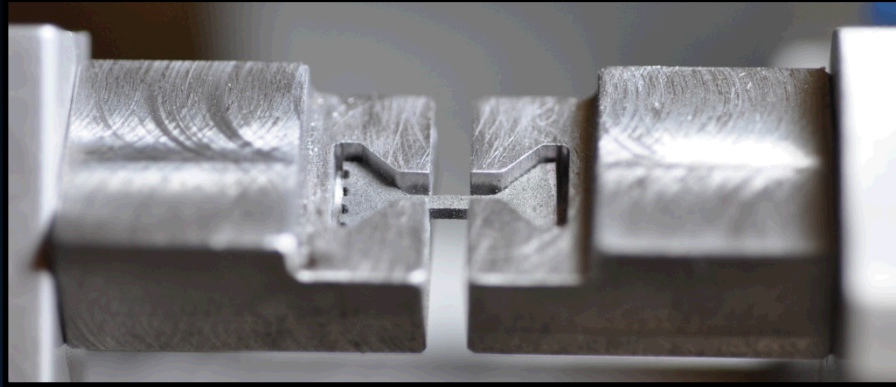


Starting simple: 'cooling fin design'

10.12.2012
14:05:00

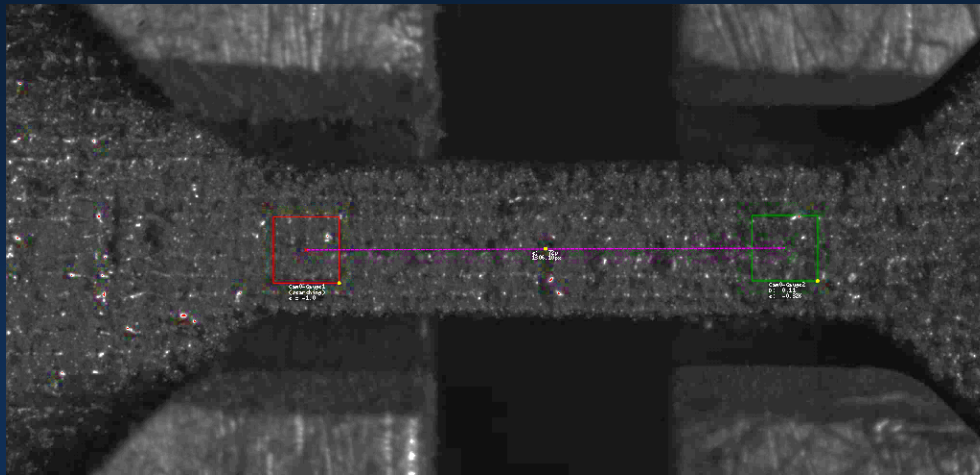


Streamline the testing process



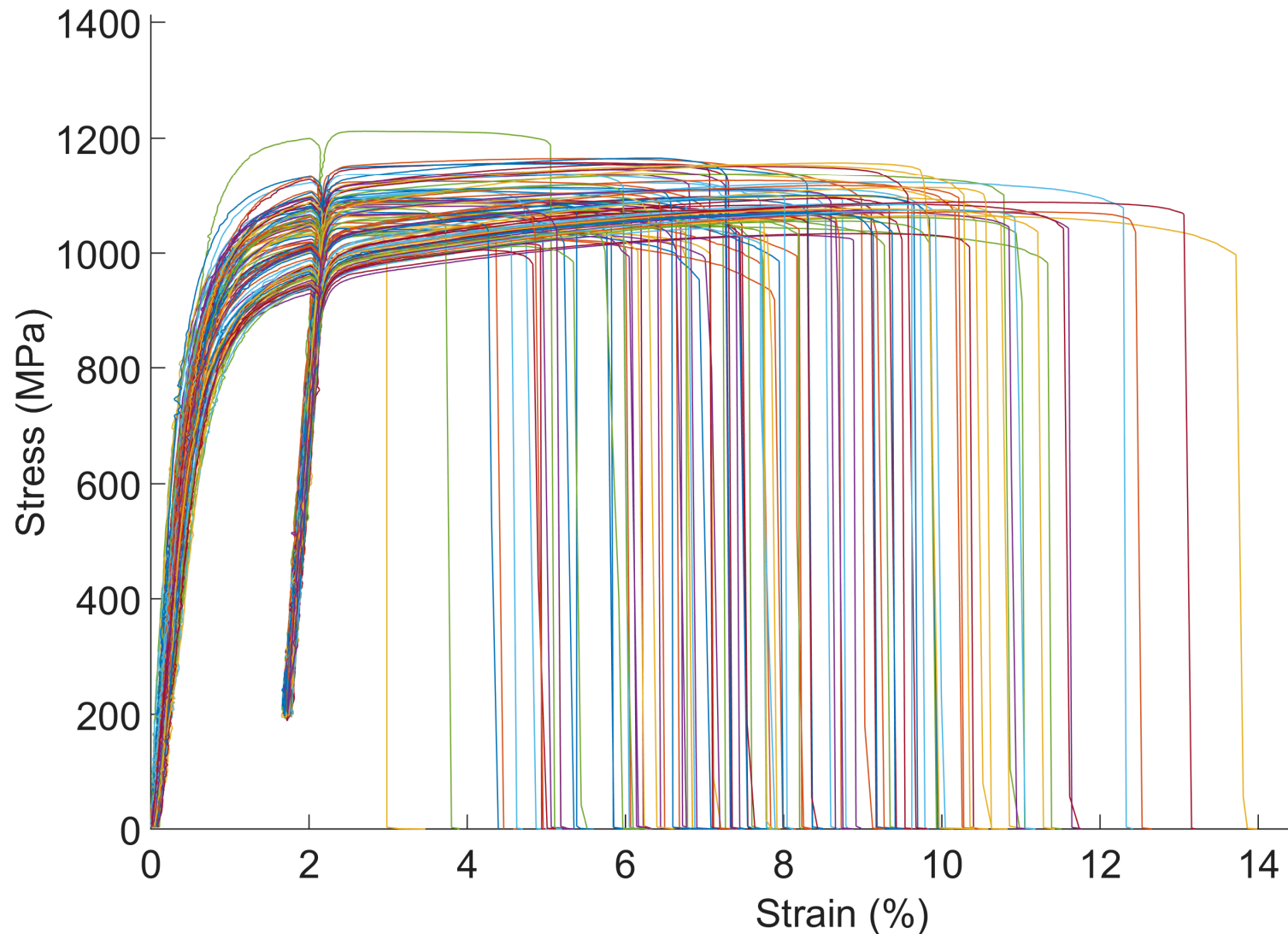
1. Adopt self-aligning 'drop-in' grips

3. Maximize software automation to reduce burden on operator



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

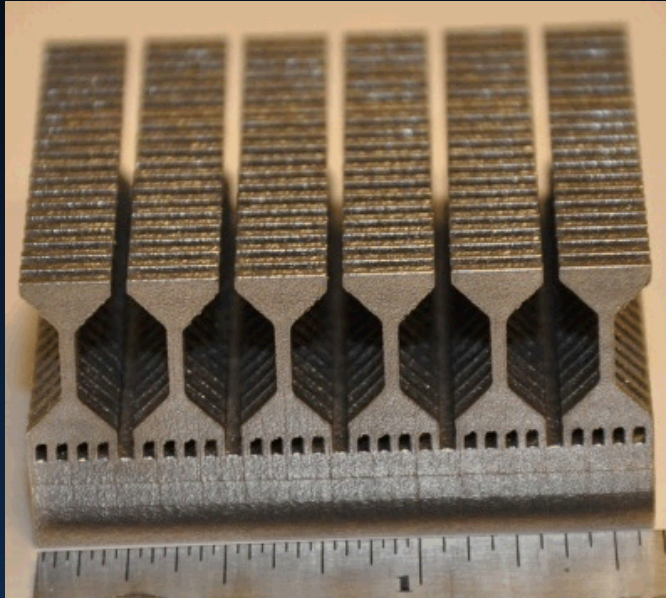
100 tensile tests in 4 hours...



A comparison of 2 major commercial vendors

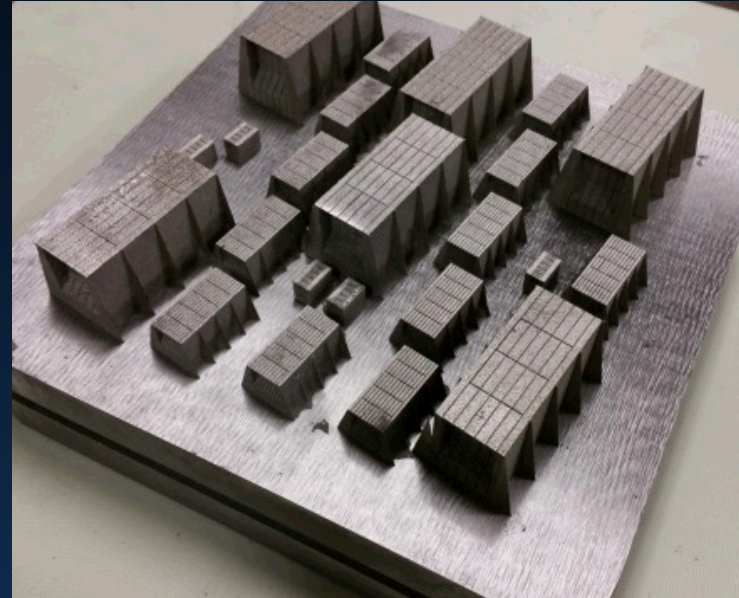


ConceptLaser Mlab



Vendor 1

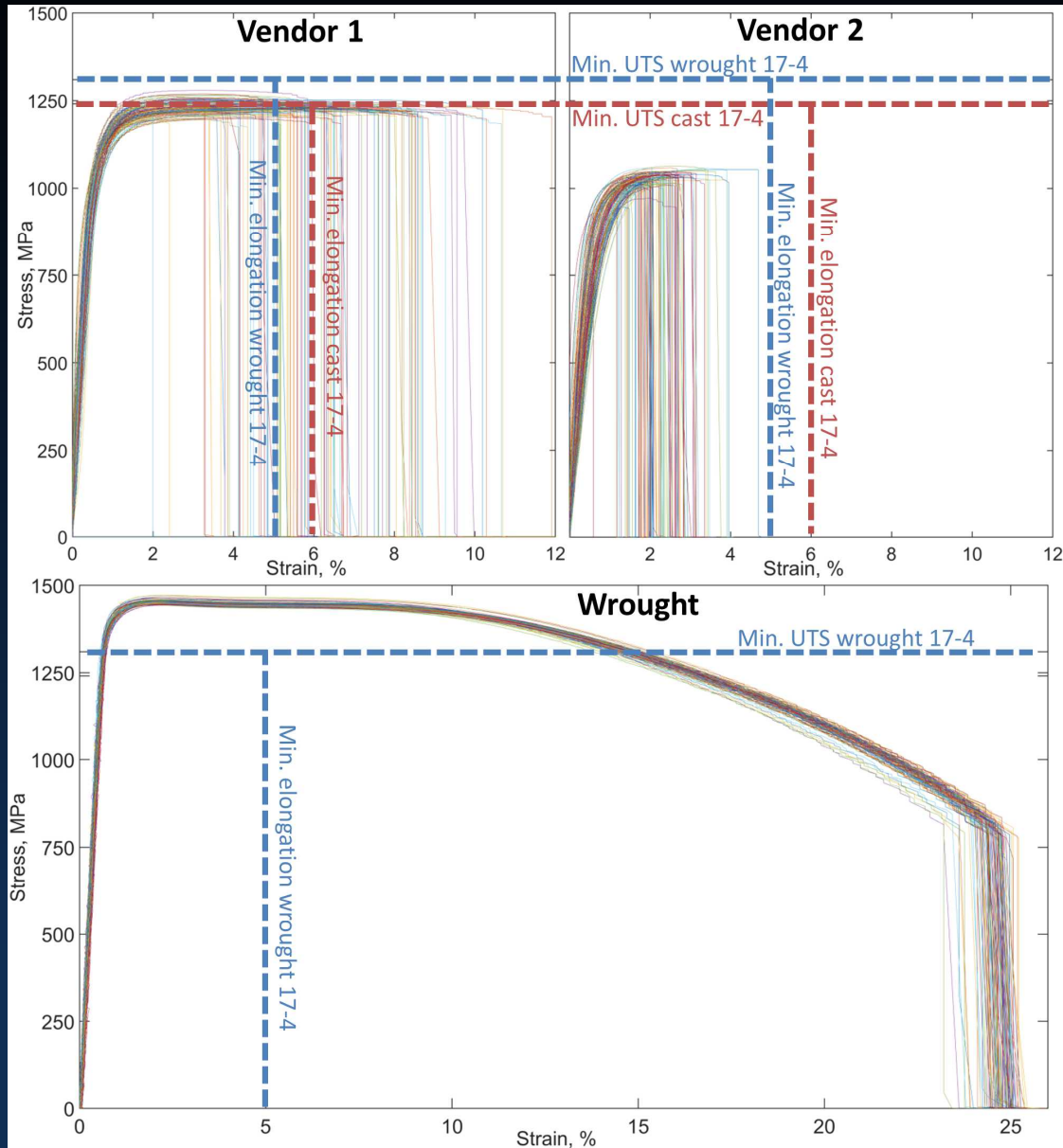
3D Systems ProX300



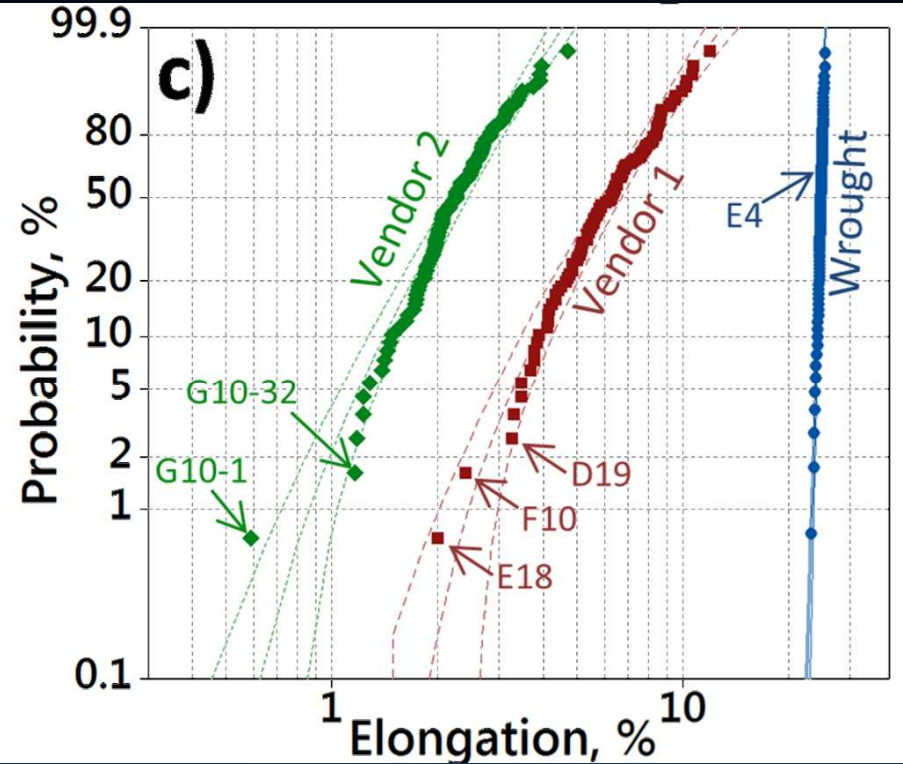
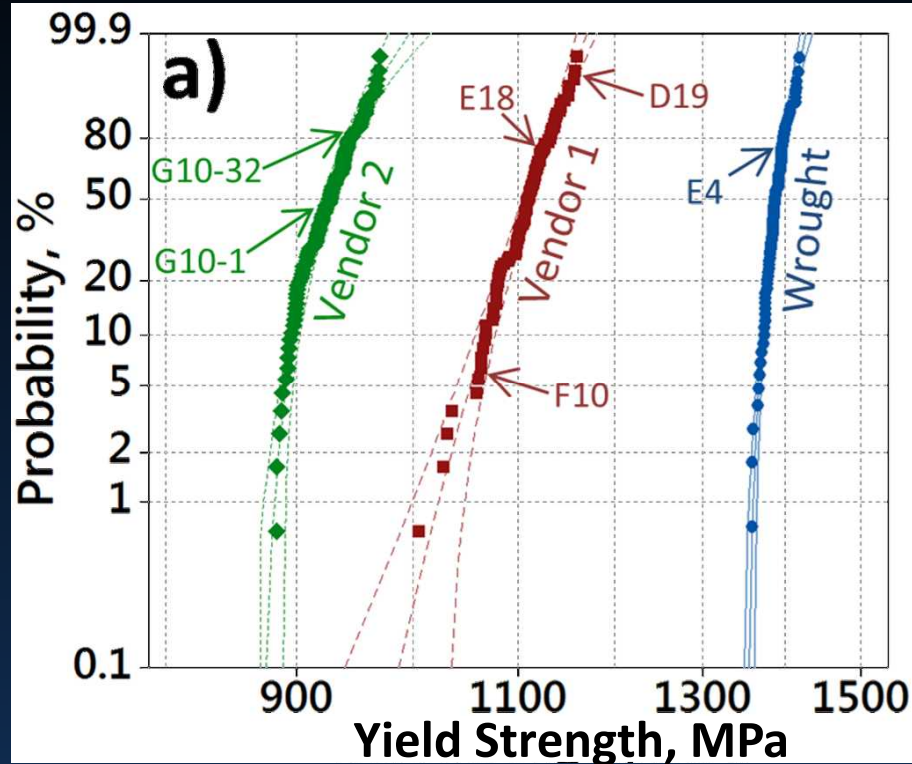
Vendor 2

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

Comparing 100 tests from 3 sources



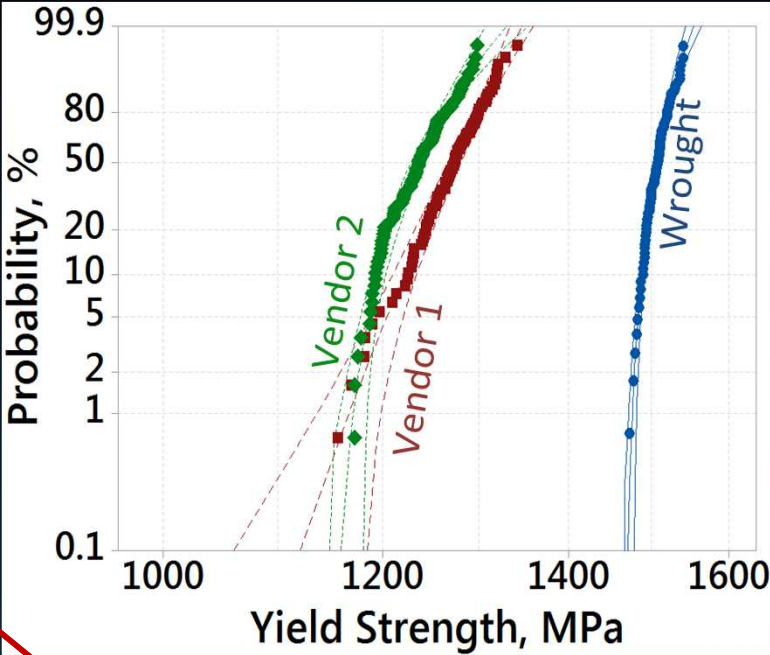
3-Parameter Weibull Fits to Distributions



What is the origin of different properties???

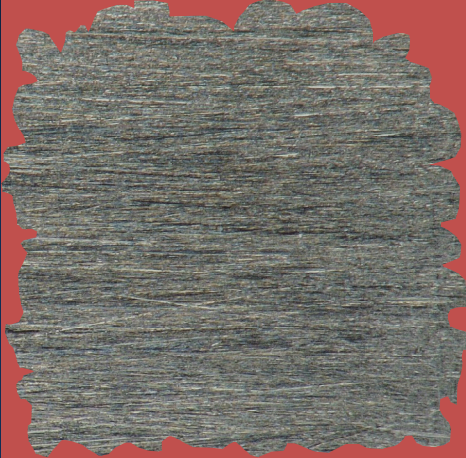
Effect #1: Surface roughness

Figure 10-10
Effect of Surface Roughness on Yield Strength



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

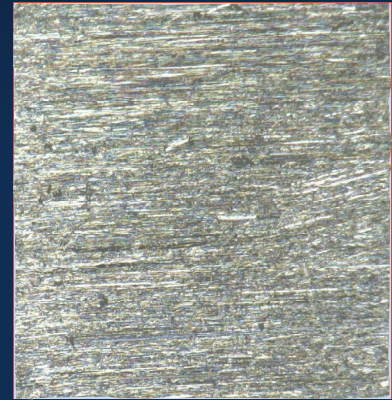
b) Vendor 2



a) Vendor 1



c) Wrought

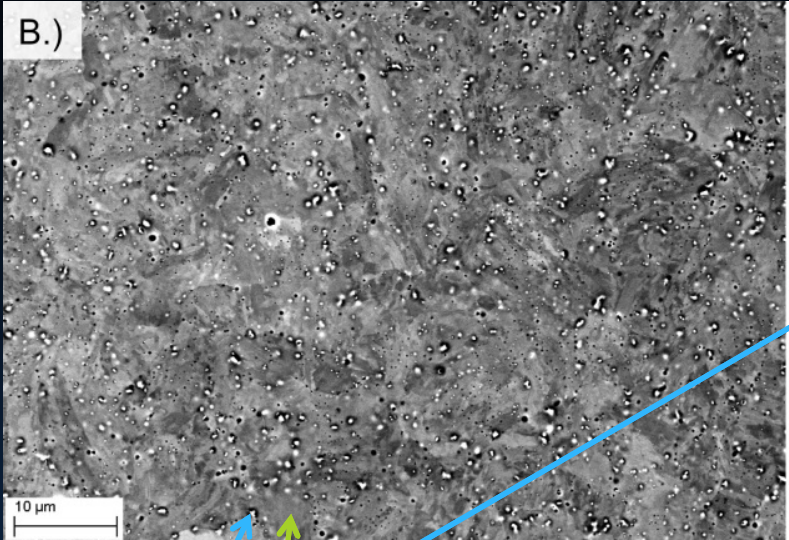


500µm

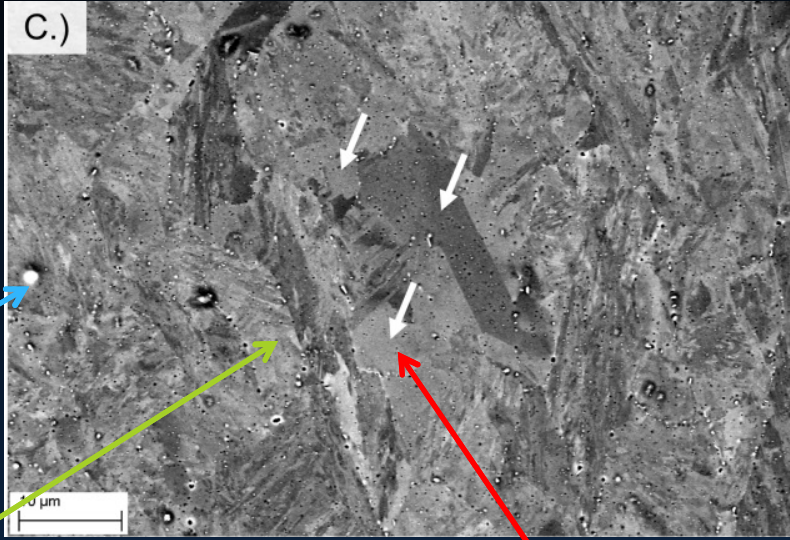
Effect #2: Phase content



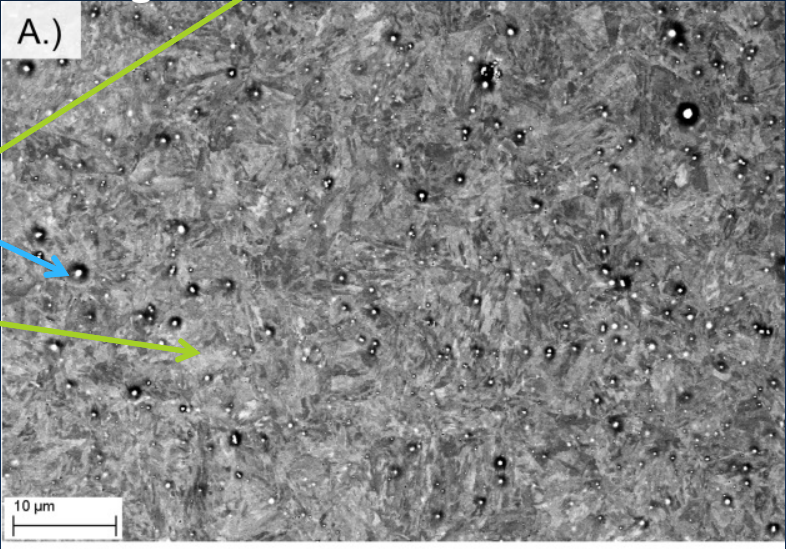
Vendor 1



Vendor 2



Wrought



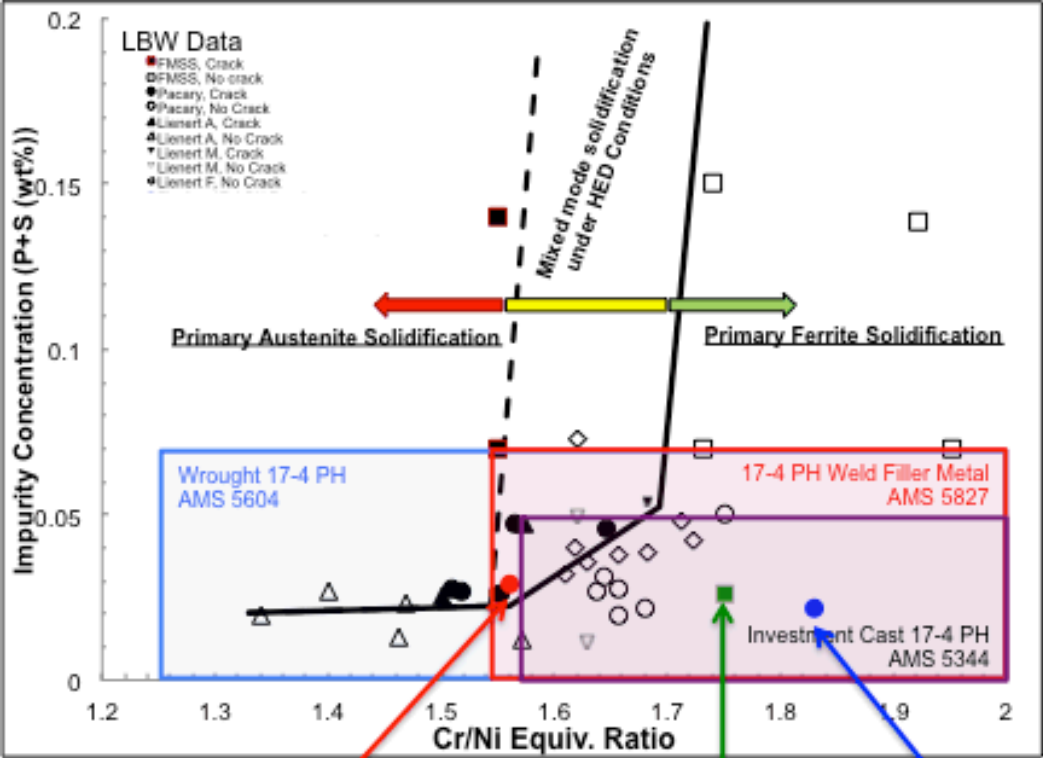
Nb carbides

Lath Martensite

Retained austenite!

Why Austenite in Vendor 2 material???

| |
|--|
| |
| Nominal Wrought Composition (AMS5604) |
| Wrought Composition** |
| Nominal Invest. Cast Composition (AMS5344) |
| Vendor 1 Composition* |
| Vendor 2 Composition* |
| NS=none speci |
| *compared to |
| **compared to |



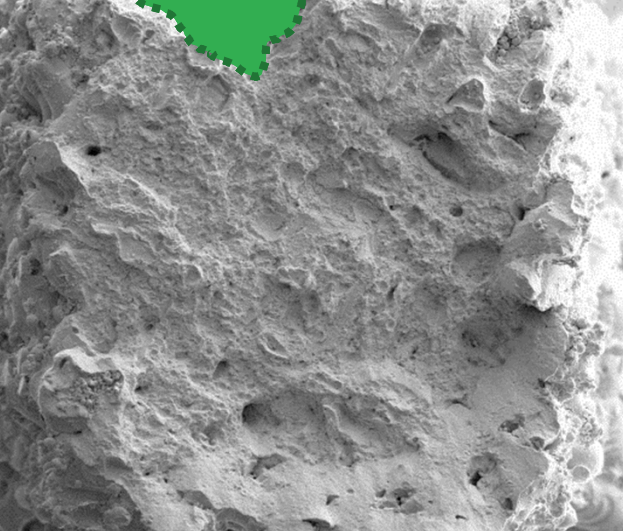
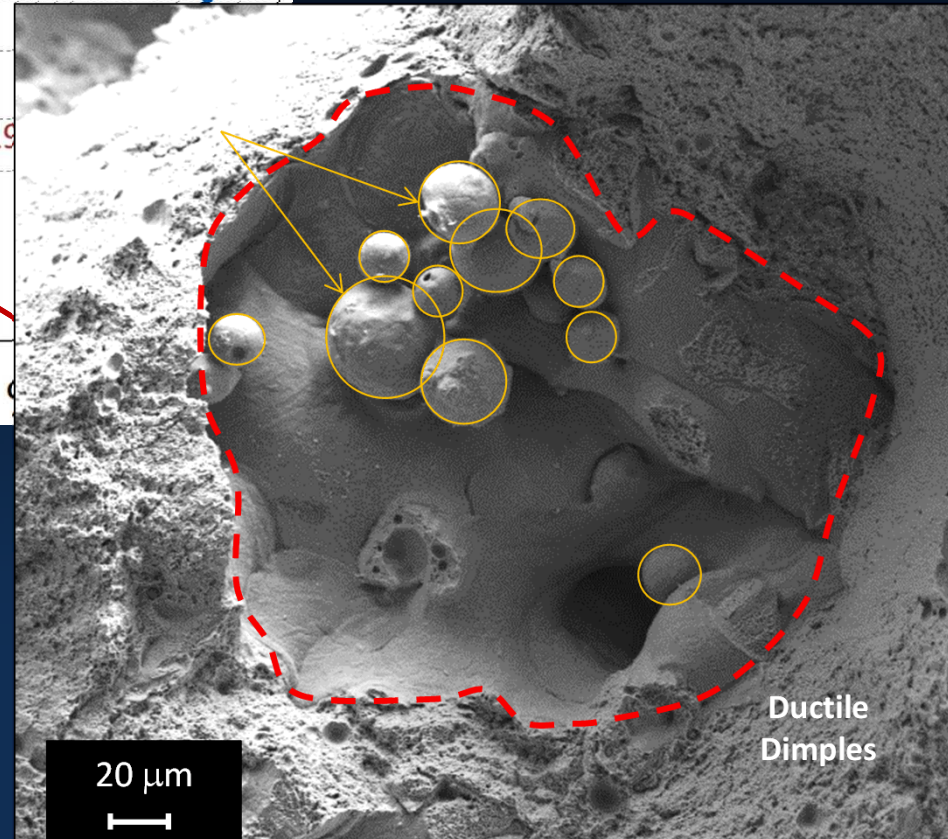
Vendor #2
 M_s : -10°C

17-4 PH sheet
 M_s : 109°C

Vendor #1
 M_s : 100°C

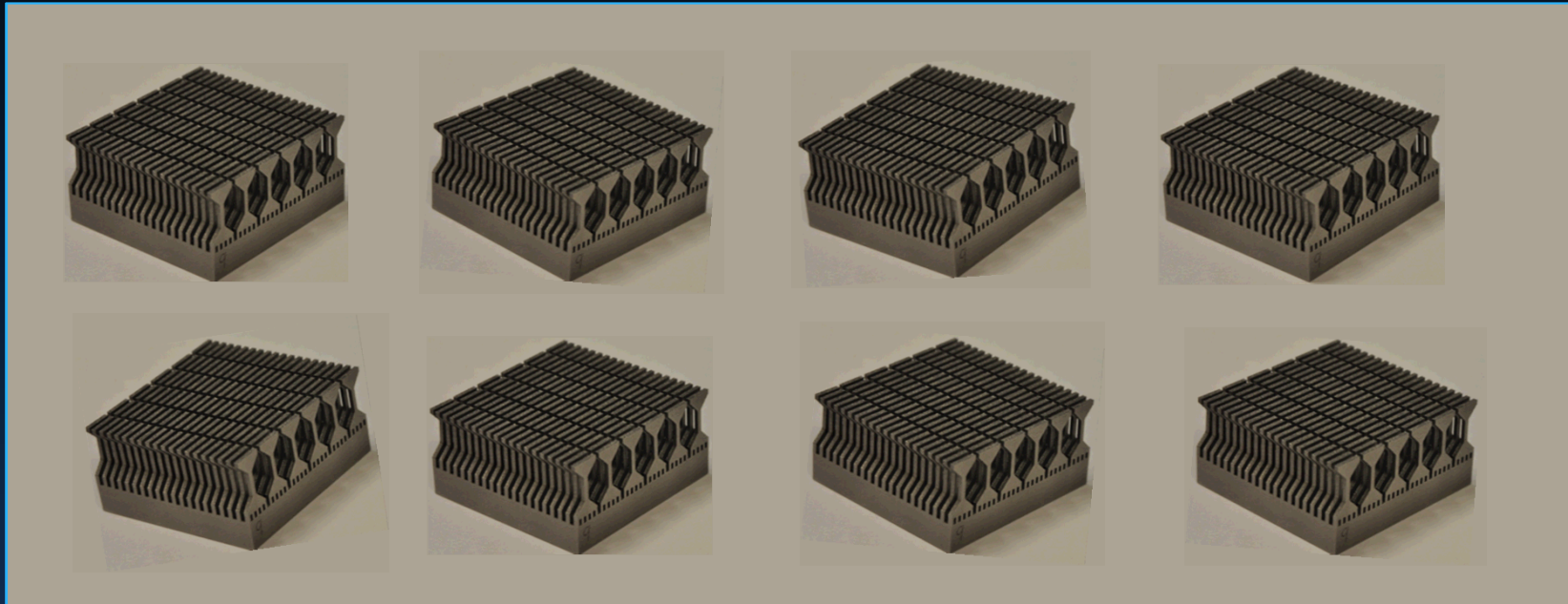
| | Tin | Nitrogen | Molybdenum | Iron |
|--|-----------|-----------|------------|------|
| | NS | NS | 0.05 Max. | |
| | 0 | 0.023 | 0.28 | |
| | 0.02 Max. | 0.05 Max. | NS | |
| | 0 | 0.056 | 0.045 | |
| | 0 | 0.15 | 0.17 | |

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Slide 21

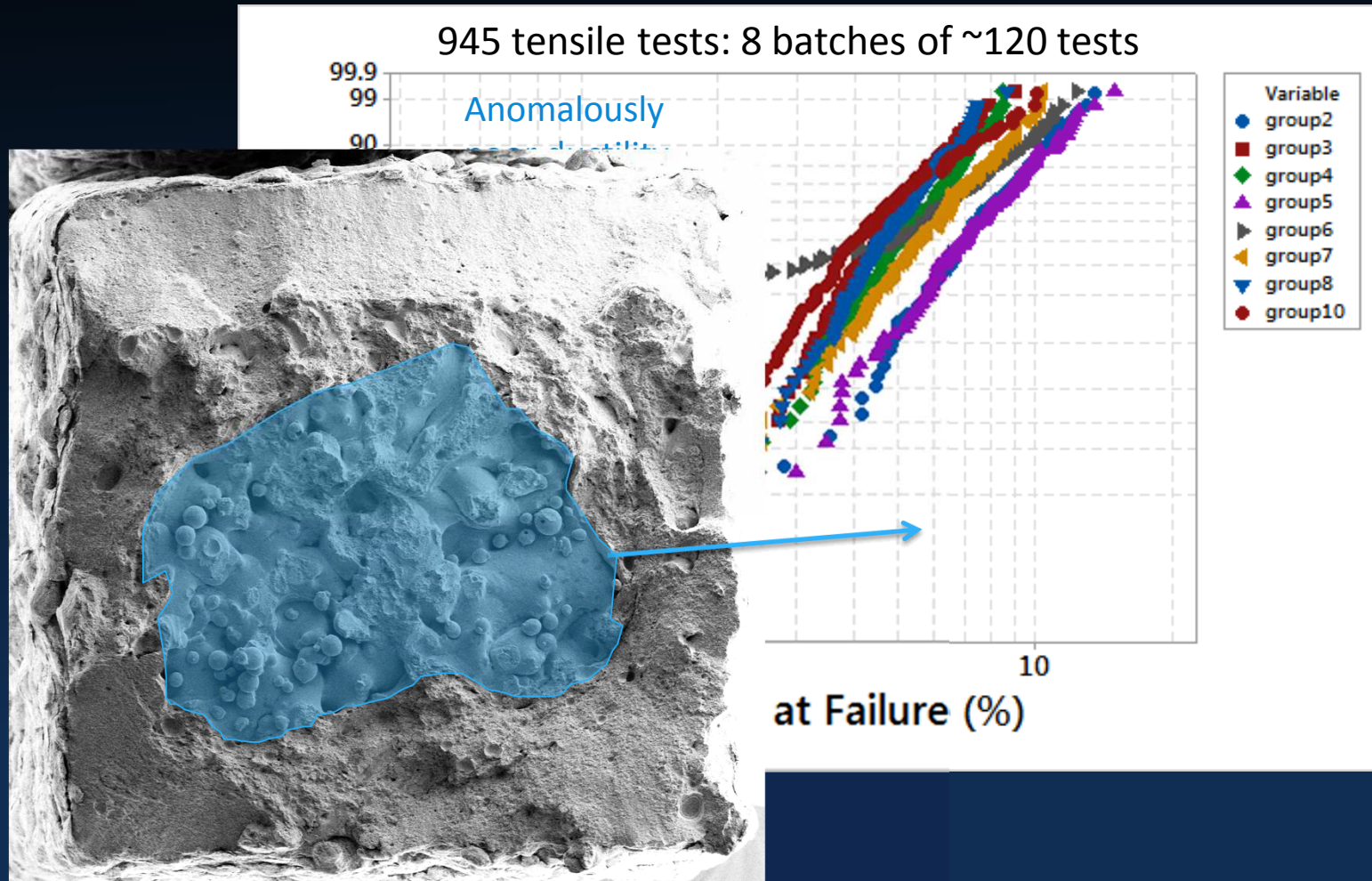
How consistent are 8 separate builds of the same 'cooling fin' from the same vendor?



(960 tensile bars!)

Distributions from 8 nominally identical cooling fins (Vendor 1)

10/24/2012
10:00:00 AM
10/24/2012

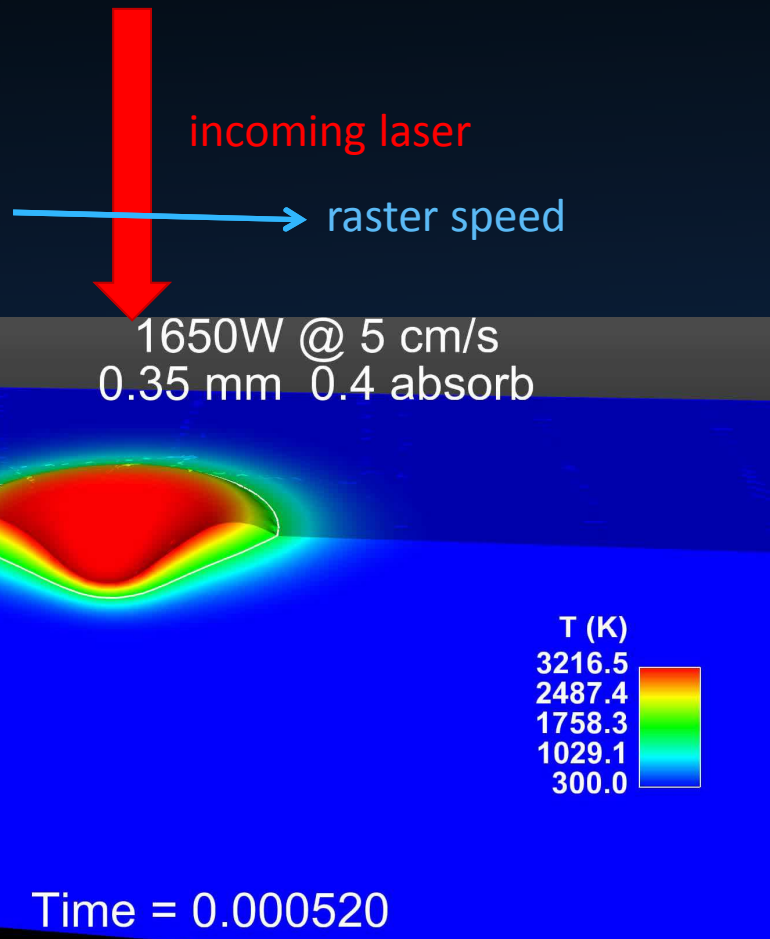


Why such poor ductility in one build???

How do we fix this?



→ Understand and control the sources of flaw formation

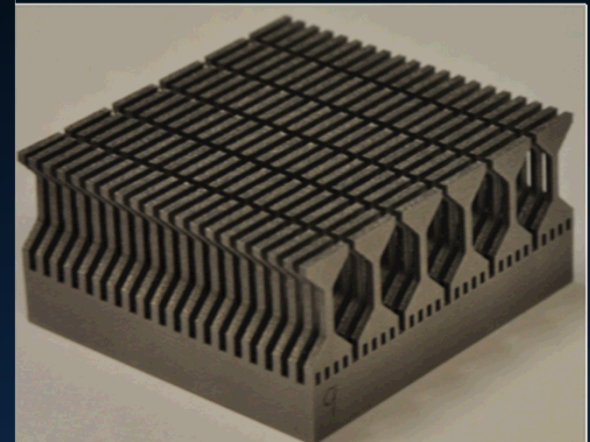


- Laser/plume interactions, raytracing
- Plasma fluid mechanics
- Radiation heat transfer
- Laser energy adsorption
- Thermal expansion
- Non-equilibrium vapor pressure
- Evaporation with latent heat
- Pressure-temperature relations
- T-dependent heat capacity
- Incompressible fluid dynamics
- Convective/conductive 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

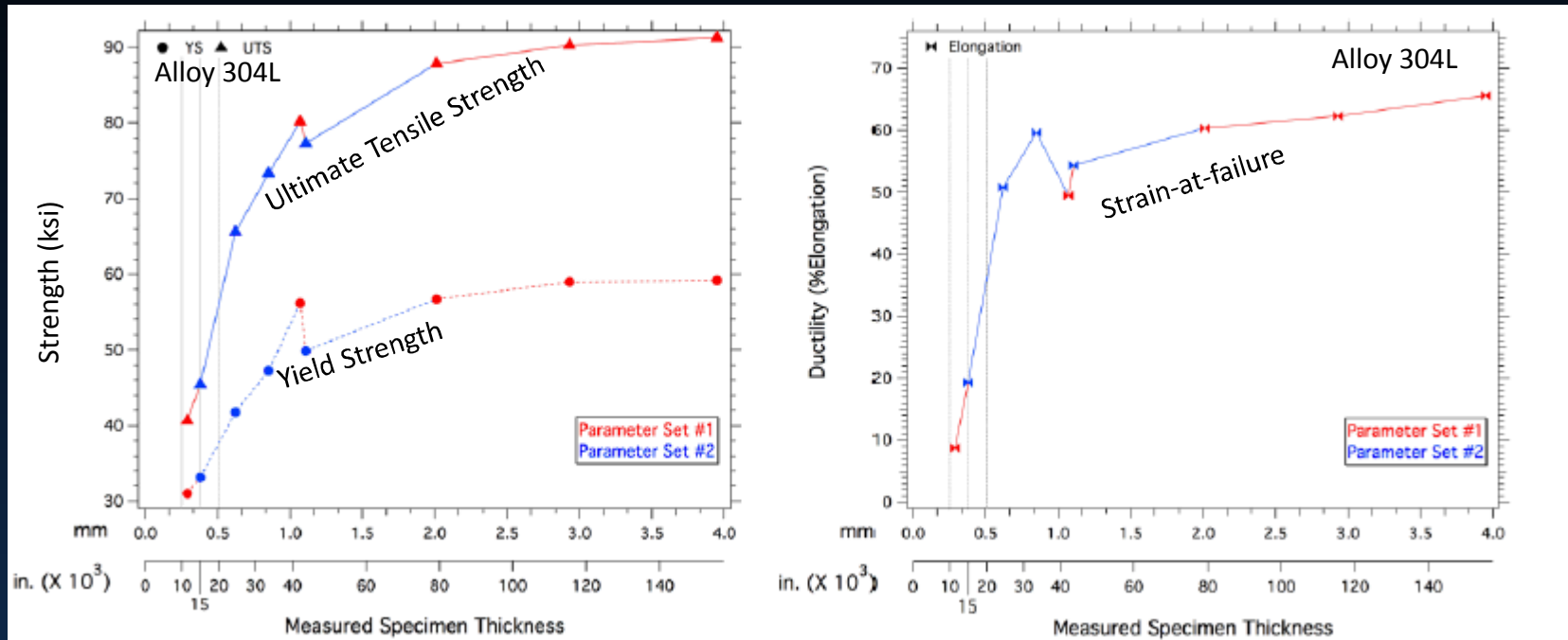
Summary...

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.

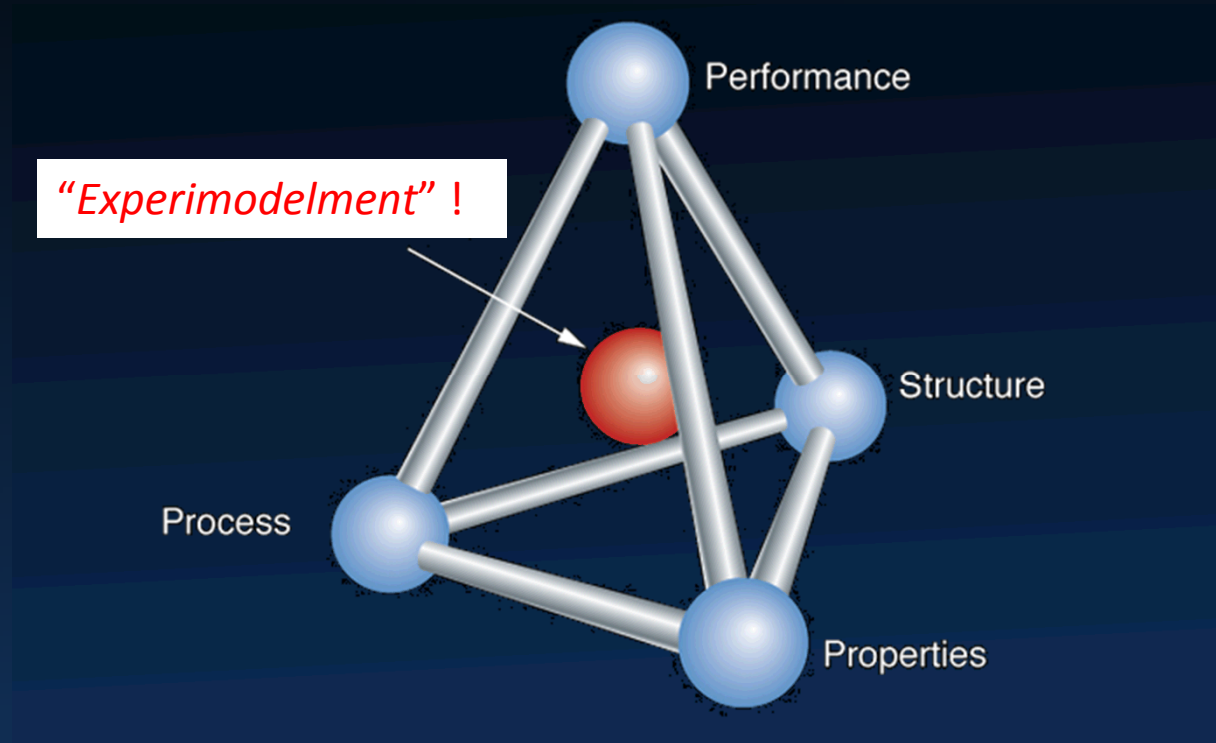


Future work...

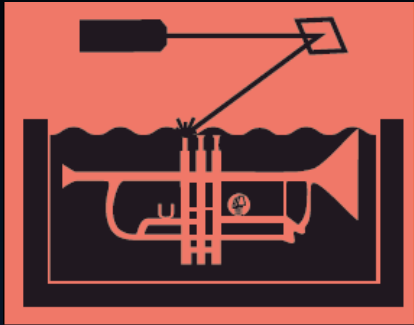


How does sample thickness affect defect populations and resulting property distributions?

What is the origin of different properties?

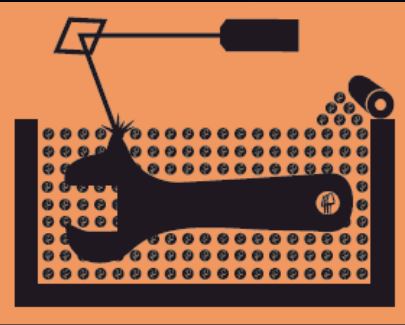


8 Families of AM Processes (ASTM F2794)



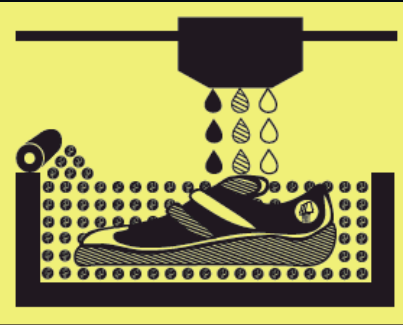
VAT
PHOTOPOLYMERIZATION

Alternative Names:
SLA™ - Stereolithography Apparatus
DLP™ - Digital Light Processing
3SP™ - Scan, Spin, and Selectively Photocure
CLIP™ - Continuous Liquid Interface Production



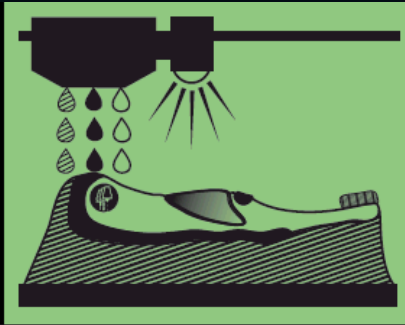
POWDER BED
FUSION (PBF)

Alternative Names:
SLS™ - Selective Laser Sintering; DMLS™ - Direct Metal Laser Sintering; SLM™ - Selective Laser Melting; EBM™ - Electron Beam Melting; SHS™ - Selective Heat Sintering;



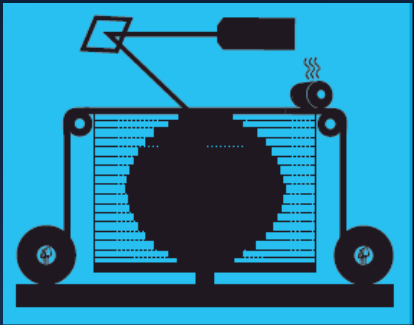
BINDER
JETTING

Alternative Names:
3DP™ - 3D Printing
ExOne
Voxeljet



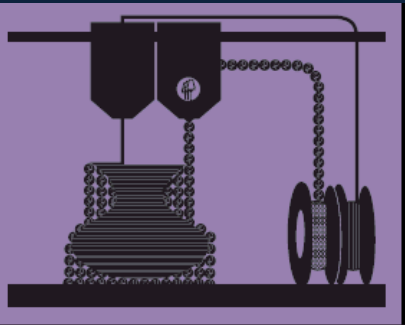
MATERIAL
JETTING

Alternative Names:
PolyJet™
SCP™ - Smooth Curvatures Printing
MJM - Multi-Jet Modeling
ProJet™



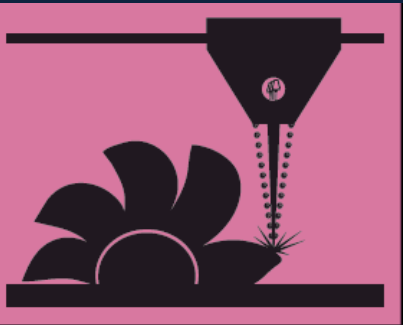
SHEET
LAMINATION

Alternative Names:
LOM - Laminated Object Manufacture
SDL - Selective Deposition Lamination
UAM - Ultrasonic Additive Manufacturing



MATERIAL
EXTRUSION

Alternative Names:
FFF - Fused Filament Fabrication
FDM™ - Fused Deposition Modeling



DIRECTED ENERGY
DEPOSITION (DED)

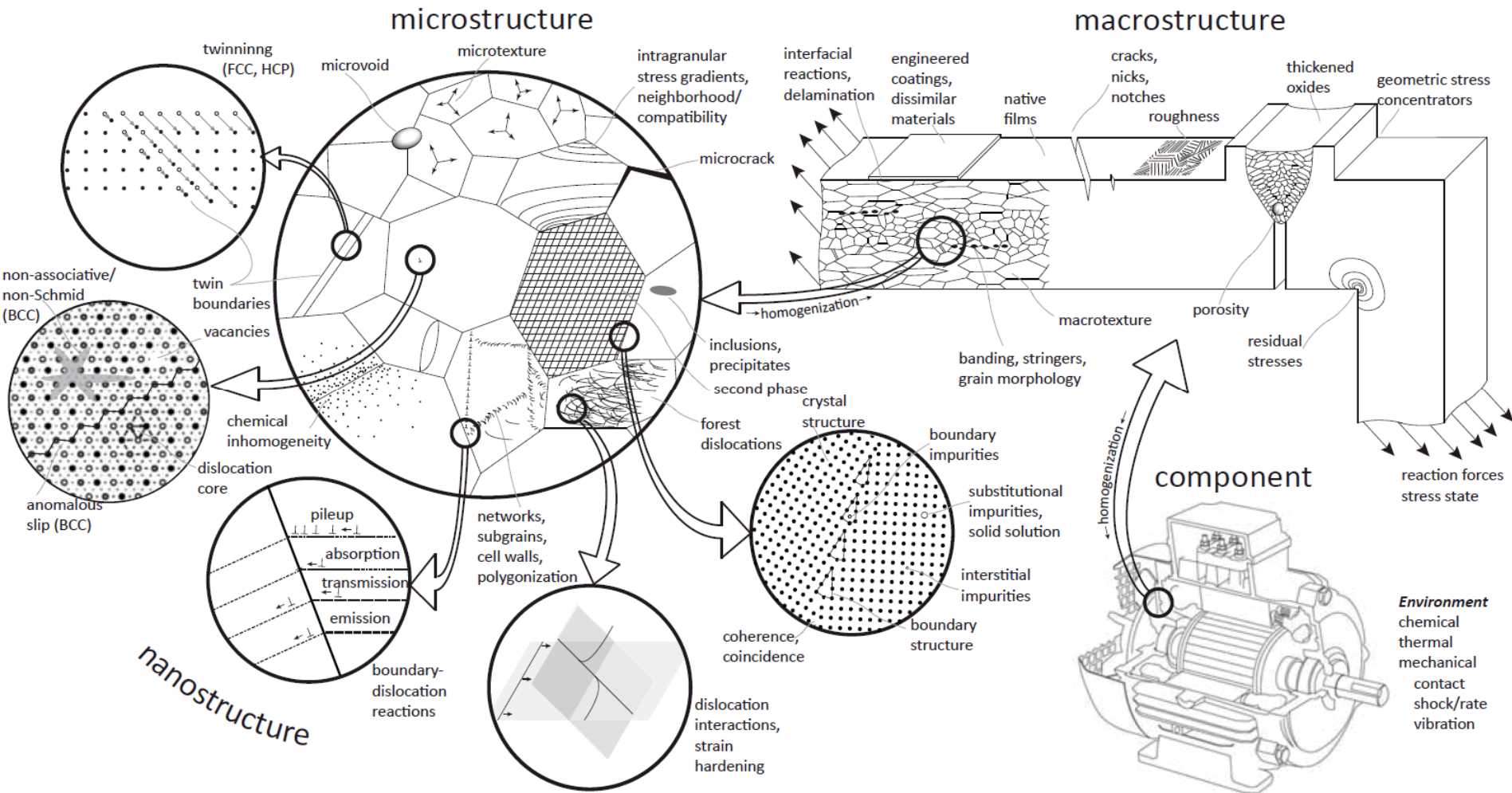
Alternative Names:
LMD - Laser Metal Deposition
LENS™ - Laser Engineered Net Shaping
DMD™ - Direct Metal Deposition



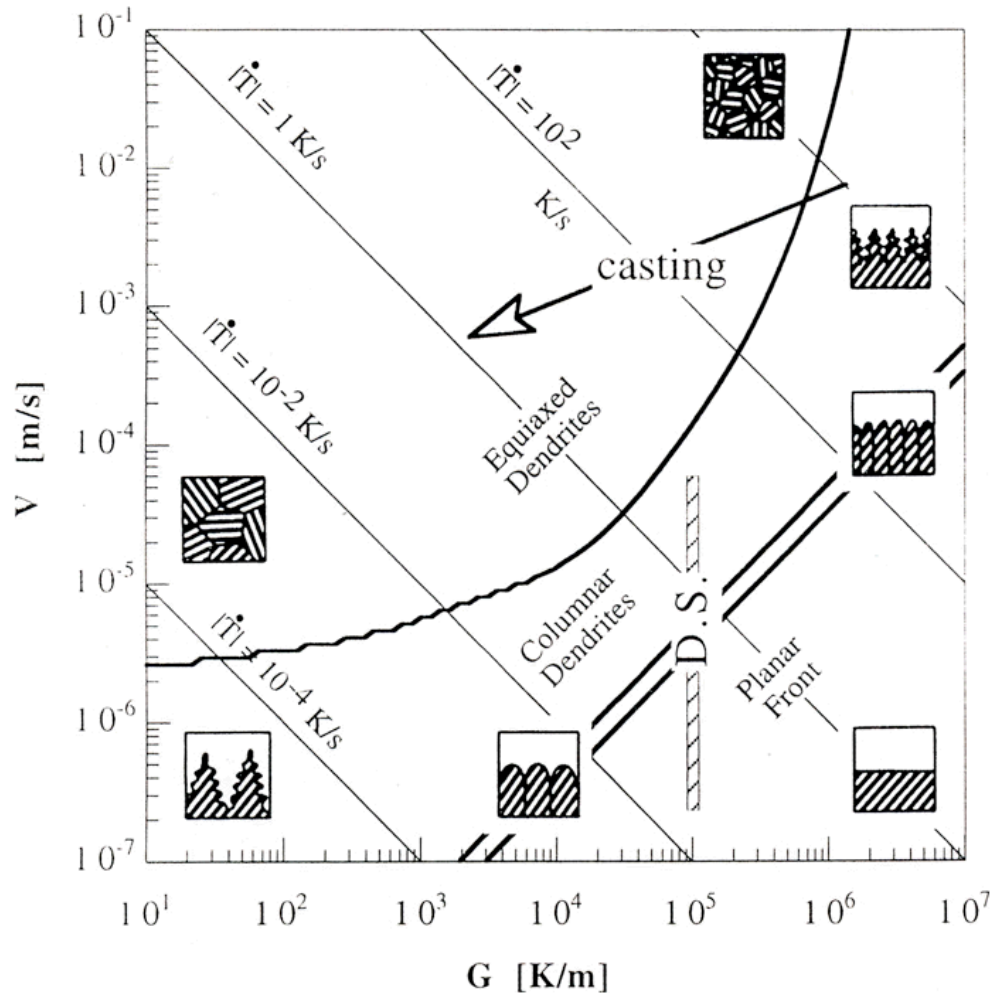
HYBRID

Alternative Names:
AMBIT™ - Created by Hybrid Manufacturing Technologies

What is the origin of different properties?



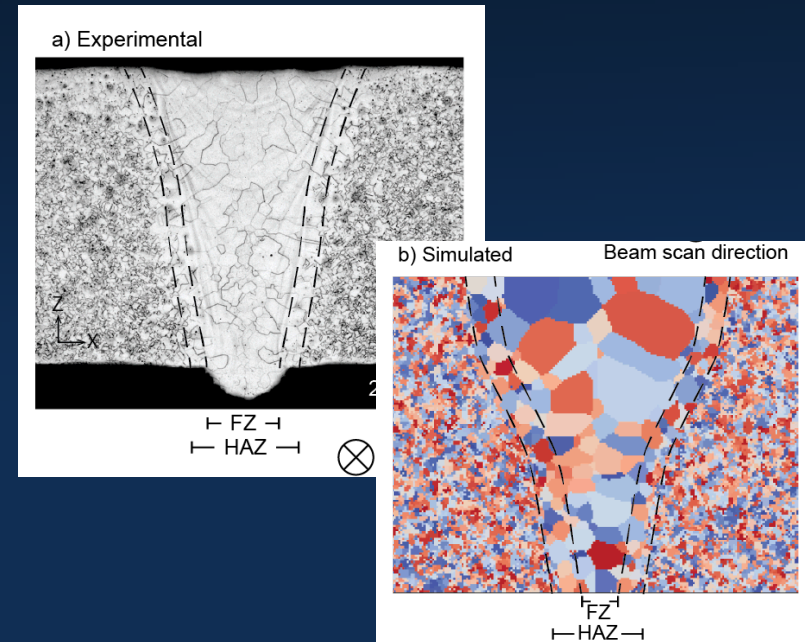
Ultimate goal: Predict solidification microstructure



Potts Kinetic Monte Carlo

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

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

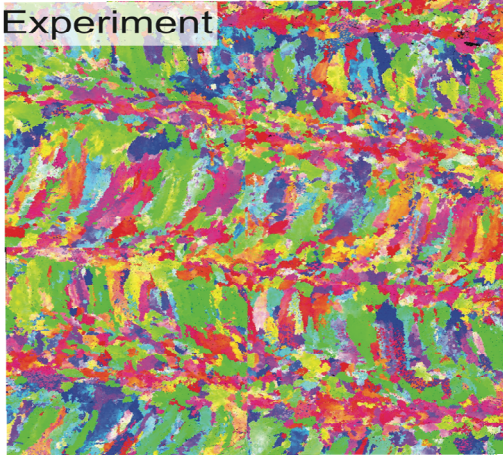


Capturing complex solidification microstructure

3.8 kW EBSD results

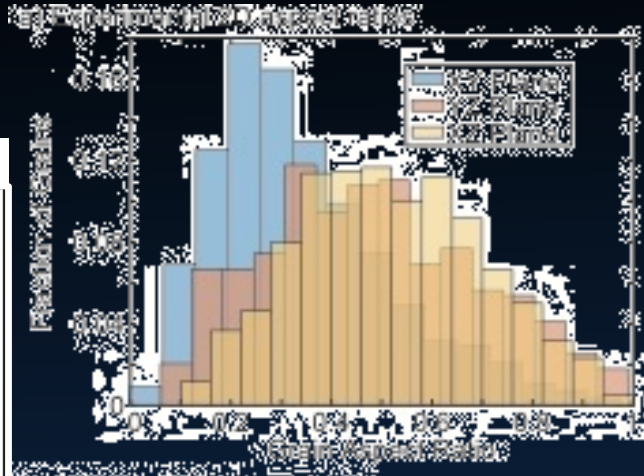
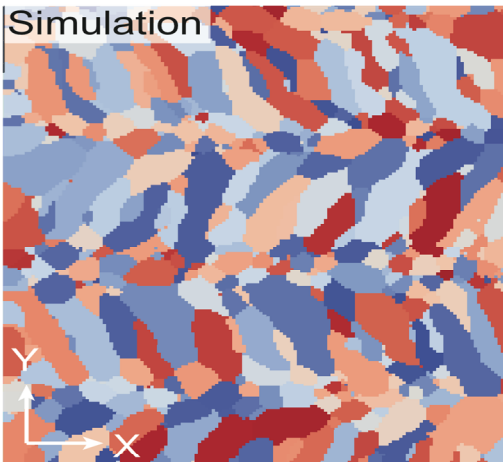
XY Plane

Experiment

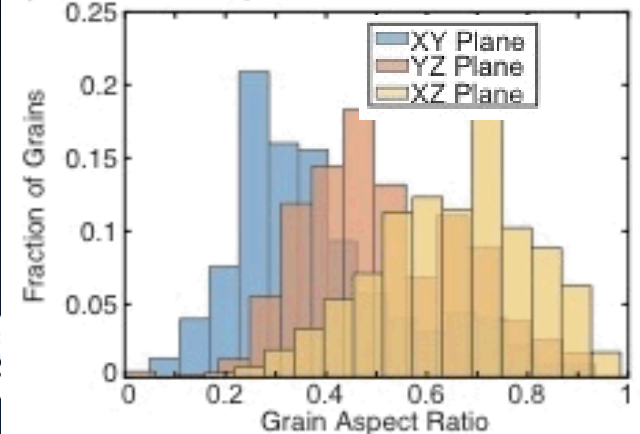


1.0 mm

Simulation



b) Simulated 2D aspect ratios



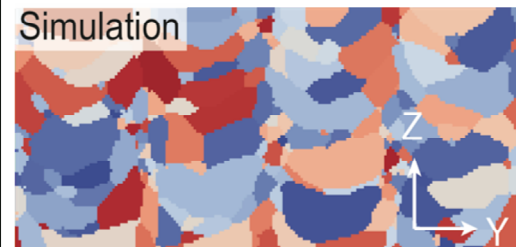
YZ Plane

Experiment



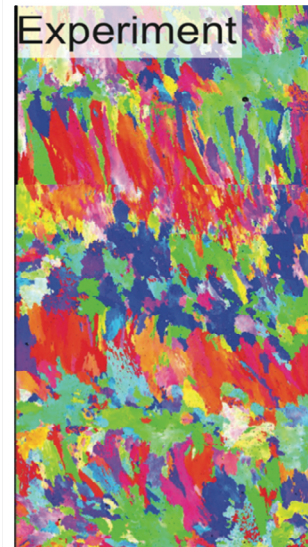
1.0 mm

Simulation



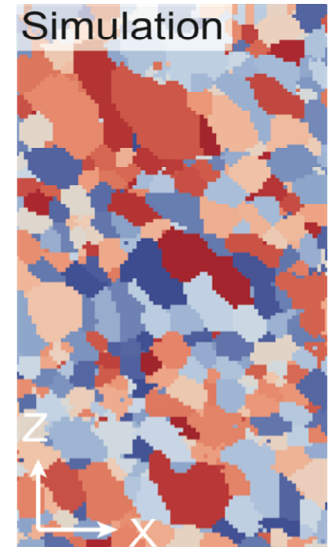
XZ Plane

Experiment

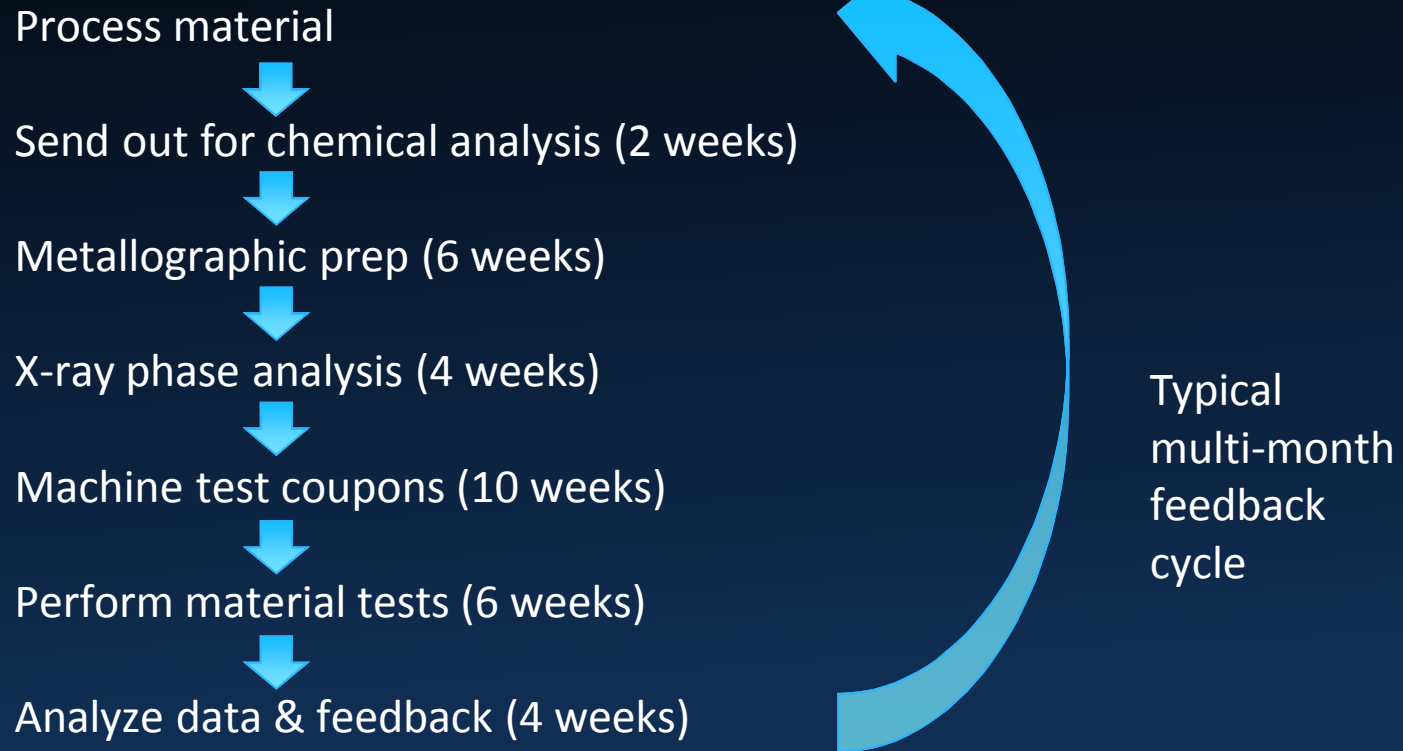


1.0 mm

Simulation



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

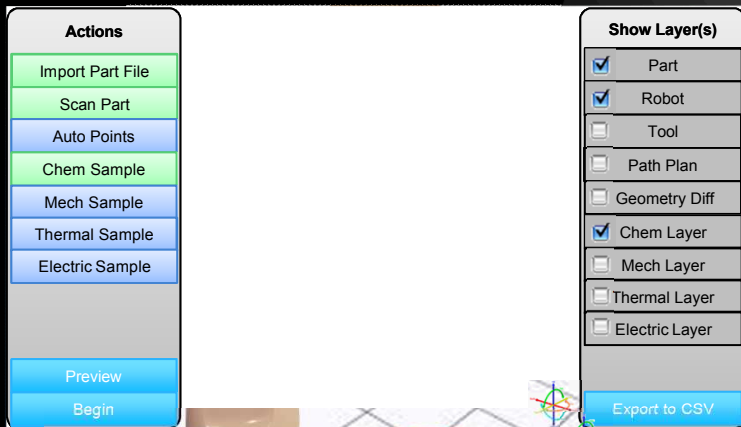


Properties 'Alinstante'

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

...

