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High-throughput testing reveals rare, catastrophic defects

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Operated By Lockheed Martin

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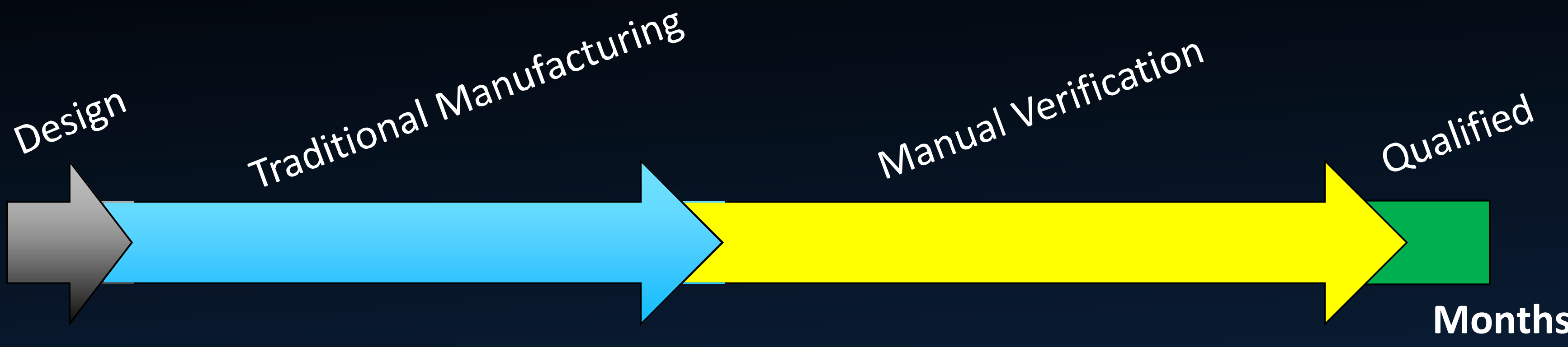
Changing timelines…



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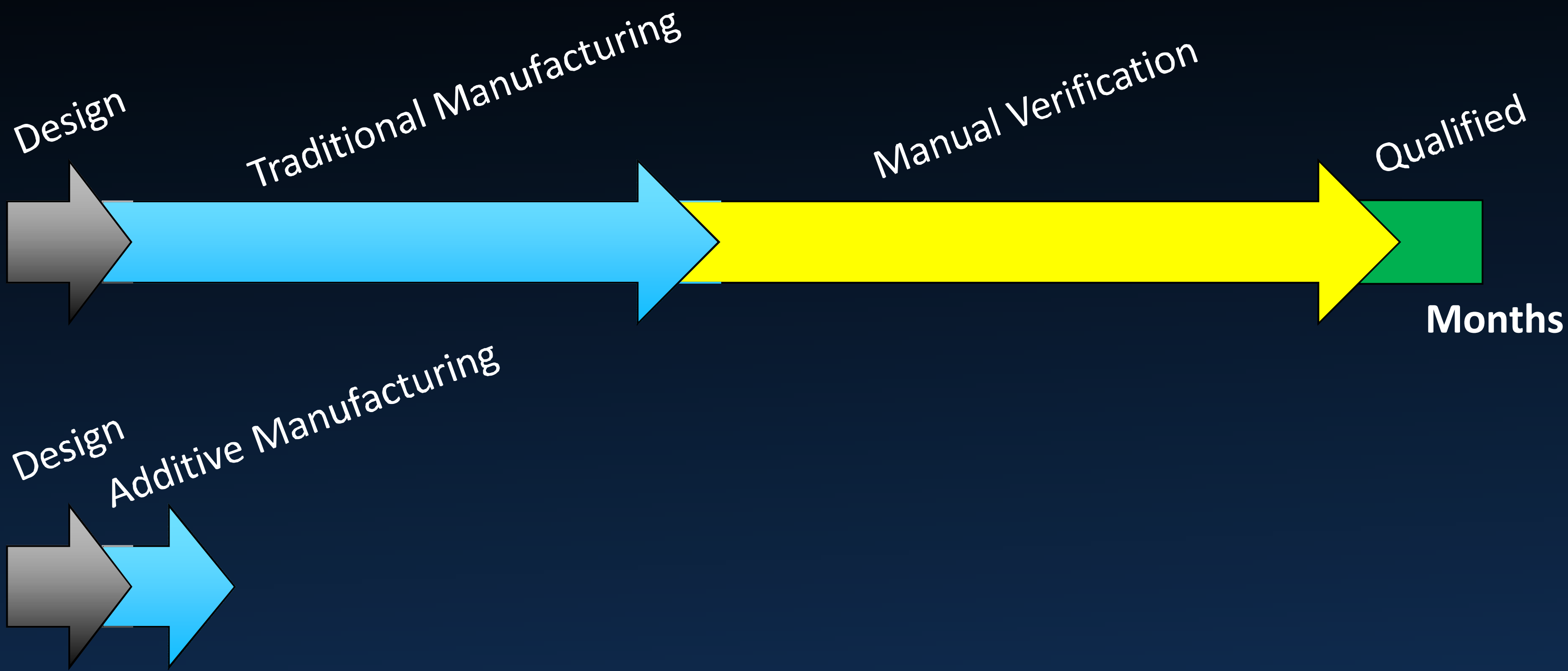

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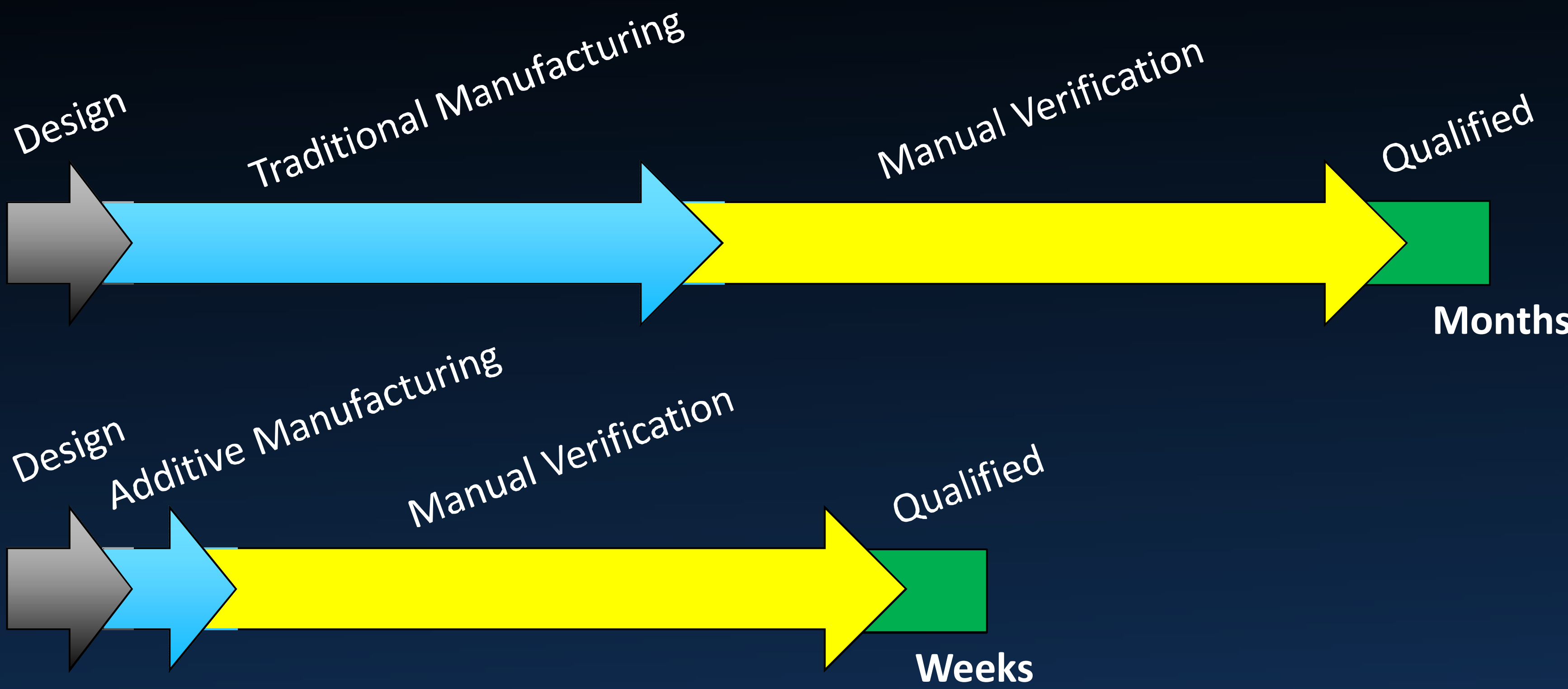

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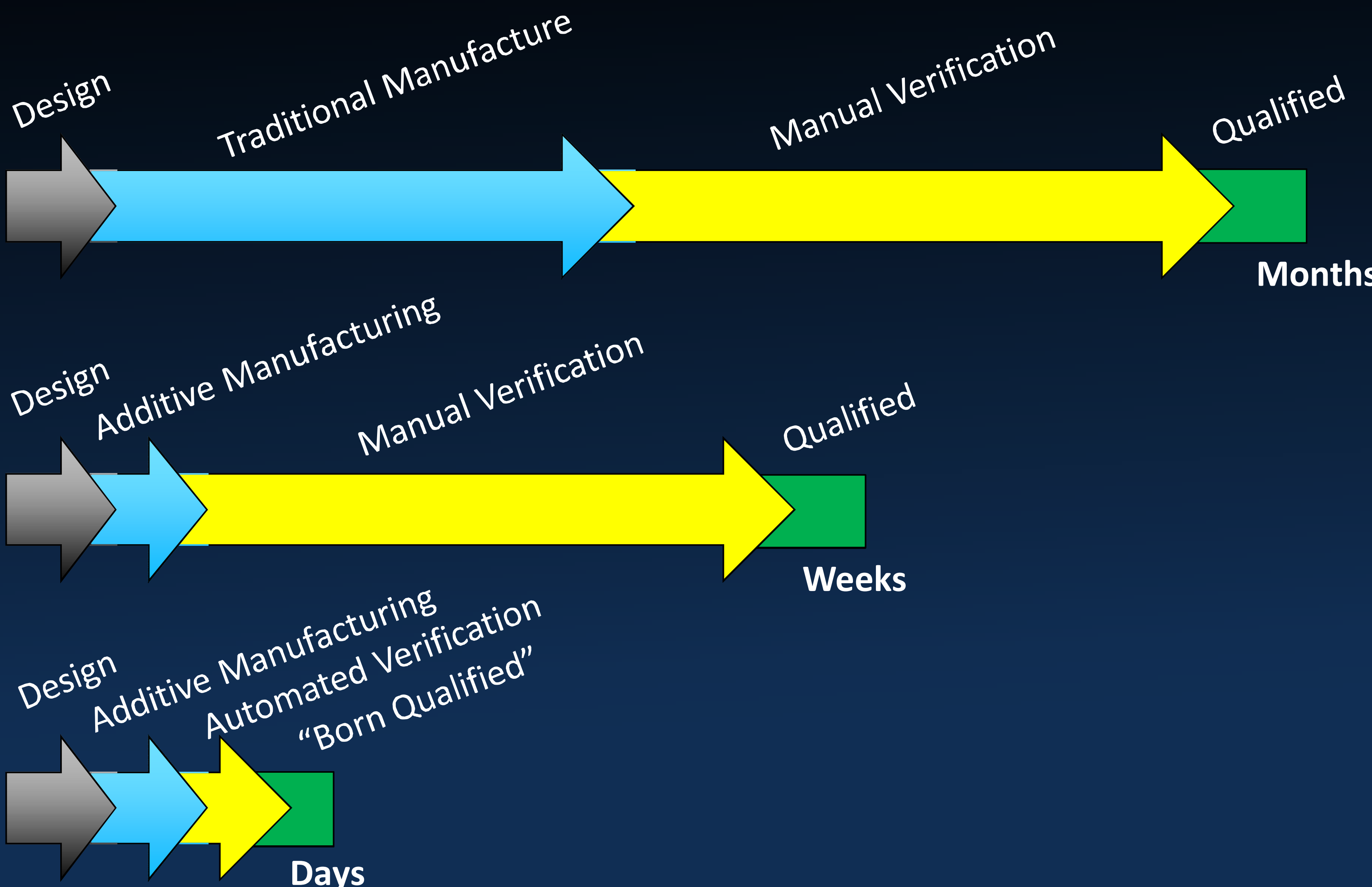
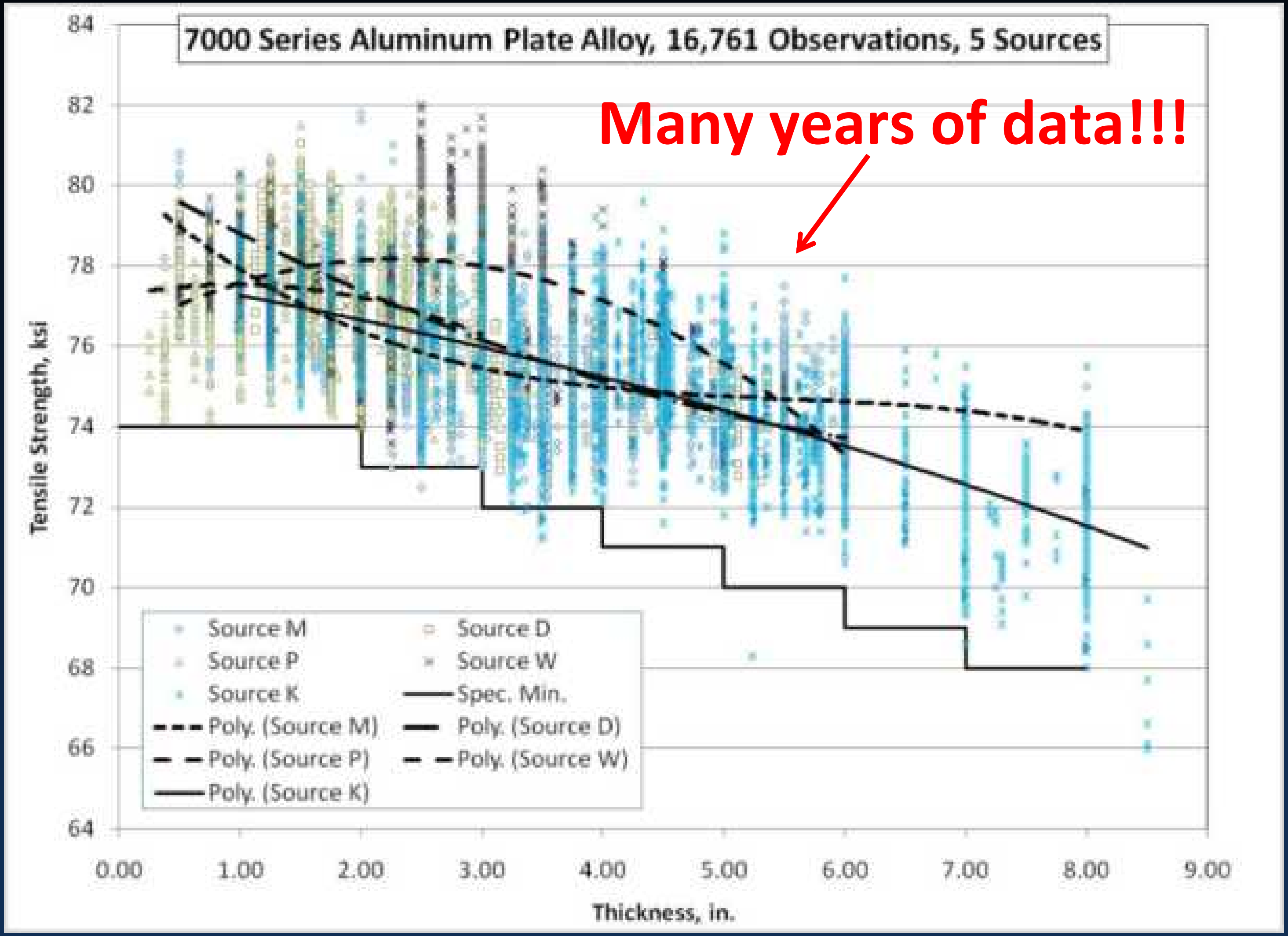
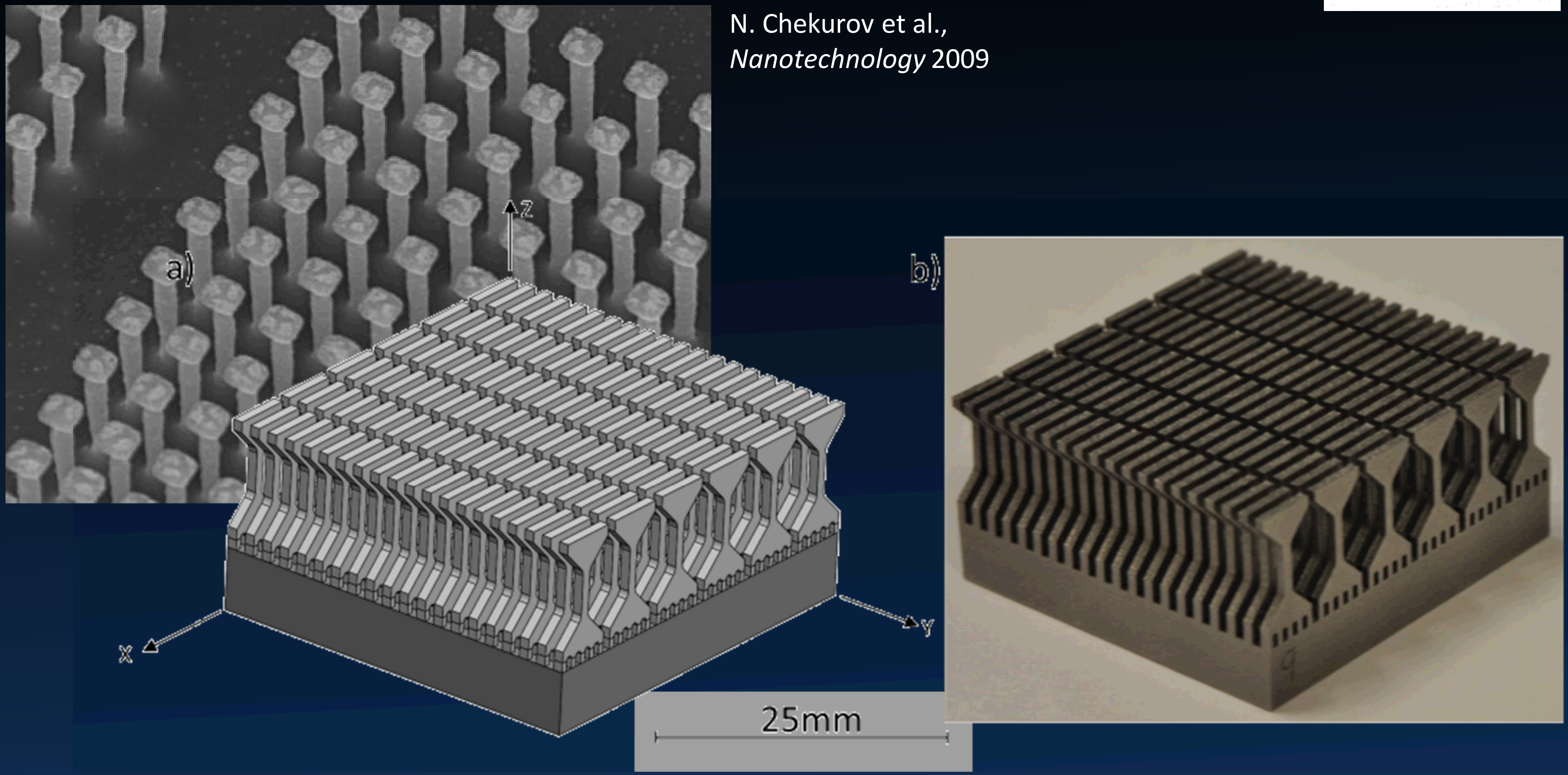


How conventional materials are qualified…



How can we rapidly qualify AM materials?

AM offers an opportunity for rapid statistics

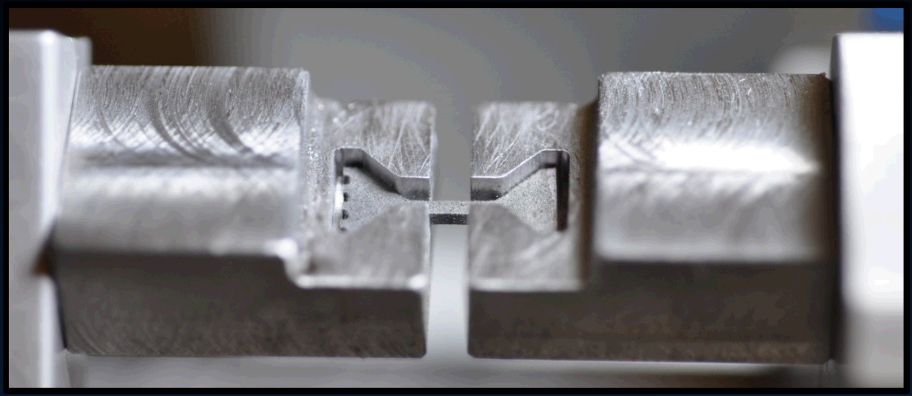


N. Chekurov et al., *Nanotechnology* 2009

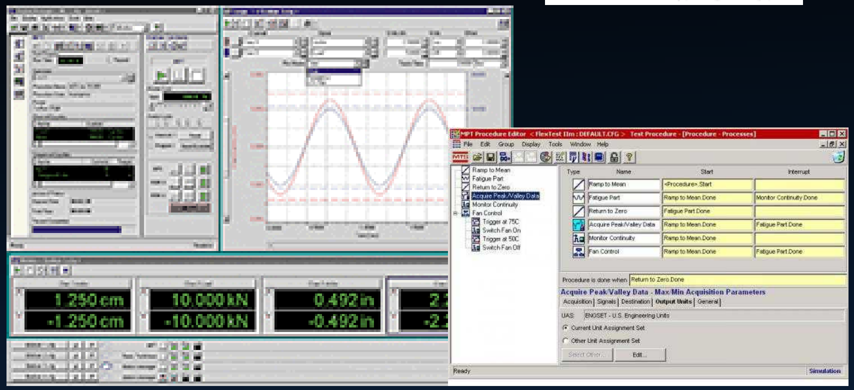
Not quite a material property test…
A standardized structural performance test

B. Salzbrenner et al., *J Mater. Process. Tech.*, 2017

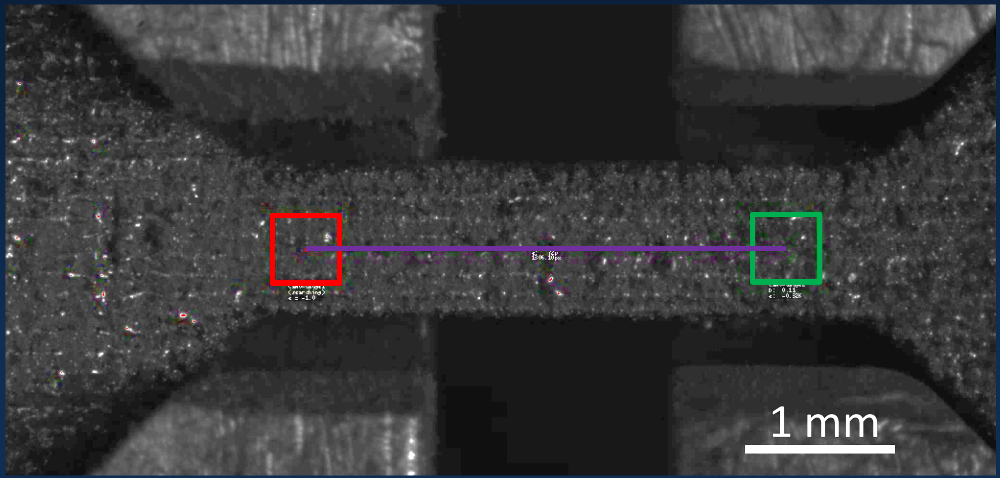
Streamline the testing process



1. Self-aligning ‘drop-in’ grips



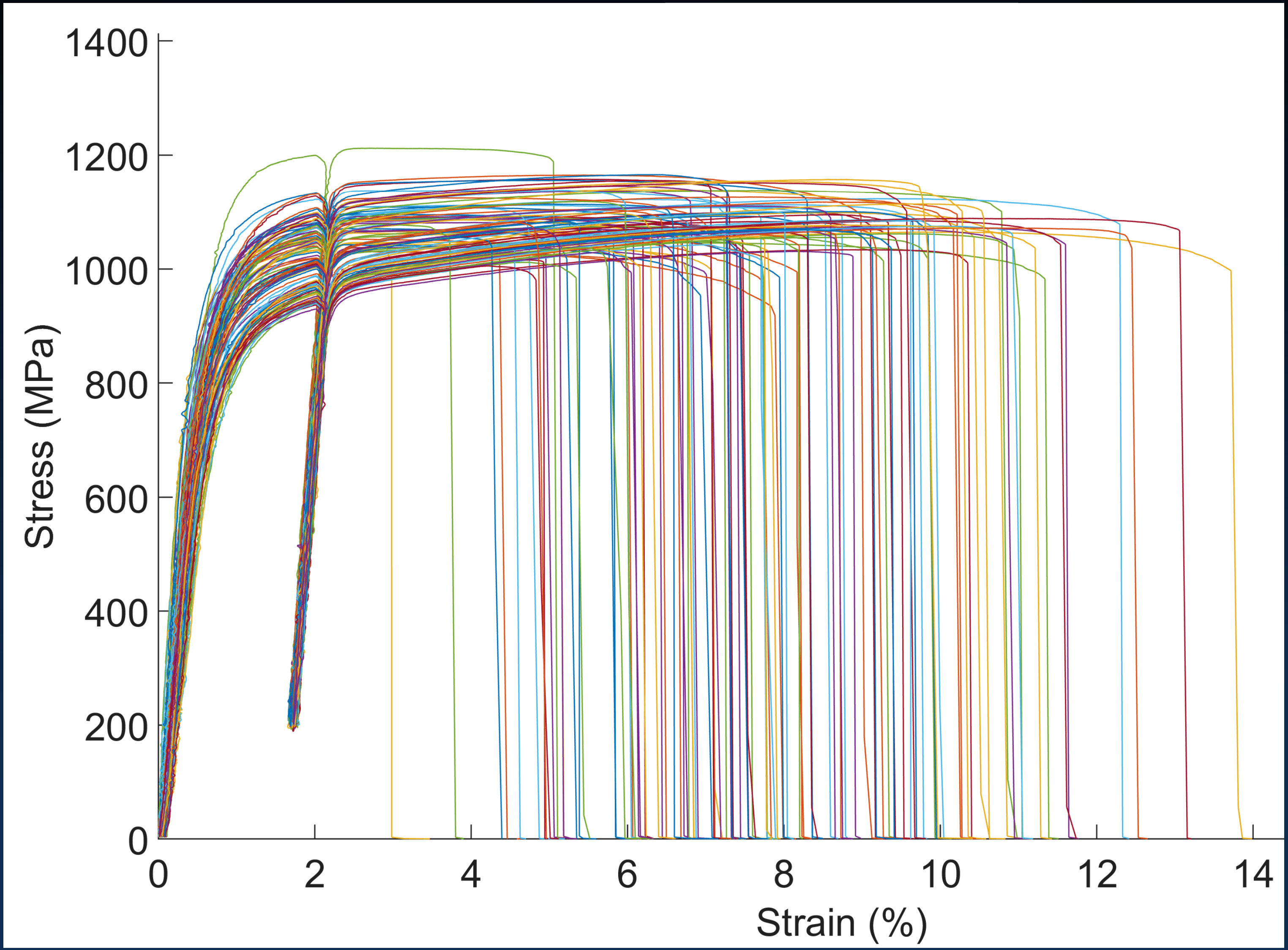
3. Maximize software automation to reduce burden on operator



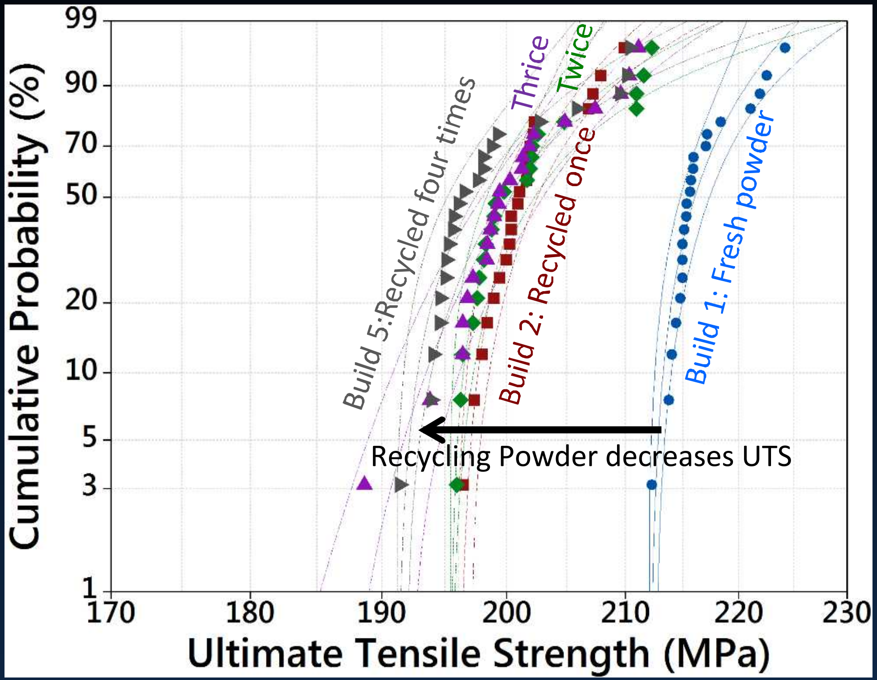
2. Non-contact virtual extensometer with “live” digital image correlation

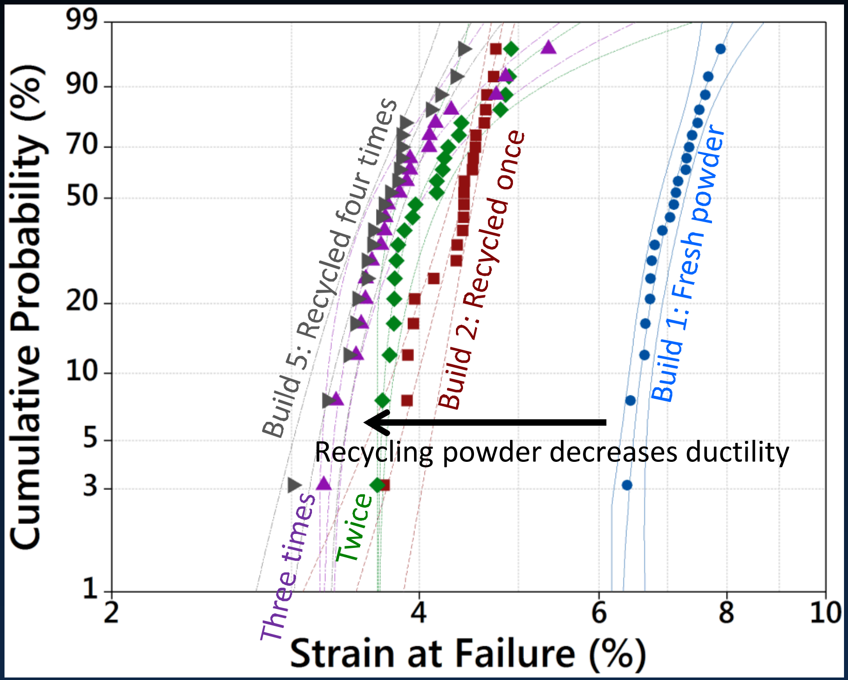
B. Salzbrenner et al., *J Mater. Process. Tech.*, 2017

100 tensile tests in 4 hours…



Rapid evaluation of powder reuse effects

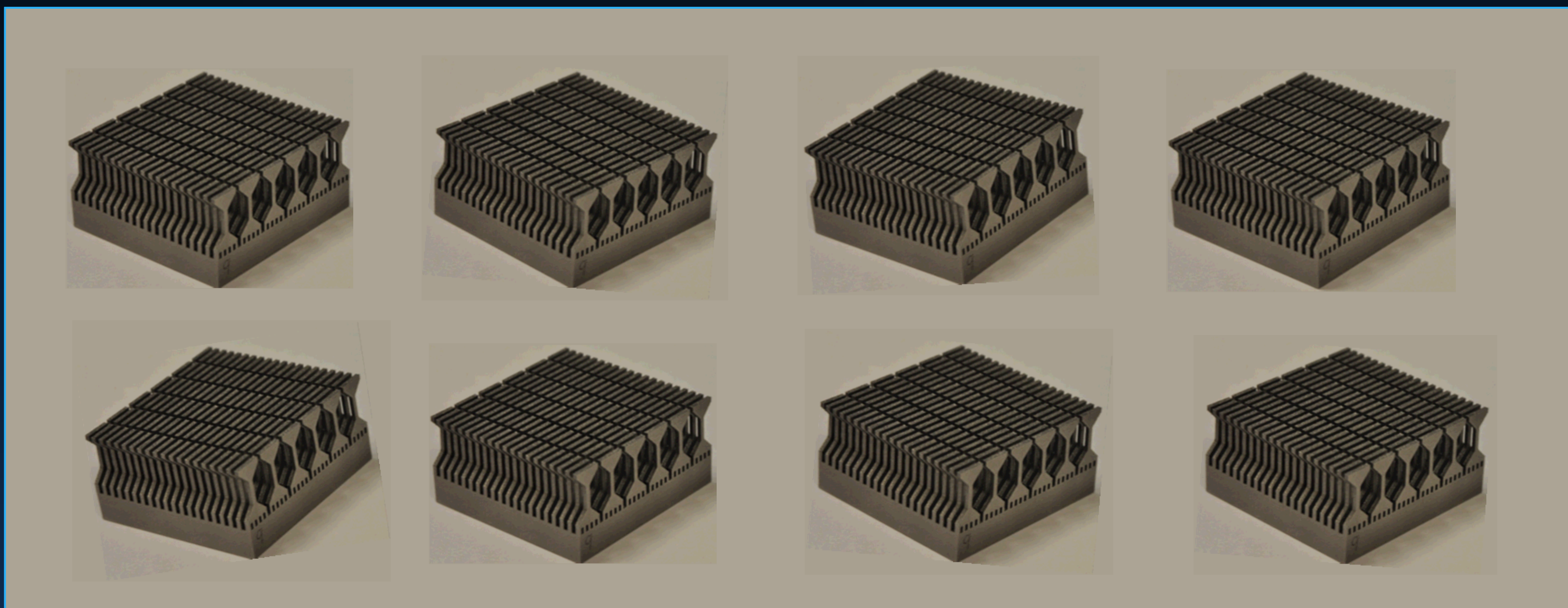




Al-Si-Mg Alloy, Renishaw

$$P_f = 1 - \exp\left[-\left(\frac{\sigma - \sigma_0}{\sigma_\theta - \sigma_0} \right)^m \right]$$

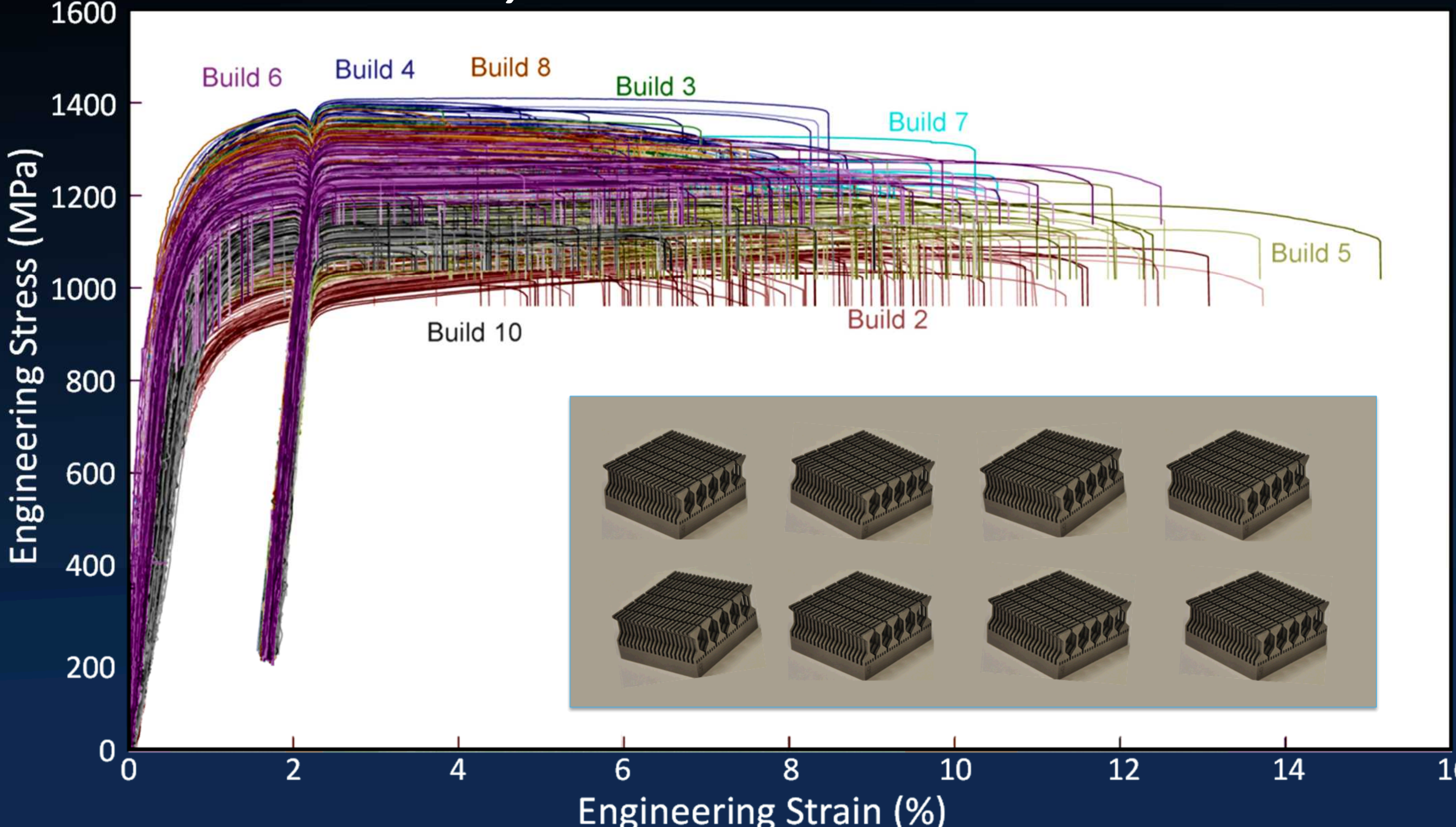
How consistent are 8 separate builds of the same 'cooling fin' from the same vendor?



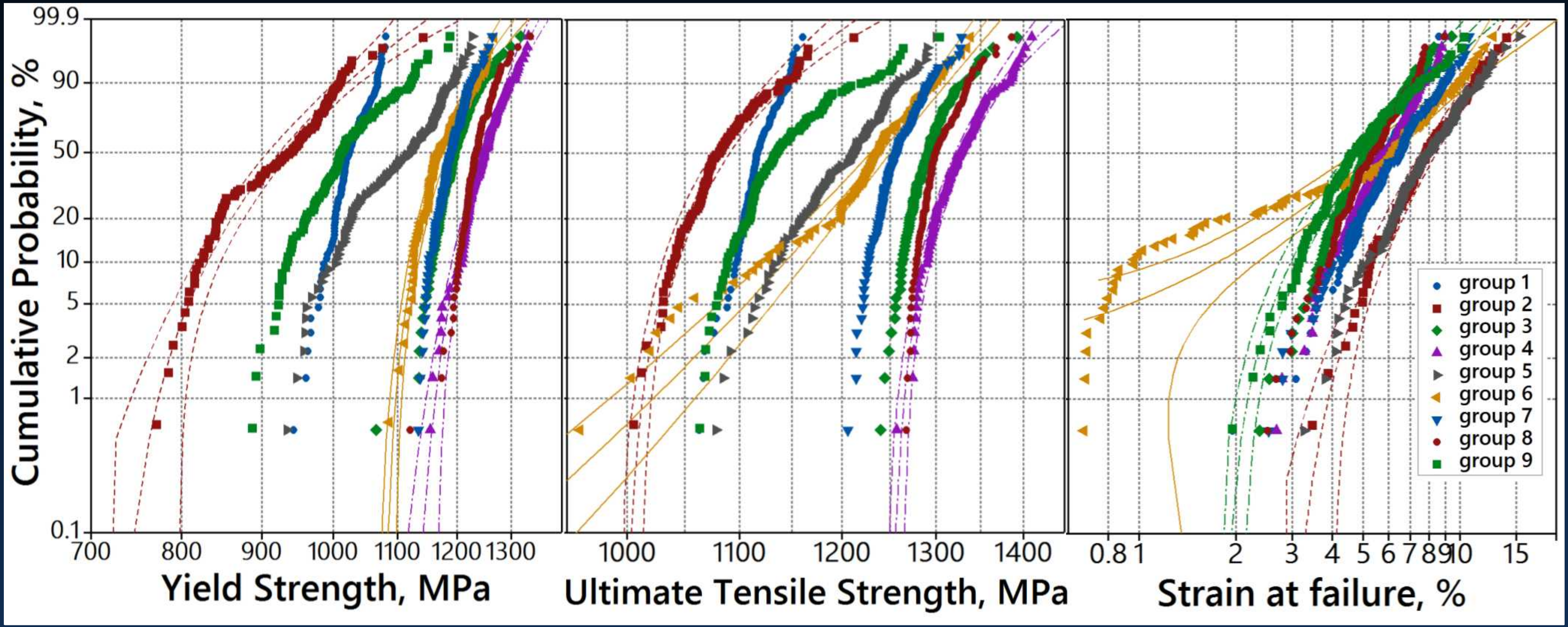
960 tensile bars, produced in 2 weeks for ~$10 each

Alloy: 17-4PH

"Big data"?: 945 tensile tests from 8 nominally identical builds

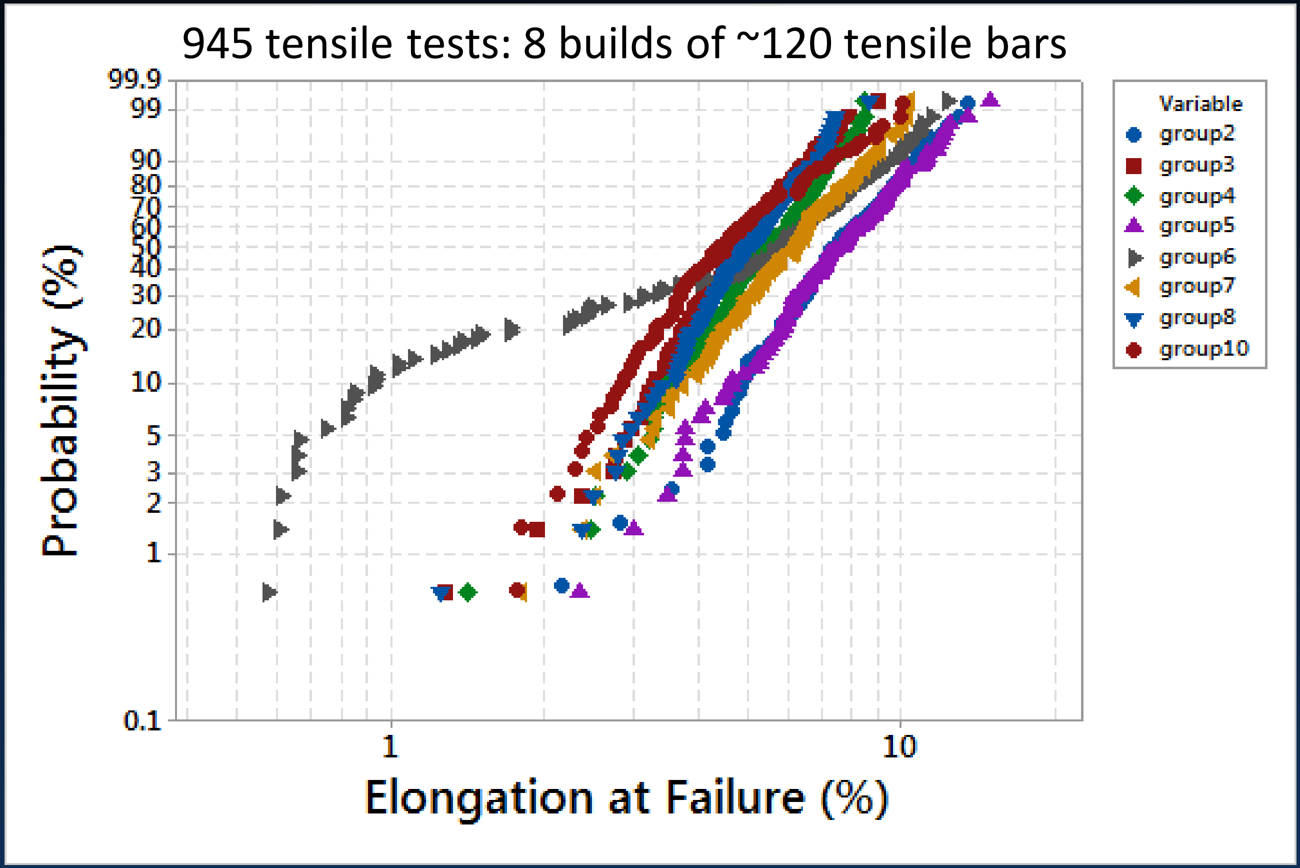


Weibull CDFs illuminate "within-build" and "between-build" variability

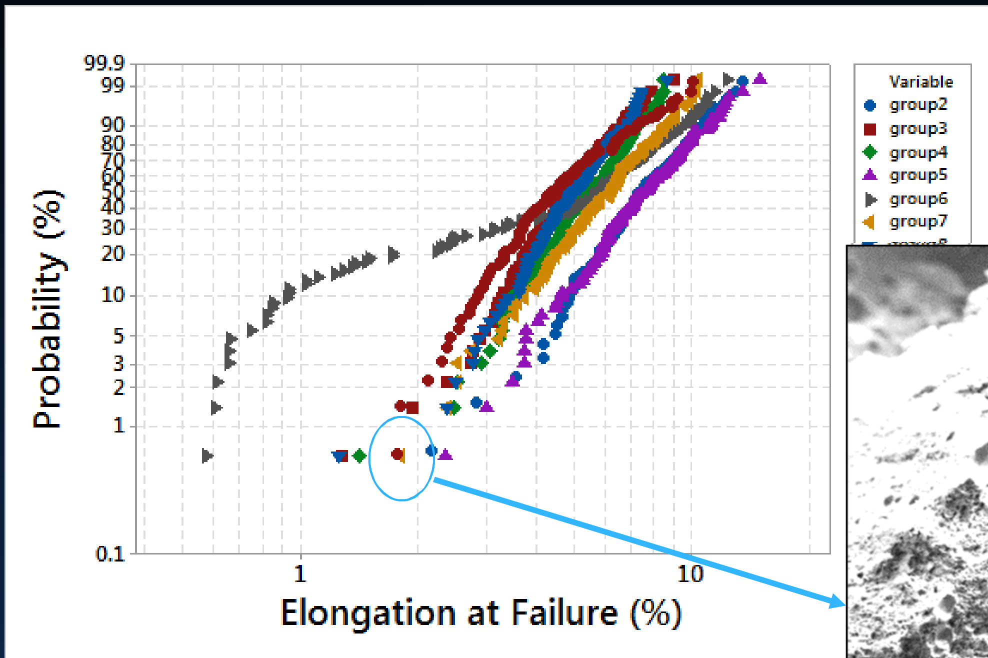


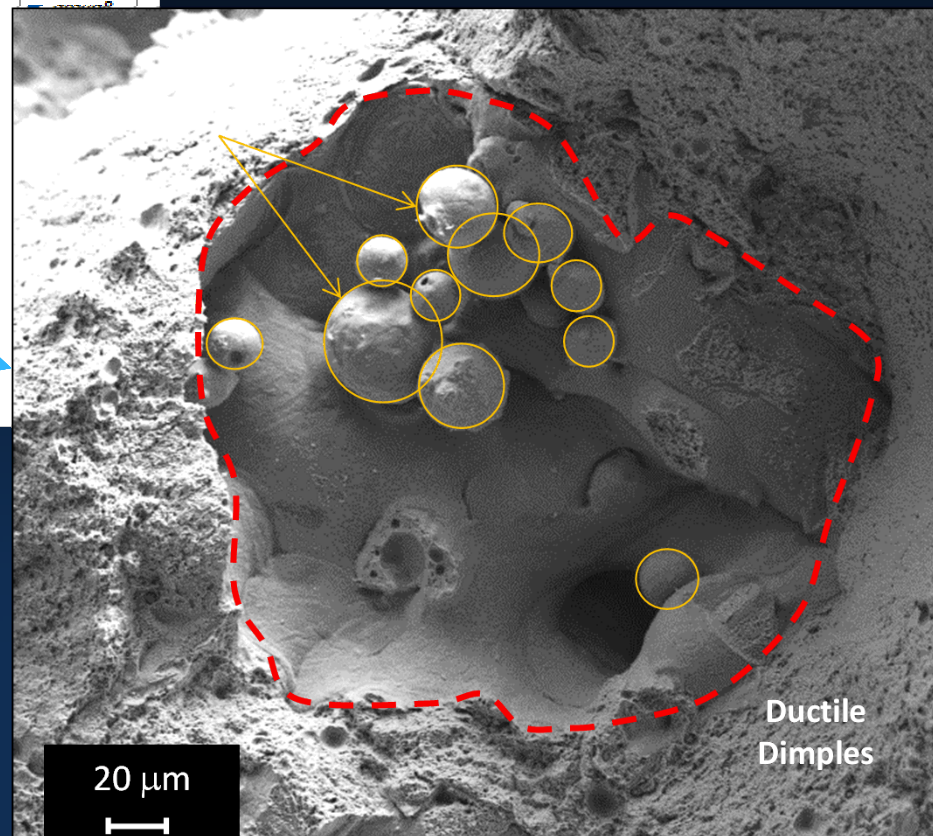
$$P_f = 1 - \exp\left[-\left(\frac{\sigma - \sigma_0}{\sigma_\theta - \sigma_0}\right)^m\right]$$

Unpacking the variation in ductility…



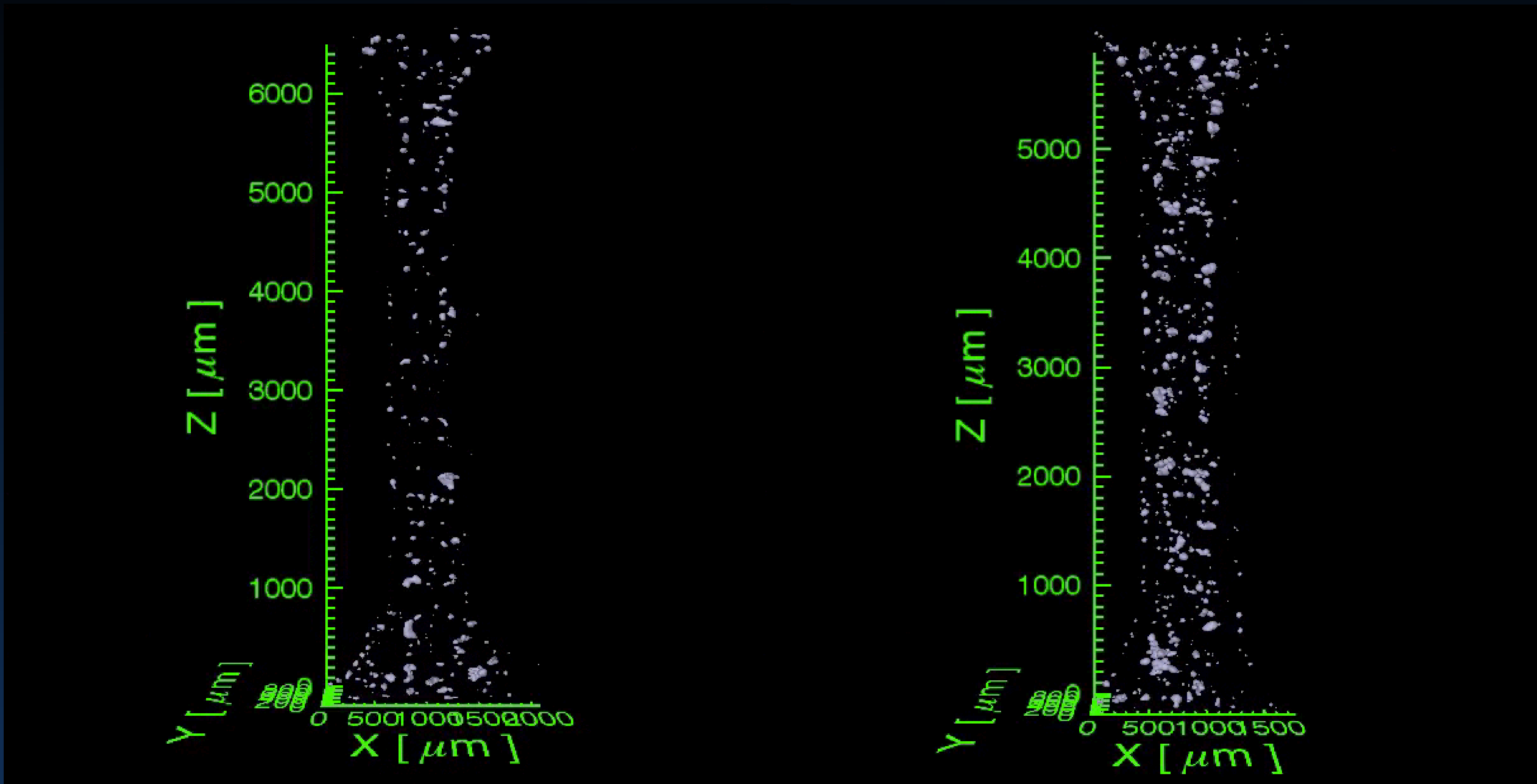
"Typical" Ductility-Limiting Flaws





Fractography is not high-throughput!

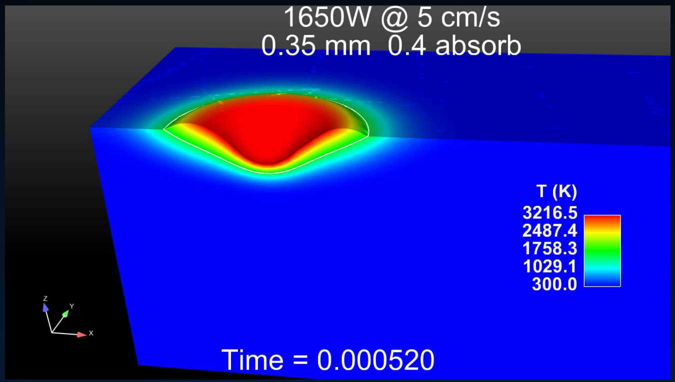
X-ray CT Scans are not high-throughput!

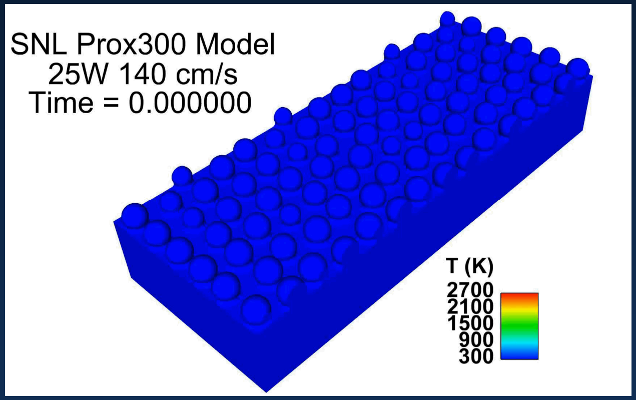


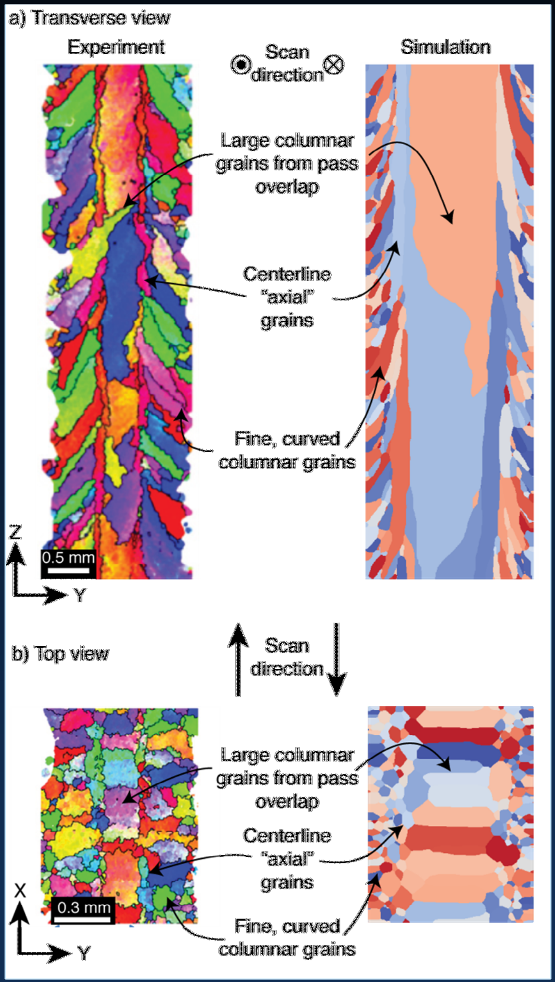
- 100 CT Scans ~ $30,000 and 3 months…
- Need high-throughput CT, in-process detection, or other inferrential detection method

Collaboration with J. Madison, O. Underwood

Modeling the AM solidification process





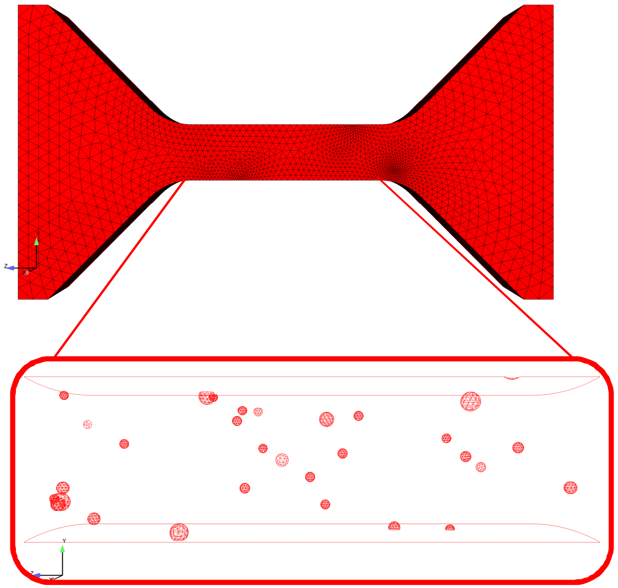


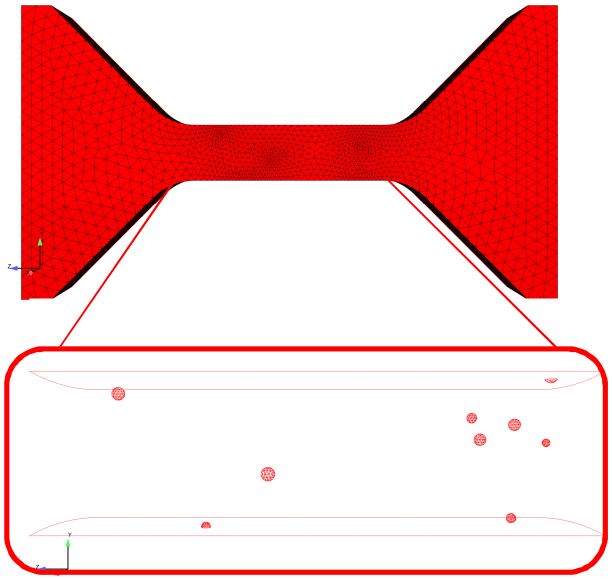
This is a **herculean** challenge

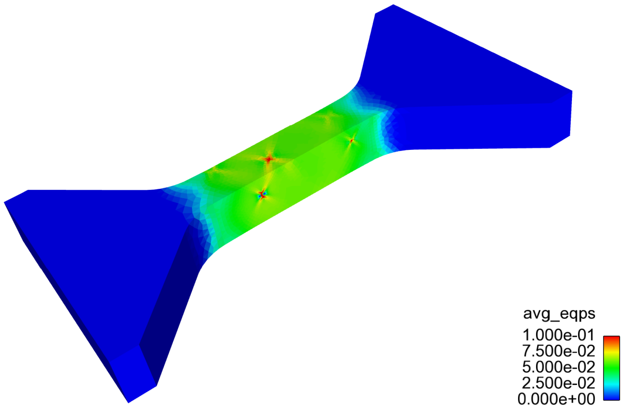
- Powder packing
- Laser/plume interactions
- Plasma fluid mechanics
- Radiation heat transfer
- Laser energy adsorption, radiation
- Thermal expansion
- Non-equilibrium vapor pressure
- Evaporation with latent heat
- Pressure-temperature relations
- T-dependent heat capacity
- Incompressible fluid dynamics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

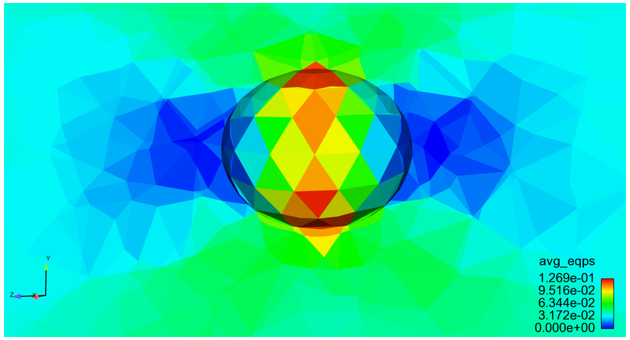
Finite Element Analysis of Porosity Effects



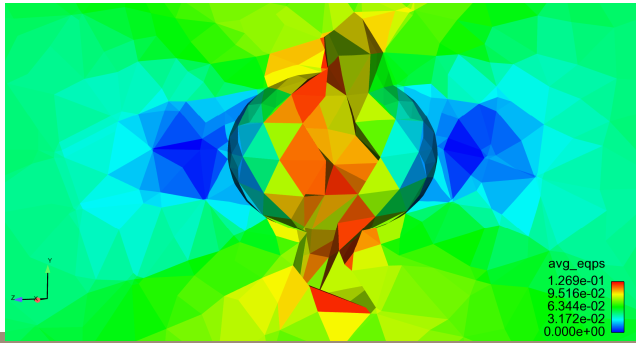




$$\dot{\phi} = \sqrt{\frac{3}{2}}\dot{\epsilon}_p \frac{1-(1-\phi)^{m+1}}{(1-\phi)^m} \sinh\left[\frac{2(2m-1)}{2m+1}\frac{\langle \frac{I_1}{3} \rangle}{\sqrt{3J_2}}\right]$$



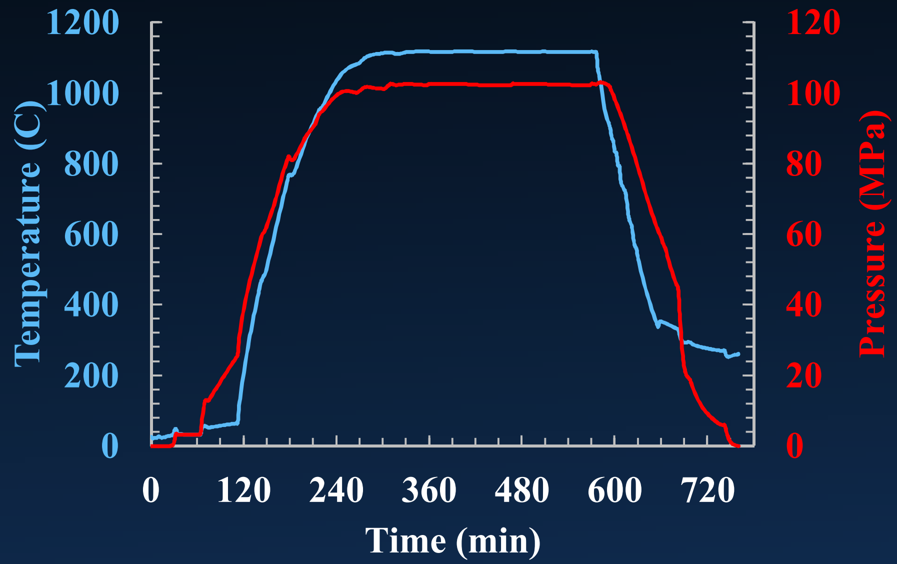
Hypothesis: process-induced defects will intensify and localize deformation, but that microscale void mechanisms will still ultimately lead to failure (decoupled scales).



Collaboration with J. Ostien

Hot Isostatic Press (HIP) Remediation

HIP Treatment: 1120°C, 100MPa for 6 hr



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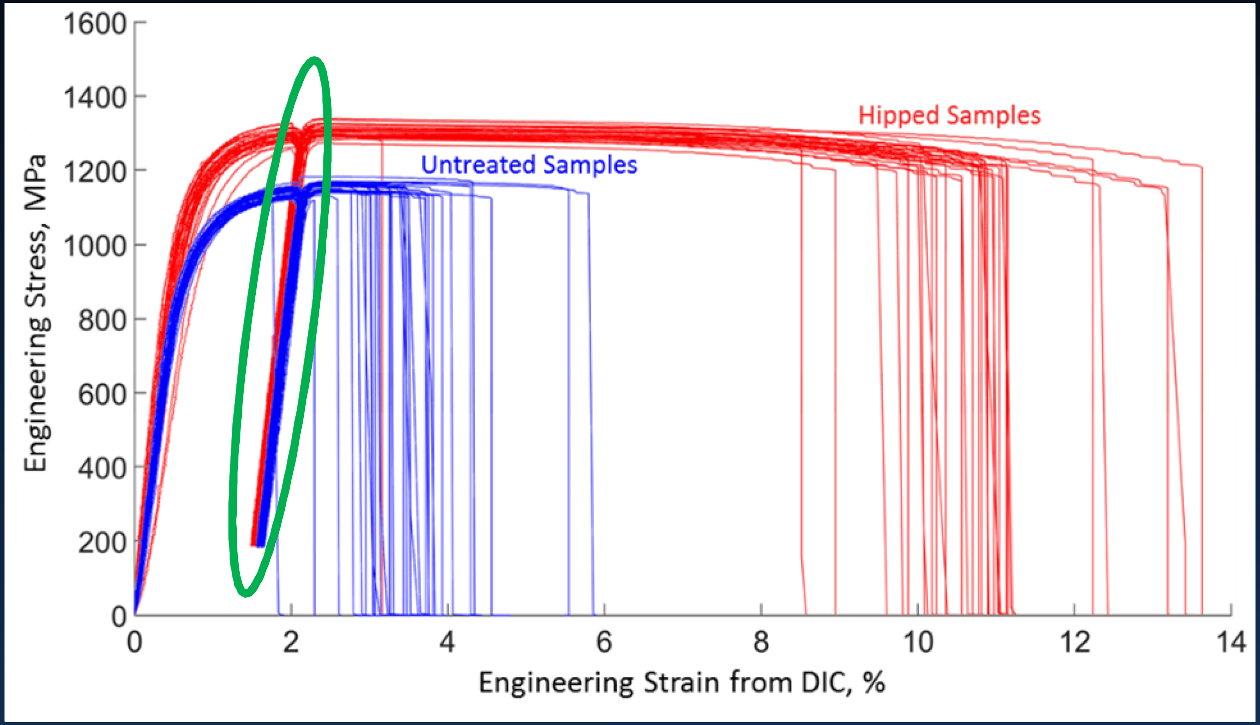


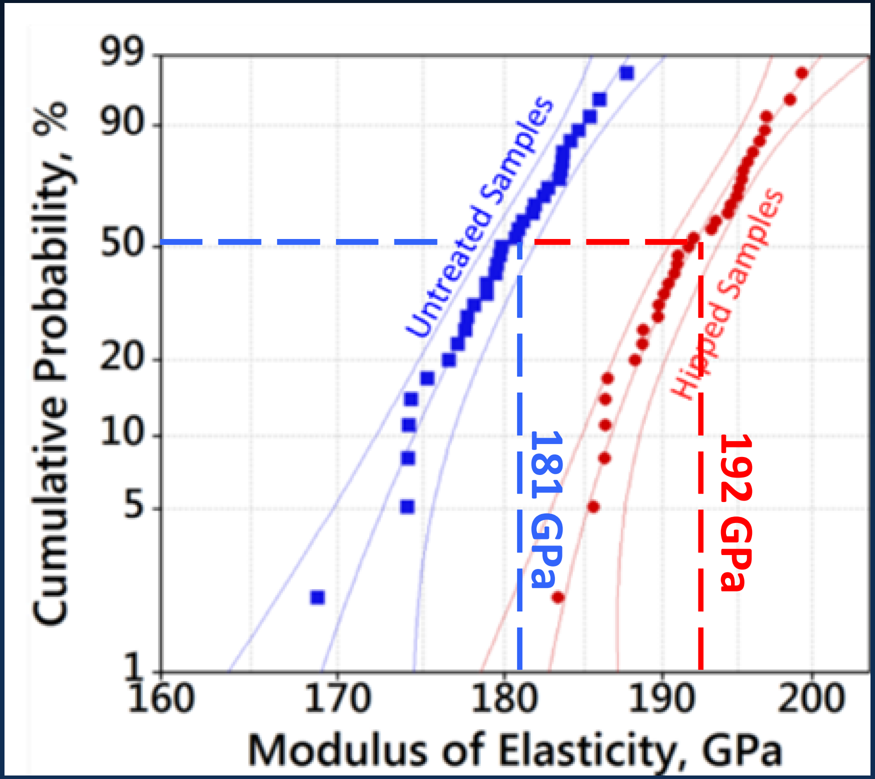
Effect of Porosity on Modulus

$E_p = E_0 * (1 - a * P)$ $a = 1.9$ [Choren et al, J. Mater Sci, 2013]

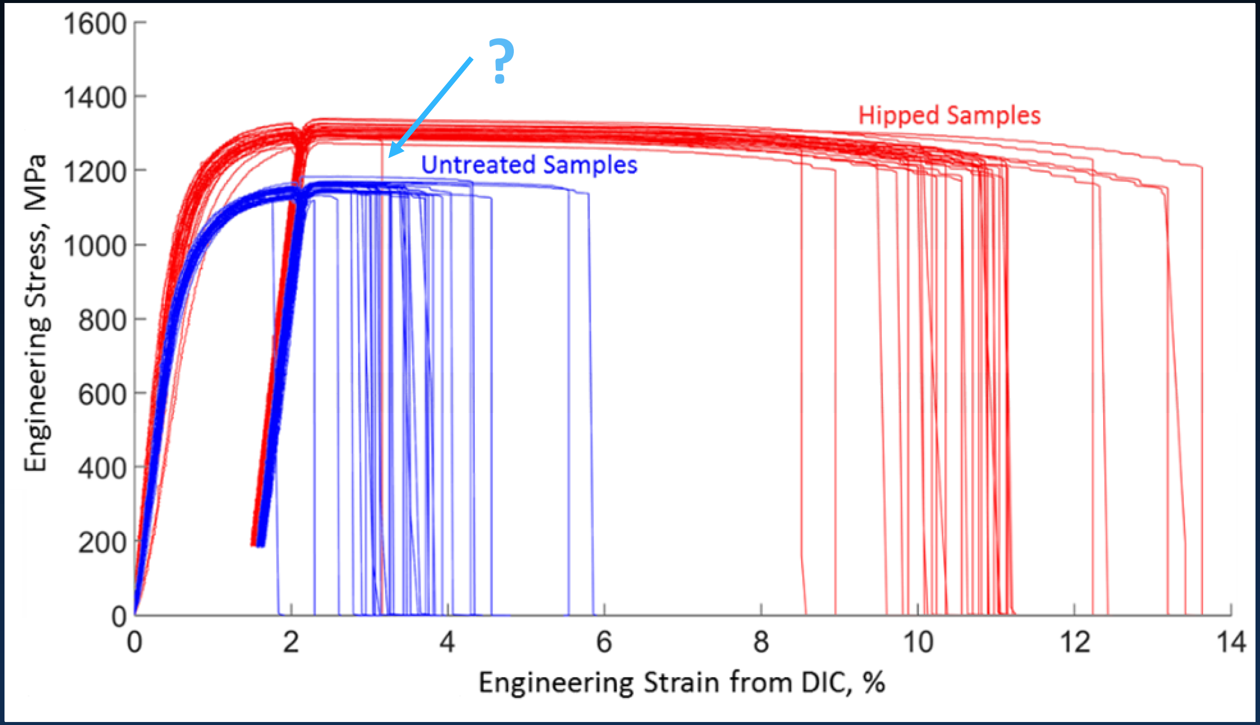
$E_0 = 195$ GPa

$\Longrightarrow E_{0.06\%} = 195$ Gpa

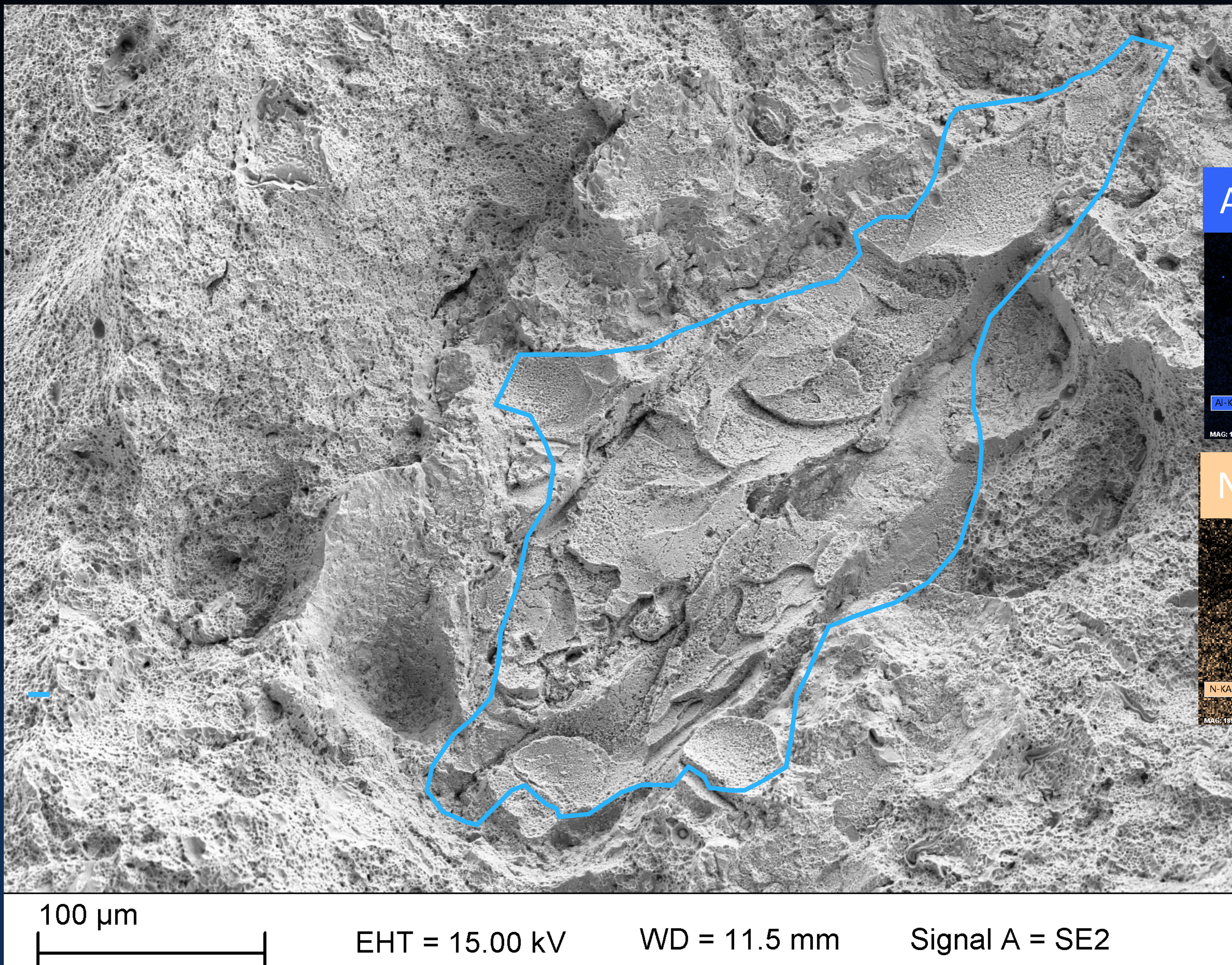
$E_{3.3\%} = 183$ Gpa

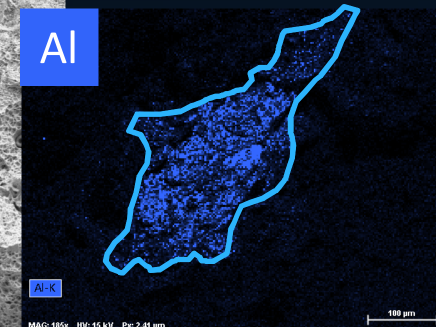


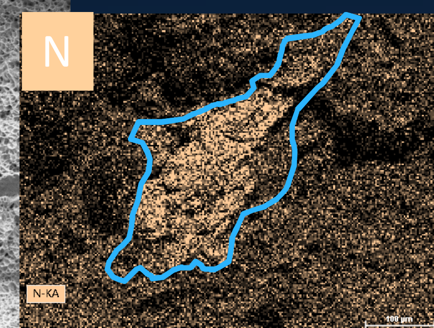
Hot Isostatic Press (HIP) Remediation



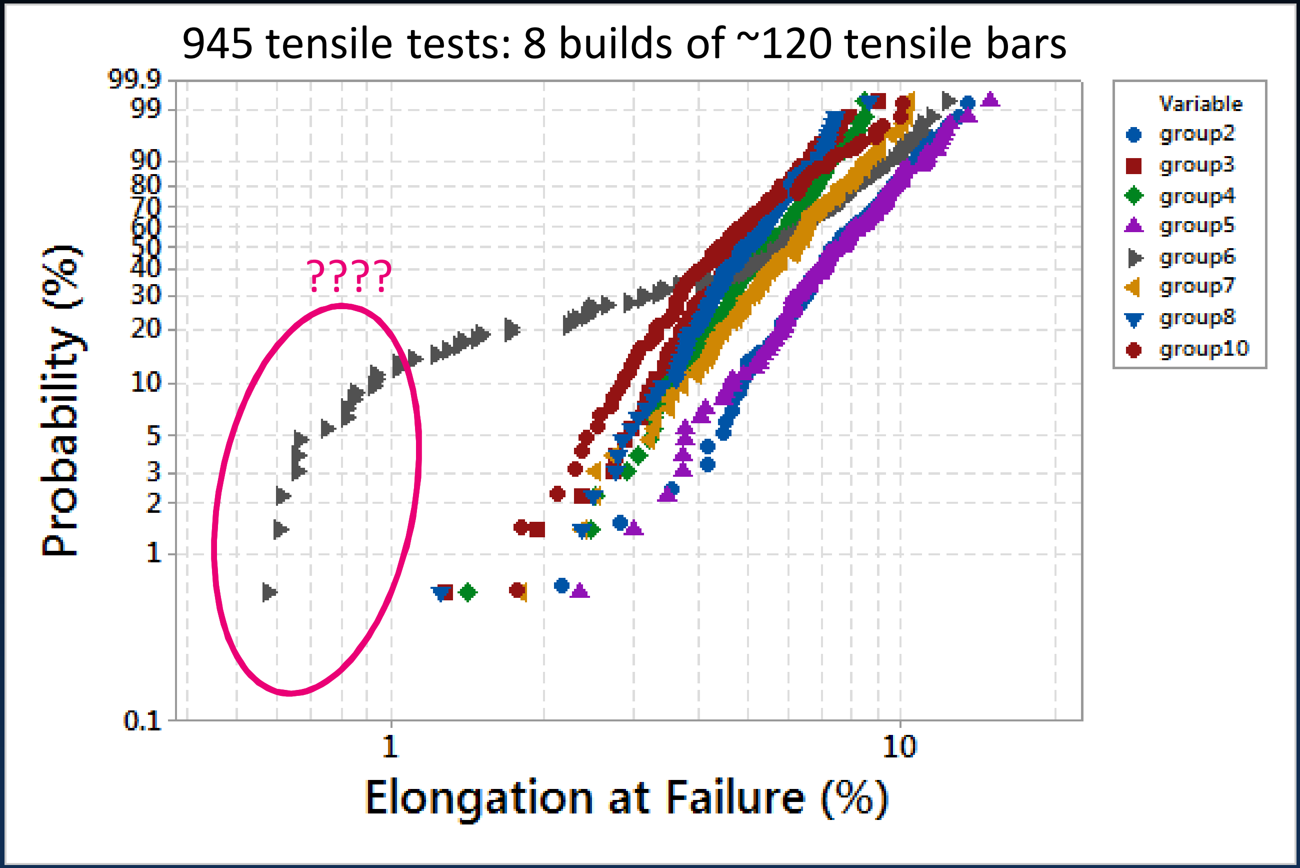
Low Outlier: Aluminum-rich region!?



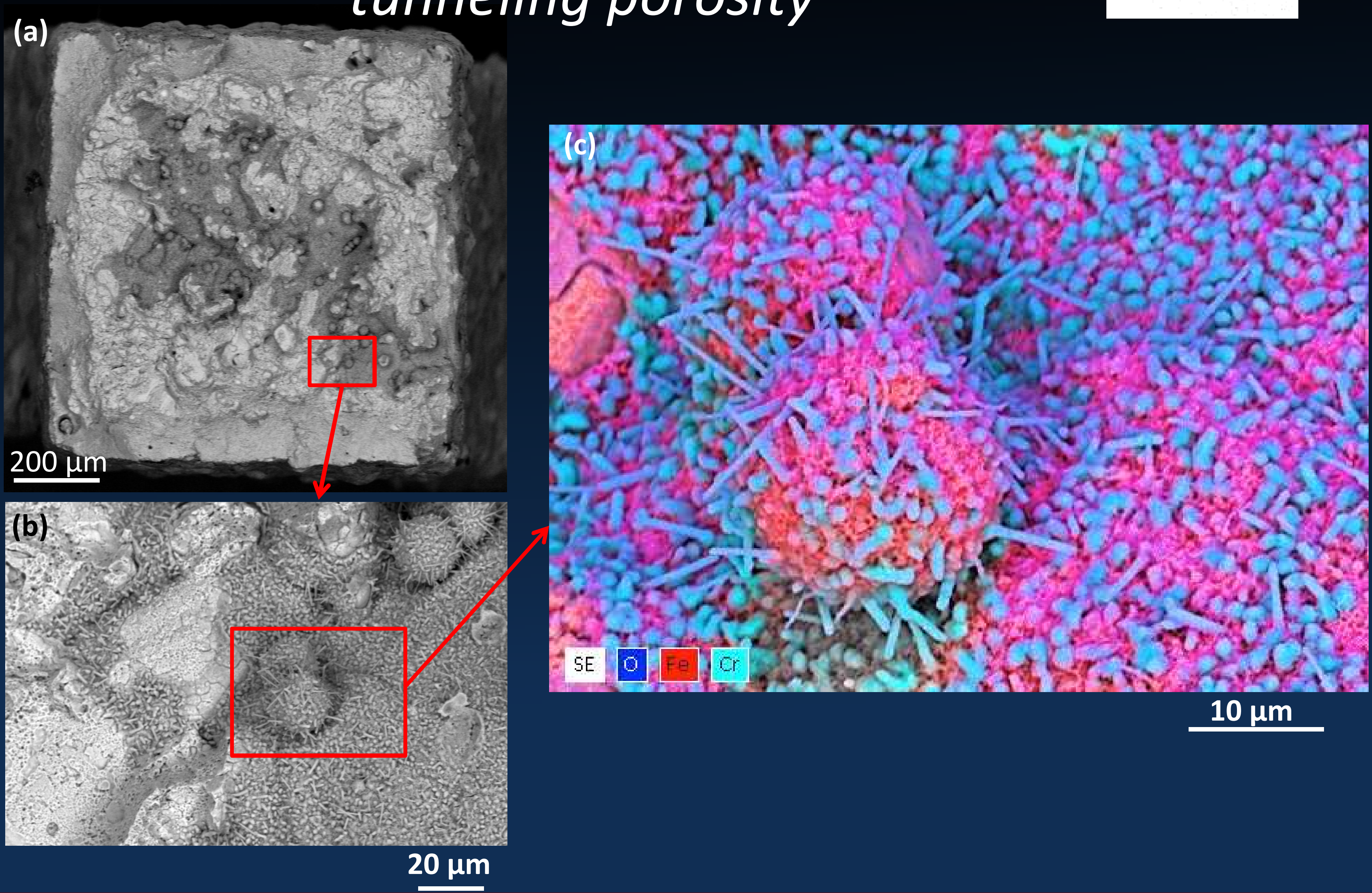




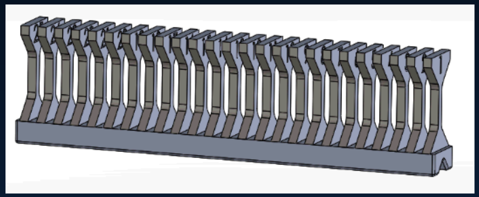
Distributions from 8 nominally identical cooling fins (Vendor 1)

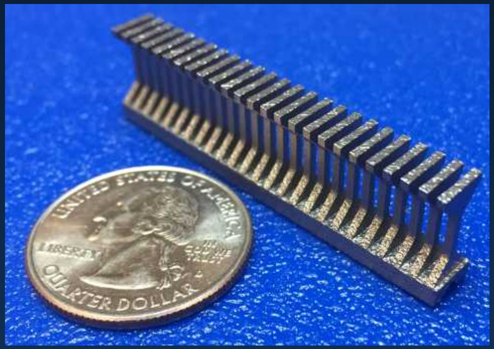


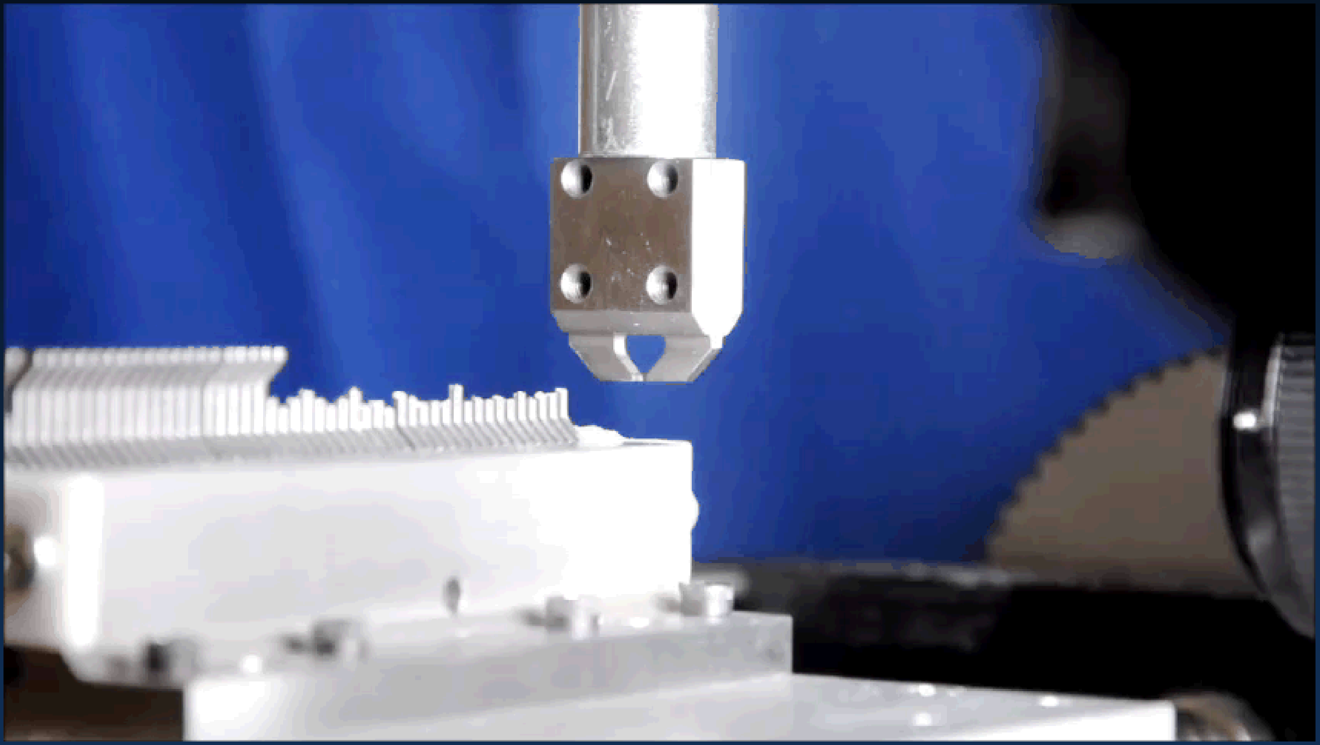
Anomalous 'low ductility' caused by "tunneling porosity"



Next level of Automation…



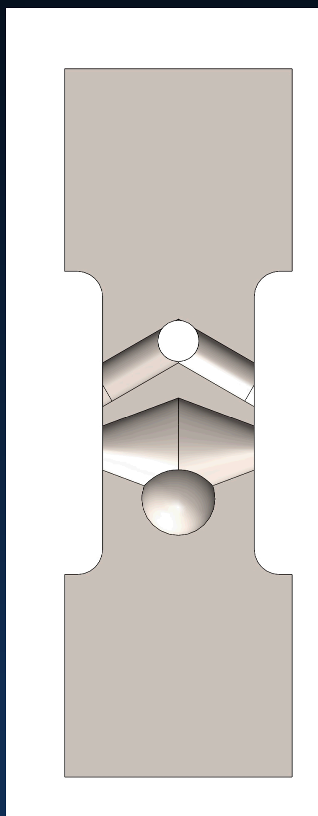


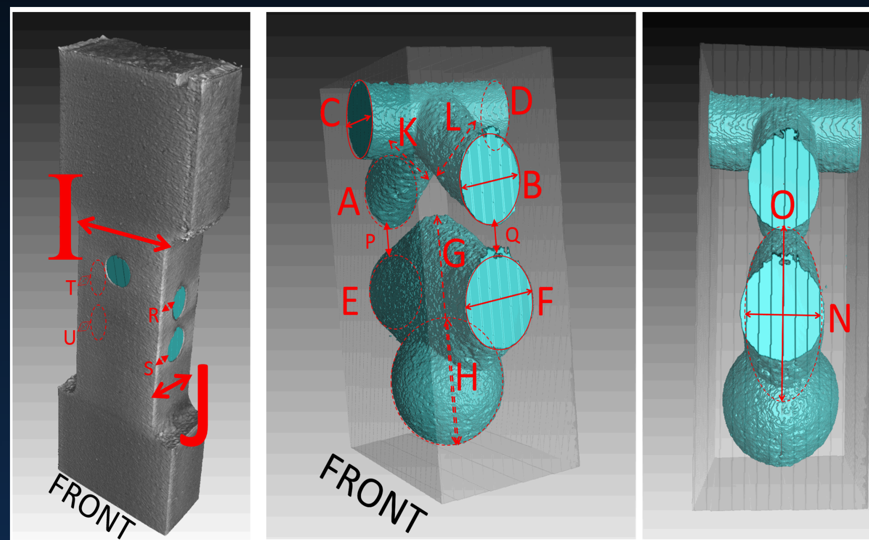


>100 tensile tests/hr with minimal operator burden

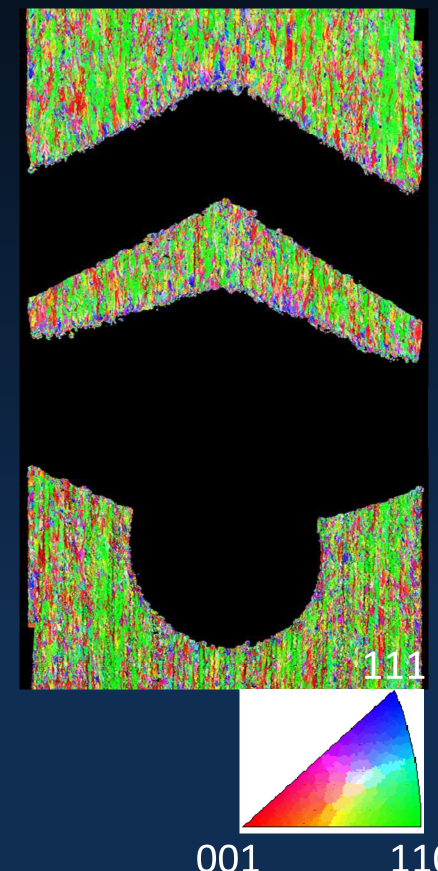
Announcing the 3rd Sandia Fracture Challenge

Provided with tensile data, CT data, roughness, microstructure, etc, ***predict*** the conditions (force, displacement) for fracture…





Alloy: 316L
Production method: Laser Powder Bed Fusion



Know someone who might be interested? E-mail **blboyce@sandia.gov**

See previous Fracture Challenges: *B.L. Boyce et al., Int. J. Fracture,* 2014; 2016

Summary…

- High-throughput methods permit rapid insight into both “typical” variation of material properties and statistically anomalous rare events.
- The anomalous defects are missed in small-populations of tests
- Modeling can help us understand the role of these defects and process paths to eliminate the defects.
- More development is needed on both high-throughput post-process and in-process characterization

Automation beyond the tensile test…

Properties

Tensile strength
Ductility
Toughness
Hardness
Wear & friction
Permeability
Thermal expansion
Reactivity/corrosion
Electrical conductivity
Resonance
etc.

Structure

Geometry
Roughness
Porosity
Chemistry
Phase content
Grain Size
Crystal Texture
Residual stress
Dislocation content
etc.

In-Process

In-process monitoring
Adaptive Feedback Control

Post-Processes

Surface remediation
Heat treatment
Subtractive machining
Coating
Joining
Integration
etc.

* Some measurements, like resonance testing, can be used to infer multiple aspects (geometry, density, modulus, residual stress, etc)

A diagnostic artifact provides an inspection surrogate and a process monitor…

Material & Structural Properties

Mechanical Properties
Arrays of tensile bars used to investigate stochastic tensile properties. Arrays of two different-sized tensile bars allow exploration of size-dependent mechanical properties

Structural Dynamics
Several cantilever beams of two heights can be used to test the resonance frequency of the material.

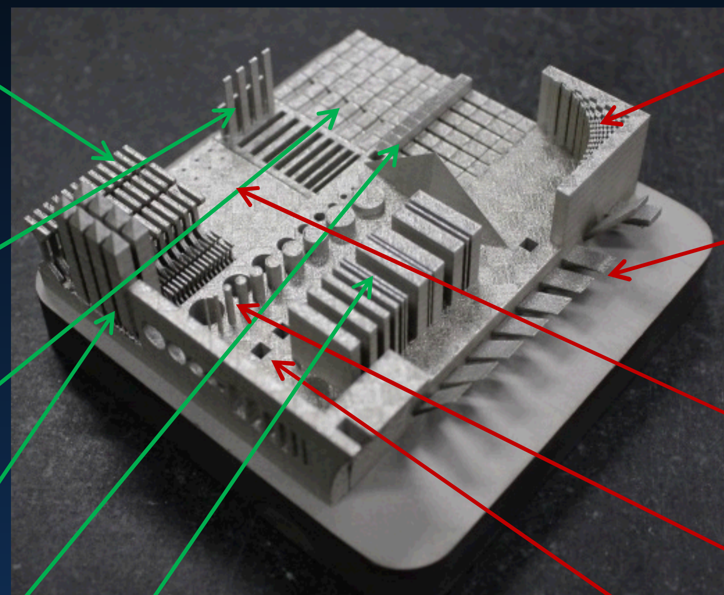
Notched Features
Arrays of notched features intended to explore stress-concentration effects on reliability and develop break-away coupons

Material Chemistry
Coupons to readily verify the composition and monitor contaminant levels.

Surface Roughness
Several features explore the interplay between geometry and the resulting surface roughness

Residual Stresses
Several features may be used to quantify the stress-induced warpage. Also, regions of the part exacerbate internal residual stresses to be measured by x-ray/ neutron diffraction or hole drilling.

Sandia Artifact printed in stainless steel alloy 17-4PH using a commercial vendor (Fineline) with a ConceptLaser Mlab Printer



Printability Limits & Metrology

Minimum Feature Dimensions
Evaluate printability and dimensional accuracy for a wide range of feature types including theoretical sharp corners

Overhangs & Bridges
Incrementally sized features intended to determine the maximum dimension that will maintain structural integrity of the part. Features push printer to failure point.

Internal voids
Intentional internal void arrays of varying dimension allow inspectability assessment

Aspect Ratios
A wide range of aspect ratios explores the printability limits of positive and negative features

Consistency features
Arrays of nominally identical features allow evaluation of repeatability

Most existing artifacts (e.g. NIST AM artifact) emphasize dimensional metrology and ignore material/structural properties. This compact array employs many dual-purpose features and many arrays of features for statistical repeatability analysis.