SAND2022-3831C

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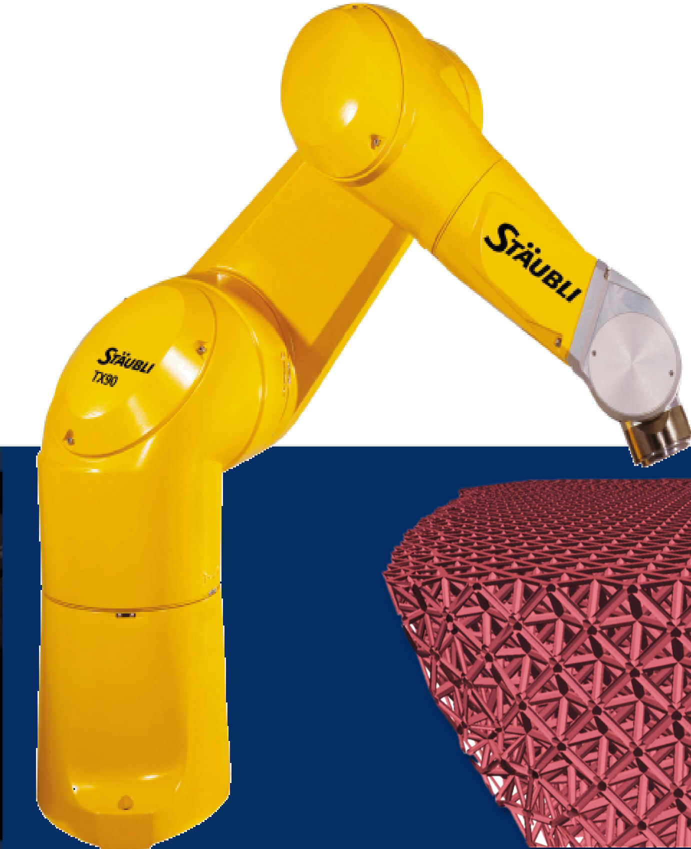
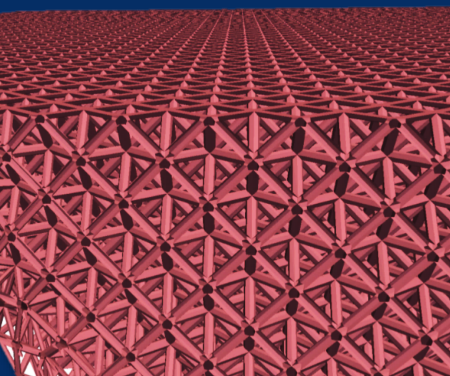
# Stochastic Failure in Additively Manufactured Alloys

**Brad L. Boyce**, Brad C. Salzbrenner, Bradley H. Jared, Jeffrey M. Rodelas, Jonathan D. Madison, Jay Carroll

Materials Science and Engineering Center
Sandia National Laboratories, Albuquerque, NM, USA



U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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# Accelerated Cycles of Learning…

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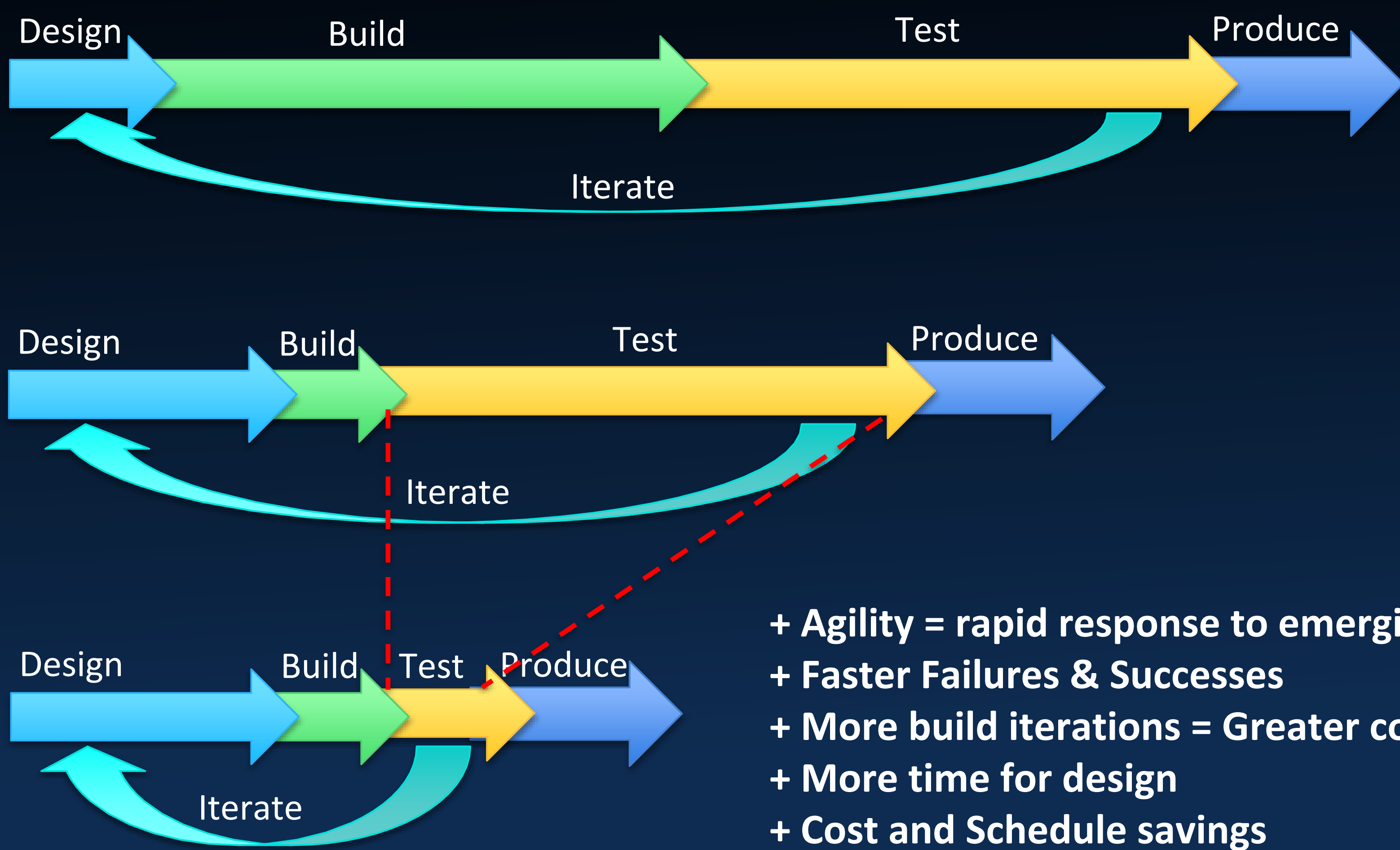


**+ Agility = rapid response to emerging threats**
**+ Faster Failures & Successes**
**+ More build iterations = Greater confidence**
**+ More time for design**
**+ Cost and Schedule savings**

# *How conventional materials are qualified…*

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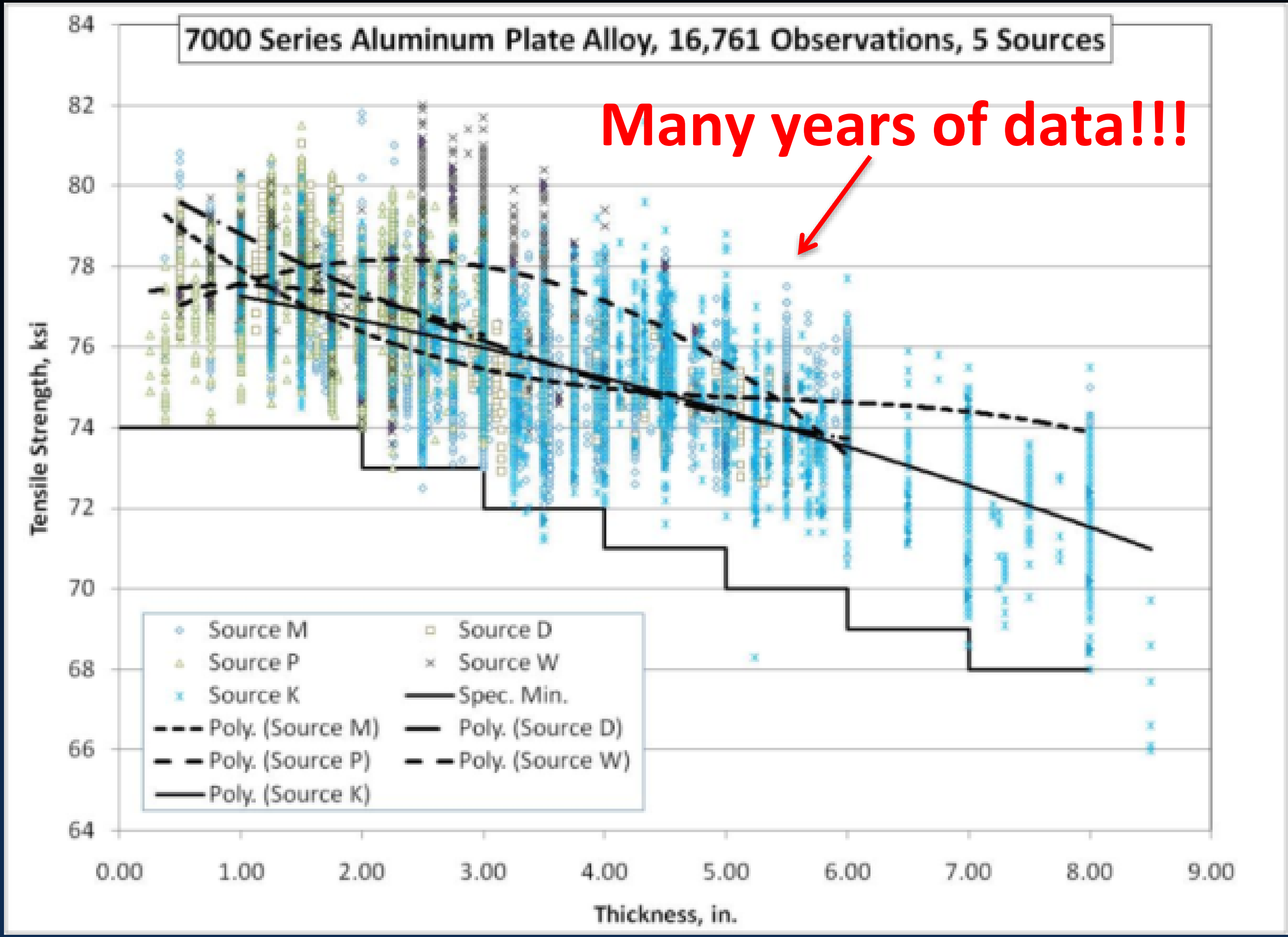
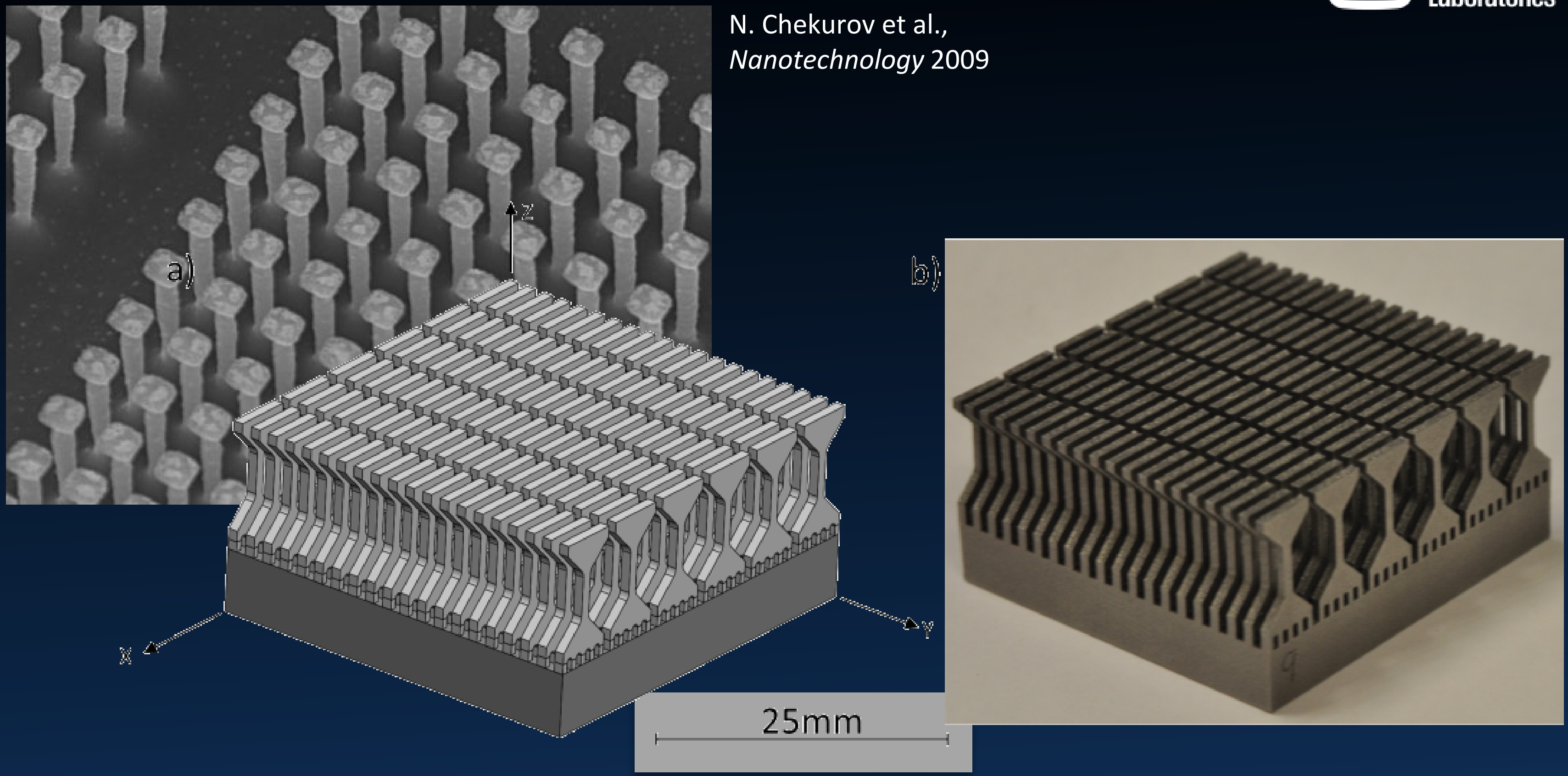



# *How can we rapidly qualify AM materials?*


*J. Rubadue, Path to Inclusion of Static Design Properties in the '… '(MMPDS) Handbook for Technology Exchange at Penn State, 11/5/13 - Battelle*

# 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*

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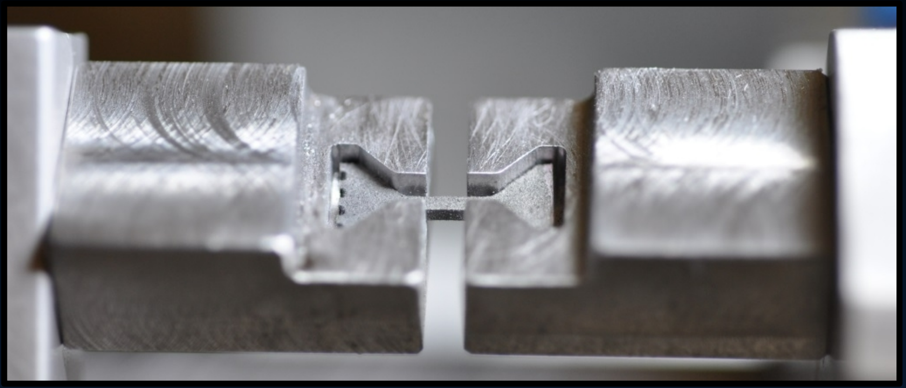
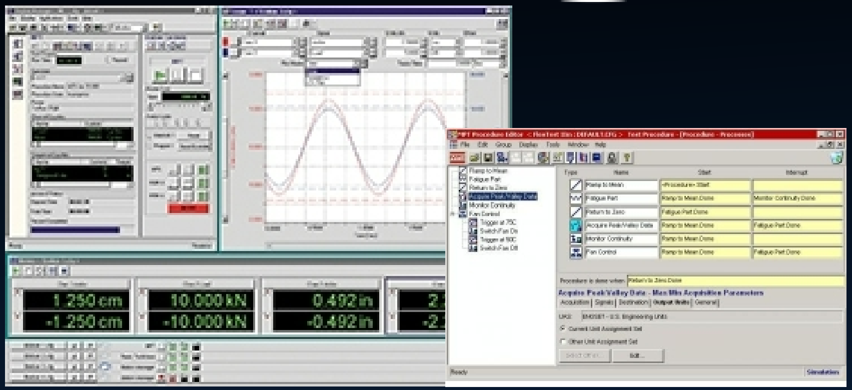
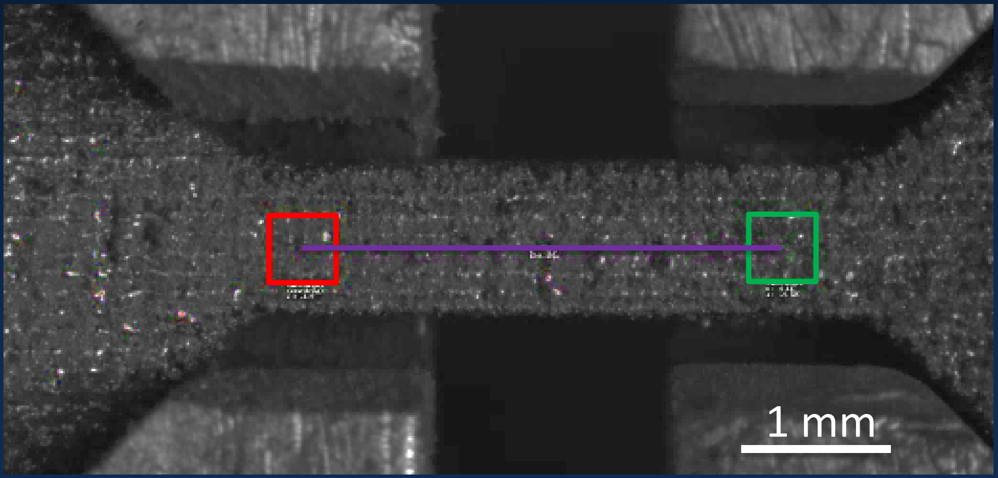


1. Self-aligning 'drop-in' grips




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

# 2nd Generation "High-throughput"

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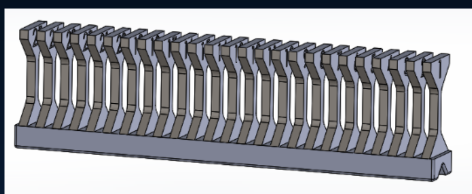

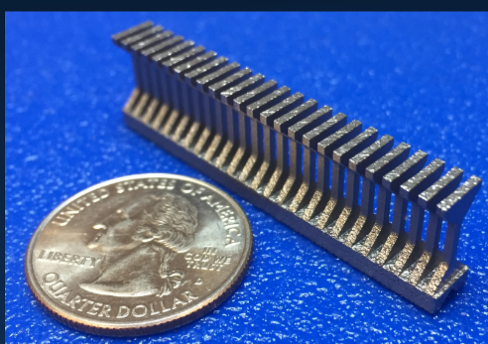


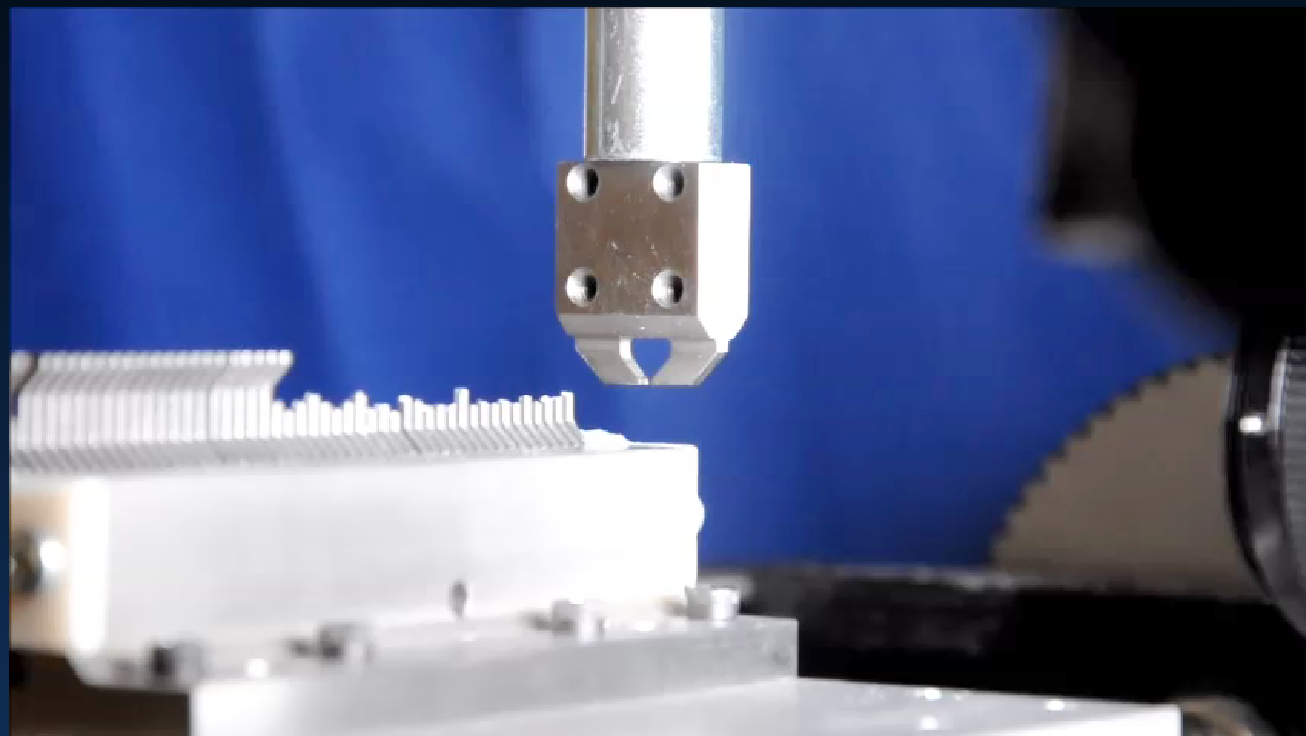

**>100 tensile tests/hr with minimal operator burden**

# *100 tensile tests in 4 hours…*

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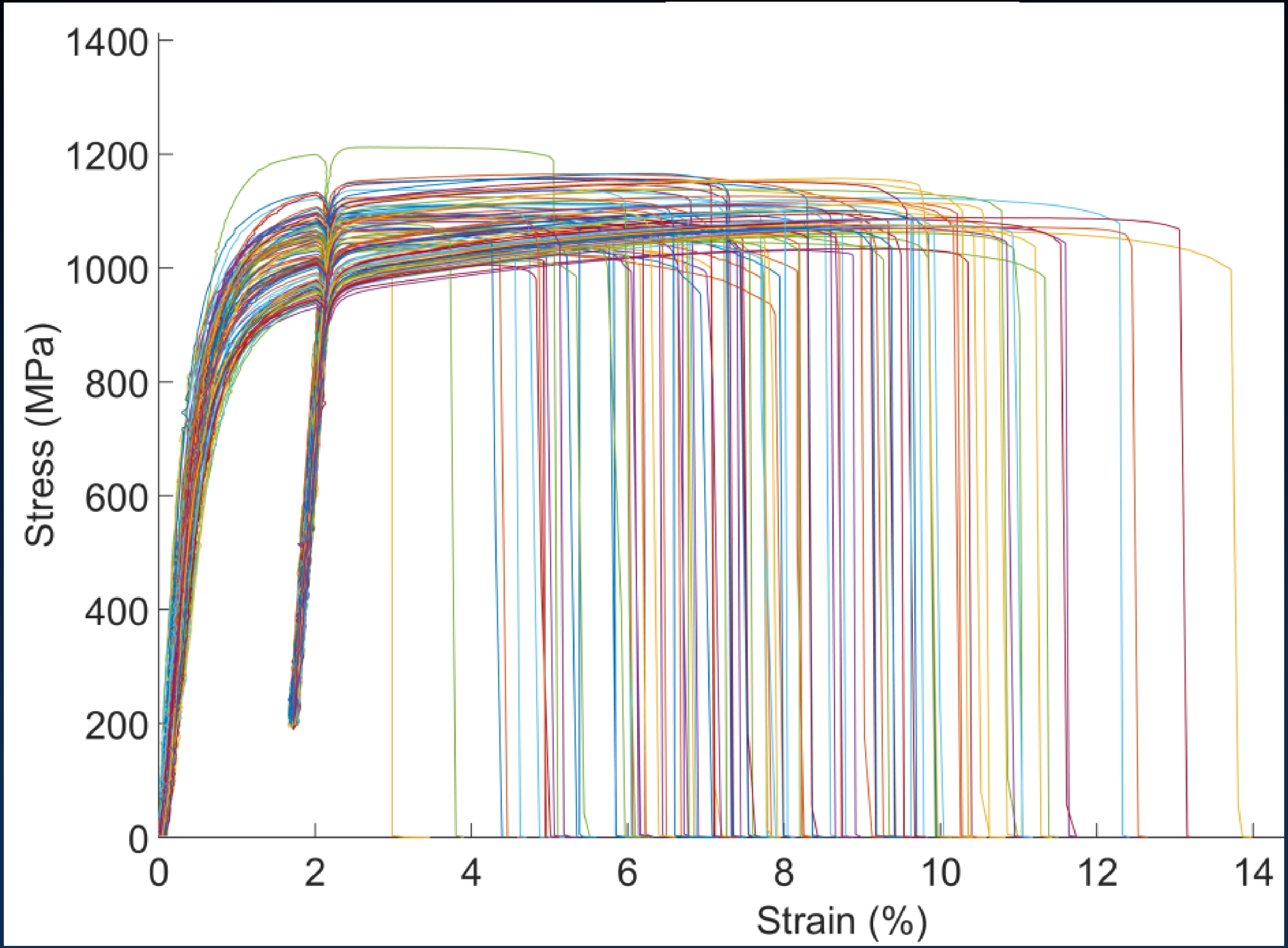
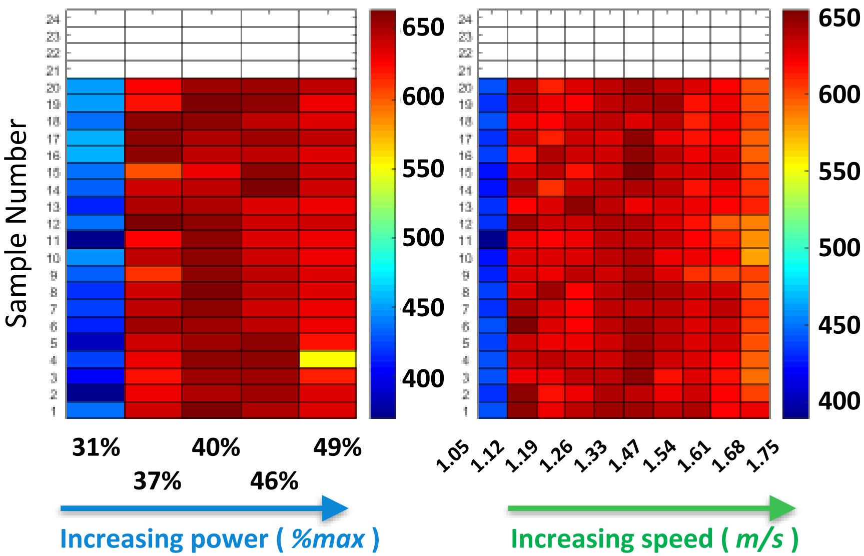
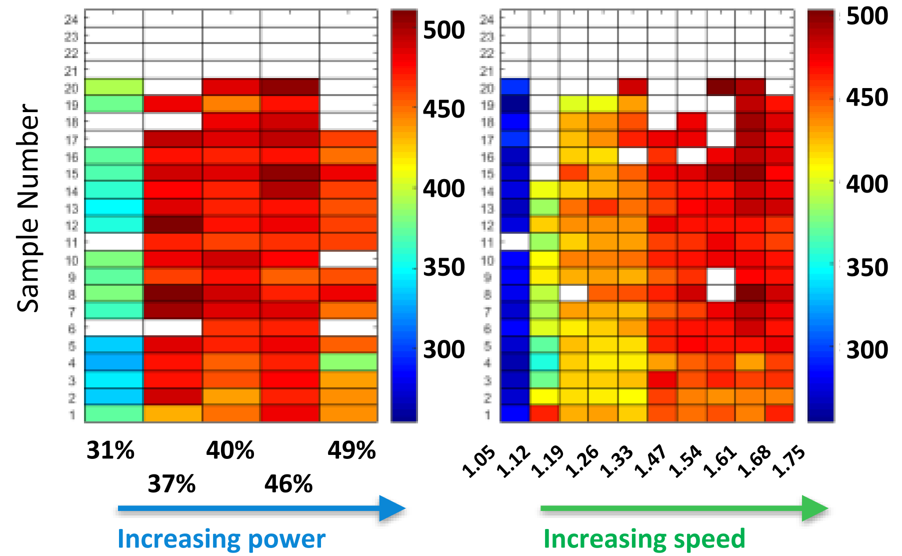


# Process Optimization Maps: ~400 tensile

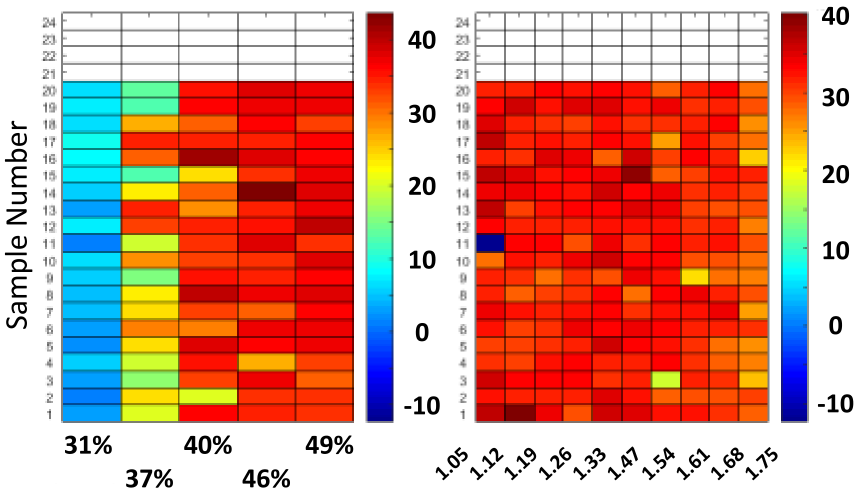
## Ultimate Tensile Strength (MPa)



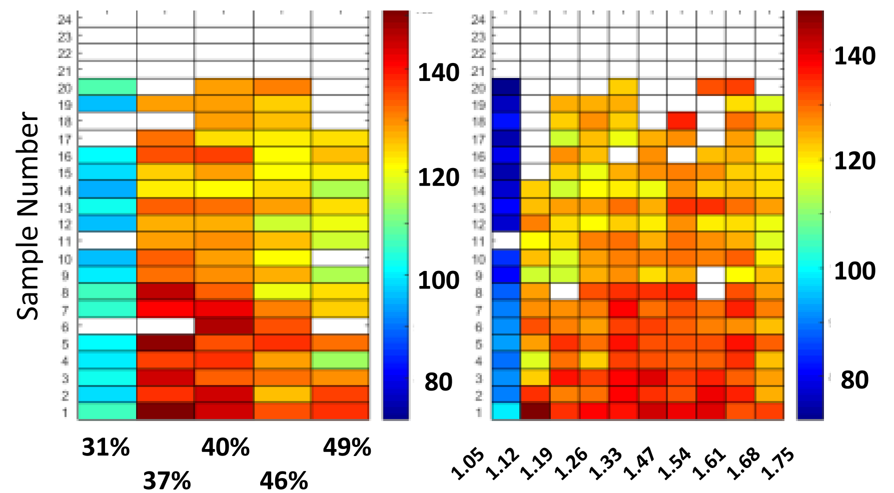

## Yield Stress (MPa)



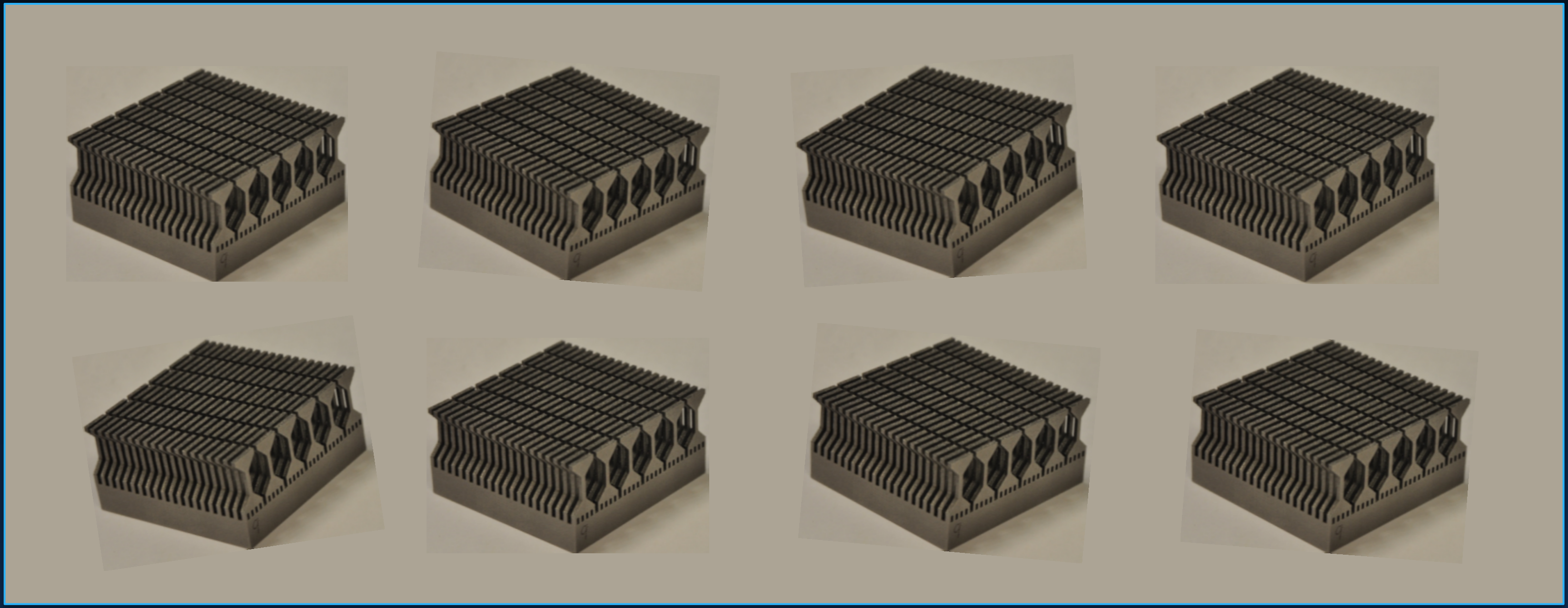

## Elongation to Failure (%)




## Modulus (GPa)



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



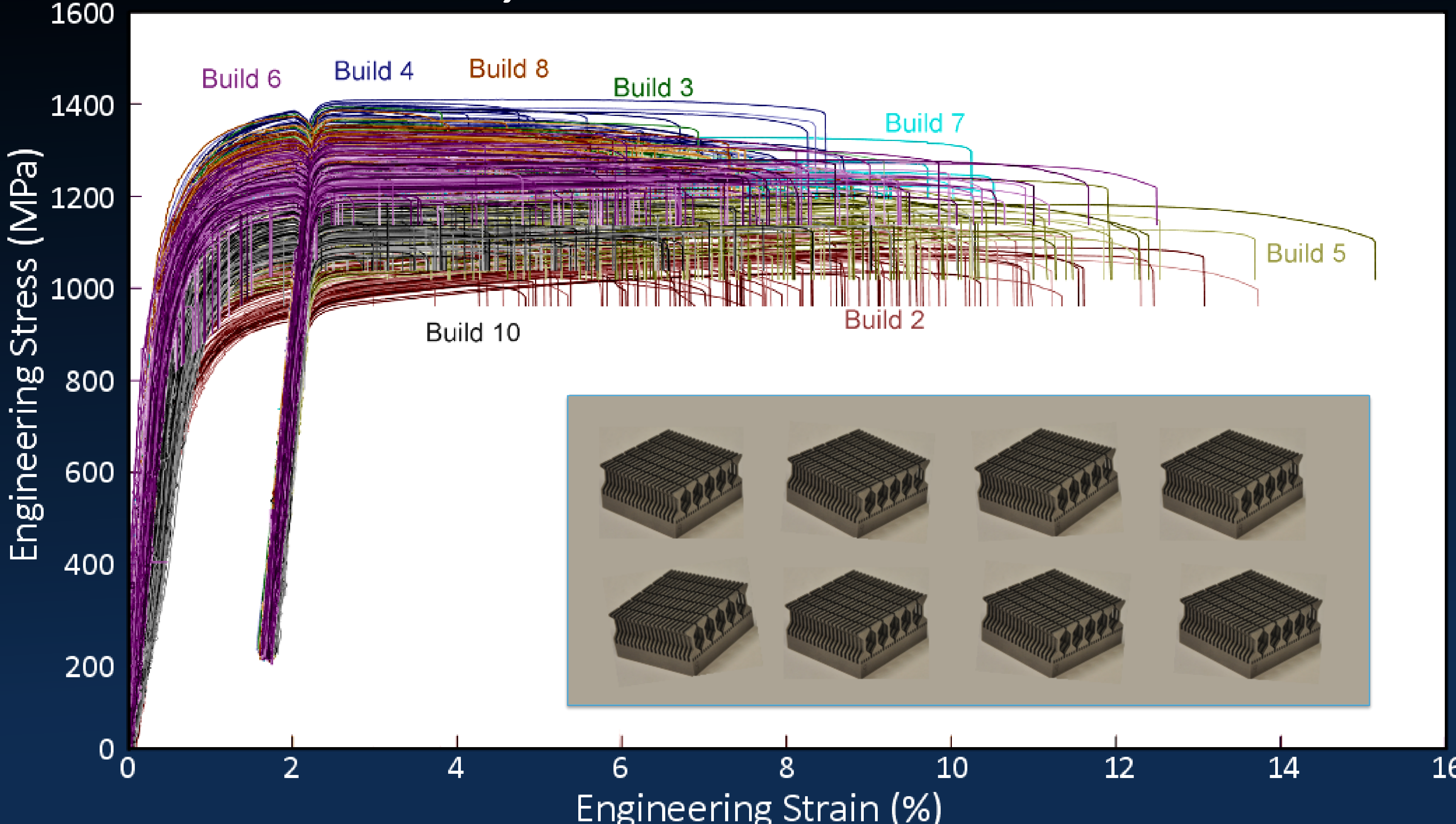
*960 tensile bars, produced in 2 weeks for ~$10 each*

Alloy: 17-4PH



B.L. Boyce et al., *Advanced Engineering Materials*, 2017

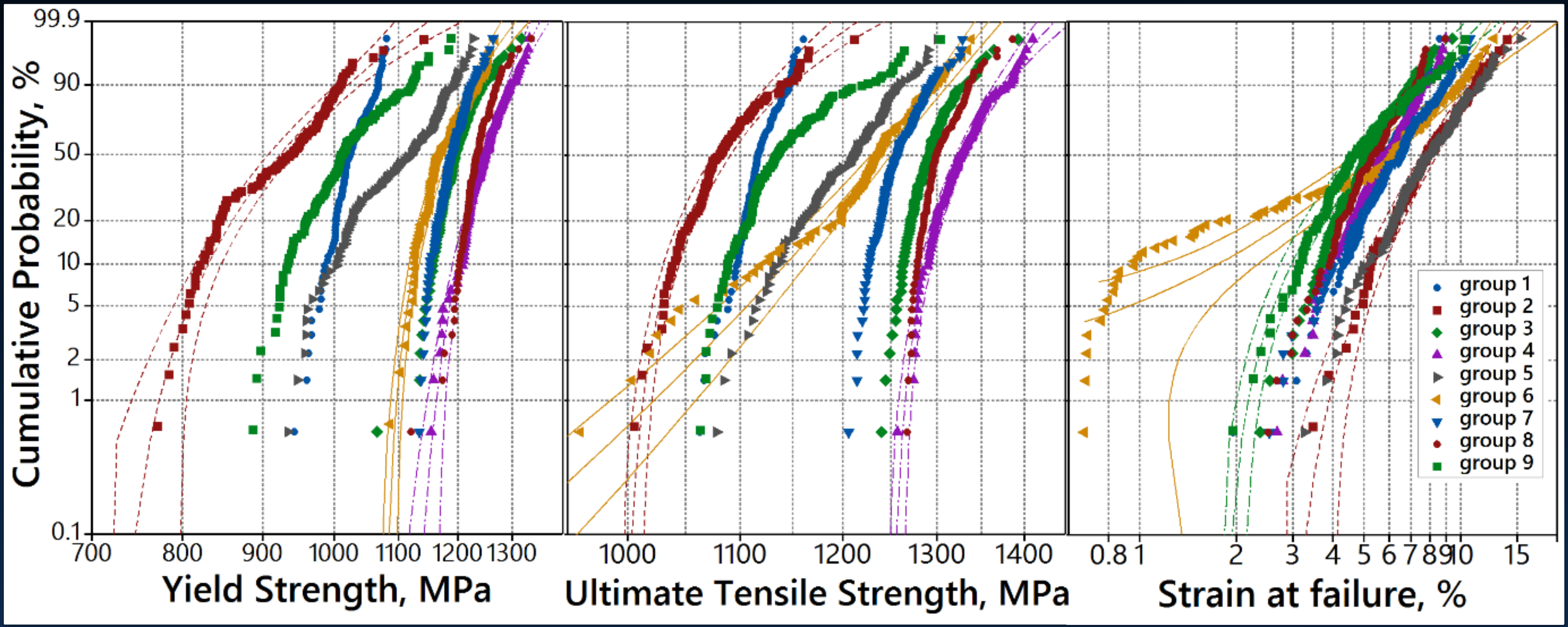
# "Big data"?: 945 tensile tests from 8 nominally identical builds






B.L. Boyce et al., *Advanced Engineering Materials*, 2017

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

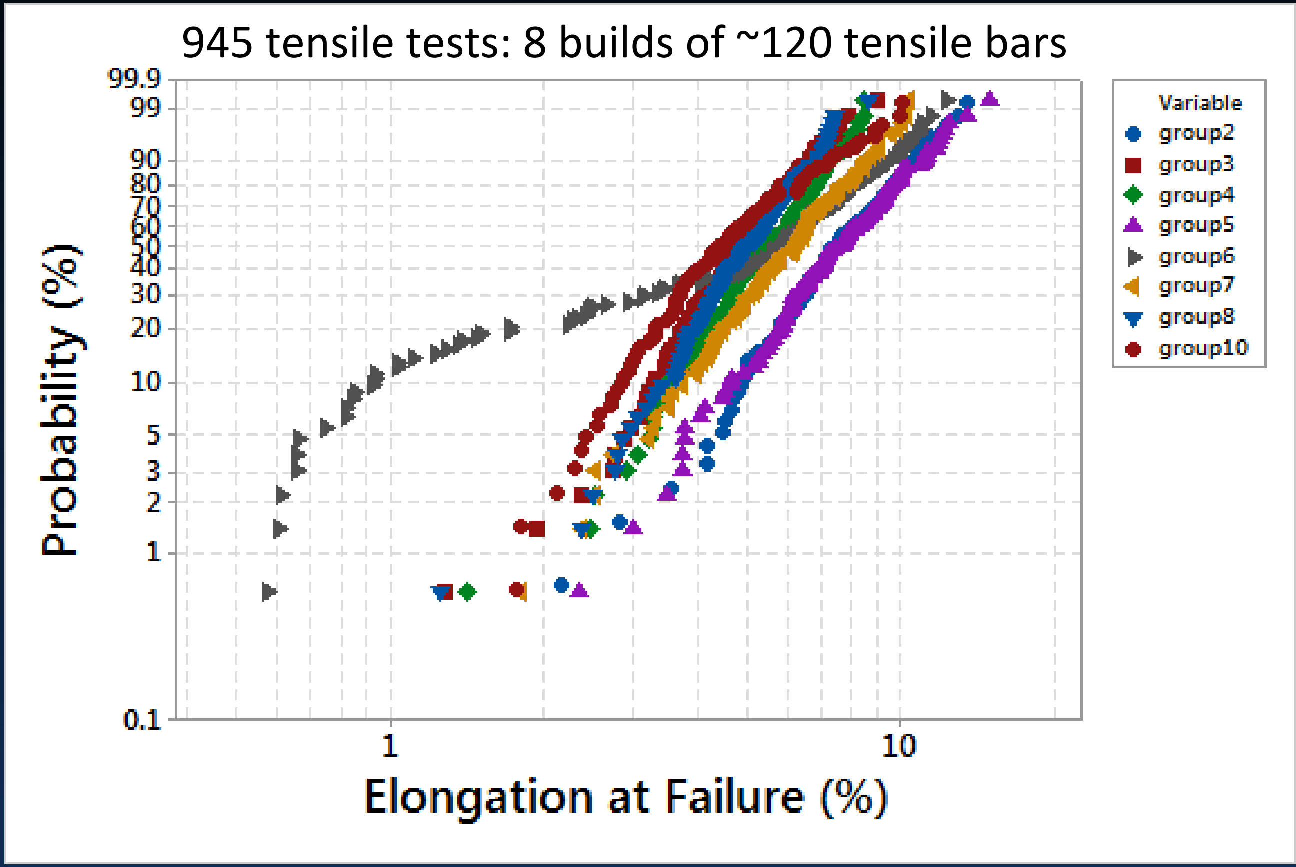



$$P_f = 1 - \exp\left[-\left(\frac{\sigma - \sigma_0}{\sigma_\theta - \sigma_0}\right)^m\right]$$



B.L. Boyce et al., *Advanced Engineering Materials*, 2017

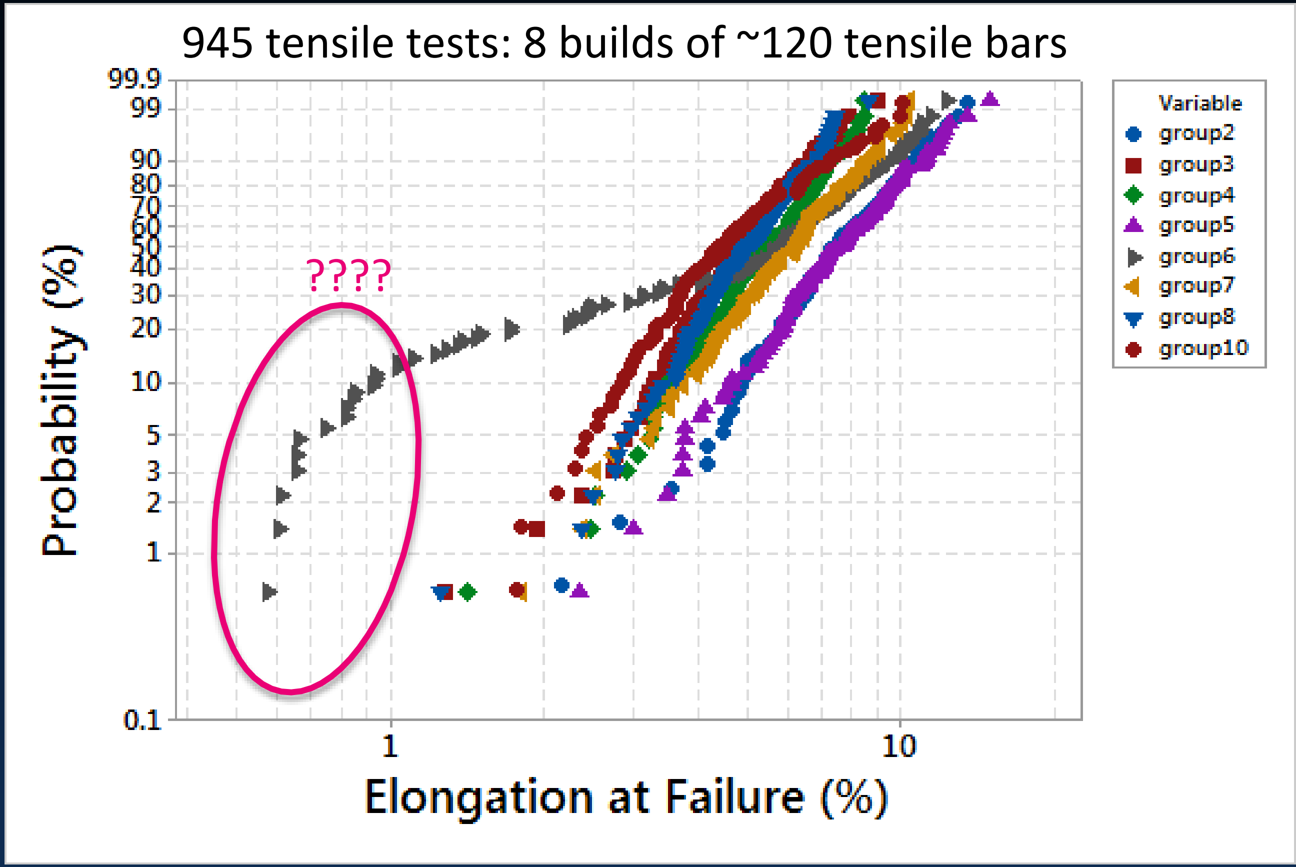
# *Unpacking the variation in ductility…*






B.L. Boyce et al., *Advanced Engineering Materials*, 2017

# Distributions from 8 nominally identical cooling fins (Vendor 1)



# Anomalous 'low ductility' caused by "tunneling porosity"

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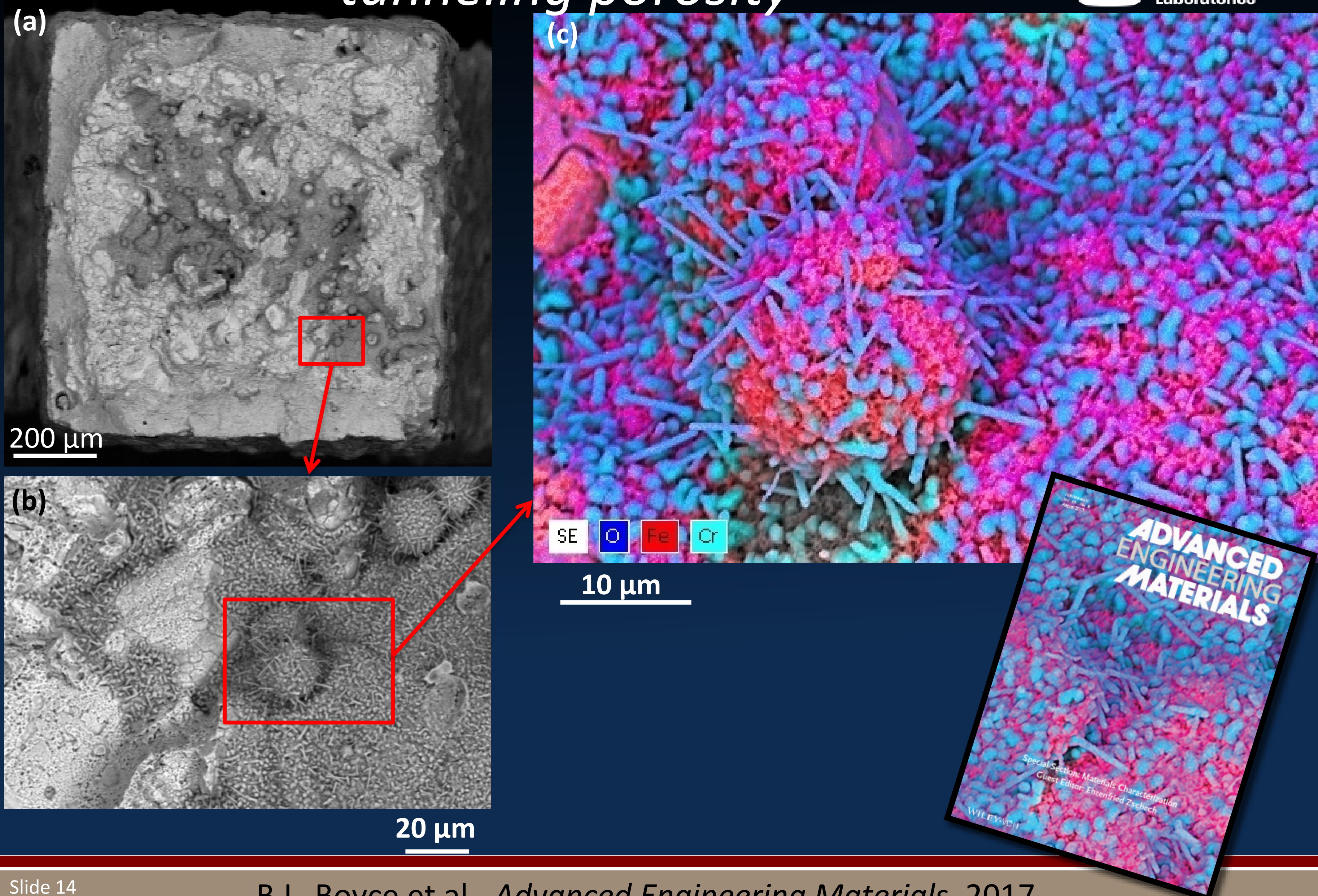


B.L. Boyce et al., *Advanced Engineering Materials*, 2017

# “Typical” Ductility-Limiting Flaws

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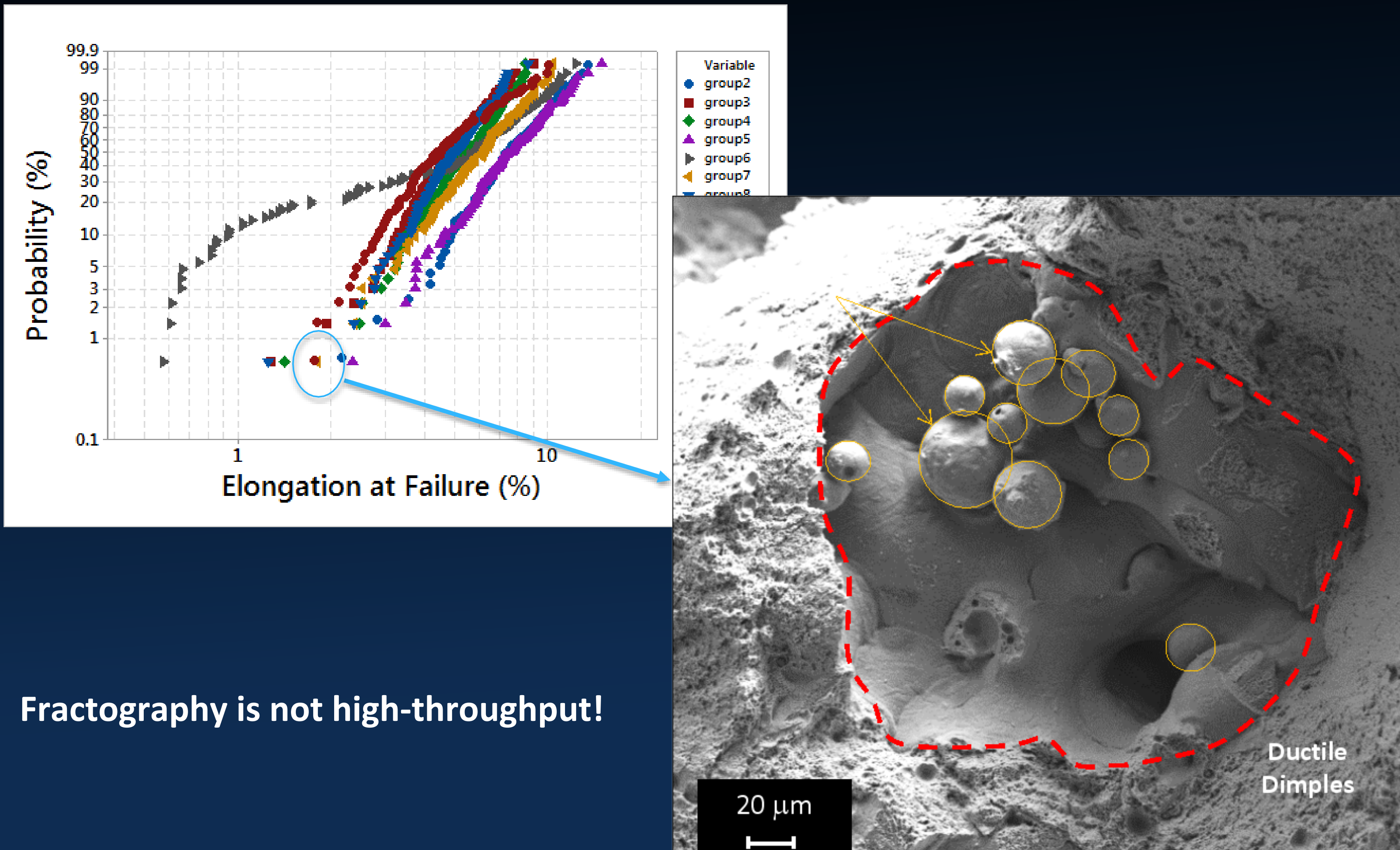


**Fractography is not high-throughput!**



B.L. Boyce et al., *Advanced Engineering Materials*, 2017

# *X-ray CT Scans are not high-throughput!*

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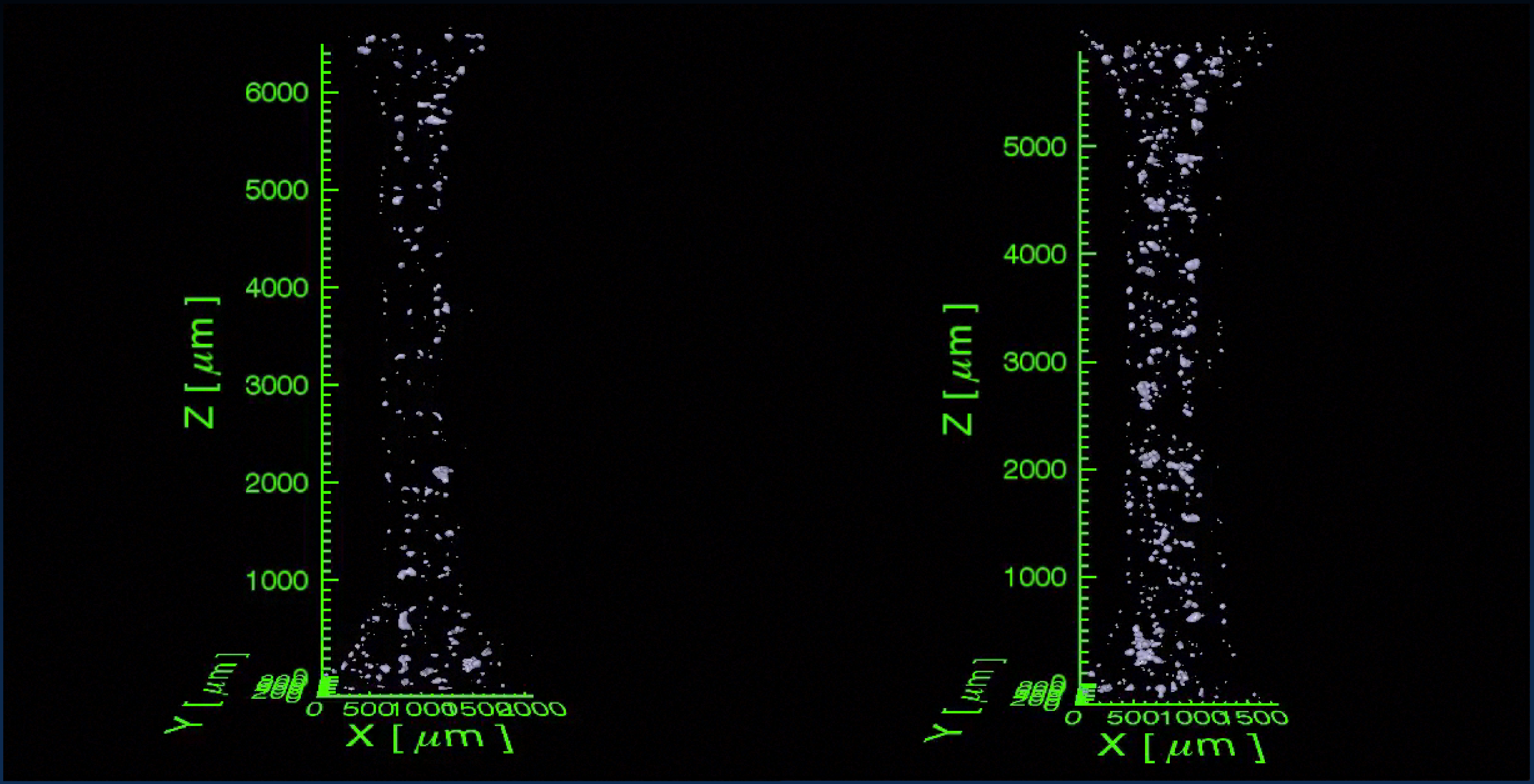
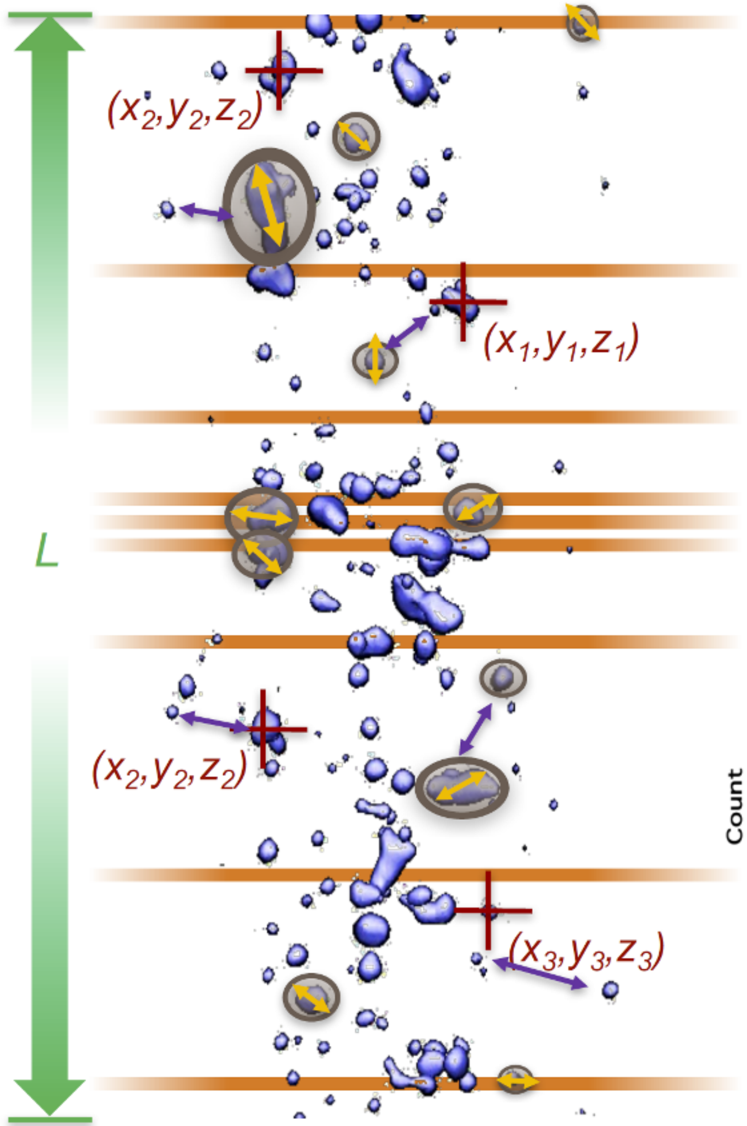


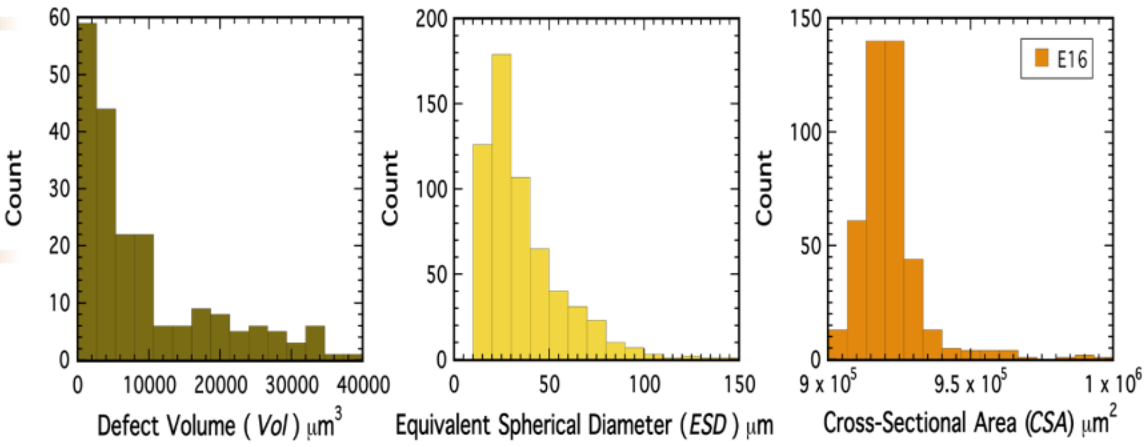

- 100 CT Scans ~ $30,000 and 3 months…
- Need high-throughput CT, in-process detection, or other inferrential detection method


Collaboration with J. Madison, O. Underwood

# What Porosity Metrics Matter?




- Total Volume of Defects ( $V_{tot}$ )
- Pore Volume Fraction ( $V_{fract}$ )
- Spatial Location of Pores *(x, y, z)*
- Total Number of Defects *(N)*
- Total Defects/Length *(N/L)*
- Average Defect Volume ( $V_{avg.}$ )*
- Average Equivalent Spherical Diameter ( $ESD_{avg.}$ )*
- Average Cross-Sectional Area ( $CSA_{avg.}$ )*
- Average Nearest Neighbor Distance ( $NND_{avg.}$ )*



# *Pairwise correlation analysis*

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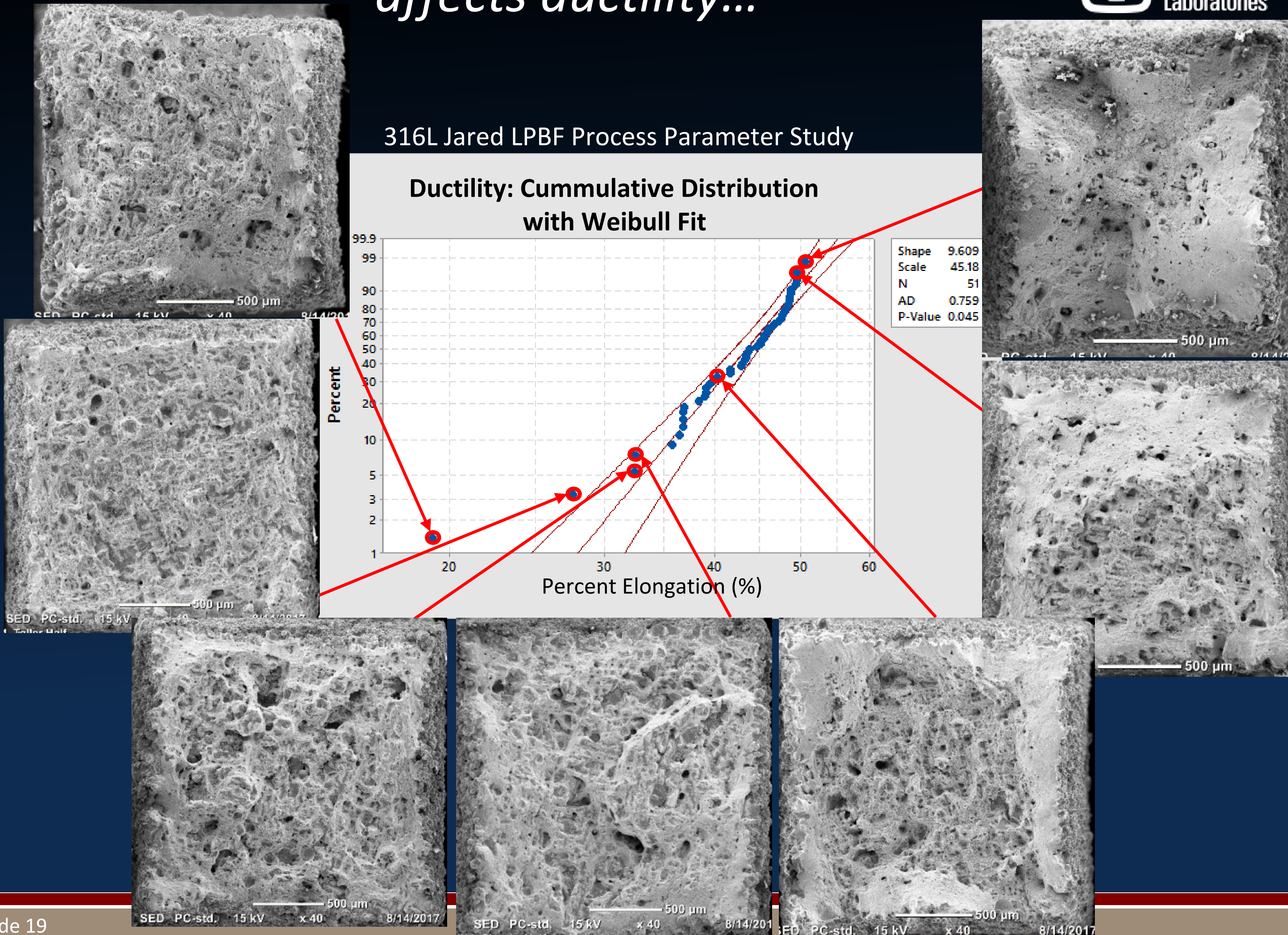
| $R^2$ | Yield Stress (MPa) | Unloading Modulus (GPa) | Ultimate Tensile Strength (MPa) | Elongation to Failure (%) | Ductility (%) |
|---|---|---|---|---|---|
| **Material Properties** | | | | | |
| **Yield Stress (MPa)** | 1.00 | | | | |
| **Unloading Modulus (GPa)** | 0.72 | 1.00 | | | |
| **Ultimate Tensile Strength (MPa)** | 0.79 | 0.83 | 1.00 | | |
| **Elongation to Failure (%)** | 0.27 | 0.24 | 0.58 | 1.00 | |
| **Ductility (%)** | 0.11 | 0.12 | 0.45 | 0.91 | 1.00 |
| **Area (mm)** | -0.75 | -0.63 | -0.50 | 0.09 | 0.22 |
| **Processing Parameters** | | | | | |
| **Power (% max)** | 0.23 | 0.19 | **0.51** | **0.74** | **0.68** |
| **Velocity** | **0.59** | 0.38 | 0.27 | -0.08 | -0.24 |
| **Hatch Pattern** | 0.26 | 0.15 | 0.06 | 0.06 | 0.07 |
| **Defect Structure** | | | | | |
| **Density** | 0.27 | 0.38 | **0.68** | **0.72** | **0.62** |
| **Defects / Unit Length ($mm^{-1}$)** | **0.49** | 0.32 | **0.56** | **0.48** | 0.39 |
| **Avg. Defect Volume ($um^3$)** | 0.32 | 0.24 | 0.11 | 0.06 | 0.27 |
| **Avg. ESD (um)** | 0.14 | 0.25 | -0.06 | -0.14 | 0.08 |
| **Total Defect Volume (voxels)** | 0.42 | 0.29 | 0.28 | 0.21 | 0.35 |
| **Volume of Dogbone (voxels)** | 0.11 | **-0.58** | 0.17 | 0.38 | 0.30 |
| **Defect Vol. Fract. - sample (%)** | 0.41 | 0.31 | 0.27 | 0.18 | 0.33 |
| **Defect Vol. Fract. - gage (%)** | 0.42 | 0.29 | 0.28 | 0.21 | 0.35 |

# *Fracture surfaces show that porosity network affects ductility…*



# *Finite Element Analysis of Porosity Effects*

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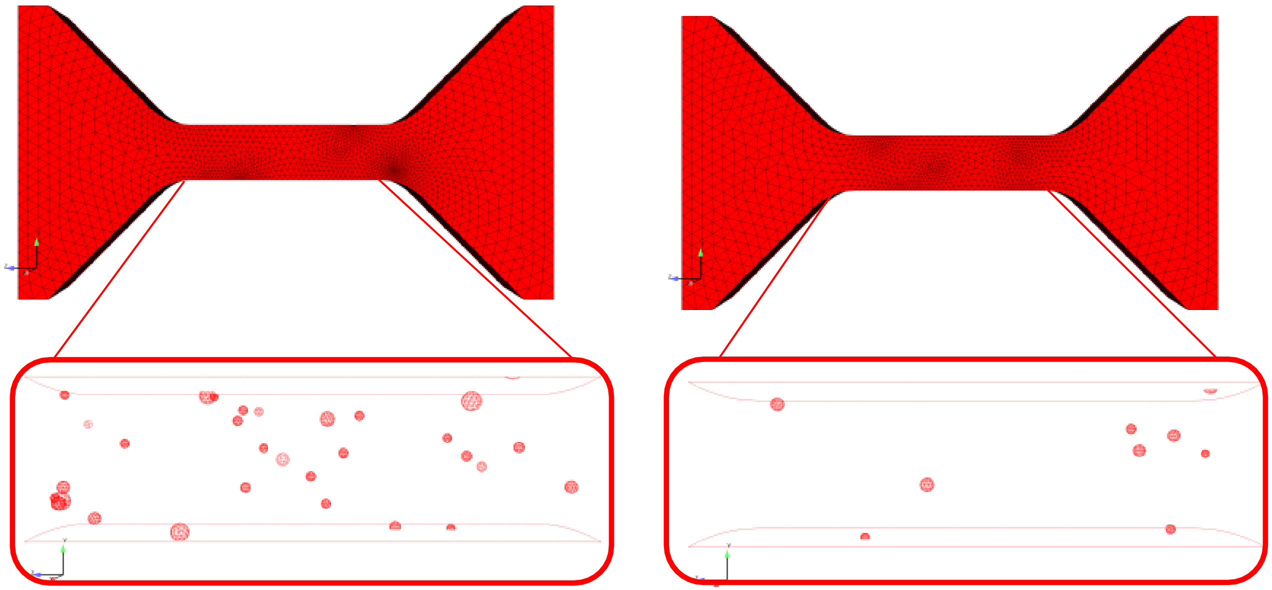
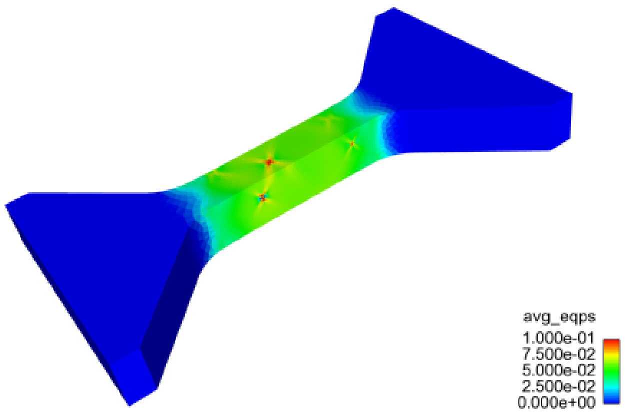
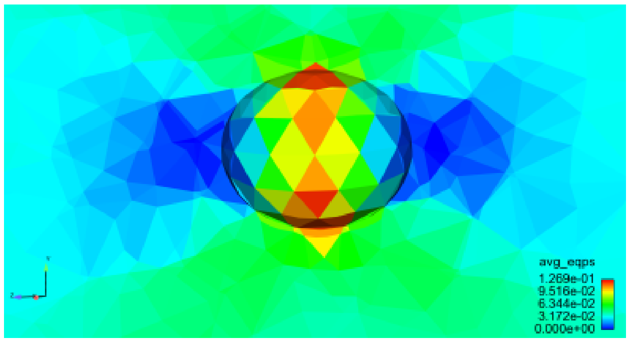
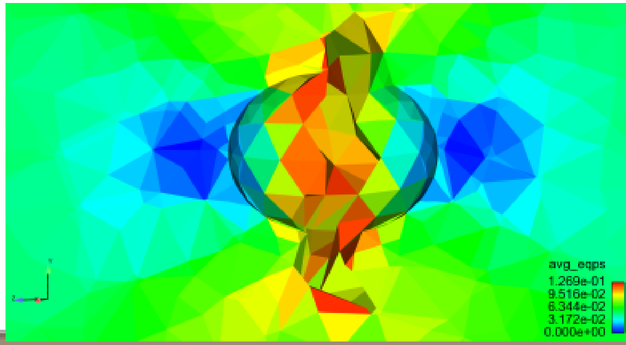





$$\dot{\phi} = \sqrt{\frac{3}{2}}\dot{\epsilon}_p \frac{1-(1-\phi)^{m+1}}{(1-\phi)^m} \sinh\left[\frac{2(2m-1)}{2m+1}\frac{\langle \frac{I_1}{3} \rangle}{\sqrt{3J_2}}\right]$$



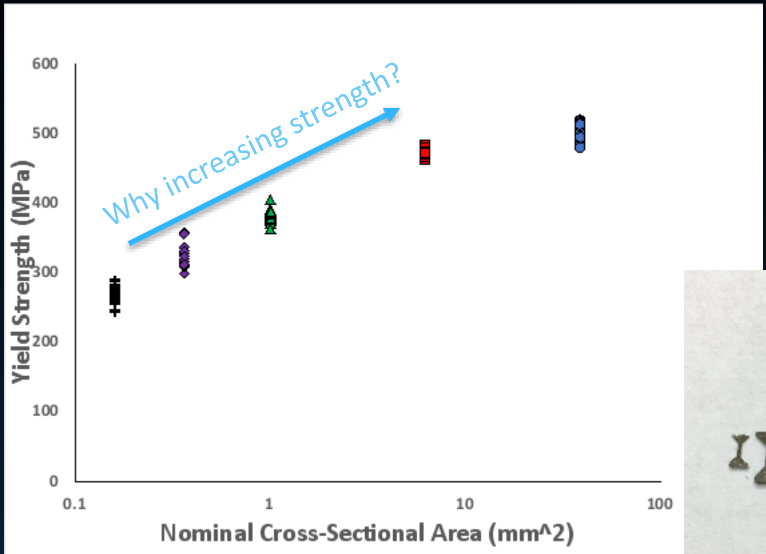

**Hypothesis**: process-induced defects will intensify and localize deformation, but that microscale void mechanisms will still ultimately lead to failure (decoupled scales).

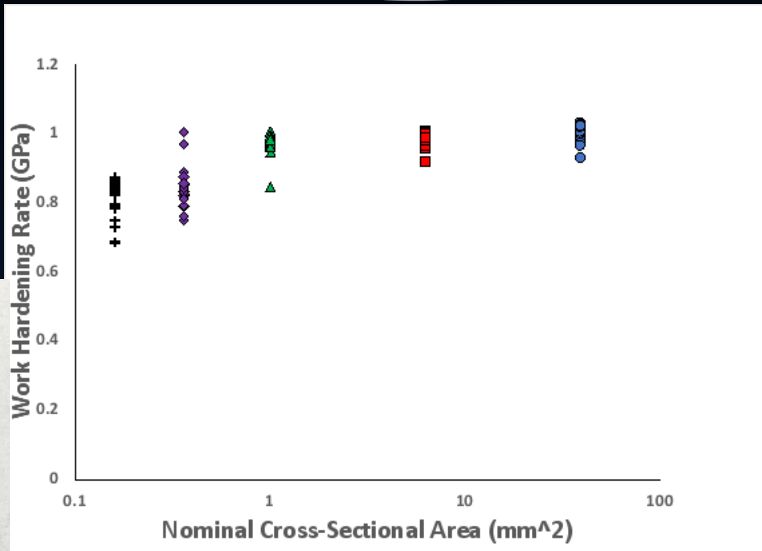


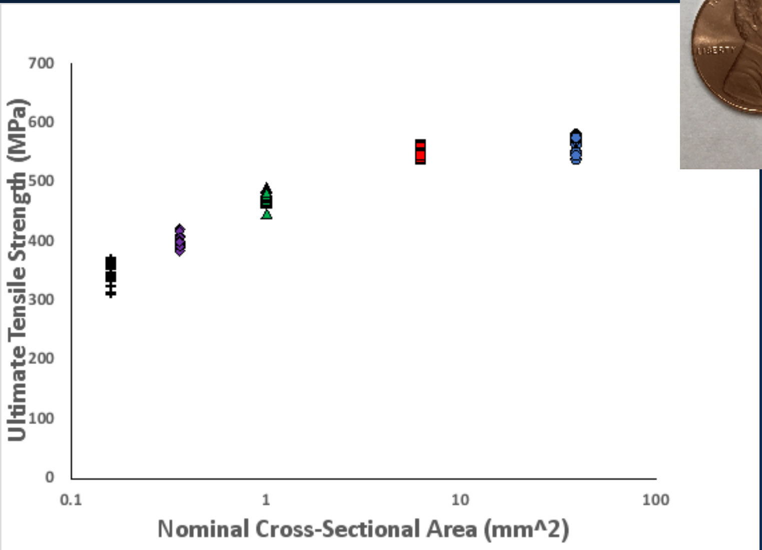


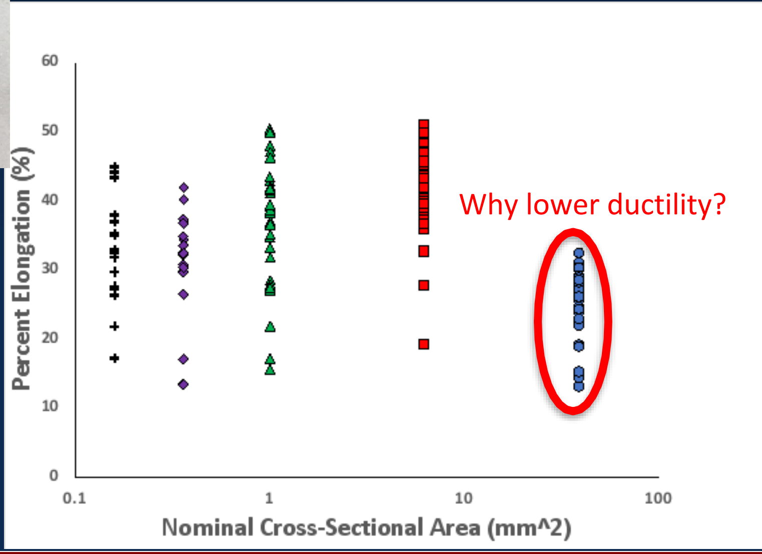

Collaboration with J. Ostien

# Size Effect: Is behavior size dependent?

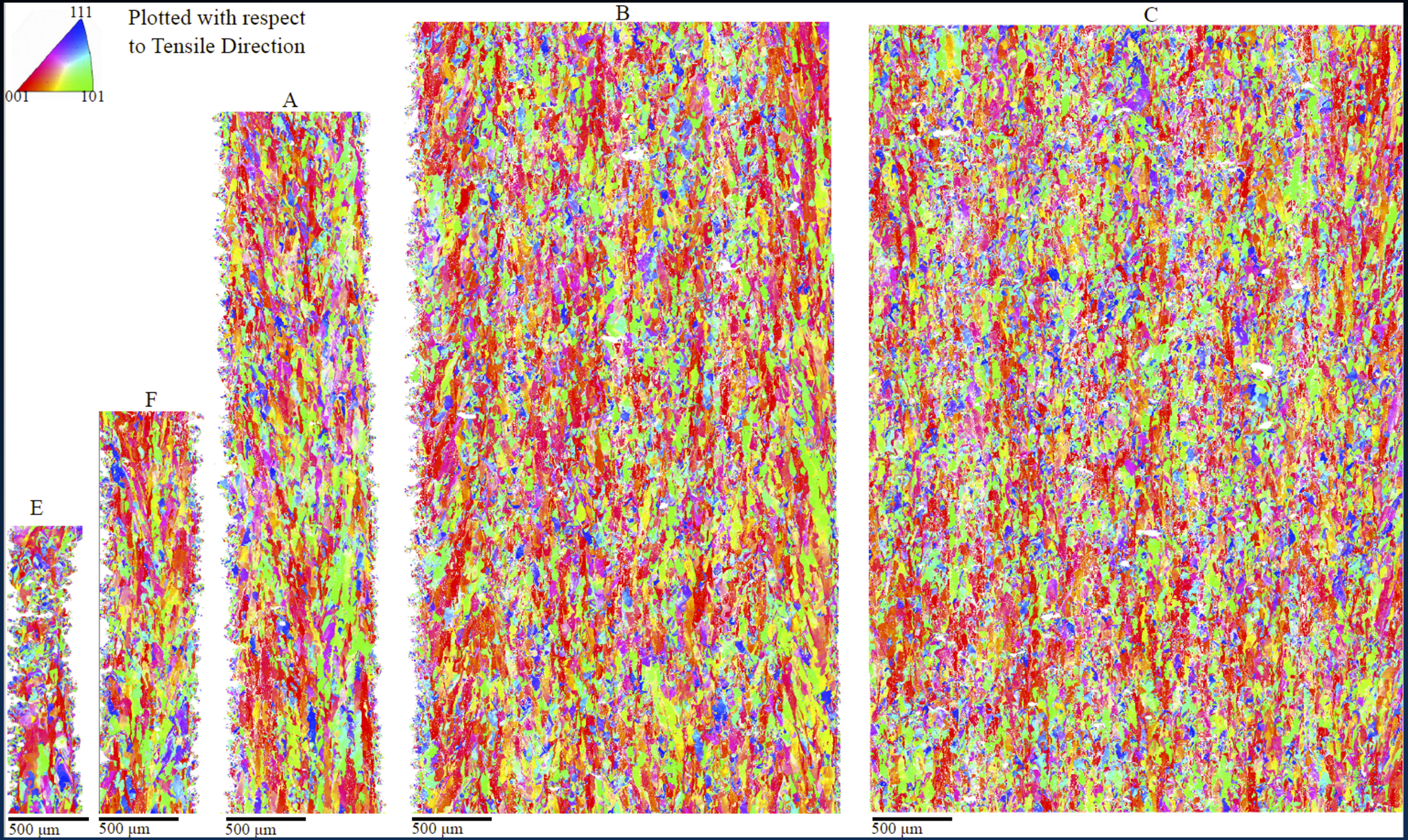


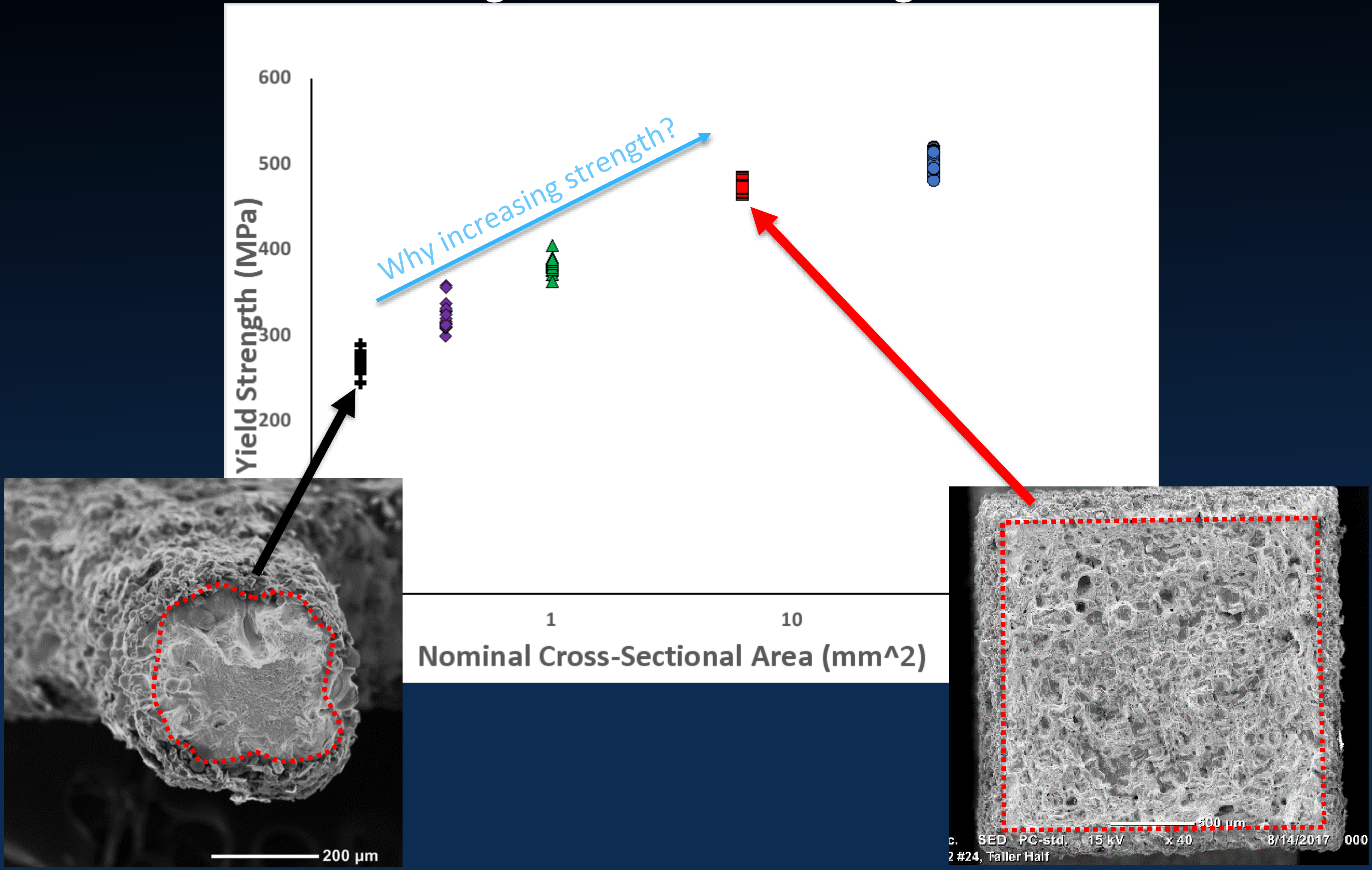



# Microstructure doesn't change much with sample size



# First order size effect: inaccuracy in estimating true load-bearing area



# *Ductility effect in largest samples is due to a bad (highly porous) print layer…*

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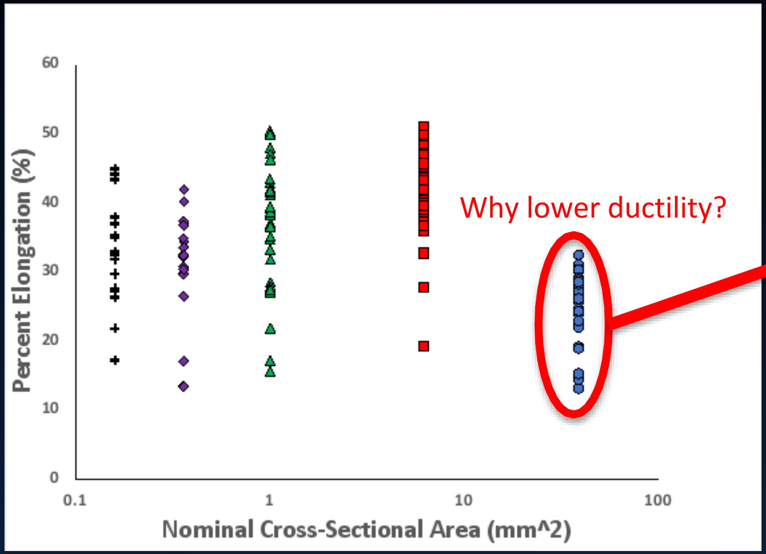
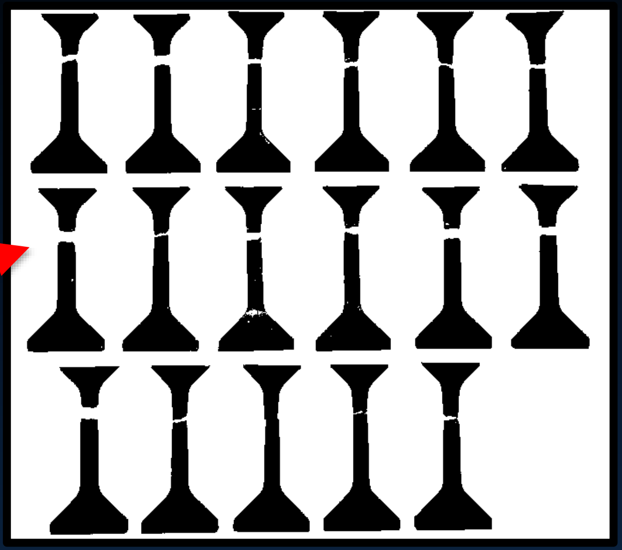
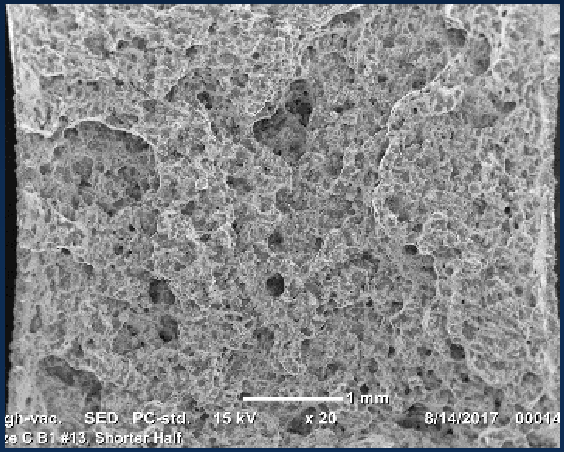
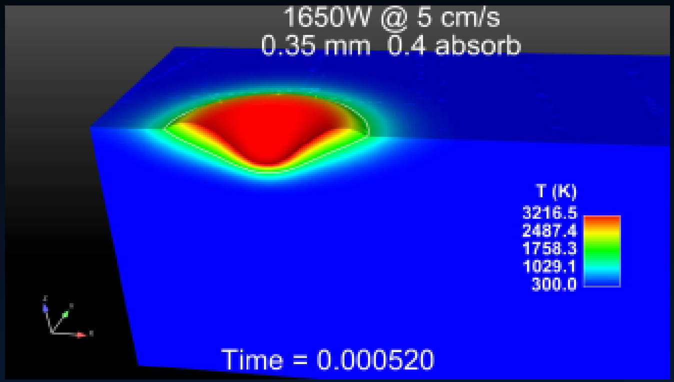


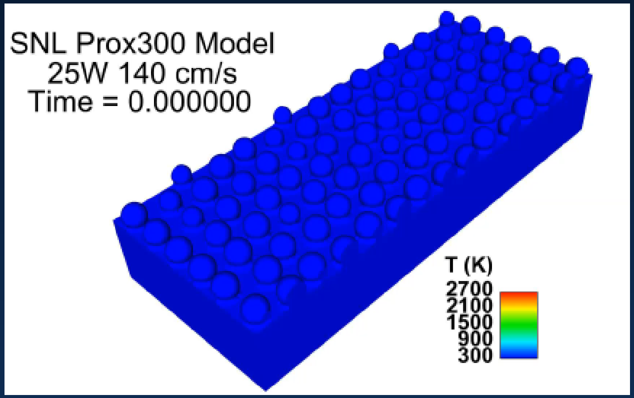



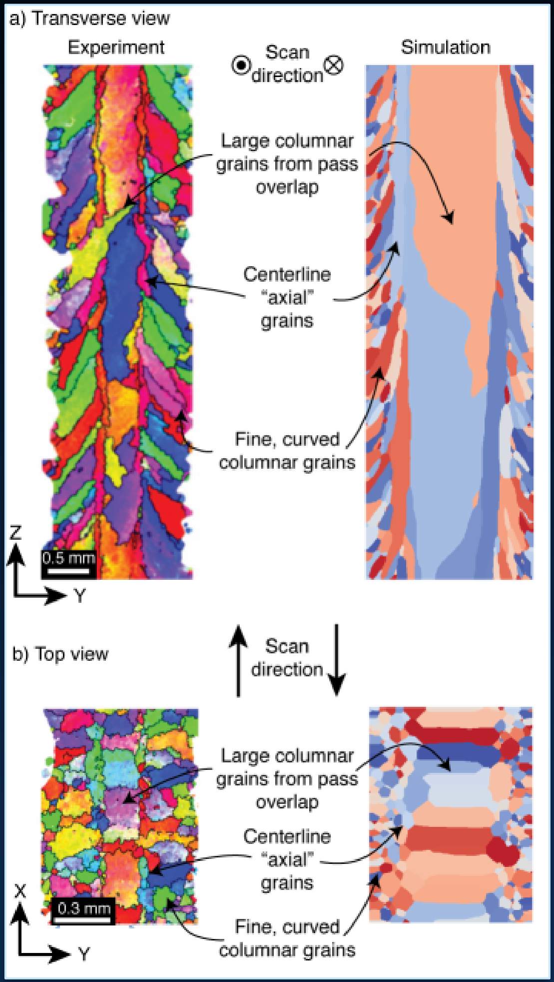
Size C Fracture Location



# *Modeling the AM solidification process*




<u>This is a **herculean** challenge</u>

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 3rd Sandia Fracture Challenge

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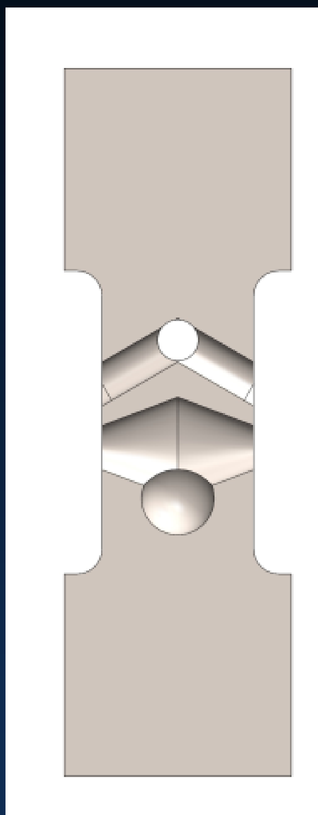
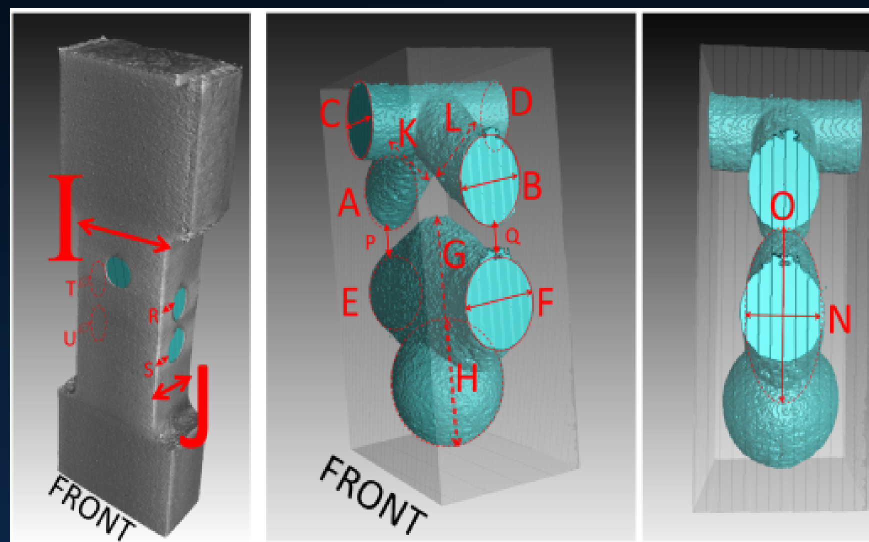
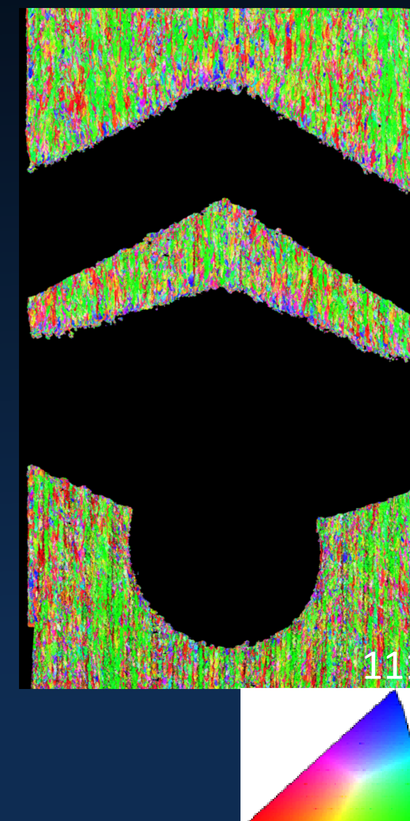
Provided with tensile data, CT data, roughness, microstructure, etc, ***predict*** the conditions (force, displacement) for fracture…






Alloy: 316L

Production method: Laser Powder Bed Fusion






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

# Leveraging the External Community

Sandia National Laboratories

Sandia National Laboratories

NASA

MINES ParisTech

MIT Massachusetts Institute of Technology

Cornell University Founded A.D. 1865

The University of Texas at Austin

Northwestern University 1851

GE

Univerza v Mariboru

The American University in Cairo

UIC University of Illinois at Chicago

Natural Resources Canada / Ressources naturelles Canada

CanmetÉNERGIE

*Leadership en écoInnovation*

RWTH AACHEN UNIVERSITY

ONERA

THE FRENCH AEROSPACE LAB

UCLA Bruins

GLOBAL ENGINEERING & MATERIALS, INC.

*Engineering and Innovative Solutions*

UNIVERSITY OF MIAMI

UT DALLAS

Chongqing University 1929

Tsinghua University 1911

Zhejiang University 1897

UNIVERSITY OF Cincinnati

MISSOURI

Dalian University of Technology 1949

Naval Surface Warfare Center NSWC

A Tradition of Excellence

THE UNIVERSITY OF ARIZONA

RUHR UNIVERSITÄT BOCHUM

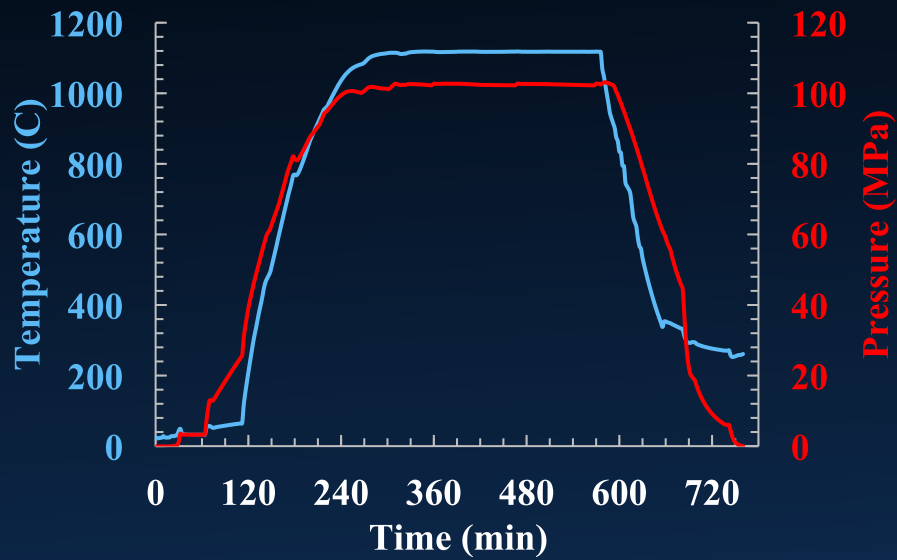
RUB

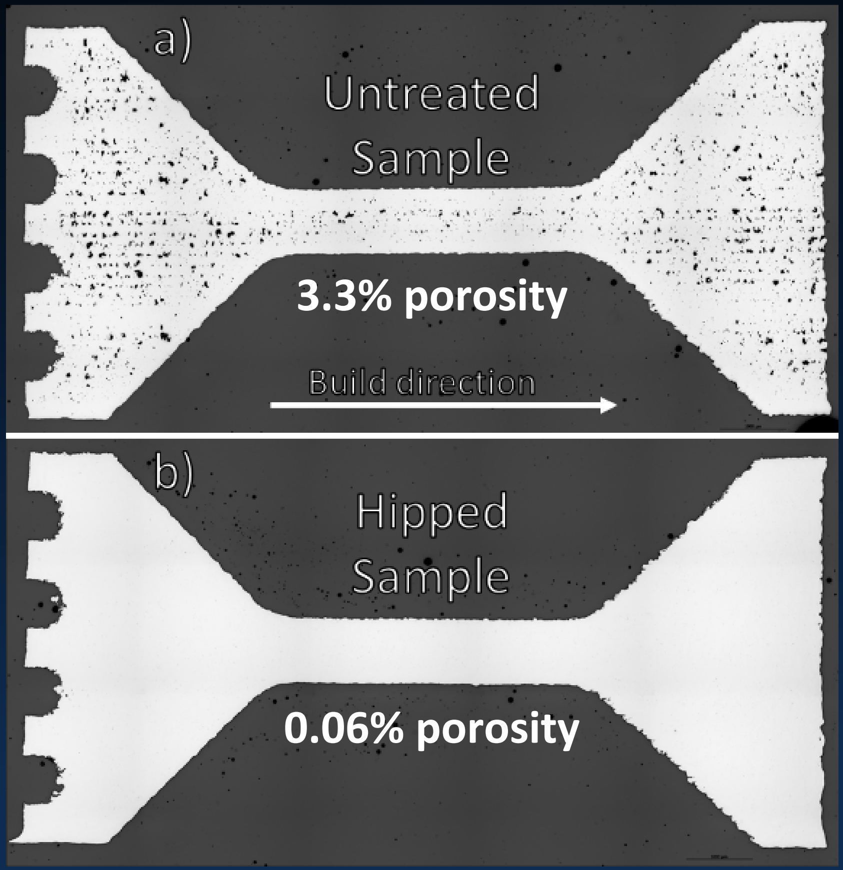
# *Three additional examples Of high-throughput*

*1) HIP remediation of porosity*
*2) Build-location effects*
*3) Powder reuse effects*

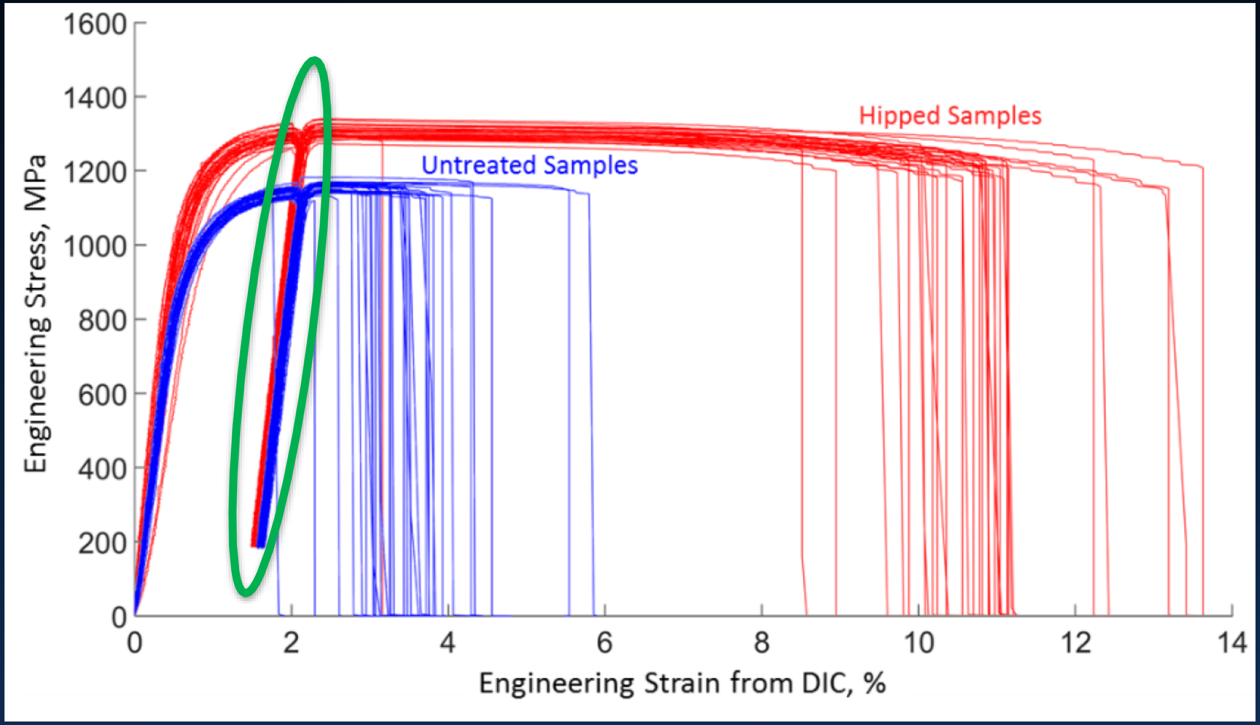
# *Hot Isostatic Press (HIP) Remediation*

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



# *Hot Isostatic Press (HIP) Remediation*

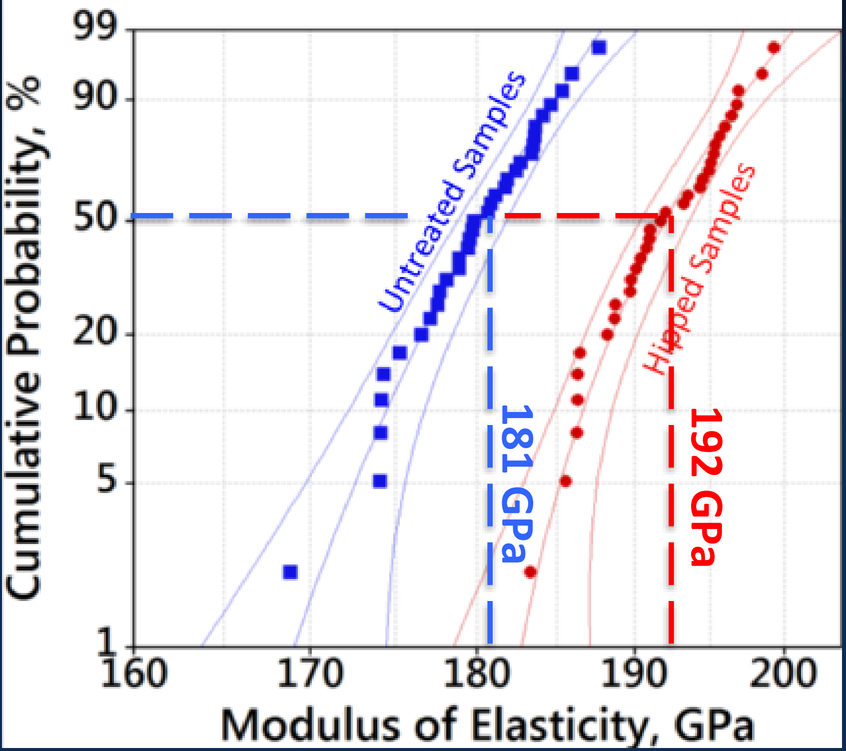


# Effect of Porosity on Modulus

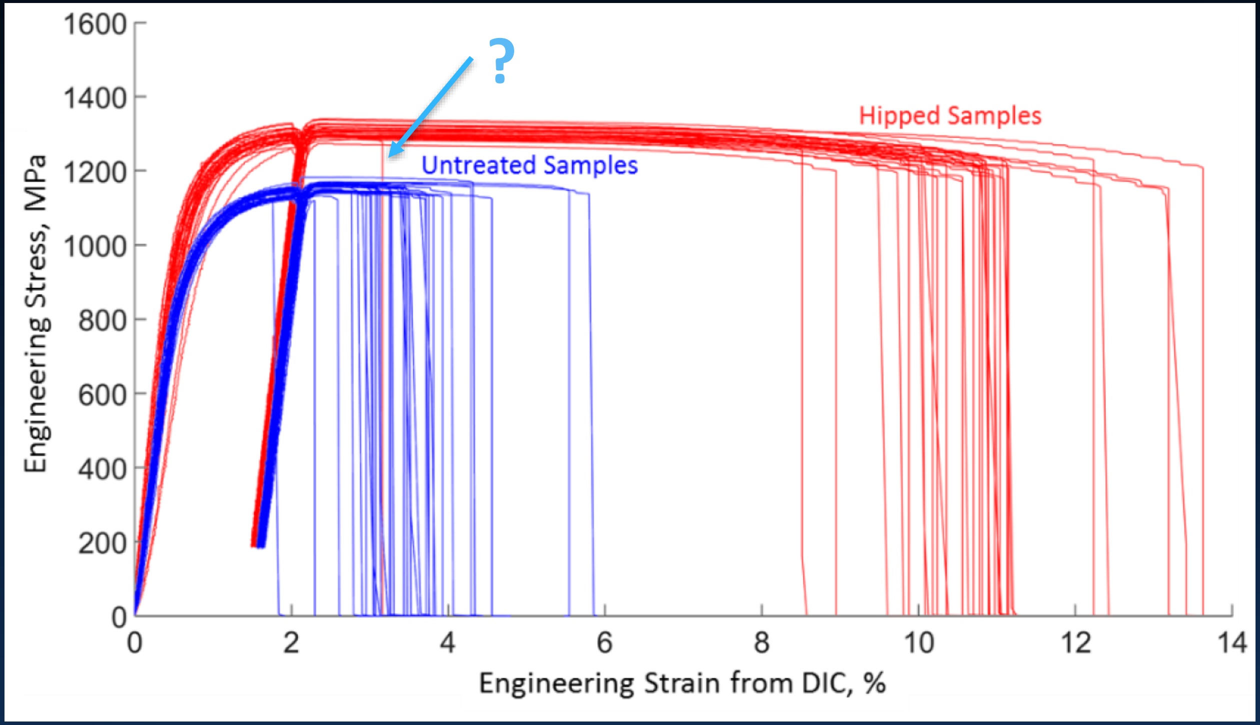
$$E_p = E_0 * (1 - a * P)$$

$a = 1.9$ [Choren et al, J. Mater Sci, 2013]
$E_0 = 195$ GPa

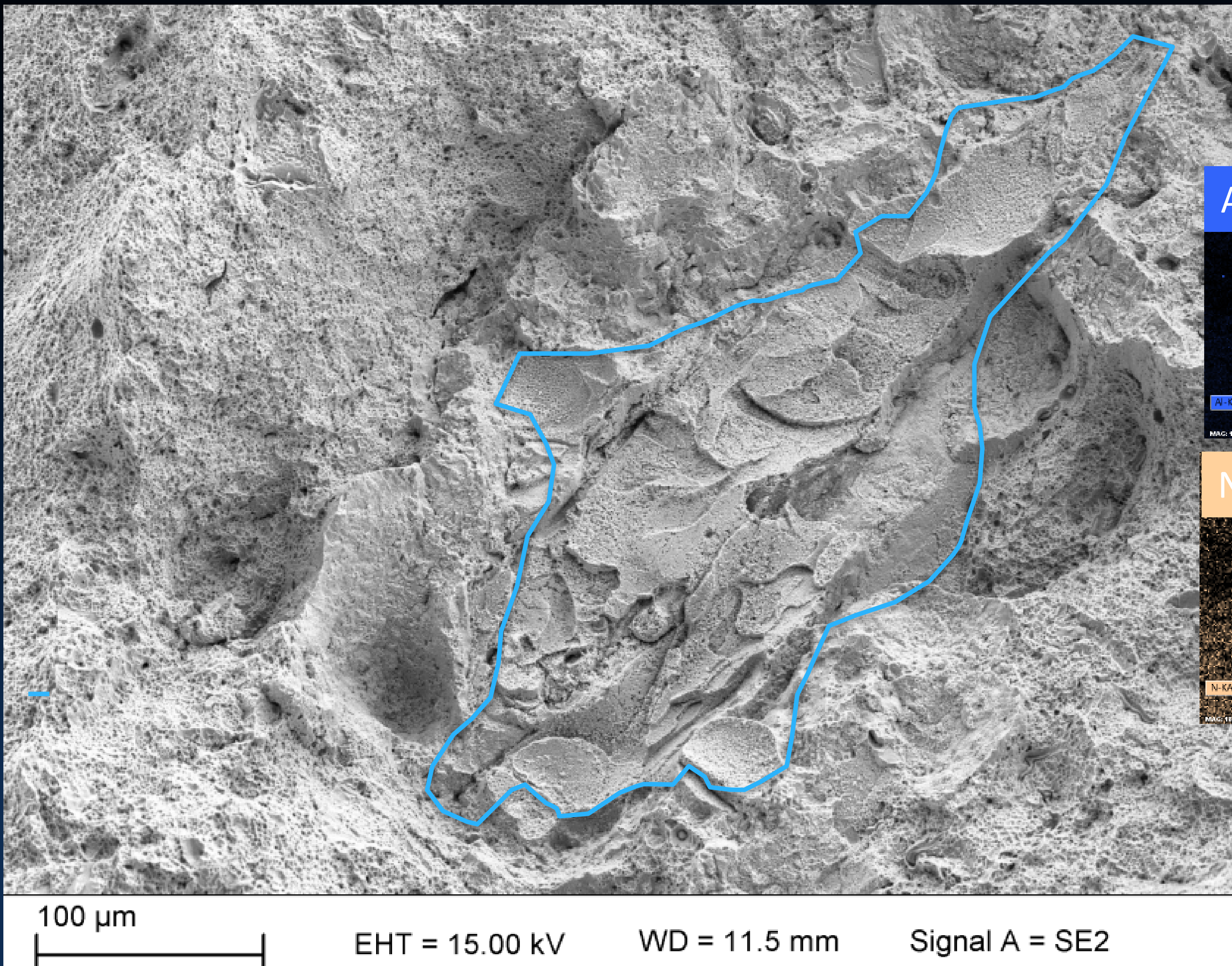
$\Longrightarrow E_{0.06\%} = 195$ Gpa
$E_{3.3\%} = 183$ Gpa

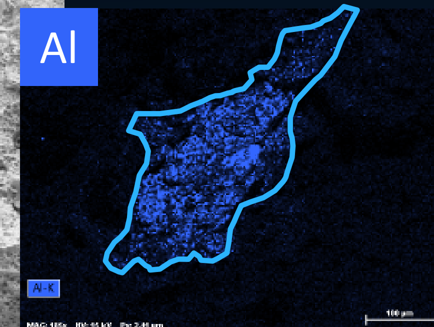


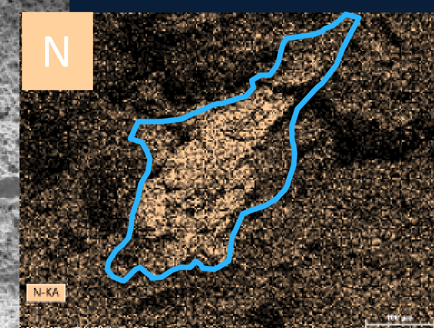
# *Hot Isostatic Press (HIP) Remediation*



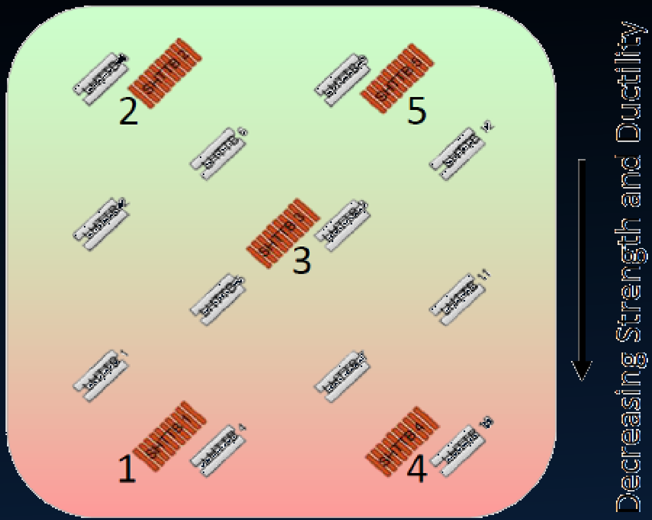
# *Low Outlier: Aluminum-rich region!?*

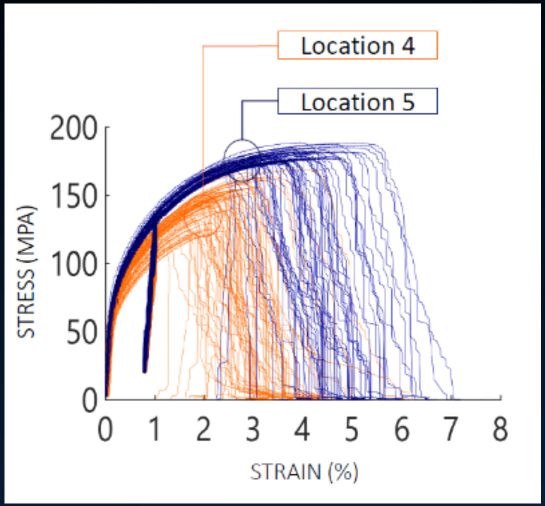


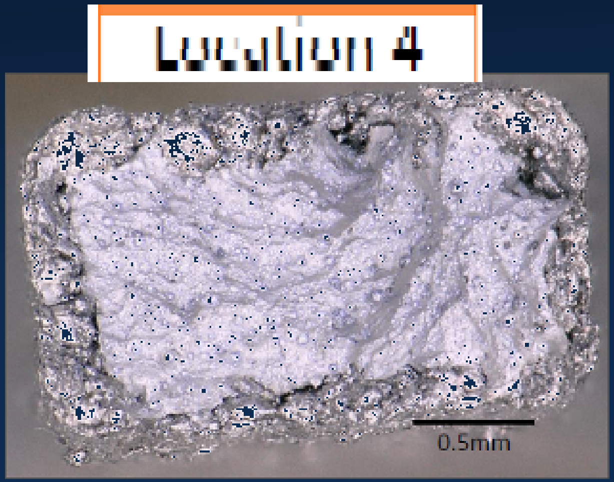



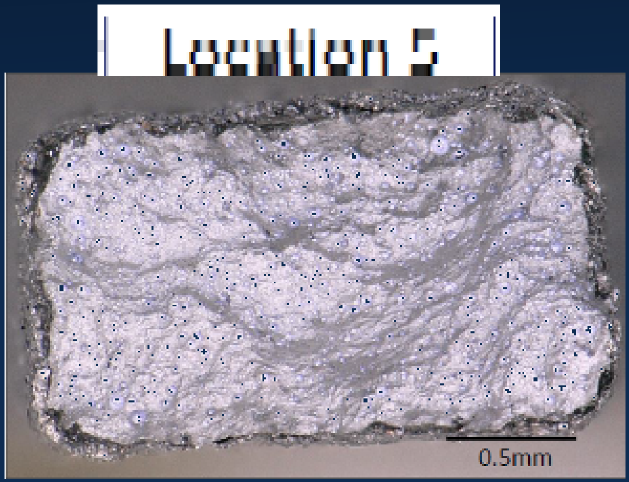
# *Effect of Build-Location*



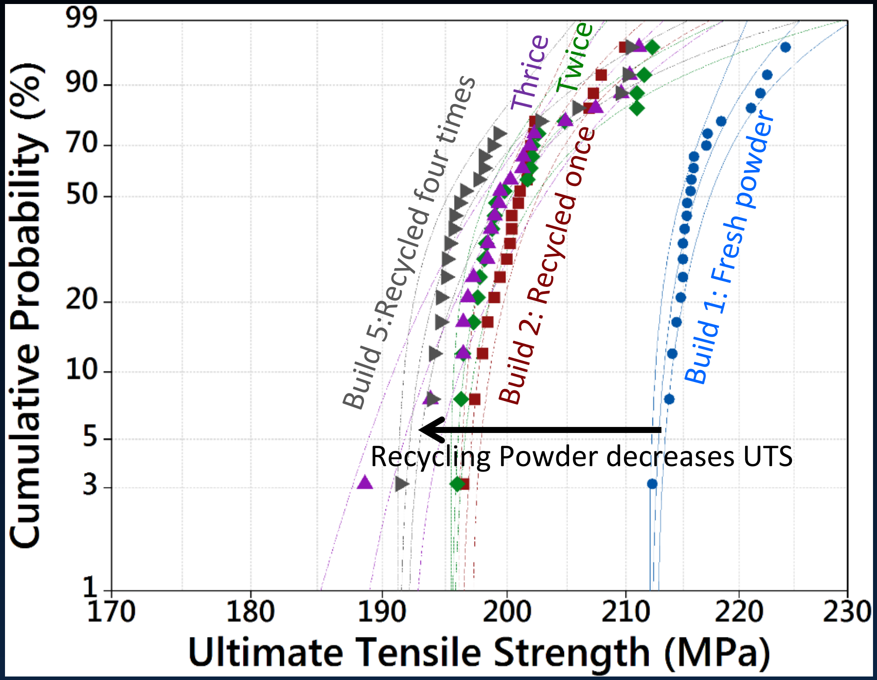

Al-Si-Mg Alloy, Renishaw

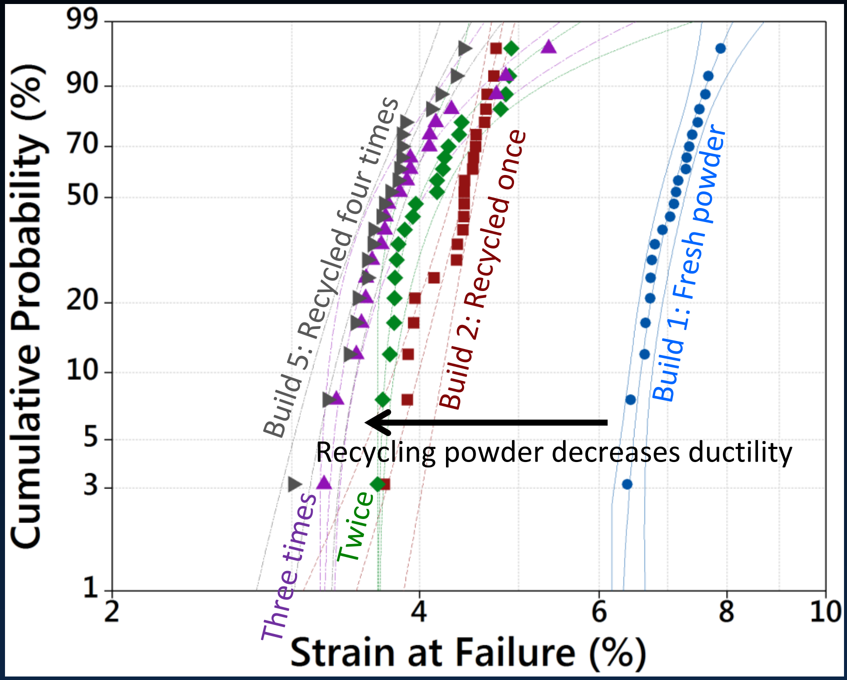


# Rapid evaluation of powder reuse effects

Sandia National Laboratories




Al-Si-Mg Alloy, Renishaw

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

# *Summary…*

Sandia National Laboratories

- 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…*

Sandia National Laboratories

**Properties**

Fatigue
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…

Sandia National Laboratories

## 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.

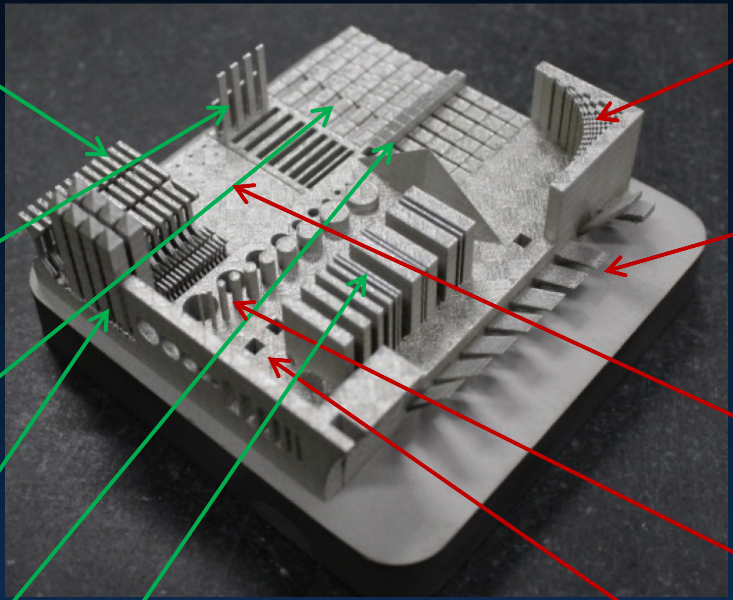
**Notched Features**
Arrays of notched features intended to explore stress-concentration effects on reliability and develop break-away coupons

**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.