The Challenges and Consequences of Material Uncertainties in Metal Laser Powder Bed Fusion

Bradley H. Jared, Brad Boyce, Jon D. Madison, Jakob Ostien, Jeff Rodelas, Brad Salzbrenner, Laura P. Swiler, Olivia D. Underwood, David J. Saiz

Sandia National Laboratories, Albuquerque, NM

Material Assurance

- Material formation concurrent w/geometry
  - want to predict part / material performance
  - how to ID a bad part?
    - must quantify <u>critical</u> defects & useful "signatures"
  - understand mechanistic impacts on properties
    - characterize stochastics
    - build process-structure-property relationships to predict margins & reliability

High Throughput Tensile Testing

- Characterizing material distributions
  - requires rapid performance quantification
  - custom dogbone per ASTM
  - digital image correlation (DIC)
  - monolithic build w/110 dogbones
- Defect dominated failure
  - ductile dimples & shear rupture planes
  - voids & lack-of-fusion boundaries are likely crack nucleation sites
  - 3-parameter Weibull fits inform design threshold
  - can inter-build performance be predicted?

Material Characterization

- Correlation study
  - 110 17-4PH samples from single part w/nominally constant process parameters
- NDE before testing
  - detect defects, performance correlations
  - density (Archimedes), resonant ultrasound spectroscopy (RUS), optical surface measurements, computed tomography (CT)
- Post mortem after testing
  - inform performance & failure mechanisms
  - fractography, metallography, composition, XRD
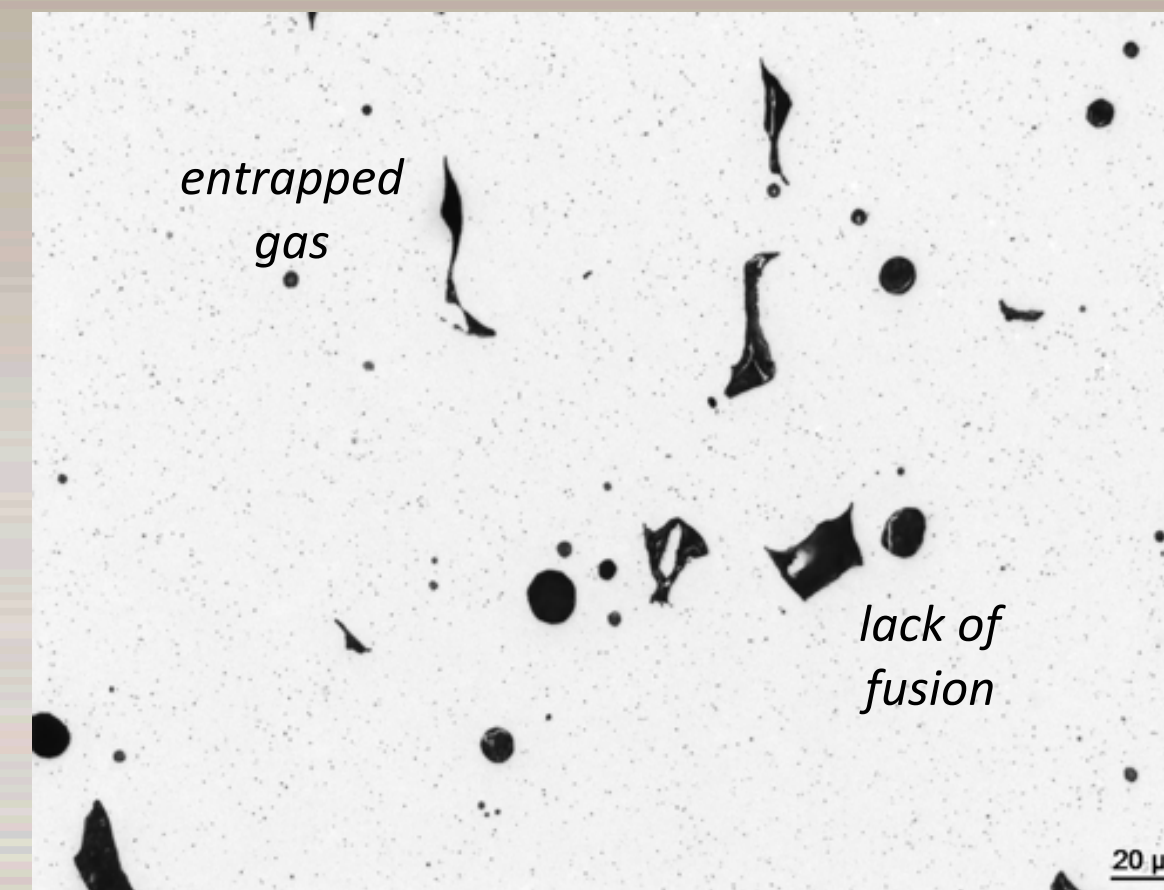
Implicit Part Correlations

- Archimedes density
- Resonant Ultrasound Spectroscopy
  - swept sine wave input from 2-point transducer (74.2 kHz - 1.6 MHz), 19 resonance peaks
- Surface finish
- No significant trends
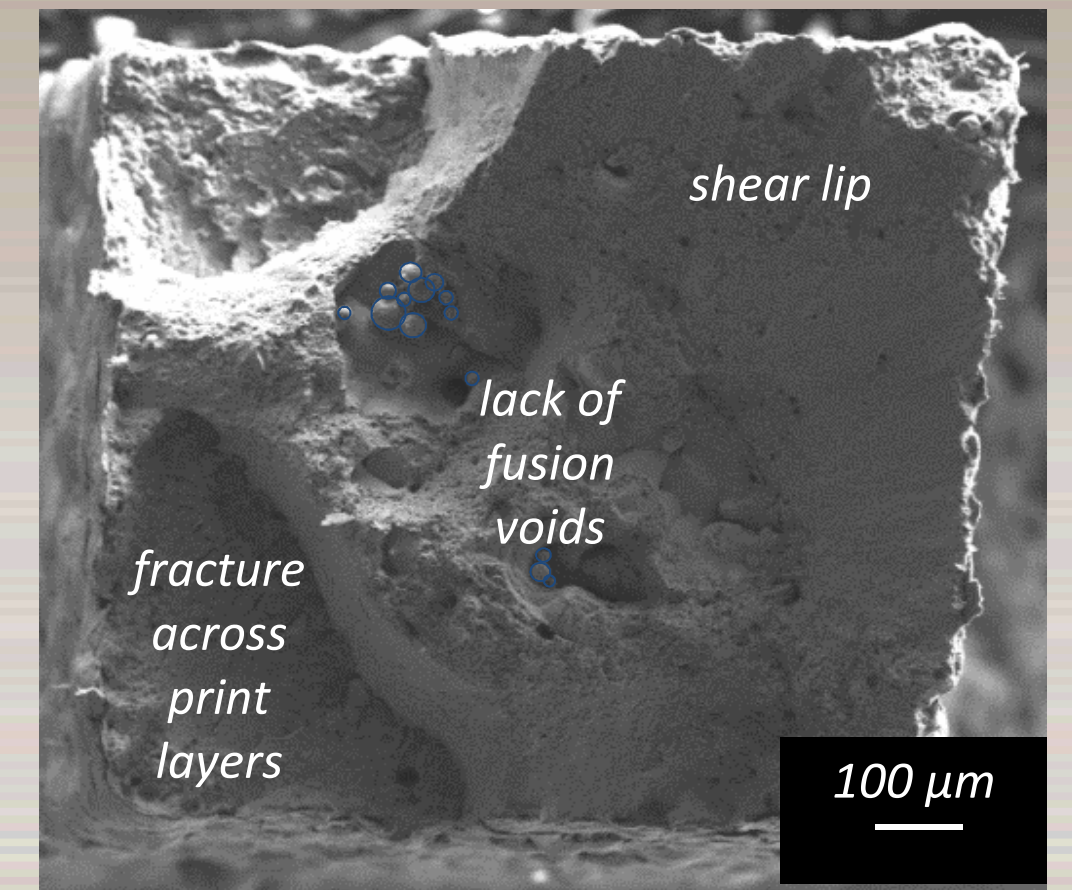
Explicit Porosity Measurements

- Computed tomography (CT)
  - NDE "gold standard" for porosity measurement
  - gage sections imaged w/resolution of 7 or 10 μm voxel edge length
- What can we see? Does it inform material behavior predictions?
  - justifiable for qualification and/or production?
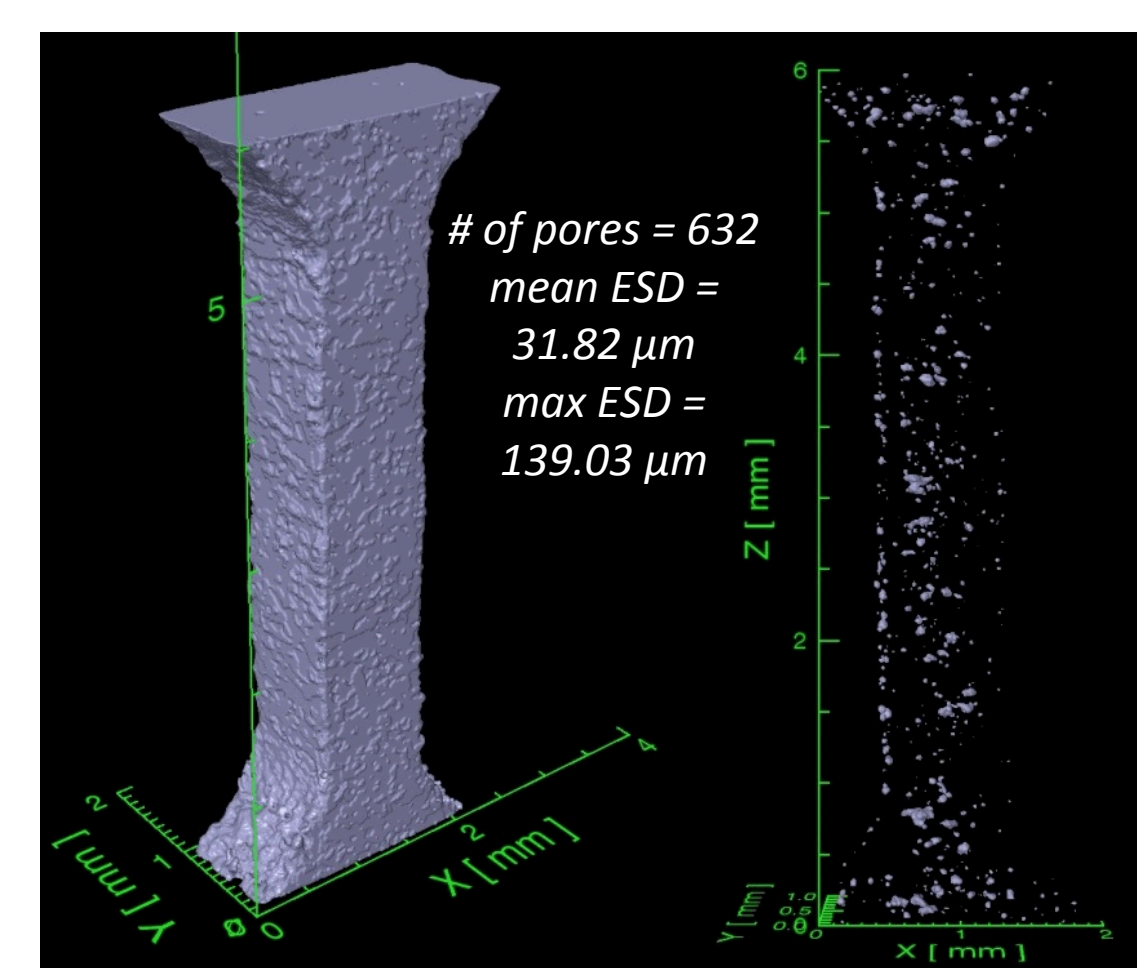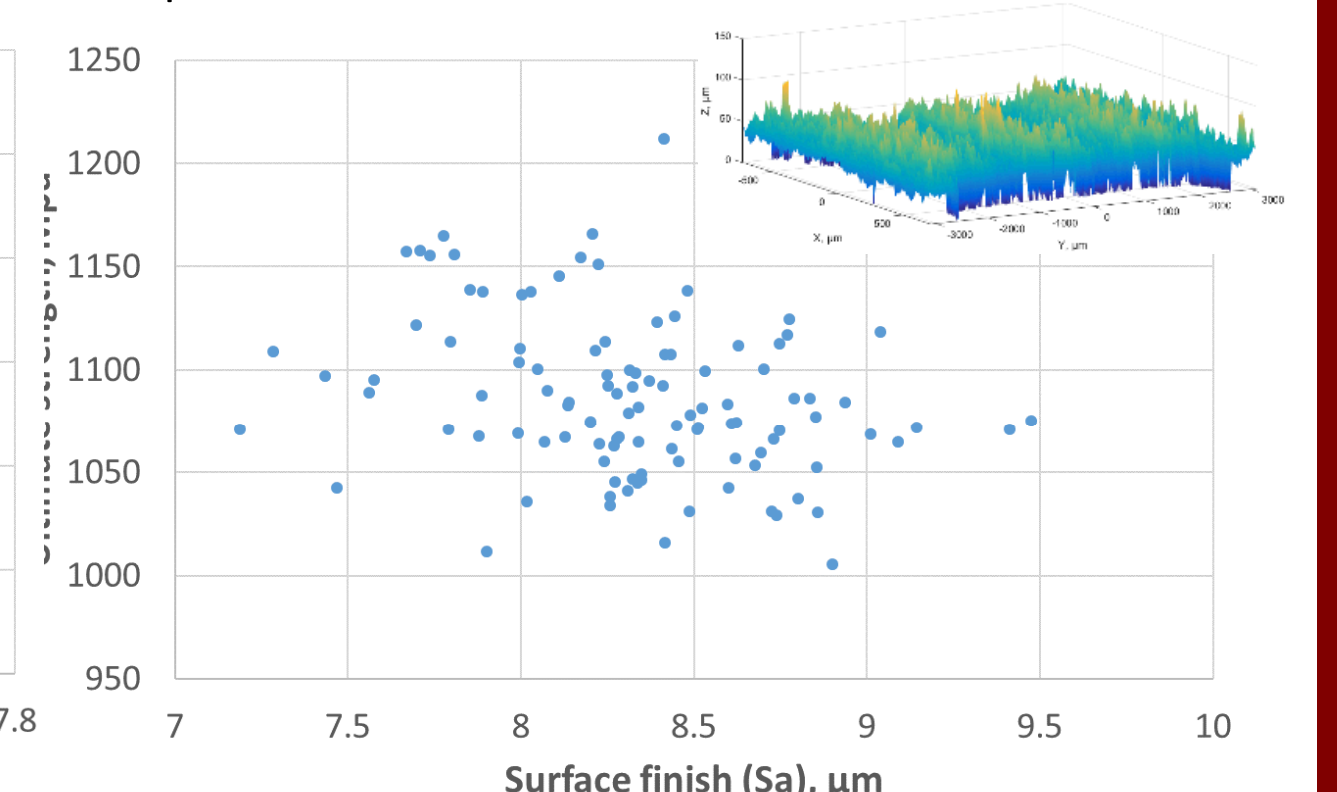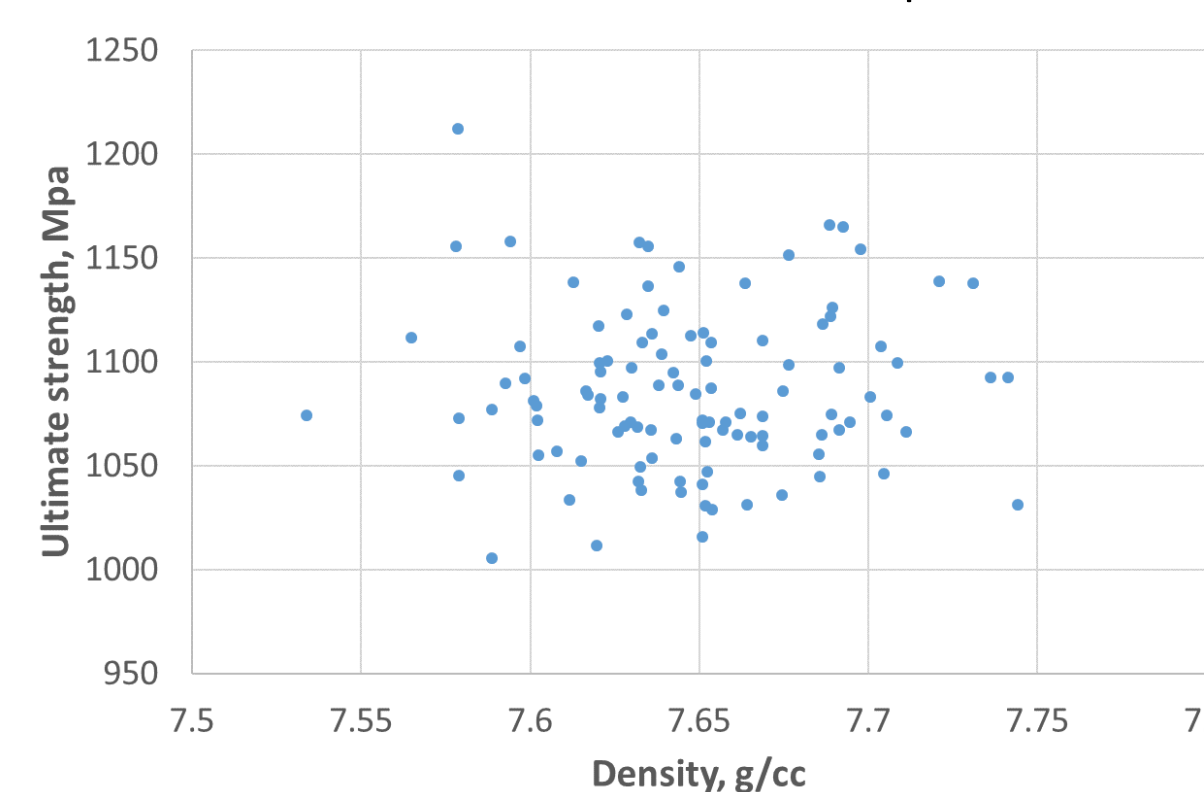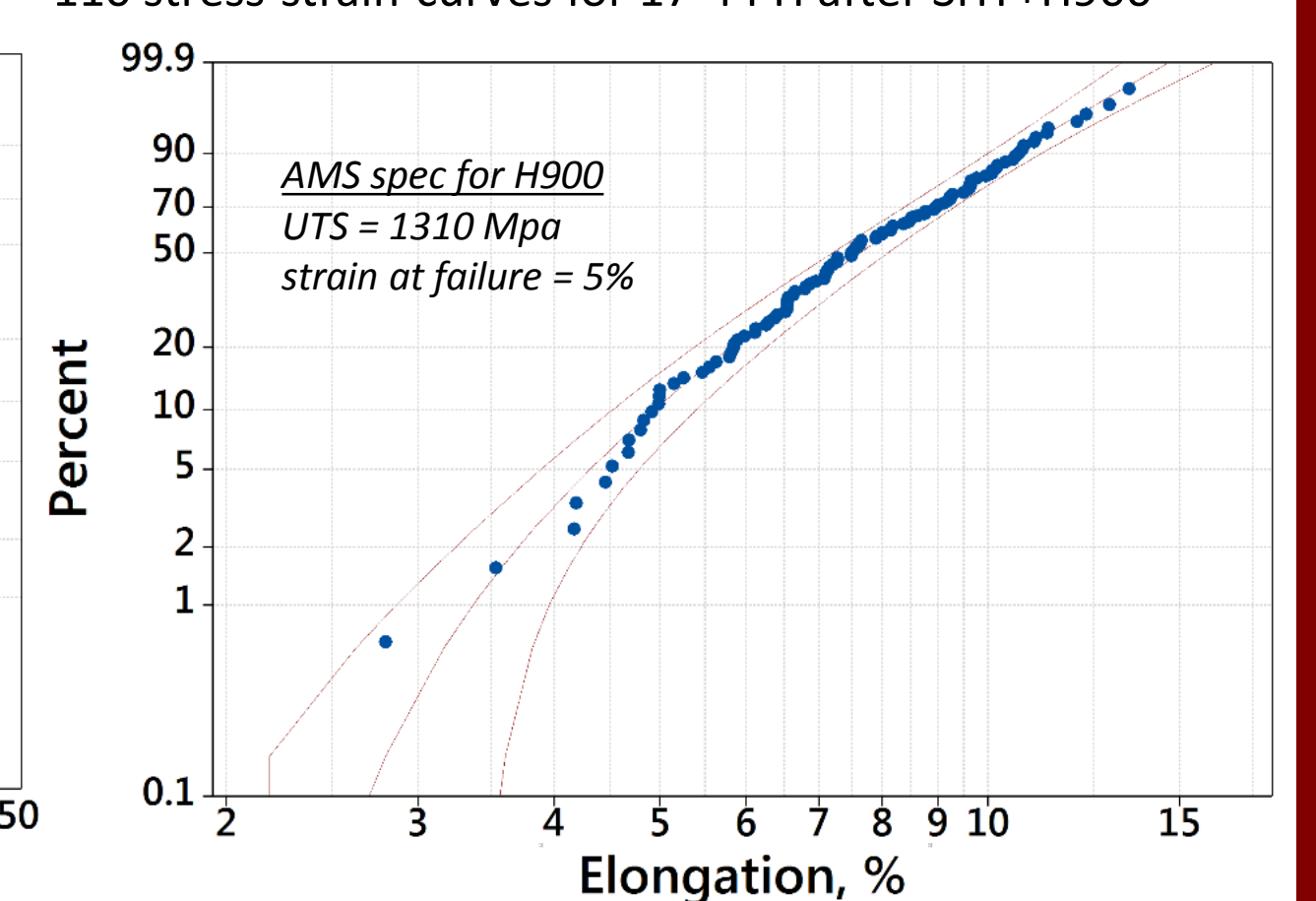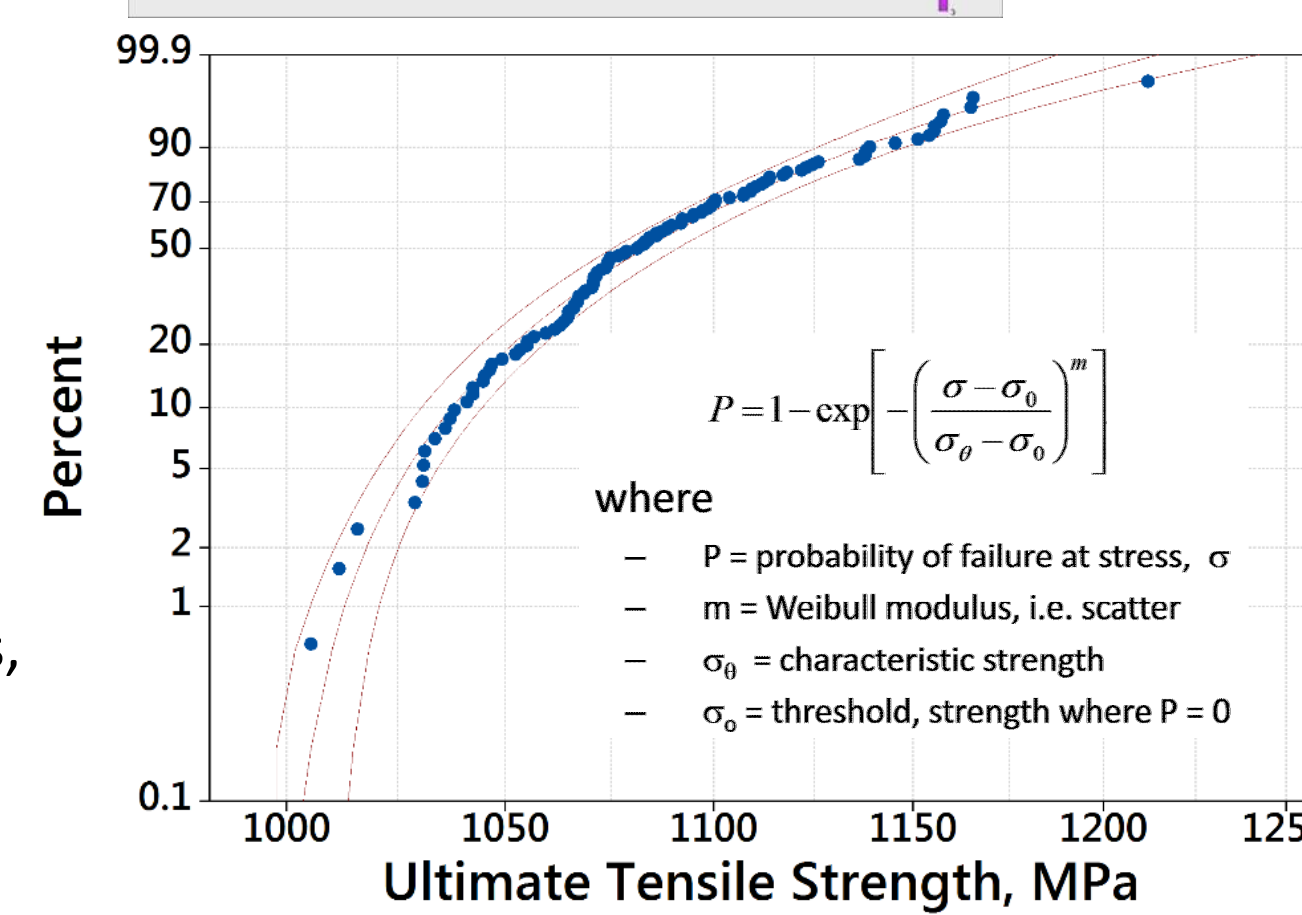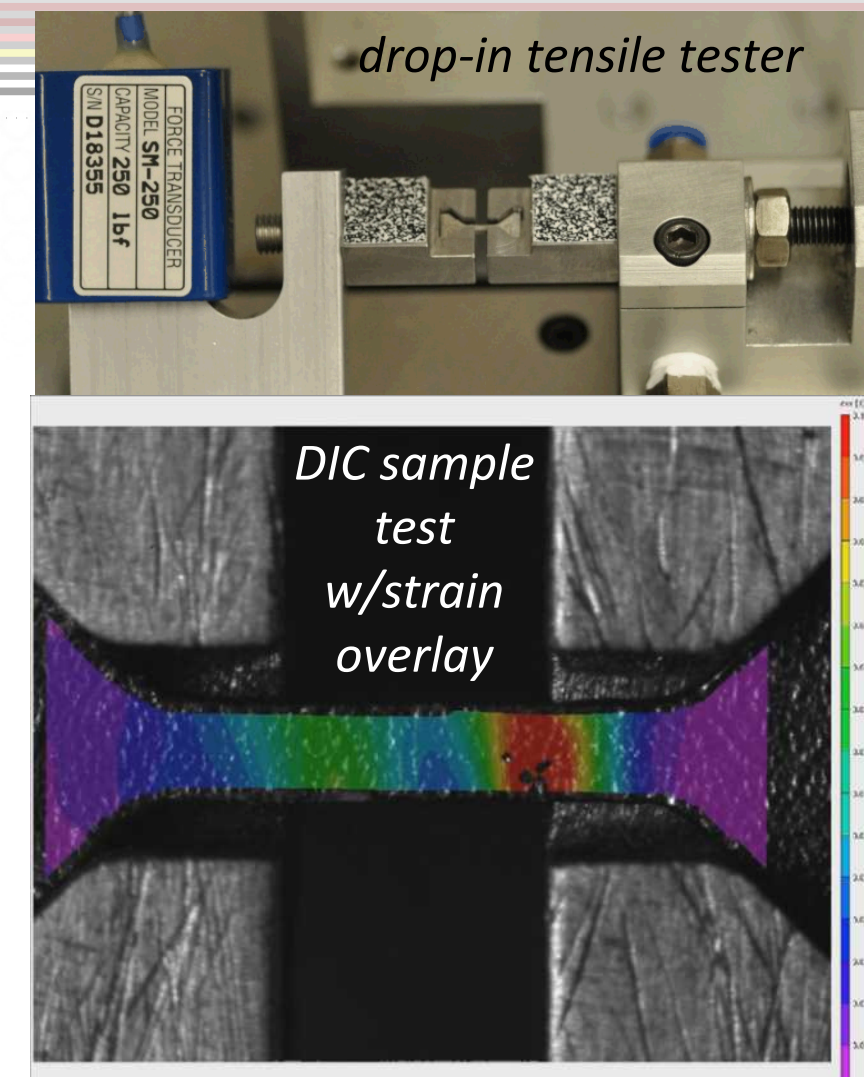- Statistical correlations are elusive

Summary

- Material assurance is a challenge
  - material behavior is complex
    - contributing factors include process, feedstock, measurement, surface finish, microstructure
  - orthogonal testing pursuing multiple signatures is invaluable for qualification / product acceptance
- Tools developed to interrogate & analyze defects
  - performance distributions can be captured efficiently & used to understand material & process
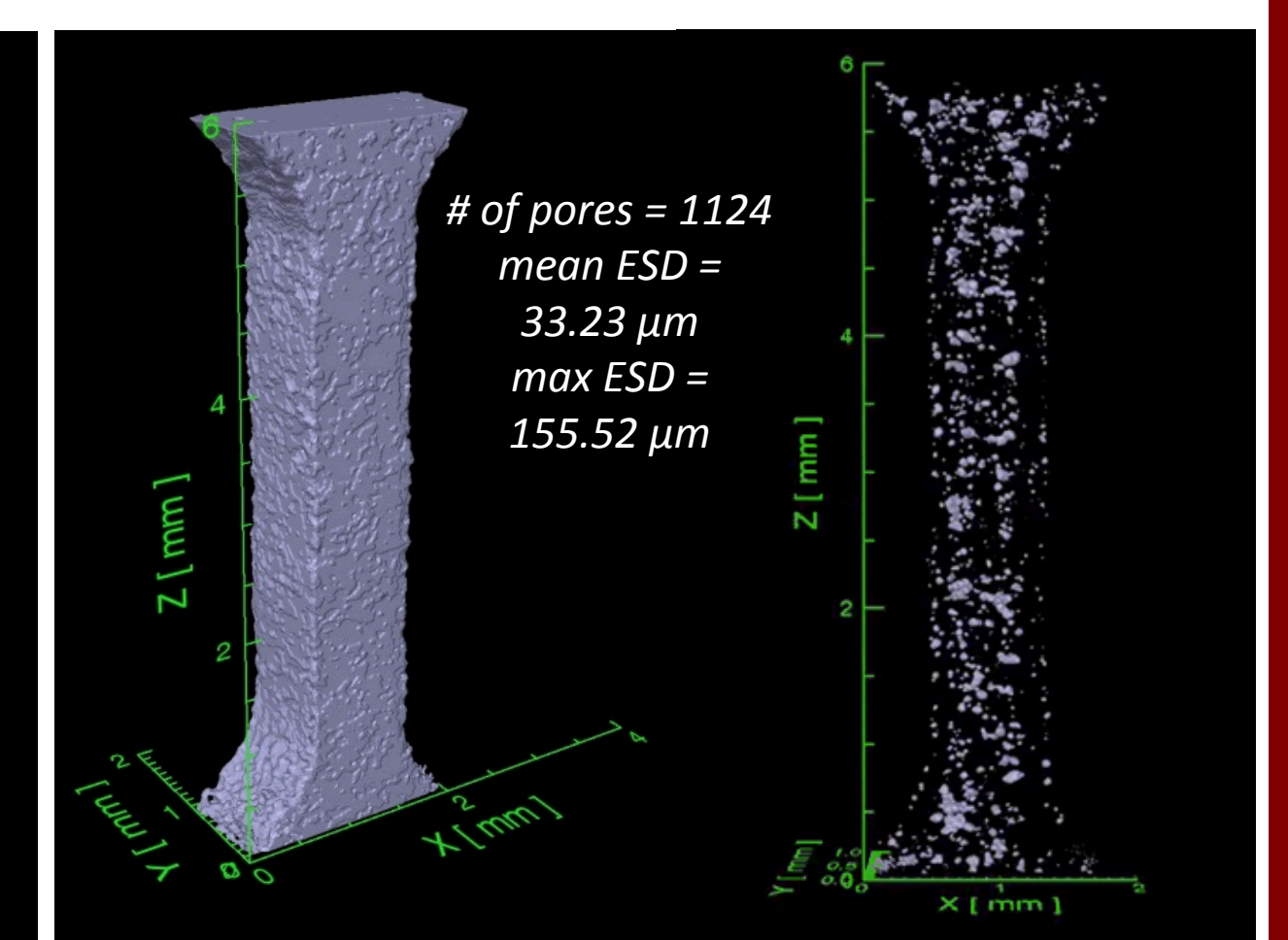

entrapped gas
lack of fusion
20 μm
17-4PH representative material defects

shear lip
lack of fusion voids
fracture across print layers
100 μm
17-4PH dogbone fracture surface after SHT+H900, failure at 2% elongation

drop-in tensile tester
DIC sample test w/strain overlay

110 stress-strain curves for 17-4 PH after SHT+H900

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

where
- P = probability of failure at stress, σ
- m = Weibull modulus, i.e. scatter
- σ_θ = characteristic strength
- σ_o = threshold, strength where P = 0

AMS spec for H900
UTS = 1310 Mpa
strain at failure = 5%

material performance fit to 3-parameter Weibull distributions

# of pores = 632
mean ESD = 31.82 μm
max ESD = 139.03 μm

# of pores = 1124
mean ESD = 33.23 μm
max ESD = 155.52 μm

dogbone B,16 CT surface image (left), porosity map (right)

dogbone C,16 CT surface image (left), porosity map (right)

stress-strain curves for B,16 and C,16
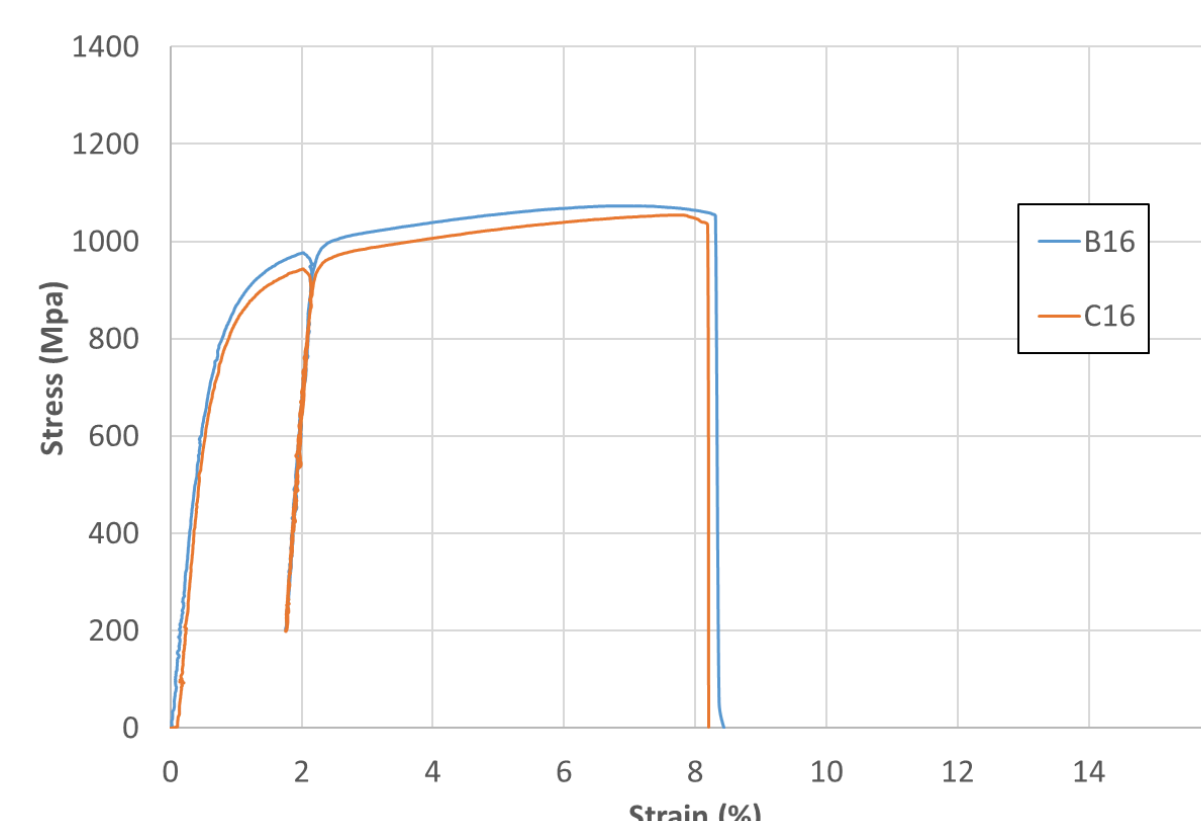
Measure	R^2
No. of Defects	0.50
Avg. NN Distance (mm)	0.40
Avg. ESD (mm)	0.36
Max CSA Redux (mm²)	0.38
Total Pore Volume (mm³)	0.27
Avg. Defect Vol. (mm³)	0.25
Max CSA Redux (%)	0.24
Maximum Pore Size	0.07
Seven factor multivariate regression	0.60

y = 1132.5 - 0.5x   R= 0.70

y = 935 + 4.73x   R= 0.63

y = 440 + 14.4x   R= 0.60

y = 1099 - 6117x   R= 0.52

y = 1059 - 4167zx   R= 0.23

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