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Rapid, High-Throughput Mechanical Evaluation of Additively Manufactured Metals

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U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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A background on efficient statistical testing in MEMS

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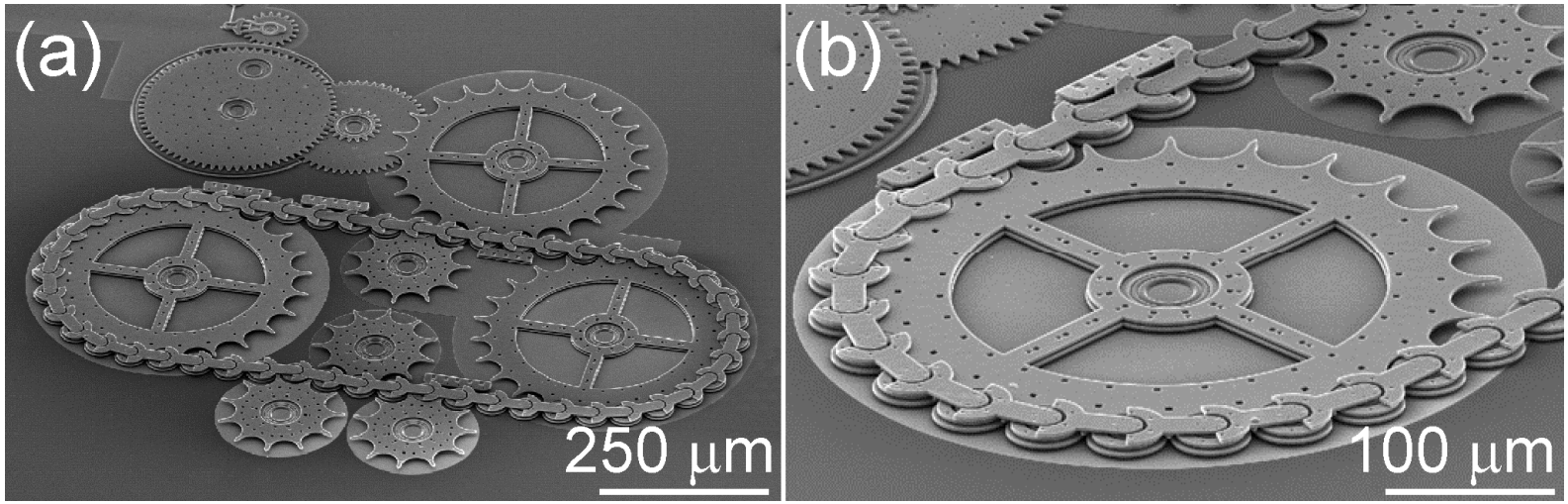
Microsystems (MEMS) is a mature additive manufacturing technique



Many MEMS concepts translate into metal additive manufacturing:

* Parametric process monitoring and control
* Adoption of diagnostic test artifacts measured alongside every build
* Adoption of rapid, automated, high-throughput material testing

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

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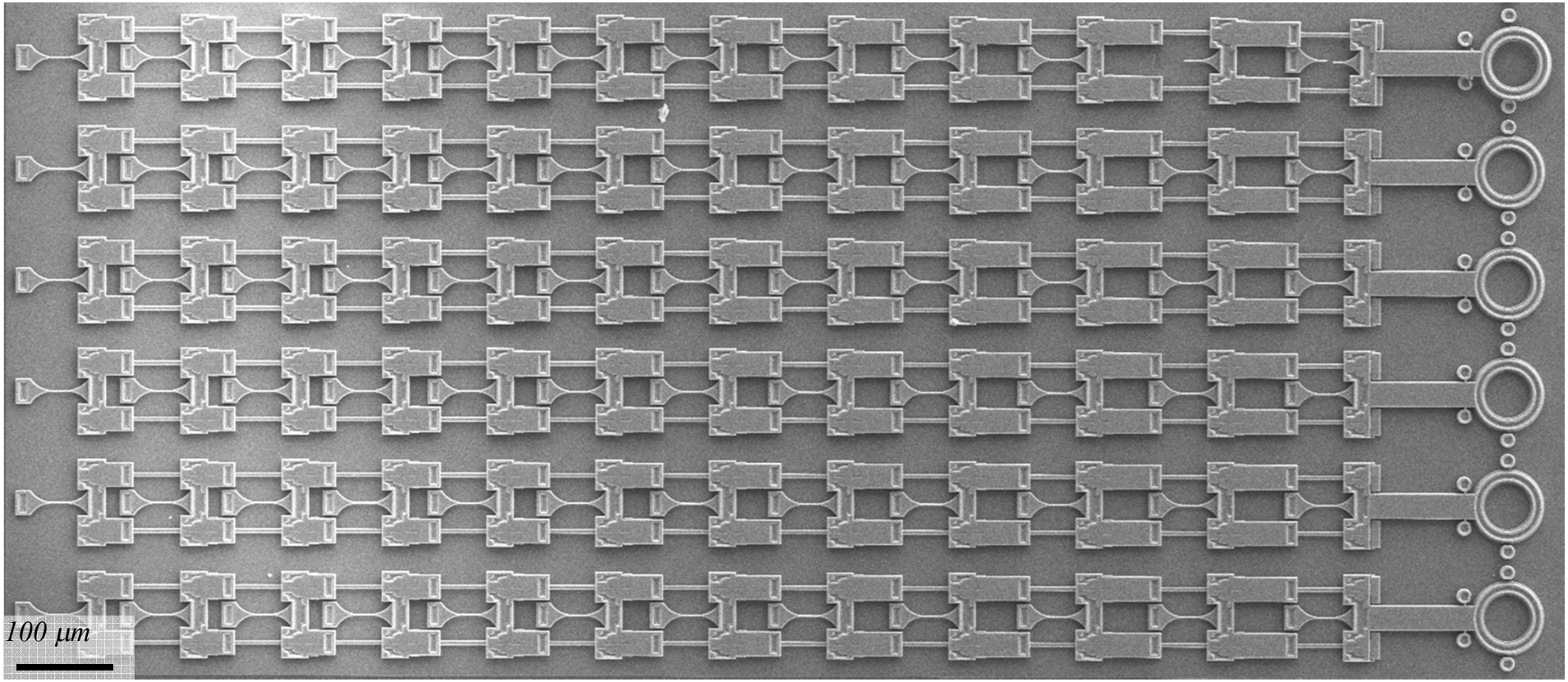

Boyce, *Experimental Mechanics,* 2010

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

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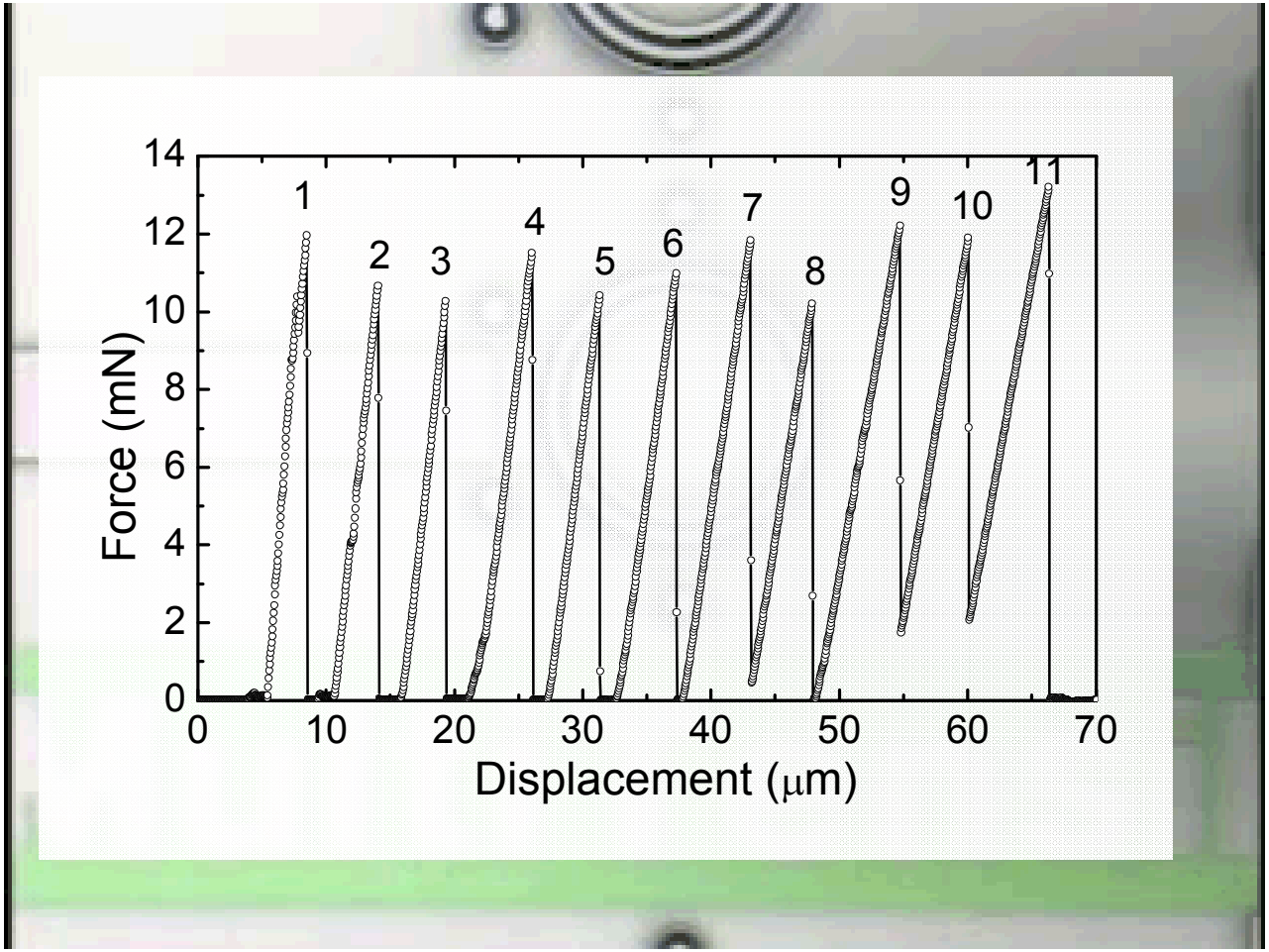


The Weibull formulation of Weakest Link Theory

Failure Probability

$$P_{\mathrm{f}} = 1 - \exp\{-n\varphi(\sigma_f)\}$$

Stress functional

Number of links in chain

$$P_{\mathrm{f}} = 1 - \exp\{-[(\sigma_{\mathrm{f}} - \sigma_{\mathrm{th}})/\sigma_{\theta}]^{m}\}$$

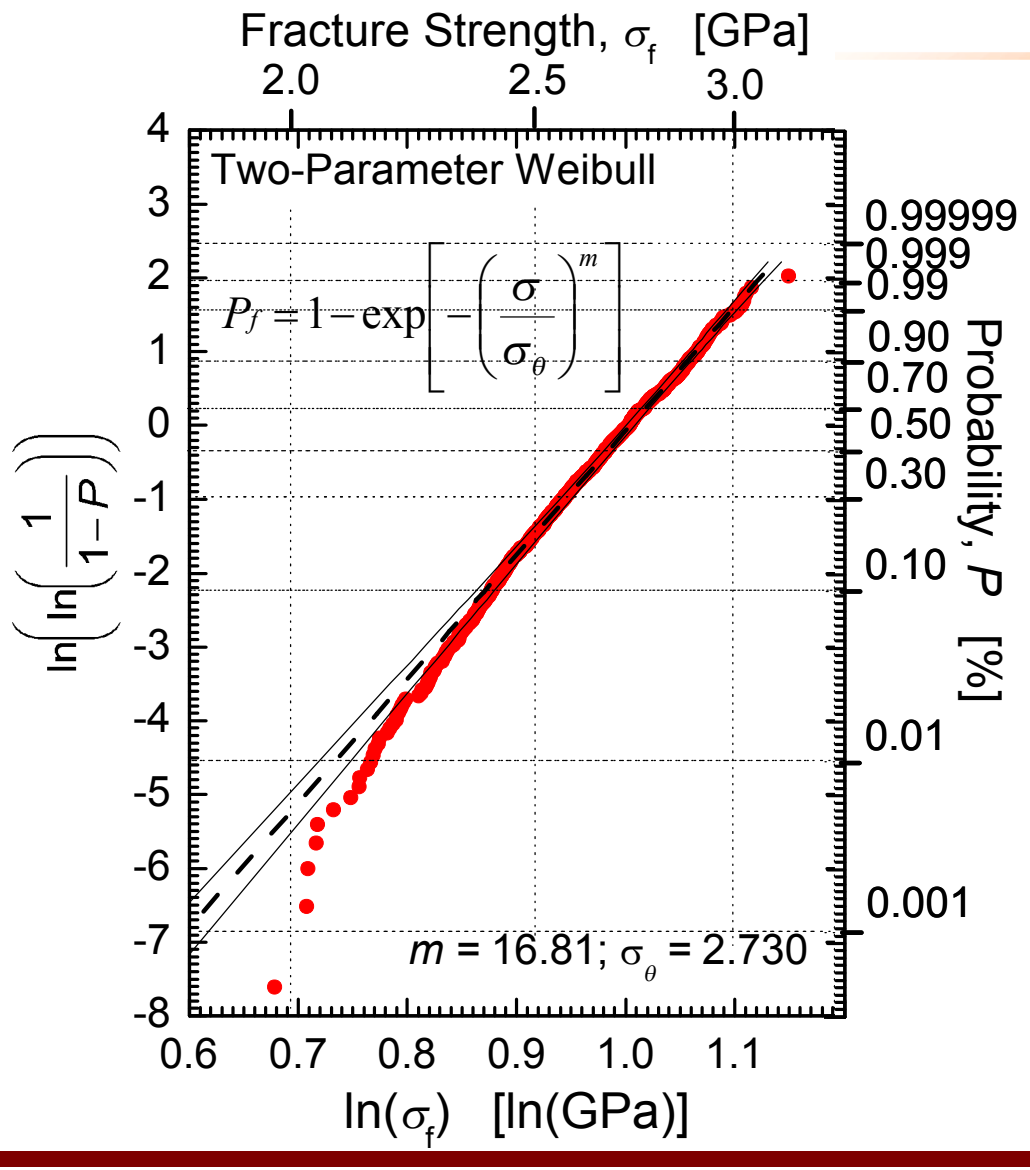
Weibull modulus

Fracture strength

Characteristic Strength

Threshold stress

Weibull Fit to 1,008 Nominally Identical Tests



Boyce, *Experimental Mechanics*, 2010

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

Sequential concept in Additive Manufacturing…

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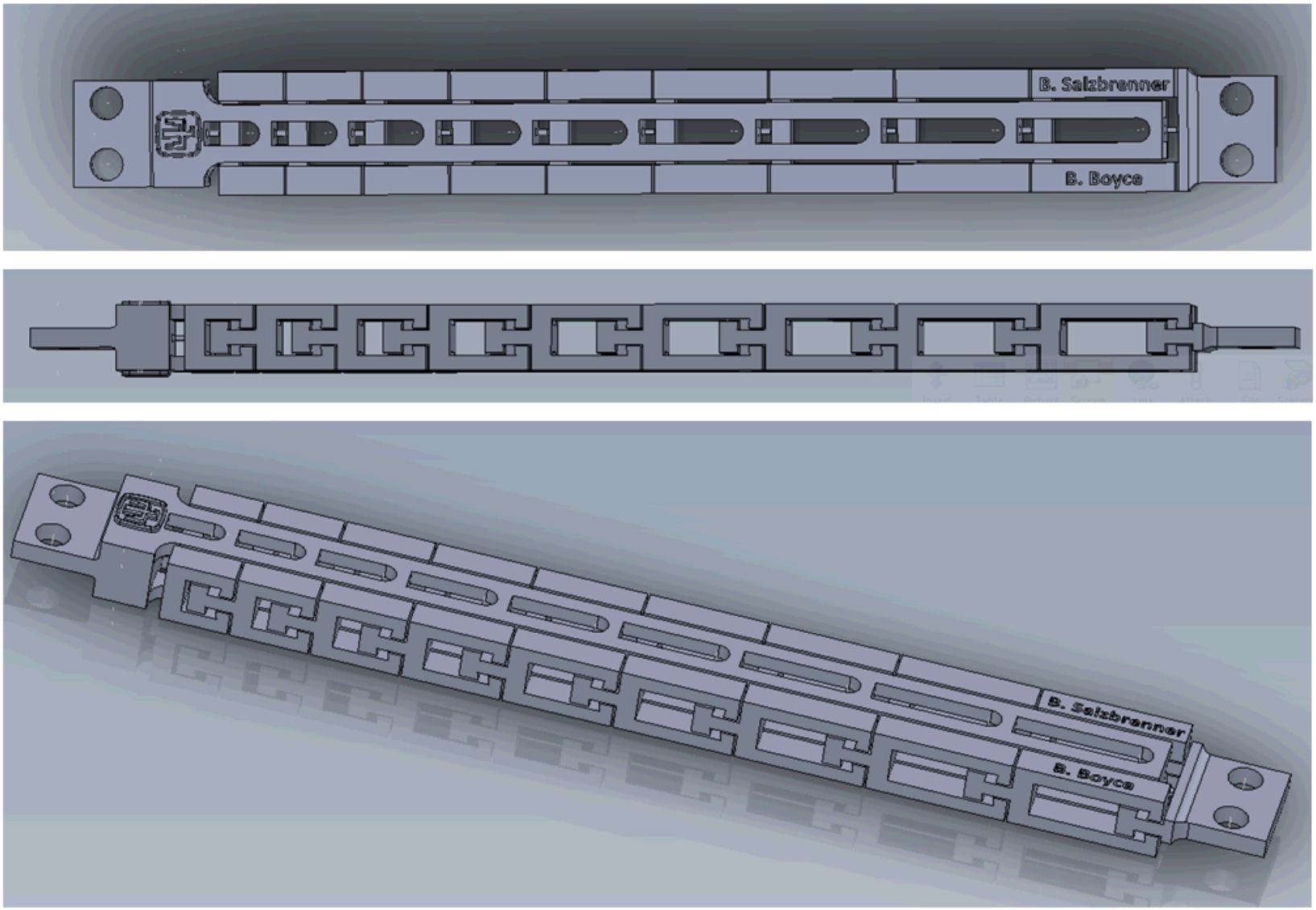

AM offers opportunities to print extensive mechancial test coupons

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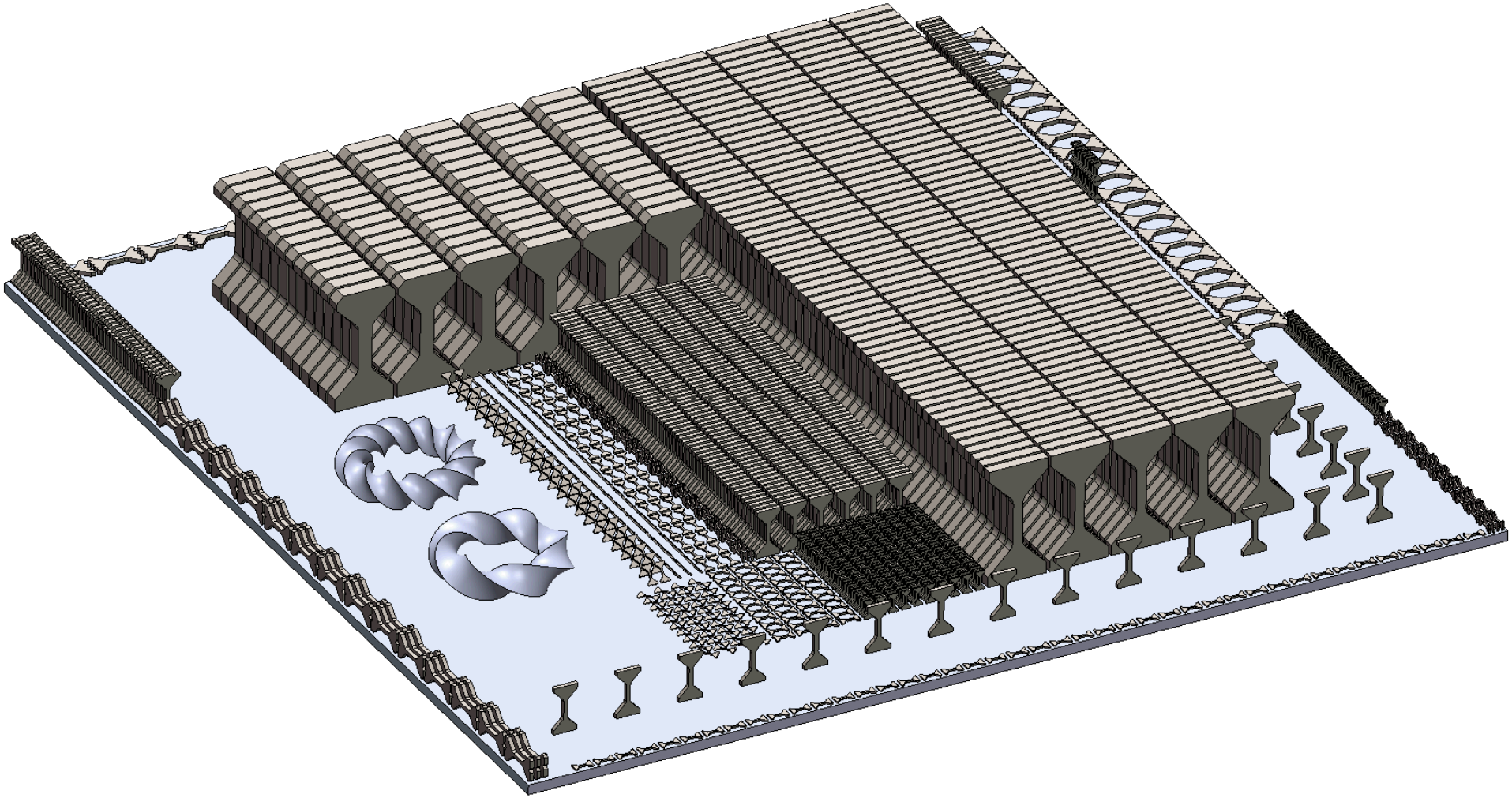
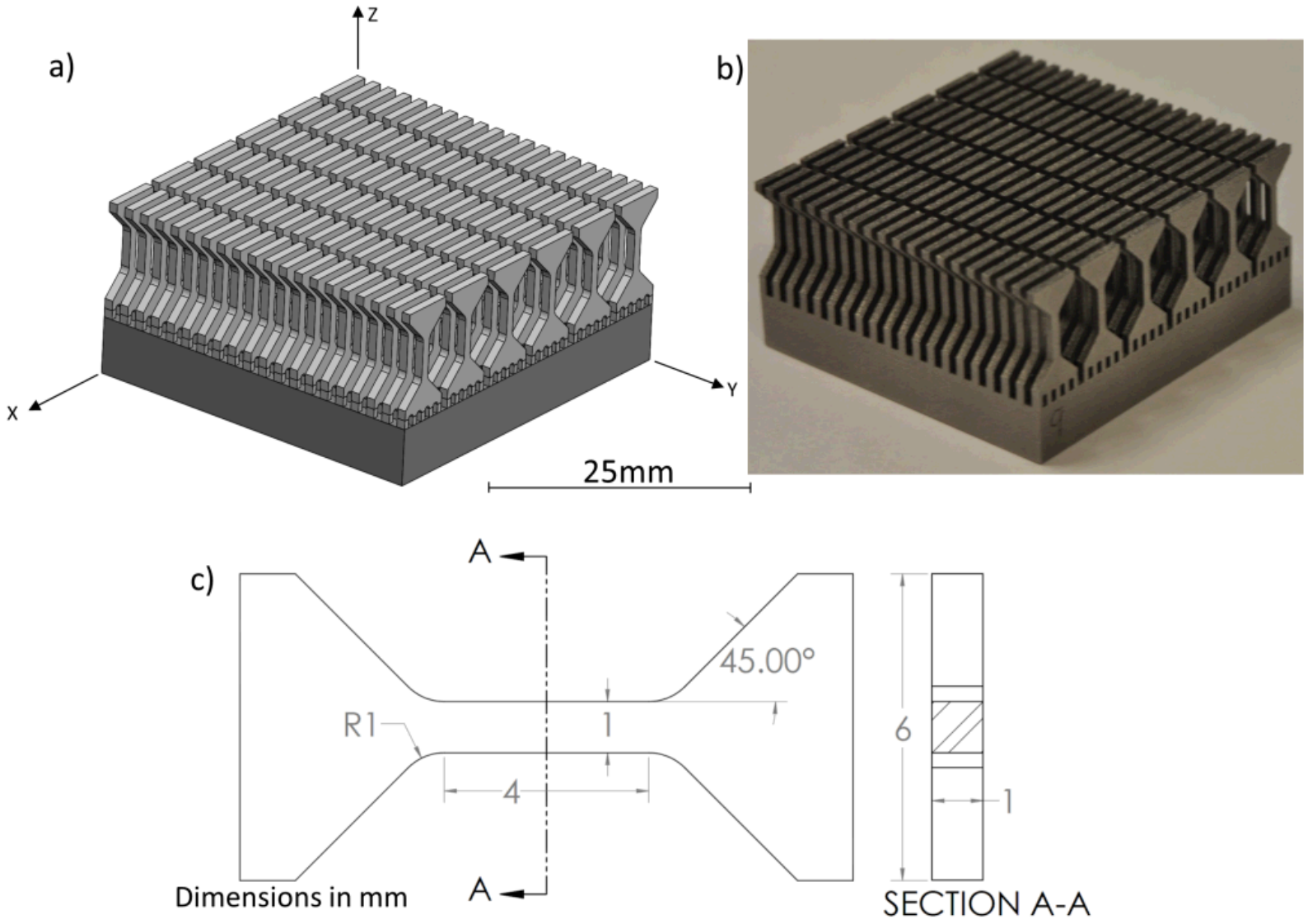
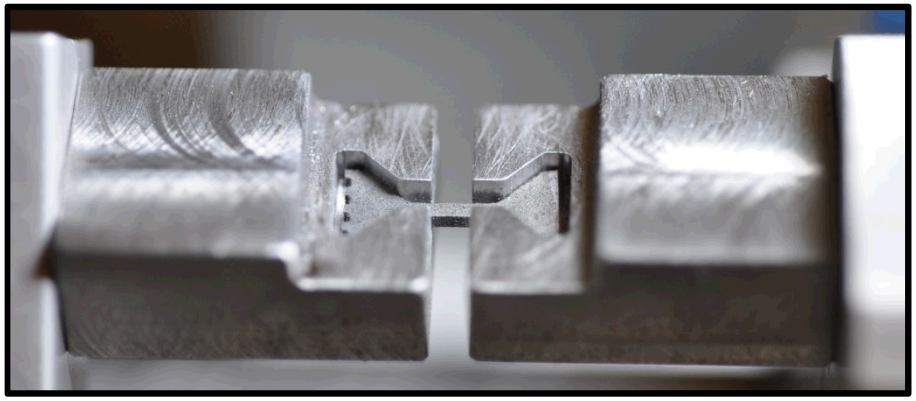


Starting simple: 'cooling fin design'

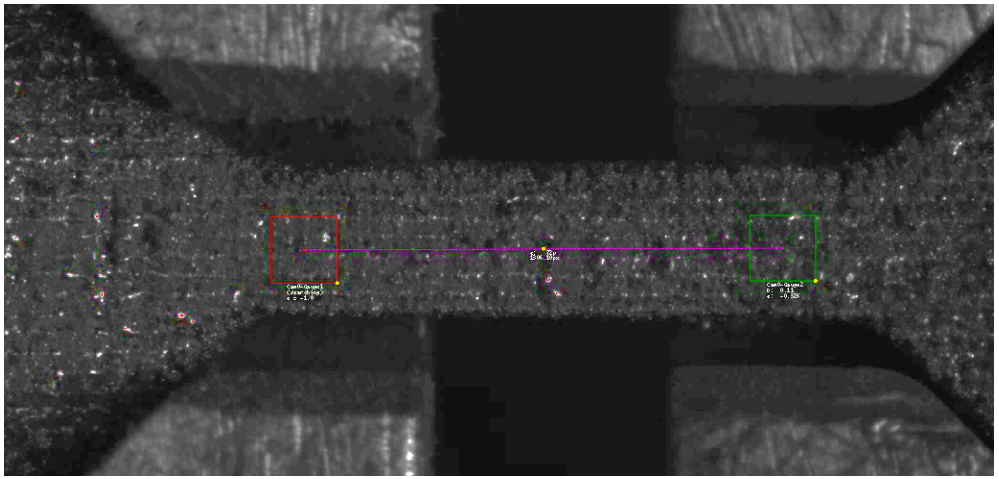


Streamline the testing process



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

A comparison of 2 major commercial vendors

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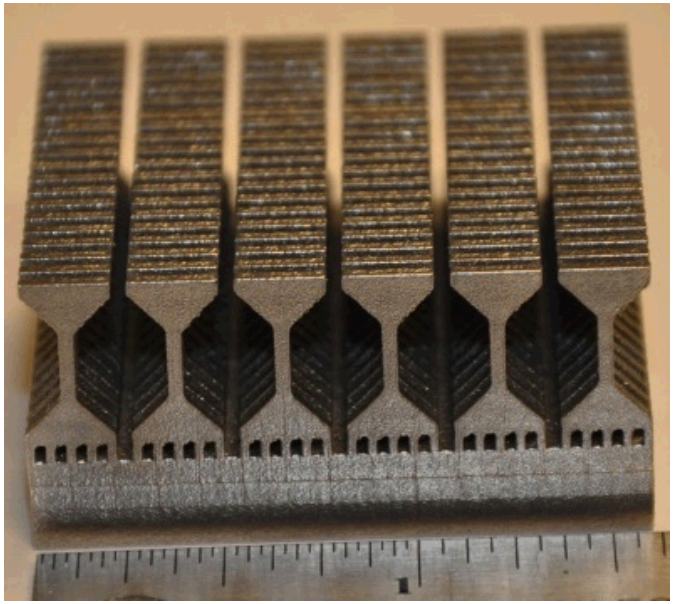
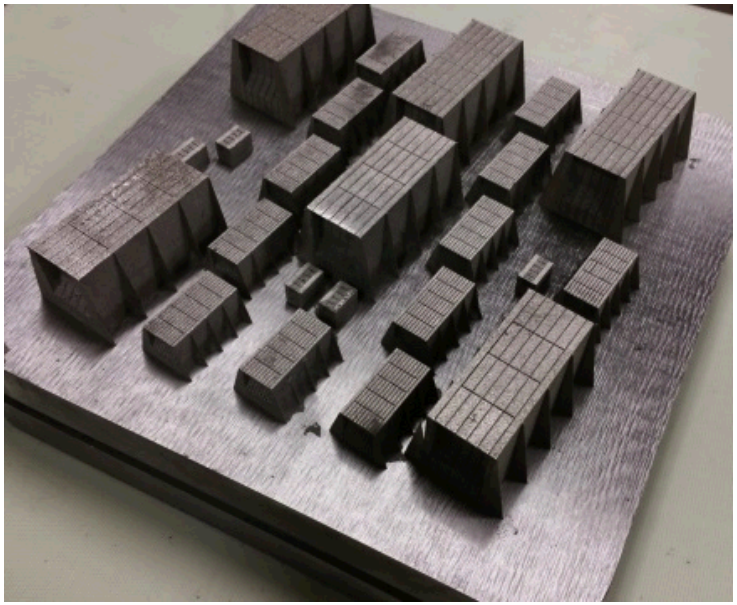


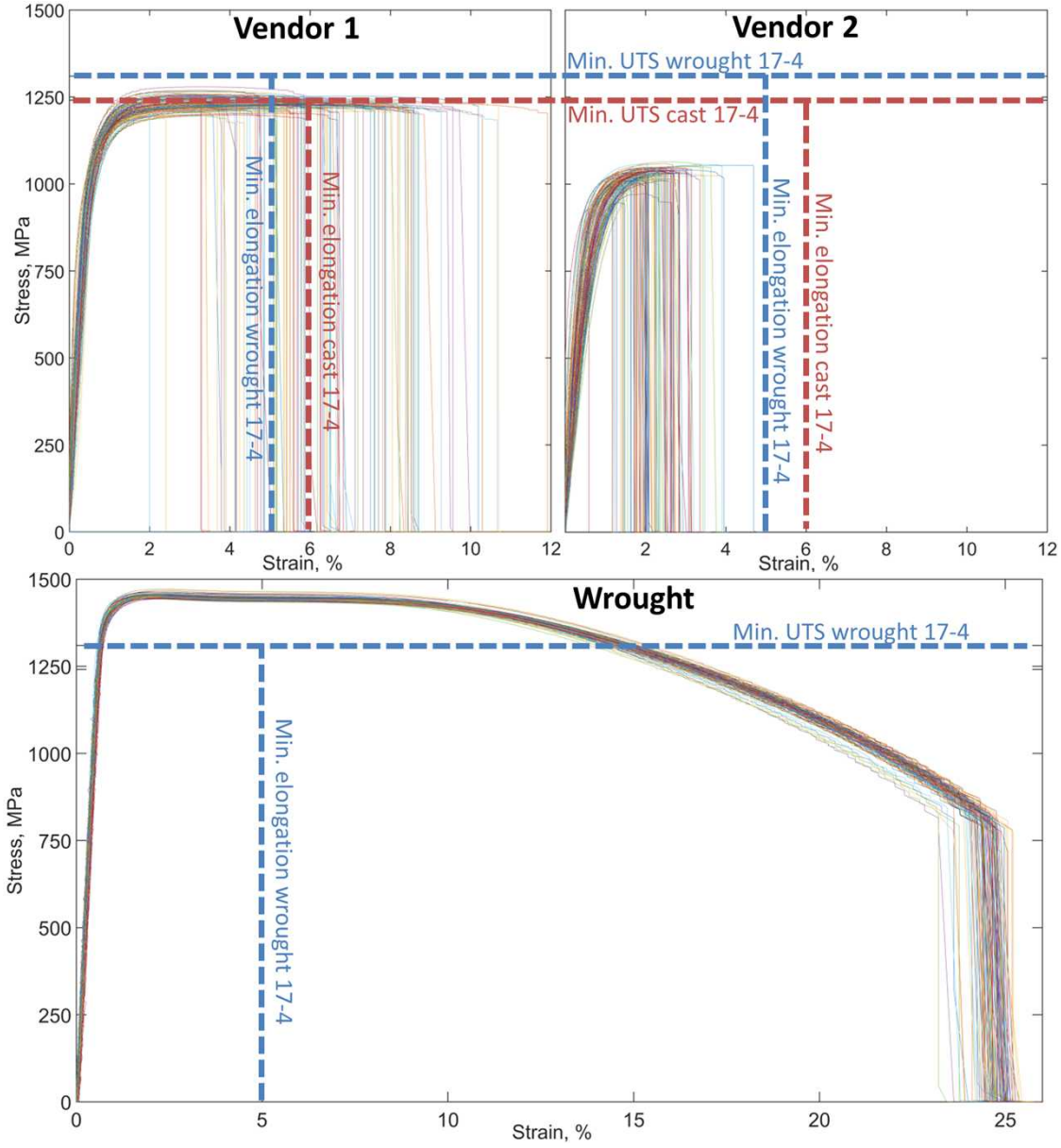
Vendor 1



Vendor 2

Alloy: PH17-4 (preciptation hardenable stainless steel)

Comparing 100 tensile results from 3 sources



The risk of 'business-as-usual': design based on Only a few mechanical tests…

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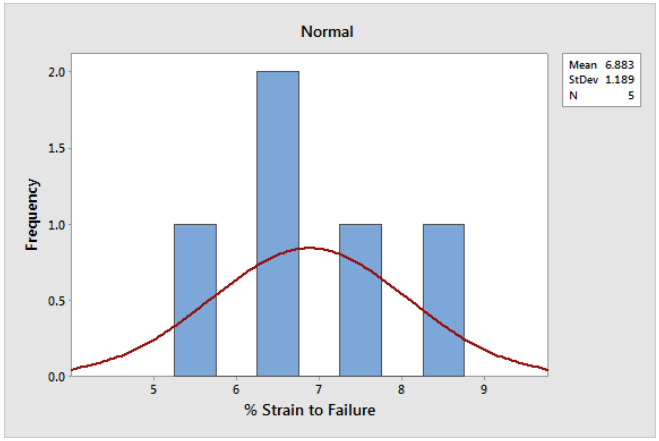
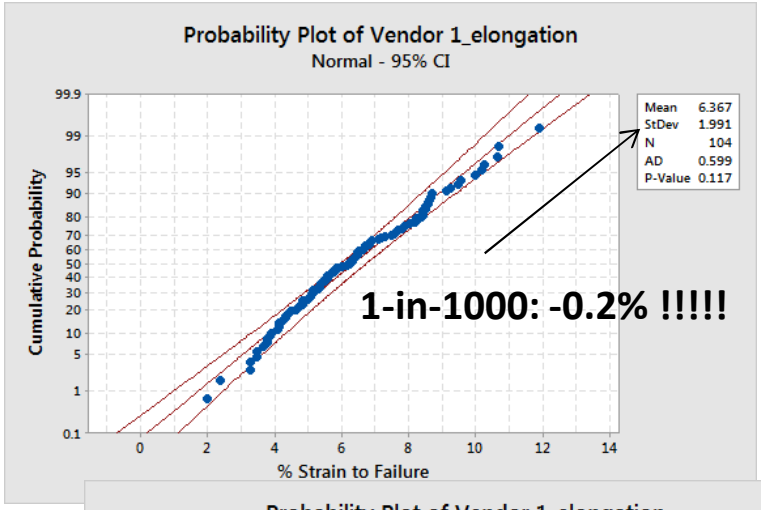
Tensile Strain-to-failure (5 tests)

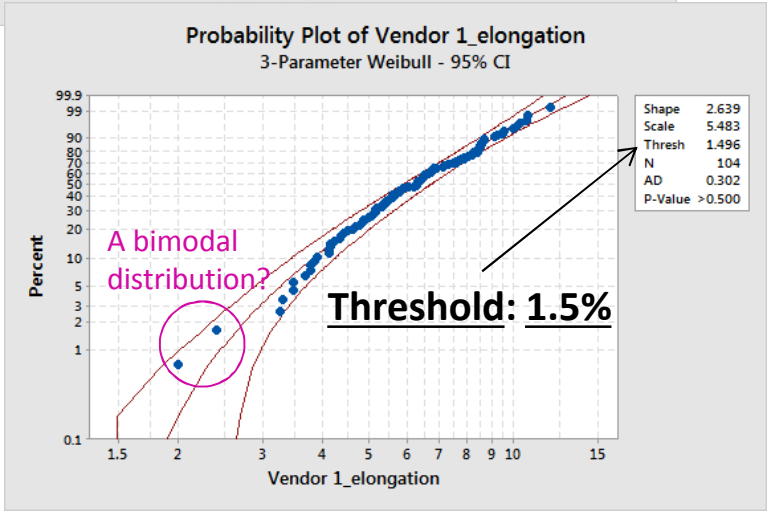
<u>Strain (%)</u>
7.6065
6.7379
5.3317
6.3108
8.4257



Average: 6.8%
Std. Dev: 1.2%

1-in-370 (3σ): 3.2%
1-in-1000: 2.8%





3-Parameter Weibull Fits to Property Distributions

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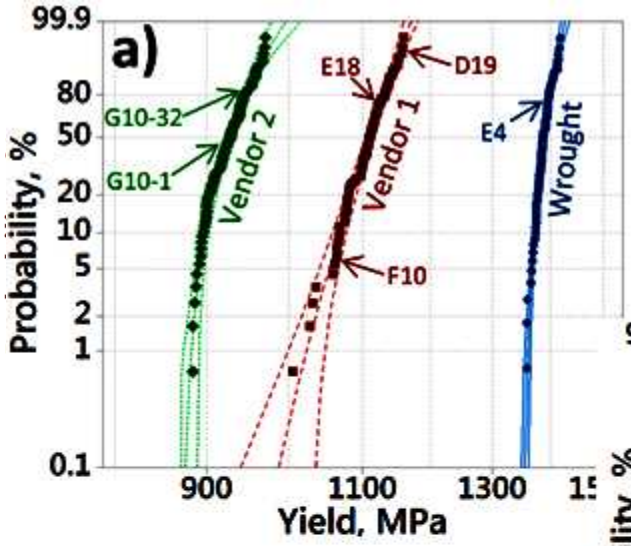
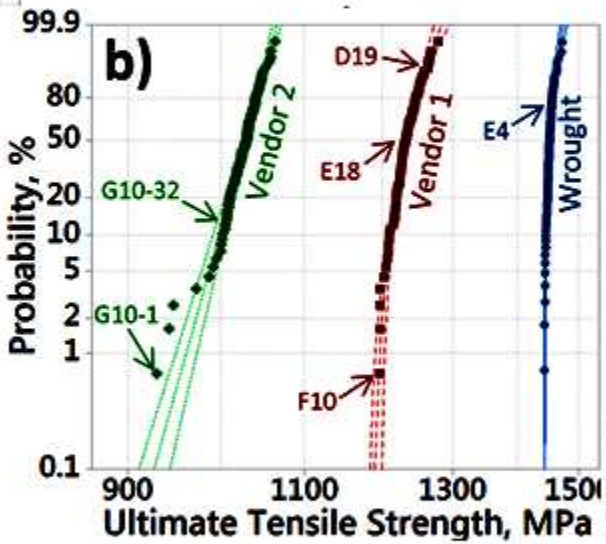
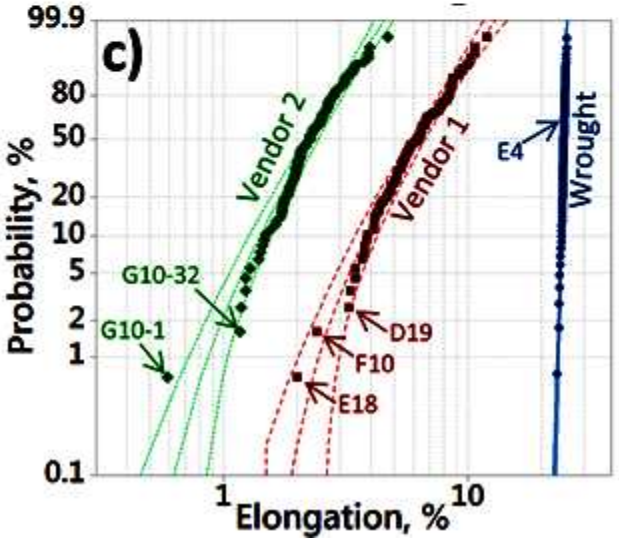
$$P = 1 - \exp\left[-\left(\frac{\sigma - \sigma_0}{\sigma_\theta - \sigma_0}\right)^m\right]$$







Comparing fracture surface from different sources

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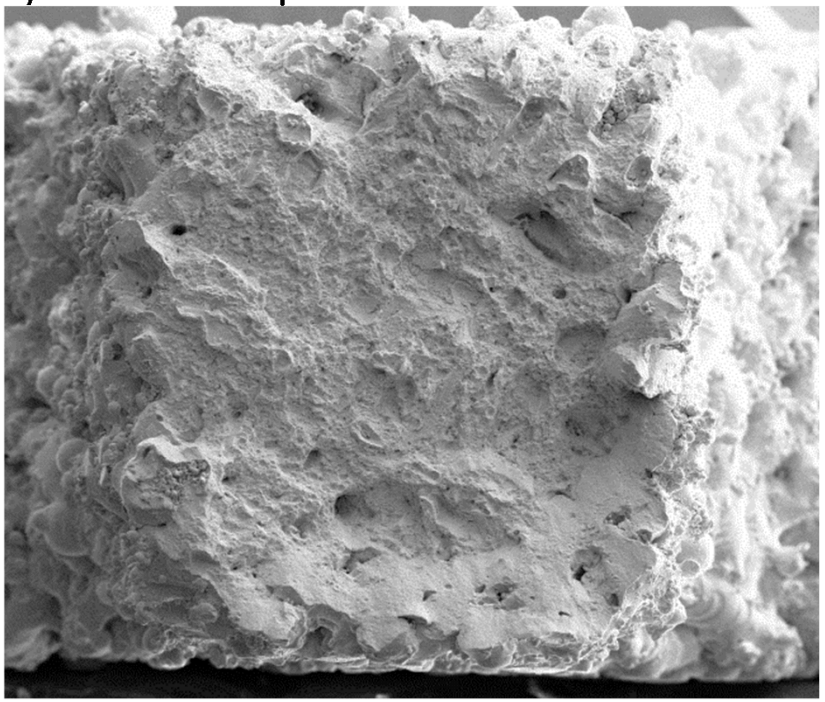
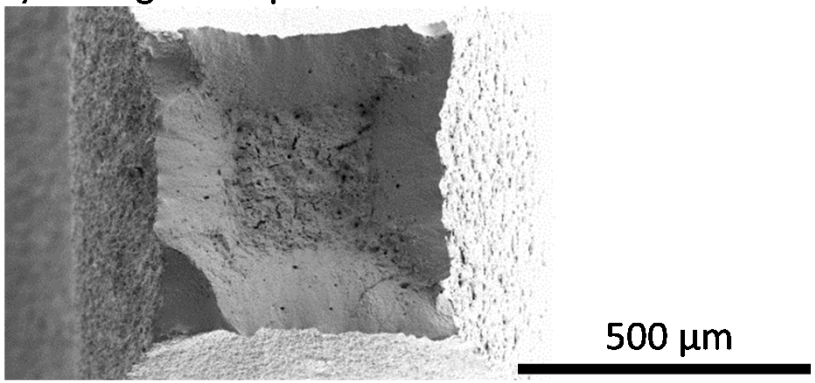
a) Vendor 1 sample F10

b) Vendor 2 sample G10-1



c) Wrought sample E4



Vendor 2: Compare High Ductility vs Low Ductility

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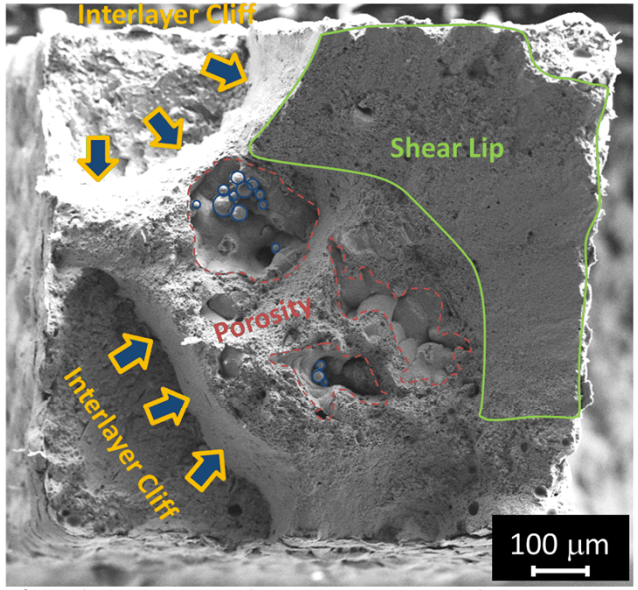
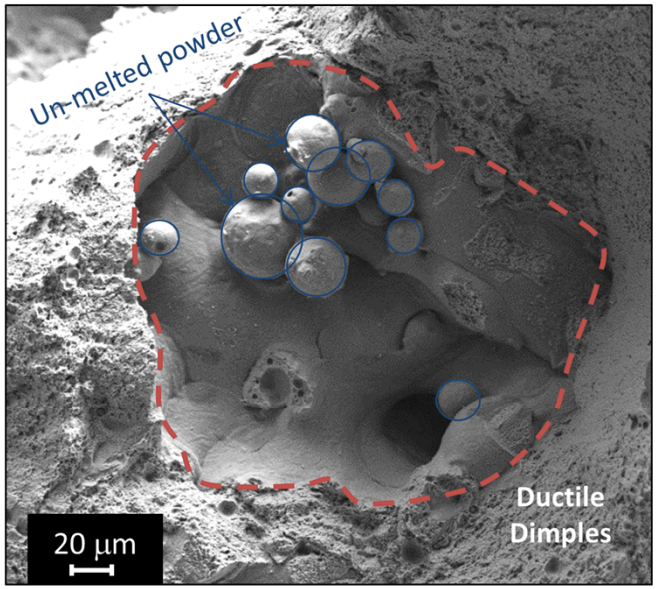
2% Strain-at-failure

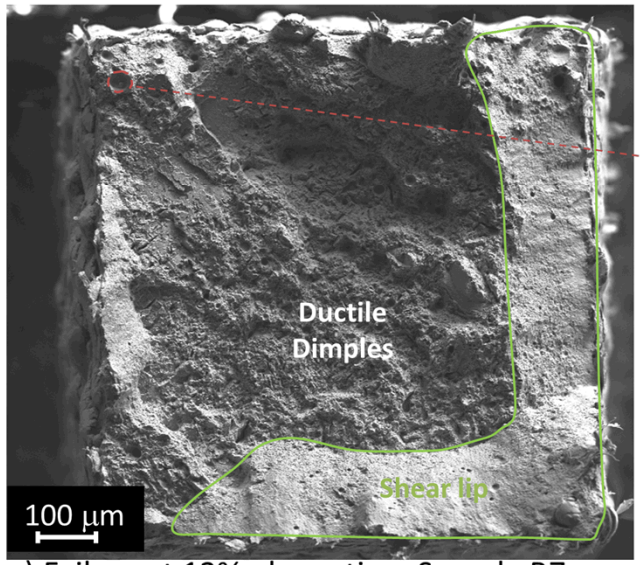


a) Failure at 2% elongation. Sample E18

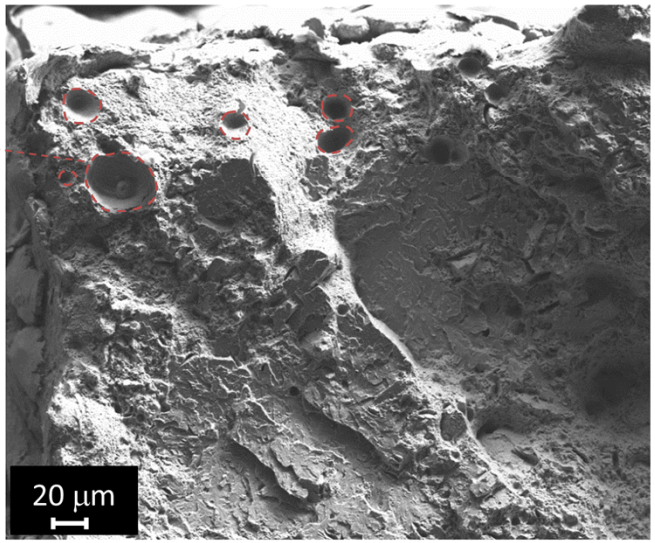


b) Close-up of lack-of-fusion porosity in sample E18

12% Strain-at-failure



c) Failure at 12% elongation. Sample B7



d) Close-up of porosity in sample B7

Now What???

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- Evaluate size-dependence of property distributions
- Evaluate modulus, fracture toughness and (possibly) fatigue resistance
- Identify process routes that mitigate defects and microstructural heterogeneities
- Apply high-throughput principles to all aspects of AM evaluation

Properties 'Al Instante'

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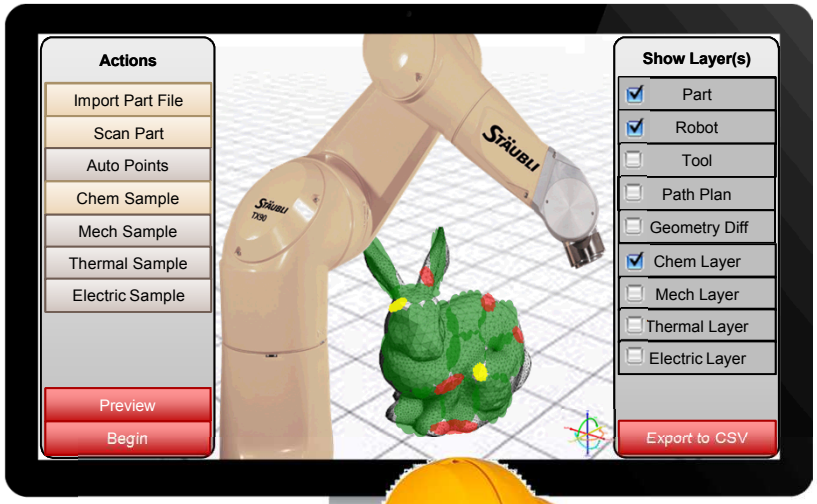
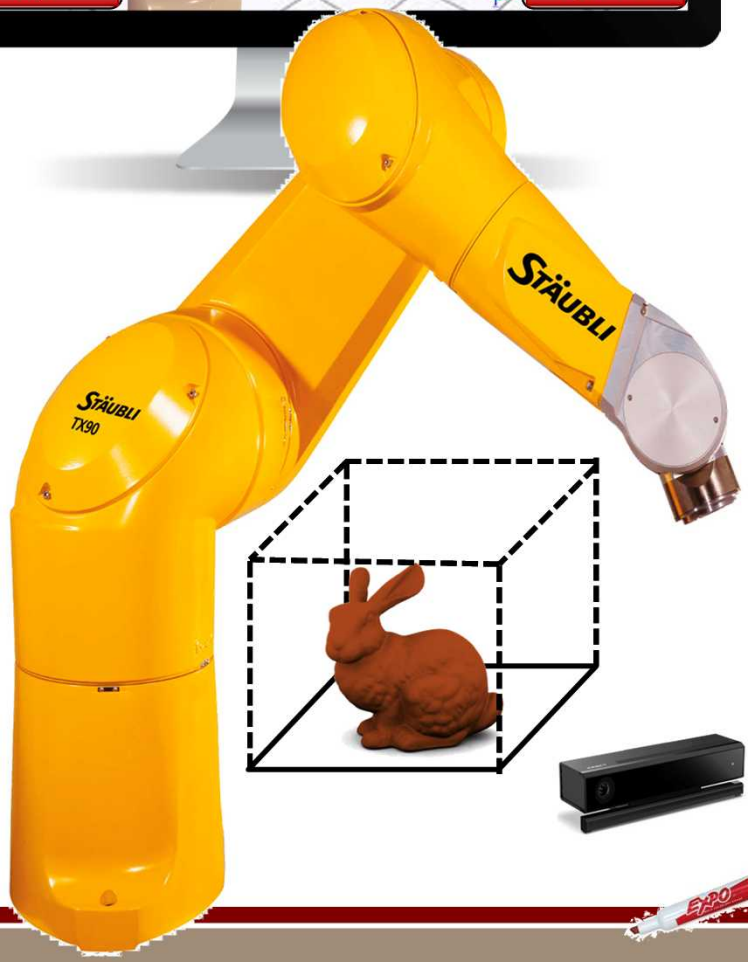
An Aspirational Goal:

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

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