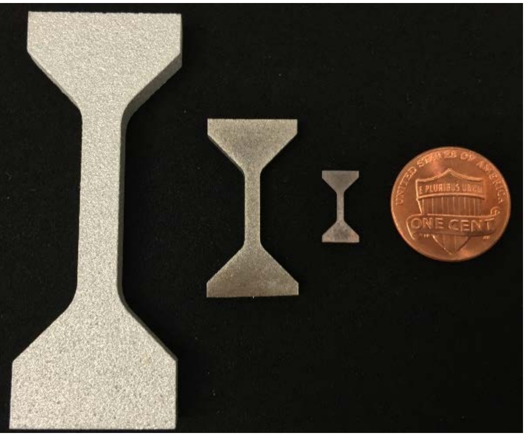
Rio Grande Symposium on Advanced Materials, 2016
SAND2016-9808C

Multiple Testing Techniques and Multiple Conclusions in AM Metals



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Sandia National Laboratories

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NNSA National Nuclear Security Administration

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9/21/2016

How to qualify AM components?

Identify key variables and their effects.

Model/Test printed components to establish requirements

Measure performance of printed components

Test surrogate specimens

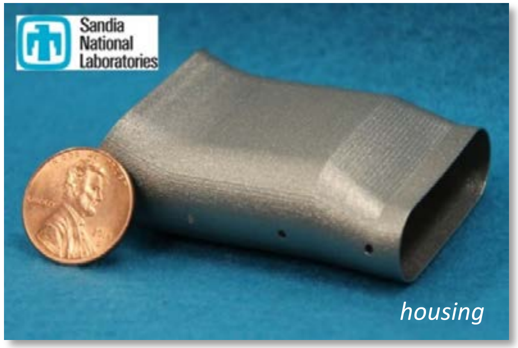
Relate material properties of surrogate specimens to component

Test surrogate specimens in production for quality control

Powder bed additive manufacturing

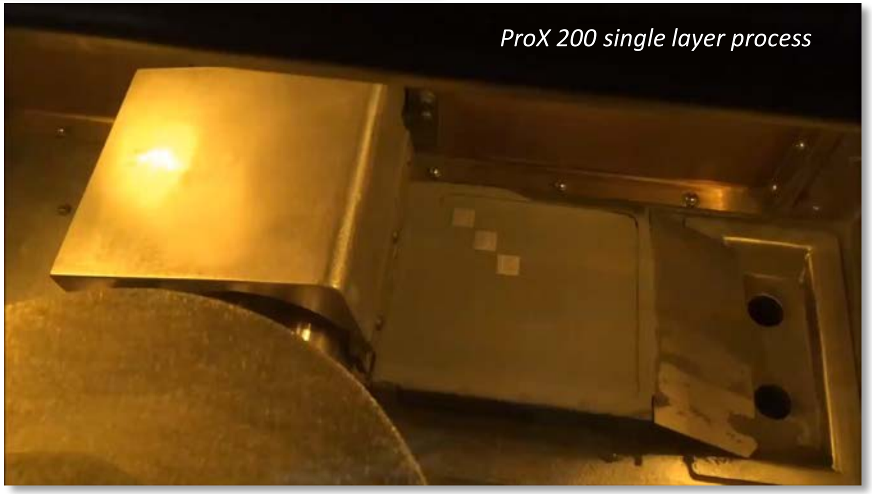
- **Powder melts @ focal point, then re-solidifies**
  - **electron beam melting (Arcam)**
  - **laser**
- **Laser performance**
  - **scan speed ~ 1m/sec**
  - **105-106 OC/sec heating & cooling rates**
  - **dimensional accuracy**
    - **0.001-0.002" at best**
    - **proportional to part size (~0.001"/in)**
  - **surface finish**
    - **>5-10 µm Sa (~ casting)**
    - **worse for downward surfaces**
    - **optimized finish sacrifices properties**
  - **geometry limits**
    - **wall thickness > 100 µm, overhangs < 45°**
  - **single material parts**
    - **Ti6Al4V, AlSi10Mg, 6061-T6, 316L SS, 304L SS, 17-4, 15-5, maraging steel, CoCr, Inconel 625 & 718, Au, Ag, W**
      - **> 99% density**
      - **strength typically near to, but less than wrought**


lattice structure



housing

3D Systems ProX 200


ProX 200 single layer process

Questions

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- **How input parameters affect performance**
  - **Powder reuse**
  - **Laser power, hatch spacing, etc.**
- **What variability do we get? Make sure conclusions are statistically significant.**
- **Specimen thickness effects**
- **Qualification- relate surrogate specimens to component behavior**

Similitude: Use surrogate specimens similar to component

- Match loading type
  - Tension, compression, torsion, etc.
  - Relevant properties: fracture (acceptable flaw size), heat transfer, etc.
- Similar printing properties
  - Thickness, aspect ratio, height
  - Print surrogates on same plate
  - Surrogates should ideally cover entire build volume
- Thin-walled shell structures
  - Loaded in compression
  - Often dynamic
  - Bending, local buckling and fracture in tension

AlSi10Mg

Element	Percent
Silicon (Si)	**9.00-11.00**
Magnesium (Mg)	**0.25-0.45**
Iron (Fe)	0.25 Max
Nitrogen (N)	0.2 Max
Oxygen (O)	0.2 Max
Titanium (Ti)	0.15 Max
Zinc (Zn)	0.1 Max
Manganese (Mn)	0.1 Max
Nickel (Ni)	0.05 Max
Copper (Cu)	0.05 Max
Lead (Pb)	0.02 Max
Tin (Sn)	0.02 Max
Chromium (Cr)	For Reference Only
Aluminum (Al)	**Balance**

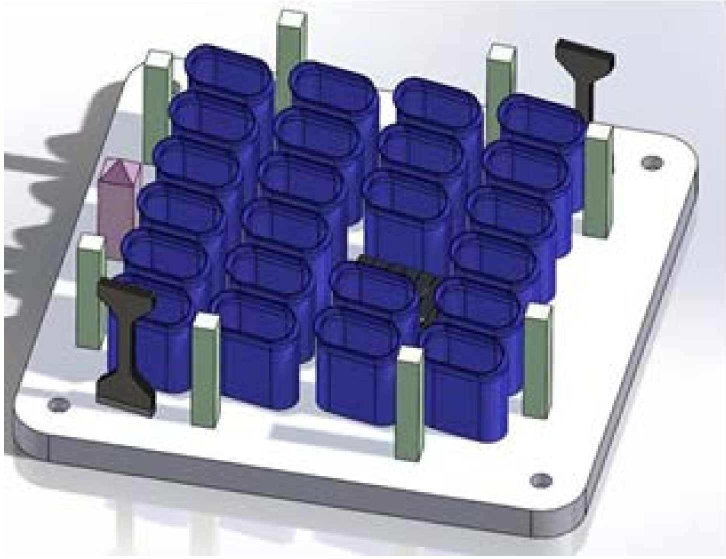
Build	Powder condition	# of tensile tests completed
1	Fresh	22
2	Recycled once	22
3	Recycled twice	22
4	Recycled 3 times	22
5	Recycled 4 times	22
6	Fresh	22
7	Recycled once	22
8	Recycled twice	22
	Total	176

- **Build surrogate specimens on same build plate as components.**

What tests to simulate component failure?

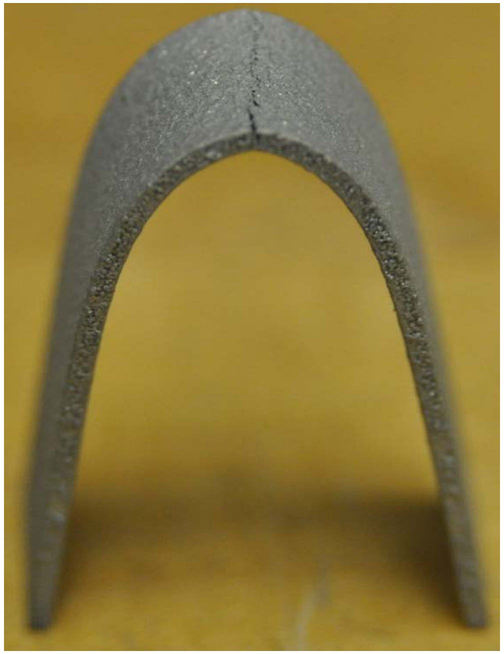
A sizable crack (millimeters) is failure for this component.

- **Actual component- destructive**
- **Bending (representative of failure mode)**
- **Charpy (direct dynamic cracking)**
- **Tension (strength and ductility)**
- **Fracture**
- **Fatigue crack growth**
- **Hardness**
- **Ultrasound**
- **Density**
- **Fractographic analysis**
- **Corrosion**
- **Thermal/electric properties**



Finger bend test

- Thin specimens bend significantly before fracture.
- Do we need thin specimens to match component?
- In practice, we care about fracture initiation. Related to ductility.
- Bending tests could give us ductility, but uniaxial tension tests are easier to get quantitative results.
- 3-pt bend tests localize failure like fracture and Charpy tests.
- 4-pt bend tests don't localize, similar to uniaxial tension tests.
- ASTM U-bend tests (E290) for quick process monitoring?



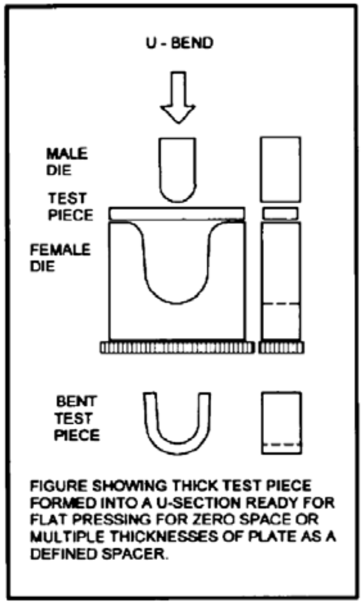


FIG. 4 Schematic Fixture for the Guided Bend, U-bend Test

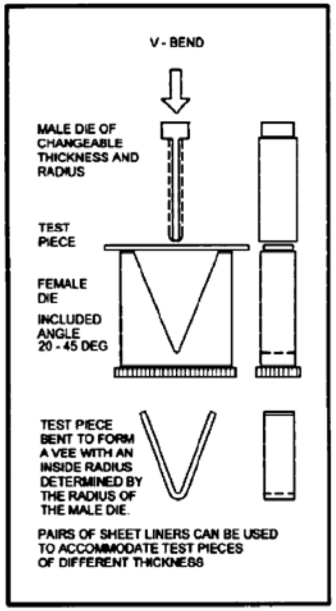
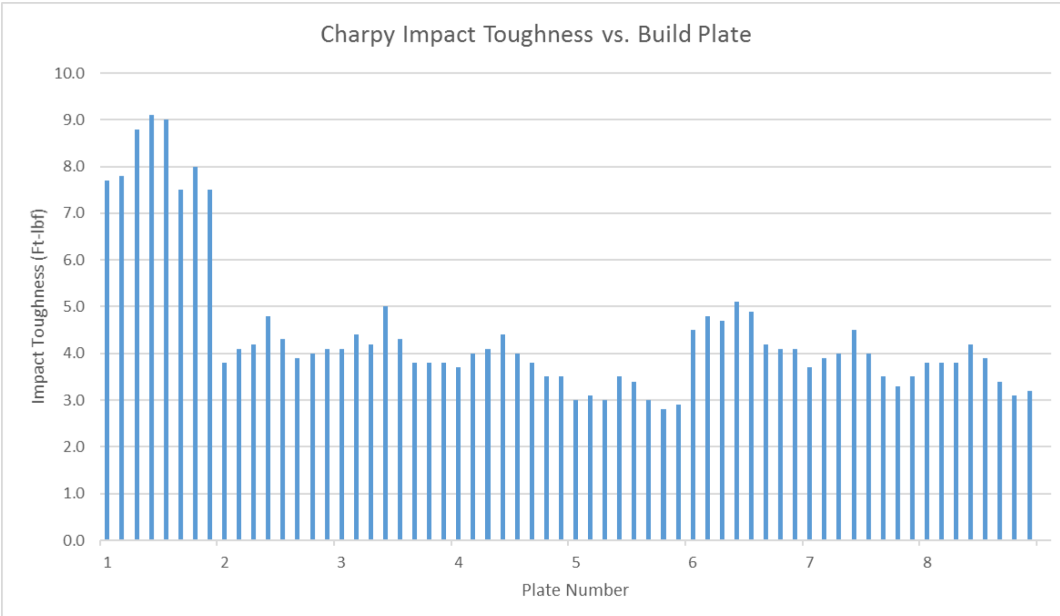
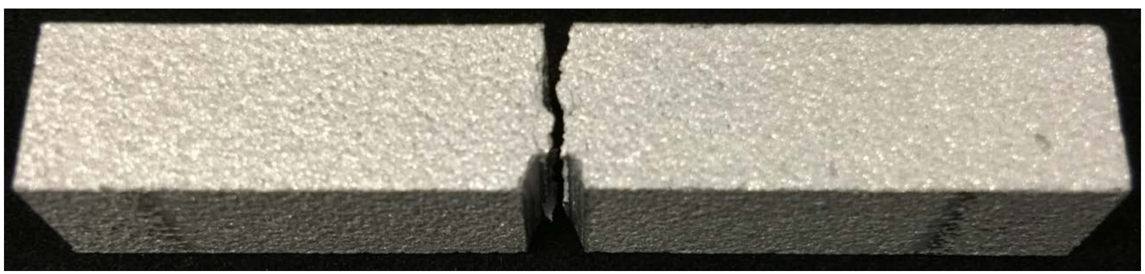
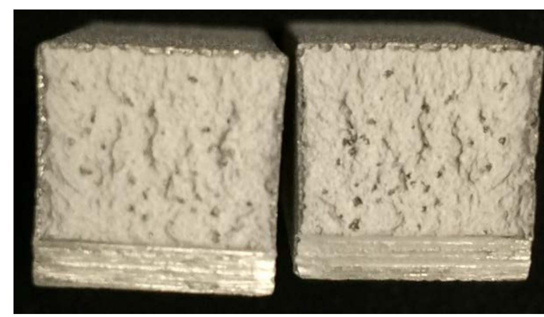


FIG. 5 Schematic Fixture for the Guided Bend, V- Bend Test

Charpy testing



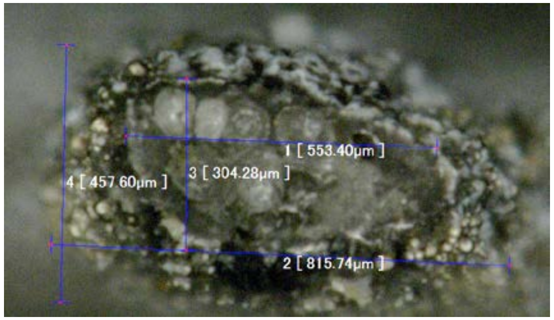


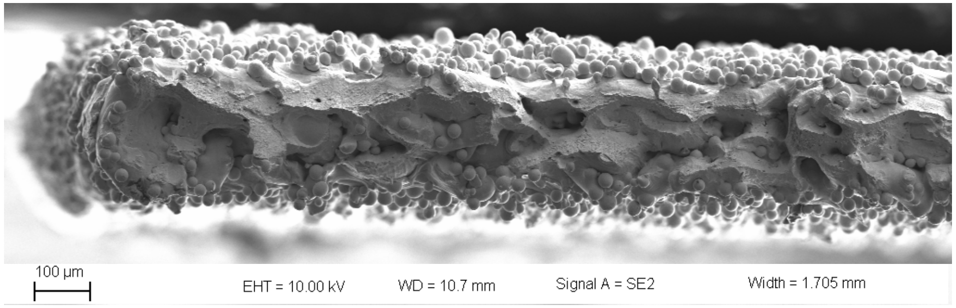


- **Quick results, easy analysis.**
- **Dynamic fracture directly relevant to application.**
- **Localized failure to one slice of material.**
- **Sensitive to overall build quality, perhaps useful for quality control.**

Cross sectional area is difficult to define

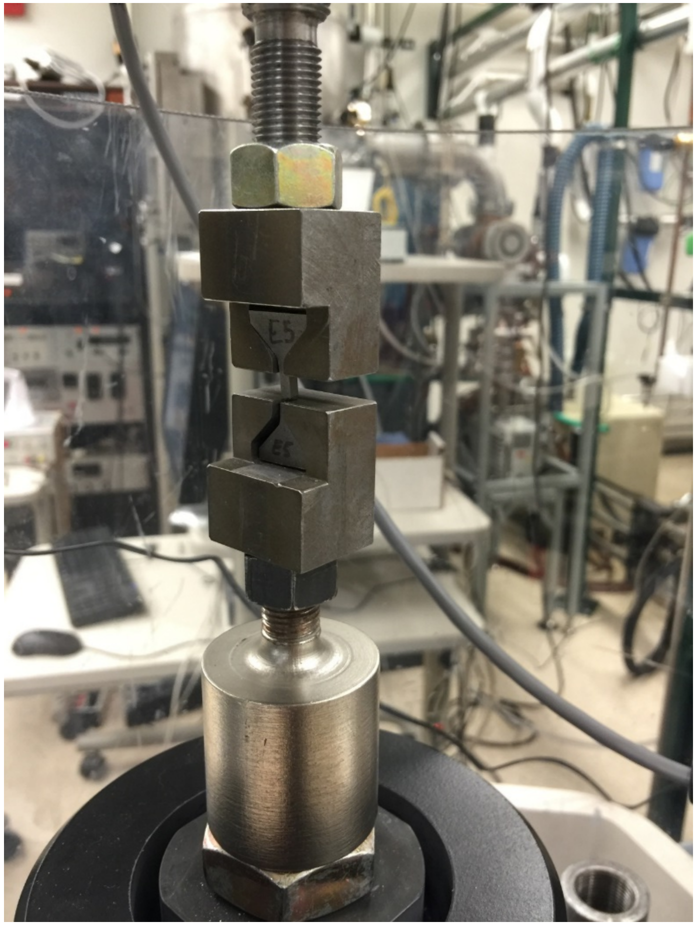
- Effective cross sectional can scale stresses significantly for small specimens.
- Affects modulus, yield strength, ultimate tensile strength.
- Scaling is roughly consistent.
- For now, use "caliper" measurements.

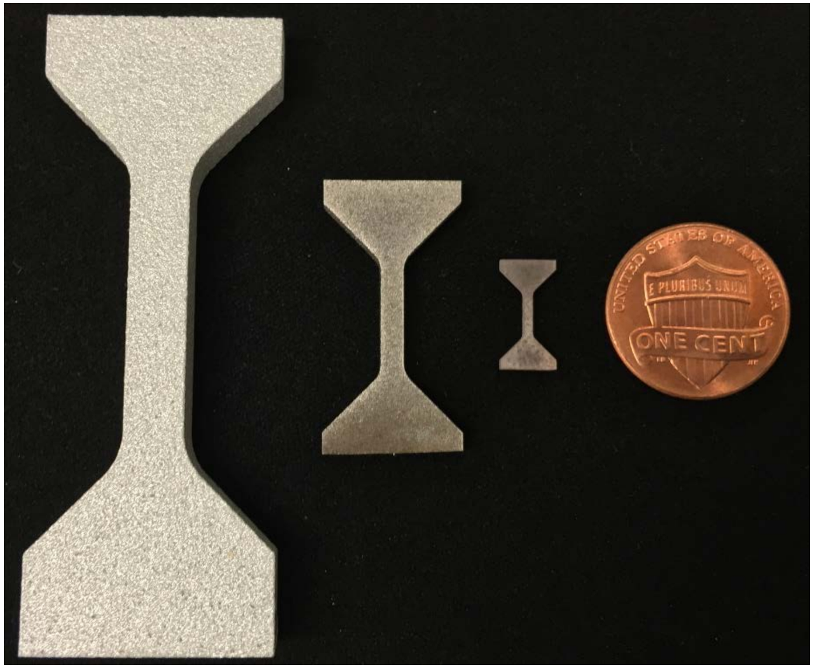




Tension testing

- **Ductility and strength are relevant to the component failure mode.**
- **Statistics to capture variability in AM properties.**



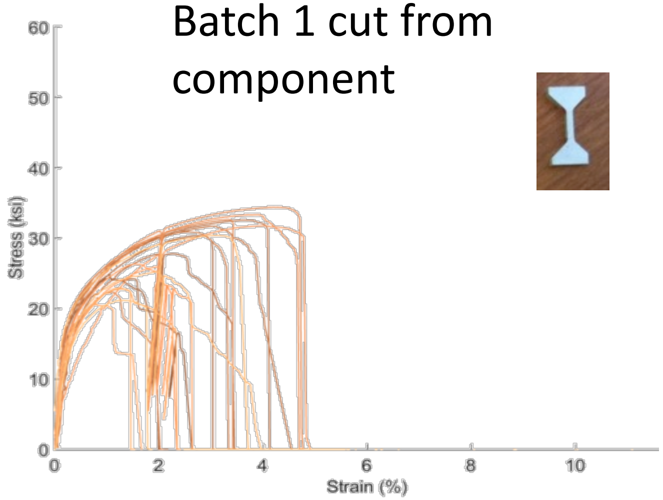


6.25 x 6.25 mm, 2.5 x 2.5 mm, 1 x 1 mm

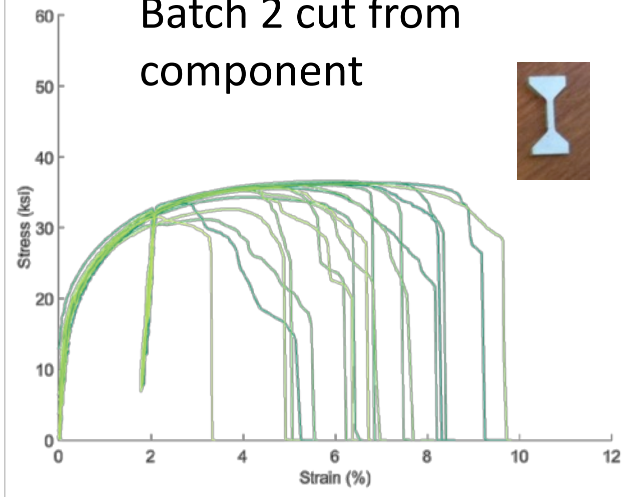
Small high throughput tension (HTT) specimens

- Large variability in ductility
- Strength variability due to surface material.

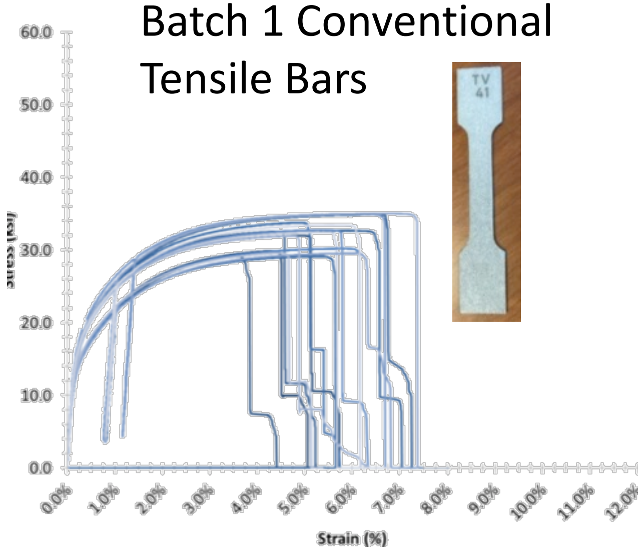
Batch 1 cut from component



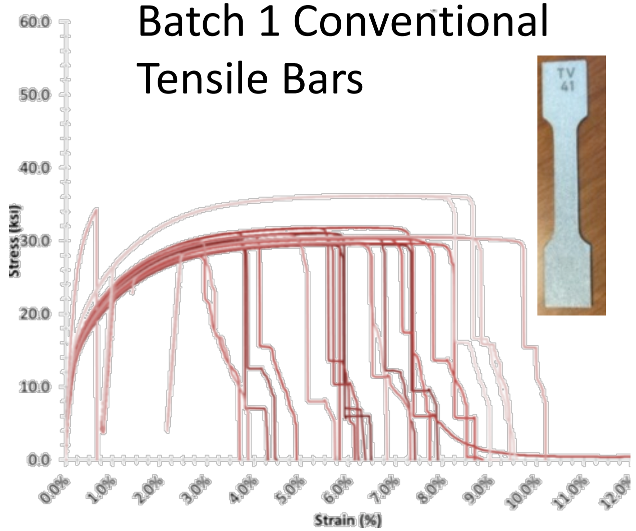
Batch 2 cut from component



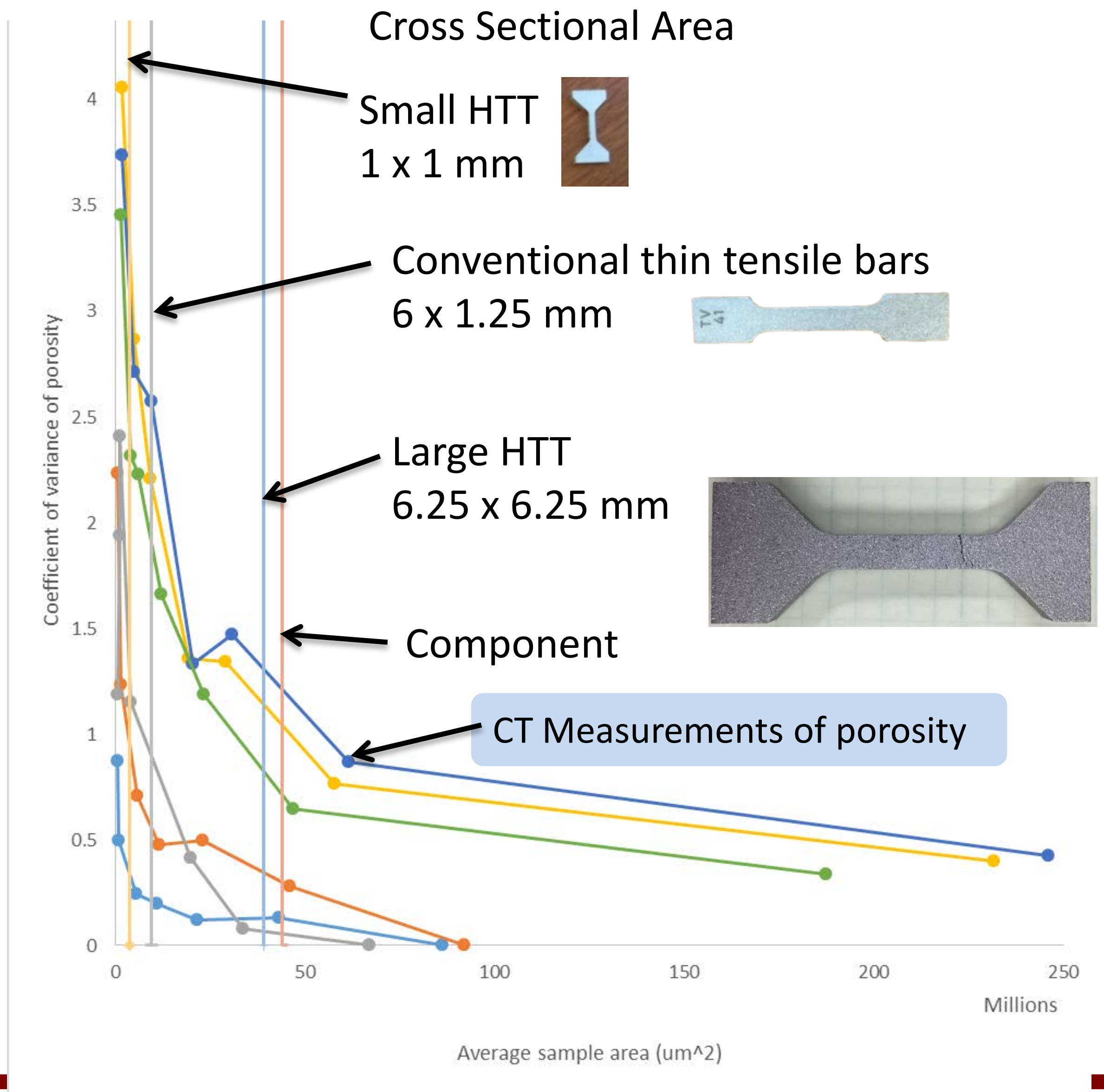
Batch 1 Conventional Tensile Bars



Batch 1 Conventional Tensile Bars

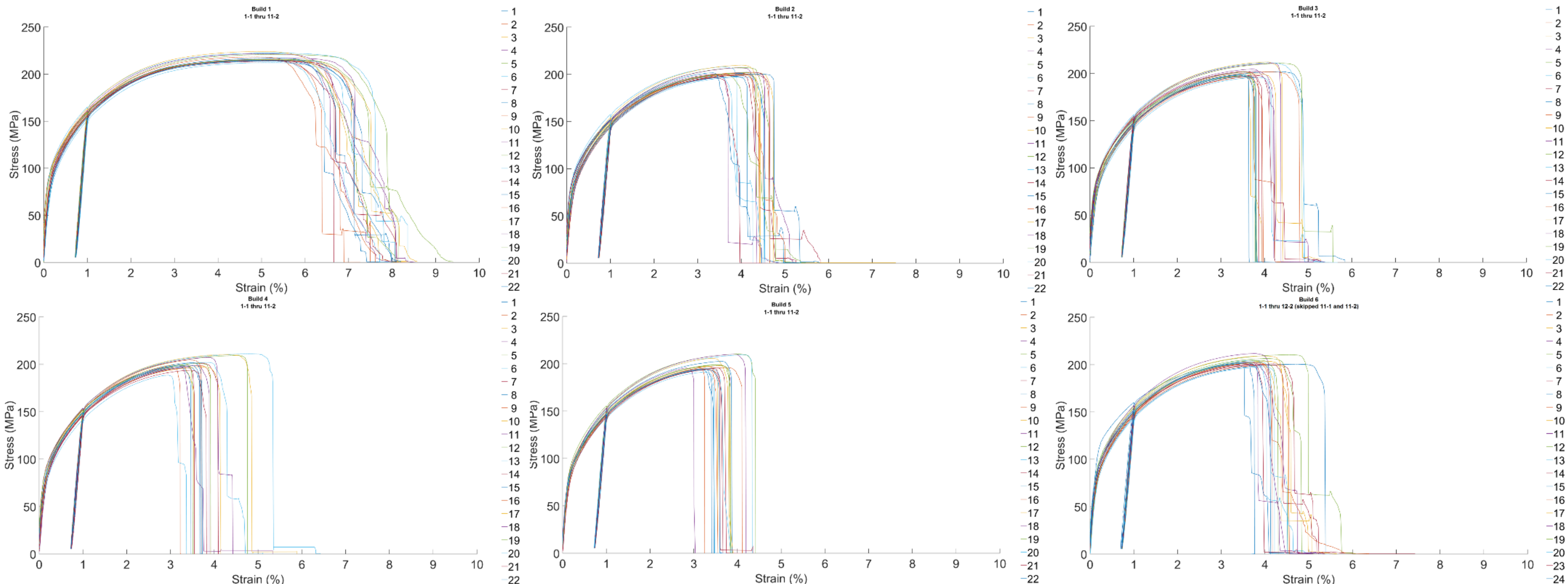


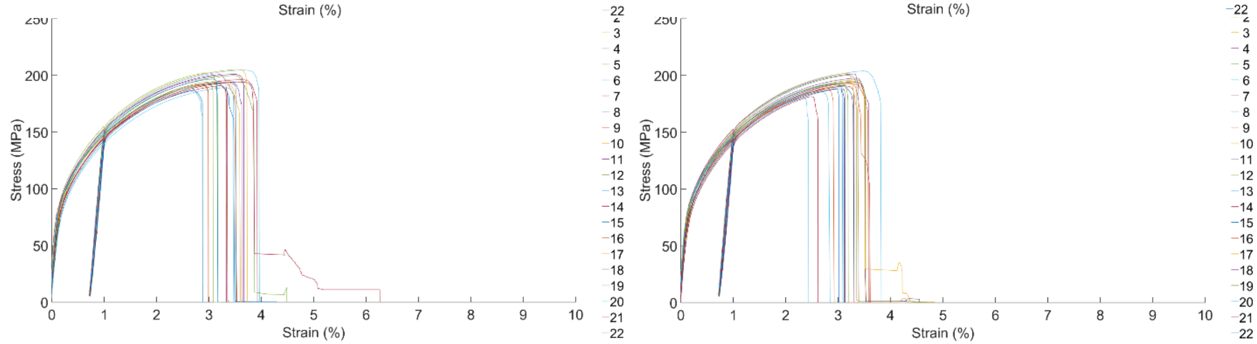
Representative volume element to minimize variability and draw tangible conclusions



- **Larger specimens have an RVE of material that is more comparable to component.**
  - **Less dominated by flaw variability**
- **Large specimens are taller than component sampling all build heights.**
- **How large is an RVE?**
  - **Depends on microstructure, void distributions, flaw probabilities**
- **Is the component an RVE?**

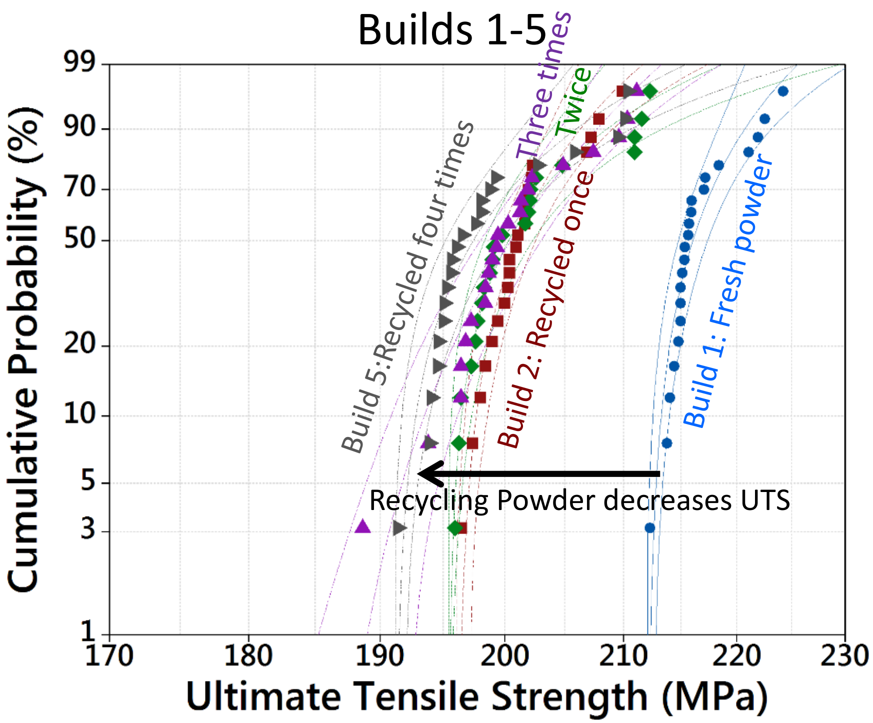
Large high throughput specimens (~190)

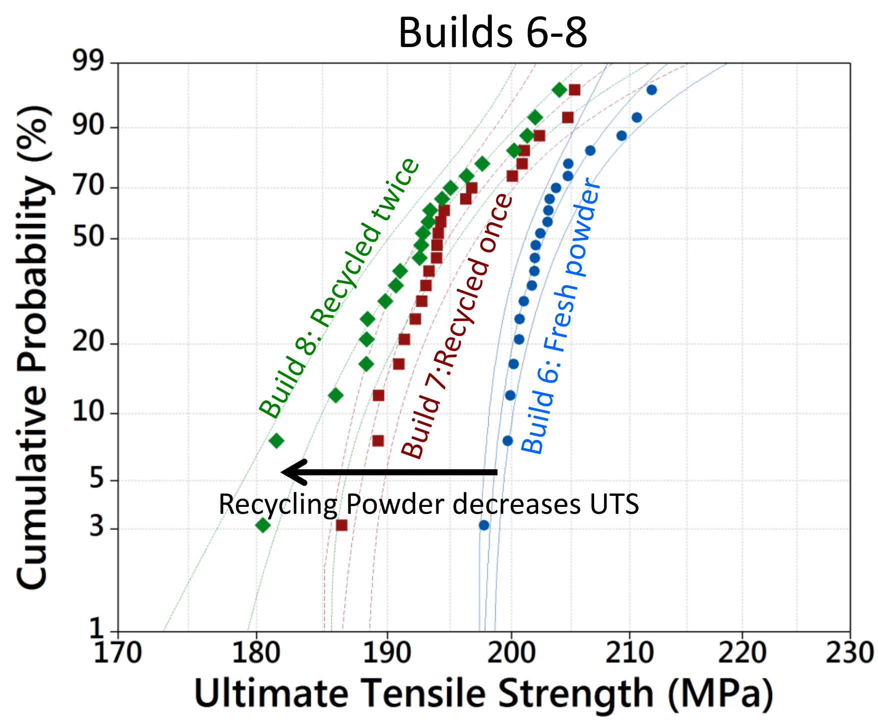




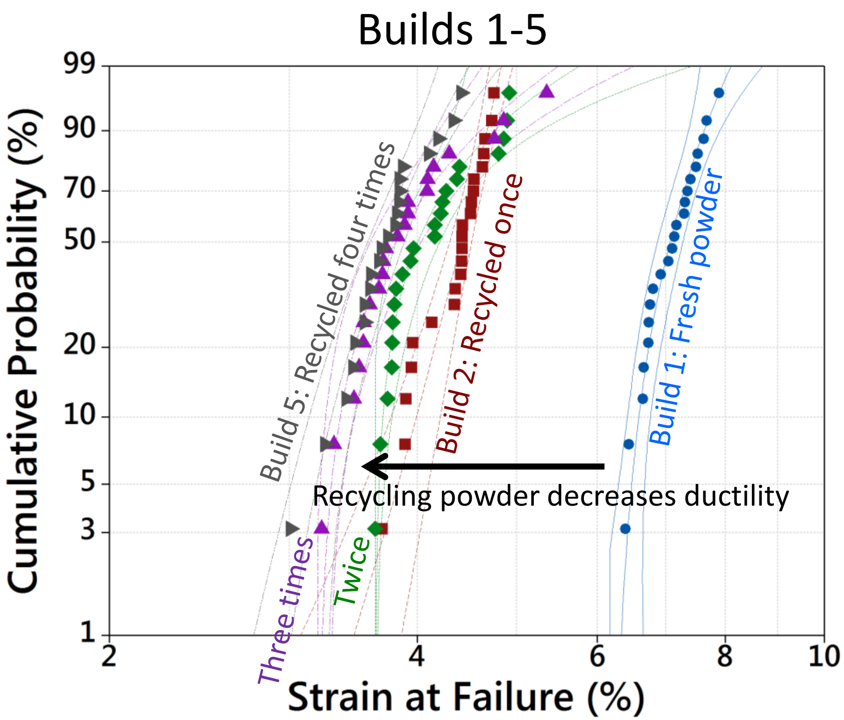
- Less variability within build plates.
- More ductile specimens fail through repeated pop-in.

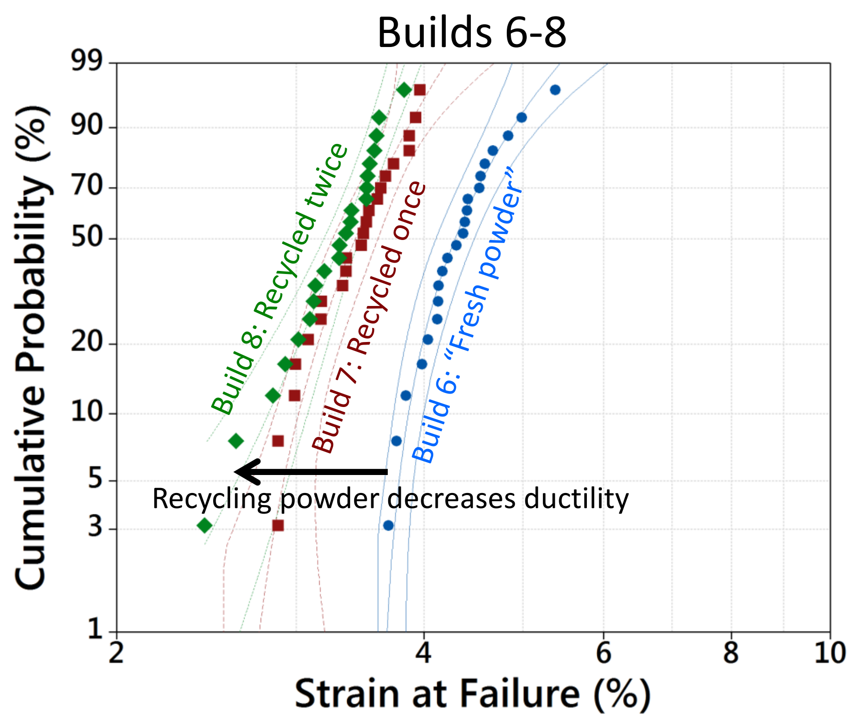
Recycling Powder Decreases UTS
Weibull 3-Parameter Distributions



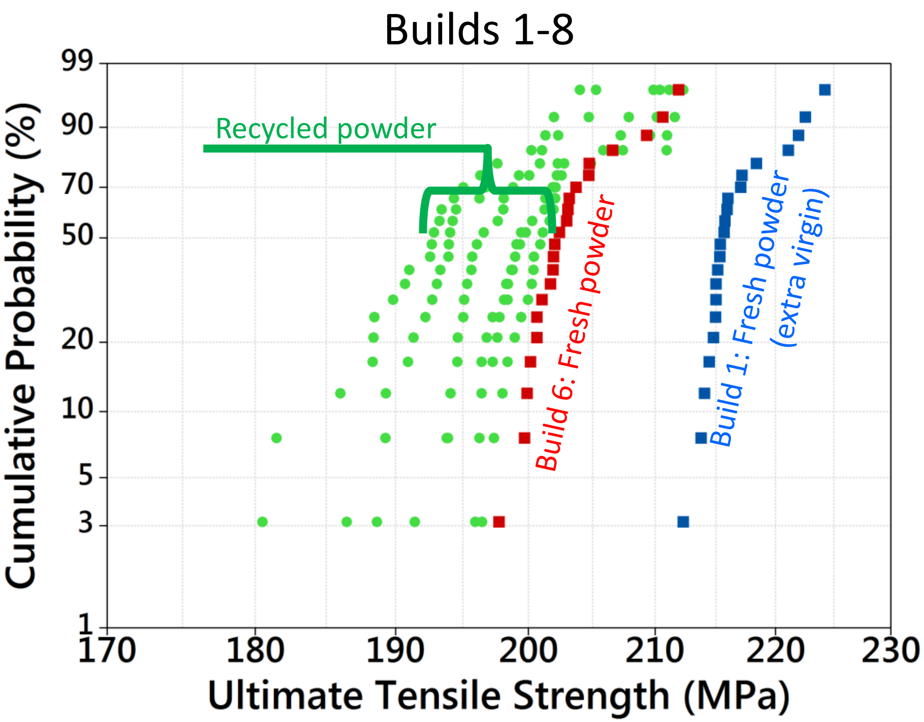


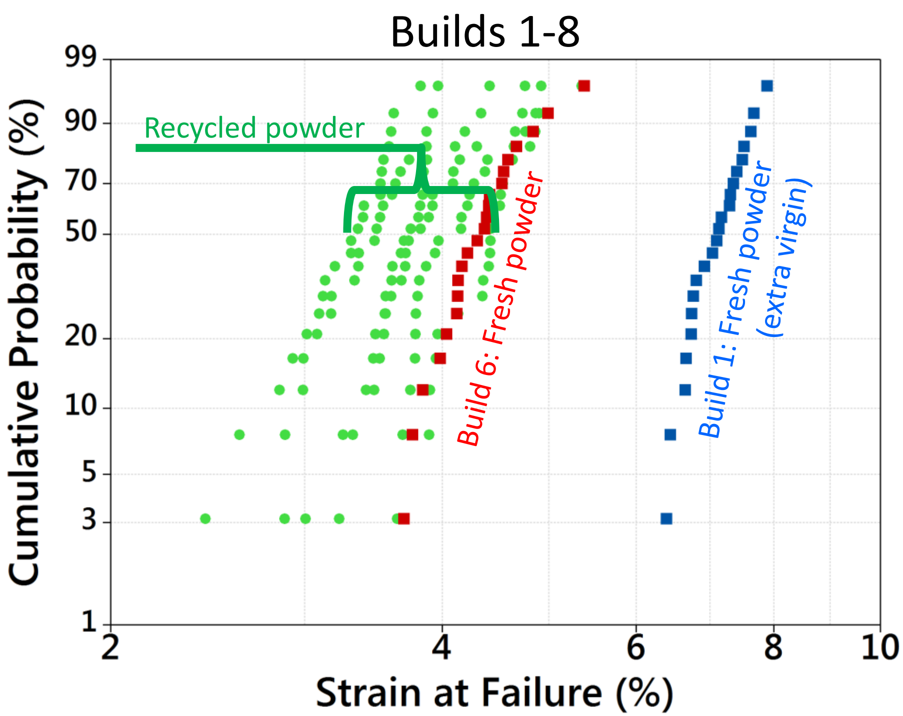
Recycling Powder Decreases Ductility
Weibull 3-Parameter Distributions





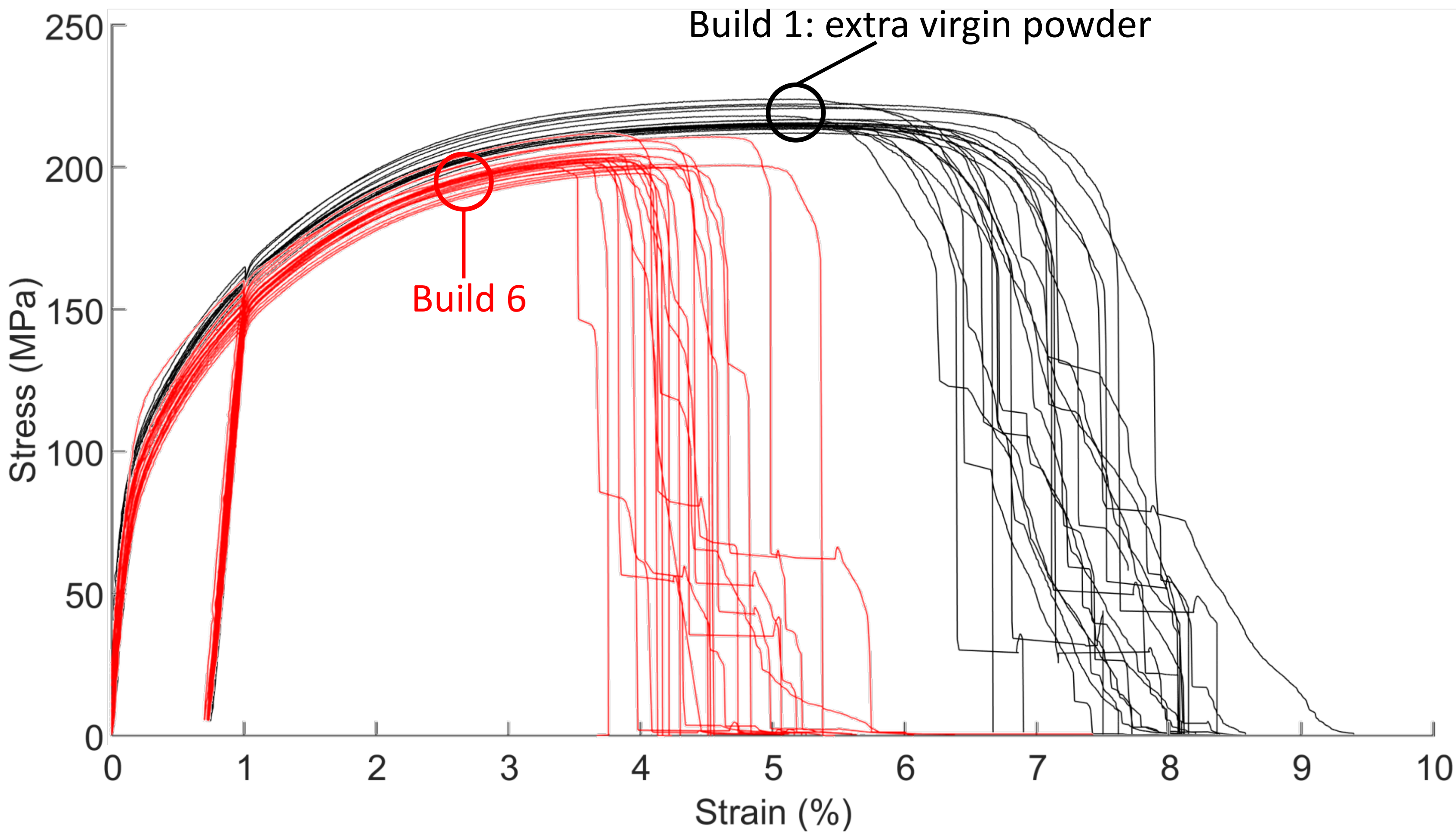
Extra virgin powder
Weibull 3-Parameter Distributions





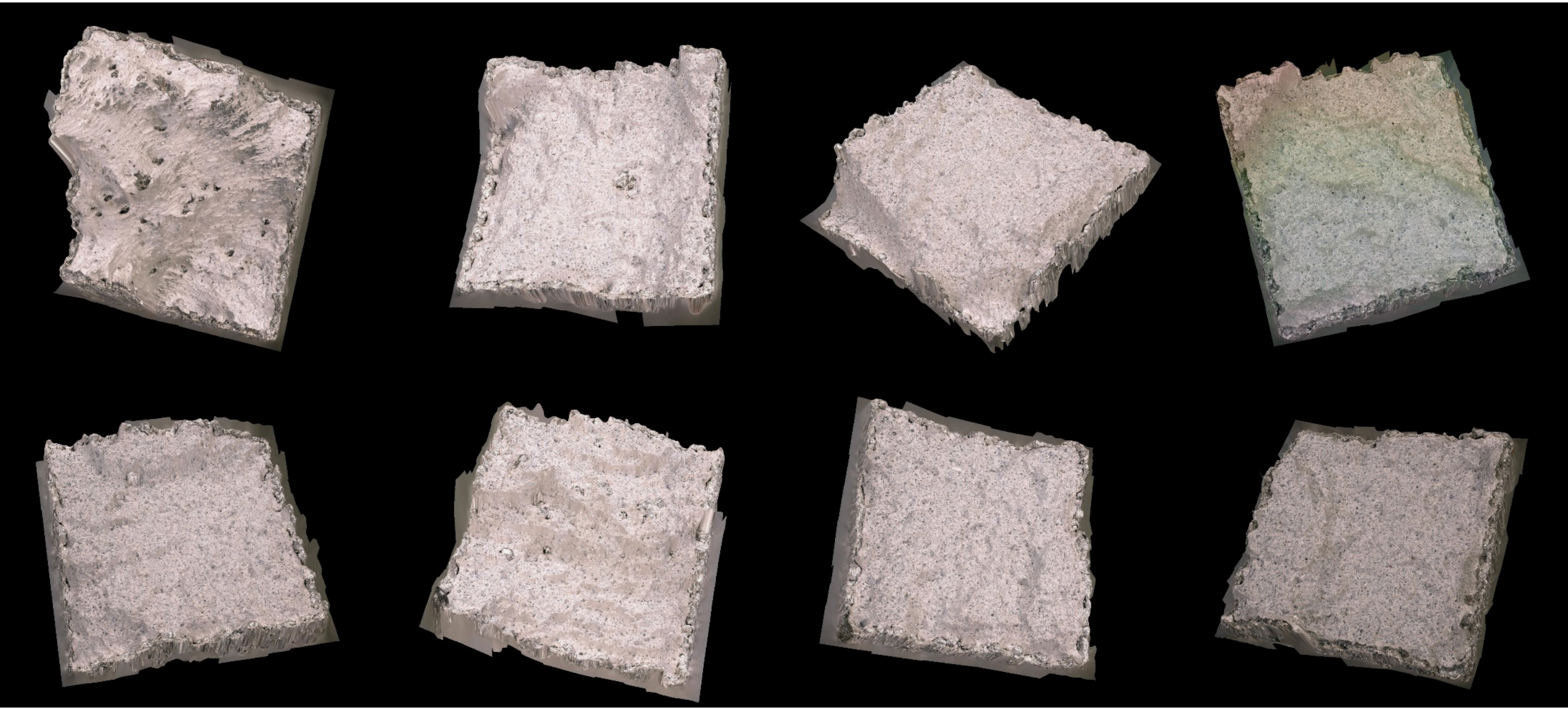
Build 6, which was built using fresh powder, performed similarly to samples made with recycled powder, perhaps due to recycled powder remaining in the machine from previous builds. The extra virgin powder from build 1 clearly stands apart from the other builds.

Build's 1 and 6- Fresh Powder



Samples from build 1 have higher ultimate tensile strength and strain to failure than build 6.

Fracture surface tortuosity appears related to strength and ductility.



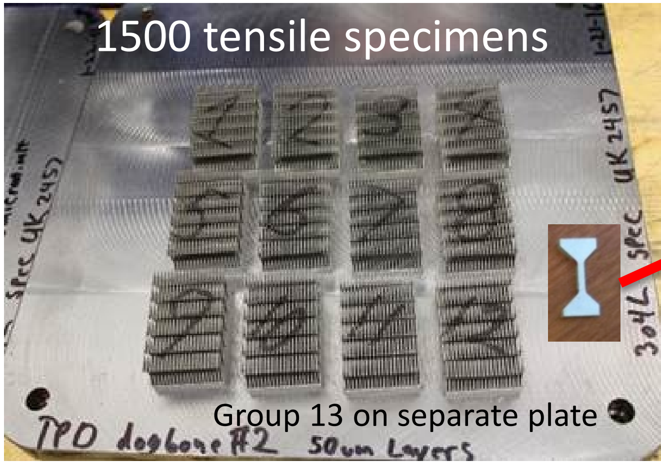
Fracture Surfaces appear to have fewer lack of fusion voids than previous builds- may contribute to ductility consistency.

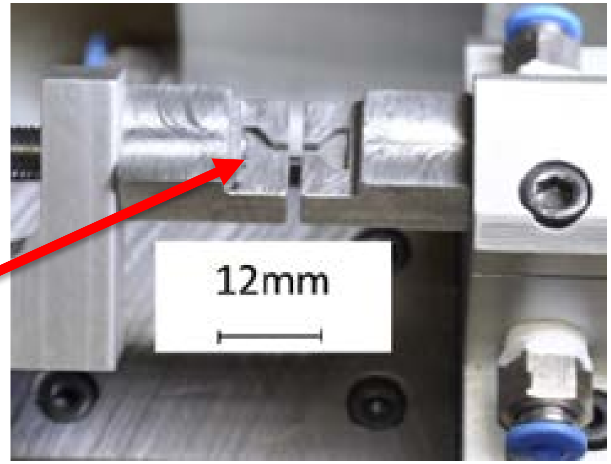
Conclusions

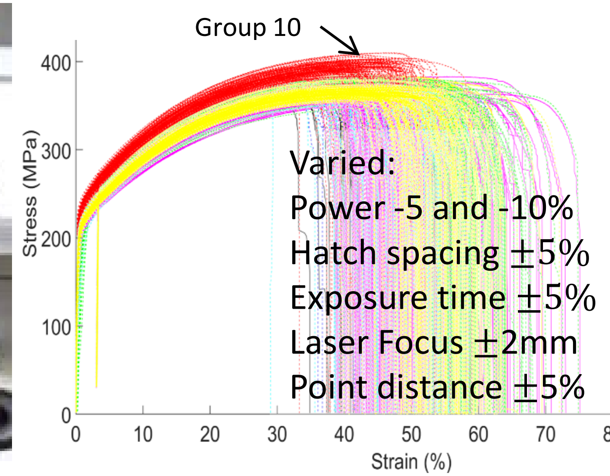
- Need appropriate tests to qualify components
- Representative volume element specimens provide much more statistically significant answers
- Many quick experiments are necessary for statistically significant conclusions.
- "Extra virgin" powder is extremely beneficial for ductility, strength and Charpy impact toughness
  - Every powder recycle degraded properties.
  - Fracture surfaces also appear to be characteristically different in plate 1.
  - Was 5000 plate 2 virgin powder and plate 1 not?
- Larger specimen cross sections appear to give more consistent ductility values.
  - Initial confirmation of RVE effect. Small HTTs from 6000 series will confirm

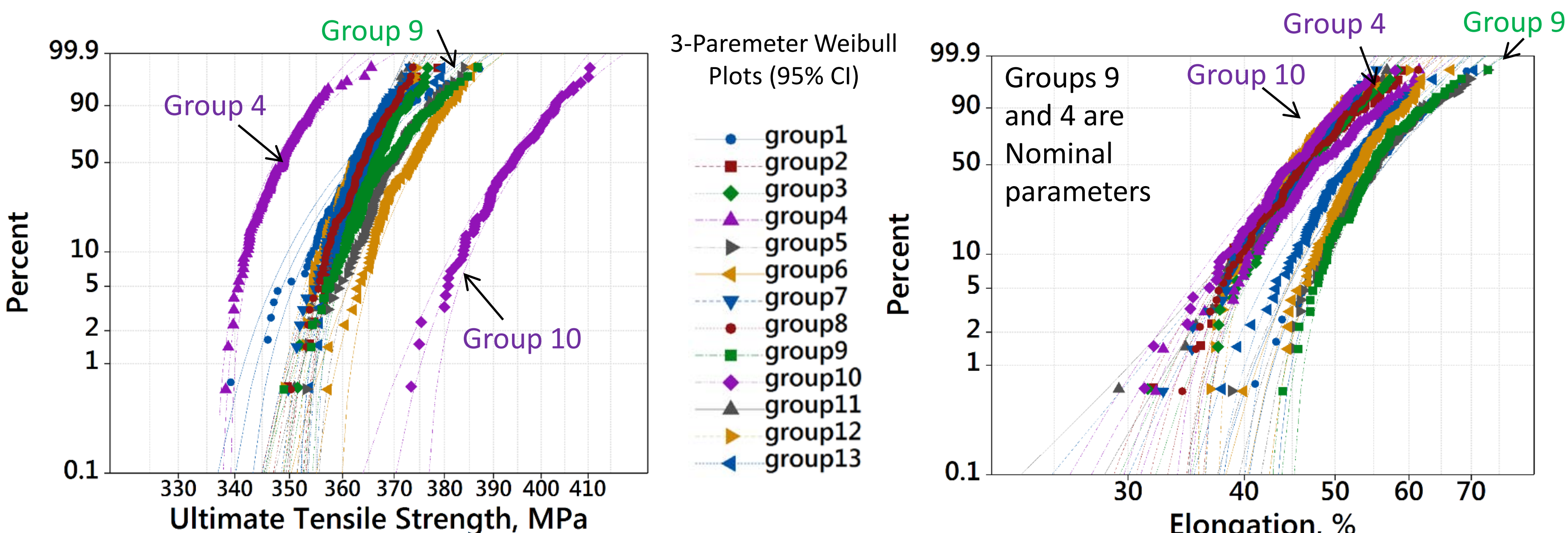
Extra Slides

Small variations in print parameters have little effect



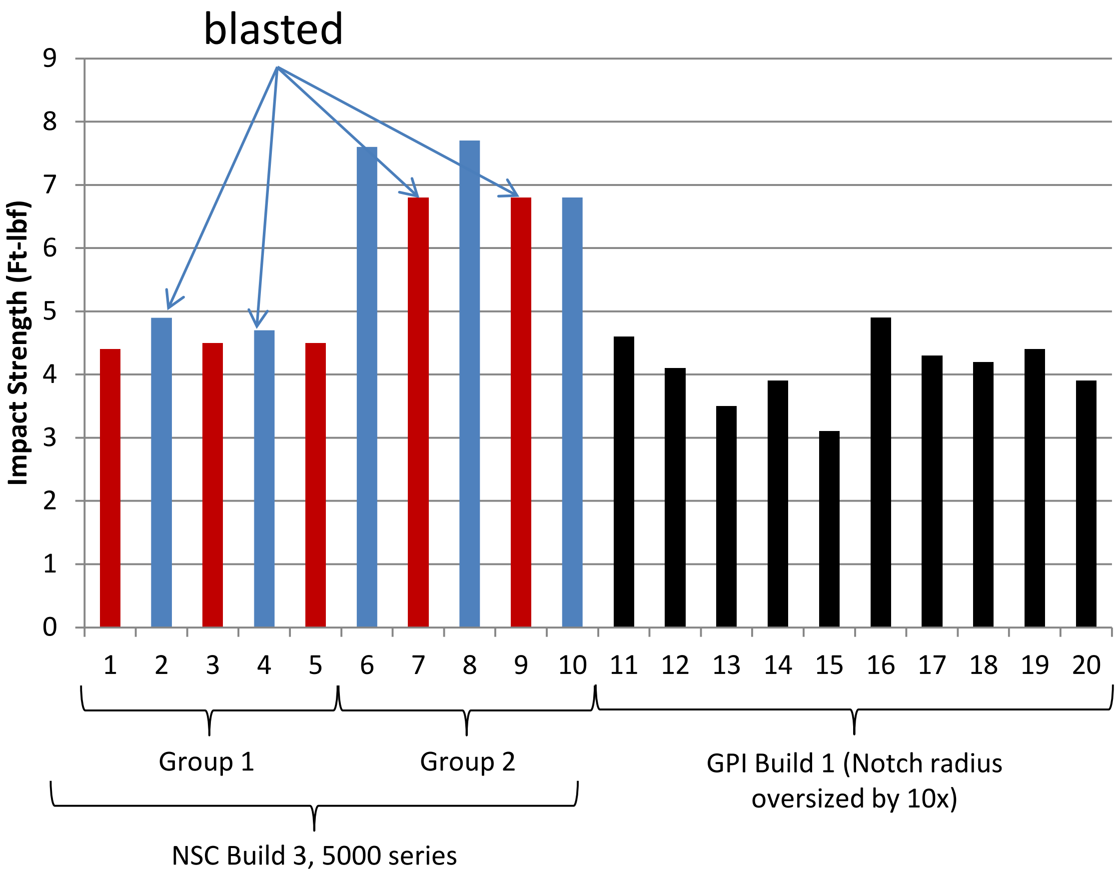






Location is most significant parameter in this study. UTS ≈ 340 – 365 ±35 MPa (53 ksi), Ductility ≈ 28 –73%

Charpy Measurements 3xxx and 5xxx series



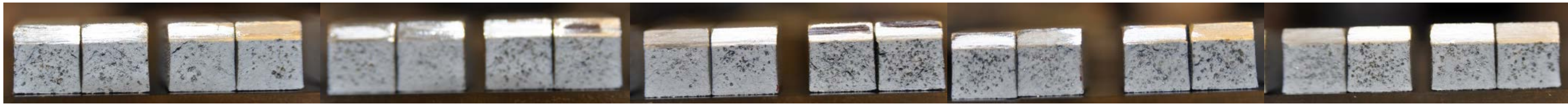
Notch on top relative to specimen #
Notch on side relative to specimen #
Unknown orientation

	Average (ft-lbf)
Build 3 Group 1	4.60
Build 3 Group 2	7.14
Build 3	5.87
GPI	4.09
Build 3 Group 1 Top	4.47
Build 3 Group 1 Side	4.80
Build 3 Group 2 Top	6.80
Build 3 Group 2 Side	7.37

7075 Al was 3.2

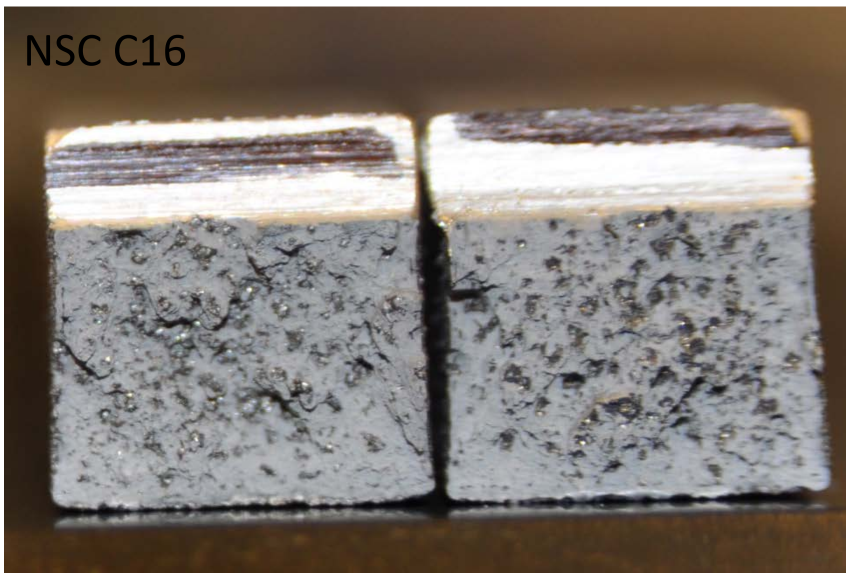
Images of Charpy fracture surfaces show voids or intermetallics are prevalent.

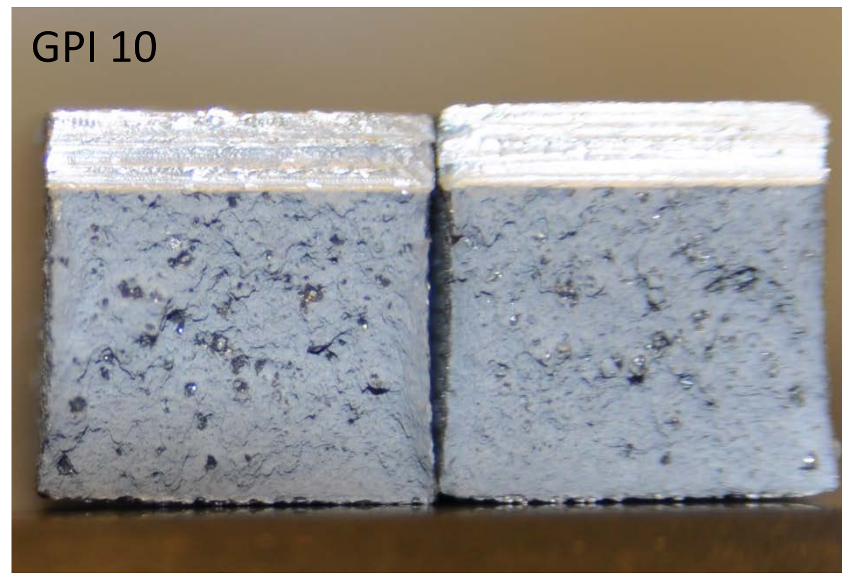
NSC Build 3



C11 C12 C13 C14 C15 C16 C17 C18 C19 C20

Group 1 Group 2

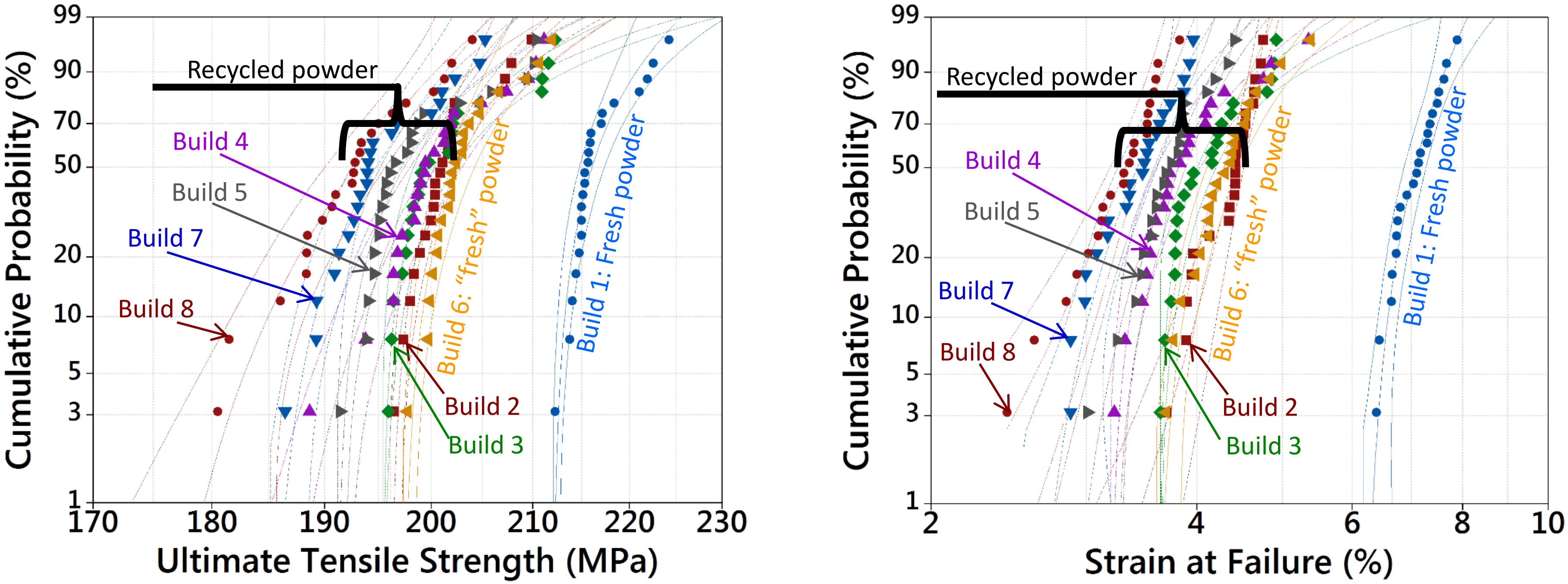




GPI Build 1

1 2 3 4 5 6 7 8 9 10

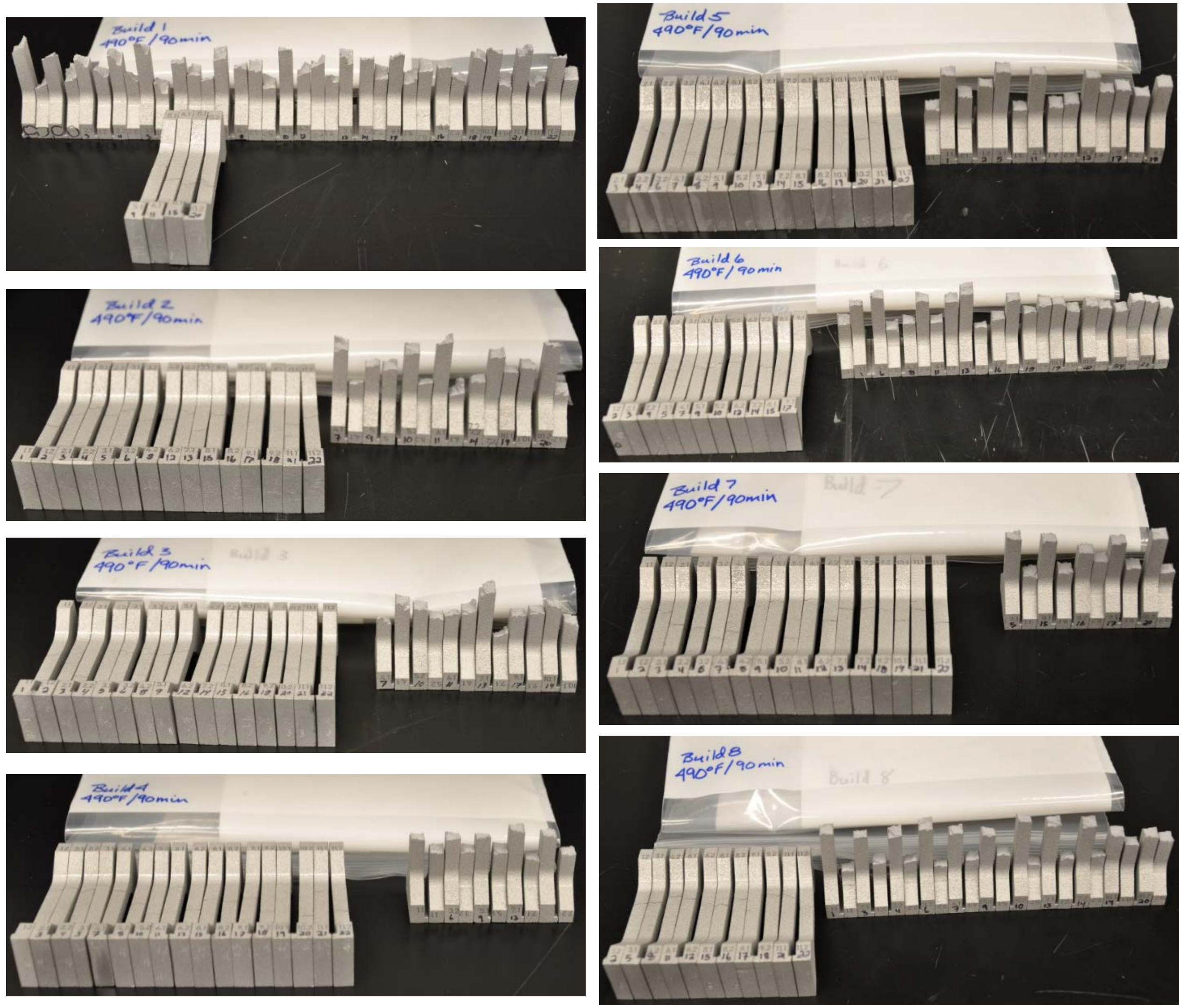
Builds 1-8
Weibull 3-parameter Distributions



Duplicate of slide 4, but with each build labeled:
The UTS and ductility both decrease as a result of powder recycling. Build 8, which has the most recycled powder, performs lowest in UTS and ductility.

All builds: general fracture locations around same height

- Most specimens fractured about ¾ up in the gage section, at approximately the same build height.
- Consequence of hall-petch due to cooling rates during build?
- Build plate 1 has much more tortuous, slanted fracture surfaces.



Specimens that appear intact are fractured, but not completely separated to preserve fracture surfaces.

Hardness testing

- **All Large HTT specimens fail around ¾ up the height of the gage section**
  - **Some small variability- not a single bad layer**
  - **Change in properties at that height due to height of other components?**
  - **Heat transfer rates causing stronger microstructures near bottom.**

Modulus- 304L and Al

- **Ultrasound vs. unloading modulus**
- **Relate to density (Al is approx. 96%)**
- **Why is my 304L modulus low when 17-4 modulus is typical?**
  - **Not machine or procedure**
  - **Check density**
  - **Negligible surface crust**

304L Issues

- **Annealing effects on machined tensile bars**
- **Rate effects**
- **Print parameters have little effect**
- **Incorrect Modulus**
- **Thin specimens- surface crust and lack of RVE adds lots of variability.**