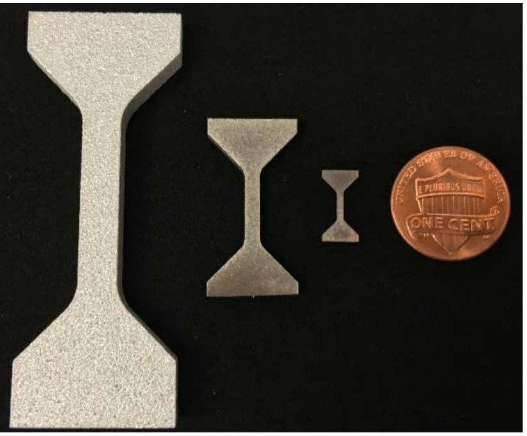
Materials Science and Technology, 2016

SAND2016-10771C

Mechanical Properties and Trends in Additively Manufactured Aluminum



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Jeffrey M. Rodelas, Lisa A. Deibler, Bradley H. Jared,
Bradley Salzbrenner, Brad L. Boyce

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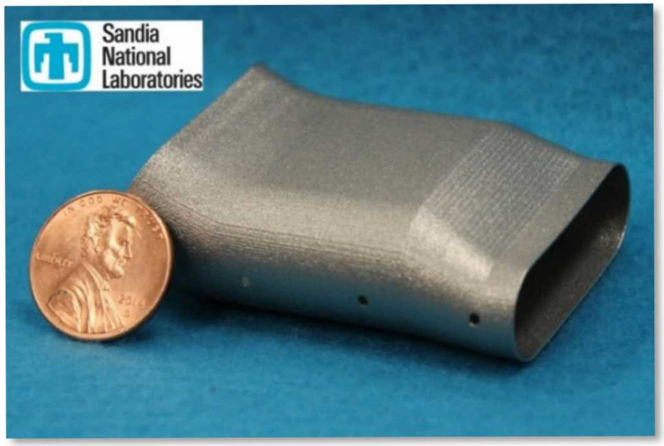
9/21/2016

Powder bed additive manufacturing

Questions

- How do input parameters affect performance
  - Powder reuse
- What are the mechanical properties for AlSi10Mg?
  - Strength
  - Ductility
- What variability do we see?



What tests to simulate component failure?

Failure is defined as a sizable crack due to compression of the component.

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

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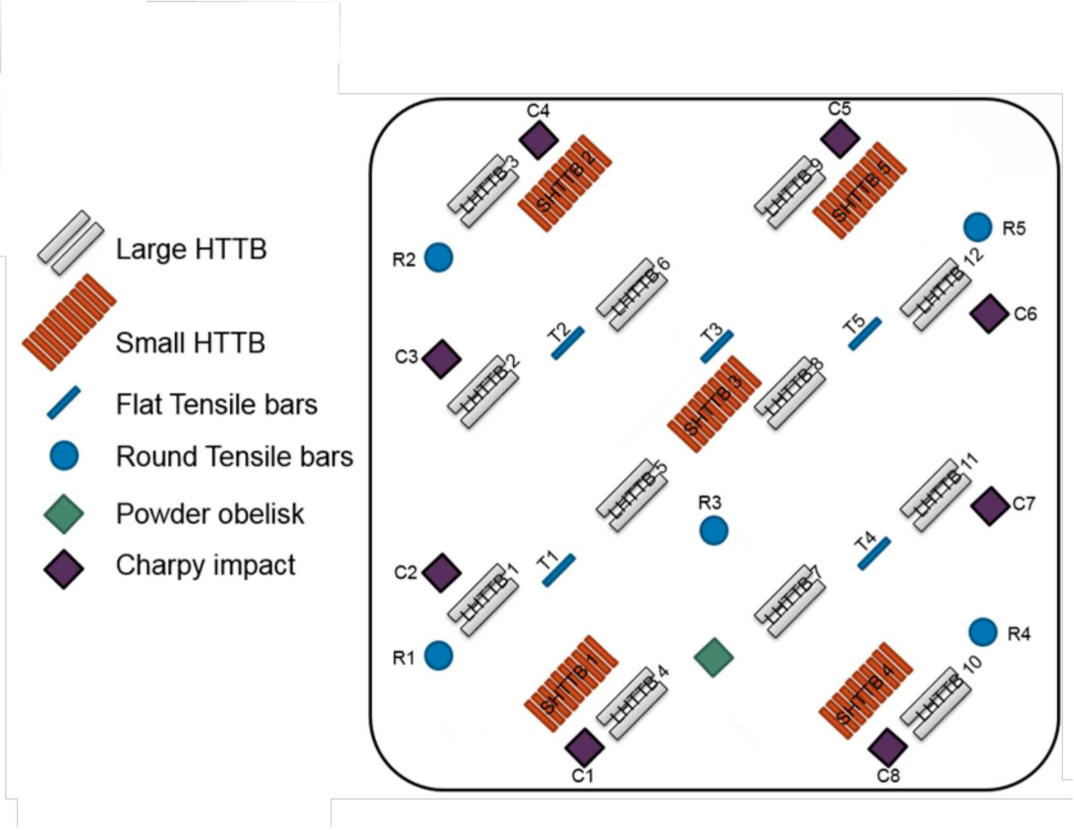
AlSi10Mg

- **Renishaw M250 Printer**
- **Powder from LPW**
- **Heat treated at 300° for 2 hrs to relieve stresses**



AlSi10Mg

Element	Percent
Aluminum (Al)	**Balance**
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

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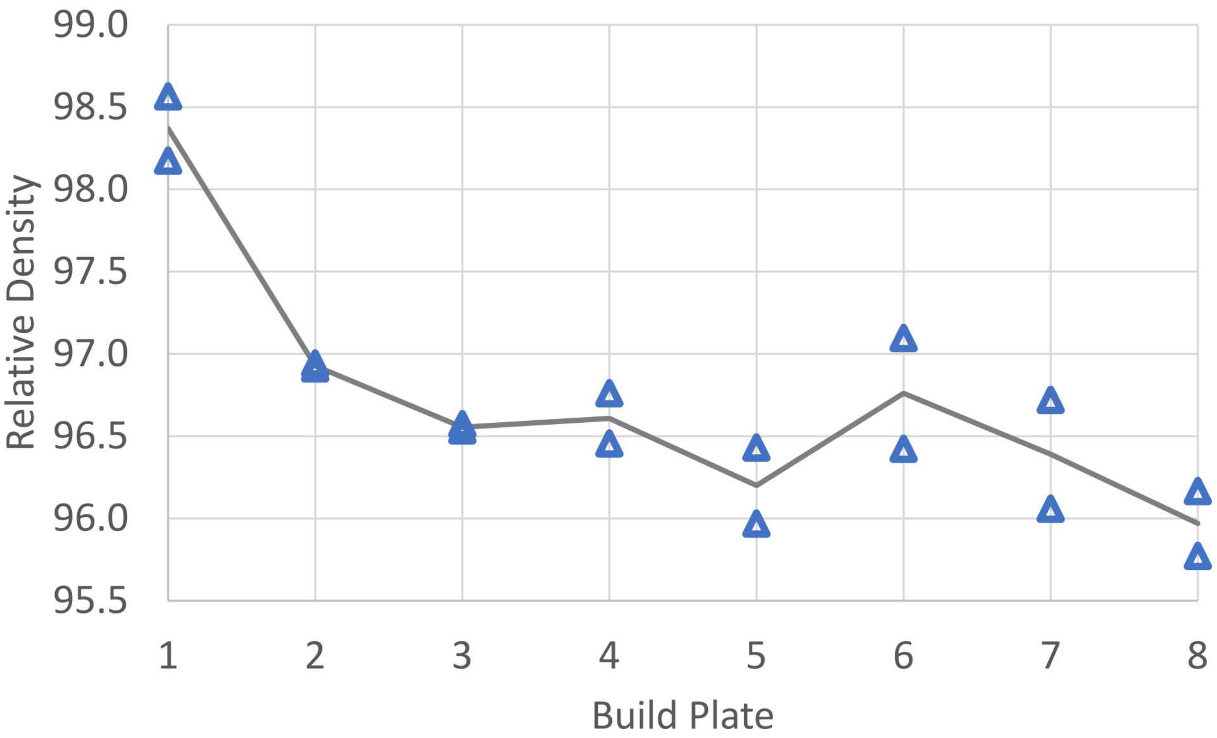
Density measurements follow powder reuse trend

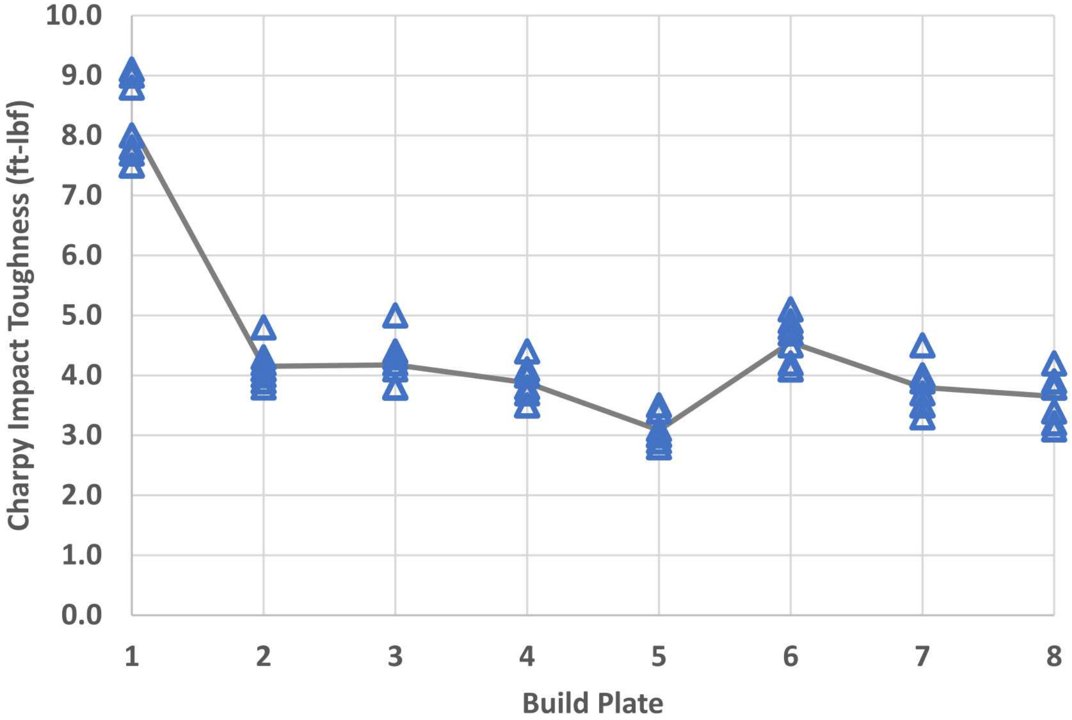
Build	Powder condition
1	Fresh
2	Recycled **once**
3	Recycled **twice**
4	Recycled **3 times**
5	Recycled **4 times**
6	Fresh
7	Recycled **once**
8	Recycled **twice**

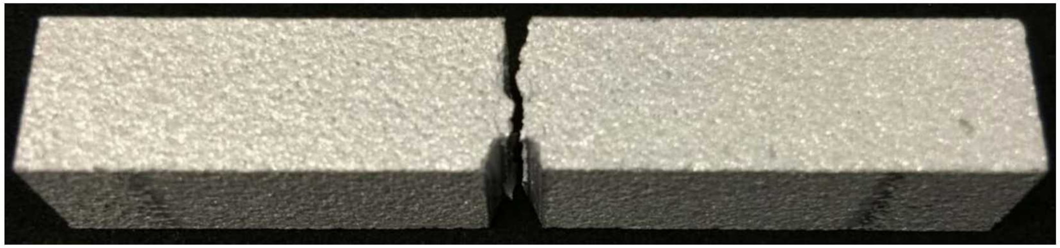


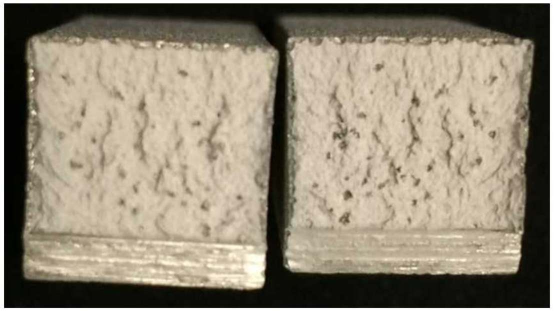
- **How do these measurements translate to mechanical behavior?**
- **Ran 64 Charpy impact tests.**
- **Ran 172 tensile tests.**

100% density is 2.67 g/cm^3

Charpy impact toughness







- 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.

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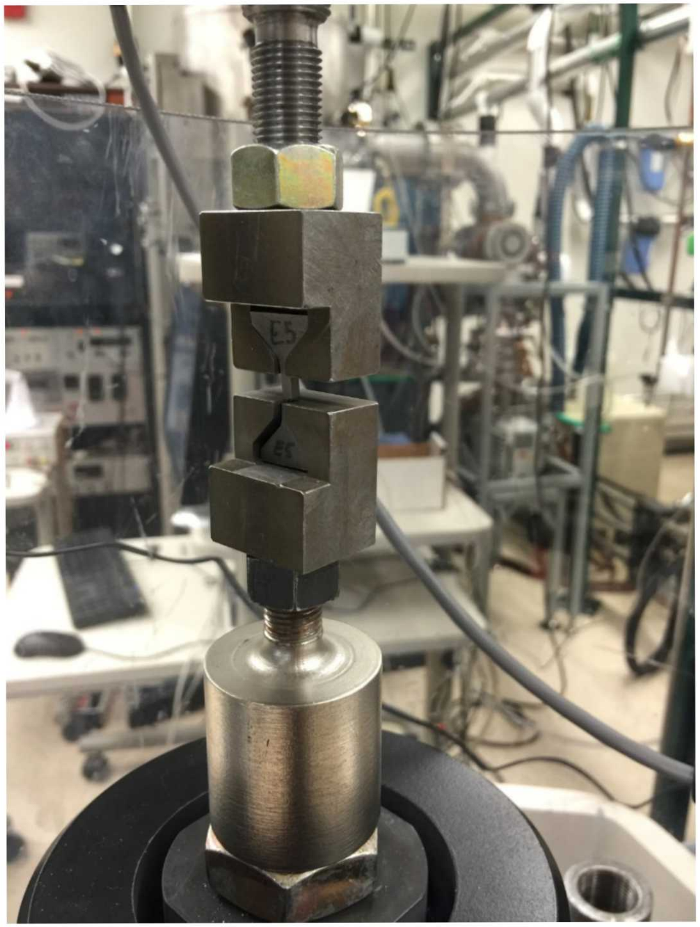
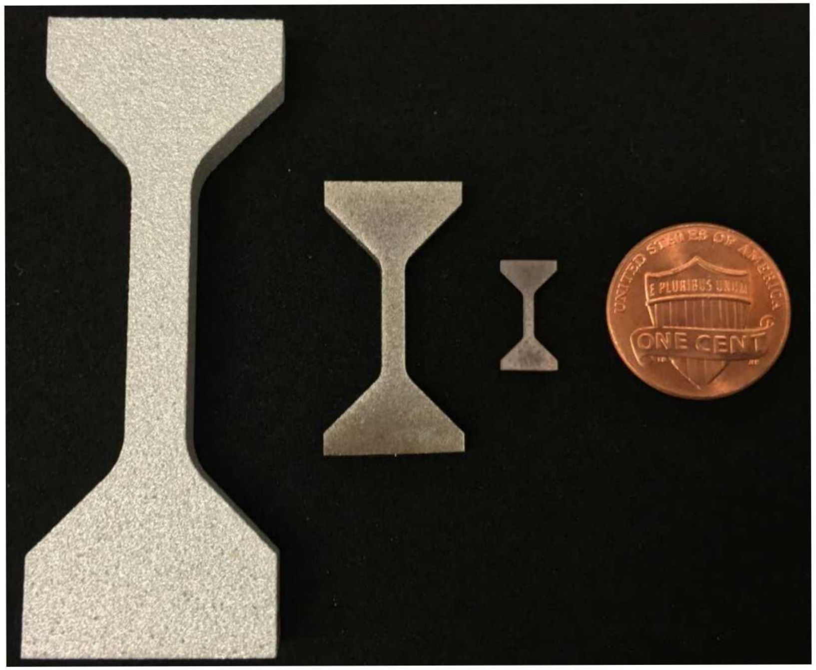
Tension testing

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



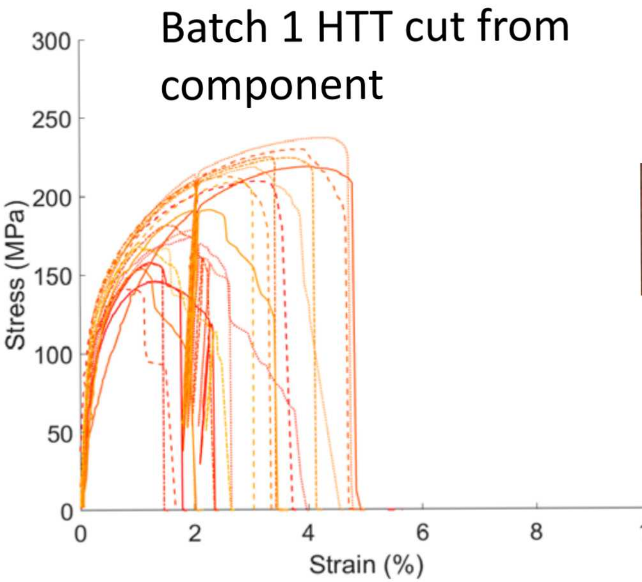


6.25 x 6.25 mm, 2.5 x 2.5 mm, 1 x 1 mm

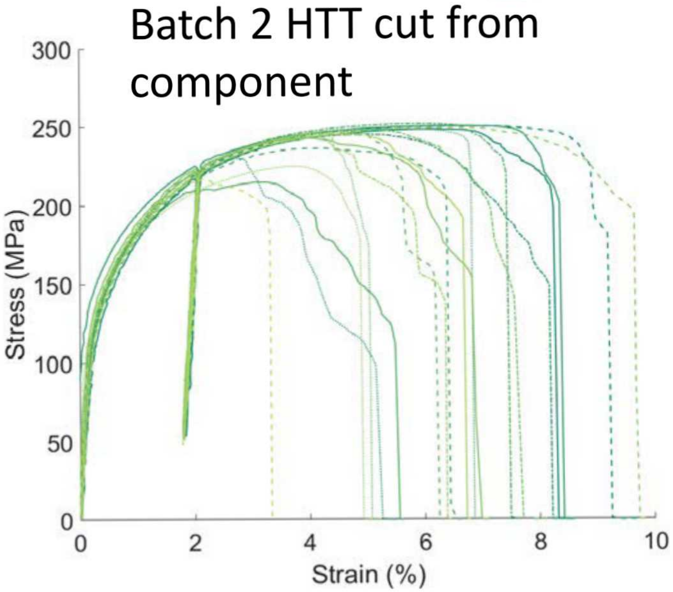
B.C. Salzbrenner, J.M. Rodelas, J.D. Madison, B.H. Jared, L.P. Swiler, Y.-L. Shen, B.L. Boyce, J. Mat. Proc. Tech. 2016

Small high throughput tension (HTT) specimens

1 x 1 mm



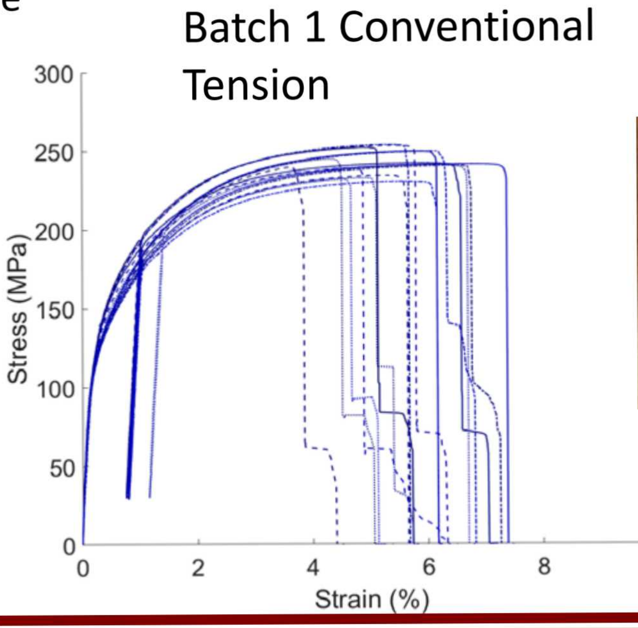
Batch 1 HTT cut from component



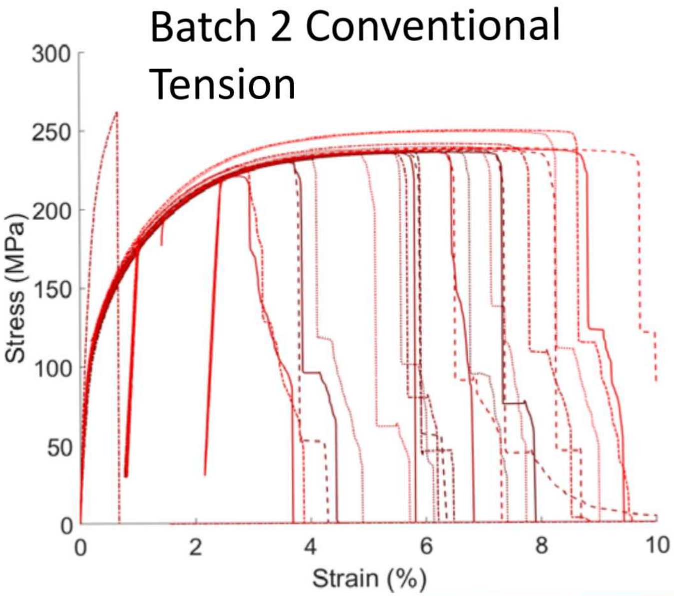
Batch 2 HTT cut from component

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

6 x 1.25 mm



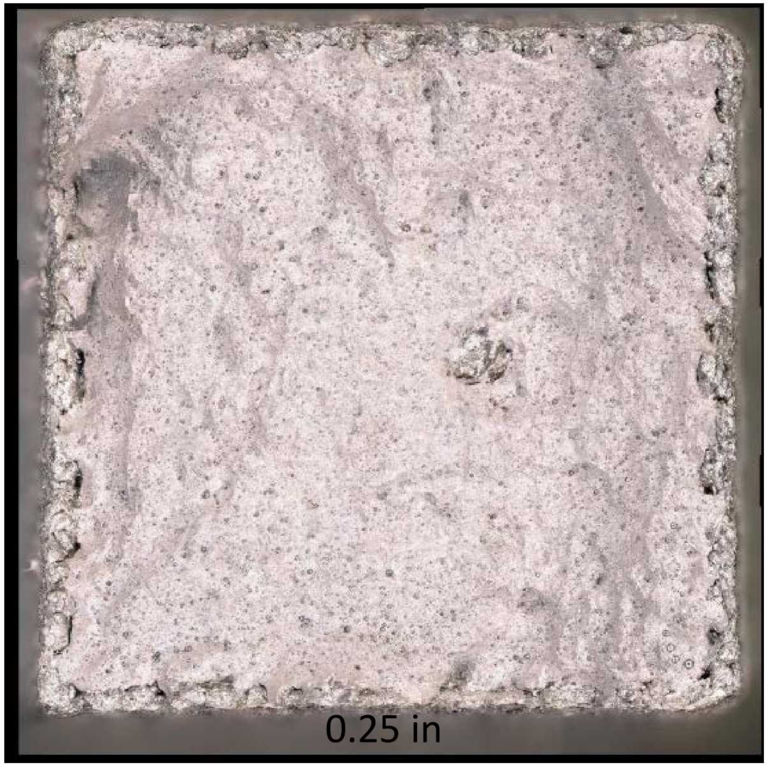
Batch 1 Conventional Tension

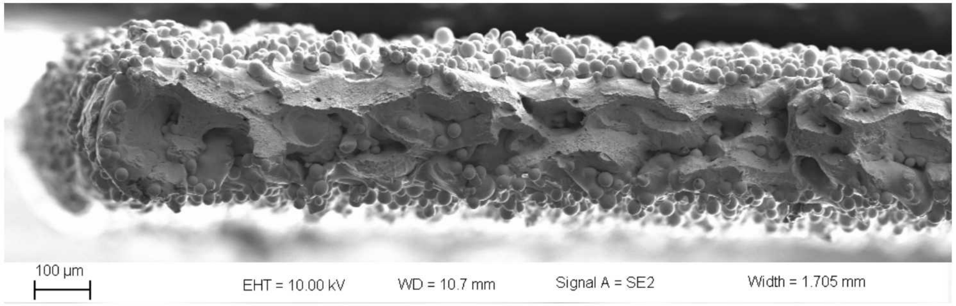


Batch 2 Conventional Tension

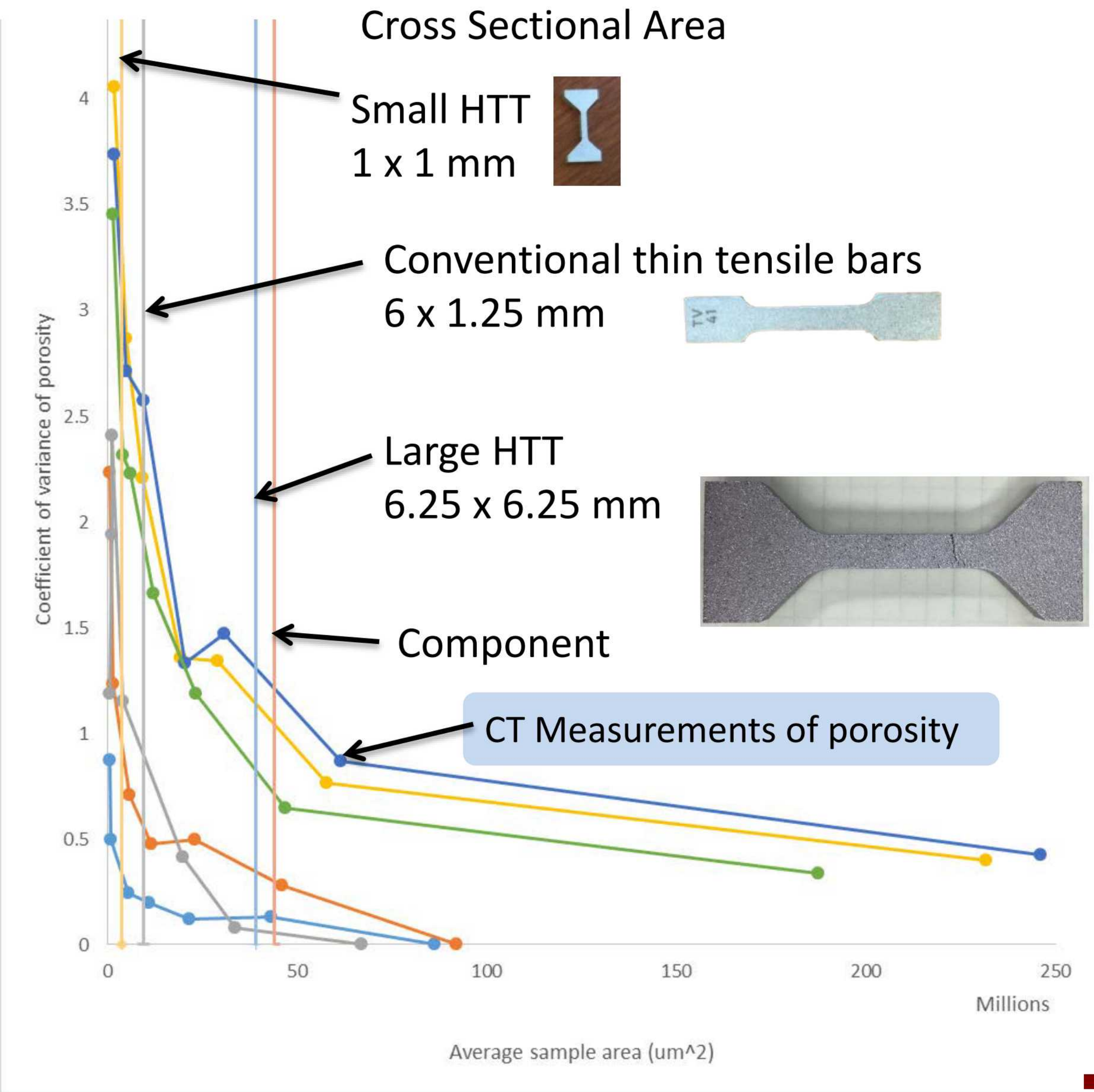
Cross sectional area is difficult to define

- 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.





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?**

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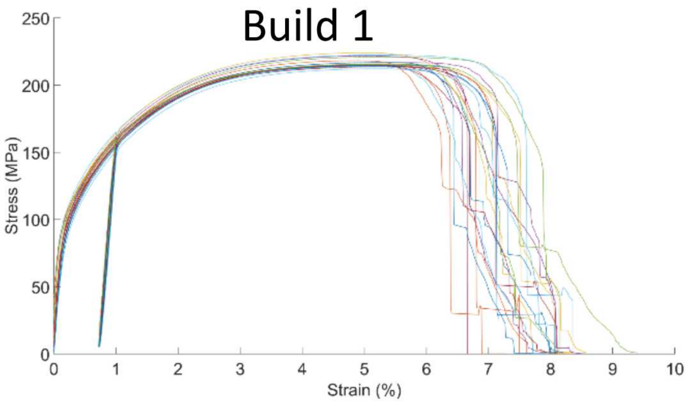
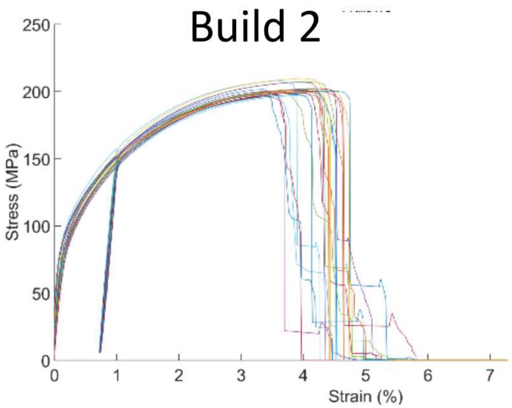
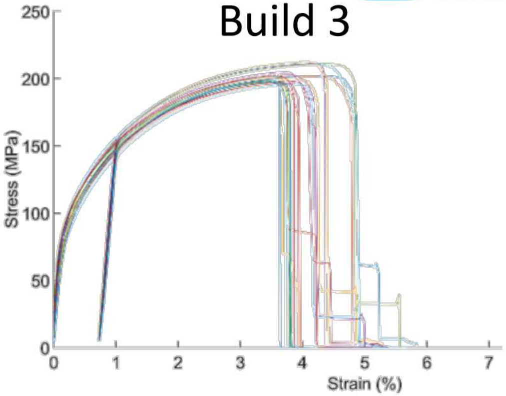
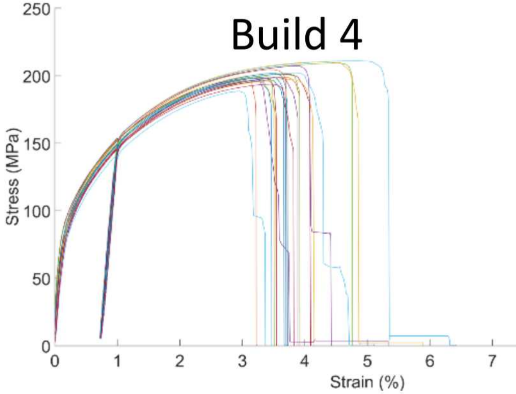
Large high throughput specimens (176 specimens)

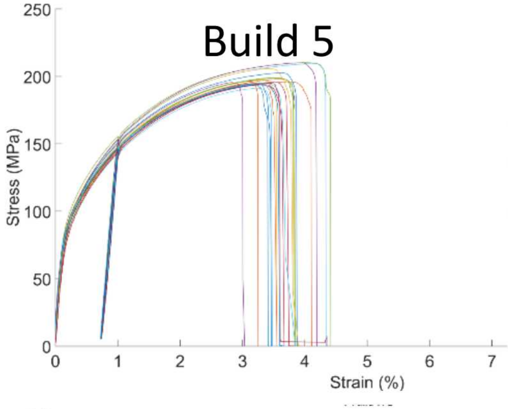
Stress (MPa)

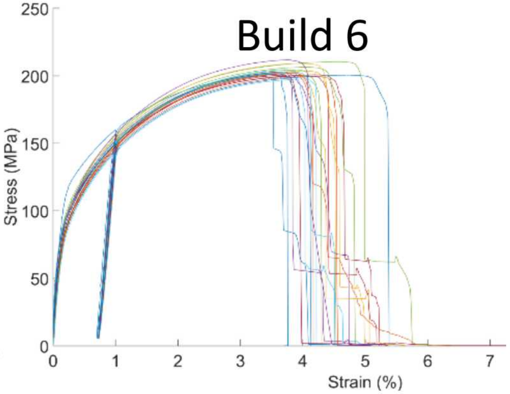


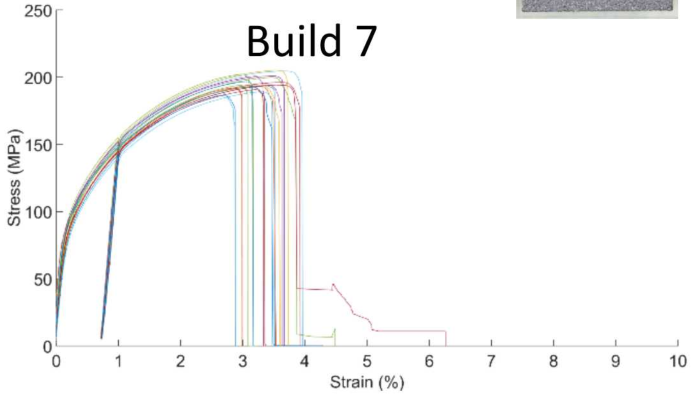


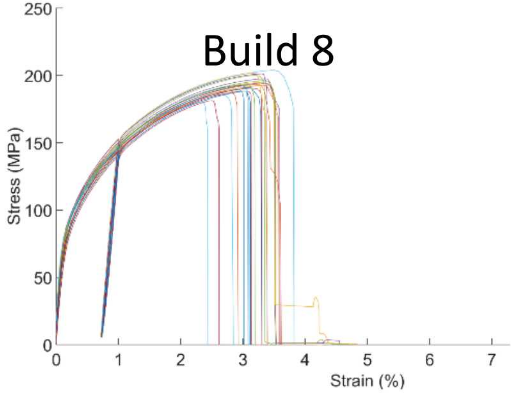








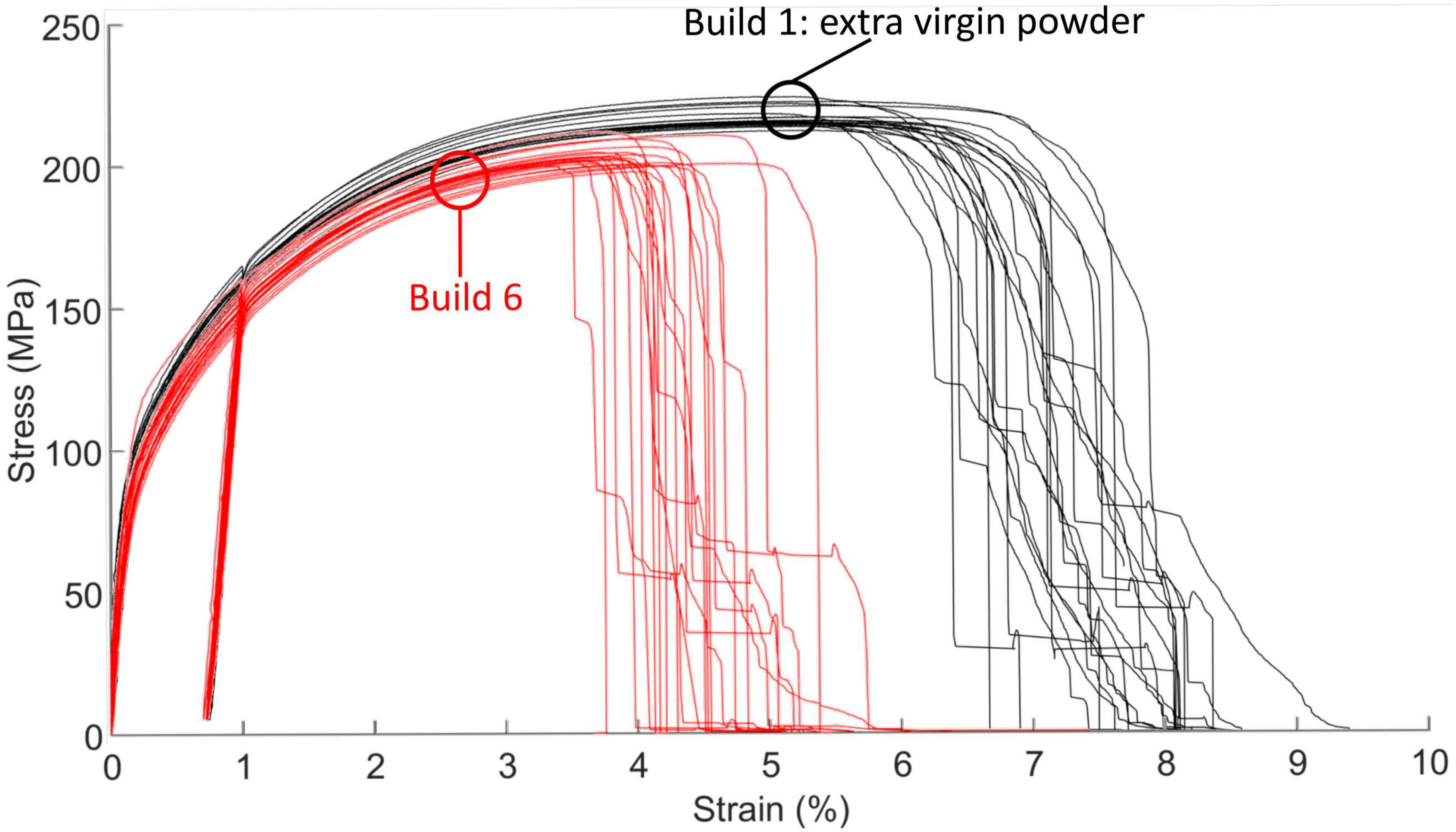




- Less variability within build plates.
- More ductile specimens fail through repeated pop-in.

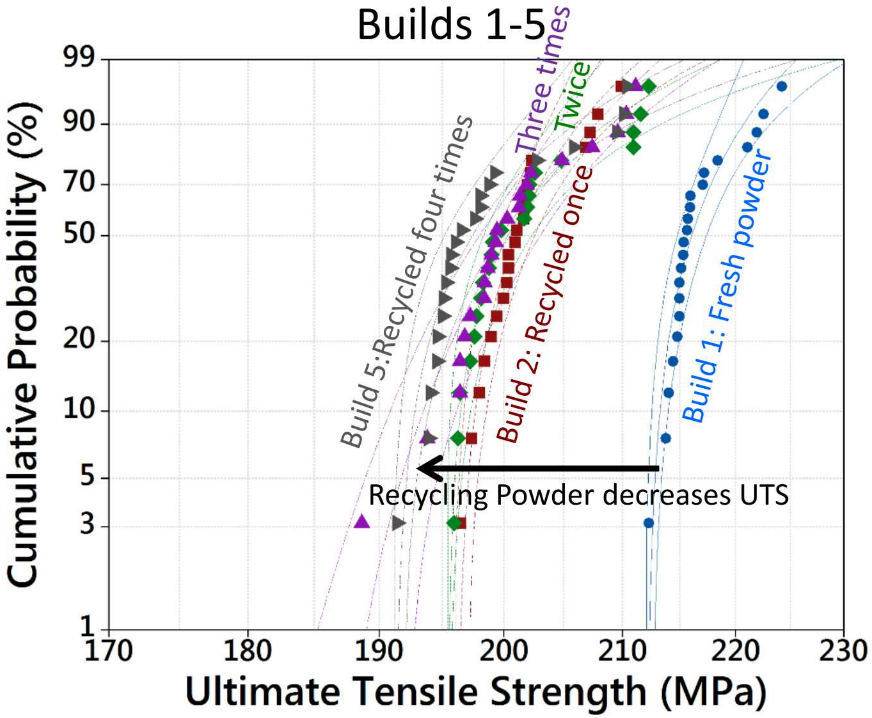
Strain (MPa)

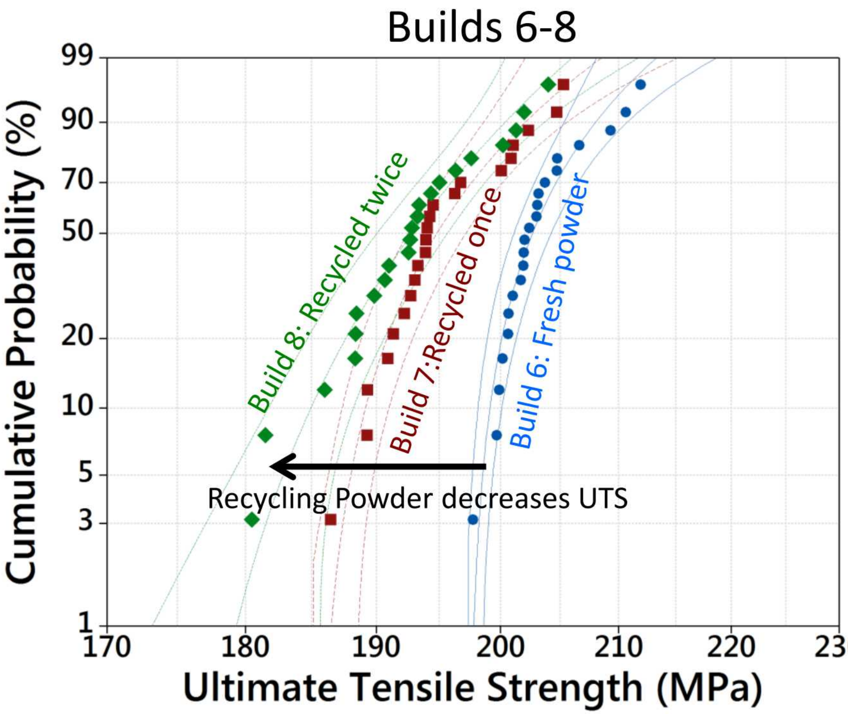
Build’s 1 and 6- Fresh Powder



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

Recycling Powder Decreases UTS
Weibull 3-Parameter Distributions





- **Recycling powder degrades strength (~10% max).**
- **Strongest build plates have least variability (steepest slope).**
- **Possible change in mechanism at upper end of tails.**

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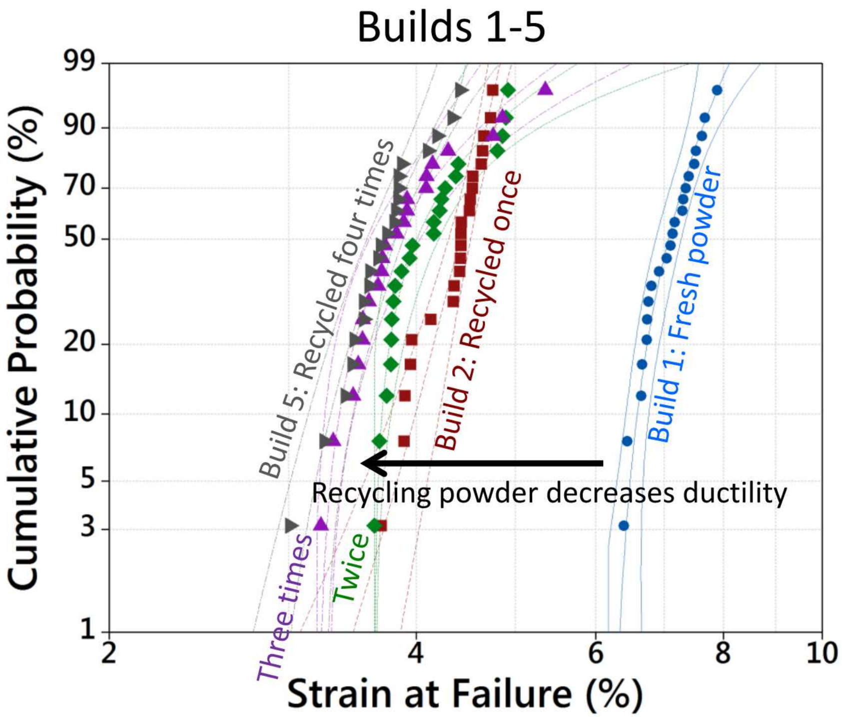
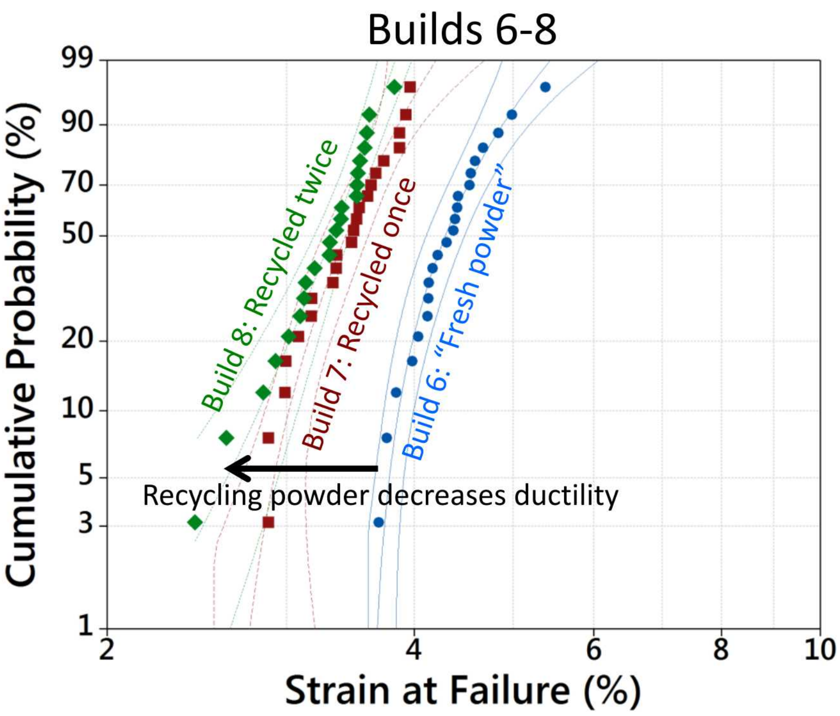
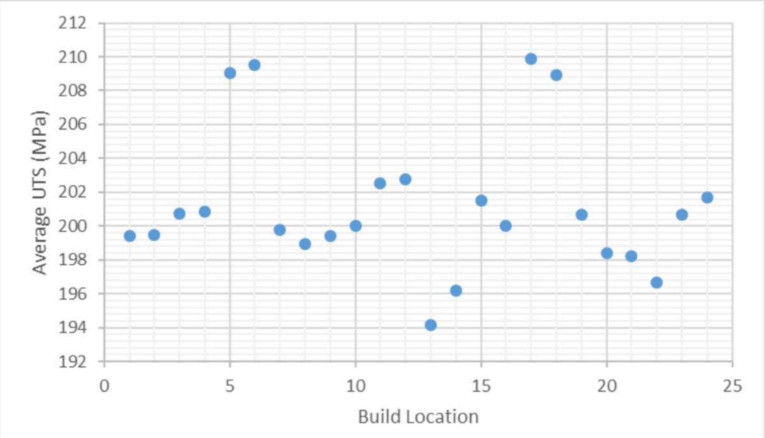
Recycling Powder Decreases Ductility Weibull 3-Parameter Distributions

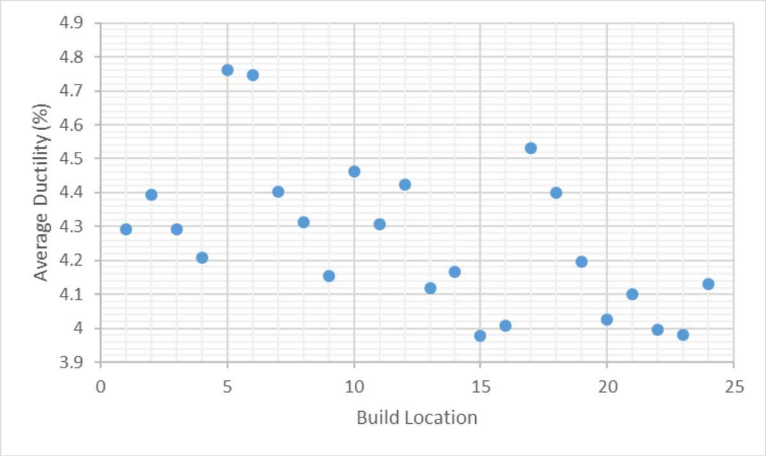


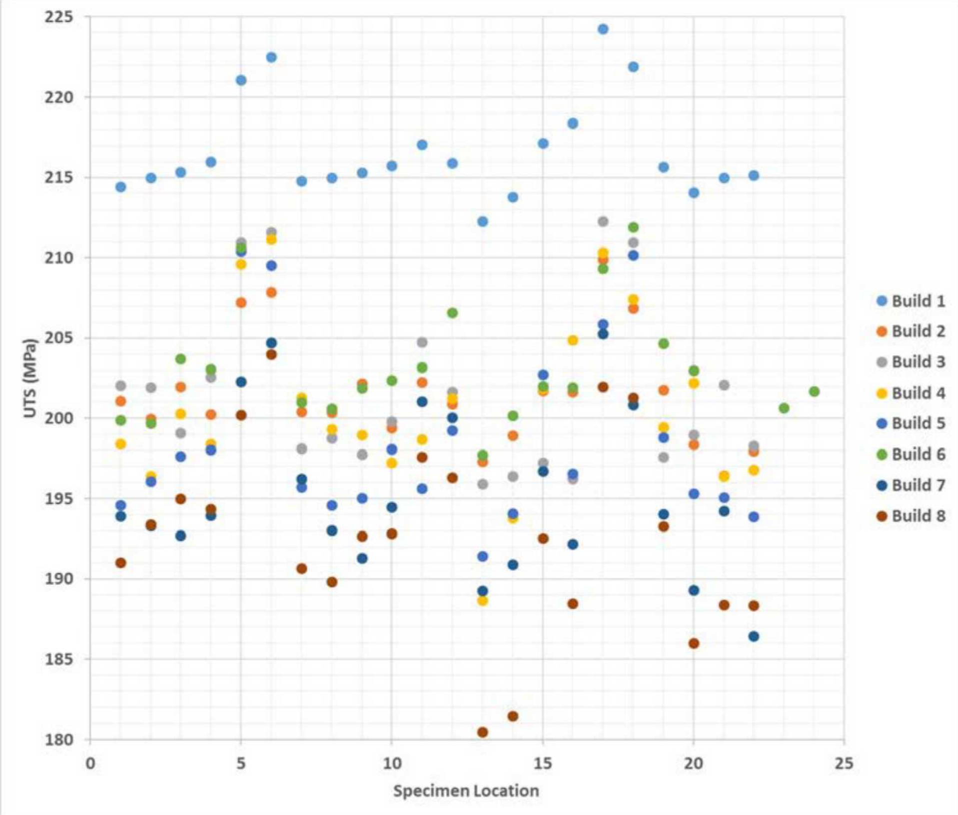


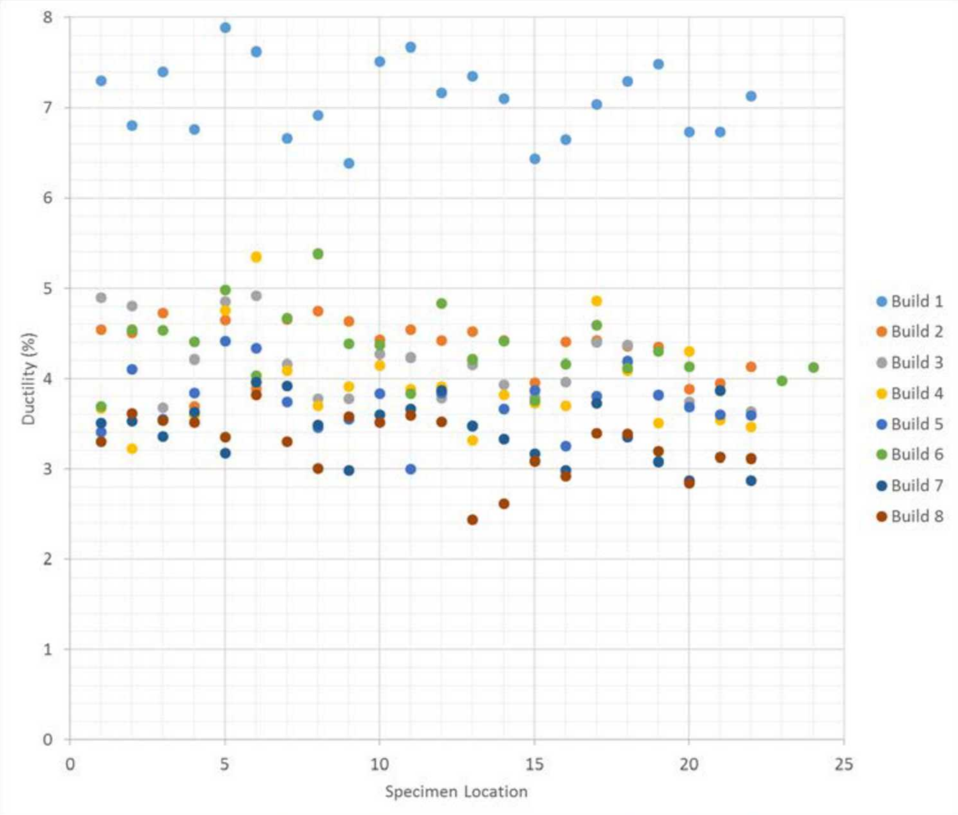
- **Recycling powder reduces ductility dramatically (~40% reduction).**

Location dependence of specimen properties

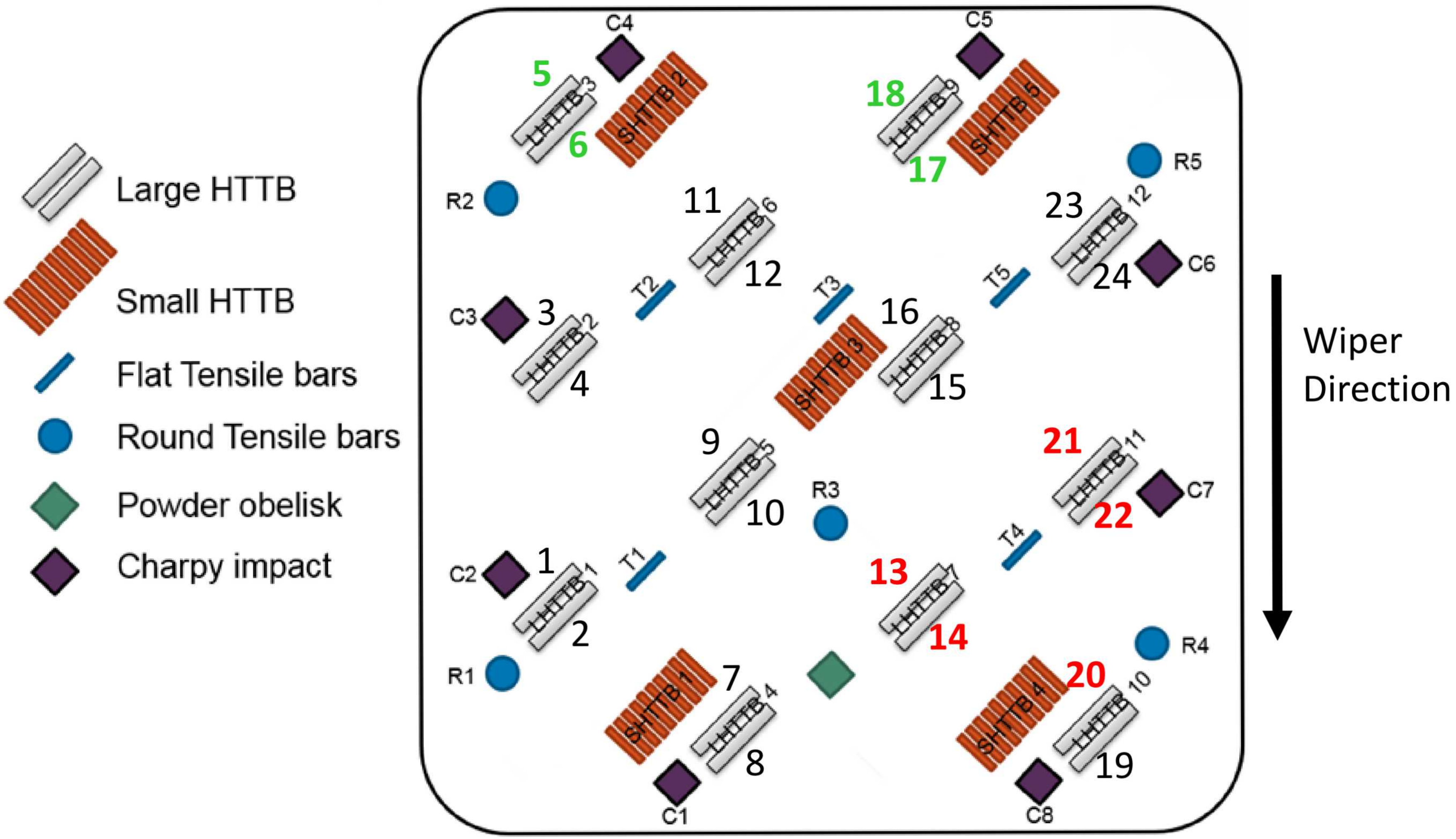




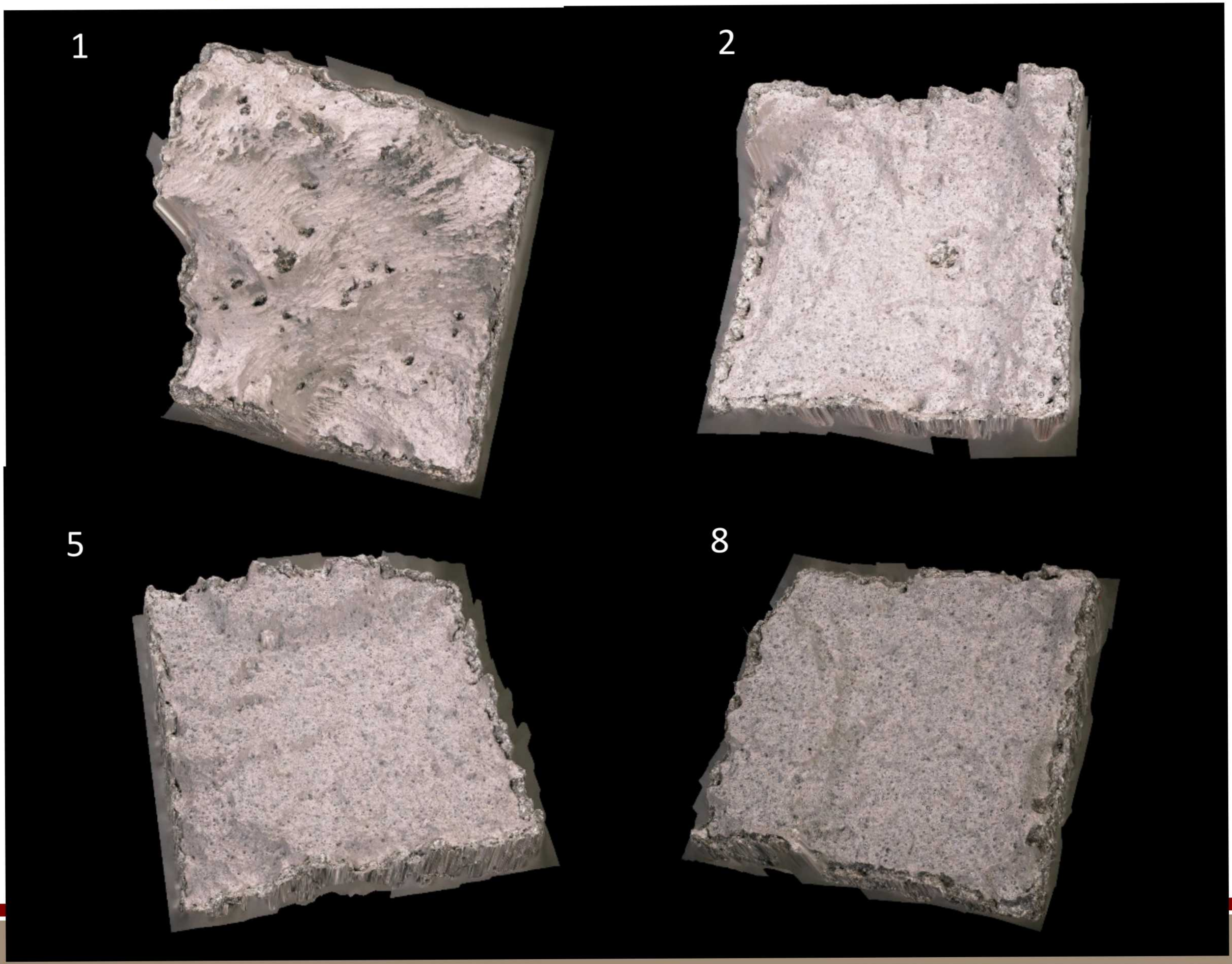




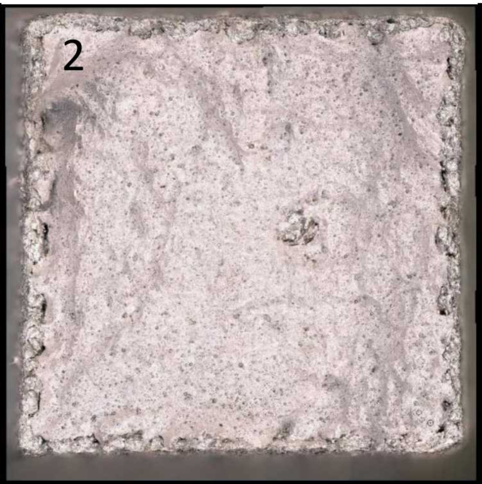
Spatial dependence in tensile strength, regardless of build plate.

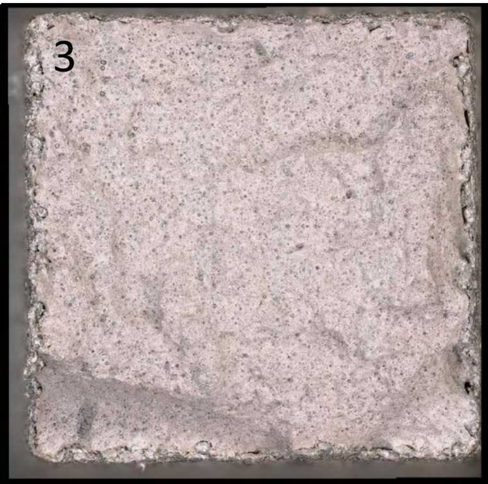


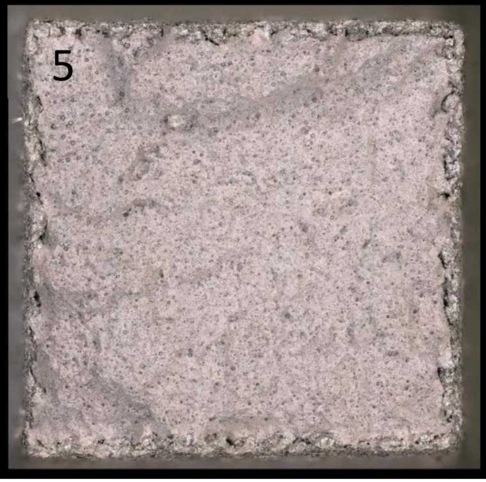
Fracture surface tortuosity appears related to strength and ductility.

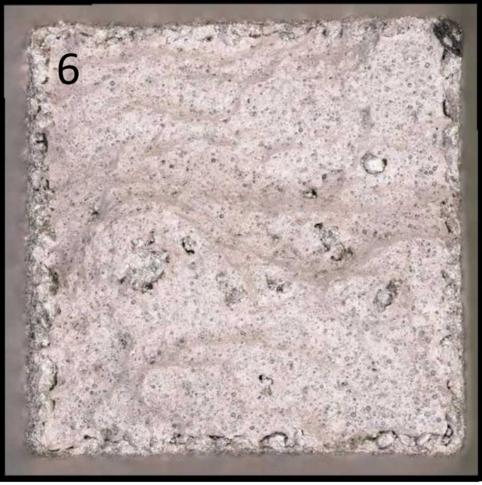


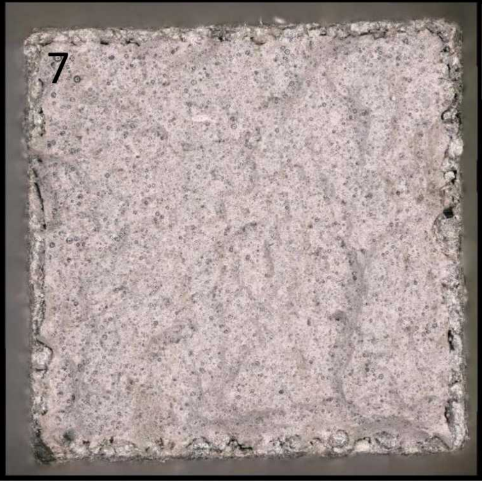
Fracture Surfaces appear to have fewer lack of fusion voids than previous builds- may contribute to ductility consistency.

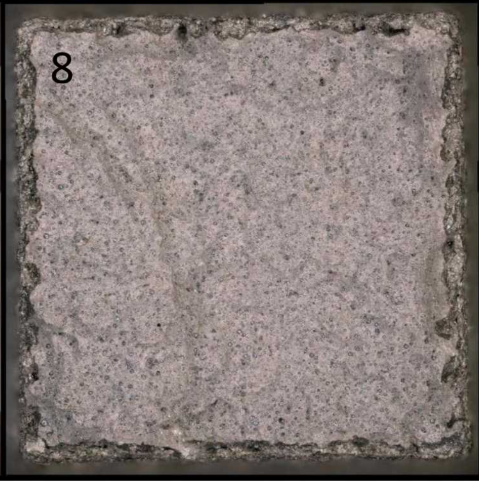












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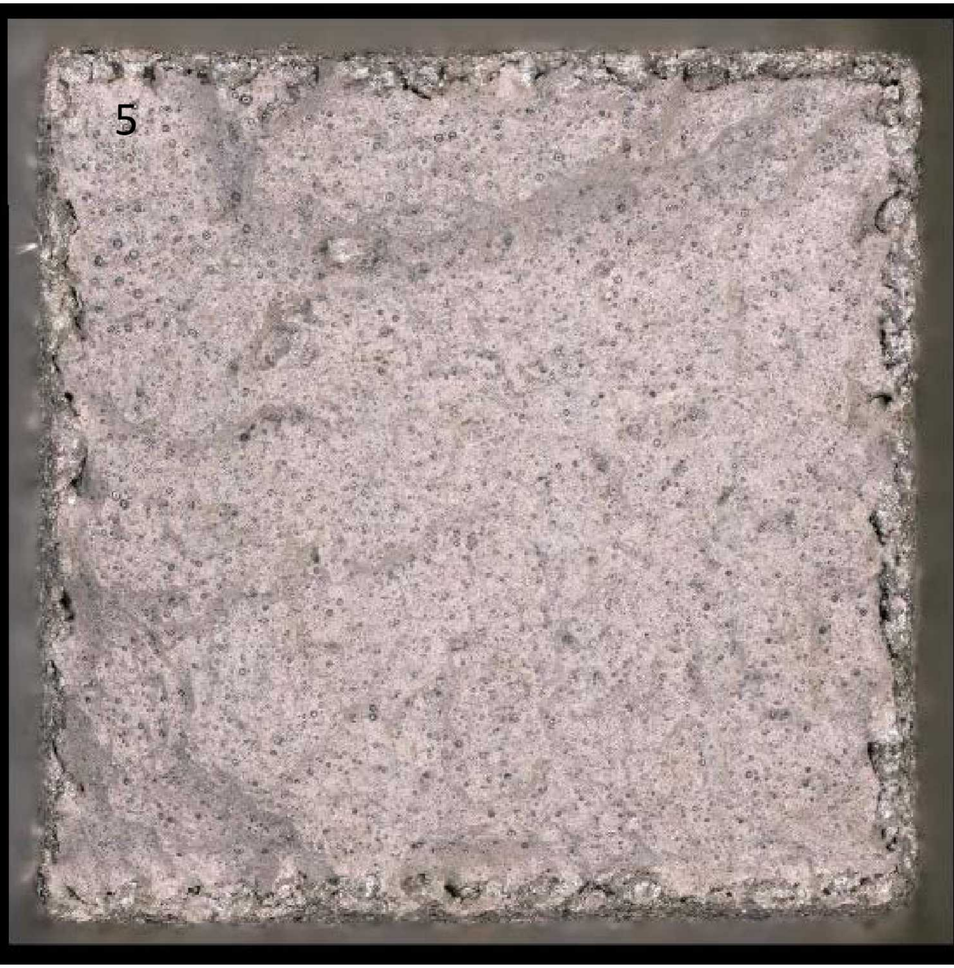
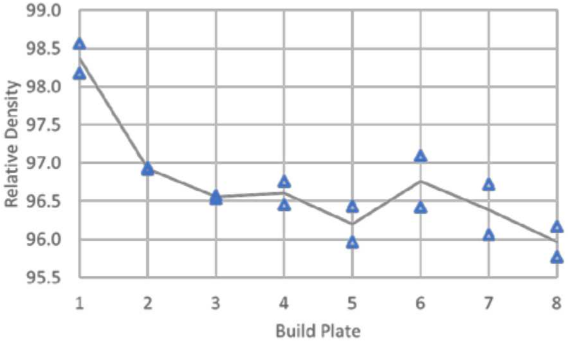
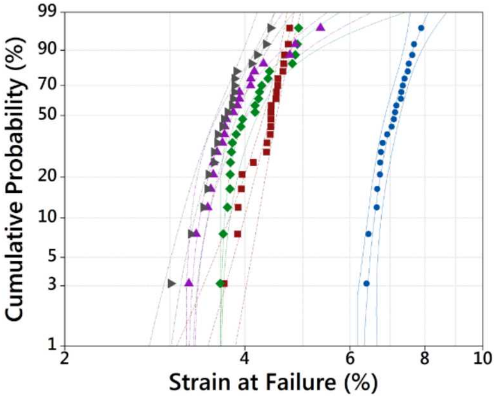
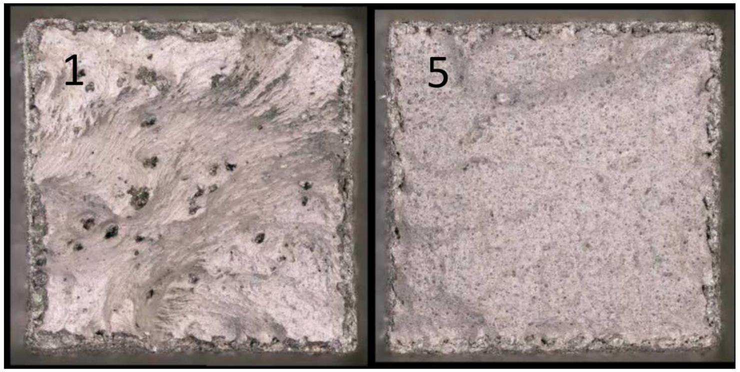


Conclusions

- Powder reuse results in lower density material (higher porosity)
- Increased porosity degrades strength, ductility, and impact toughness.
  - Plate 6 powder appears to be “used” once.
- Larger specimens, which include a representative volume element of material, provide more statistically meaningful results.
  - Ductility spread reduces to ~±0.08% per plate.
  - What if component is not an RVE?
- Small ubiquitous pores appear to dominate behavior over large lack-of-fusion pores.







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Extra Slides

Fracture surface tortuosity appears related to strength and ductility.

1

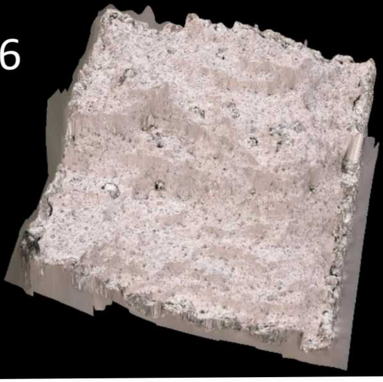
2

3

4

5

6



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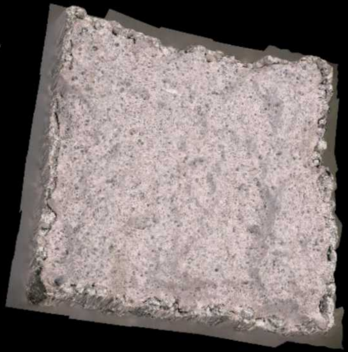

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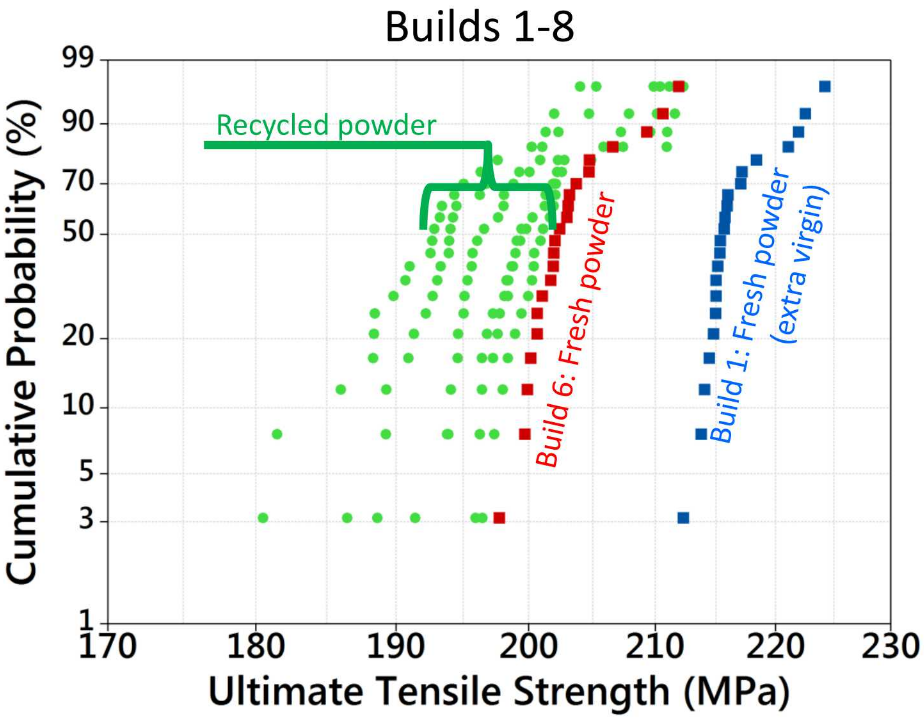
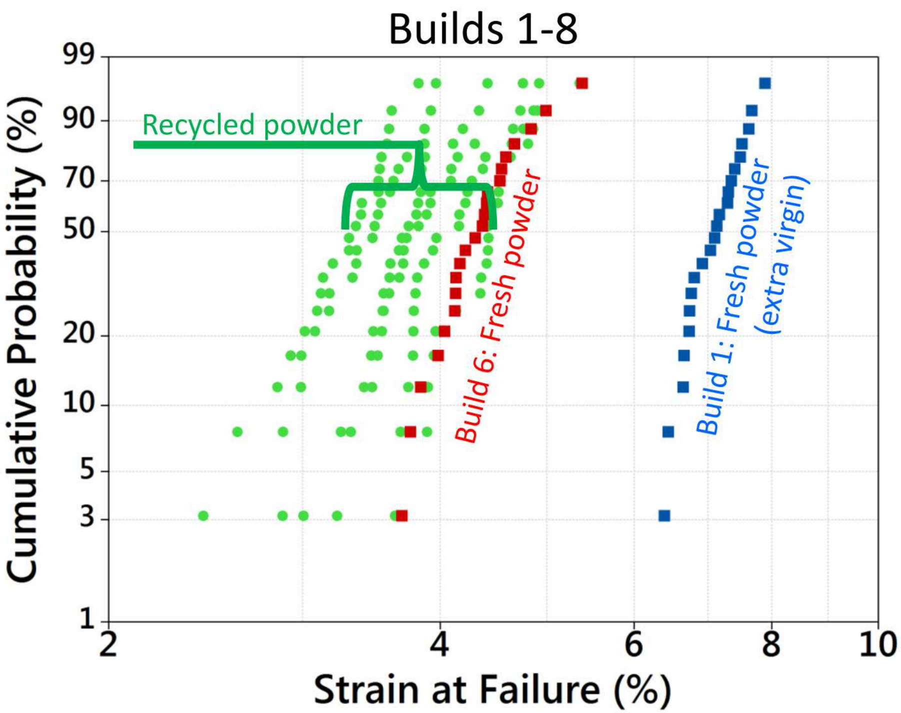
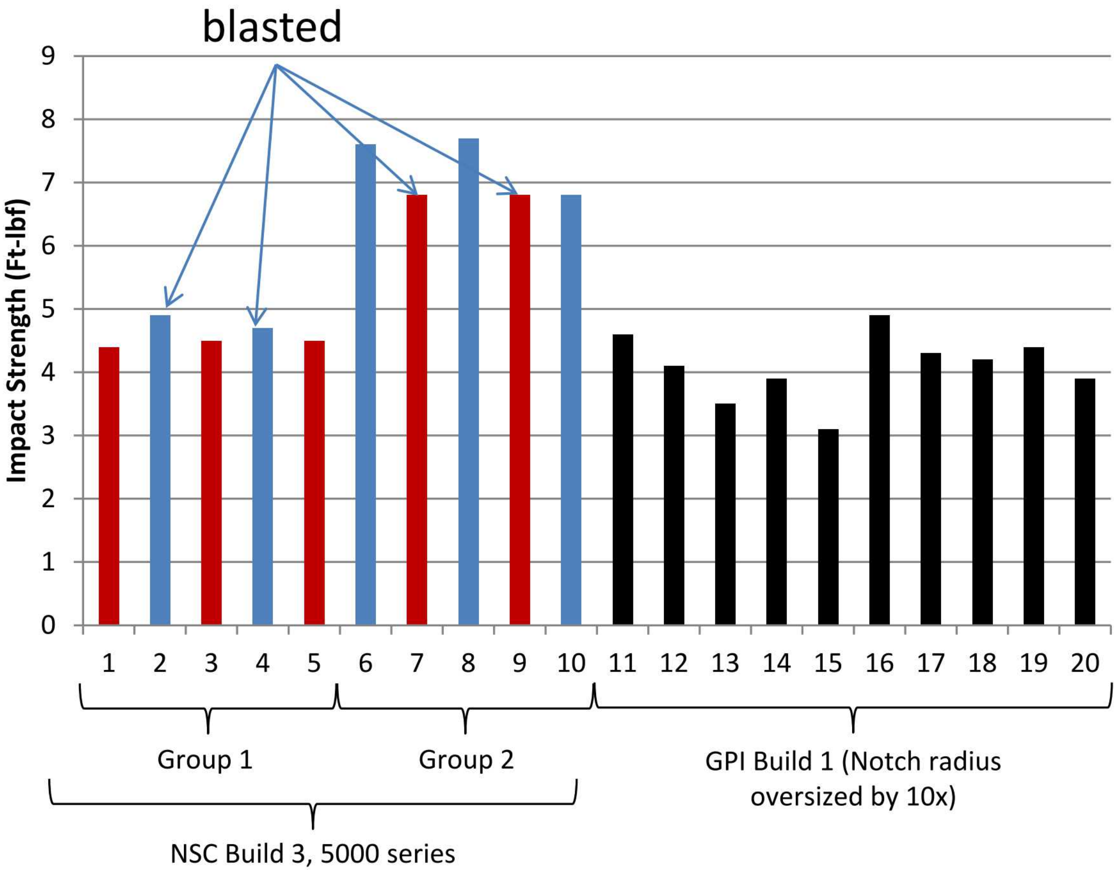
Extra virgin powder needed.
Replot of Weibull 3-Parameter Distributions





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.

Charpy Measurements 3xxx and 5xxx series



Notch on <u>top</u> relative to specimen #
Notch on <u>side</u> 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

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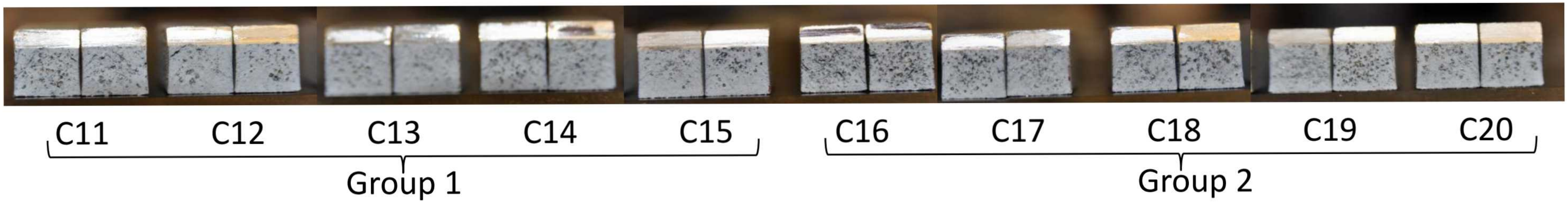
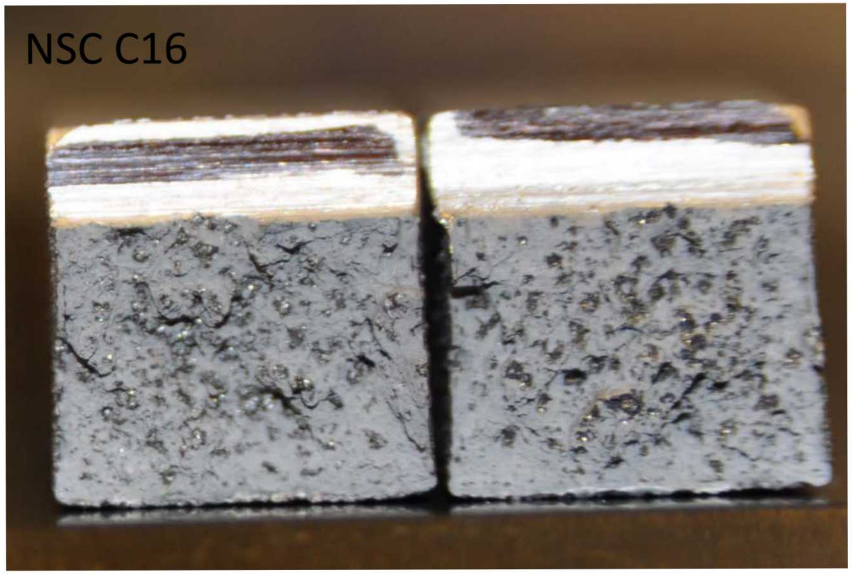
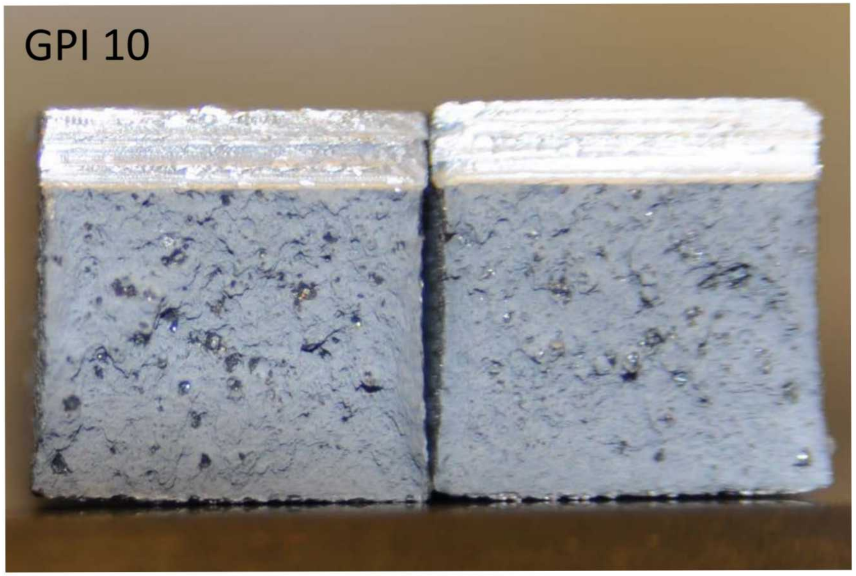
Images of Charpy fracture surfaces show voids or intermetallics are prevalent.

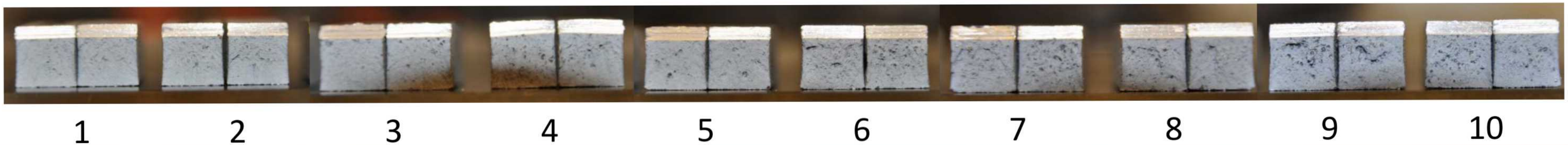
NSC Build 3





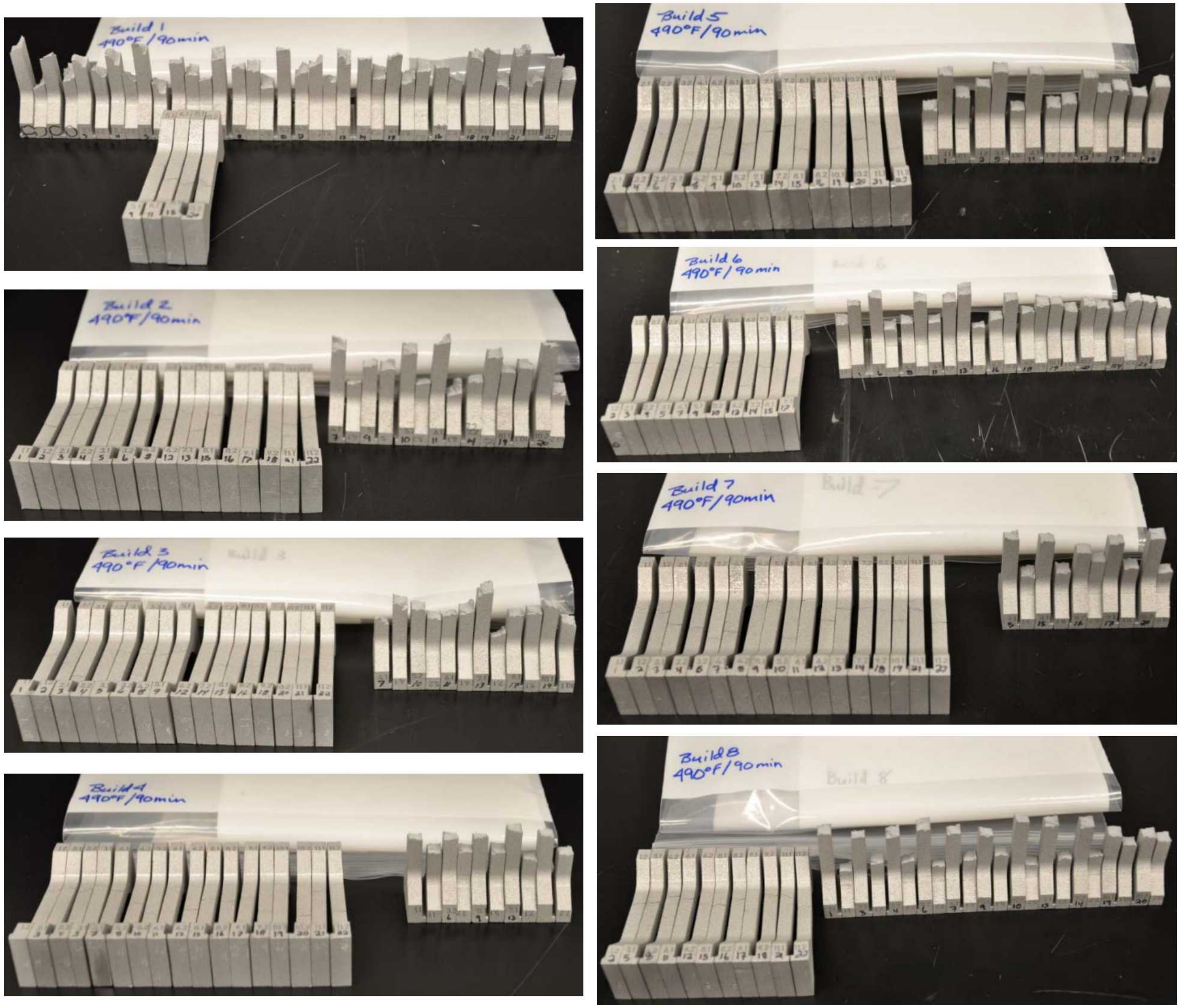


GPI Build 1



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.

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