SEM, Reno 6/5/2019

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Critical Flaws and Their Effects in AM Metals

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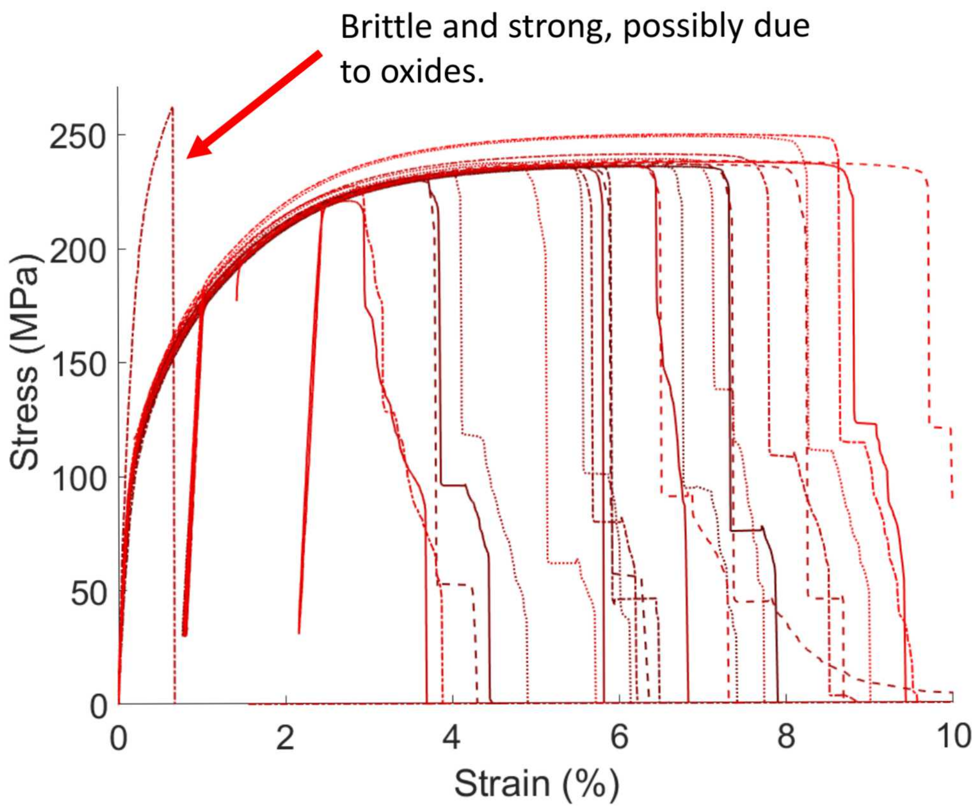
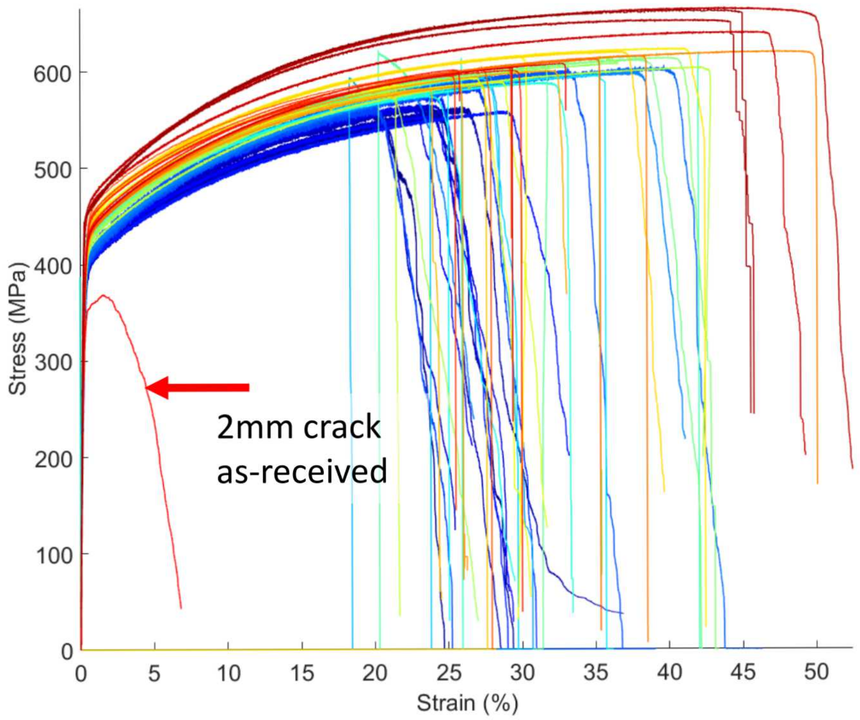
AM parts exhibit frequent disqualifying flaws in addition to significant variability.

28 AM AlSi10Mg medium conventional tensiles

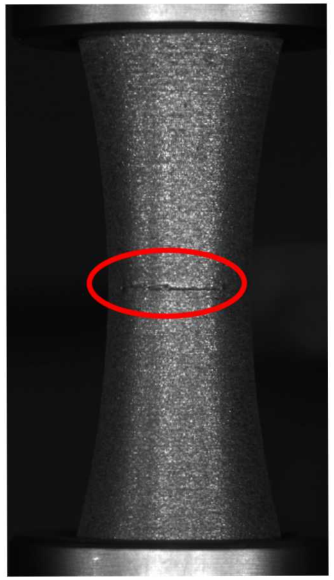


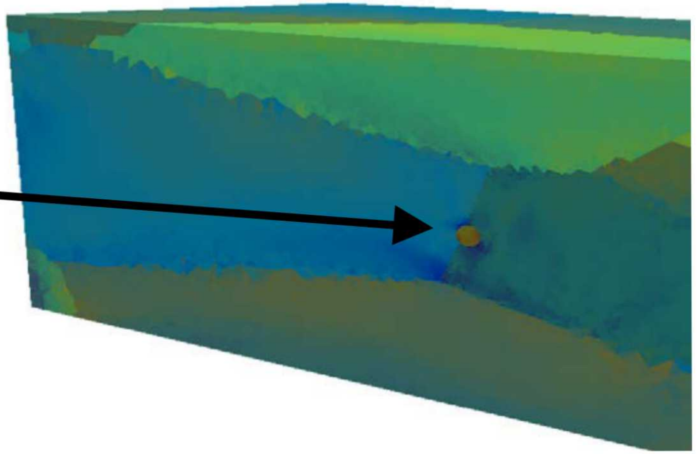
45 AM 304L medium conventional tensiles



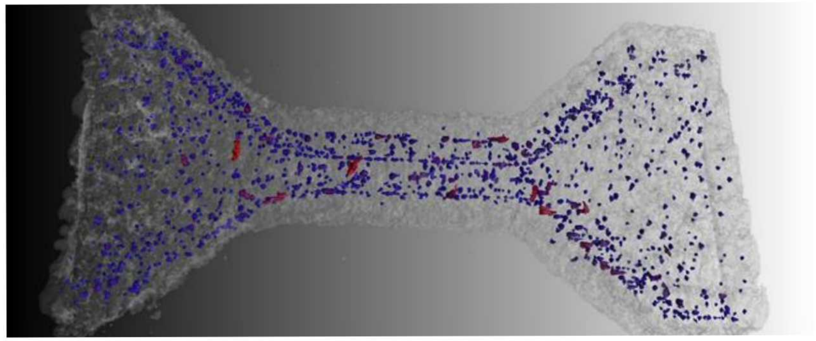
Damage tolerant approach

1. **Assume all AM components have flaws**
2. **Which flaws matter?**
3. **Identify flaw types**
   - **Cracks**
   - **Voids**
   - **Bulk porosity**
   - **Microstructure-based flaws**
4. **Print intentional flaws of varying sizes and types**
5. **Predict critical flaw sizes in different regions for each flaw type**
6. **Non destructively inspect each component for critical flaws**
   - **Critical flaw size is now defined for each region of the part.**





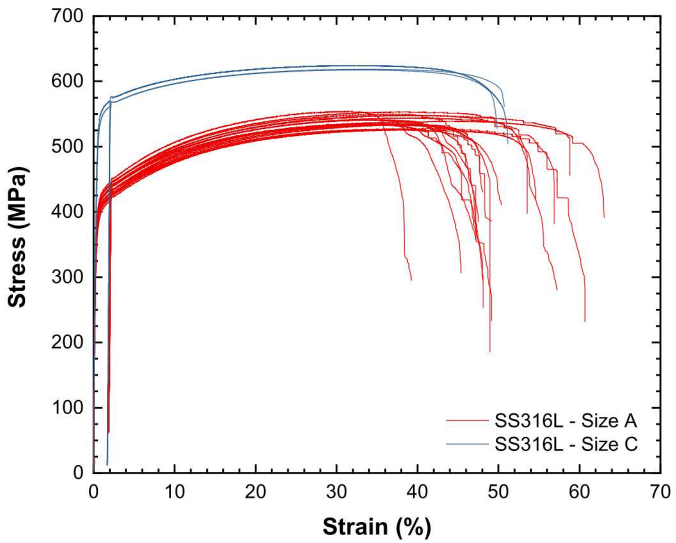
FE model including flaw with microstructure

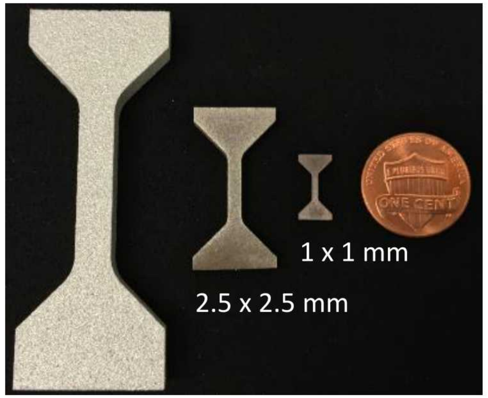


316 Stainless Steel vs. AlSi10Mg

316 Stainless Steel
- Ductility = 60%
- K = 120 MPa√m
- Charpy Impact toughness >120 ft-lbs

AlSi10Mg
- Ductility = 10%
- K = 40 MPa√m
- Charpy Impact toughness >8 ft-lbs

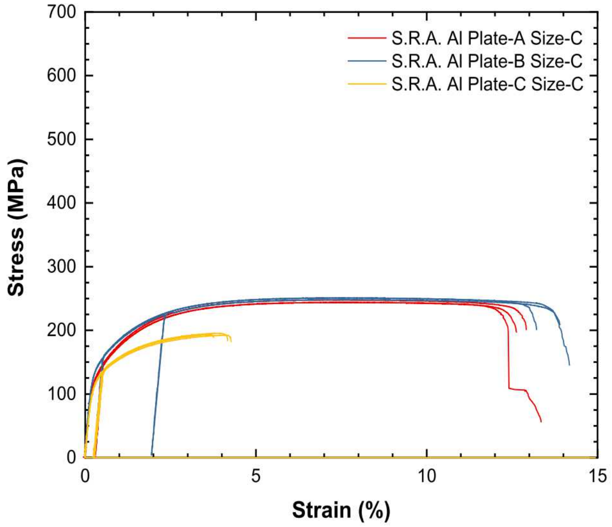




1 x 1 mm

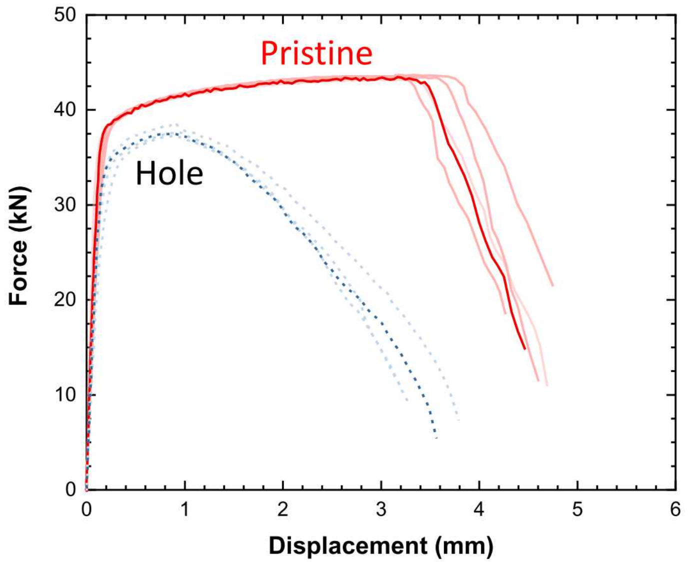
2.5 x 2.5 mm

6.25 x 6.25 mm



316 Stainless Steel vs. AlSi10Mg

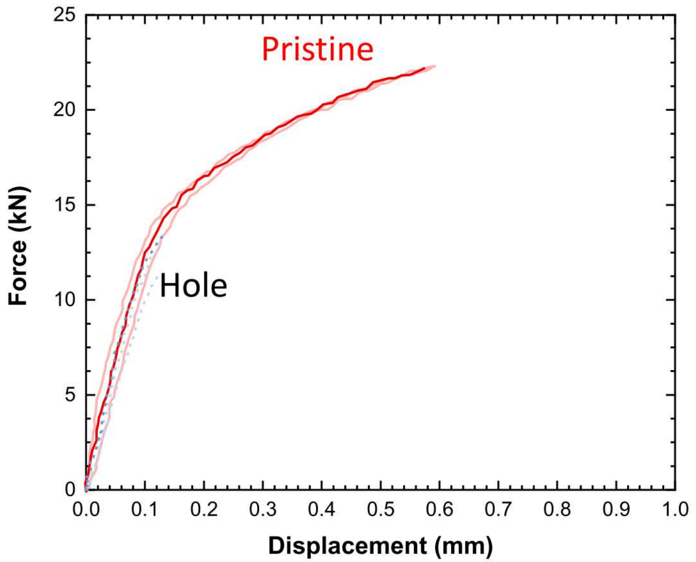
316 Stainless Steel
- **K = 100 MPa√m?**
- **Charpy Impact toughness >120 ft-lbs**
- **Ductility = 60%**



Hole reduces strength by 10% and ductility by 20%

2 mm Through-hole Corner Cube Void

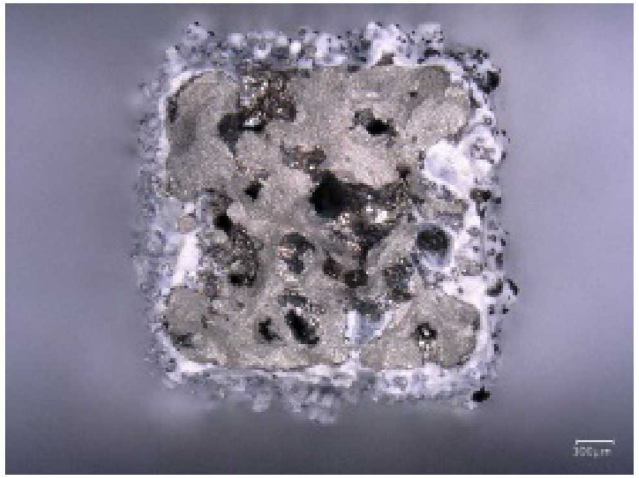
AlSi10Mg
- **K = 20 MPa√m**
- **Charpy Impact toughness >8 ft-lbs**
- **Ductility = 10%**

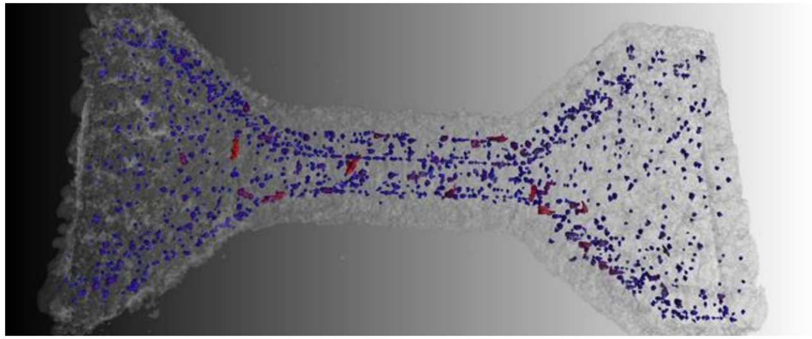


Hole reduces strength by 40% and ductility by 65%

What about multiple voids?

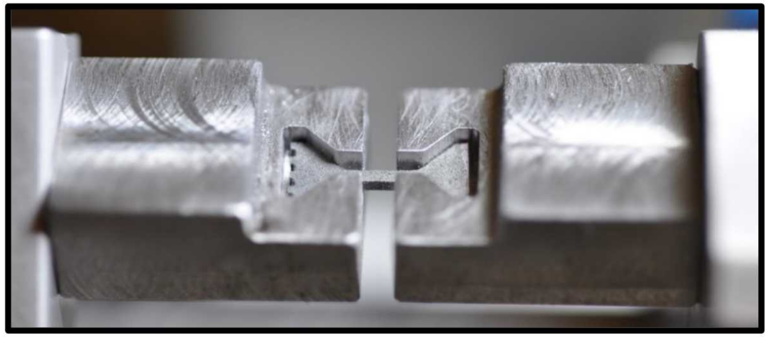
Different build conditions can create different levels of porosity.



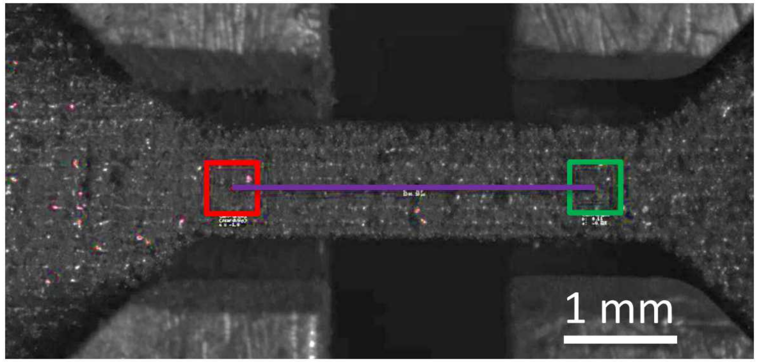


High throughput tensile testing, ~30 samples per hour, gives statistical distributions of structural properties.

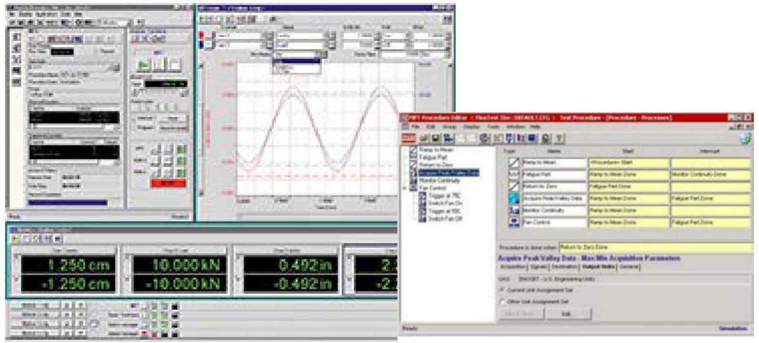
1. Self-aligning 'drop-in' grips

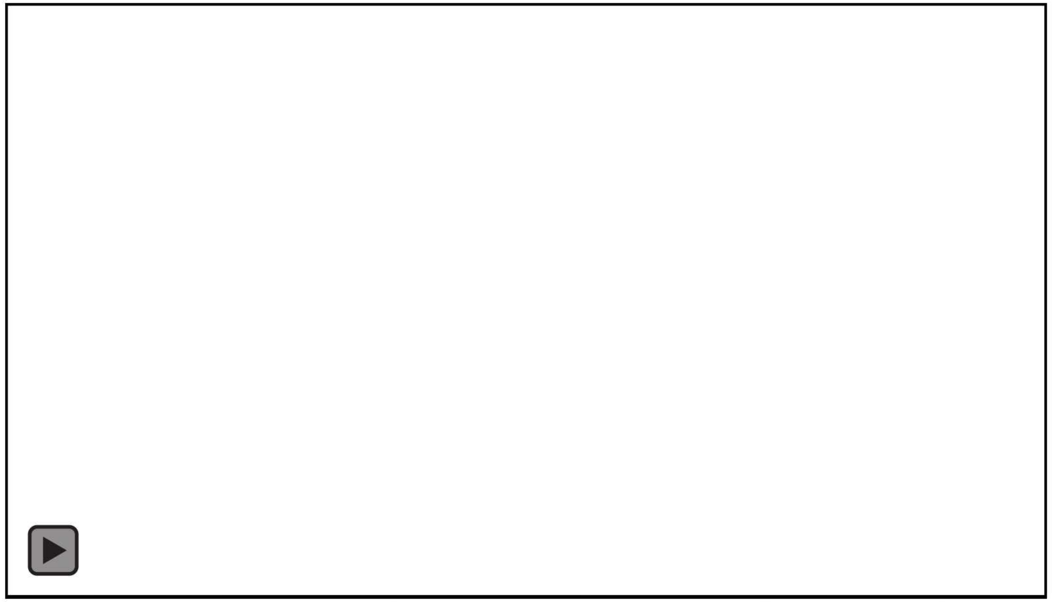


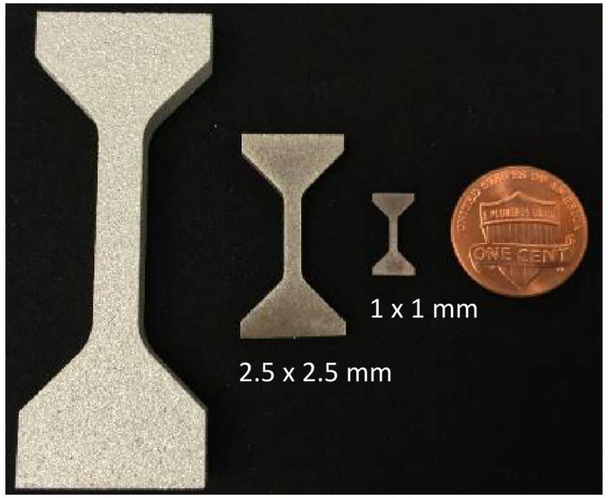
2. Non-contact virtual extensometer with "live" digital image correlation



3. Maximize software automation to reduce operator burden







6.25 x 6.25 mm

B. Salzbrenner et al., *J Mater. Process. Tech.*, 2017

Powder reuse of AlSi10Mg gives different levels of porosity and tensile properties for each build plate.

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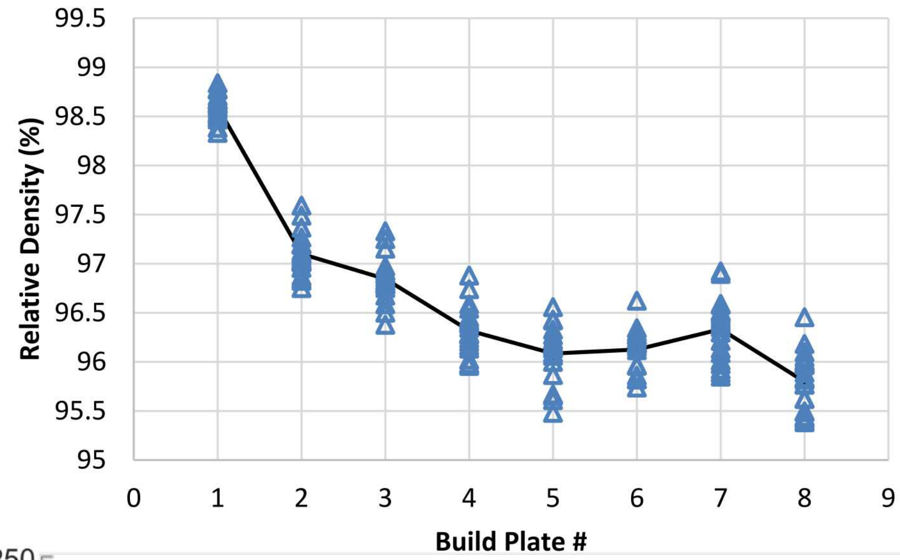
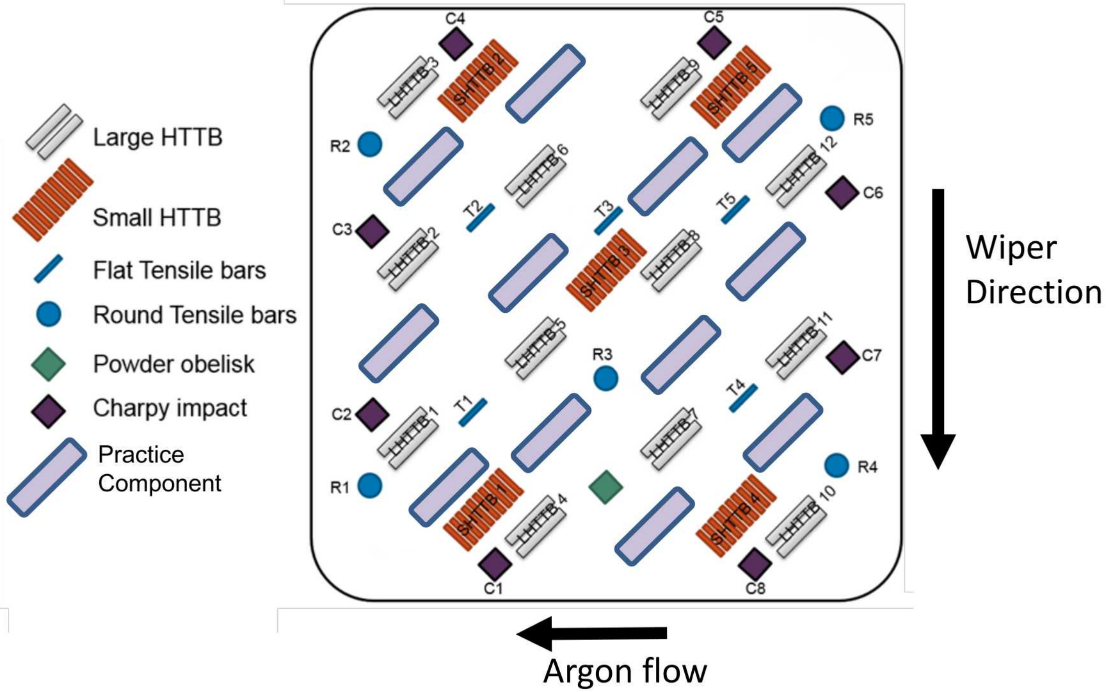
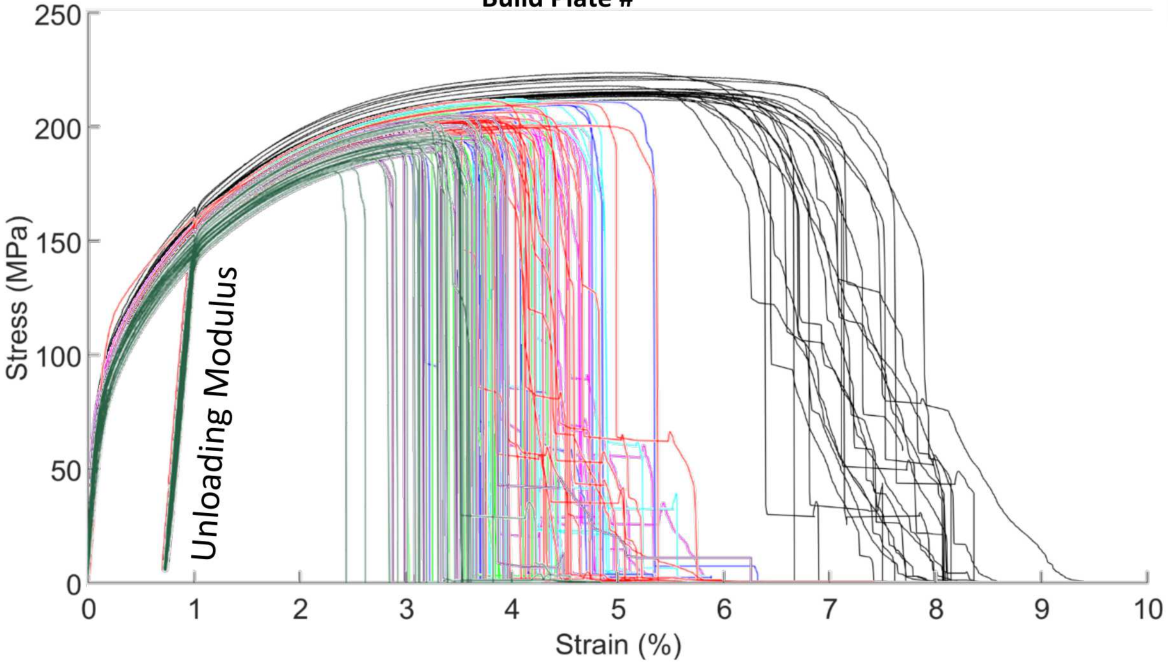
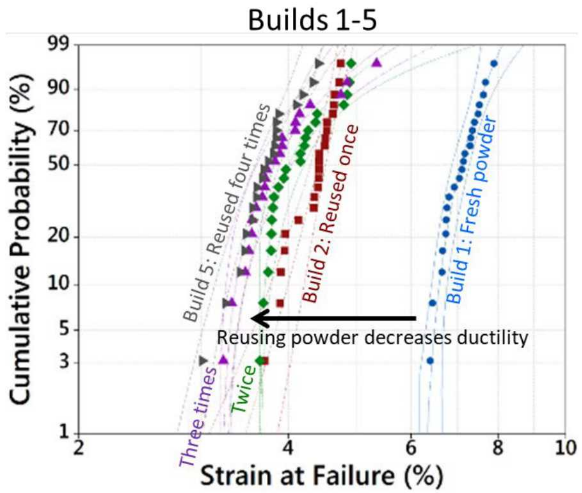


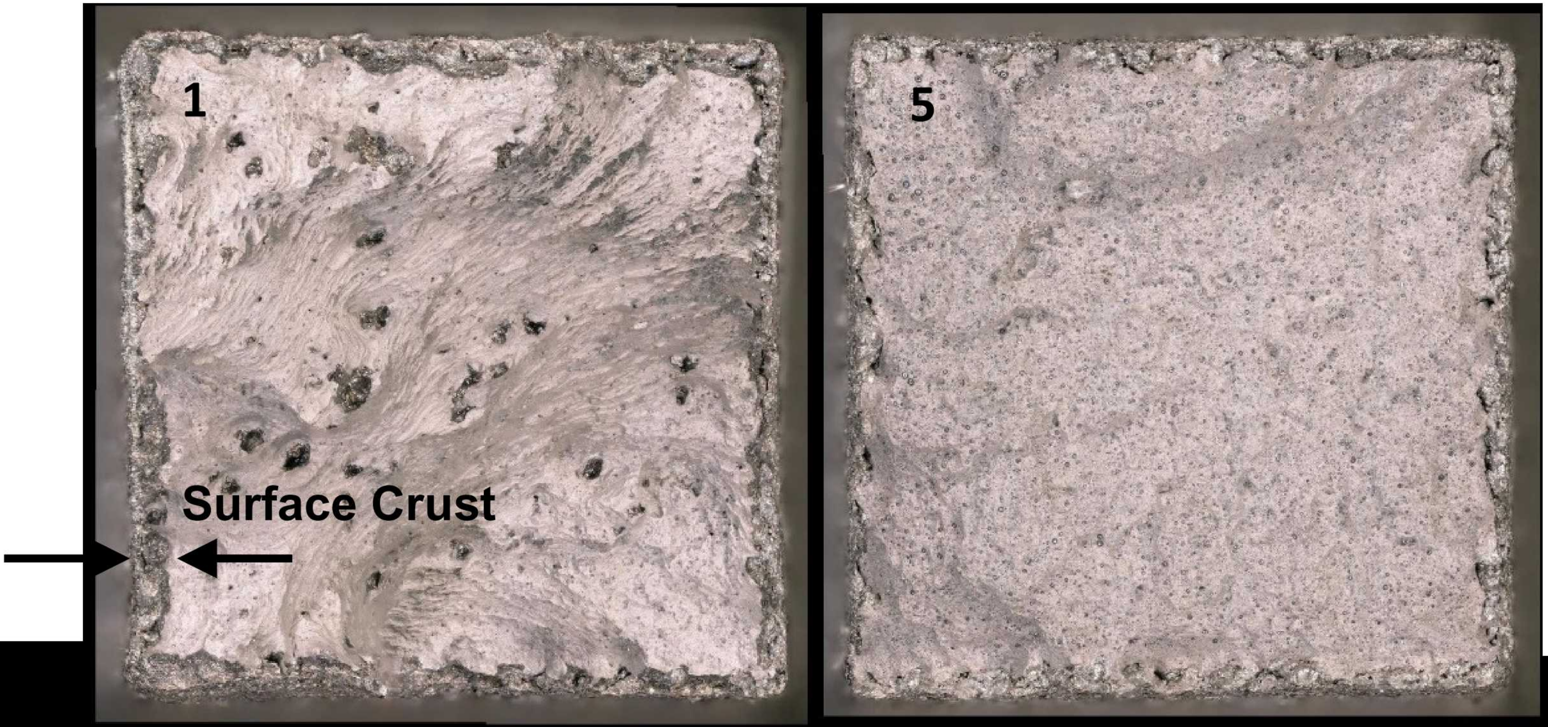


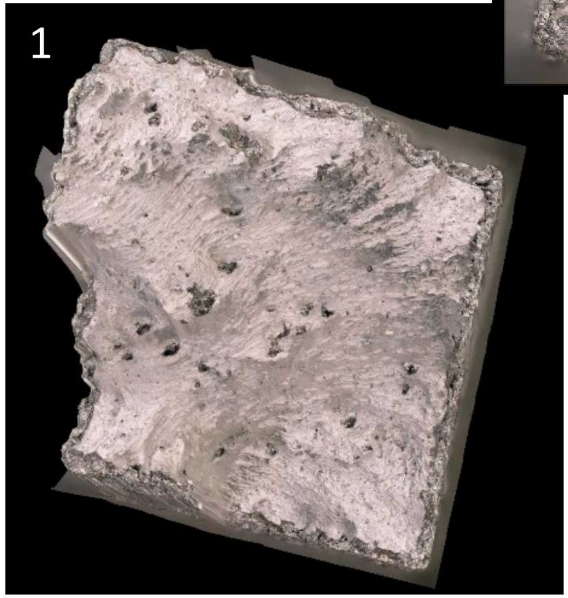


Build	Powder condition
1	Fresh Powder
2	Reused once
3	Reused twice
4	Reused 3 times
5	Reused 4 times
6	Fresh (stored) Powder
7	Reused once
8	Reused twice

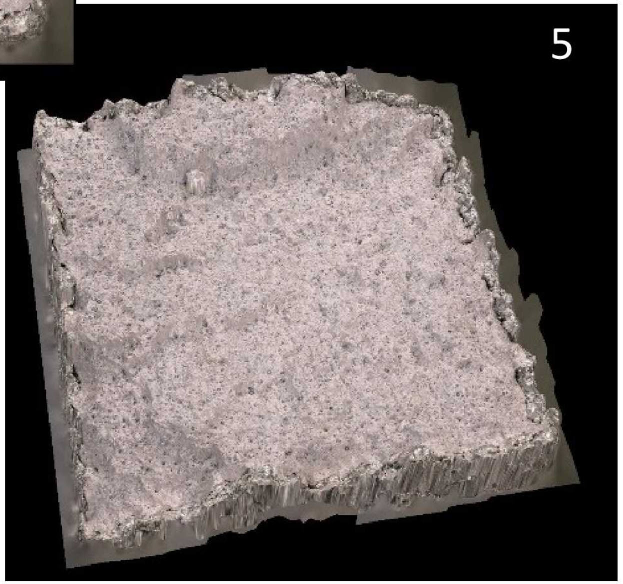


Lower strength specimens have substantially more small voids (20-50 µm).

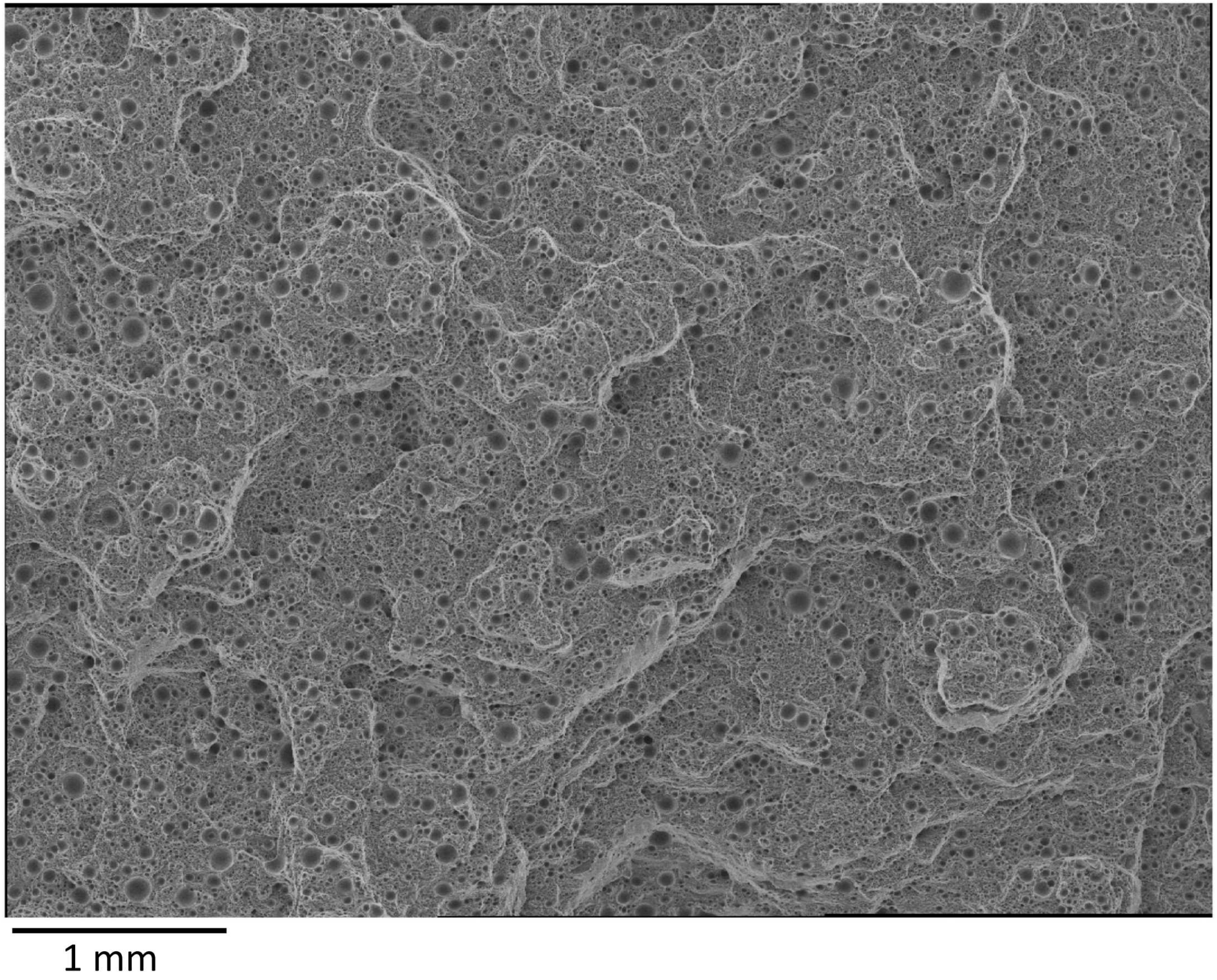




- Simply searching for voids above some diameter threshold is insufficient.
- Millions of small voids reduce ductility and strength more than a few large voids.
- Many small voids allow for straight fracture path.
- We are in a density dominated regime.
- Surface Crust around edge of sample. Loosely-bound powder, surface roughness, and cracks.

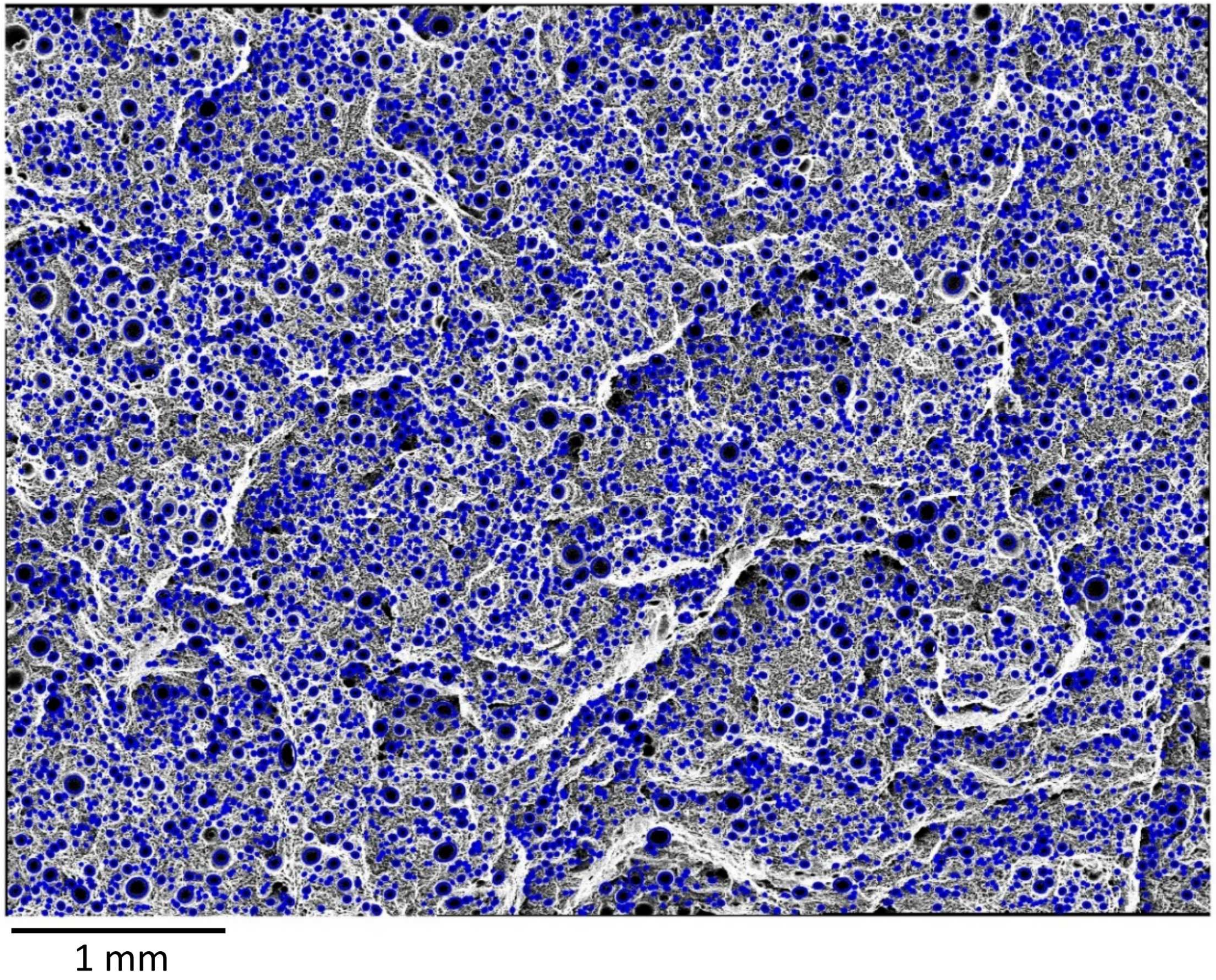


High throughput fracture surface imaging



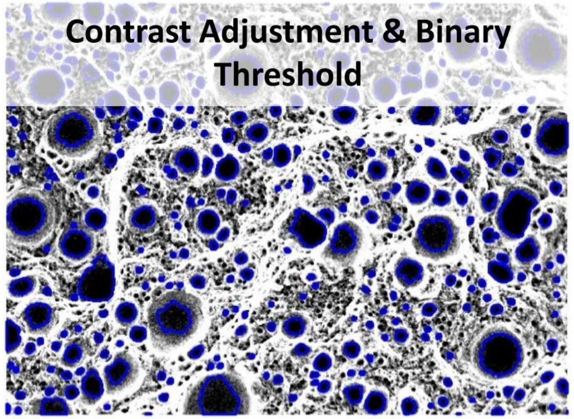
- Imaged all 172 large HTT fracture surfaces in the SEM
- Variable pressure secondary imaging

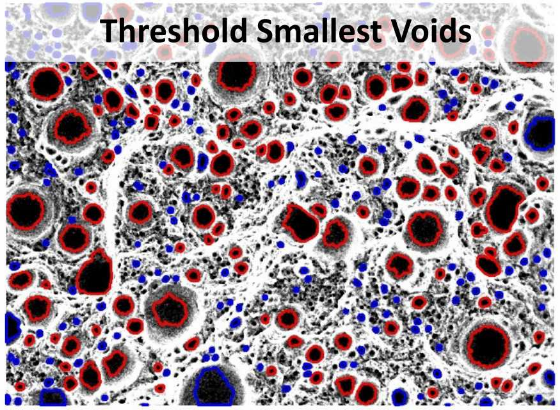
High throughput fracture surface imaging

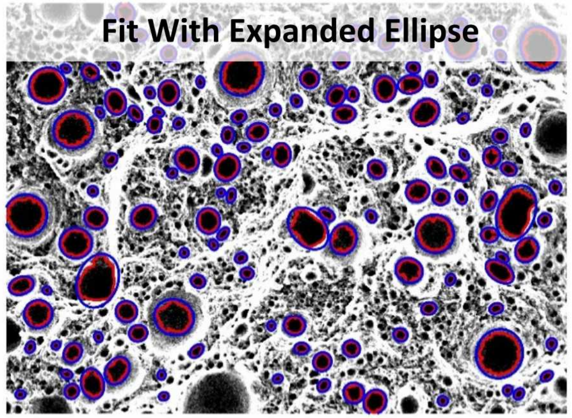


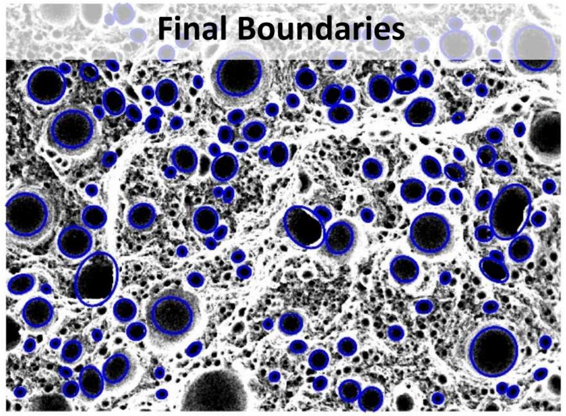
- Imaged all 172 large HTT fracture surfaces in the SEM
- Variable pressure secondary imaging

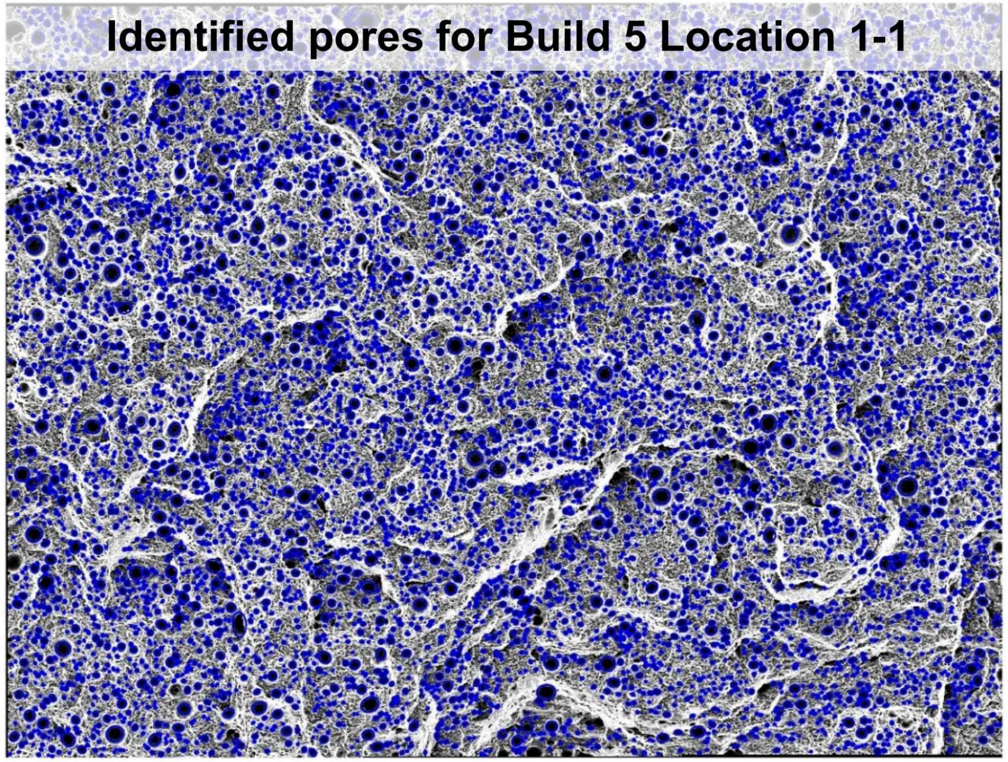
Void identification algorithm to measure porosity on fracture surfaces





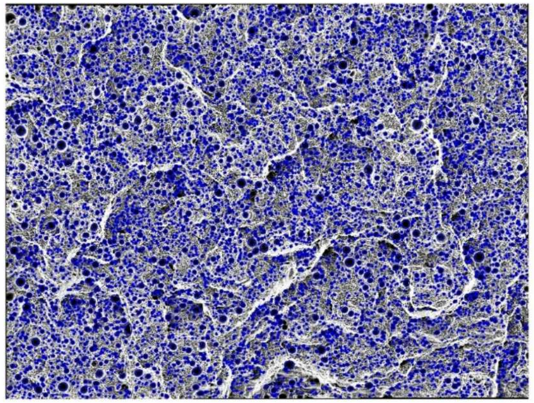


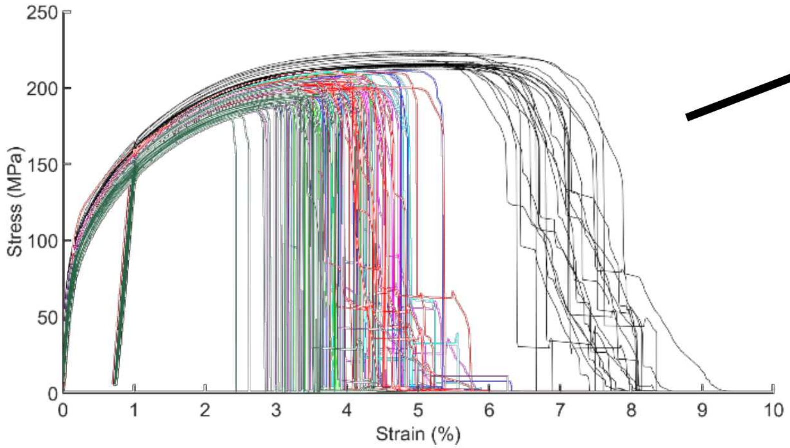


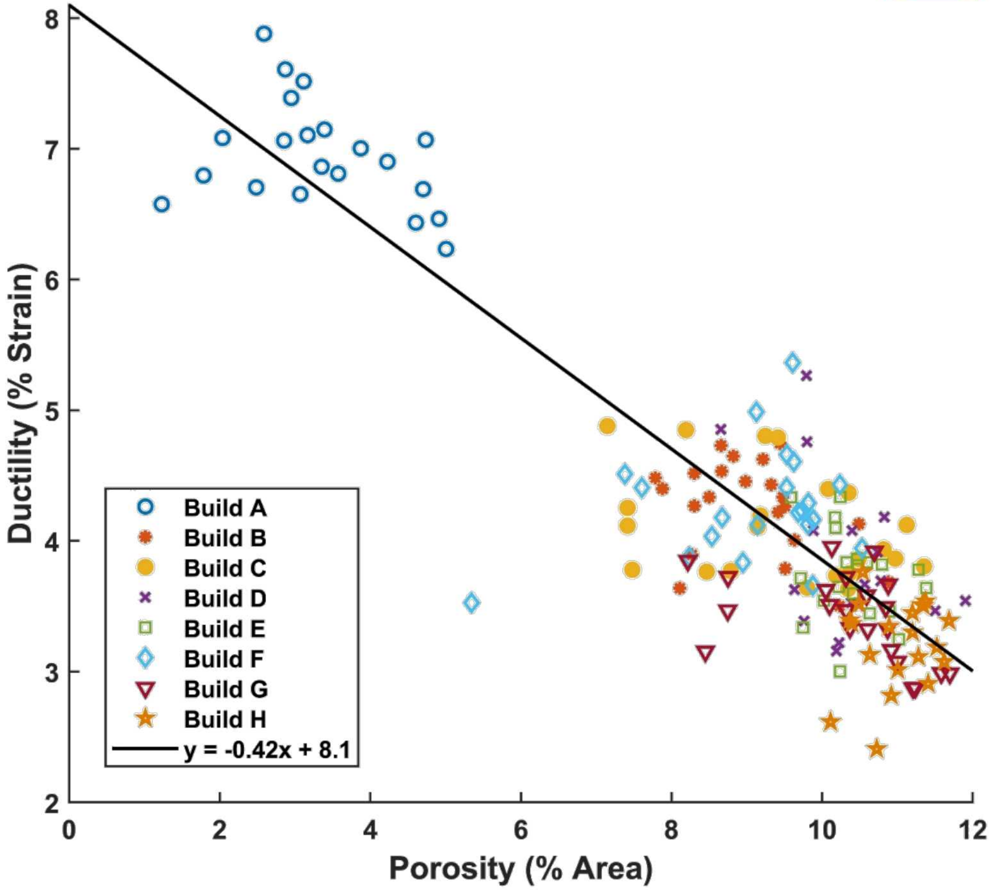


- **Identify voids on a fracture surface from high throughput SEM images.**
- **Multistep process does more than simple thresholding.**
- **Algorithm allowed ~172 fracture surfaces to be analyzed—about 10x more than was possible before.**

Compare ductility to fracture surface porosity

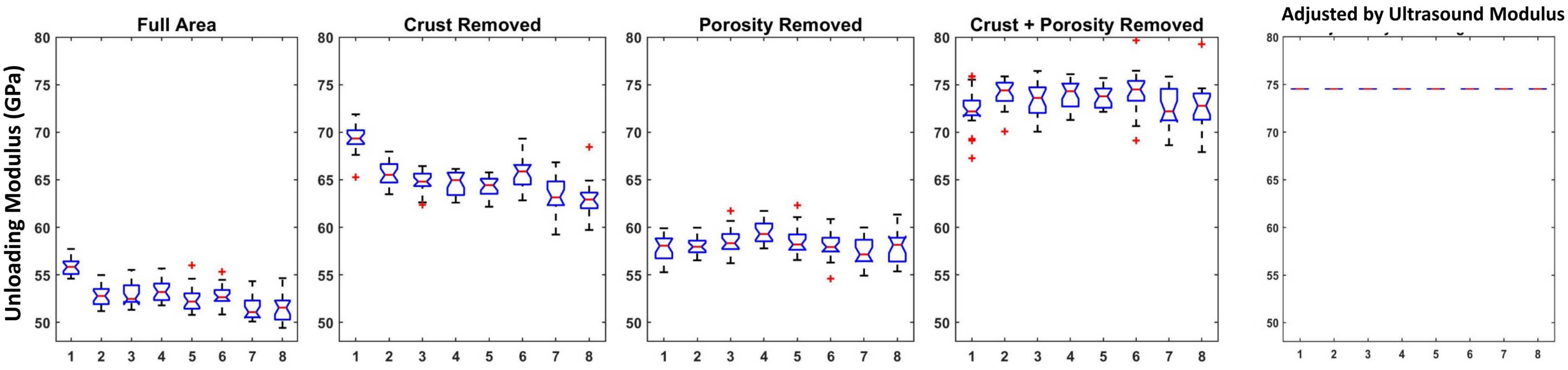




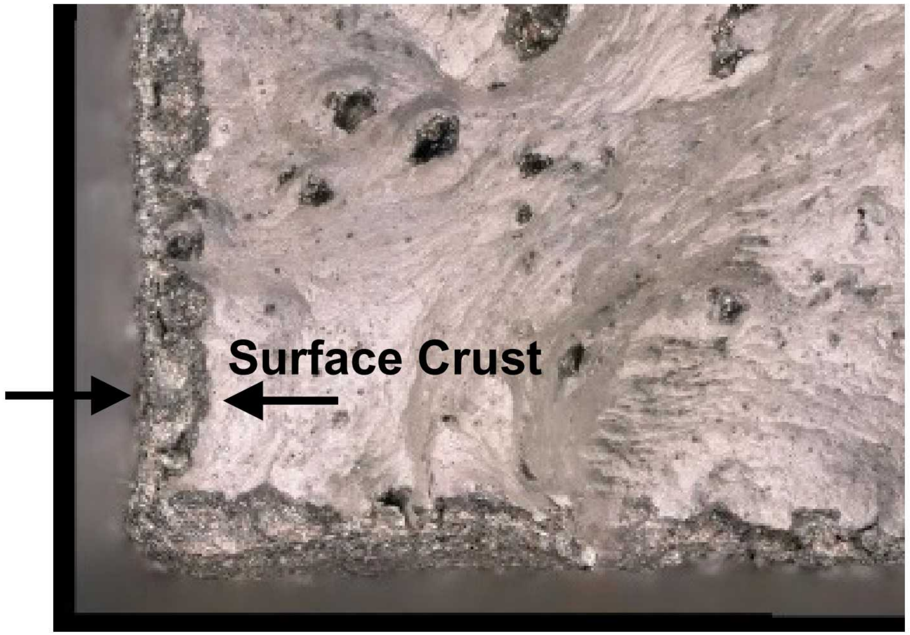


- **Increasing fracture surface porosity by 1% decreases ductility by 0.5%.**
- **Fracture porosity is NOT equivalent to density.**
- **Relationship between fracture surface porosity and density?**

Crust and porosity effects on unloading modulus



- Crust has dominant effect, but porosity is also meaningful.
- Subtracting crust and porosity gives an unloading modulus near 74 GPa (ultrasound value).
- Going forward, we can correct modulus based on unloading modulus.



Crust and porosity effects on ultimate tensile strength

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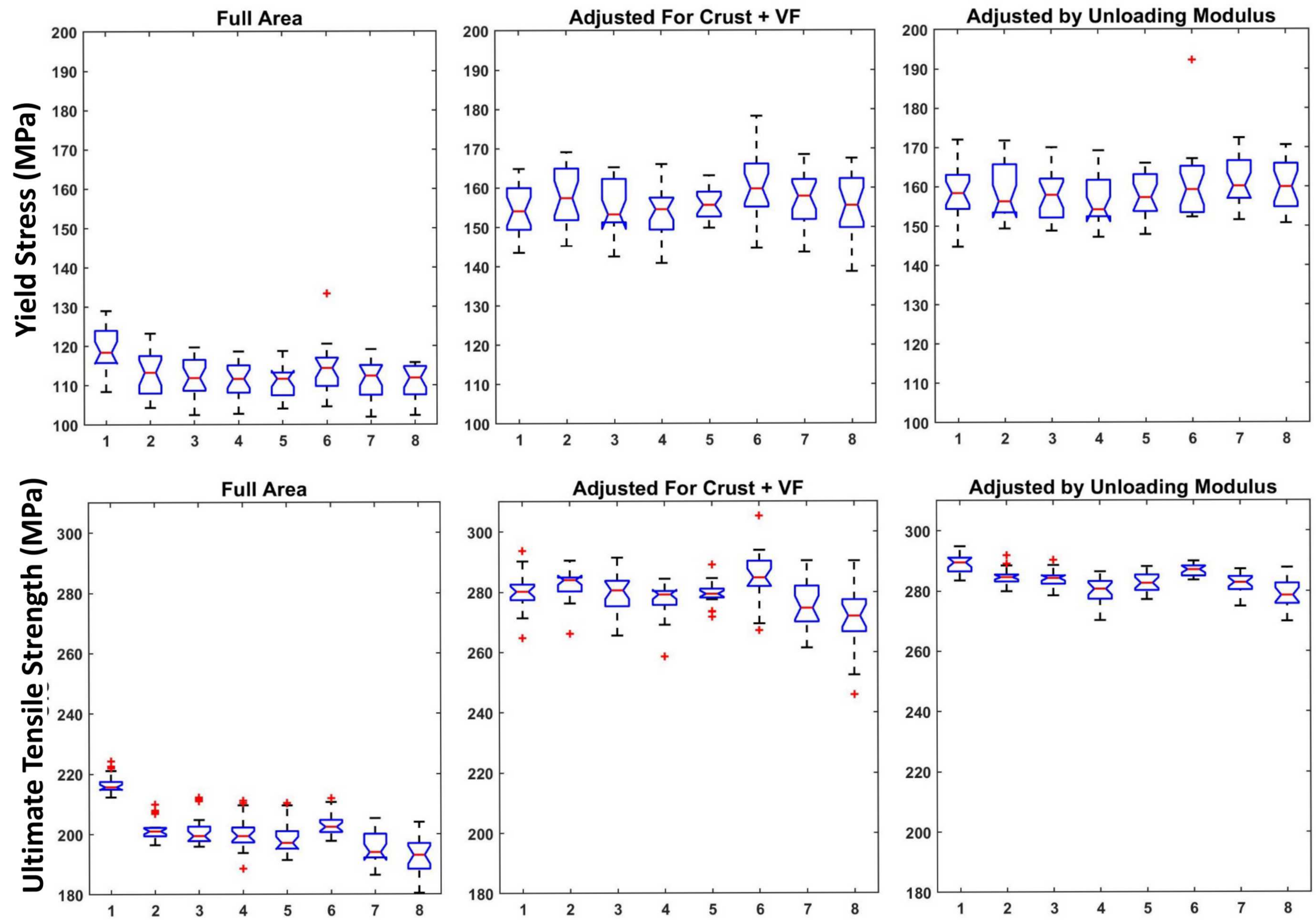

- Inherent Yield stress is 160 MPa instead of 120 MPa.
- Inherent Tensile strength is 280 MPa instead of 200 MPa.

Conclusions

1. **Introducing intentional flaws to identify critical flaw size for exemplar component.**
2. **Small ubiquitous pores can dominate tensile behavior over large lack-of-fusion pores (density-dominated regime).**
3. **Ductility can be largely predicted by porosity**