JOWOG, ABQ 10/25/2018

SAND2018-12100PE

Critical Flaws and Their Effects in AM Metals

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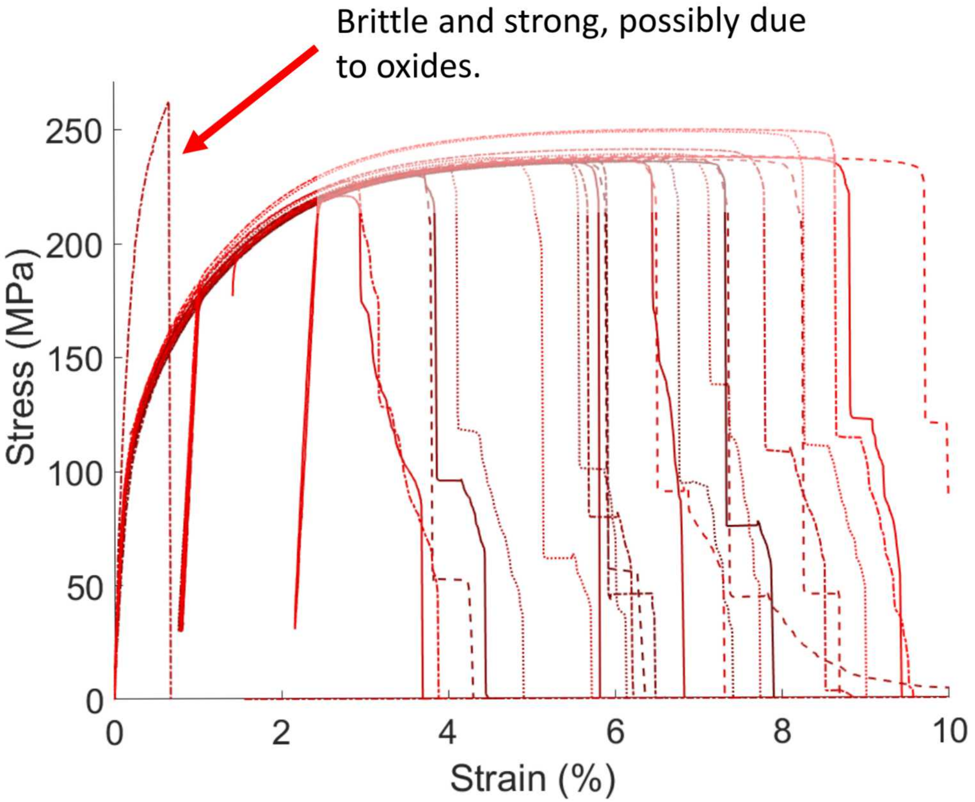
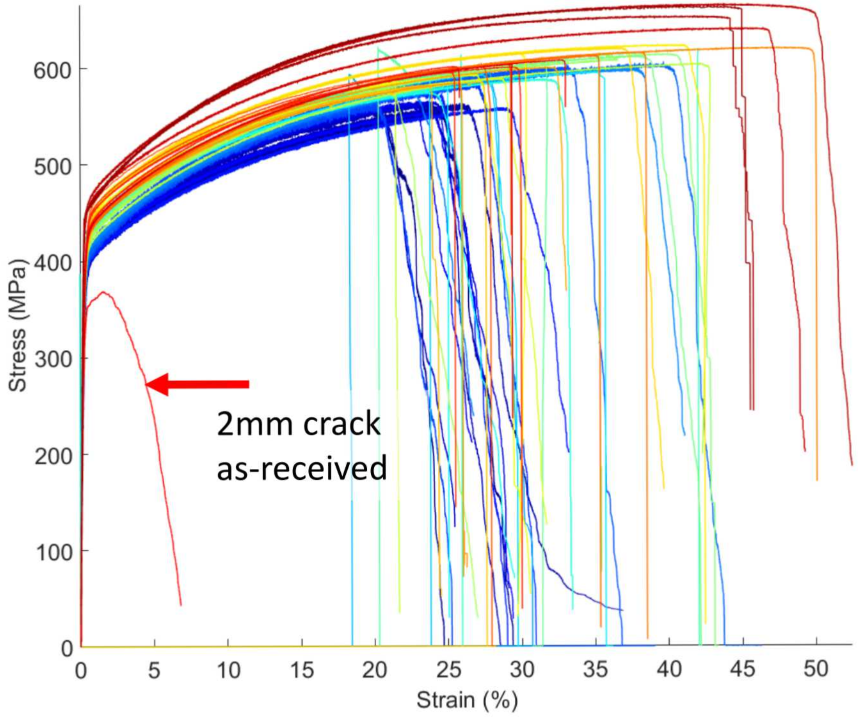
AM parts exhibit frequent disqualifying flaws in addition to significant variability.

28 AM AlSi10Mg medium conventional tensiles

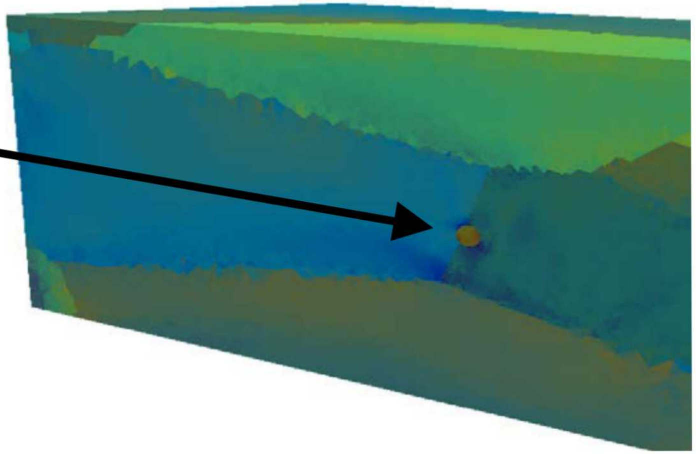


45 AM 304L medium conventional tensiles

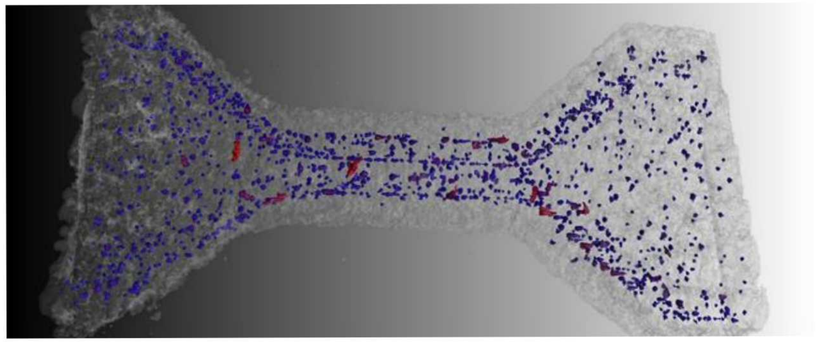


Damage tolerant approach

1. **Assume all AM components have flaws**
2. **Which flaws matter?**
3. **Identify flaw types**
   - **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 every component for critical flaws**
   - **Critical flaw size is now defined for each region of the part.**



FE model including flaw with microstructure



Intentional flaws in exemplar component, 316 SS

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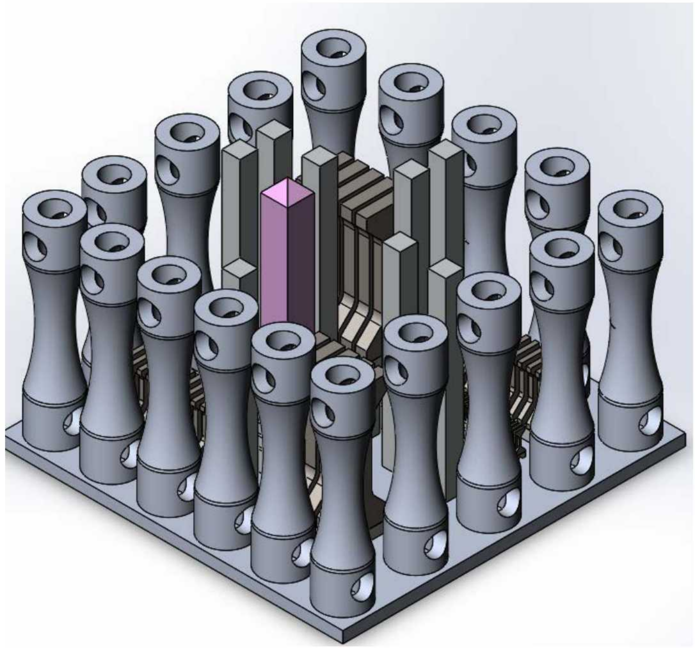
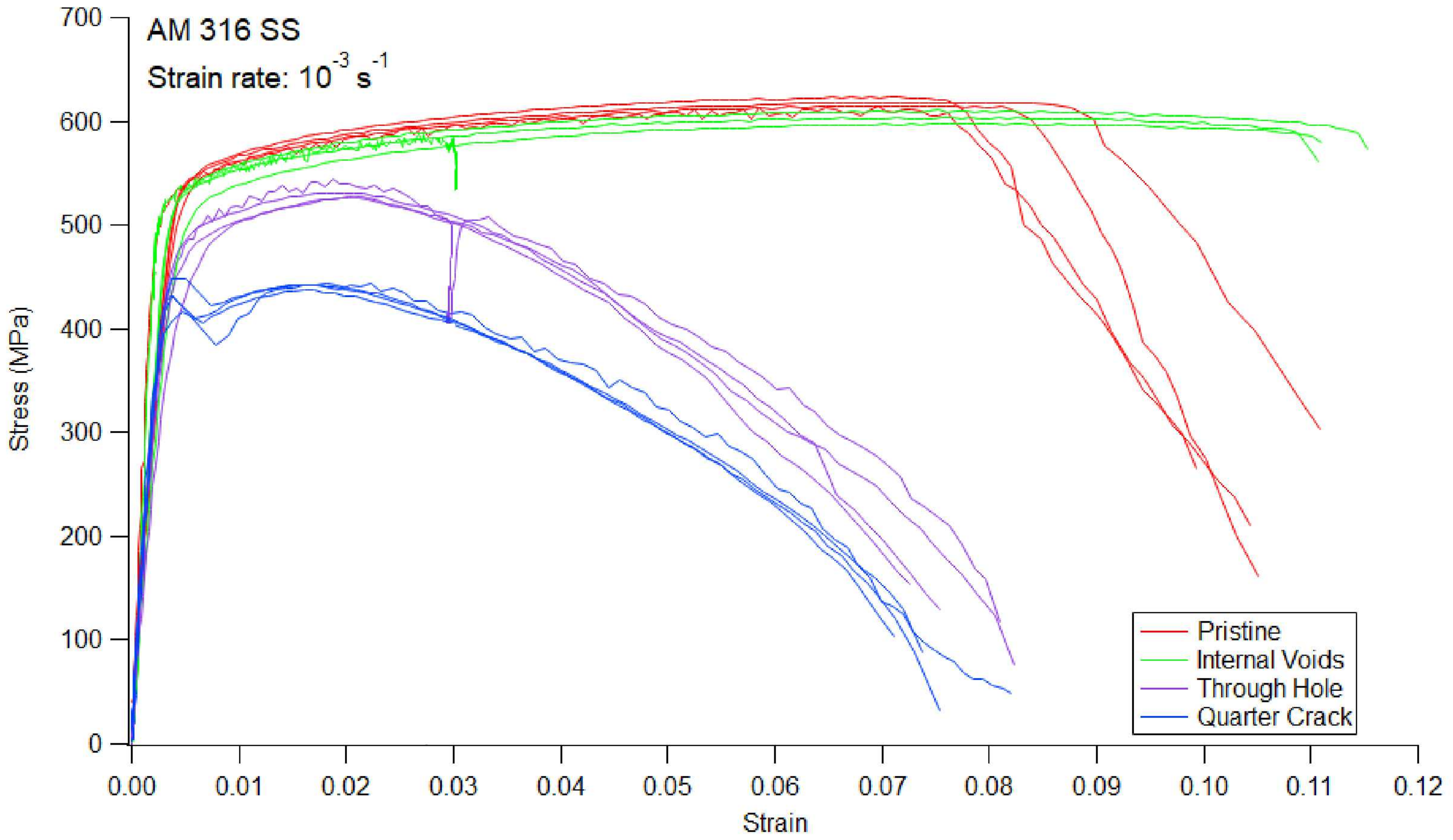
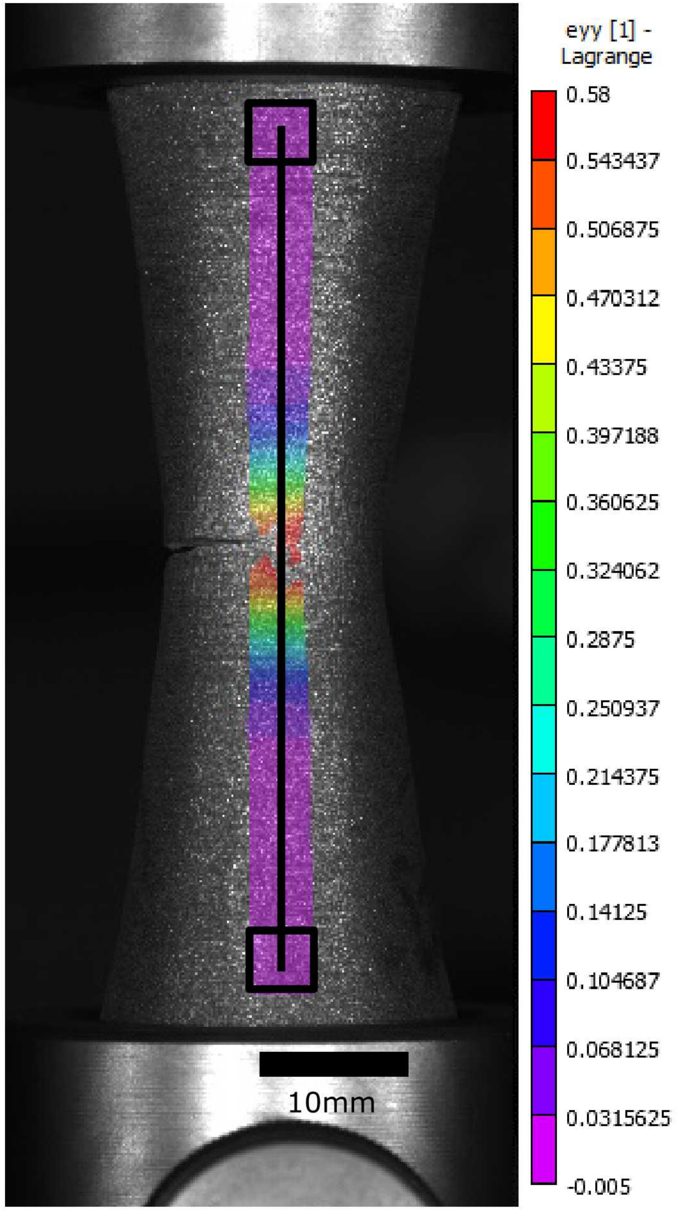
No flaws | Quarter crack | 2 mm Through hole (1 wall) | 0.2 mm Internal void

- Representative of a typical AM component.
  - Thin walled tube with changing cross section
  - Tapered wall with minimum wall thickness of 0.5 mm
- Load components in:
  - Tension
  - Compression
  - Torsion
- Which flaws reduce the load carrying capacity to below requirements?



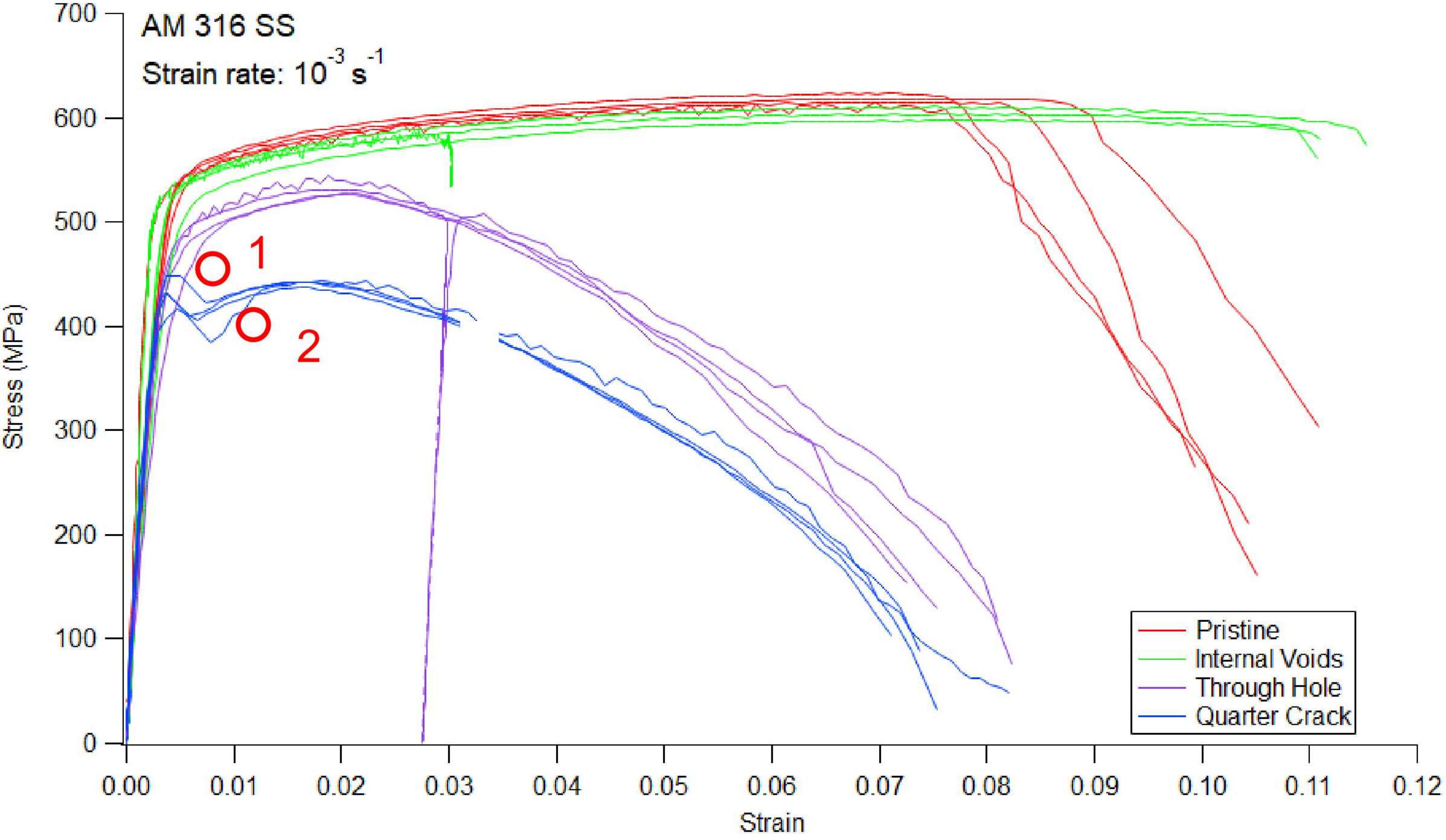
Reduction in strength is proportional to reduction in cross-sectional area.

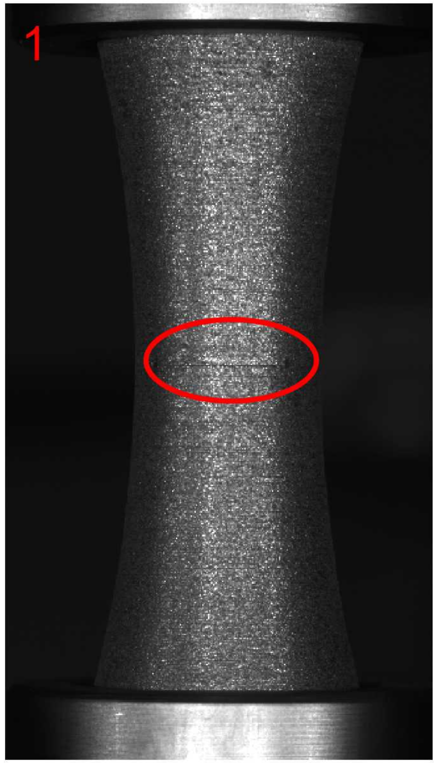


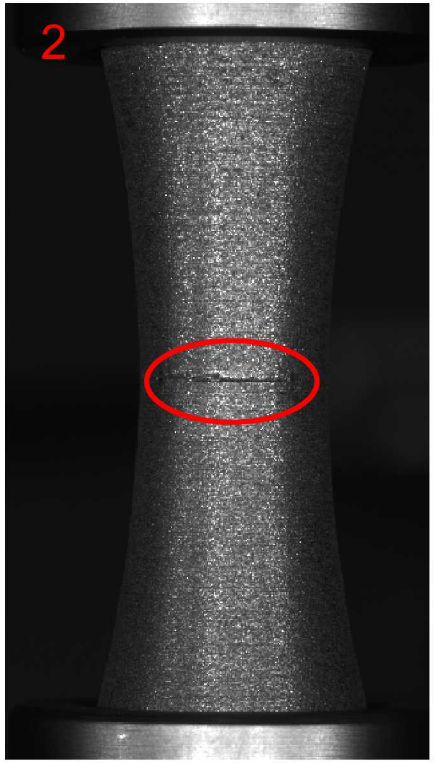


- Quarter crack specimen has 25% less strength.
- Is this the case for aluminum?
- Exemplar component needs to hold ~5 kN (corresponds to ~85 MPa) when made of aluminum.

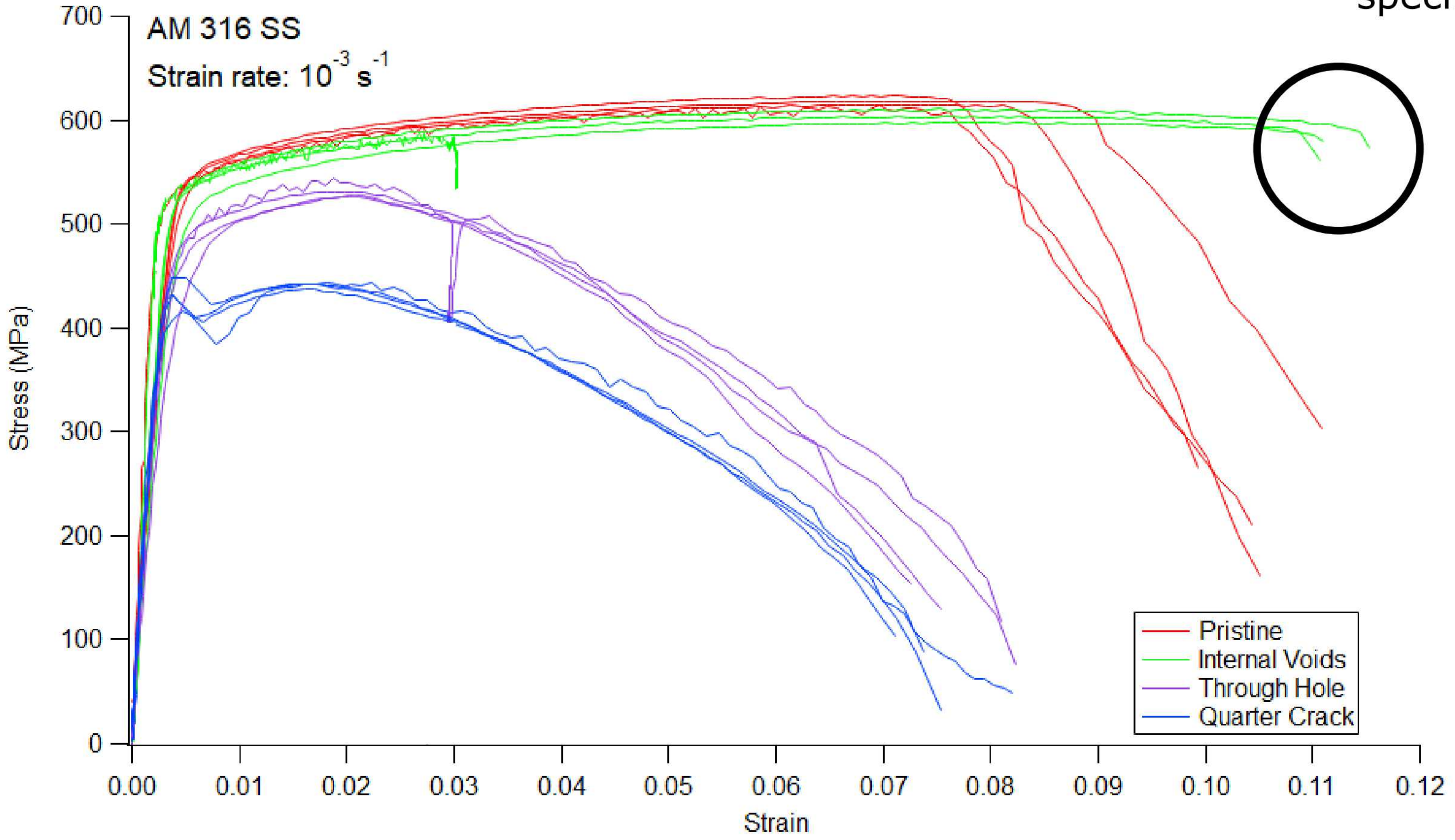
Stress-strain curves. Increasing flaw severity decreases load capacity in expected manner.



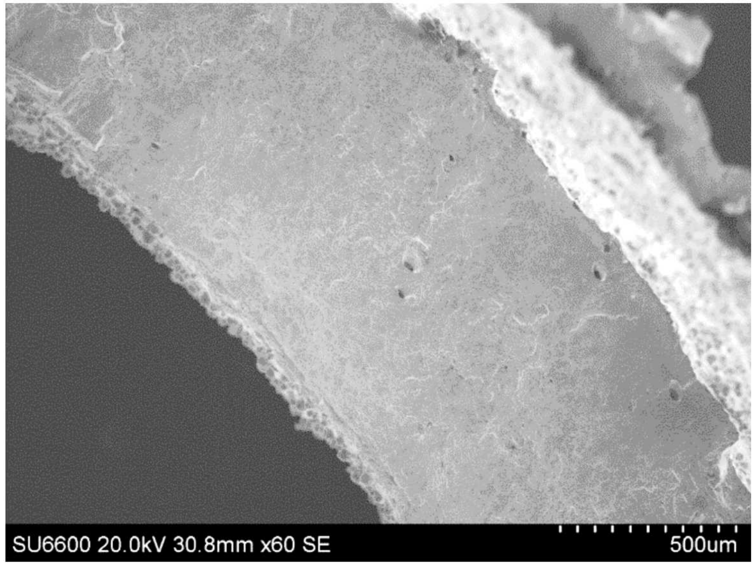


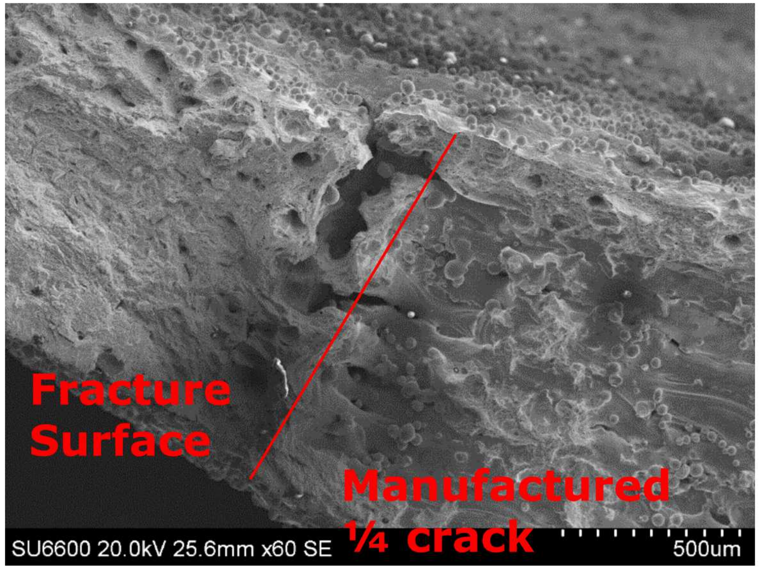


Internal void components failed in a brittle manner due to location on build plate.



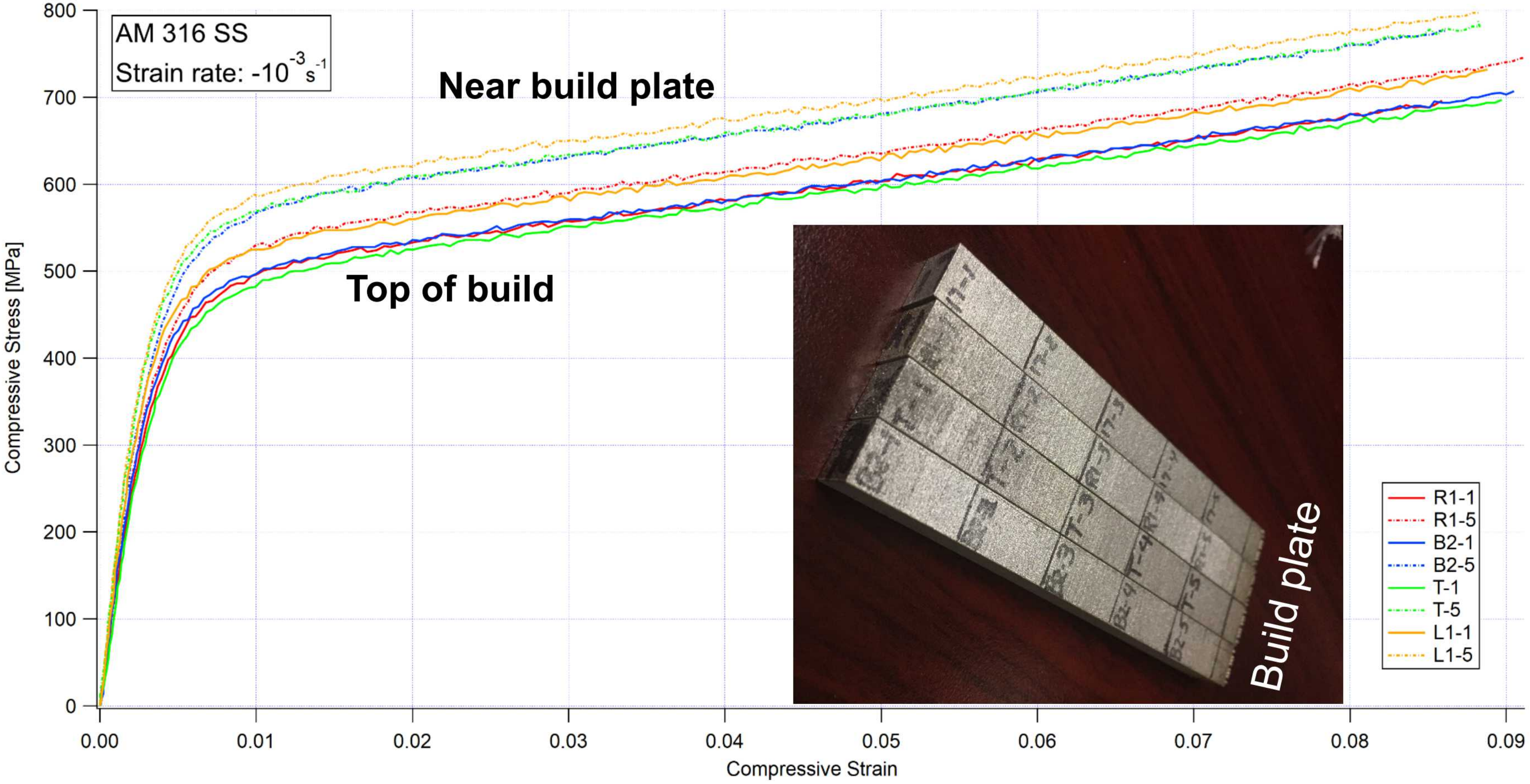
The fracture surface of internal-void specimens is indicative of a brittle fracture.

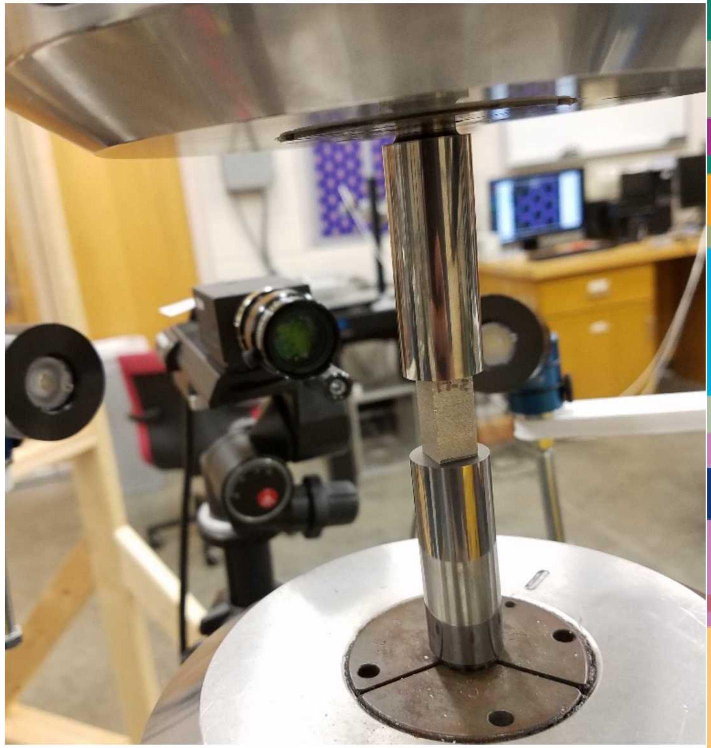


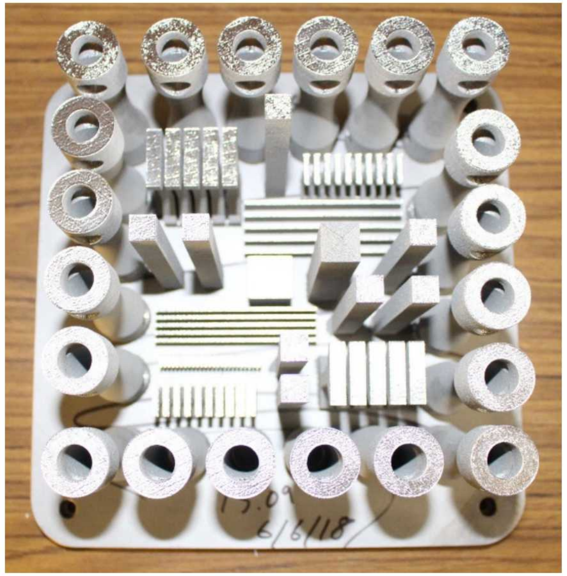


Other specimen types have a ductile fracture morphology

Compression specimens







- **Little location dependence between right, bottom, top, and left.**
- **Yield stress decreases with increasing height above build plate.**

Fracture toughness testing

AM 316 S.S. Fracture Toughness Tests		
Experiment	**# of specimens**	**K_{IC} (MPa-m$^{1/2}$)**
Diamond Saw	1	41.94
Diamond Saw Fatigue Cracked	3	39.17
AM Notch	1	37.59
AM Notch Fatigue Cracked	1	39.22

Virgin AM crack specimen

Virgin specimen

- **K value is fairly low for 316 SS, especially considering that these samples are much thinner than the ASTM standard.**
  - **ASTM standard specimen is 0.75 meters in width!**

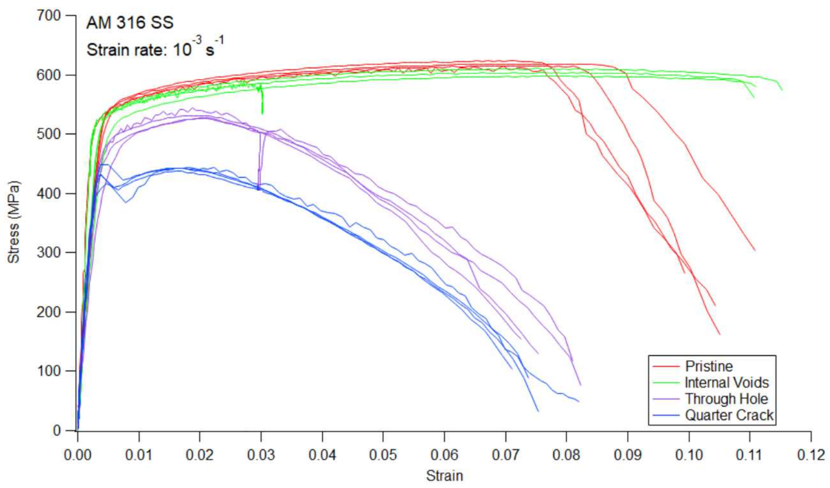
AM Exemplar component requirements (for Aluminum)

<u>Component Requirements</u>

- Hold a force of 5 kN (corresponds to ~85 MPa) in tension
- Hold 5 kN in compression
- Torsion requirement:?
- Weight Requirement: 115 g (0.25 lbs)
  - Steel components are 182 g
- Withstand expected conditions (corrosion, temperature, etc.)
- Fit within mechanical envelope and interface with neighboring parts (surface finish, etc.)

<u>Derived Requirements</u>

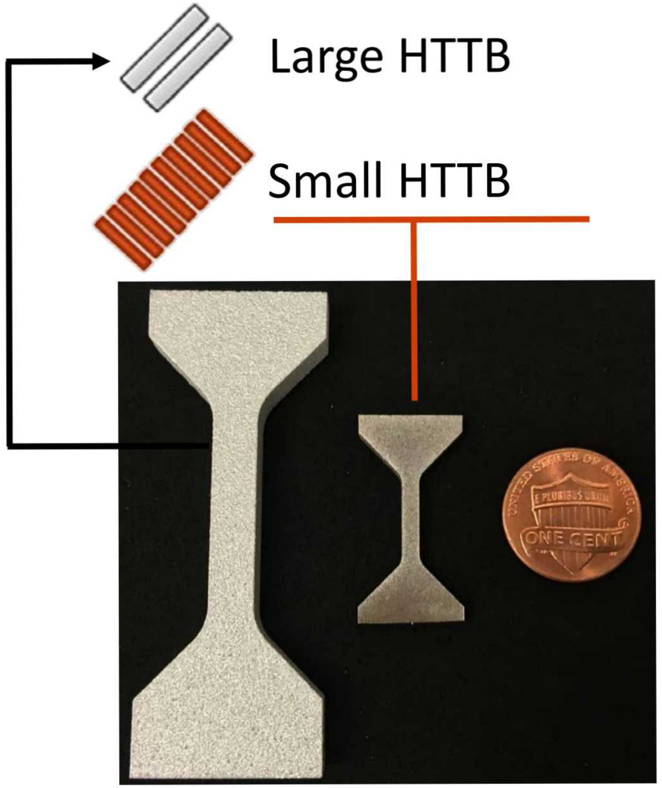
- Charpy Toughness: (Aluminum ~ 6, Steel ~130 ft-lbs).
- Density Requirement: 98% dense or more.
- Hardness? 316SS is ~90 HRB.
- Corrosion?
- Fracture toughness? KIC (plane stress) >15 MPa√m.
- Composition requirement (input powder or final composition).
- Elongation to failure
- Surface finishes
- Microstructure
- <u>Maximum acceptable flaw?</u>



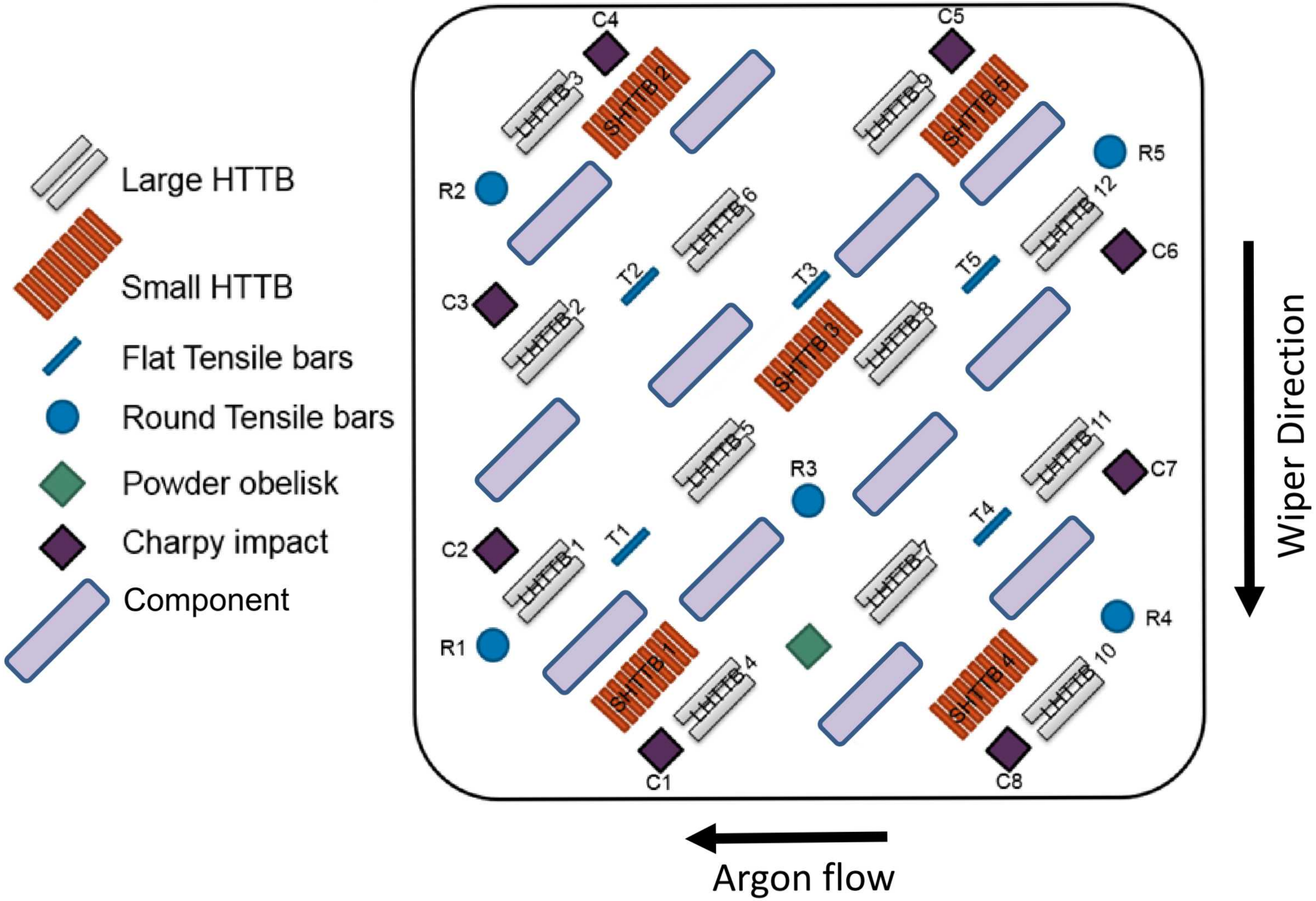
Quantify Effects of Bulk Porosity and Surface Crust Flaws

Motivation: Qualification of AM parts for high consequence applications

- **Laser powder bed printed eight plates of AlSi10Mg**

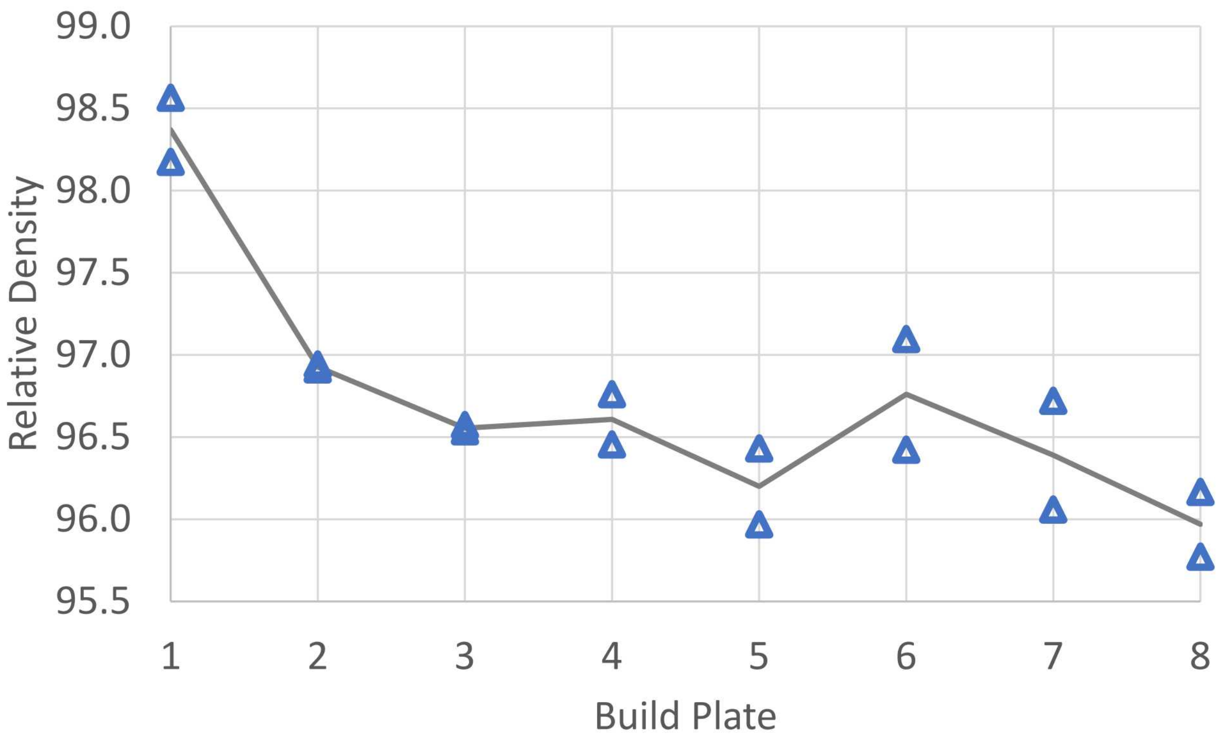


6.25 x 6.25 mm, 2.5 x 1.5 mm



What effect does reusing powder have on material properties?

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

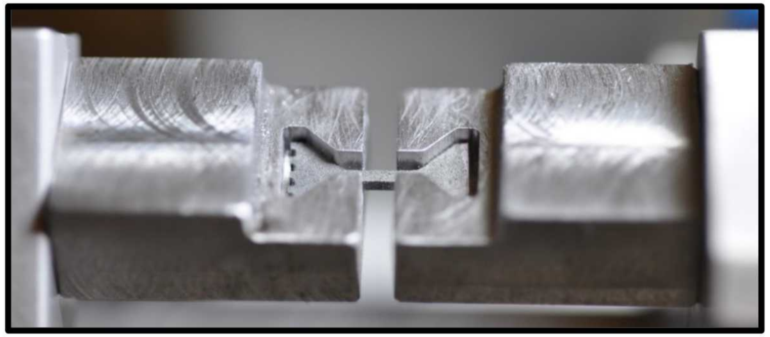


- **Only ~10% of powder goes to parts in powder bed.**
- **How do these measurements translate to mechanical behavior?**

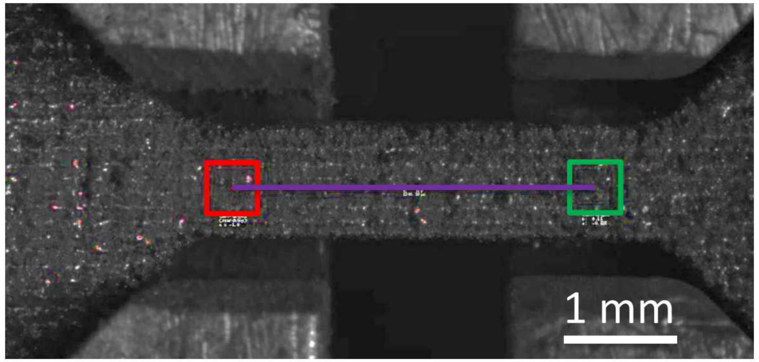
100% density is 2.67 g/cm^3

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

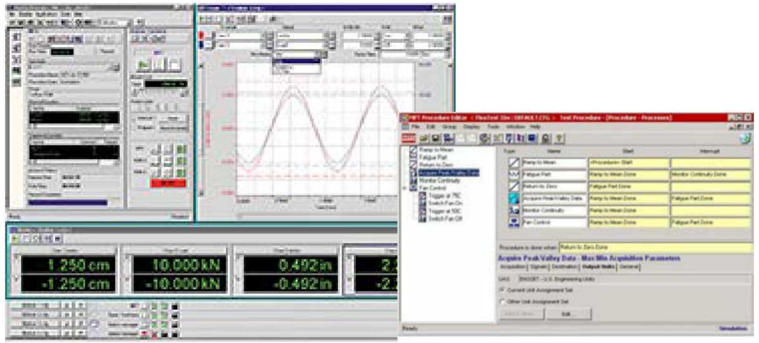
1. Self-aligning 'drop-in' grips

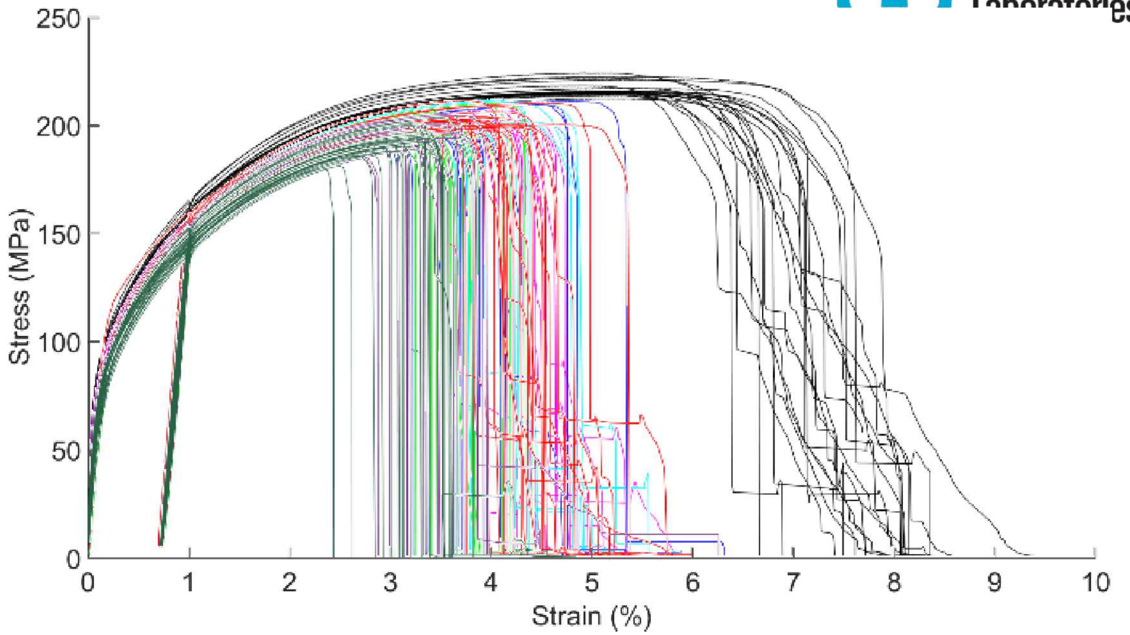


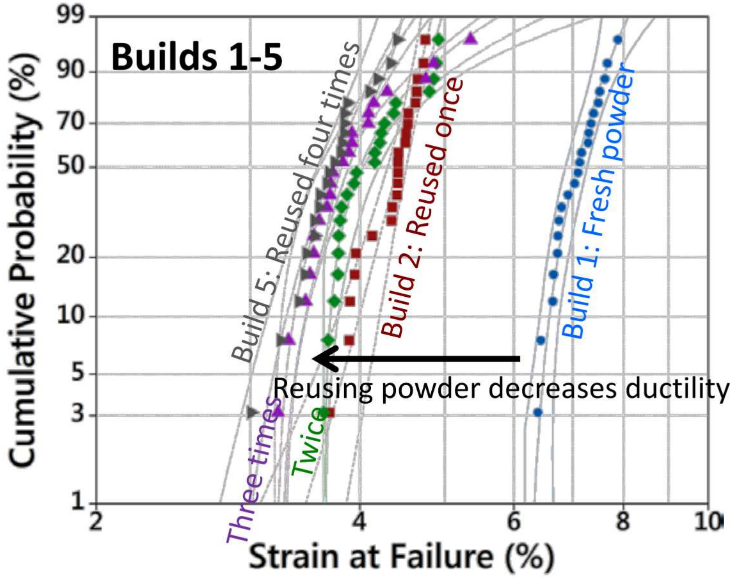
2. Non-contact virtual extensometer with "live" digital image correlation



3. Maximize software automation to reduce operator burden

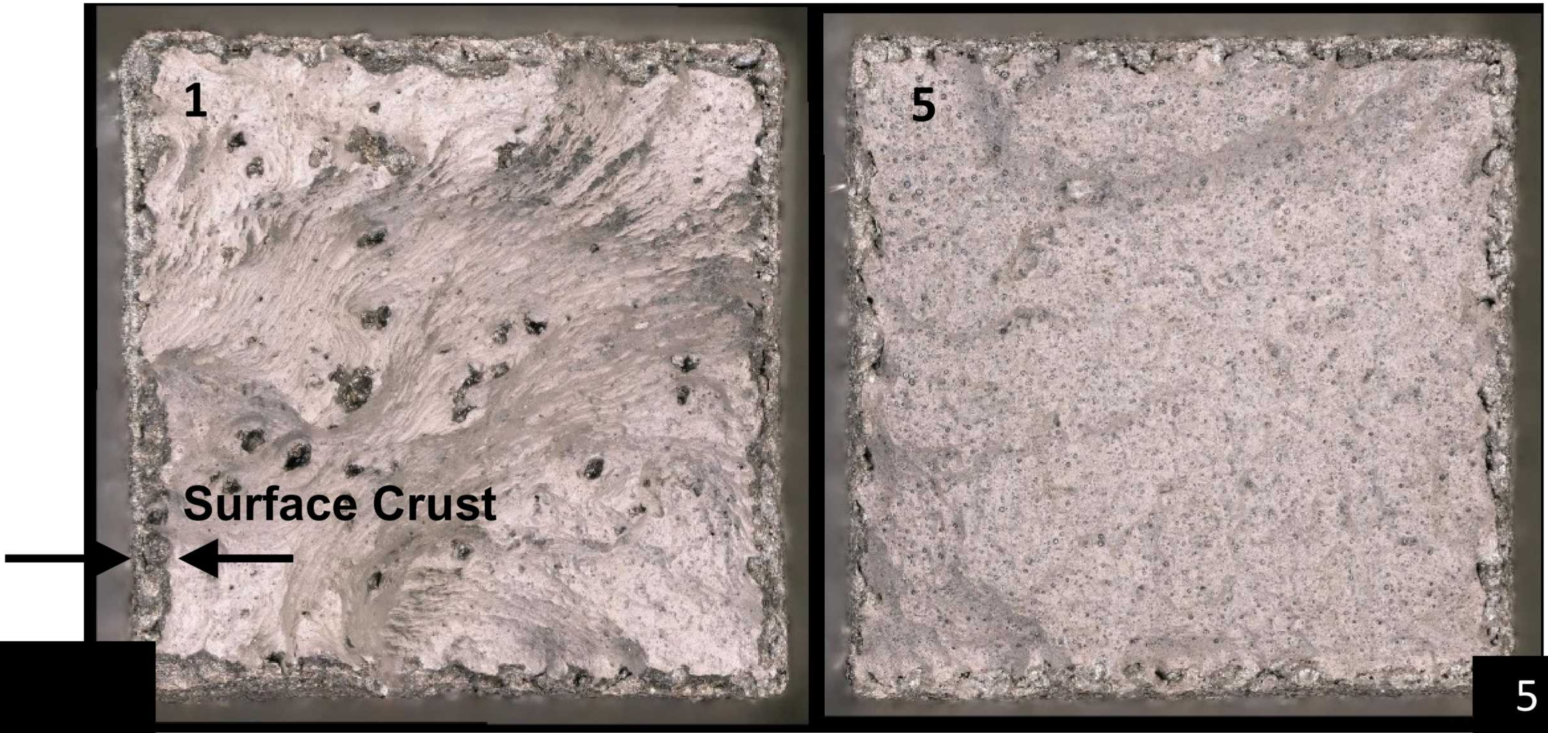


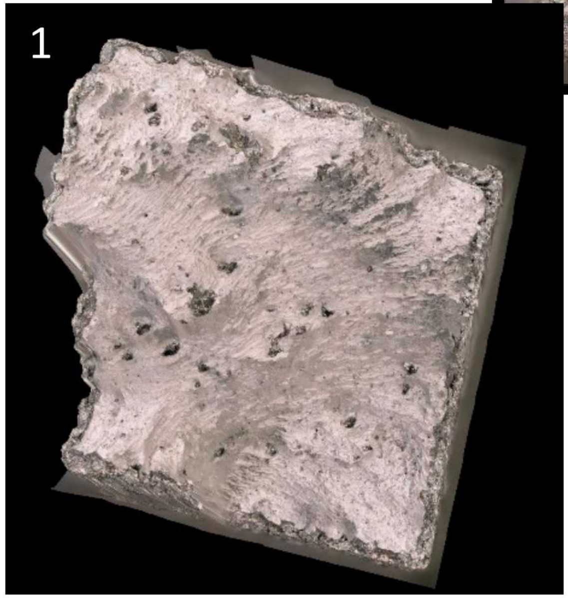




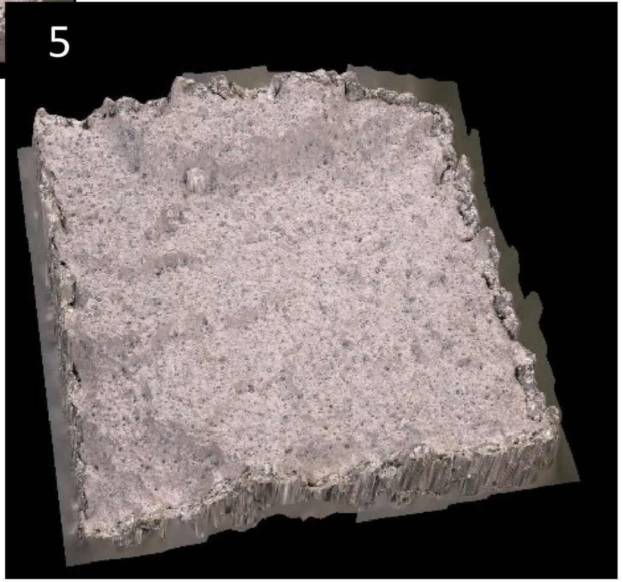
B. Salzbrenner et al., *J Mater. Process. Tech.*, 2017

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

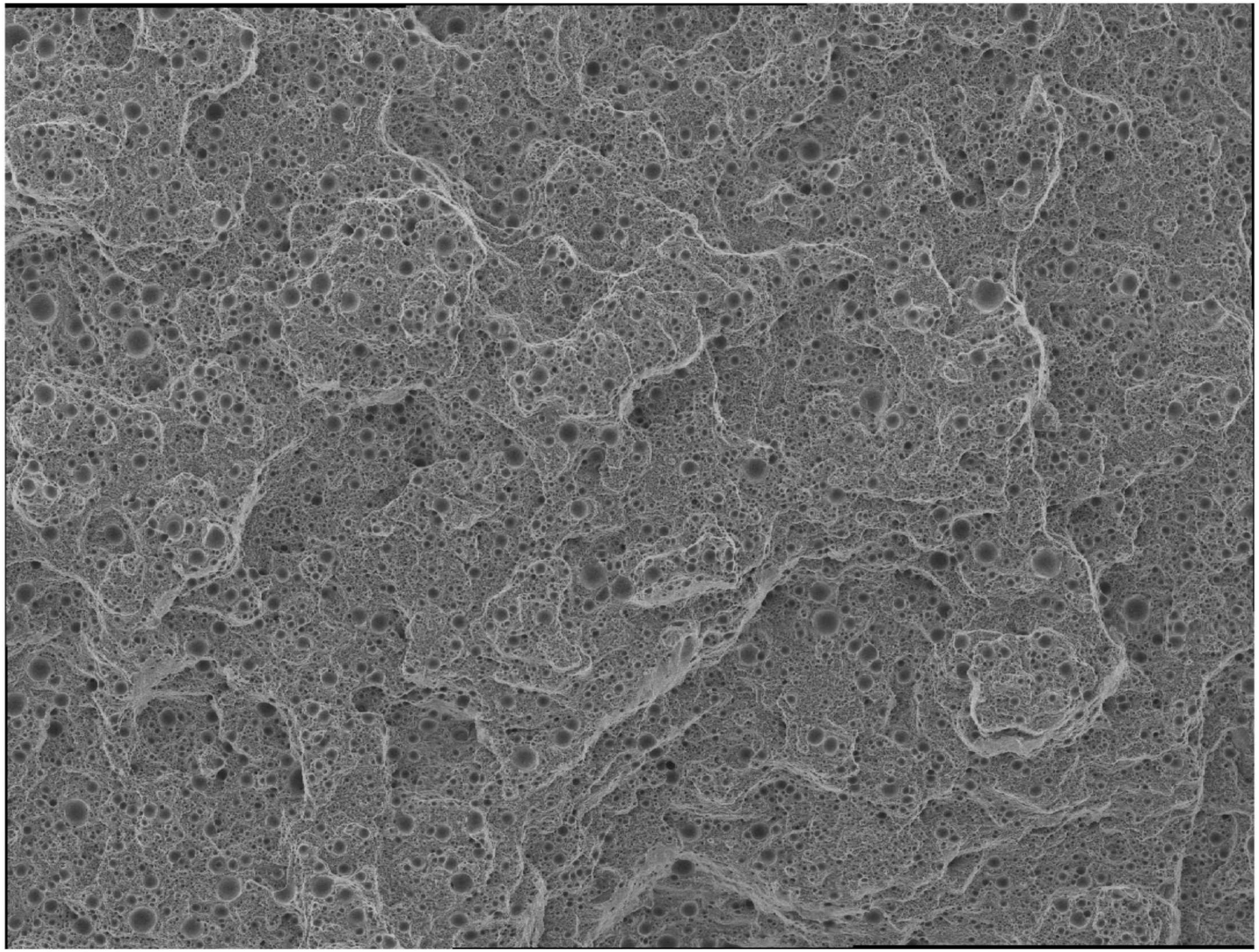




- Millions of small voids reduce ductility and strength more than a few large voids.
- Many small voids allow for straight fracture path.
- We are in a density dominated regime.
- Surface Crust around edge of sample. Loosely-bound powder, surface roughness, and cracks.

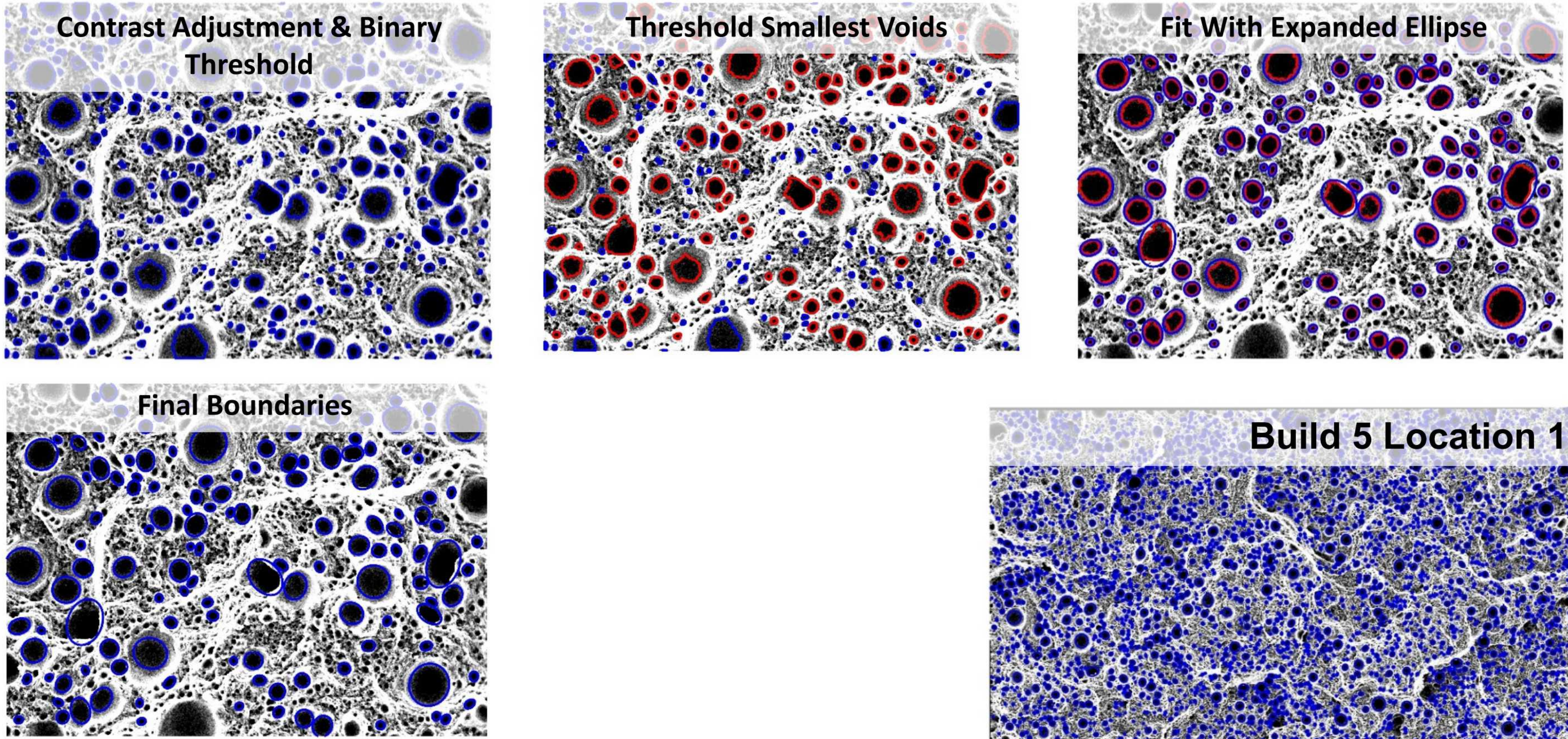


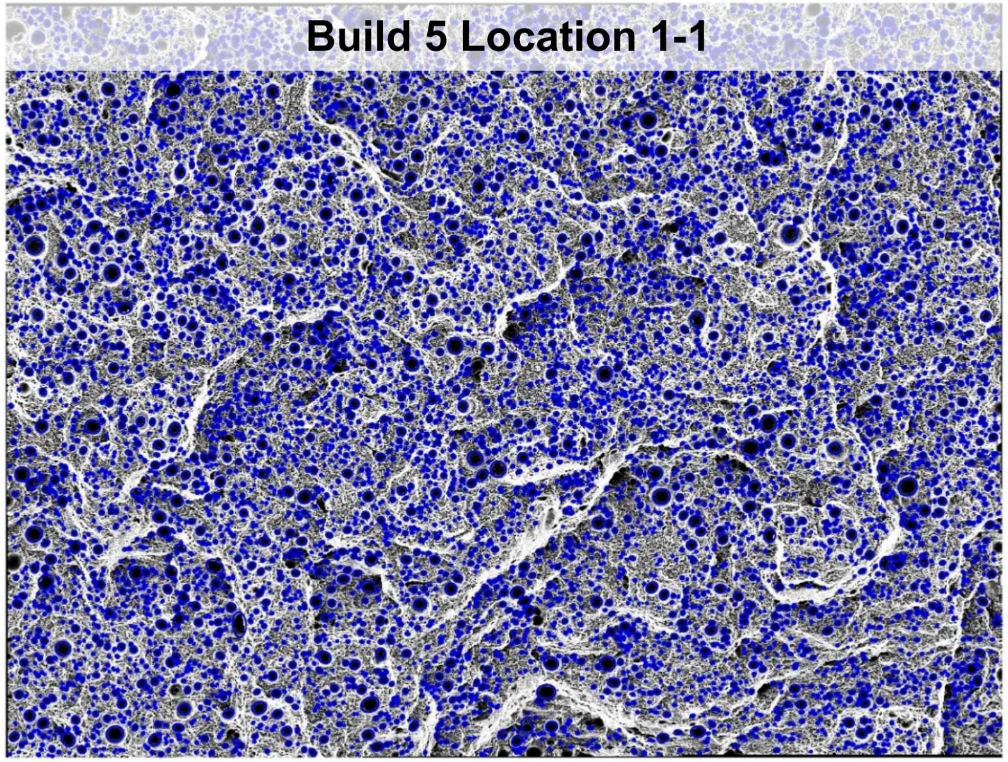
High throughput fracture surface imaging



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

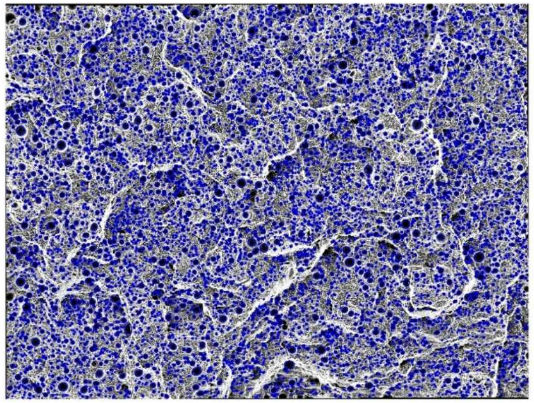
Void identification algorithm to measure porosity on fracture surfaces

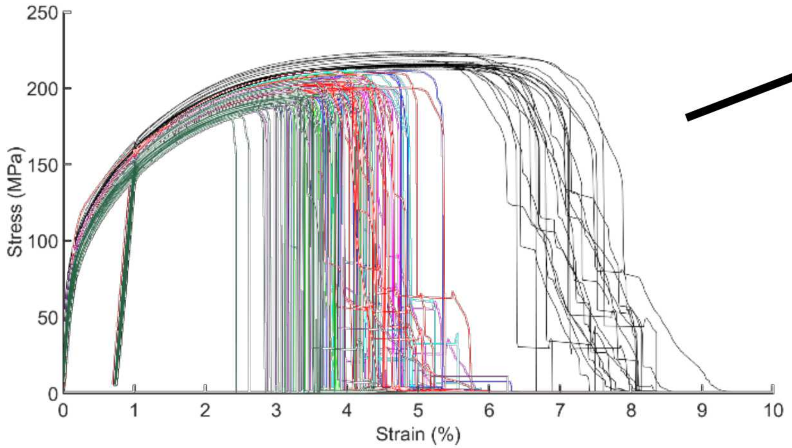


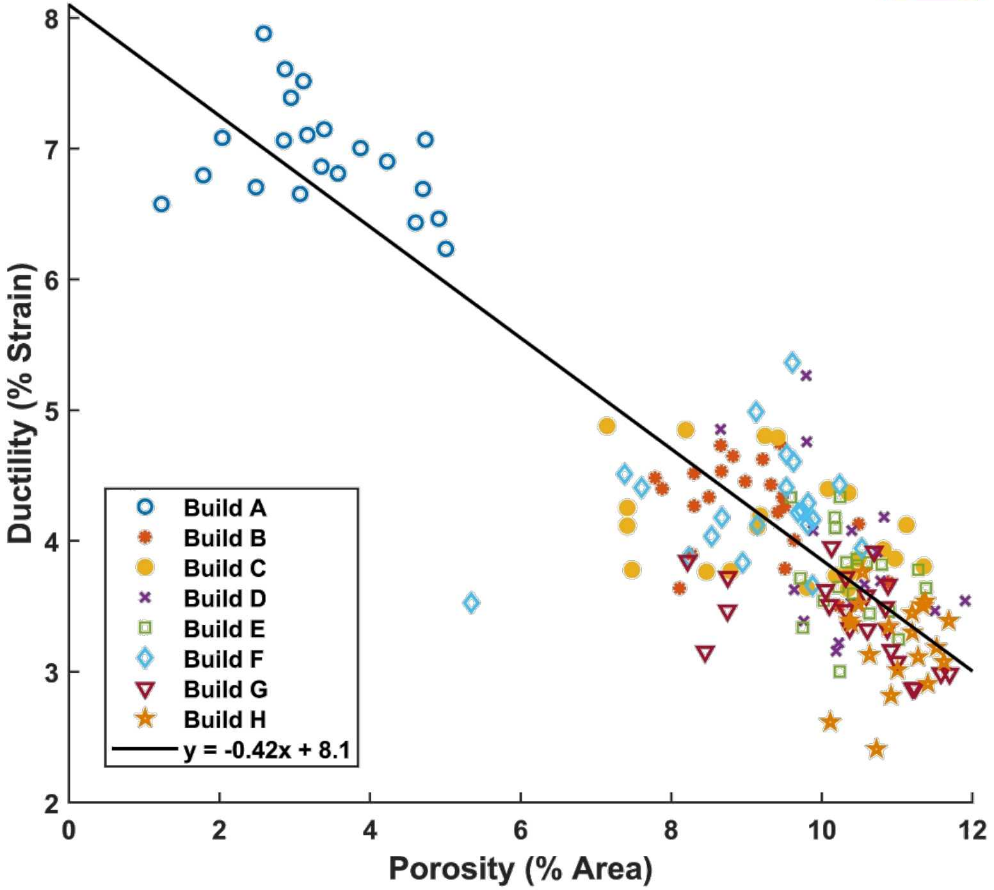


- **Identify voids on a fracture surface from high throughput SEM images.**
- **Multistep process does more than simple thresholding.**
- **Algorithm allowed ~172 fracture surfaces to be analyzed—about 10x more than was possible before.**

Compare ductility to fracture surface porosity

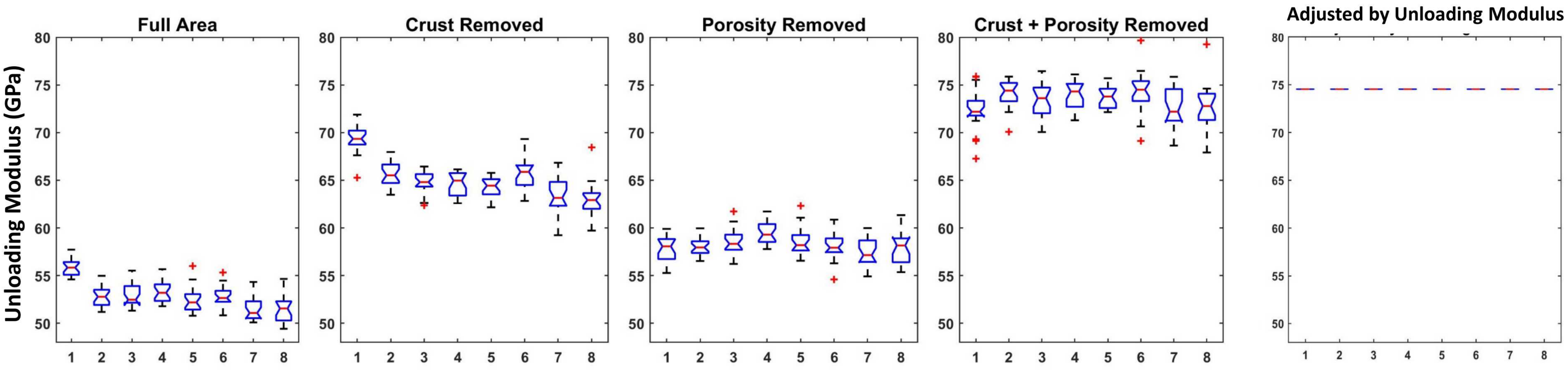




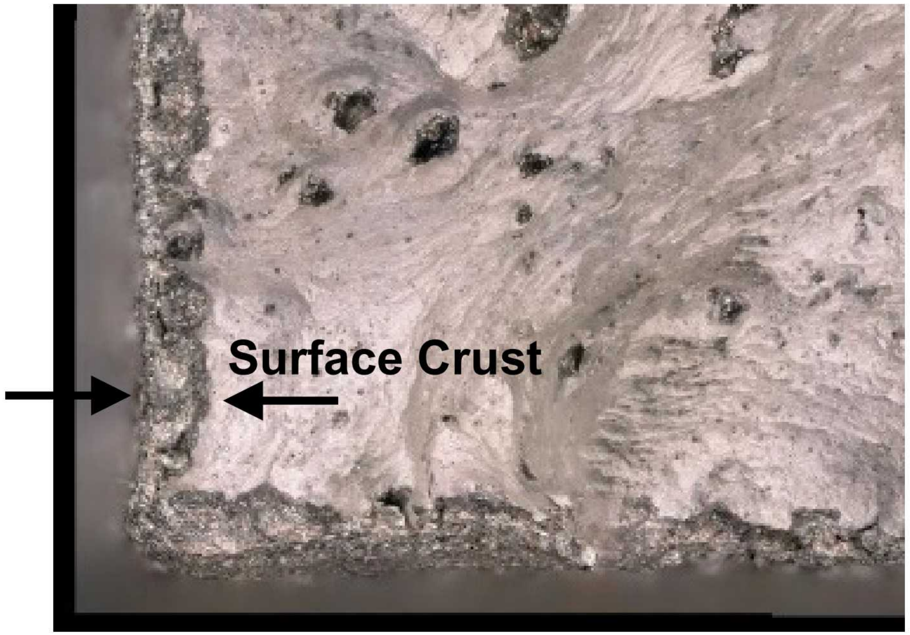


- **Increasing fracture surface porosity by 1% decreases ductility by 0.5%.**
- **Fracture porosity is NOT equivalent to density.**
- **Relationship between fracture surface porosity and density?**

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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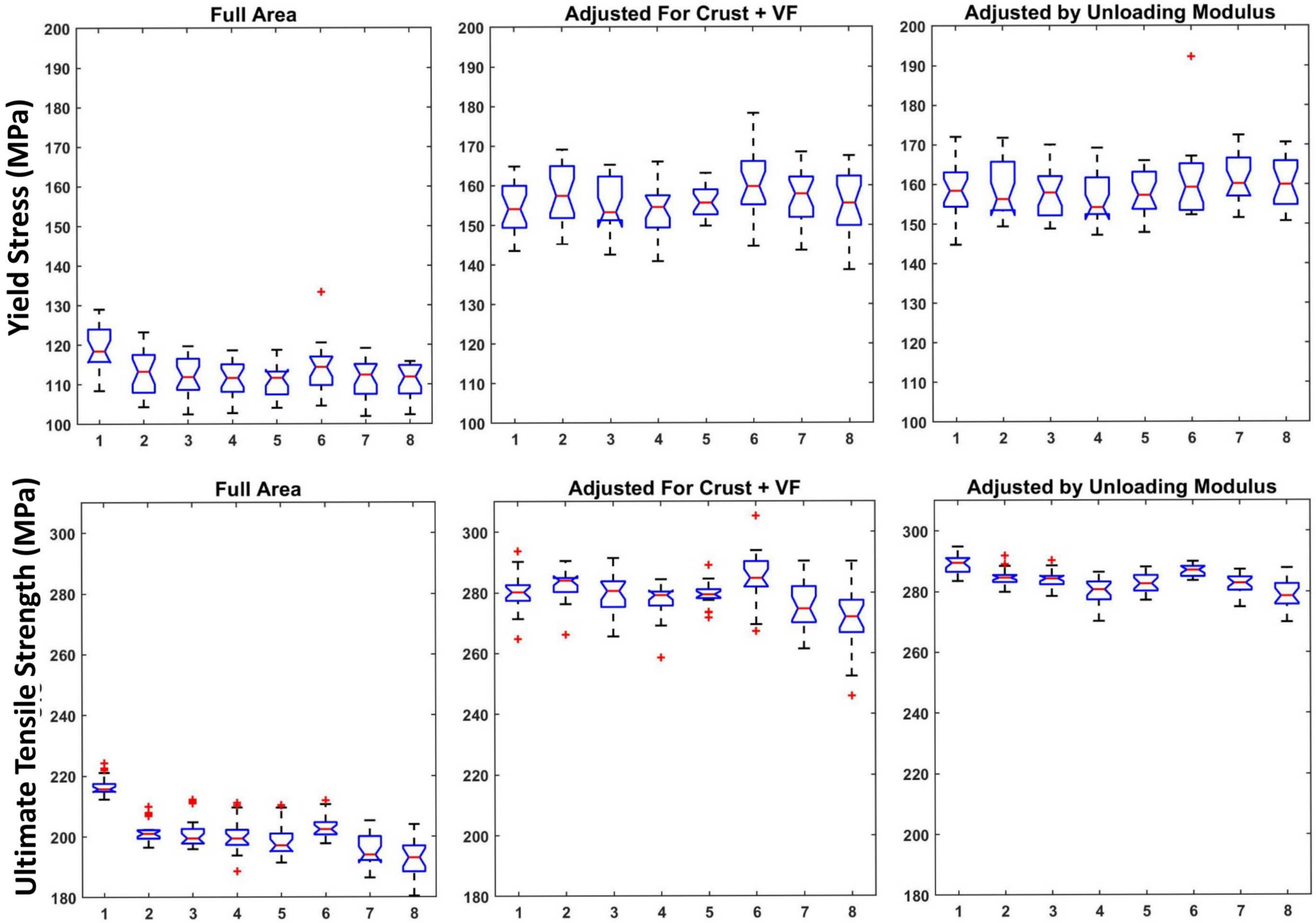
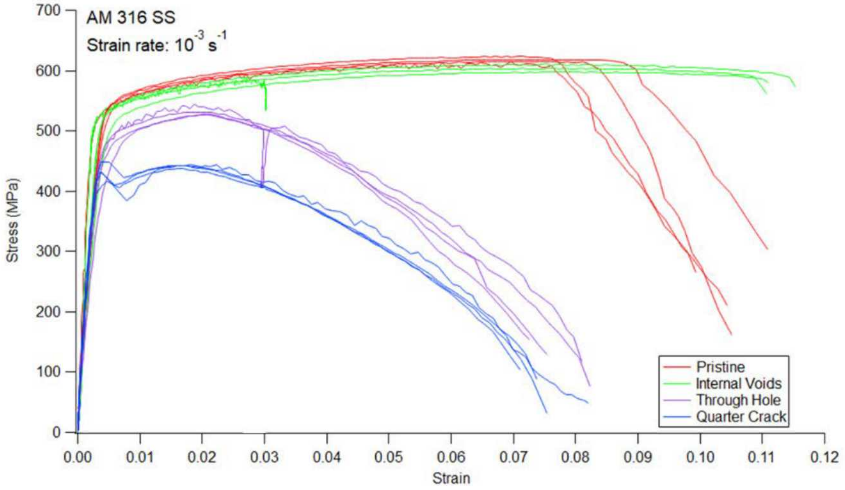
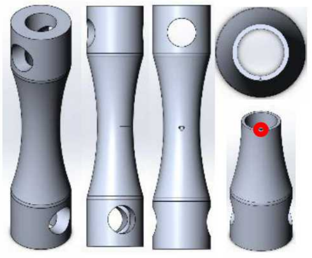


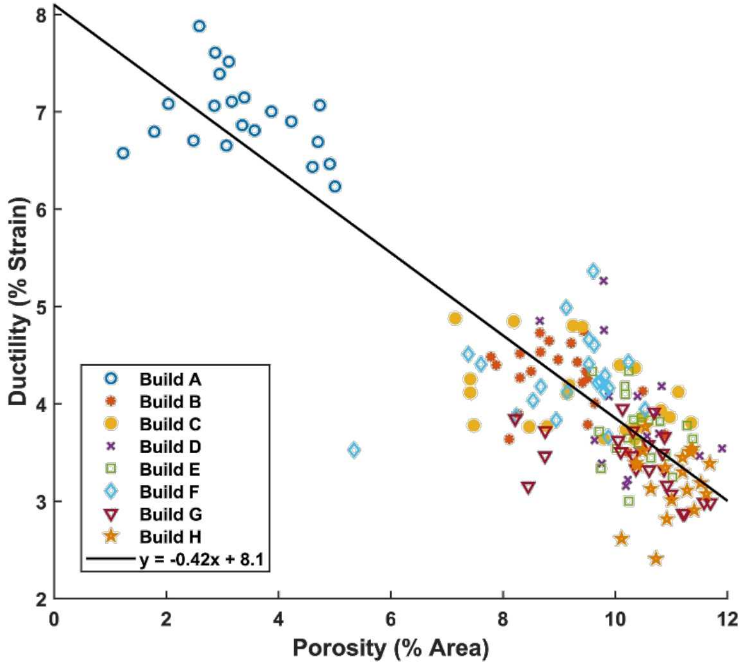
- Inherent Yield stress is 160 MPa instead of 120 MPa.
- Inherent Tensile strength is 280 MPa instead of 200 MPa.

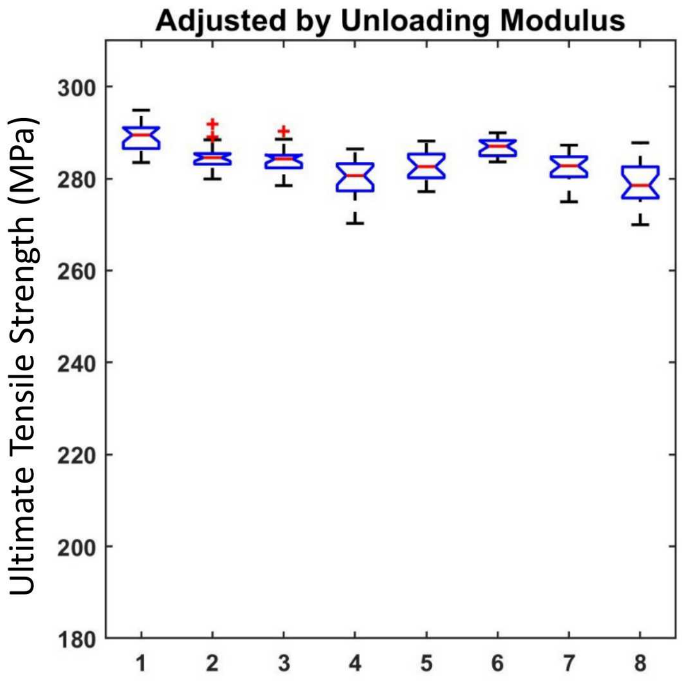
Conclusions

- **Introducing intentional flaws to identify critical flaw size for exemplar component.**
- **Small ubiquitous pores appear to dominate behavior over large lack-of-fusion pores in this density-dominated regime.**
- **Ductility can be largely predicted by porosity**
- **Obtain “inherent” material properties using unloading modulus correction.**



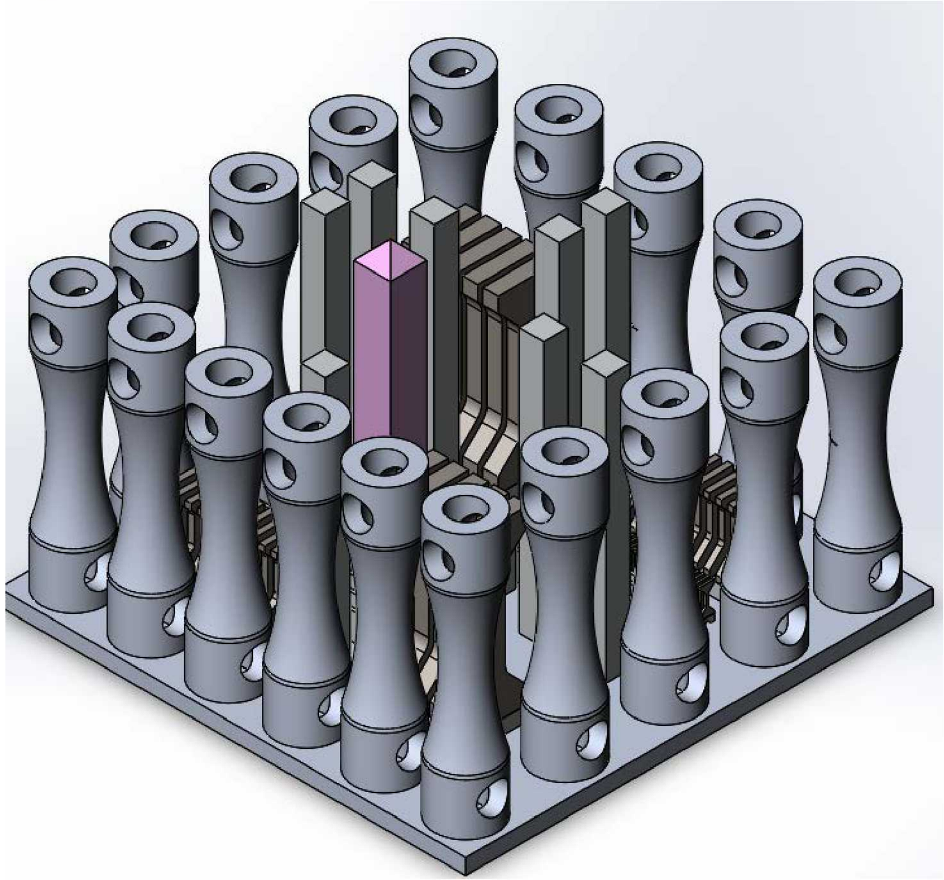


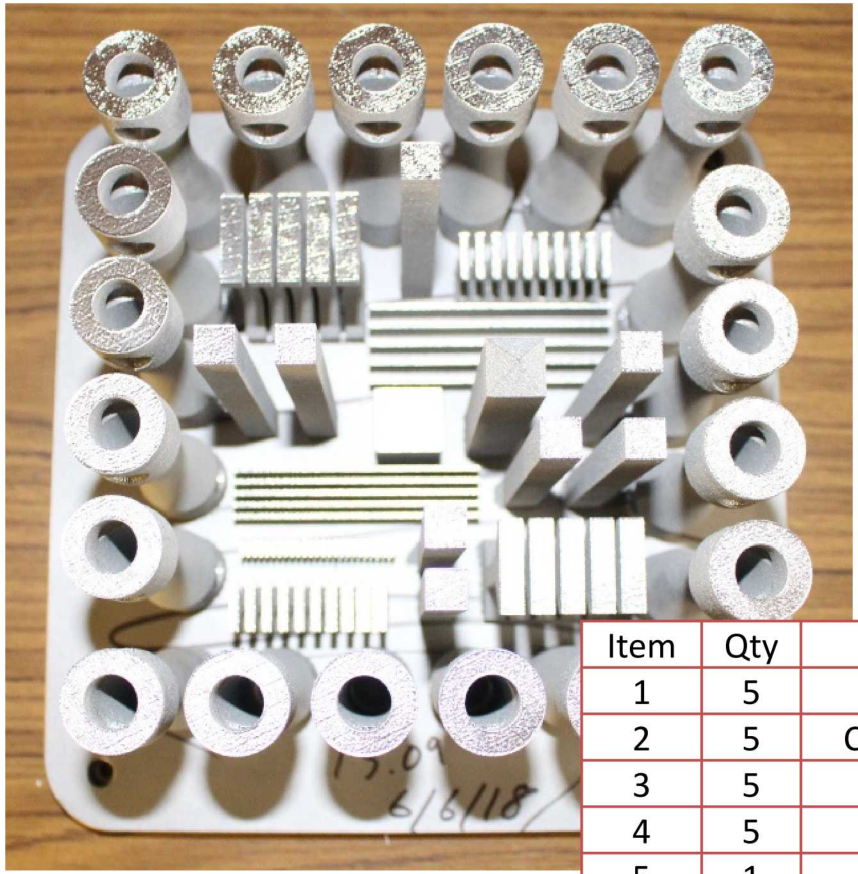




Extra slides

Additive manufacturing build plates



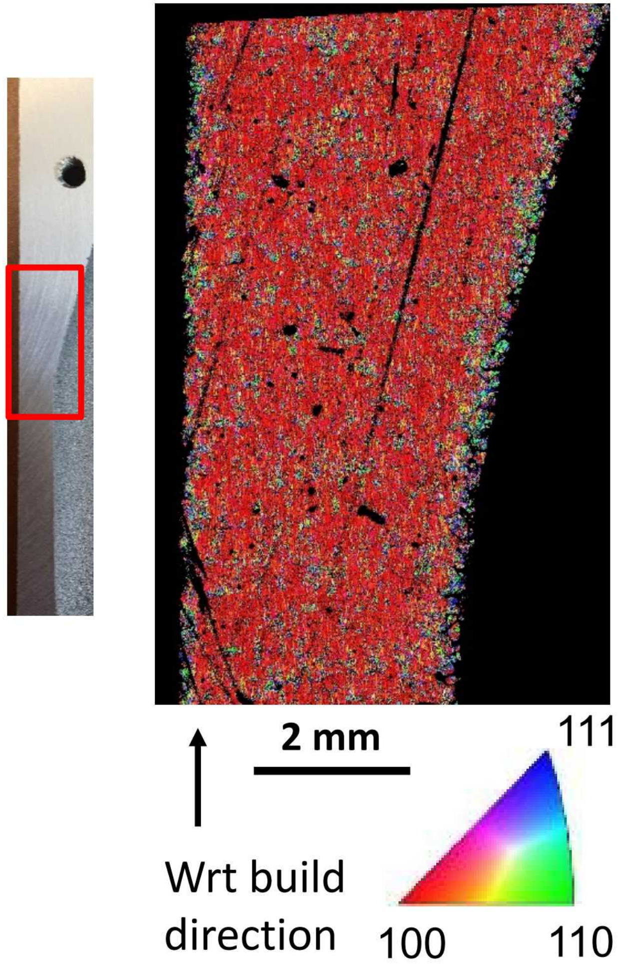


Item	Qty	Name
1	5	Component, unflawed
2	5	Component, crack 1/4 circumference
3	5	Component 2 mm hole in wall
4	5	Component, 0.5 mm hole in wall
5	1	Powder obelisk
6	1	Ultrasound/density cube
7	25	A size tensile bars
8	20	B size tensile bars
9	10	C size tensile bars
10	5	Fracture samples (printed notch)
11	5	Fracture samples (cut notch)
12	8	Metallography blocks

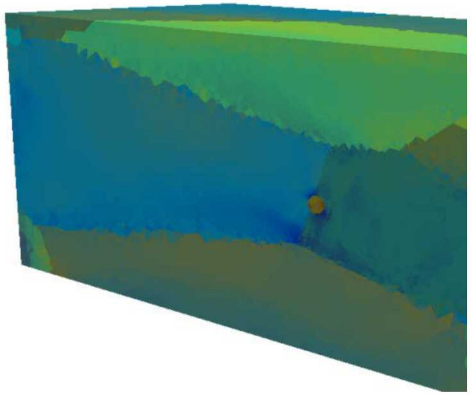
- **One SS 316 plate printed at Sandia**
- **Three AlSi10Mg plates printed at Sigma Labs**

How to detect critical flaws in AM components

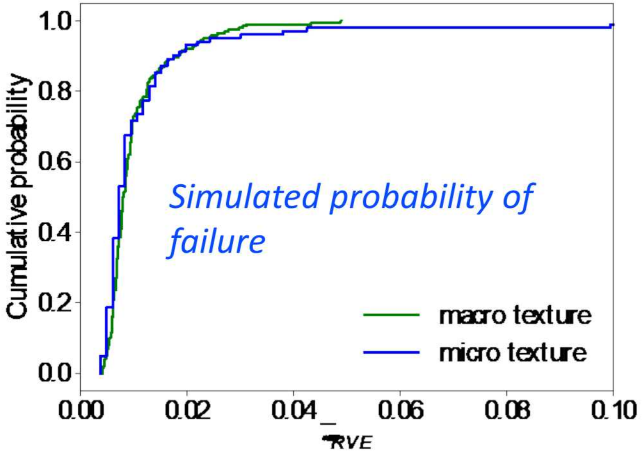
Microstructure flaws
Is extreme texture in this region a problem?



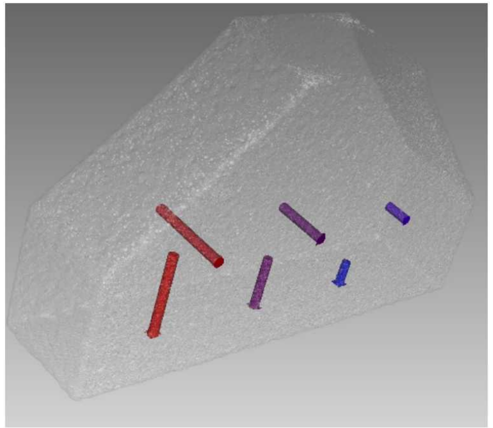
Predict thresholds with modeling
Can we predict critical flaws?

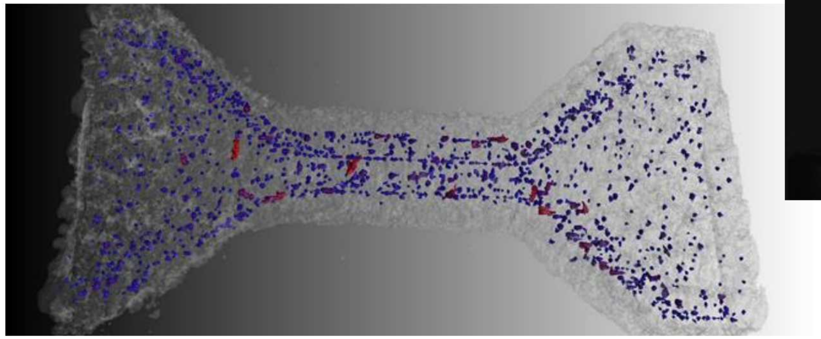


FE model including flaw with microstructure

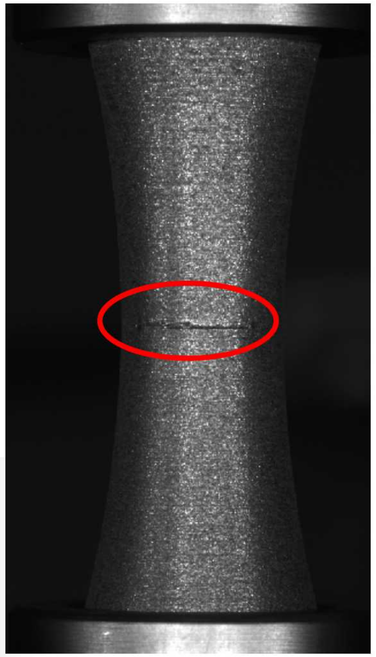


Non-destructive inspection
Can we detect critical flaws?





Experimental Validation
Are those critical flaws actually critical?



Fractography, no-flaw specimen

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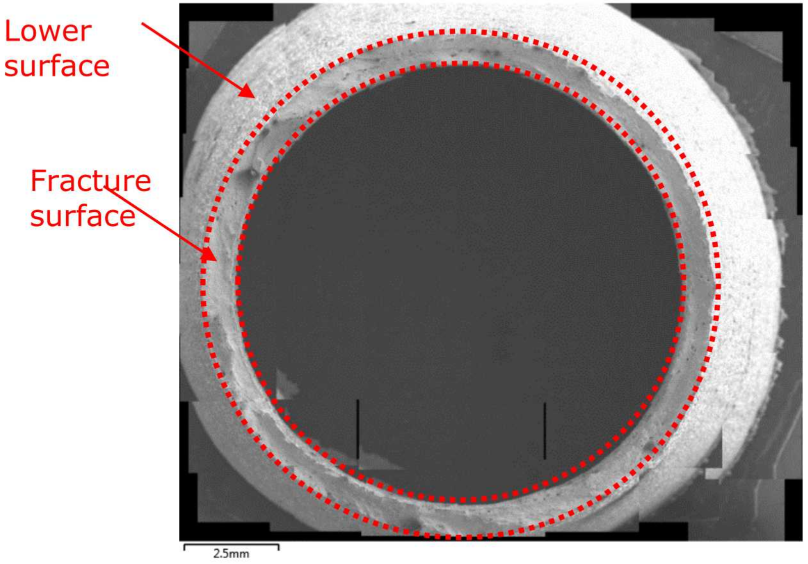
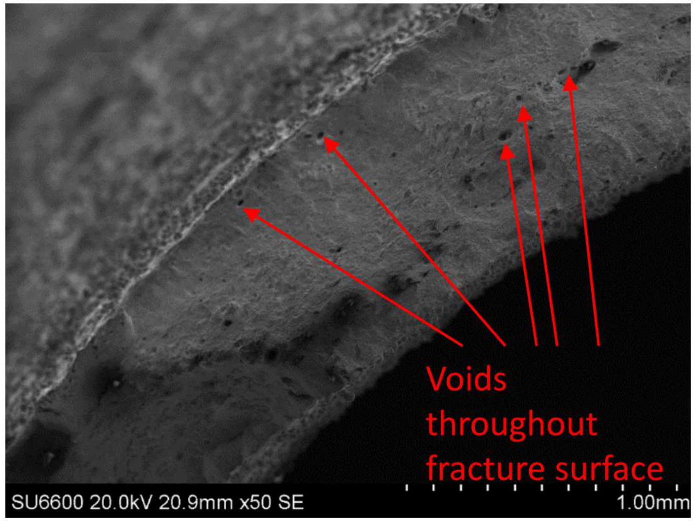
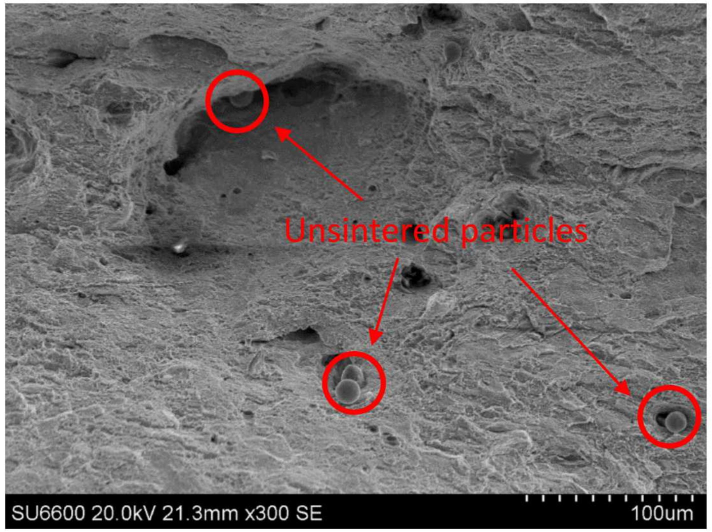
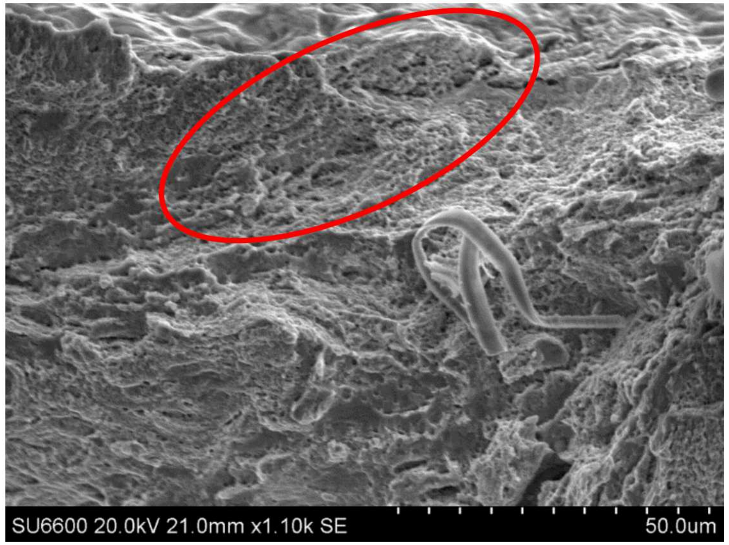
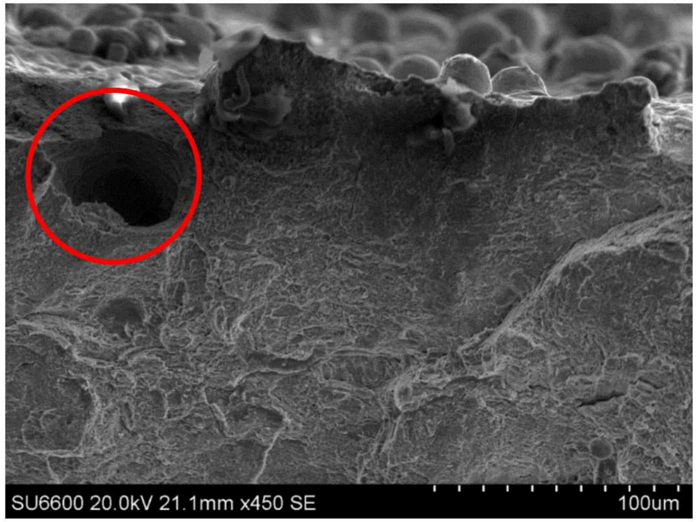




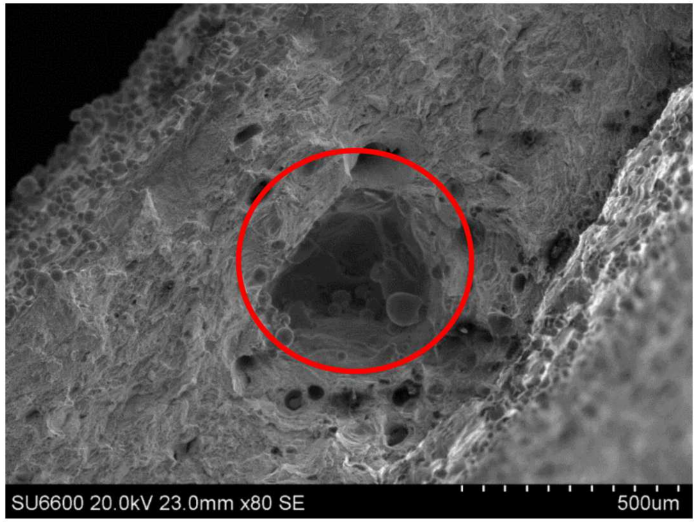




Dimpled fracture surface, showing ductile fracture

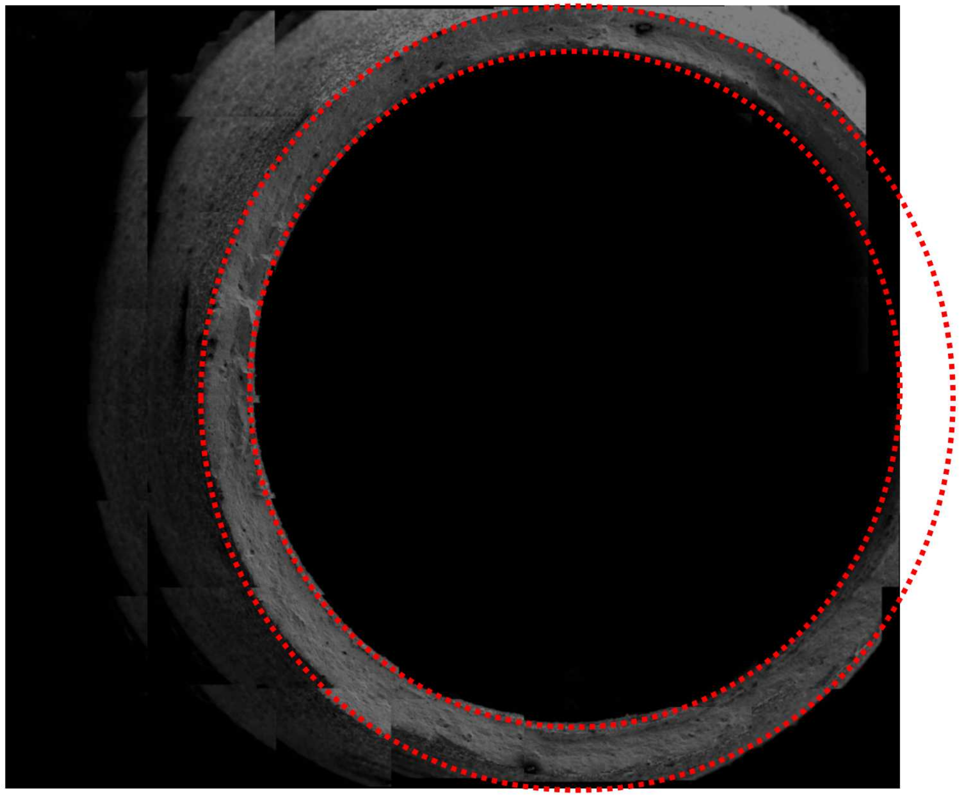


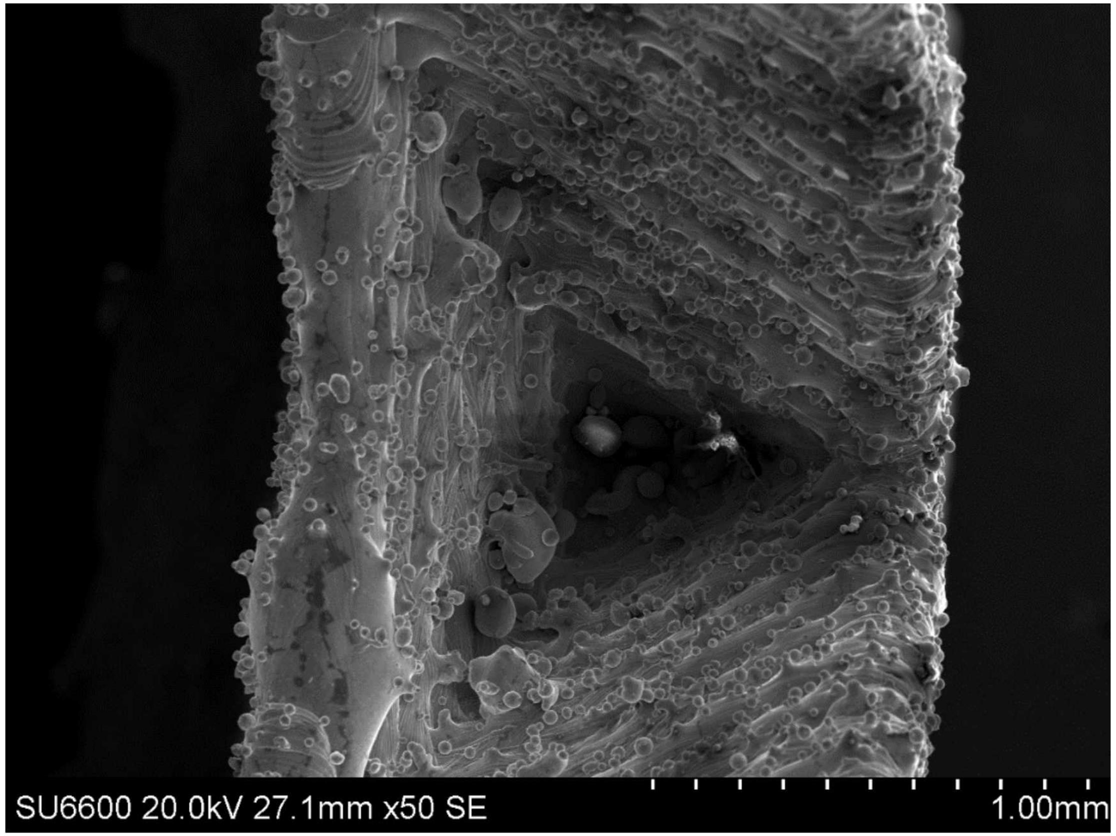
Large void near fracture surface along edge.



Unusually large void found in fracture surface.

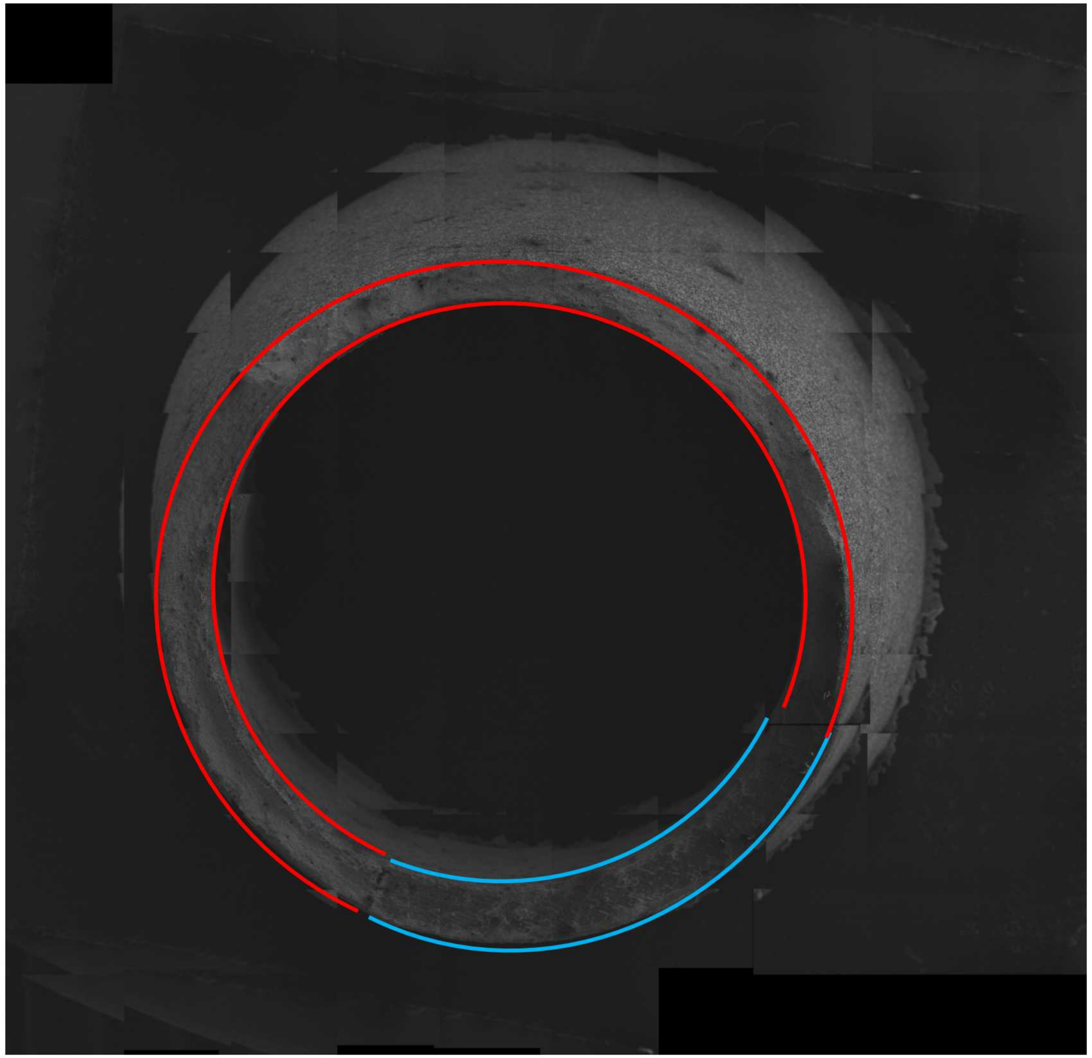
Fractography, through-hole specimen



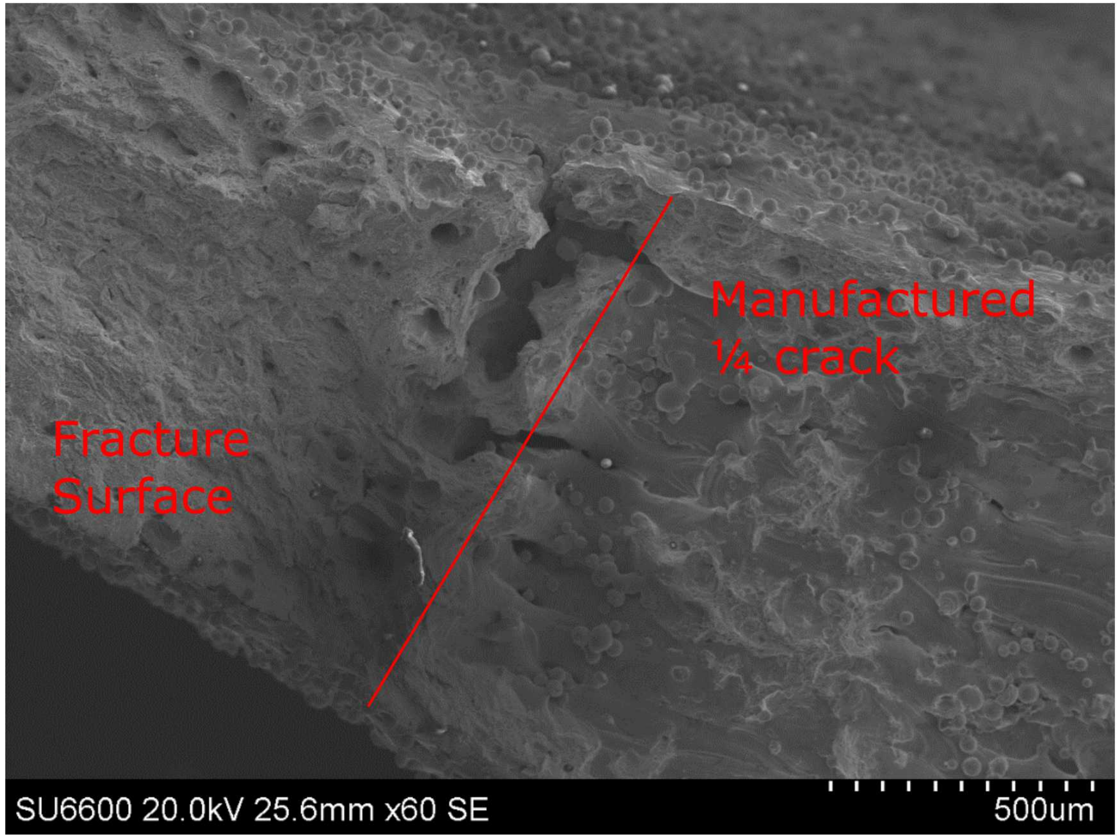


Surface of thru hole manufactured into the specimen. Each layer of additive manufacturing can be seen. Unsintered particles remain.

Fractography, quarter-crack specimen

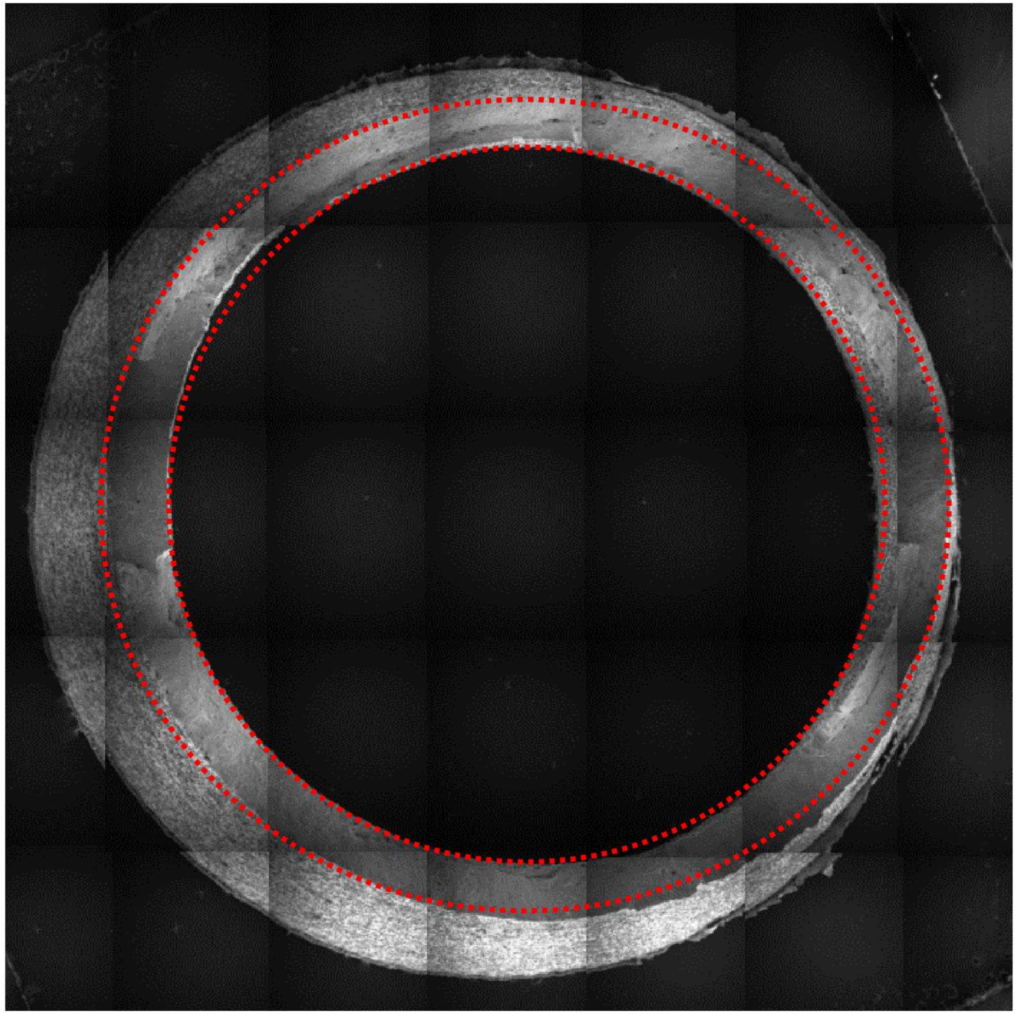


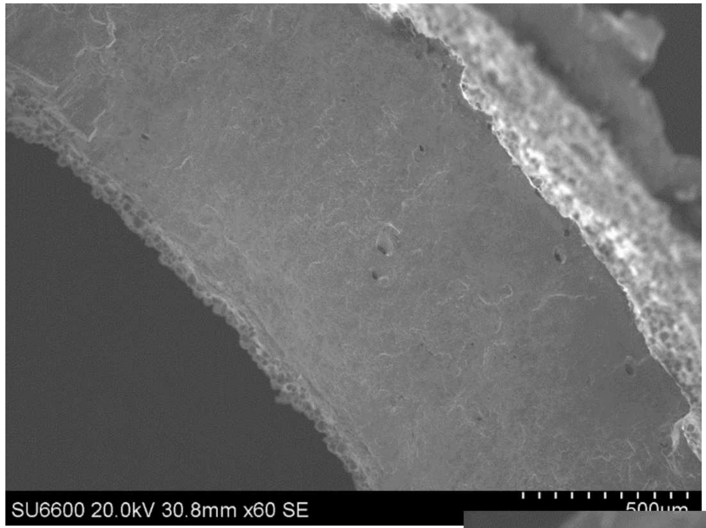
Red:
Blue:



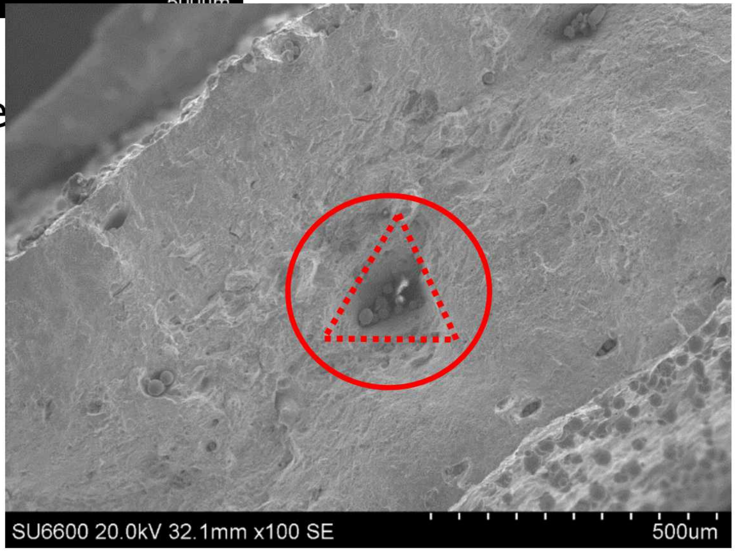
The interface between the fractured surface and the quarter crack. During the test, the specimen initially opened the quarter crack, which then continued to grow until failure.

Fractography, internal-void specimen





The fracture surface
indicative of a brittle



Potential location of internal void, diamond shaped and unsintered particles.