New Mexico Tech, February 7, 2020

SAND2020-1367PE

What counts as a flaw? Interactions between Geometry, Material Properties, and Defects in AM Metals

Jay Carroll

Sandia National Laboratories, [2]Clemson University

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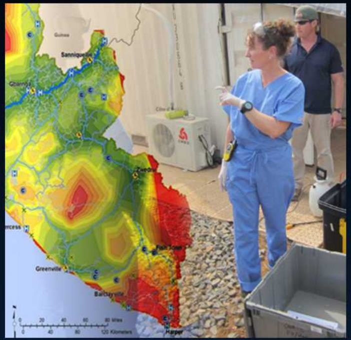
Sandia's Impact



Ebola Outbreak

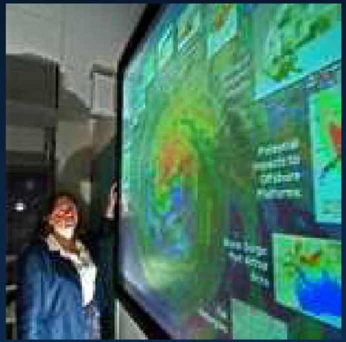
Sandia contributes to global response of Ebola outbreak by developing a sample delivery system cutting the wait time and potentially fatal exposure.

Detecting IEDs

Combat personnel now have a new tool for uncovering improvised explosive devices: Sandia's highly modified miniature synthetic aperture radar system, which is being transferred to the U.S. Army.

Cleanroom invented 1963

$50 billion worth of cleanrooms built worldwide It's used in hospitals, laboratories and manufacturing plants today.

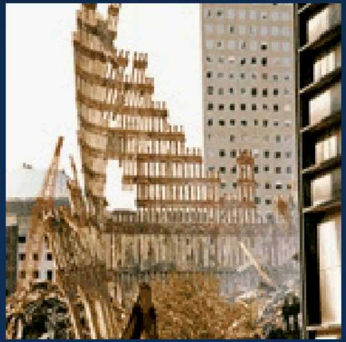


Hurricane Katrina

Sandia is called to assess flooding and infrastructure failures.

Fukushima Quake

Sandia helps clean up radioactive wastewater.



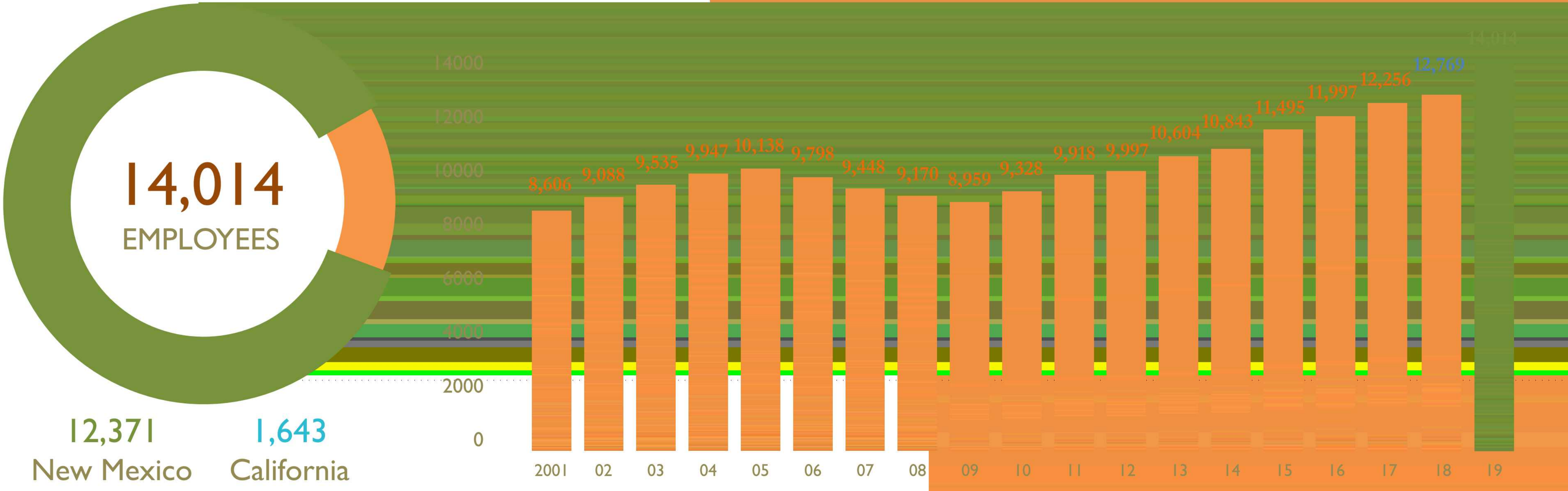
9/11

Sandia sets contingency plans for release of materials and aircraft attacks on critical facilities immediately after 9/11. Search dogs are equipped with cameras for search and rescue K-9 handlers. The capability allowed search efforts to be carried out in spaces inaccessible to humans.

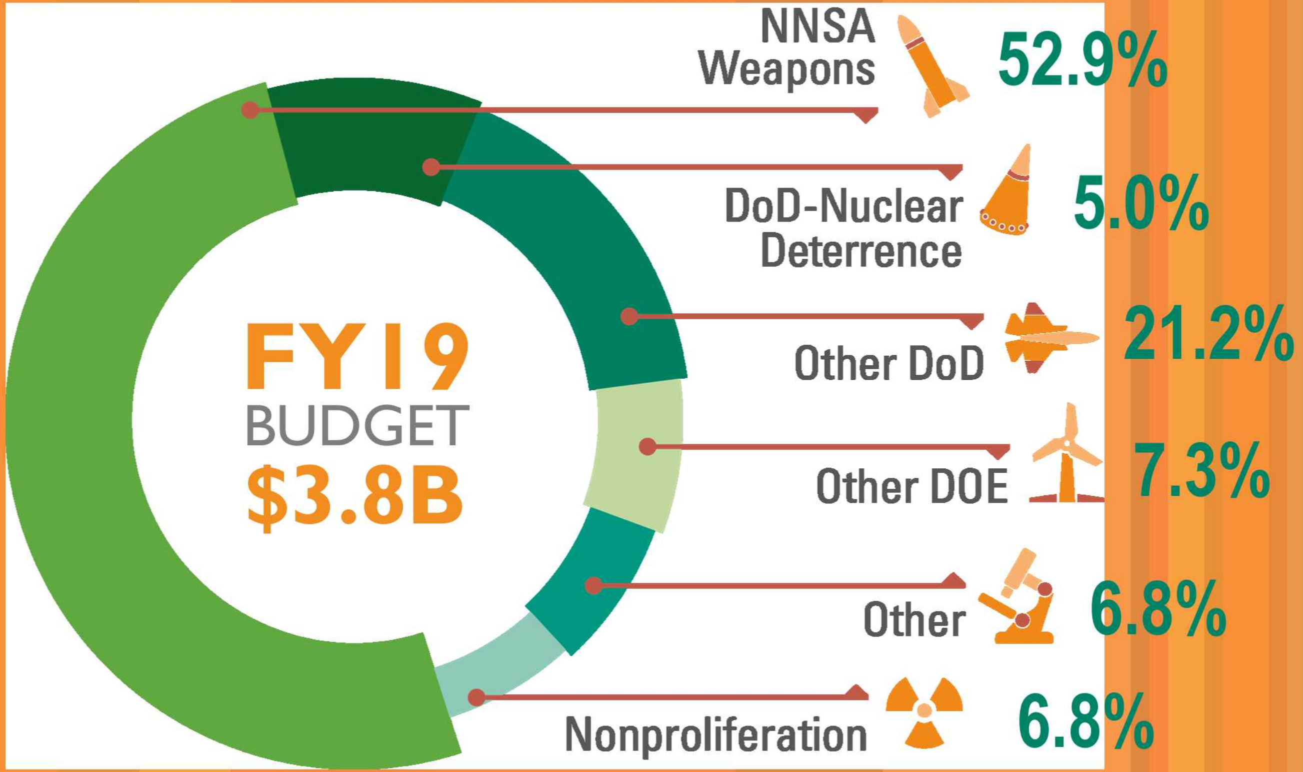
Sandia is a National Laboratory

SANDIA'S WORKFORCE IS GROWING

Staff has grown by over 5,000 since 2009 to meet all mission needs



SANDIA'S BUDGET COVERS A BROAD RANGE OF GOVERNMENT AND OTHER WORK



OTHER

Department of Homeland Security
Other federal agencies | Nonfederal entities
CRADAs, licenses, royalties | Inter-entity work

DoD

Air Force | Army | Navy
Defense Threat Reduction Agency
Ballistic Missile Defense Organization
Office of the Secretary of Defense
Defense Advanced Research Projects Agency
Intelligence Community

OTHER DOE

Science
Energy Efficiency and Renewable Energy
Nuclear Energy
Environmental Management
Electricity Delivery and Energy Reliability
Other DOE

NONPROLIFERATION

NNSA/NA20 | State Department

Why additive manufacturing?

- Can make designs that are impossible to build with conventional techniques
- Topology optimization
- Combine multiple parts into one (GE nozzle combined 20 parts into one)
- Faster turnaround (at smaller quantities)
- Lower cost (at smaller quantities)

Challenges for AM in high-consequence applications

- Can we trust the parts?
  - Quantify variability
  - Residual stresses
  - Material is created simultaneously with component
  - Identifying flaws

http://www.gereports.com/post/116402870270/the-faa-cleared-the-first-3d-printed-part-to-fly/

Types of AM

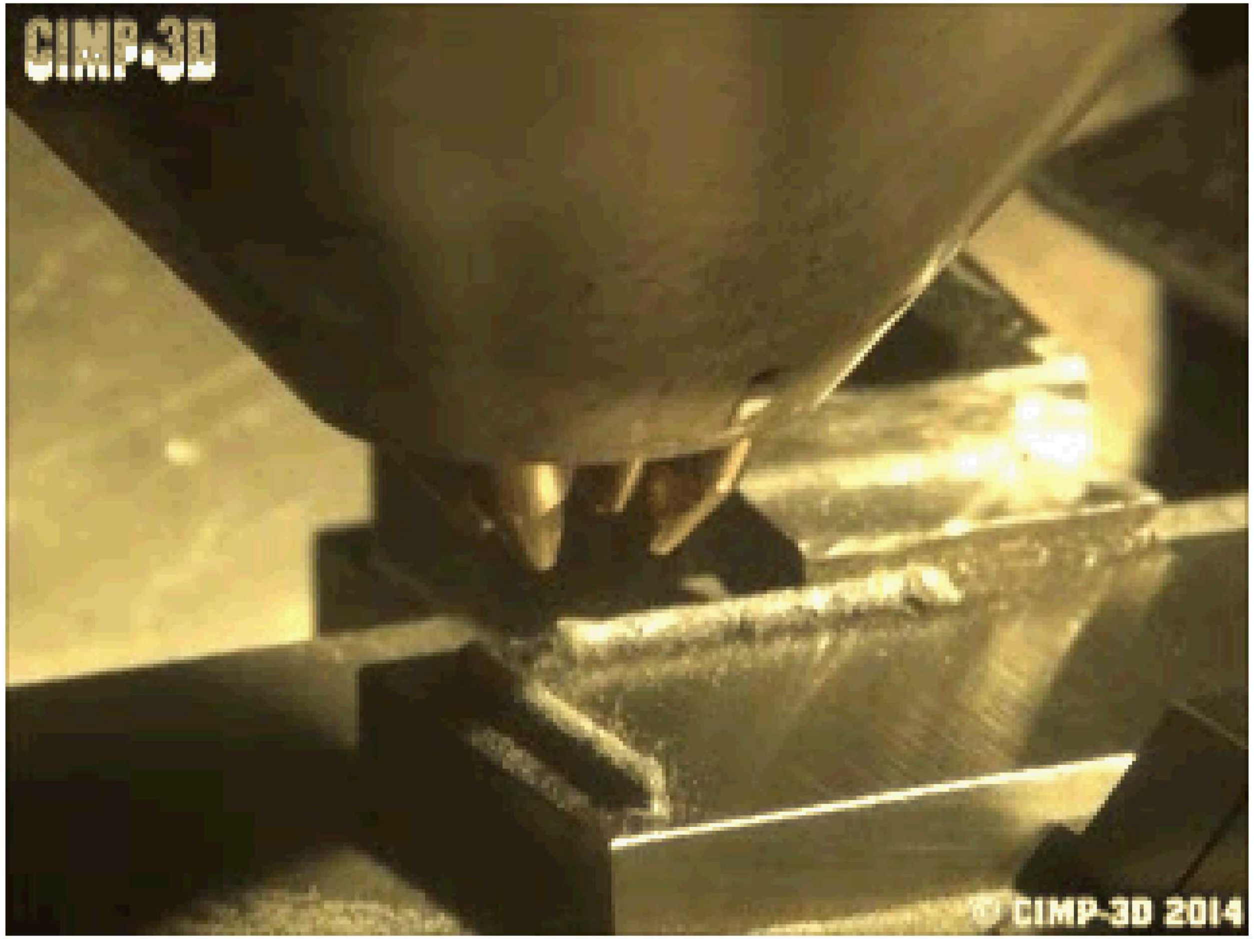
Table 1. Additive manufacturing categories as classified by ASTM.[4]

Category	Description
Binder jetting	Liquid bonding agent selectively deposited to join powder
Material jetting	Droplets of build material selectively deposited
Powder bed fusion	Thermal energy selectively fuses regions of powder bed
Directed energy deposition	Focused thermal energy melts materials as deposited
Sheet lamination	Sheets of material bonded together
Vat photopolymerization	Liquid photopolymer selectively cured by light activation
Material extrusion	Material selectively dispensed through nozzle or orifice

ASTM, Committee F42 on Additive Manufacturing Technologies, West Conshohocken, Pa., 2009.

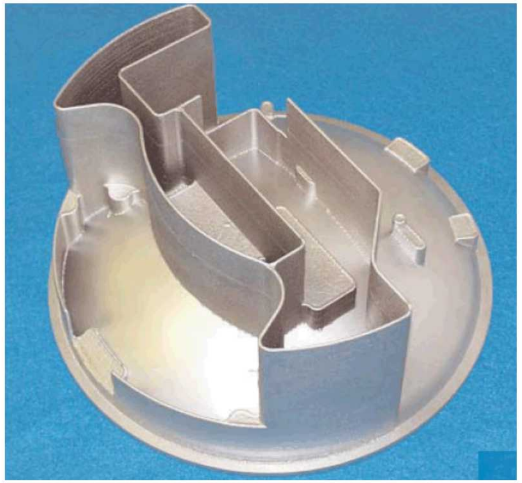
As opposed to powder-bed technology, the LENS process builds material by injecting powder feedstock with laser heating.

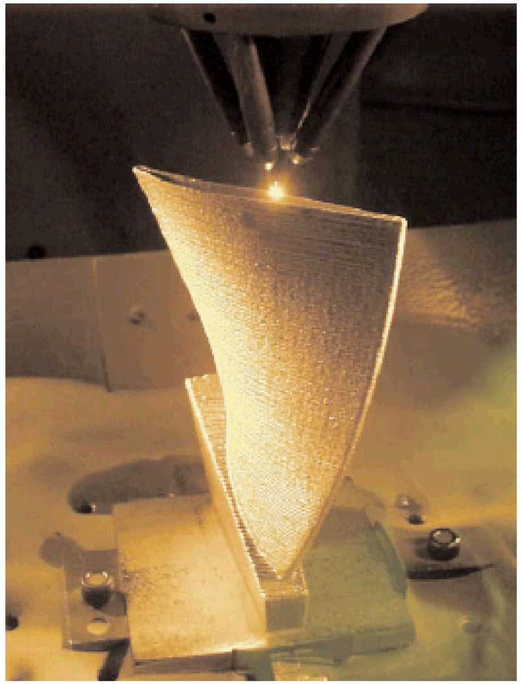
LENS = Laser Engineered Net Shaping



3.8 kW beam defocused LENS-like process

Courtesy of Todd Palmer, Pennsylvania State University



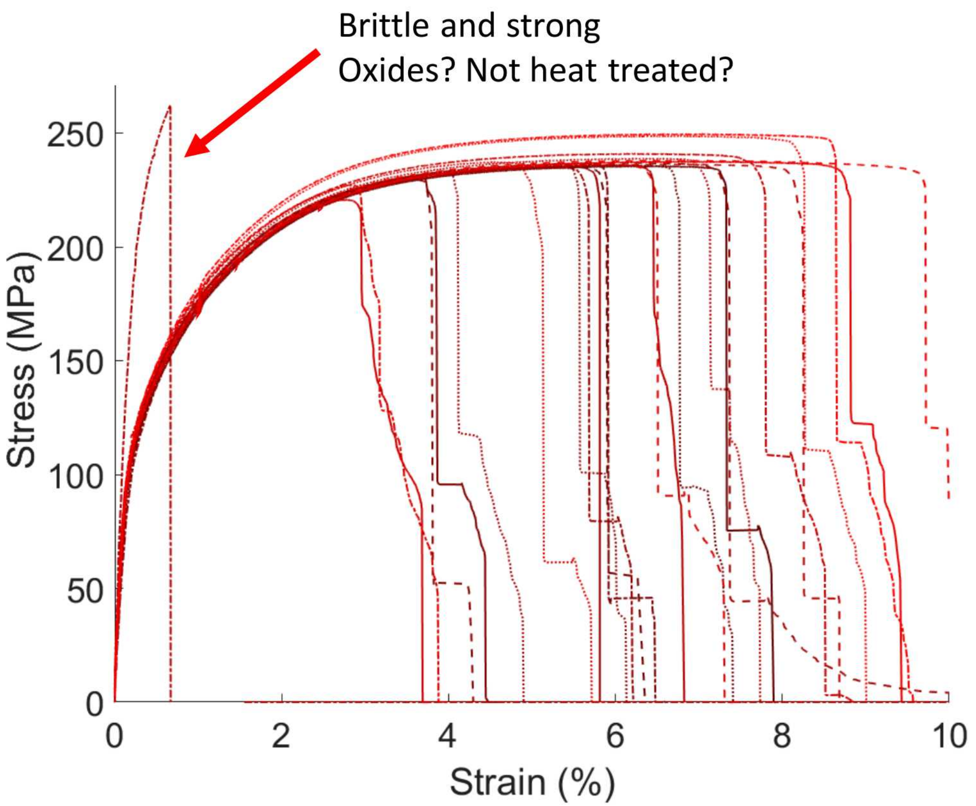


Powder bed additive manufacturing

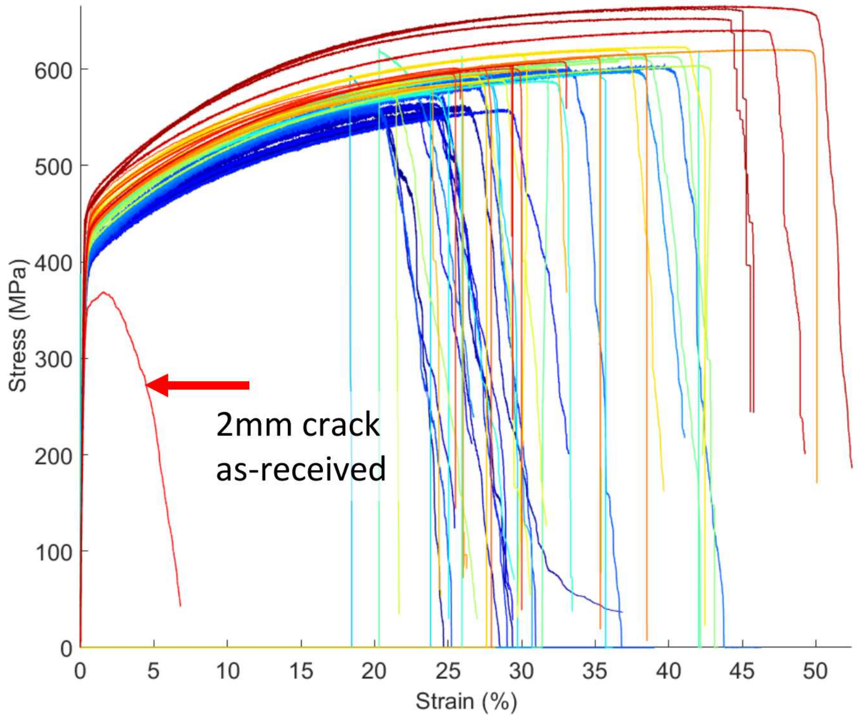
Bradley Jared (1832), Dan Kammler (2735), Gary Hux (8247)

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

28 AM AlSi10Mg medium conventional tensiles



45 AM 304L medium conventional tensiles

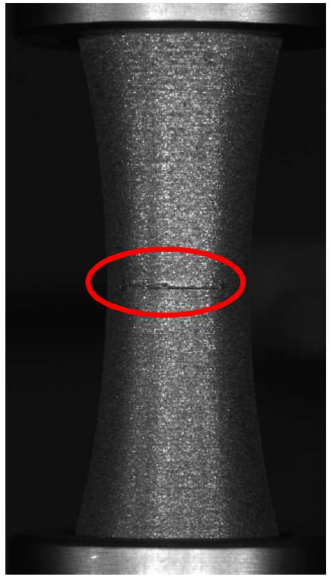


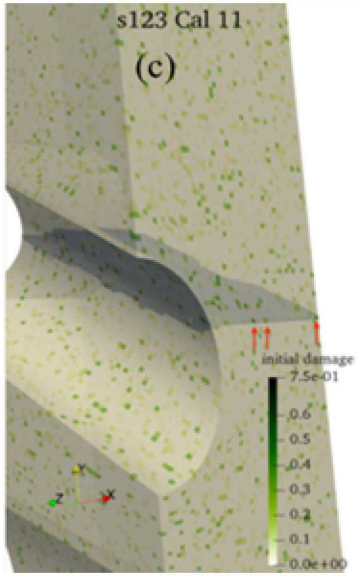
What is a disqualifying flaw?

Flaws in AM Components

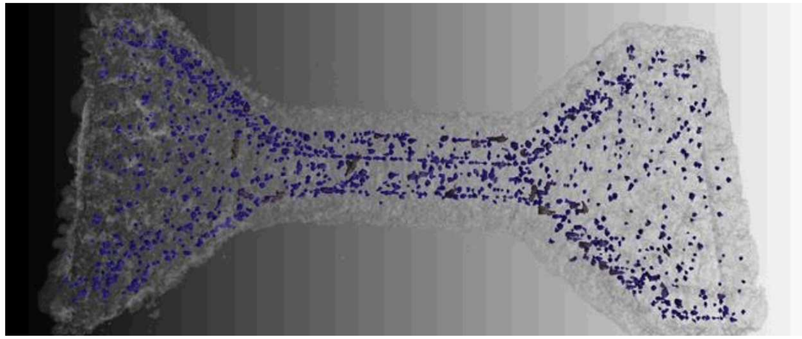
Damage tolerant approach

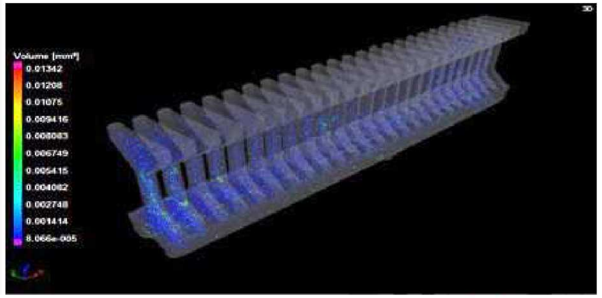
1. **Assume all AM components have flaws**
2. **Which flaws matter?**
3. **Identify flaw types**
   - **Cracks**
   - **Voids**
   - **Bulk porosity**
   - **Microstructure-based flaws**
4. **Print intentional flaws of varying sizes and types**
5. **Predict critical flaw sizes in different regions for 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 porosity





Additive Manufacturing Details

Direct Metal Laser Sintering (DMLS)

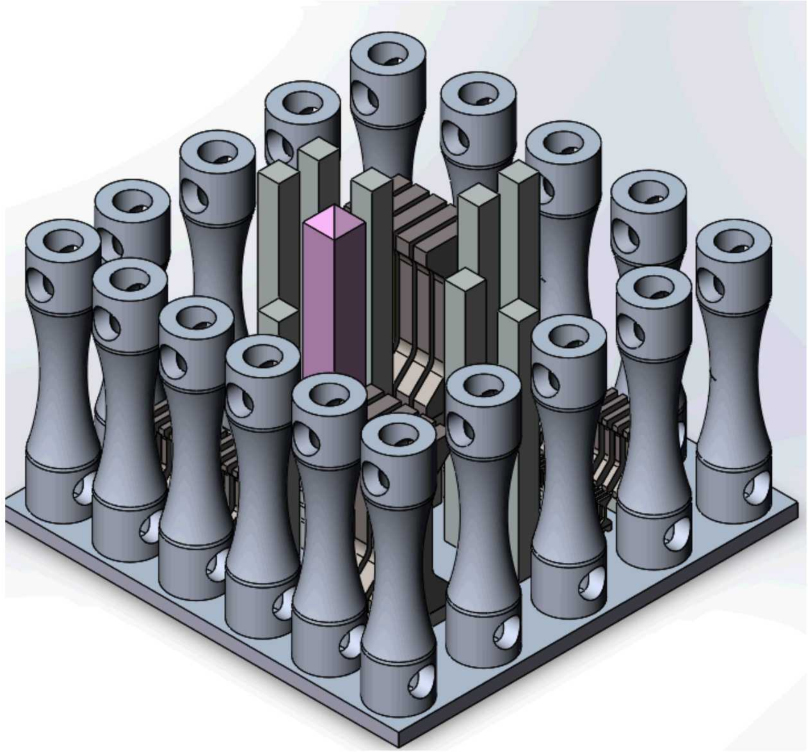
Powder Bed

SS 316L

- Renshaw AM 400
- Nominal power 200 W, hatch 0.011mm

AlSi10Mg

- EOS M290 Solid Laser Melting
- Build Plate A 370 W, 1300 mm/s, hatch 0.019 mm
- Build Plate B 278 W, 1300 mm/s, hatch 0.019 mm
- Build Plate C 185 W, 1300 mm/s, hatch 0.019 mm



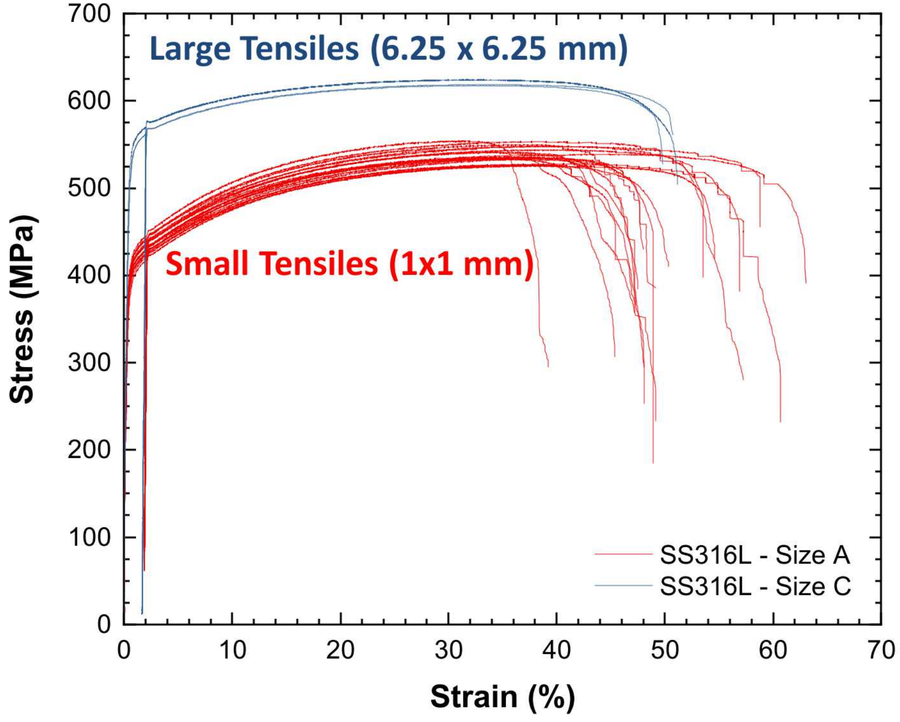
Build Plate Layout

Plate A Plate B Plate C

316 Stainless Steel vs. AlSi10Mg Tensile and Toughness Properties

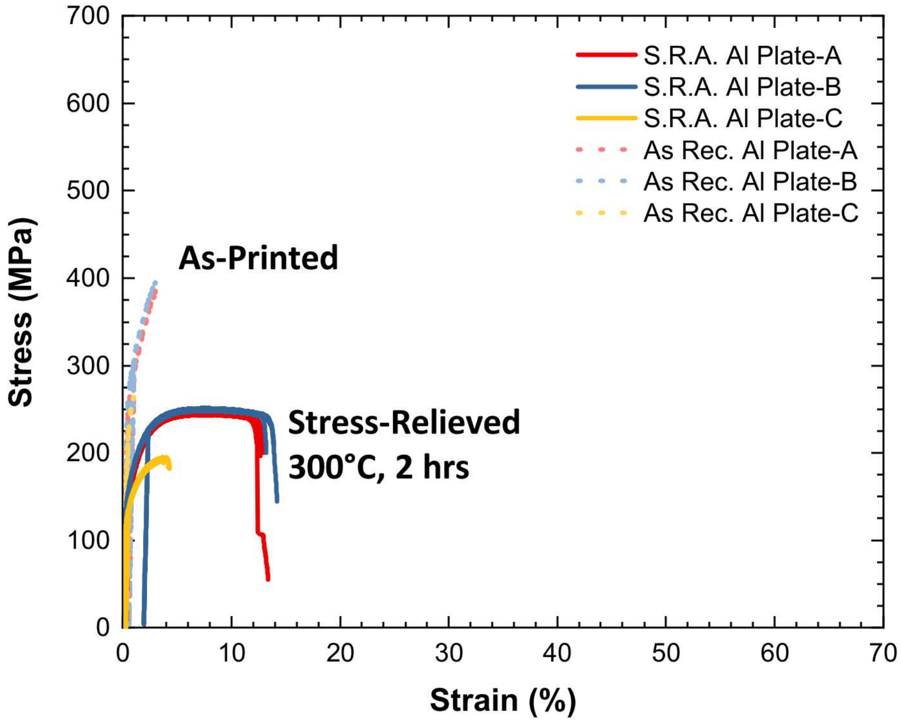
316 Stainless Steel

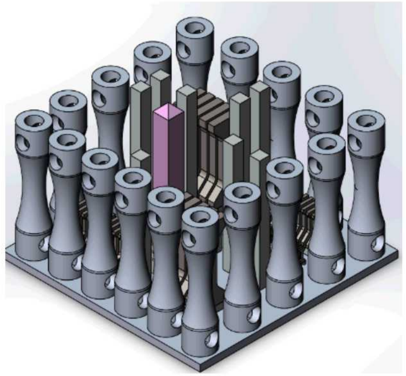
- K ~ 140 MPa√m
- Charpy Impact toughness ~120 ft-lbs
- Ductility = 50–60%

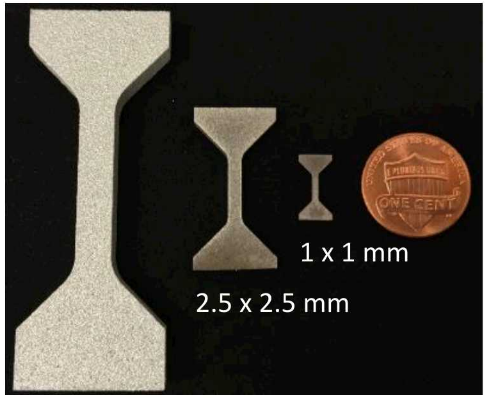


AlSi10Mg

- K ~ 20 MPa√m
- Charpy Impact toughness ~8 ft-lbs
- Ductility = 1–13%



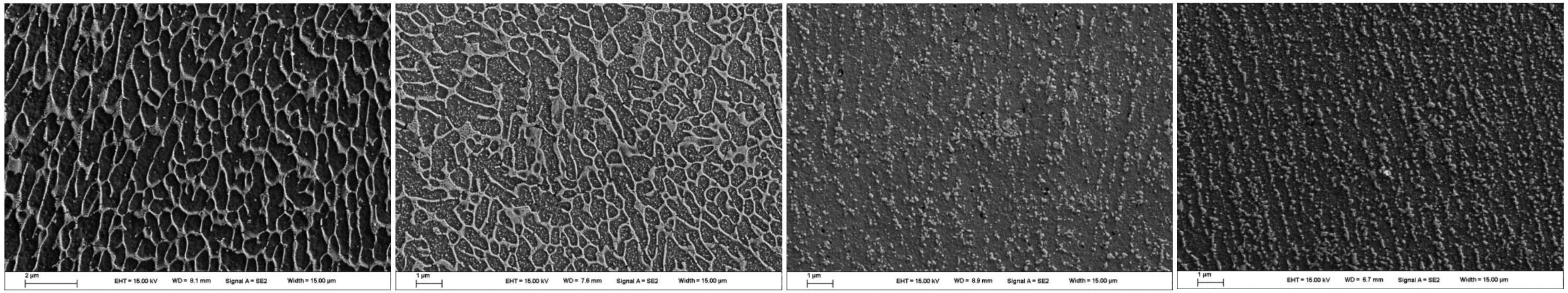




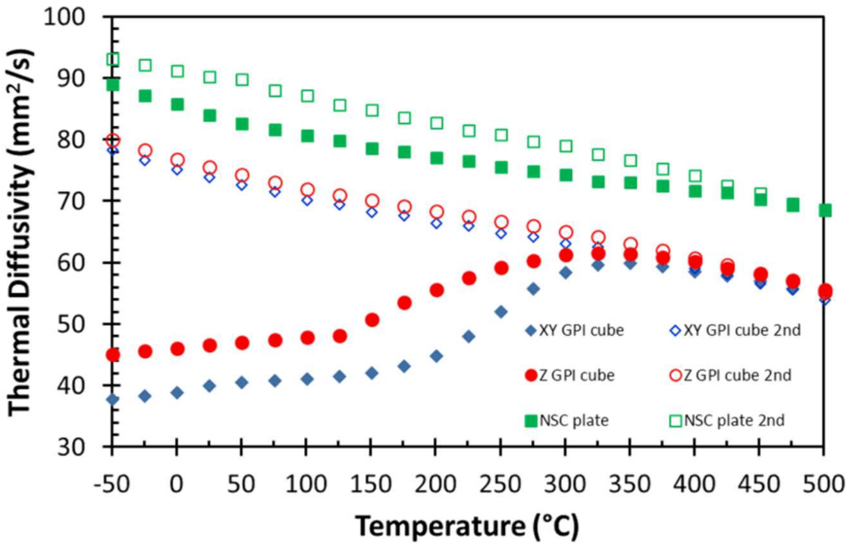
6.25 x 6.25 mm

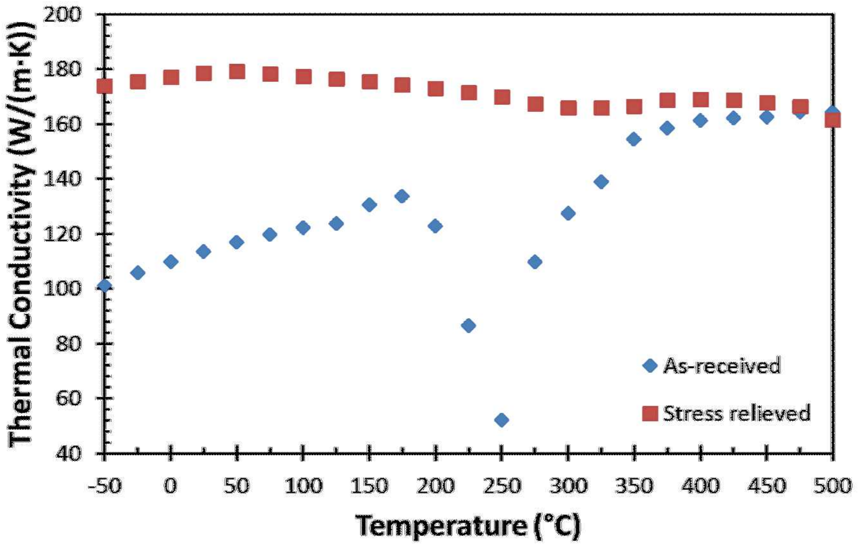
Heat treatment affects Si distribution

As –built | 240°C 15 min. | 282°C 15 min. | 307°C 15 min.



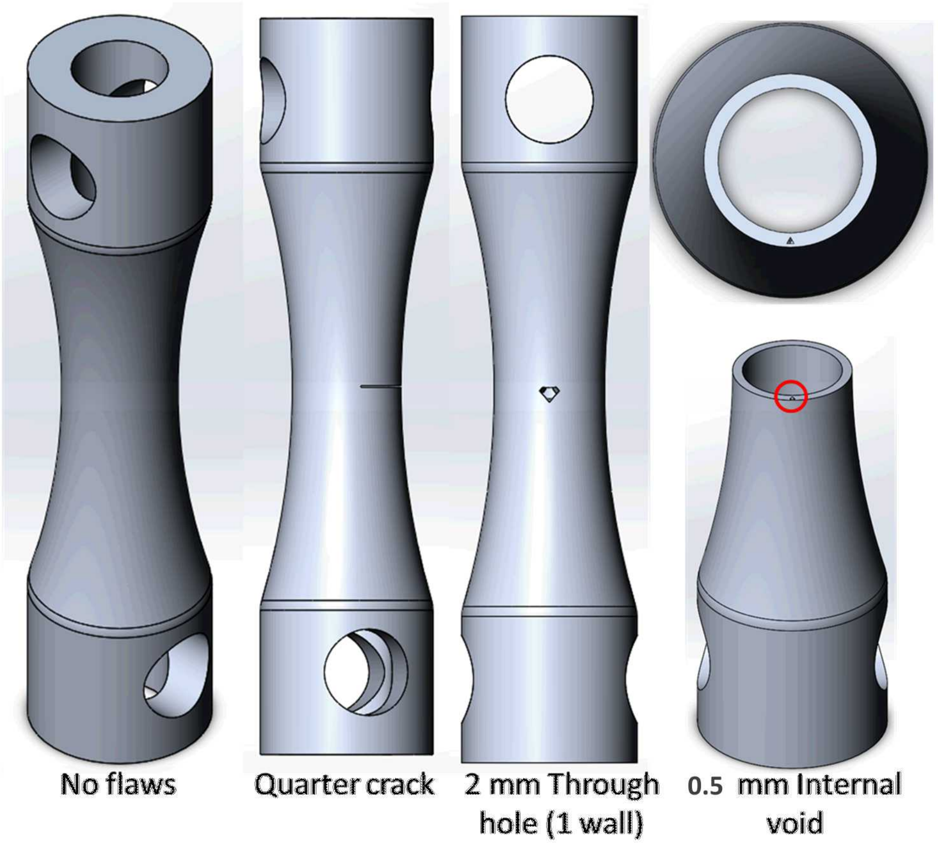
2 µm

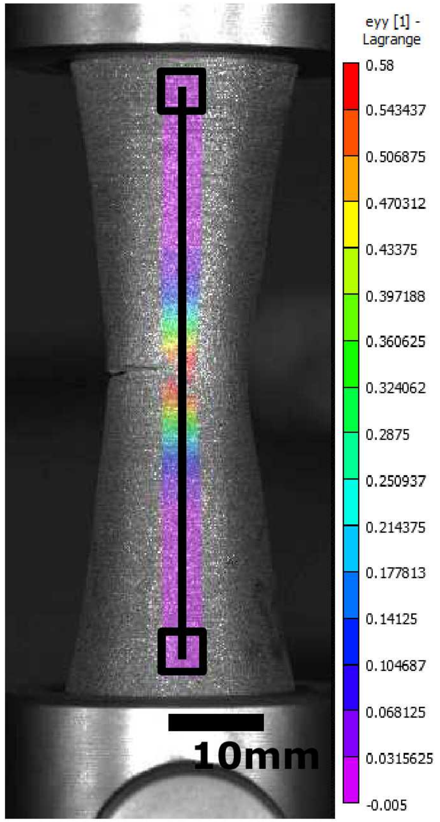


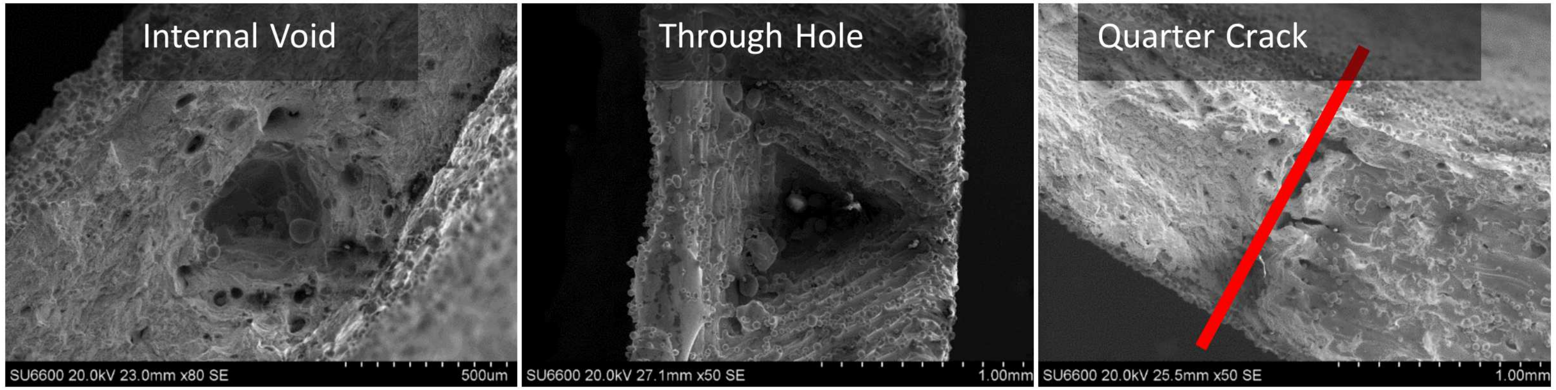


Tubular Components

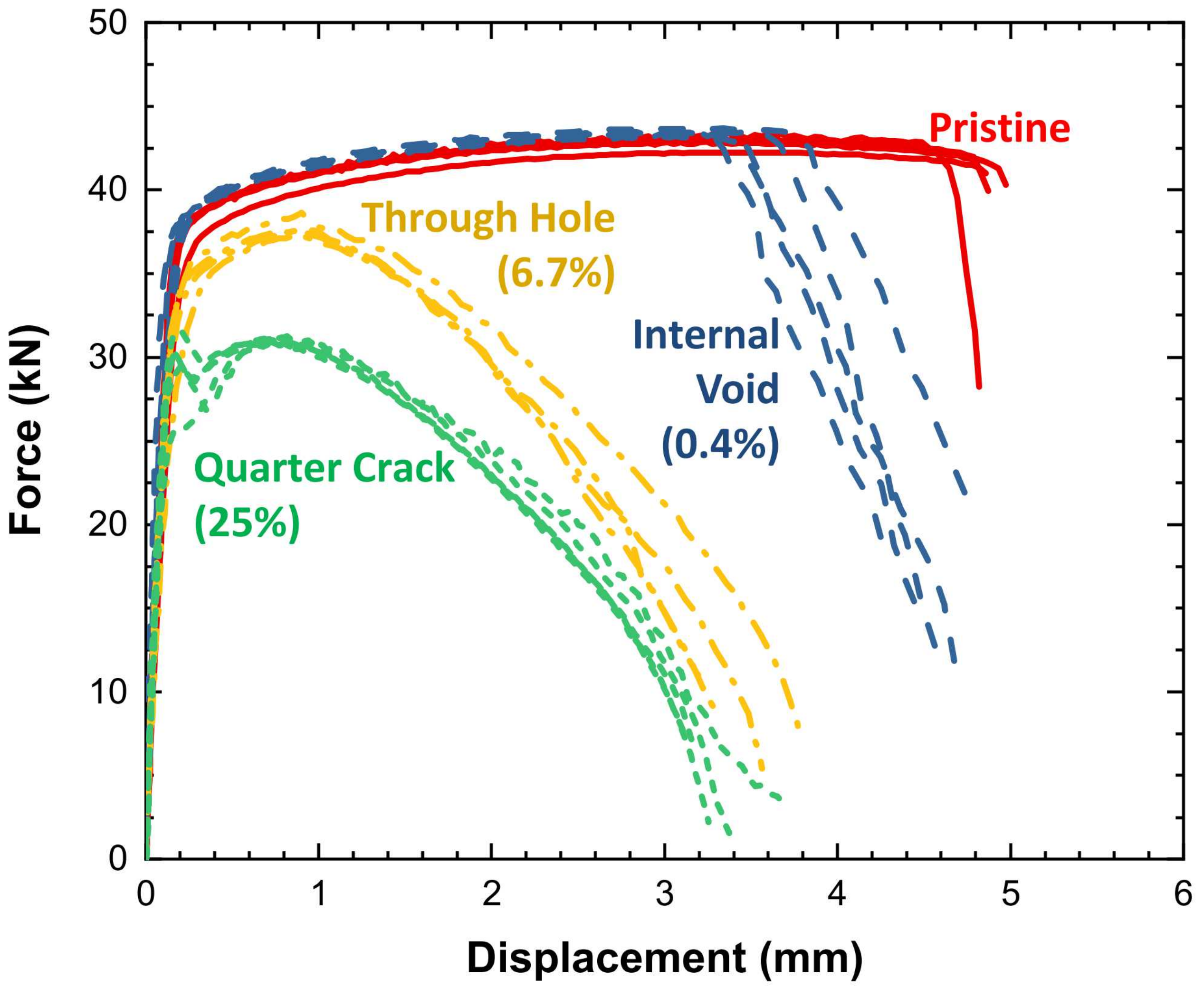
- SS 316L and AlSi10Mg
- "Pristine"
- Manufactured Defects
  - Internal Void
  - Through Hole
  - Quarter Crack
- 2D Digital Image Correlation with real-time DIC extensometers



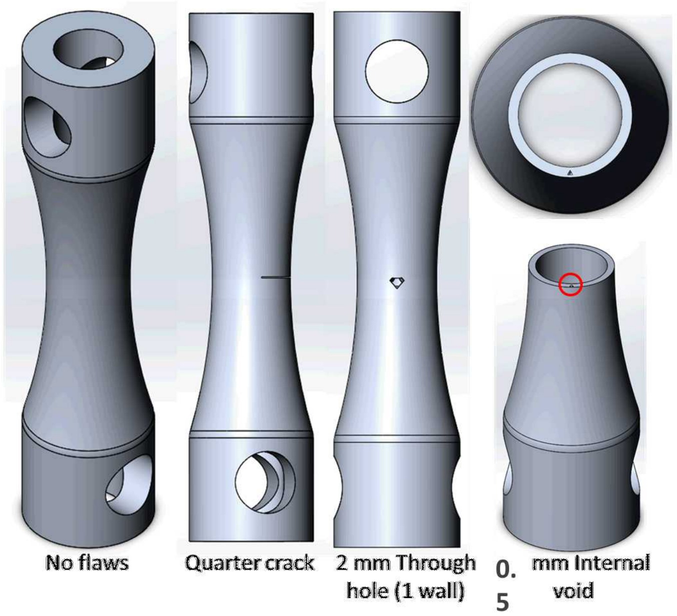




SS 316L Results



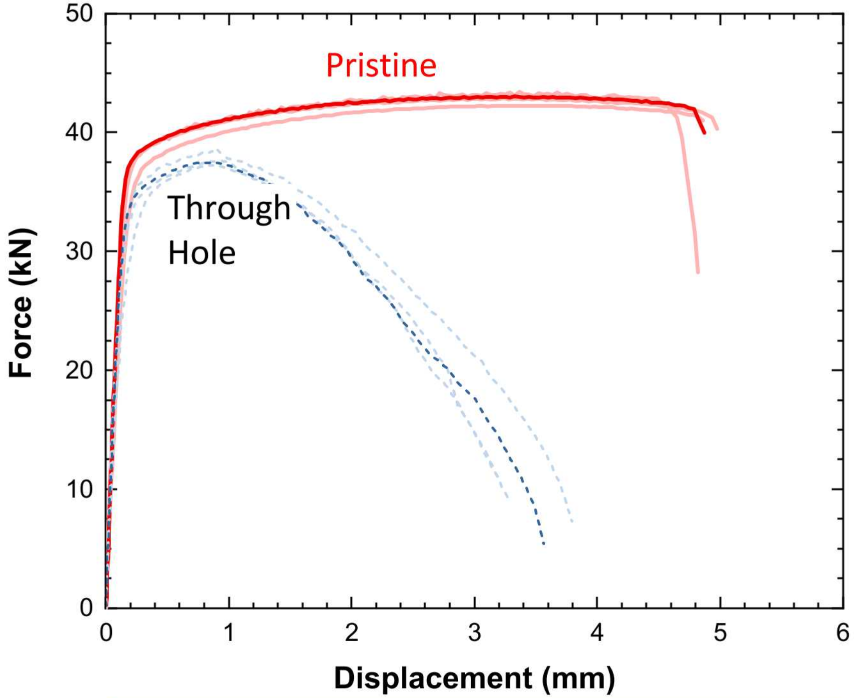
- Pristine samples drop off more sharply
- Internal void has no significant effect
- Through hole reduces strength and ductility
- Quarter crack reduces strength by ~25%
  - Crack pop-in events



Flaws impact AlSi10Mg more than 316L Stainless Steel

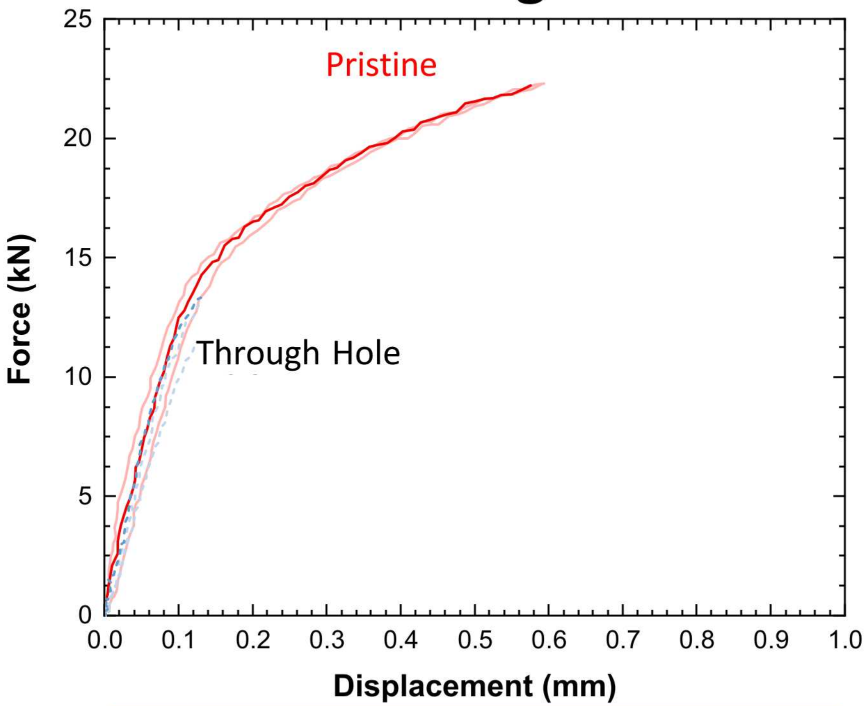
Through hole is ~6.7% of cross section

316 Stainless Steel



Hole reduces strength by 10% and ductility by 20%

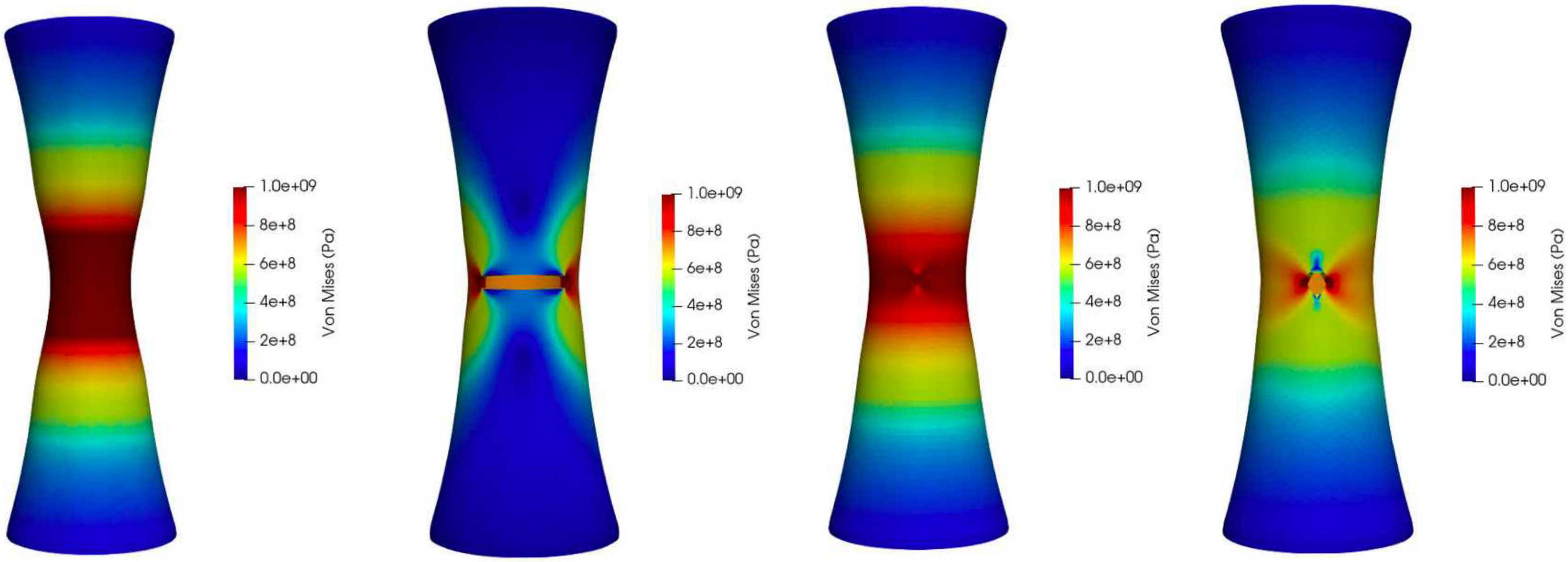
AlSi10Mg



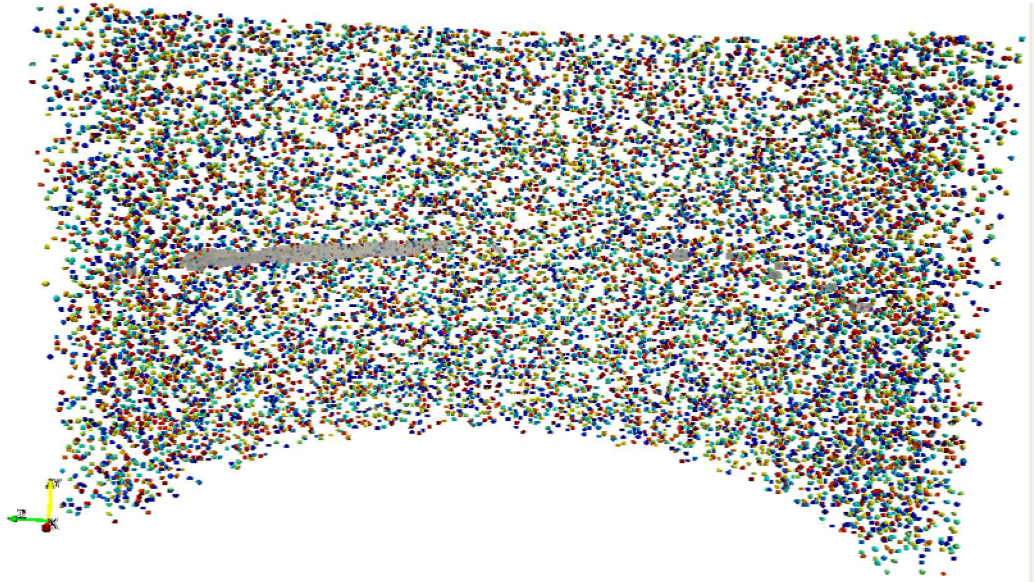
Hole reduces strength by 40% and ductility by 65%

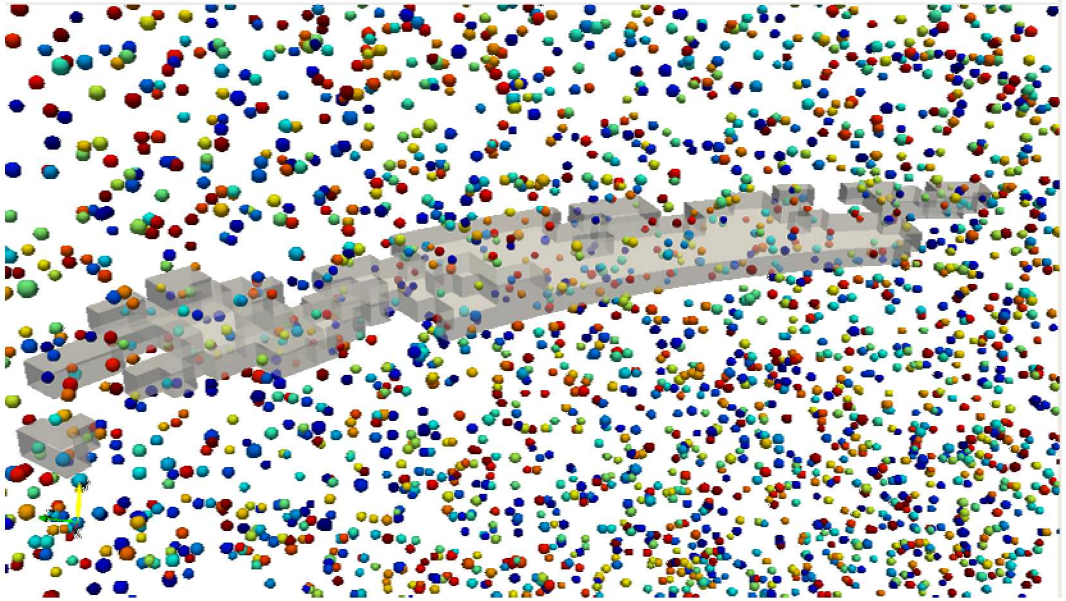
2 mm Through-hole
Corner Cube Void

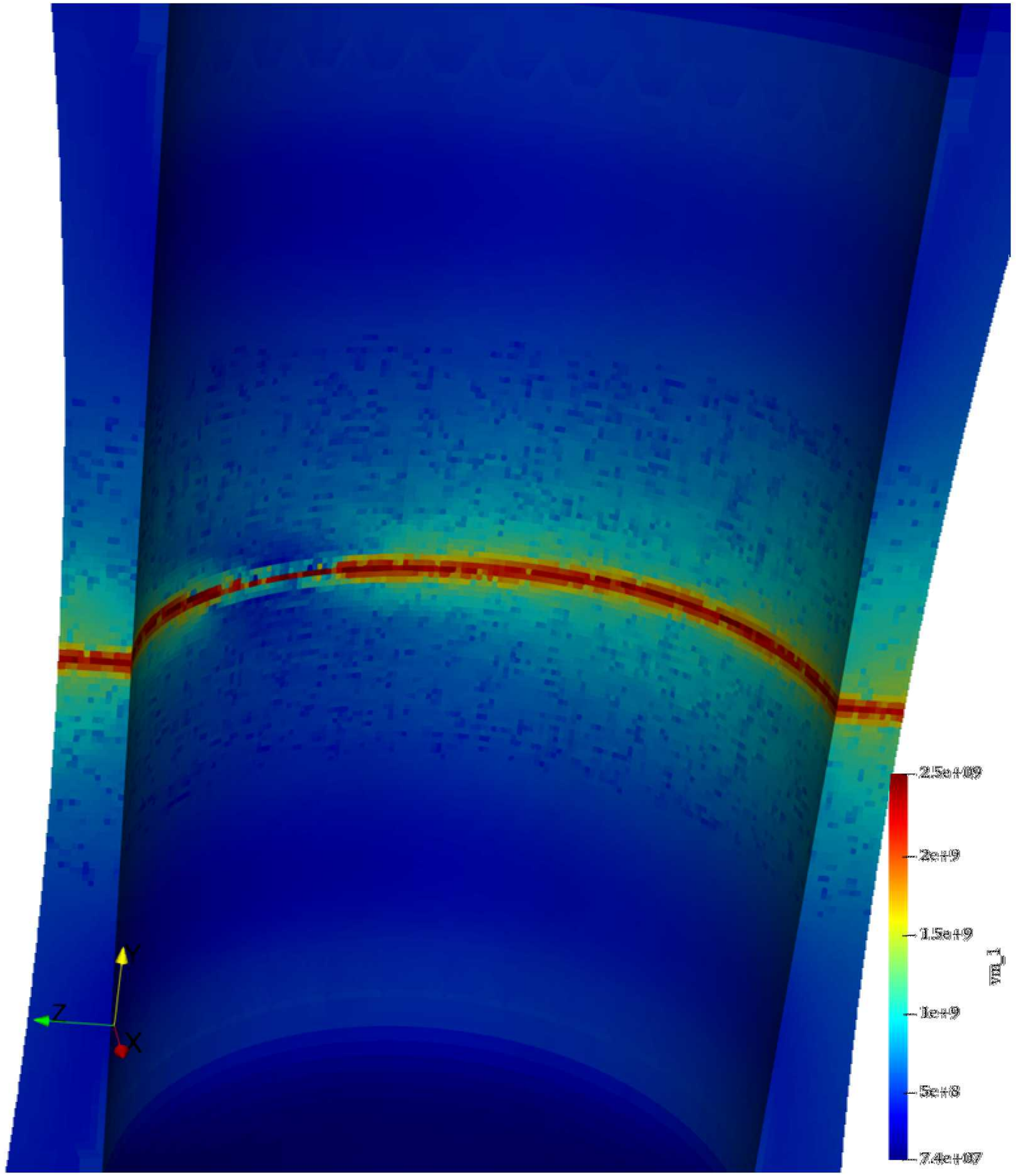
Low fidelity model indicates different hotspots for each type of geometric flaw.



Pore Distributions on Low Fidelity Tube Mesh Lead to Crack Initiation







Predicting Failure in AM Components

Fracture Surface Correlation

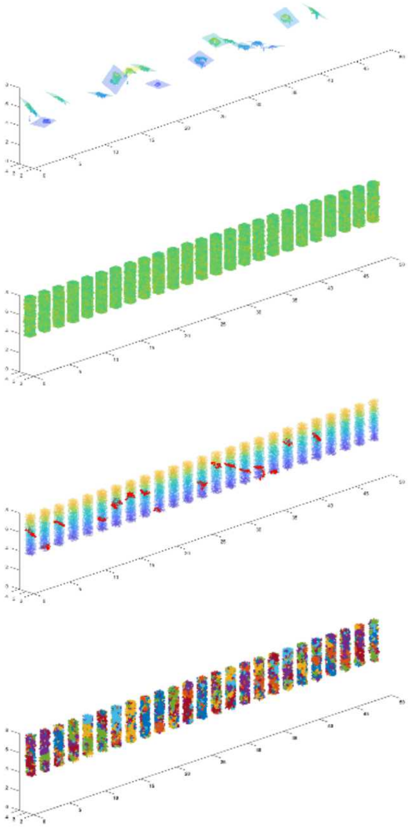
Measured

Fracture Surfaces (optical scans)

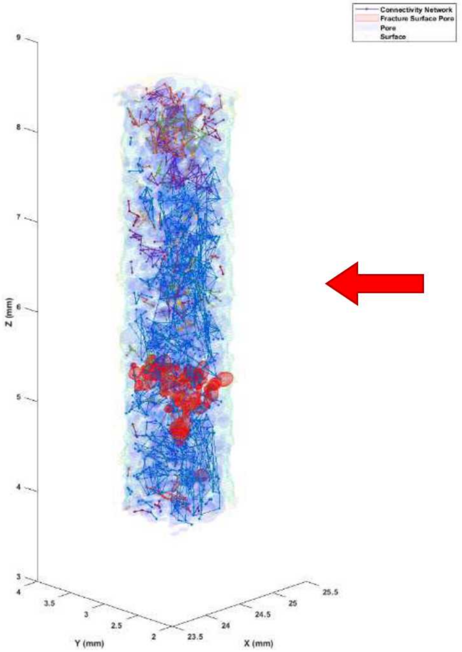
Surface Features (CT)

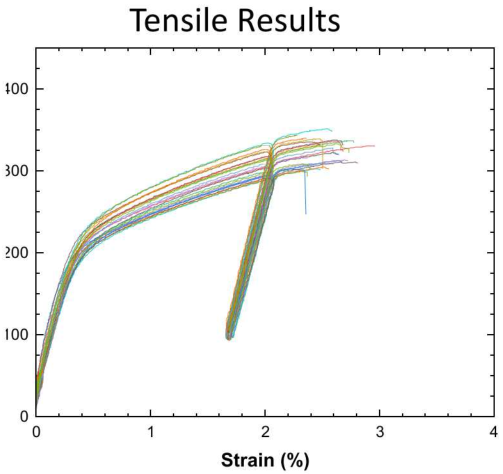
Internal Pores (CT)

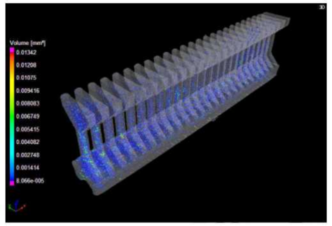
Pore Connectivity (Analysis)

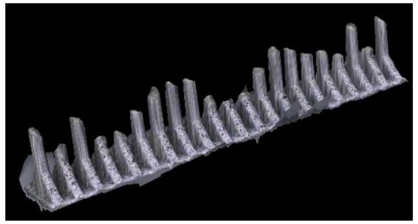


Predict fracture location and properties



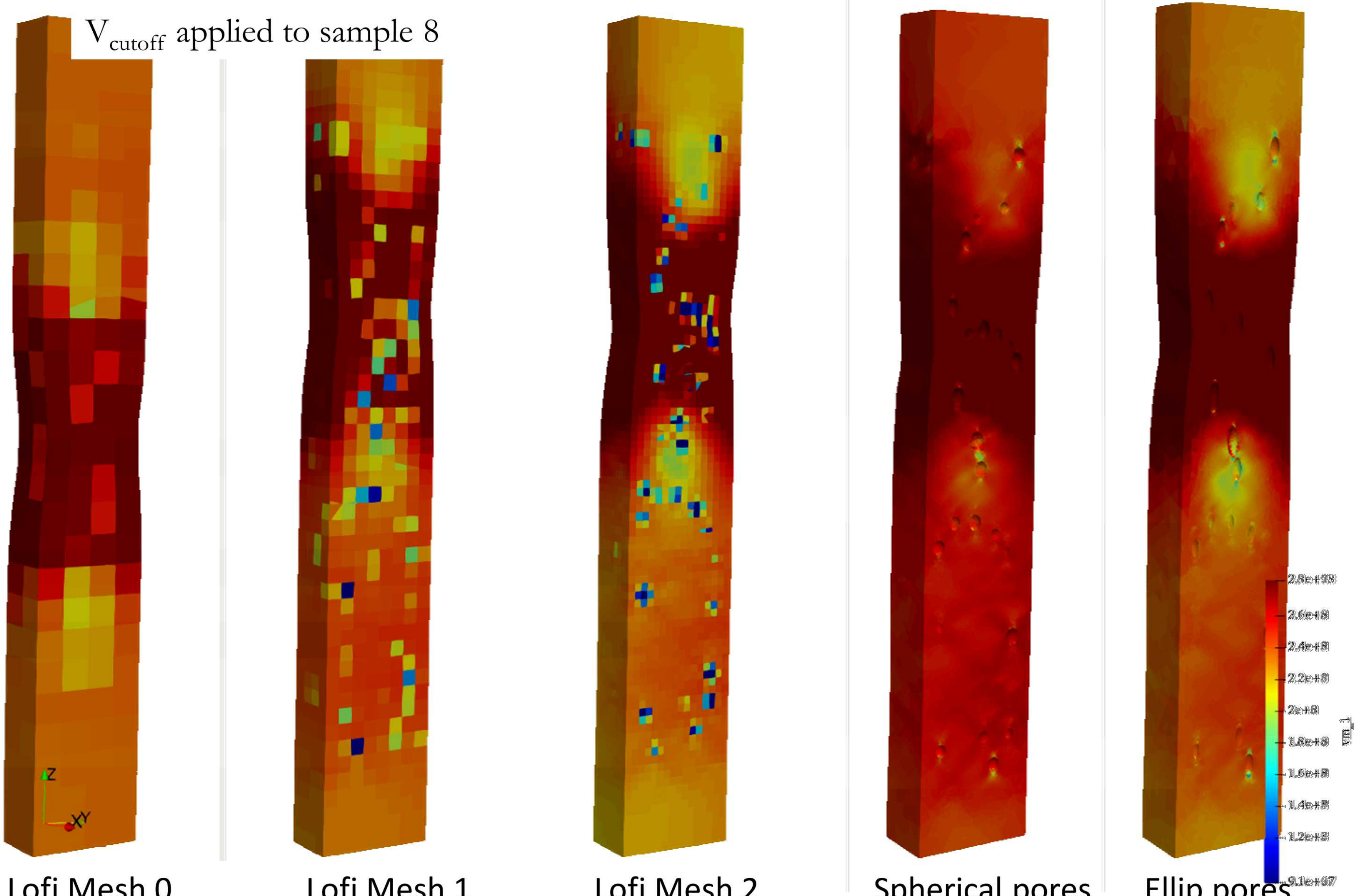






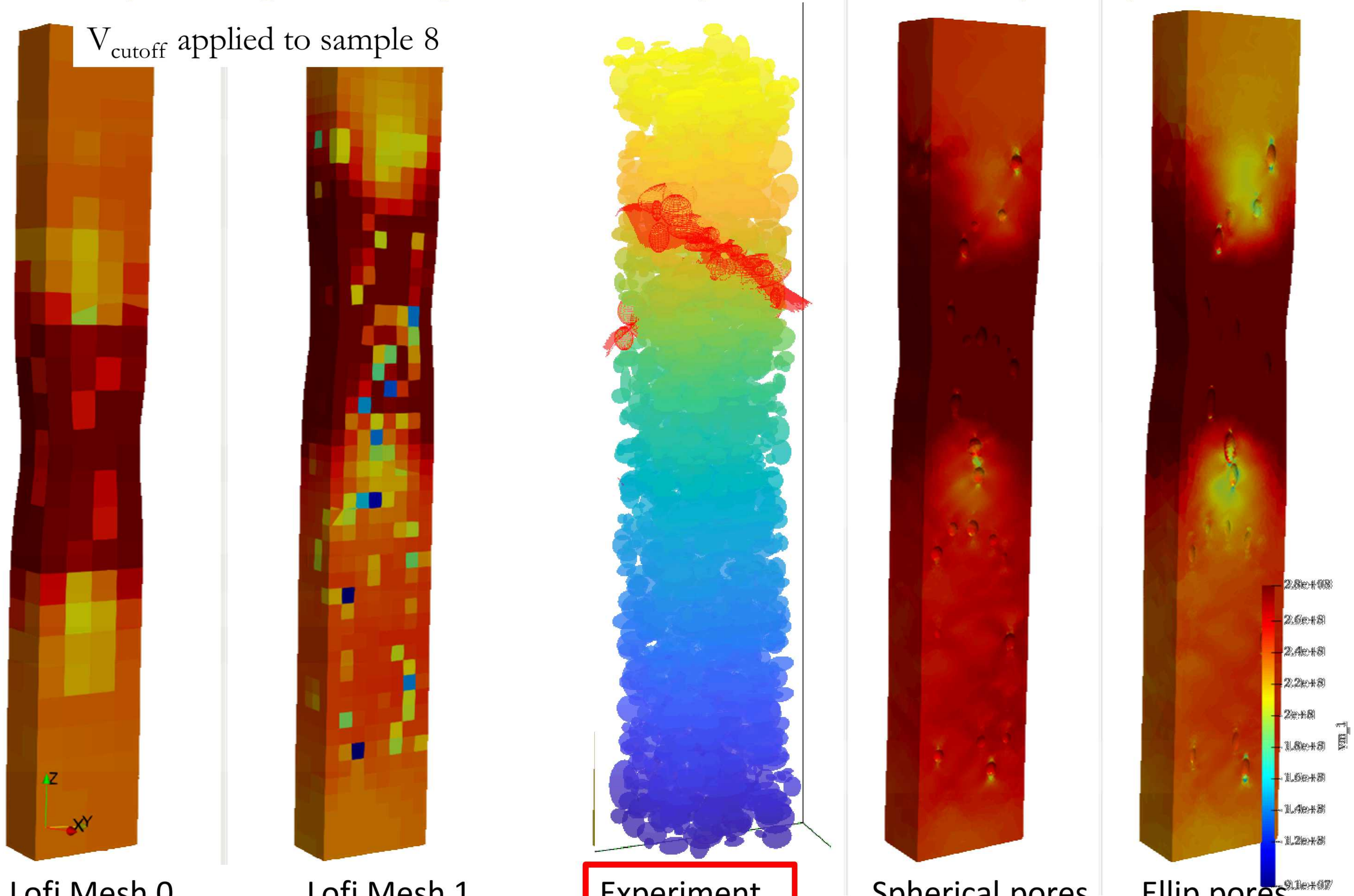
- Tested/couple data for 85 A-size tensile bars.
- Can we predict fracture location?
- Can we predict ductility, strength, etc?

Low Fidelity vs. High Fidelity Predictions (x-section at midplane)



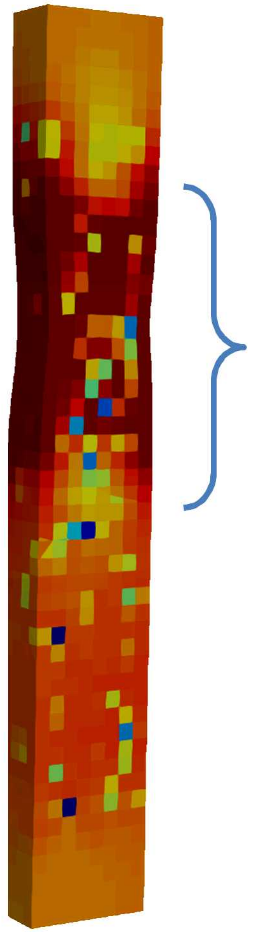
Lofi Mesh 0 | Lofi Mesh 1 | Lofi Mesh 2 | Spherical pores | Ellip pores

Low Fidelity vs. High Fidelity Predictions (x-section at midplane)

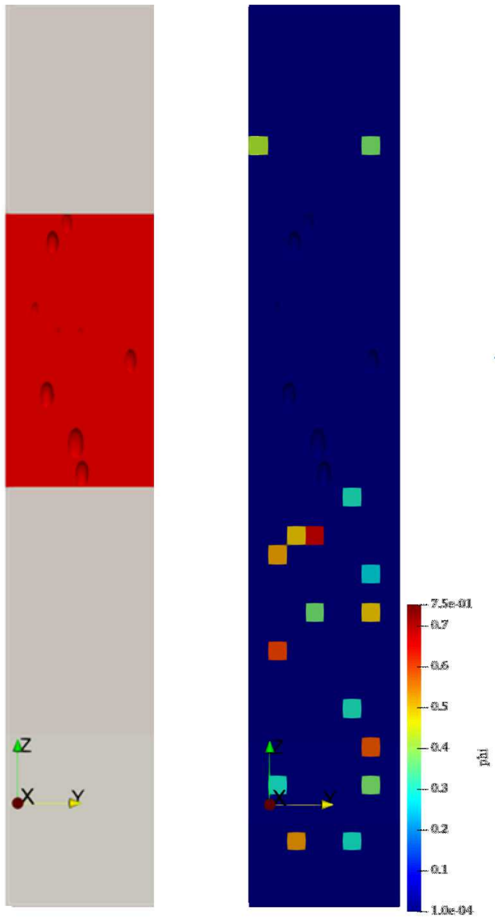


Lofi Mesh 0 | Lofi Mesh 1 | Experiment | Spherical pores | Ellip pores

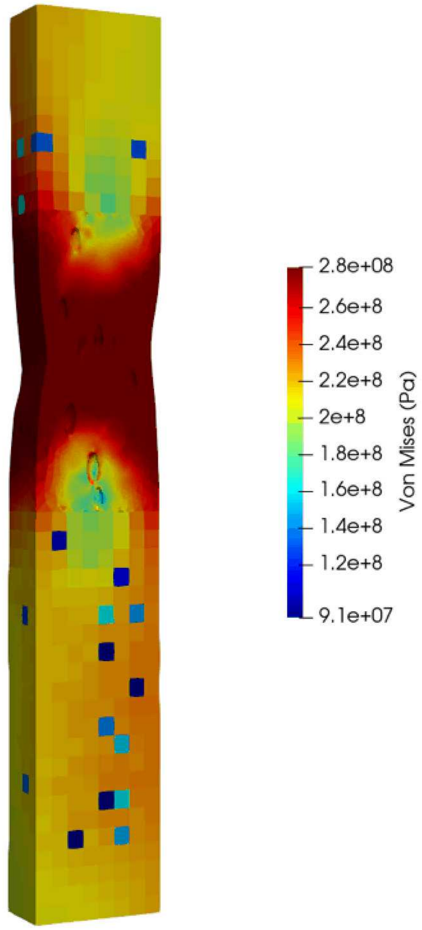
Multiscale Model: High Fidelity Mesh in Hotspot Concurrently Coupled With Surrounding Low Fidelity Mesh



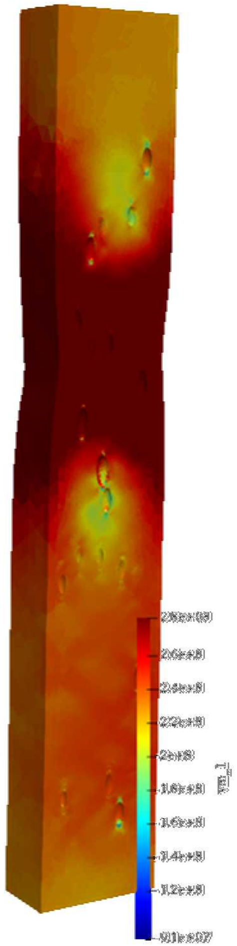
Focusing on the neck as predicted from Lofi Mesh 1



Coupled Lofi/Hifi Mesh via Multi-Point Constraints



Coupled Response with Higher Accuracy in Hotspot
~520k elements, 100 cpus



High Fidelity Results
1.5M elements, 360 cpus

Defects can combine or compete with one another to cause failure

Plate A
Defect driven

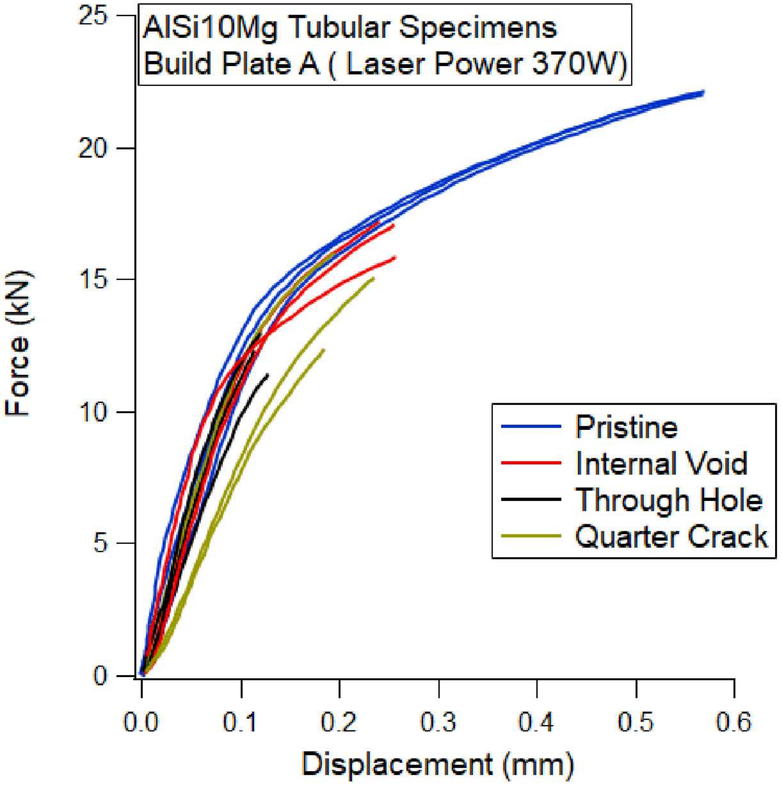


Plate B
Defect driven

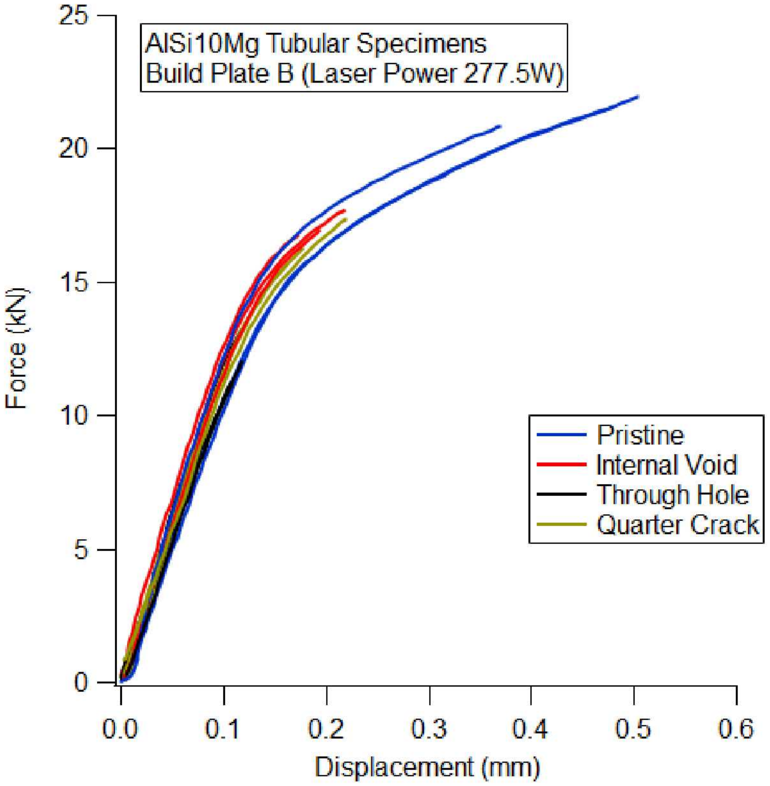
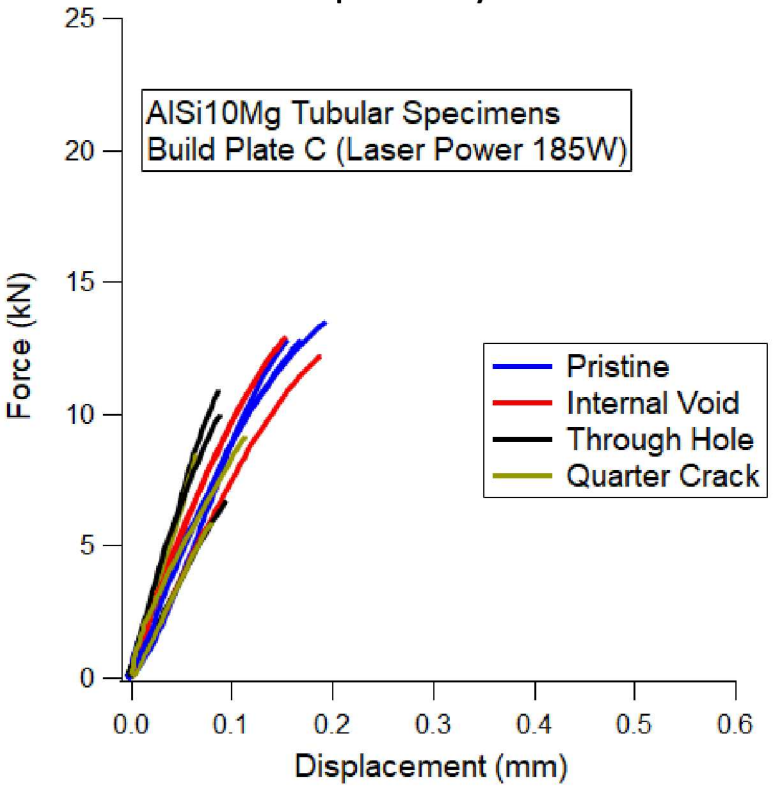


Plate C
Bulk porosity driven



- **Brittle fracture is seen in all AlSi10Mg tubular specimens (no post-peak ductility).**
- **Quarter crack was printed and may not be fully separated.**
- **In plate C, the bulk porosity outweighs large discrete flaws.**

Plate A

Plate B

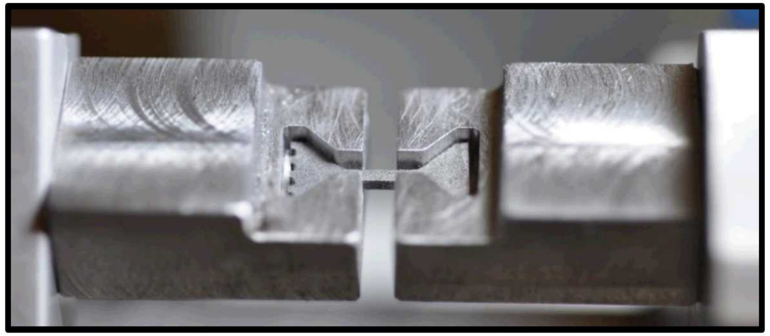
Plate C

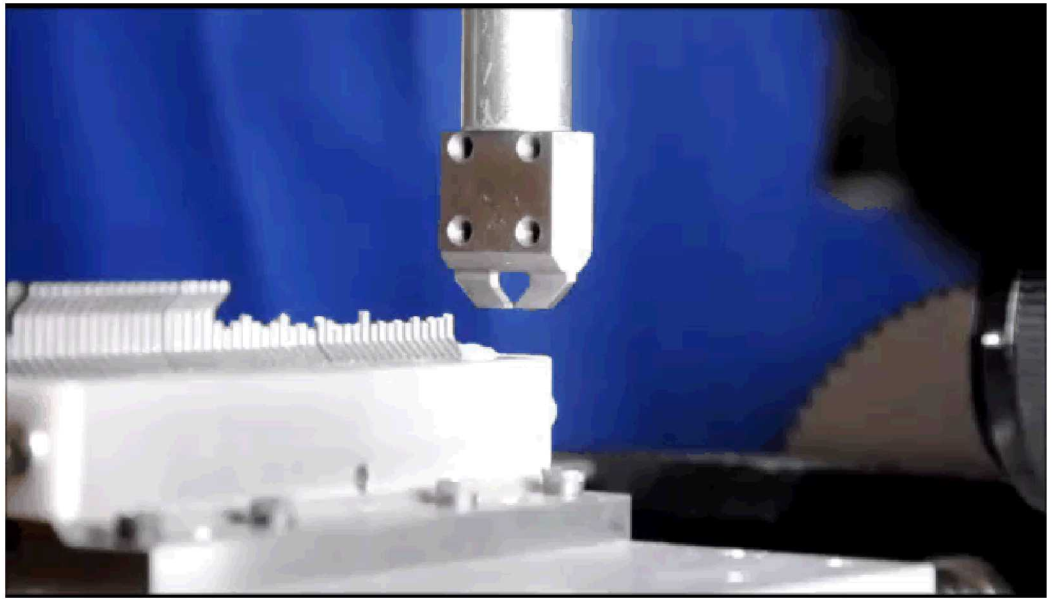
Bulk Porosity Defects

Multiple Defects Acting Together

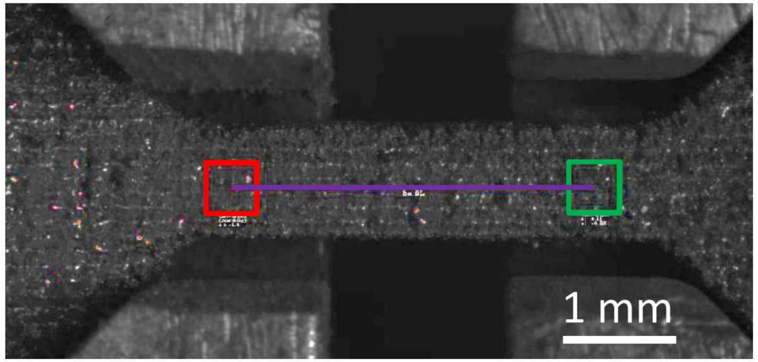
High throughput tensile testing, ~200 samples per day, gives statistical distributions of structural properties.

1. Self-aligning 'drop-in' grips

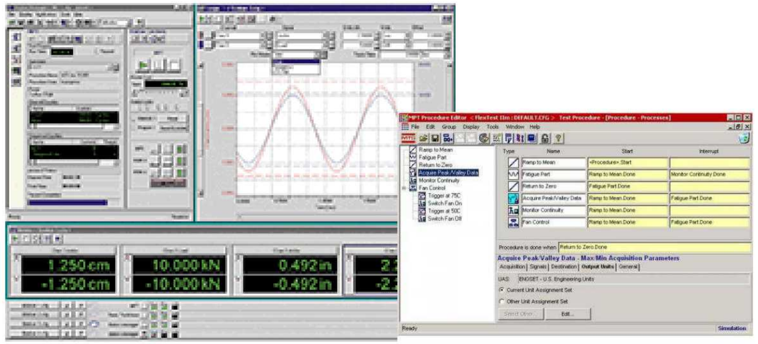


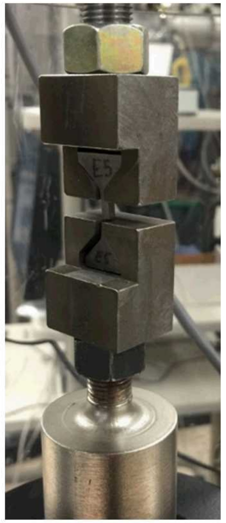


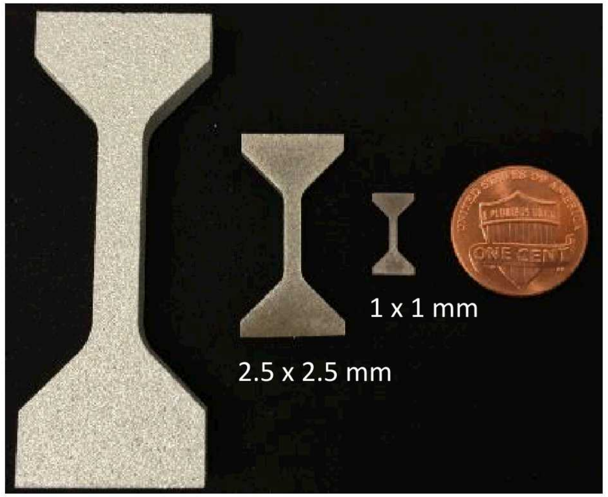
2. Non-contact virtual extensometer with "live" digital image correlation



3. Maximize software automation to reduce operator burden





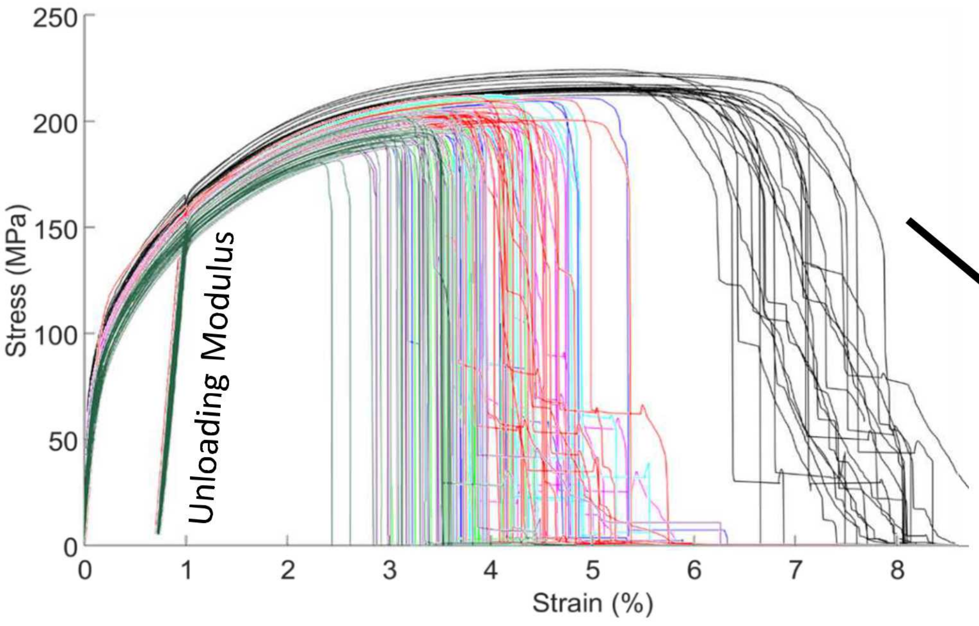


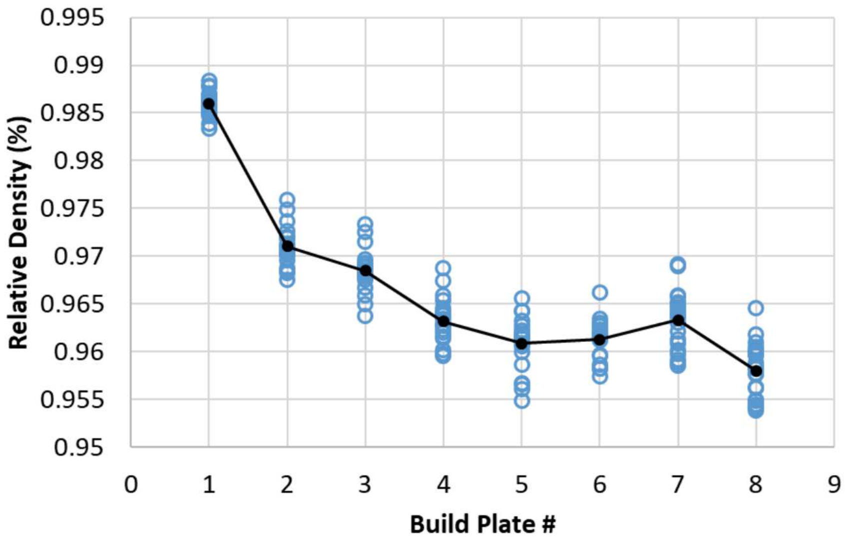
6.25 x 6.25 mm

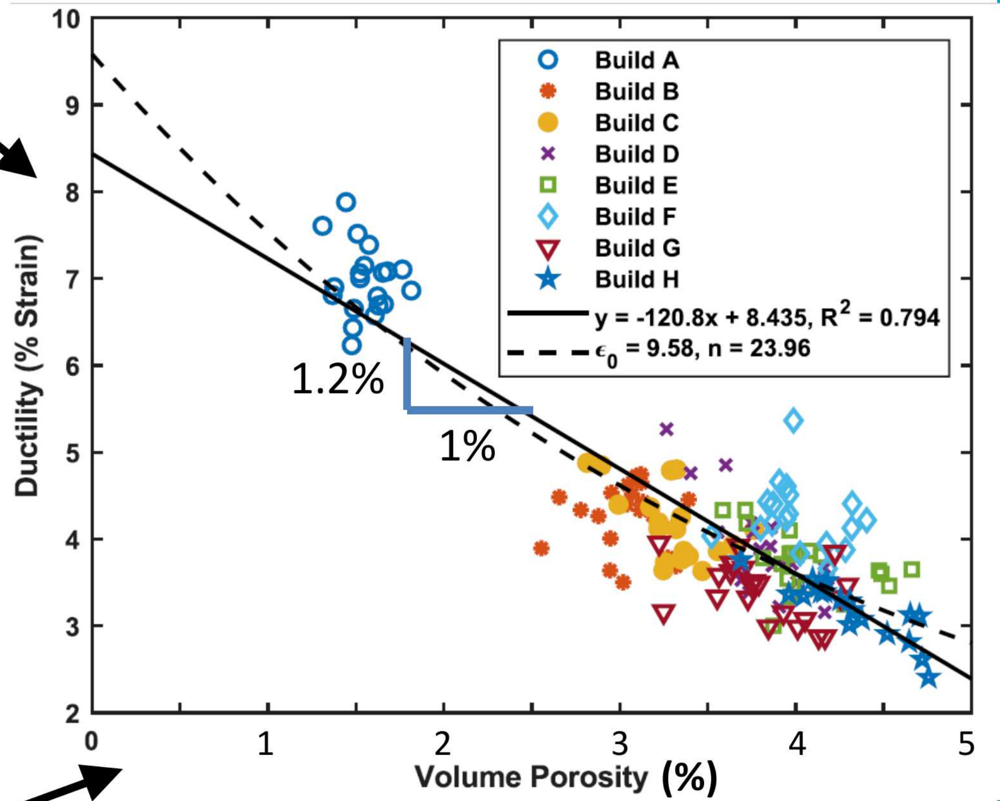
B. Salzbrenner et al., *J Mater. Process. Tech.*, 2017

Printed AlSi10Mg with different levels of porosity. Compare density to tensile properties for each build plate.

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

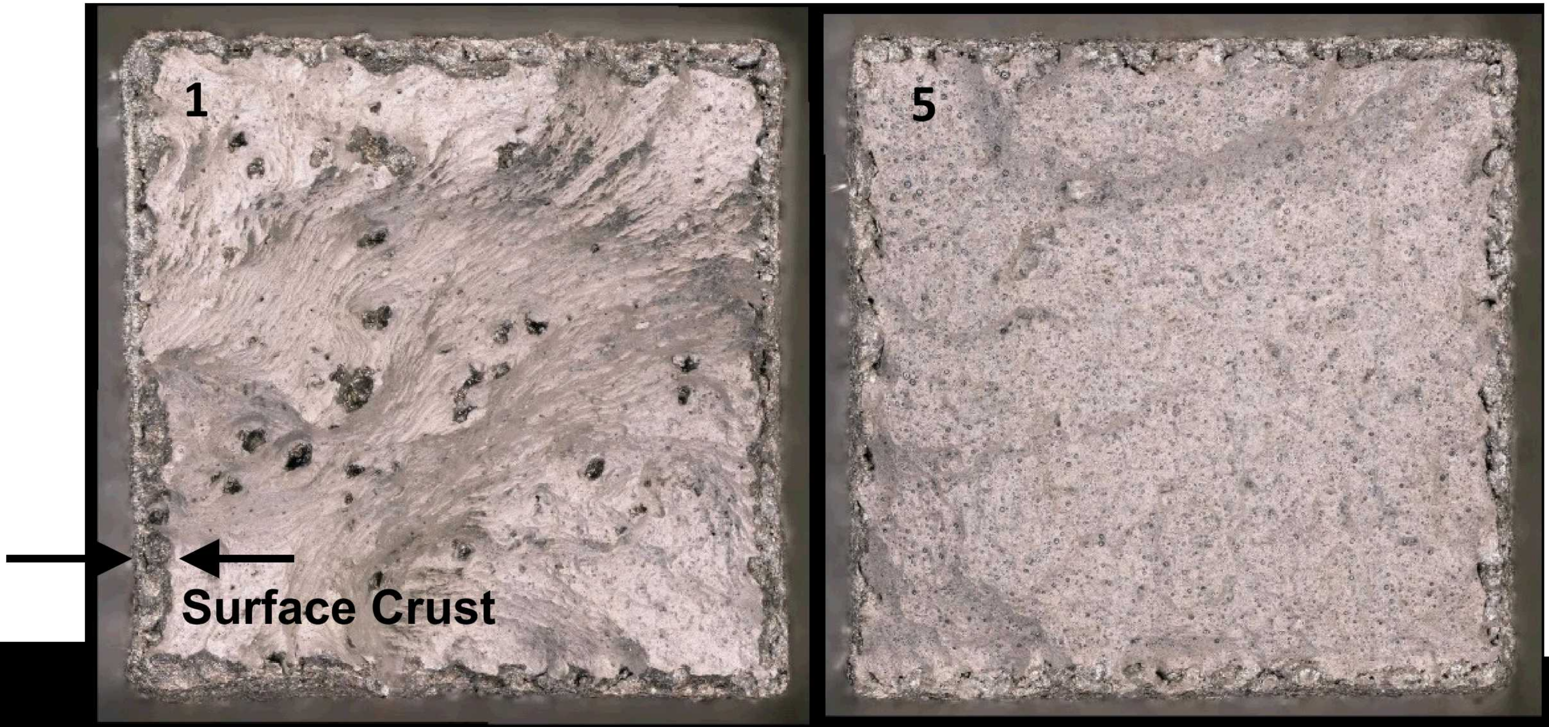


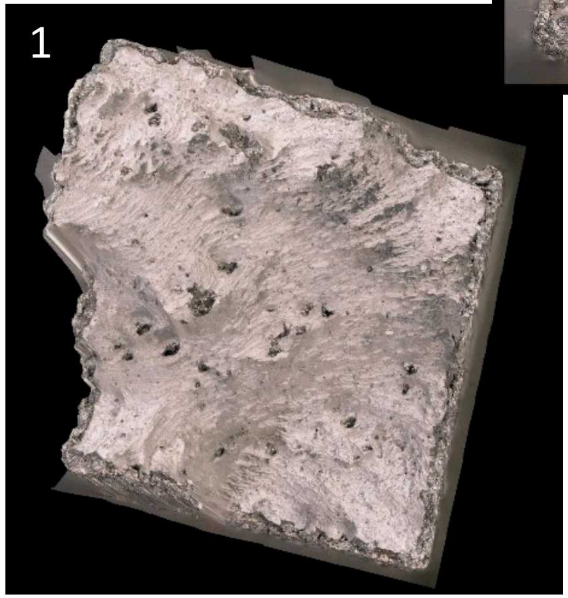


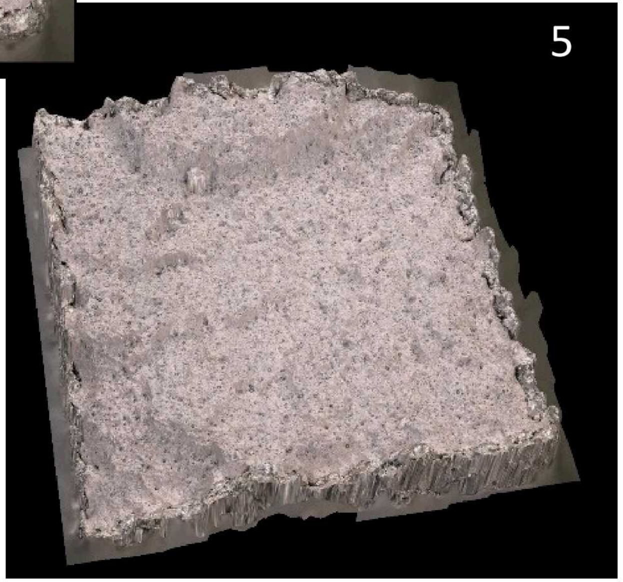


How does bulk density compare to the fracture location?

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

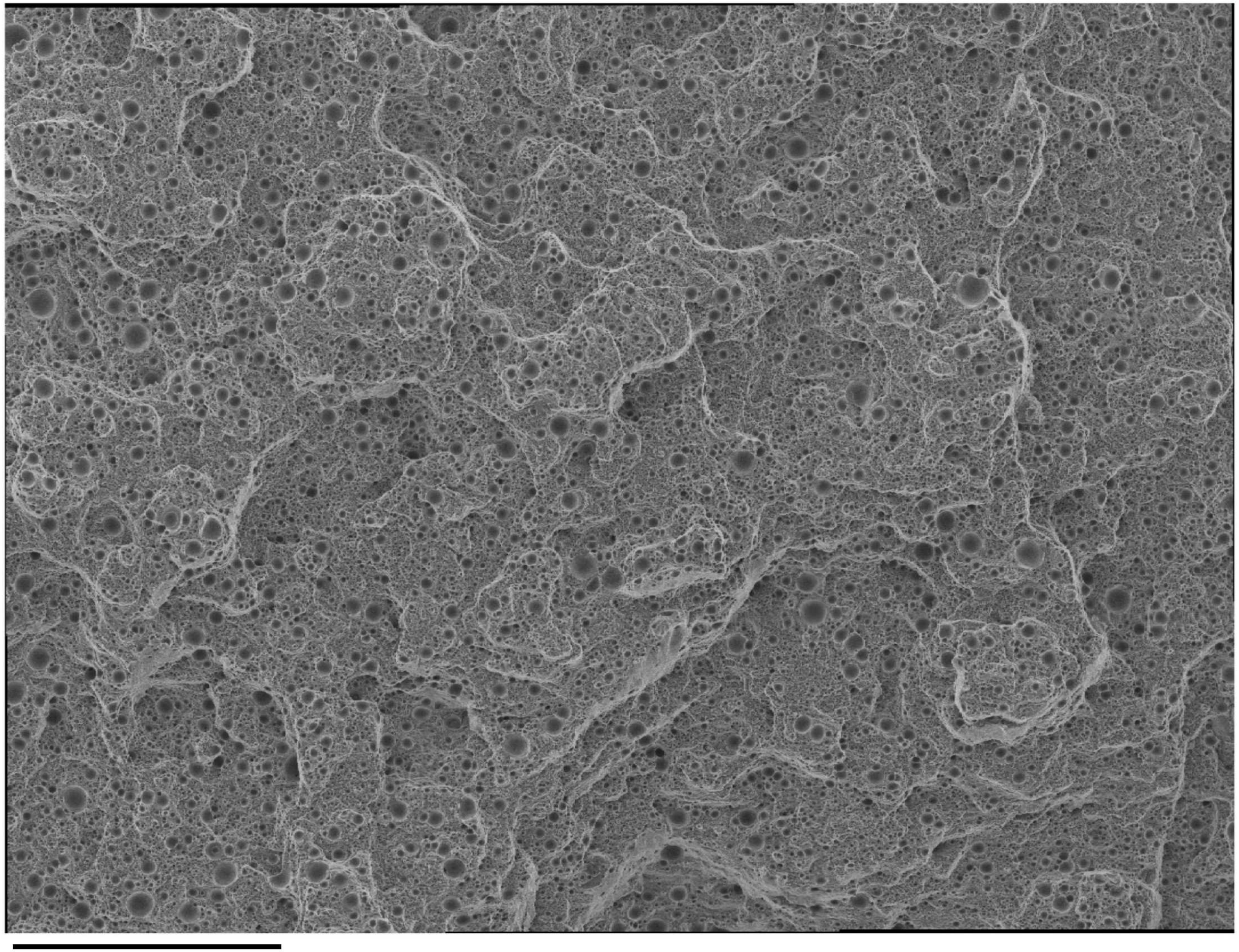






Lack-of-fusion voids

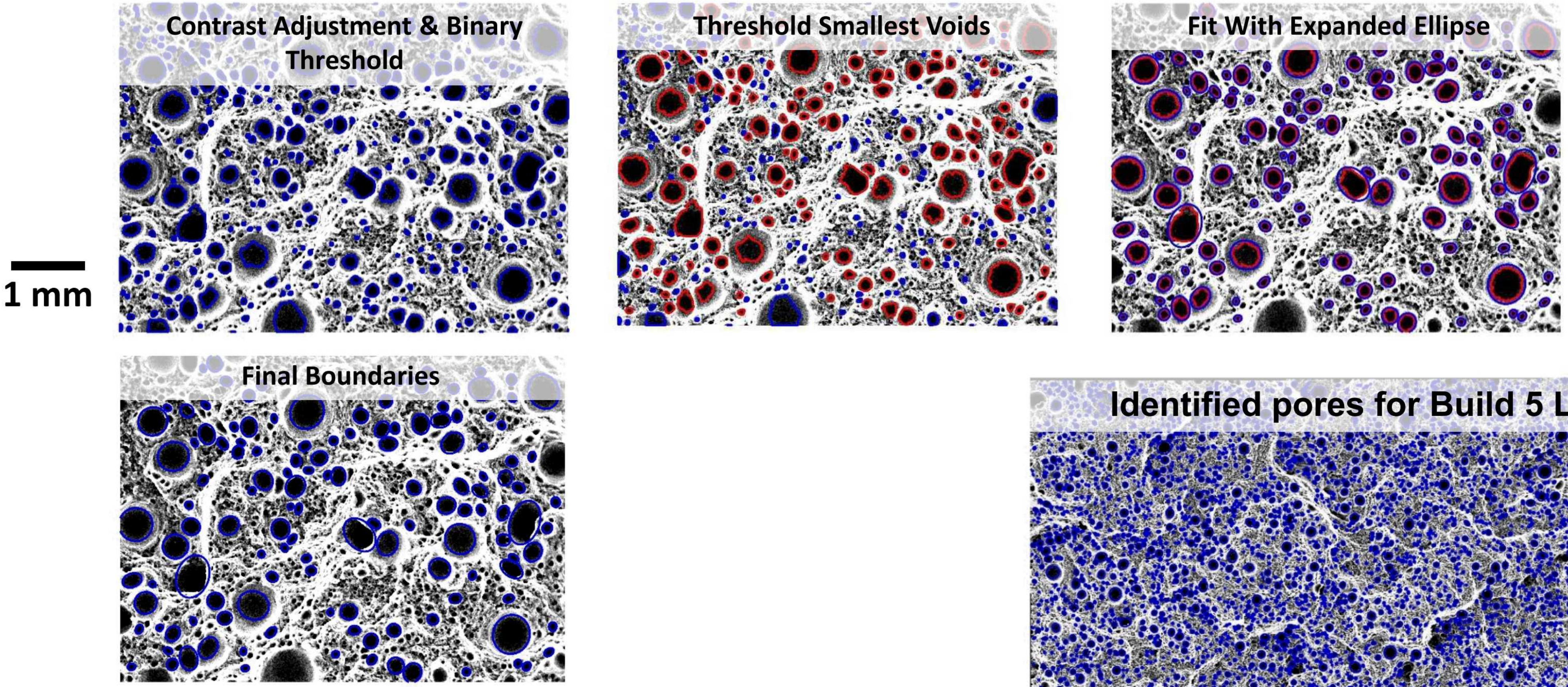
High throughput fracture surface imaging

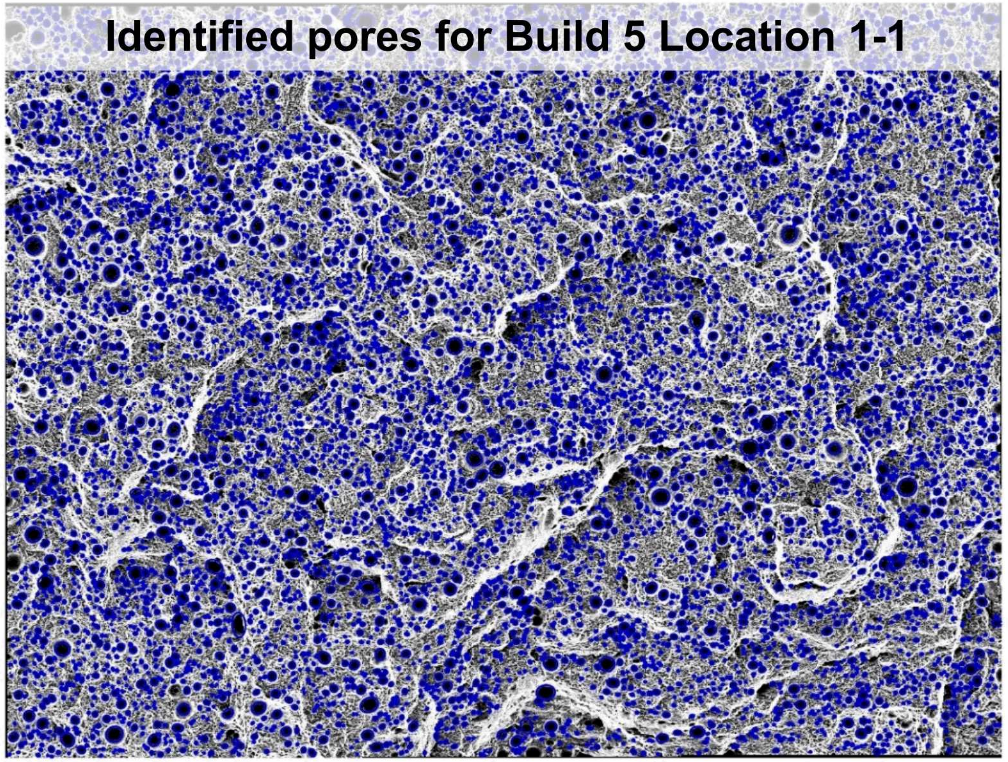


0.5 mm

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

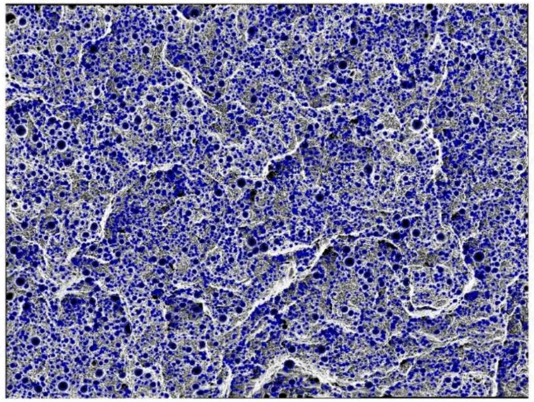
Void identification algorithm to measure porosity on fracture surfaces

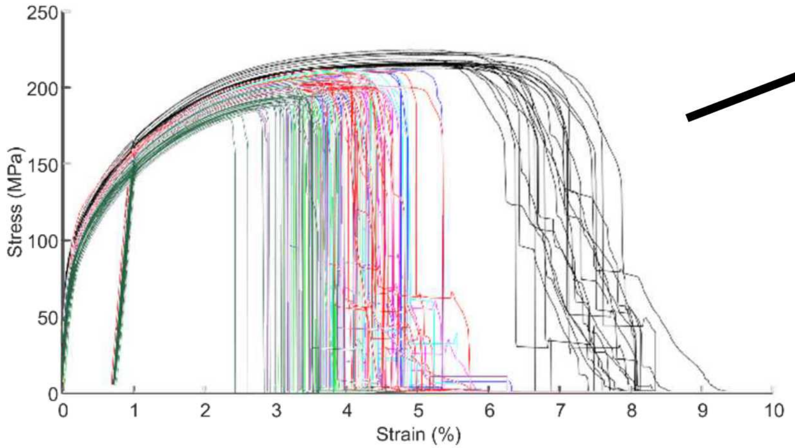


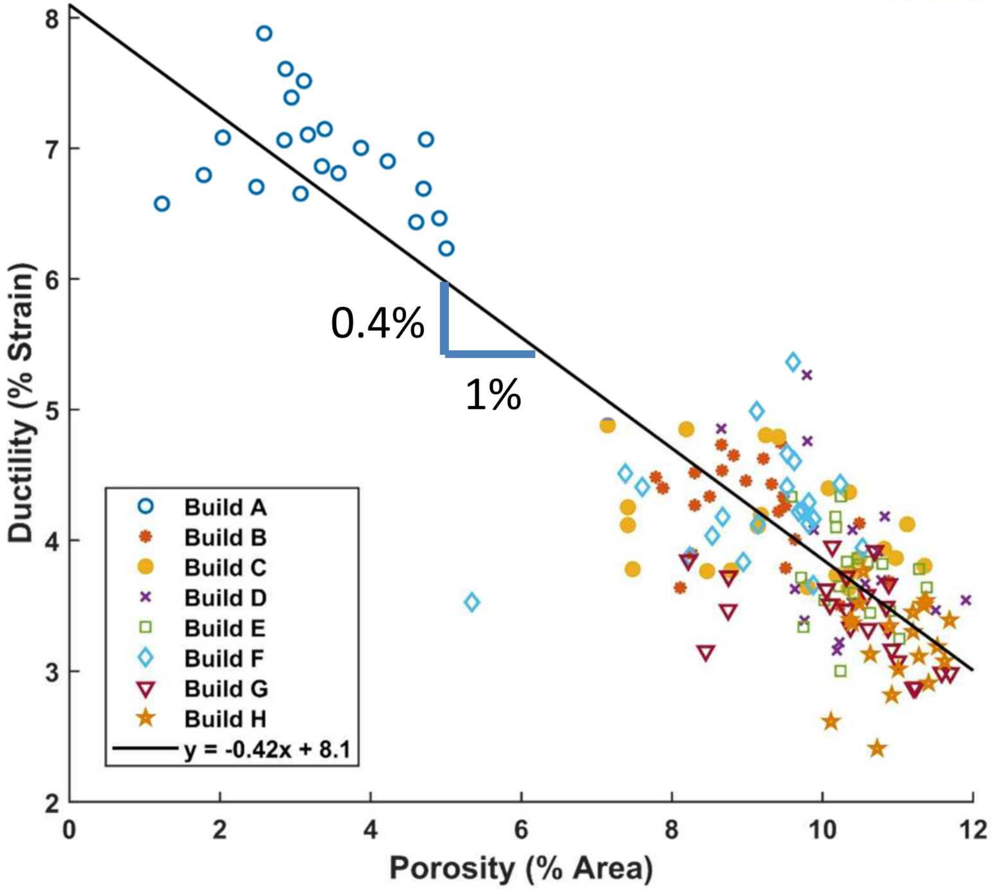


- Identify voids on a fracture surface from high throughput SEM images.
- Multistep process does more than simple thresholding.
- Algorithm allowed ~172 fracture surfaces to be analyzed—about 10x more than was possible before.

Compare ductility to fracture surface porosity

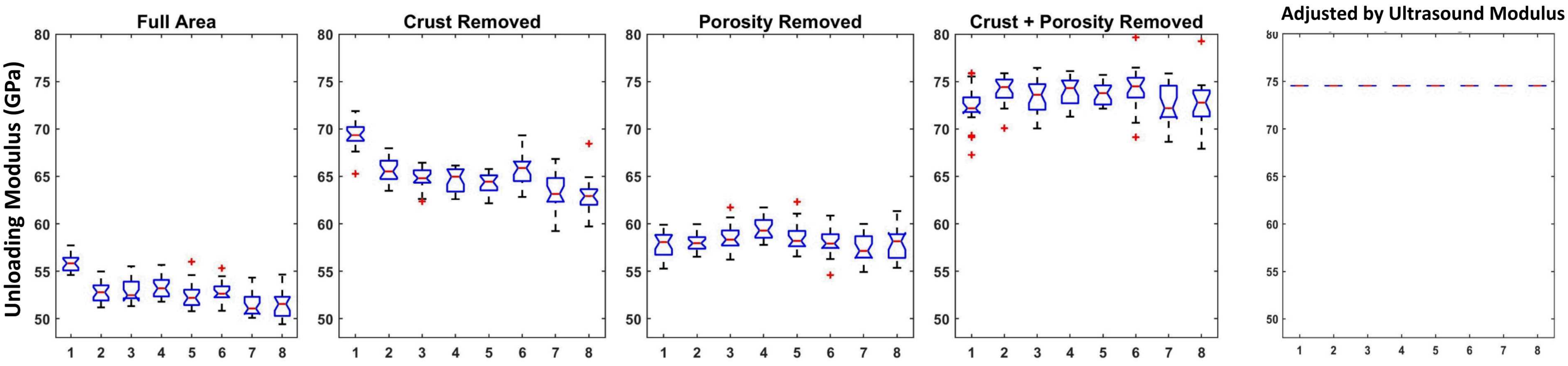




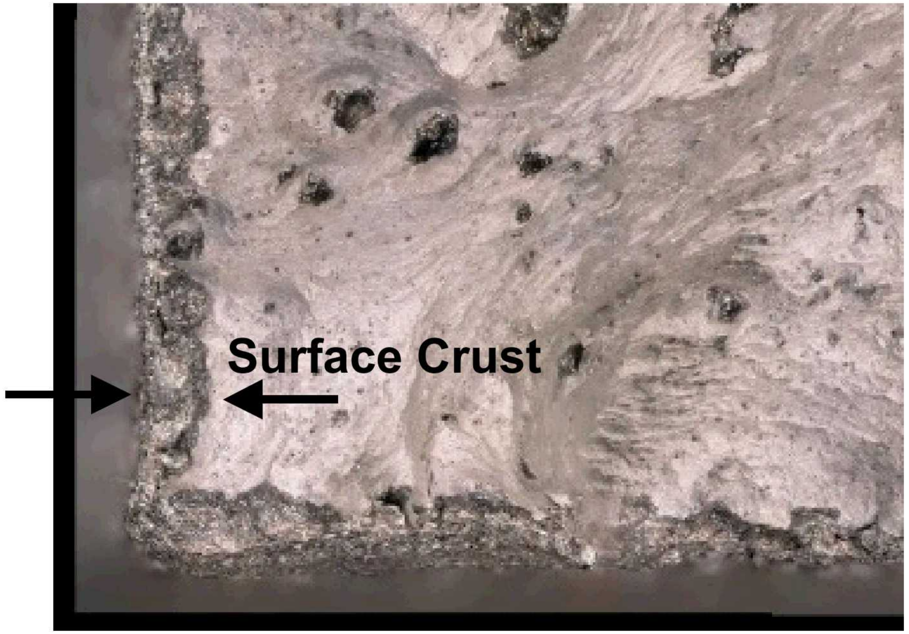


- Increasing fracture surface porosity by 1% decreases ductility by 0.5%.
- Fracture surface porosity gives same trend as bulk density.
- What can we learn from porosity measurements?

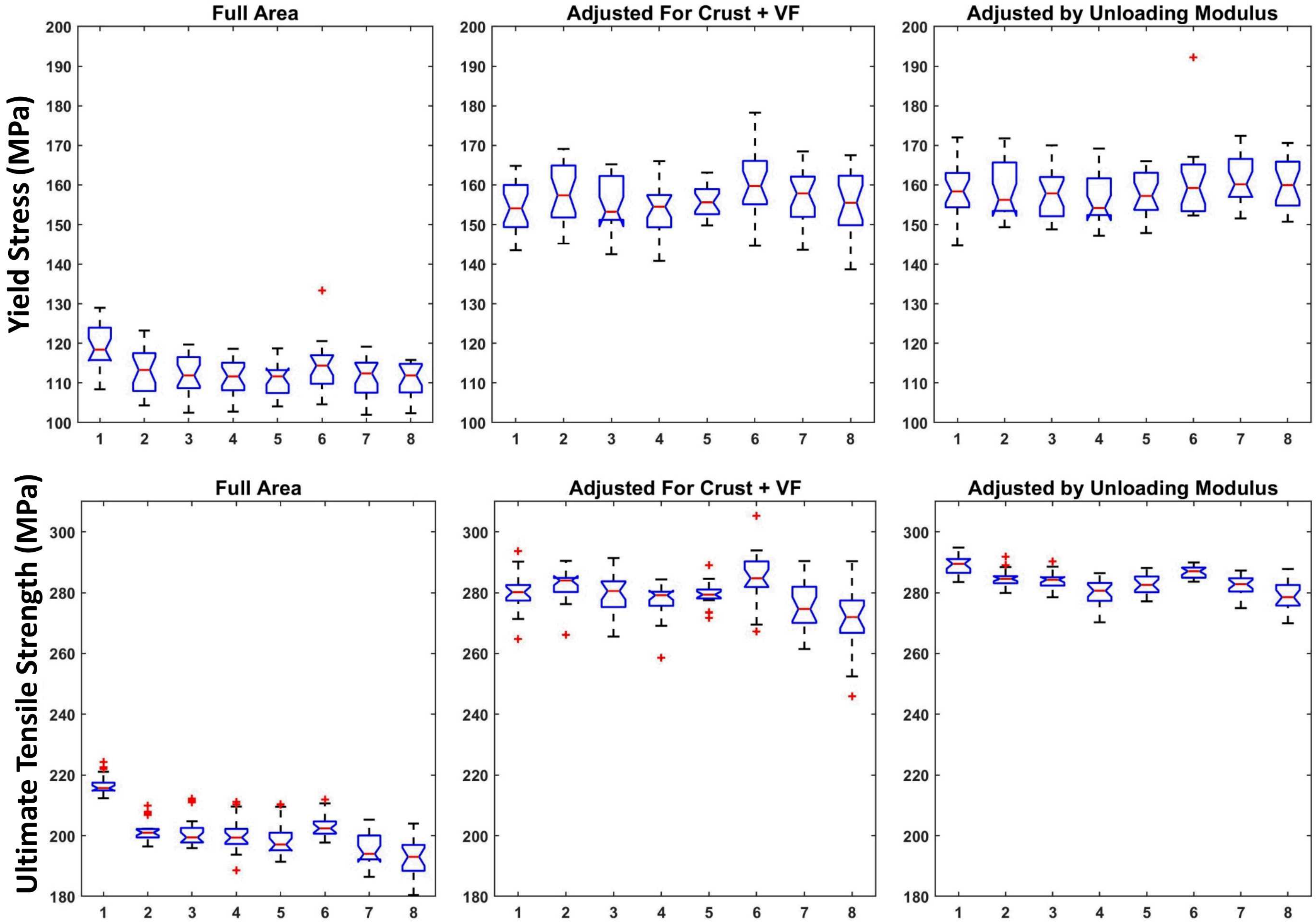
Crust and porosity effects on unloading modulus



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



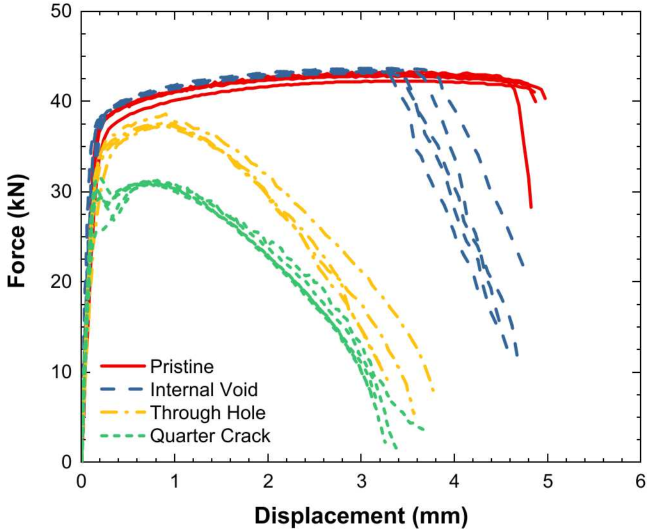
Crust and porosity effects on ultimate tensile strength

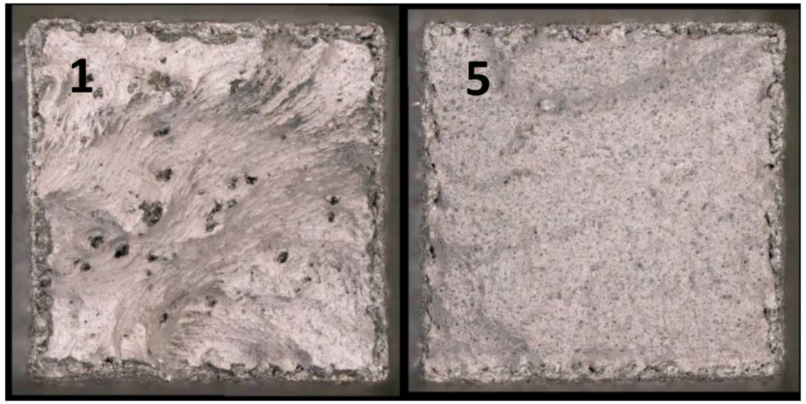


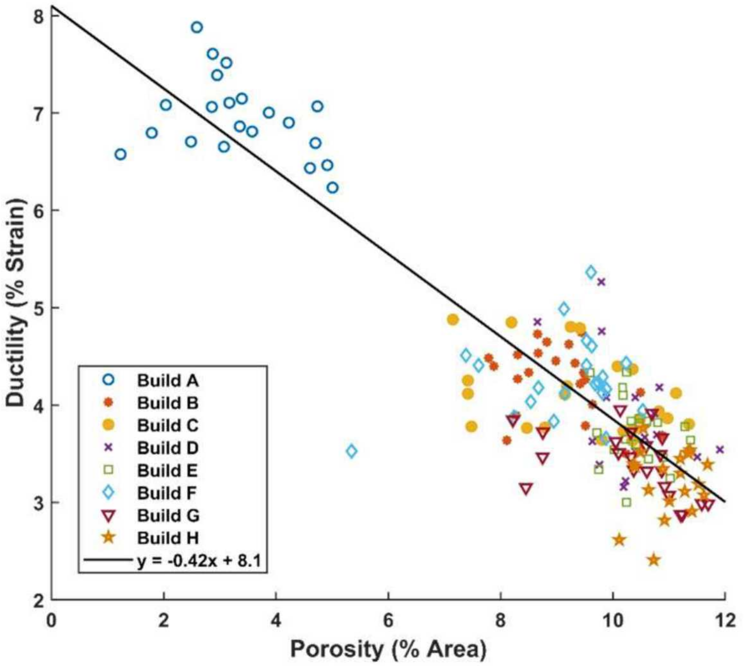
- **Inherent Yield stress is 160 MPa instead of 120 MPa.**
- **Inherent Tensile strength is 280 MPa instead of 200 MPa.**

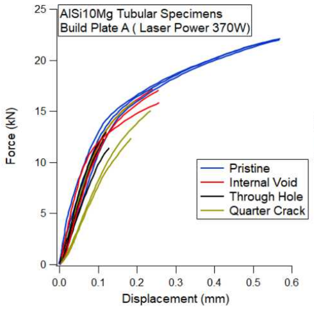
Conclusions

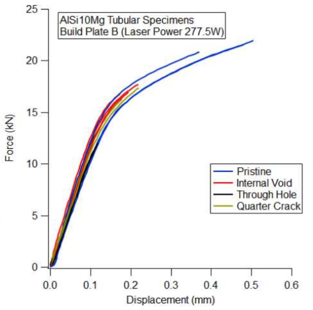
1. **Flaws interact with other flaw types and with material properties.**
2. **Small ubiquitous flaws, bulk porosity, can overwhelm other flaws and drive mechanical behavior.**
3. **Ductility can be predicted by bulk porosity in the density-dominated regime.**

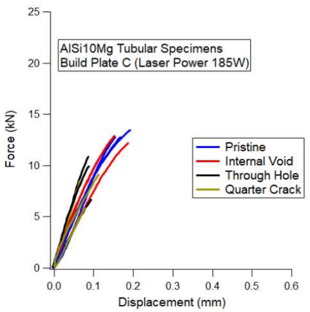












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Extra details: Laursen 3:40 B115

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Thank You

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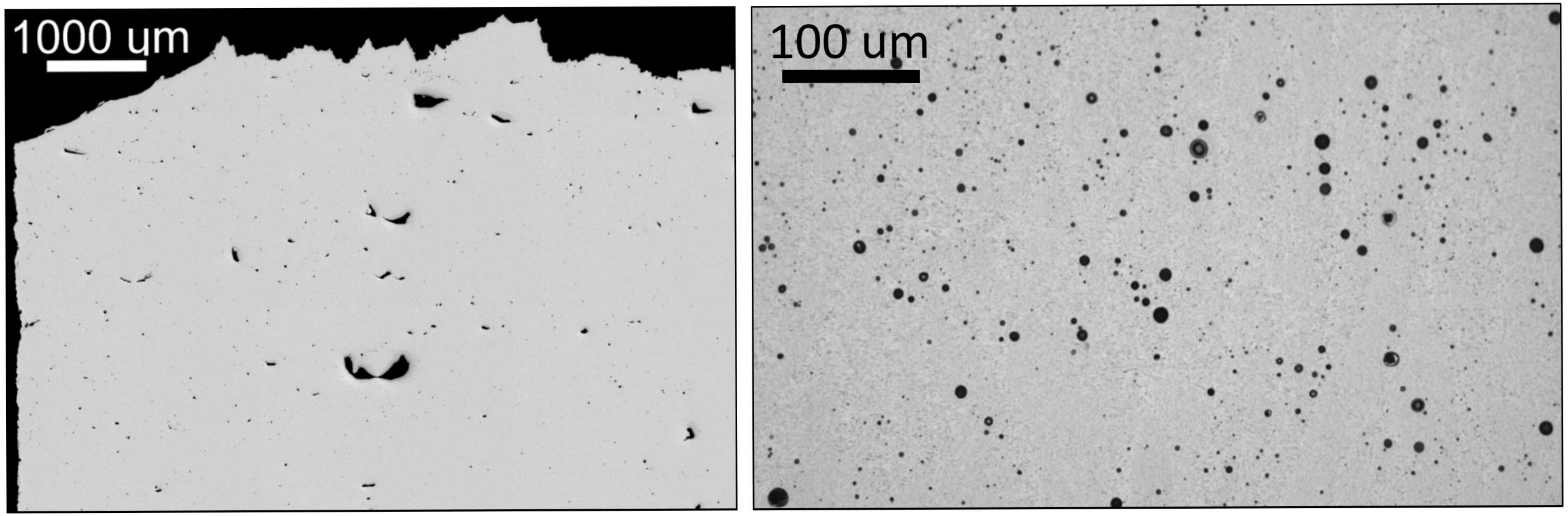
Extra Slides

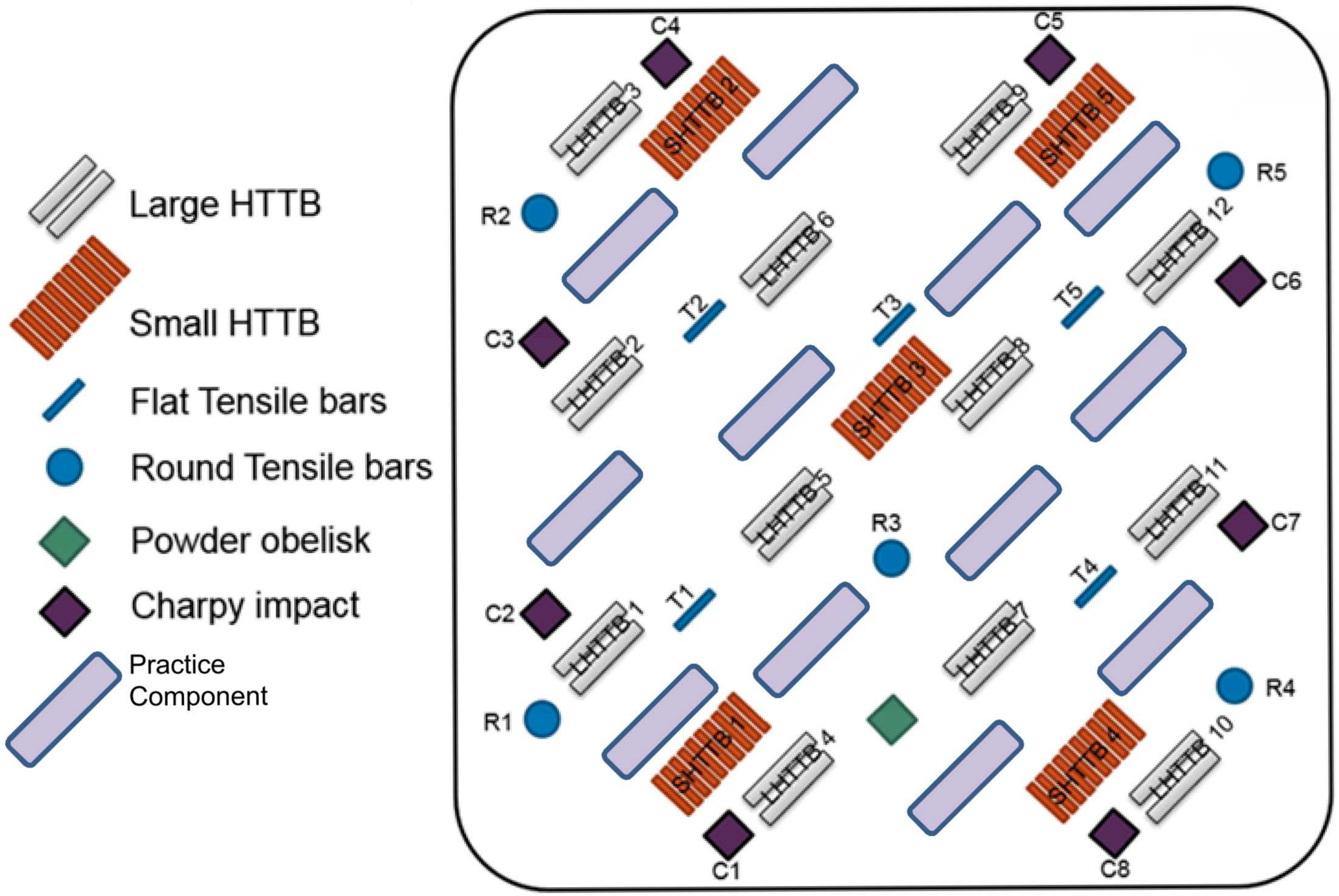
Two types of voids in these parts: Lack of fusion and gas porosity



- Porosity in Al10SiMg AM parts has a big effect on mechanical properties.

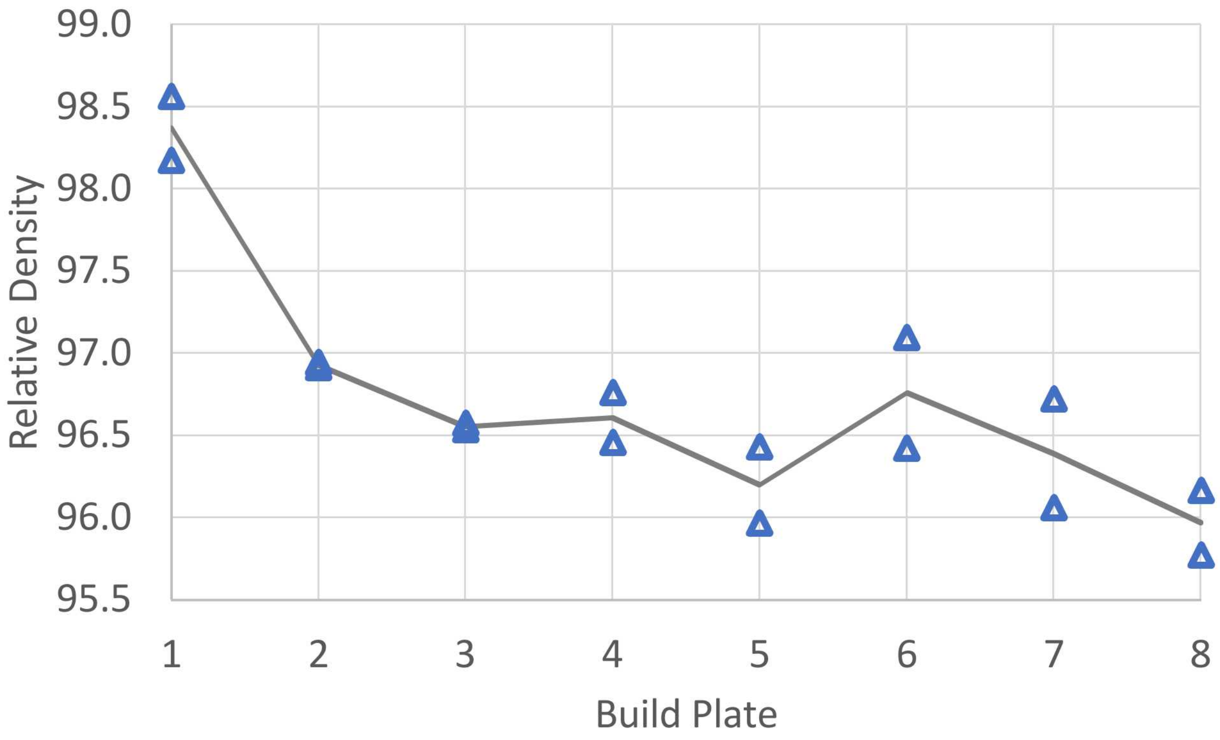
Build plate of AlSi10Mg

- **Heat treated at 300° for 2 hrs to relieve stresses and change Si configuration**



Density measurements follow powder reuse trend

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**



- **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

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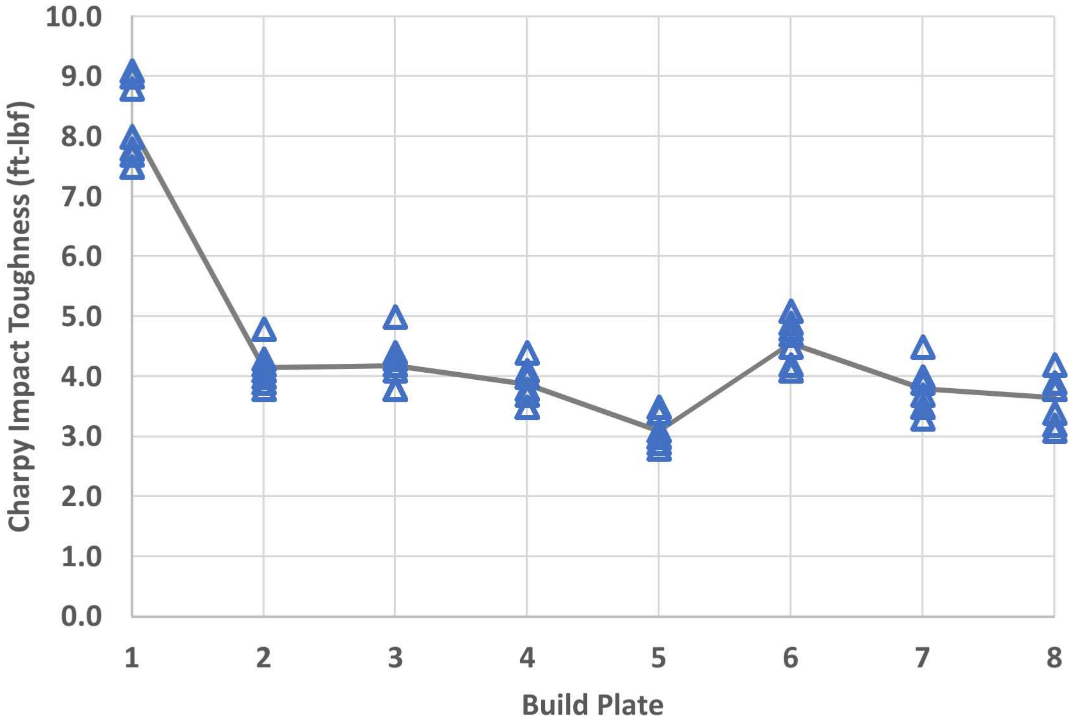
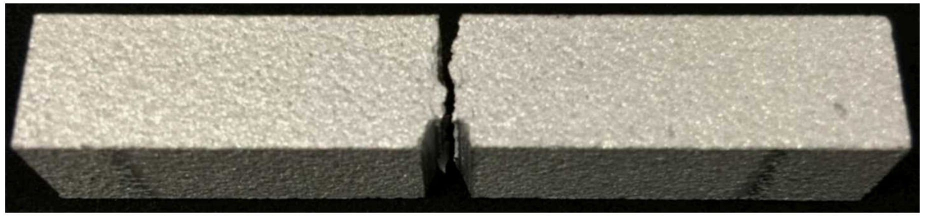
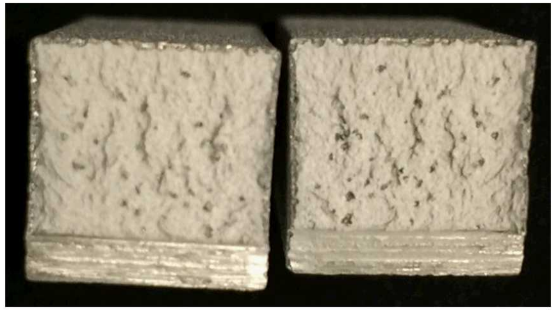
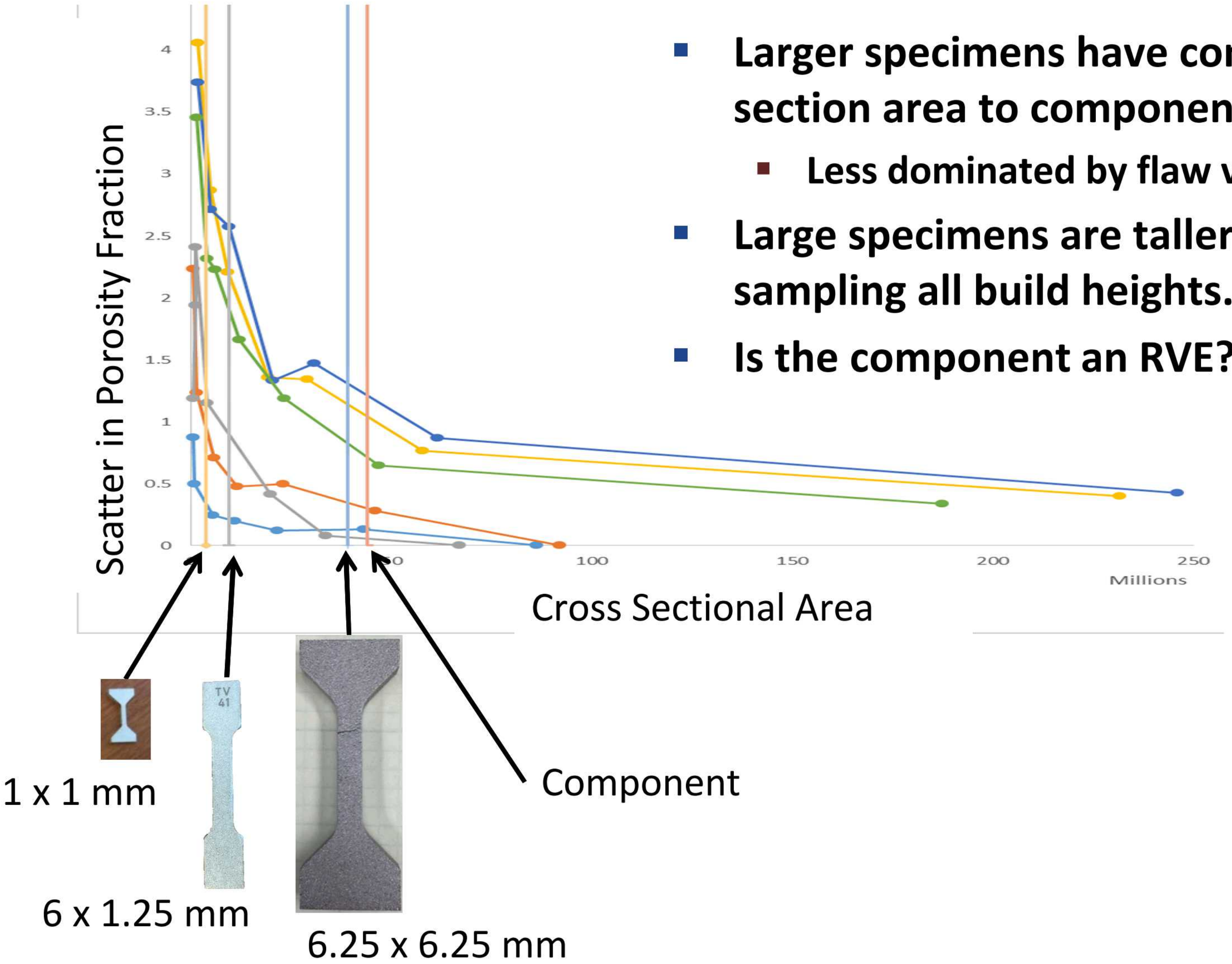






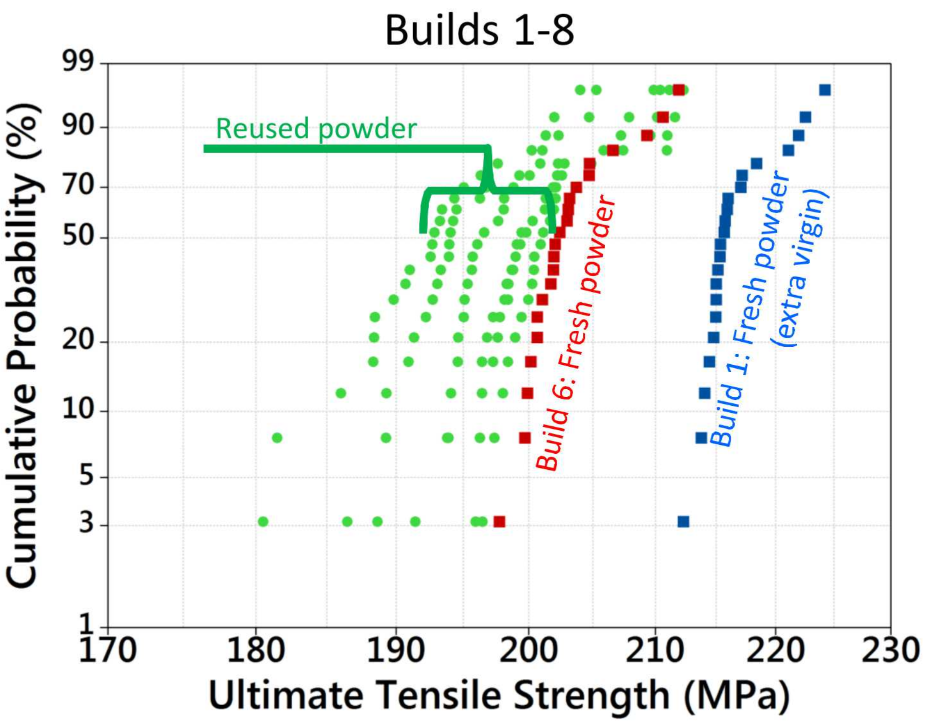
- Quick results, easy analysis.
- Dynamic fracture directly relevant to application.
- Localized failure to one slice of material.
- Sensitive to overall build quality, perhaps useful for quality control.
- Fracture toughness ~15 MPa√m

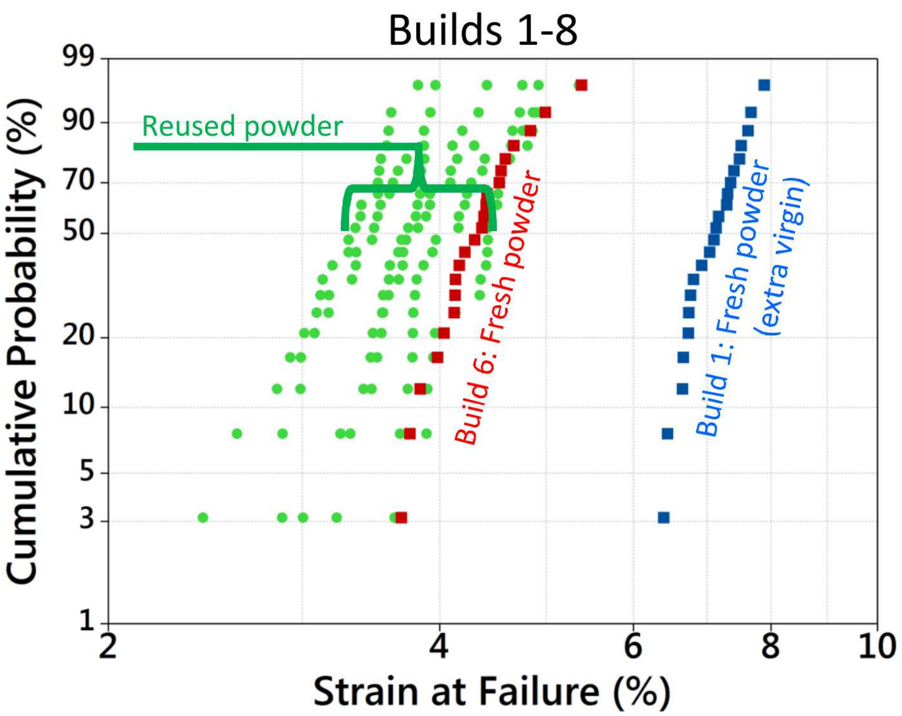
Representative volume element to minimize variability and draw tangible conclusions



- **Larger specimens have comparable cross section area to component.**
  - **Less dominated by flaw variability**
- **Large specimens are taller than component sampling all build heights.**
- **Is the component an RVE?**

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

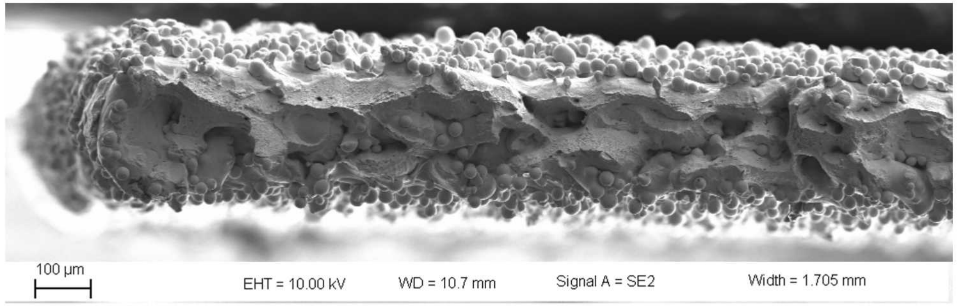




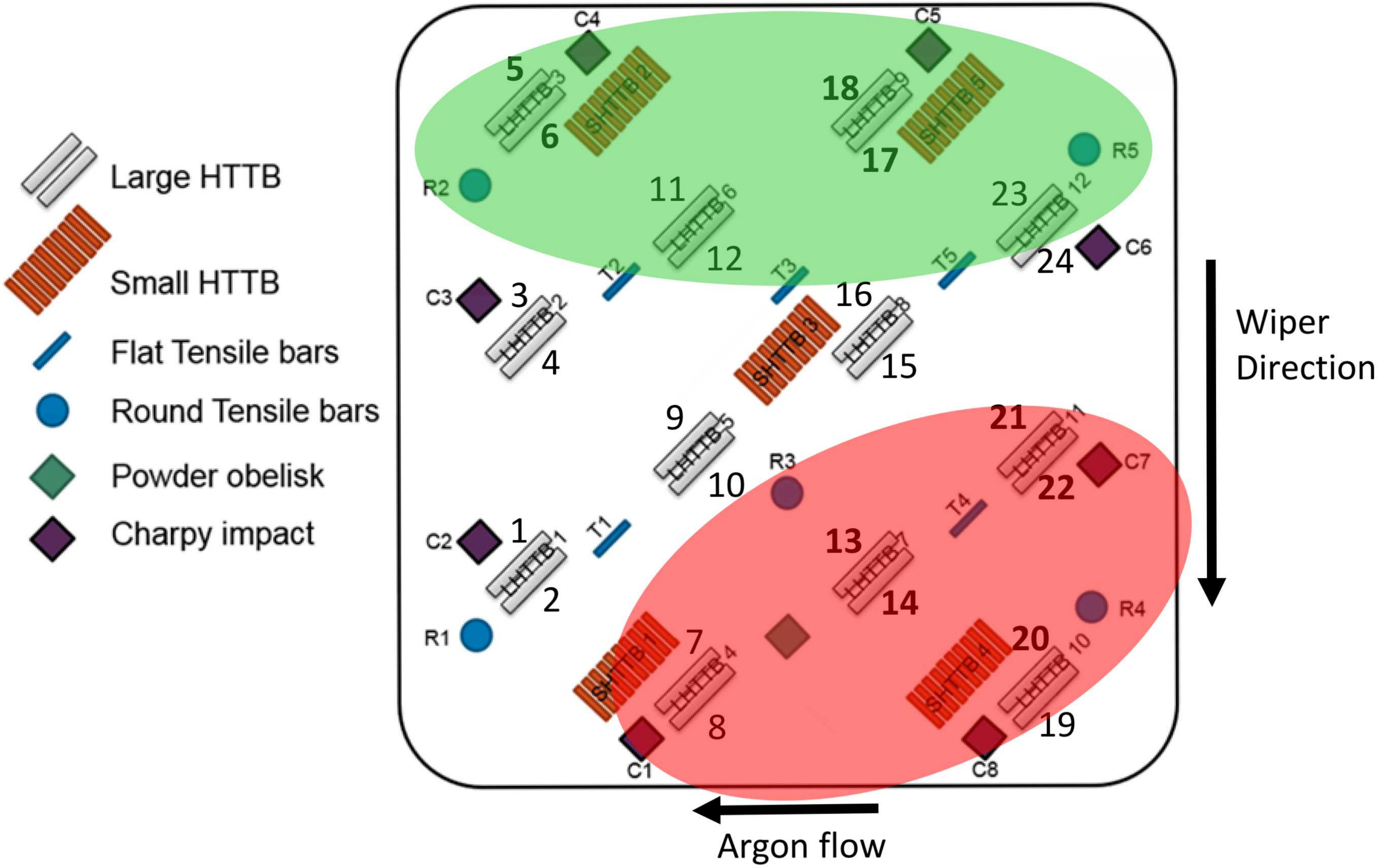
Build 6, which was built using fresh powder, performed similarly to samples made with reused powder, perhaps due to reused powder remaining in the machine from previous builds. The extra virgin powder from build 1 clearly stands apart from the other builds.

Cross sectional area is difficult to define

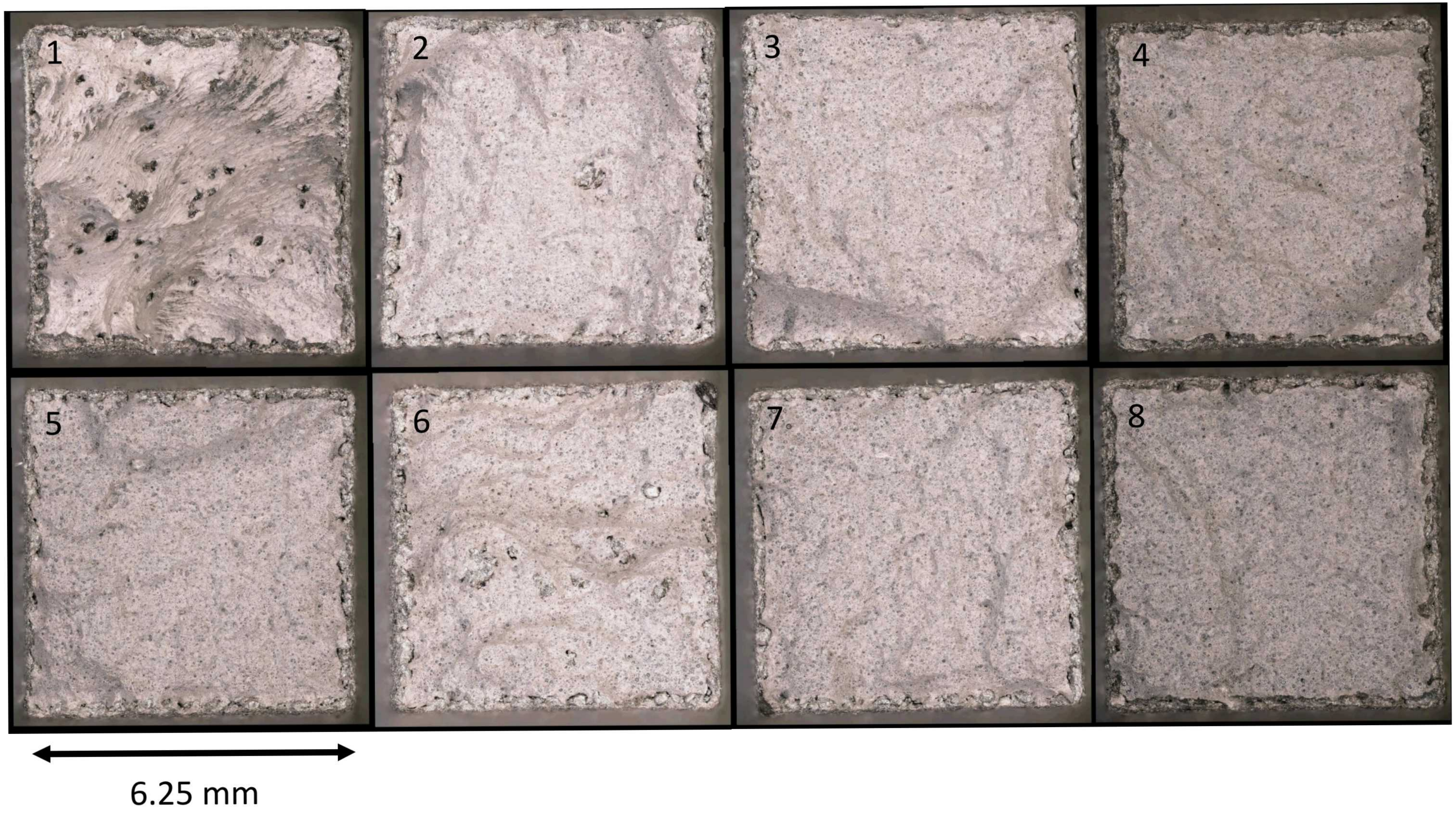
- Effective cross sectional can scale stresses significantly for small specimens.
- Affects modulus, yield strength, ultimate tensile strength.
- For now, use “caliper” measurements.



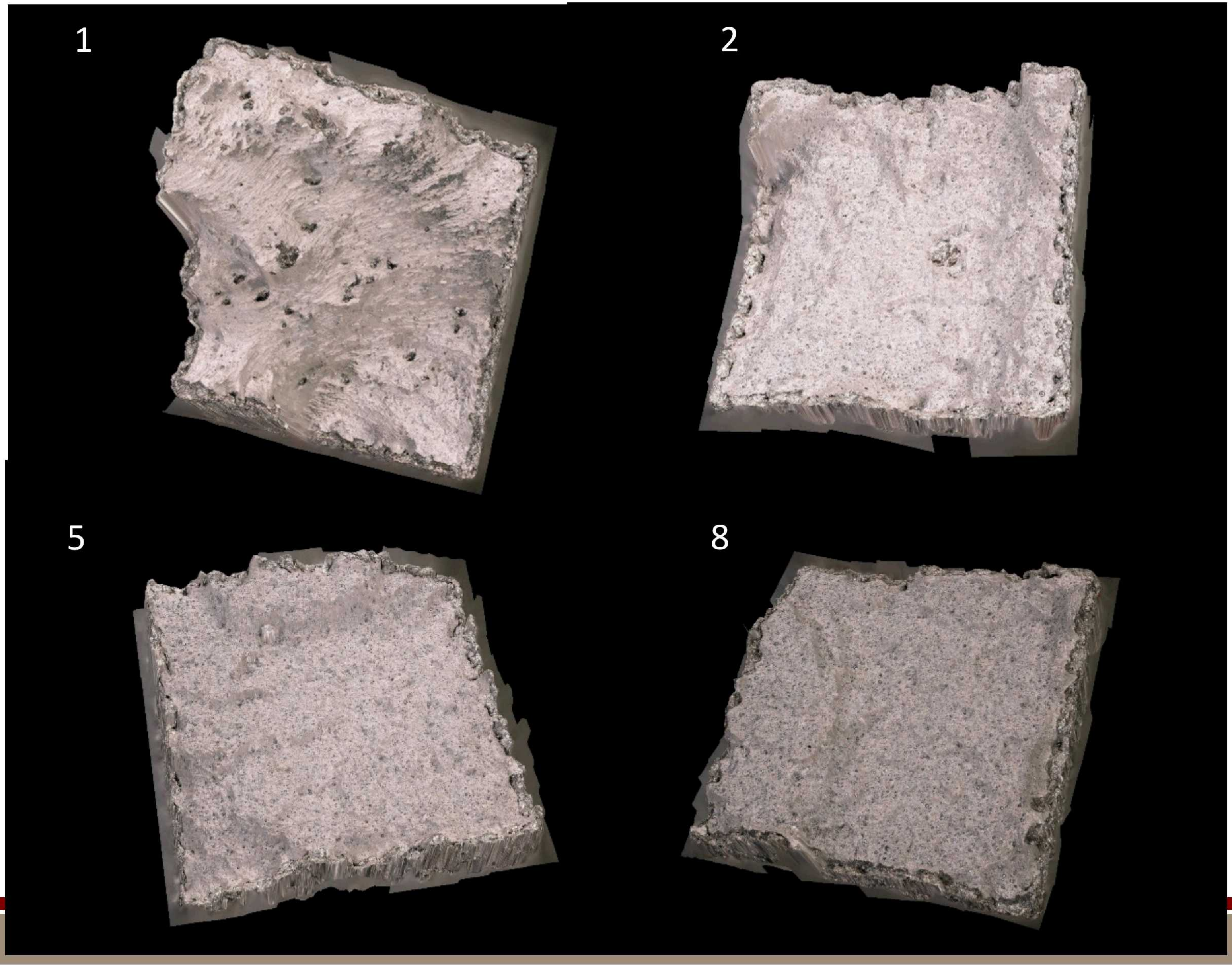
Spatial dependence in tensile strength, regardless of build plate.



“Good” build plates appear to have more lack-of-fusion voids!



Fracture surface tortuosity increases dramatically with strength and ductility. Linking up large voids in stronger samples.



Microstructure

Images showing slip planes and directions in FCC and BCC unit cells.

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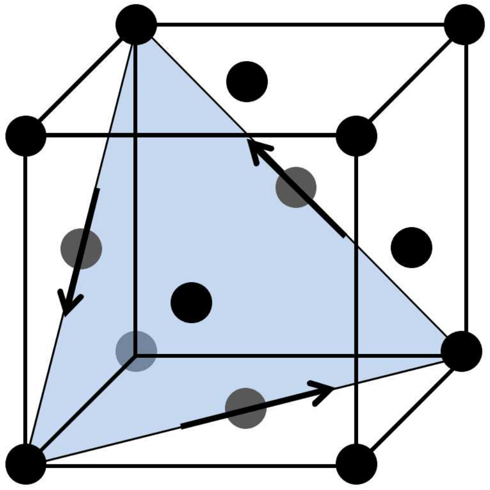
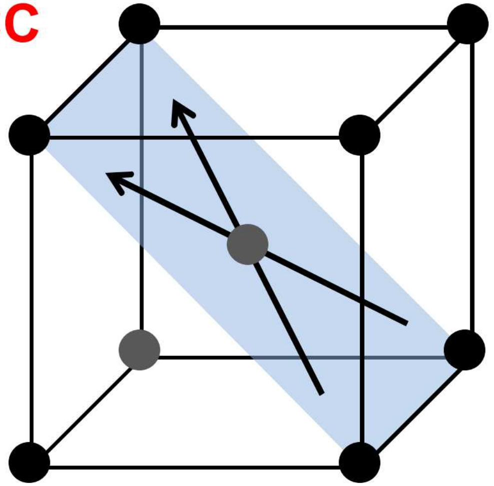
FCC

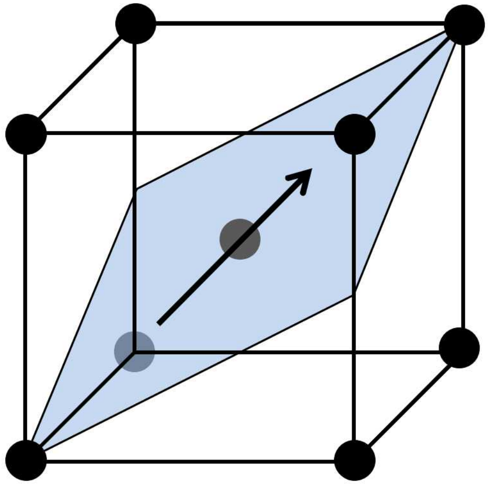


12 Slip systems:
Four {111} Planes each with three <110> Slip directions

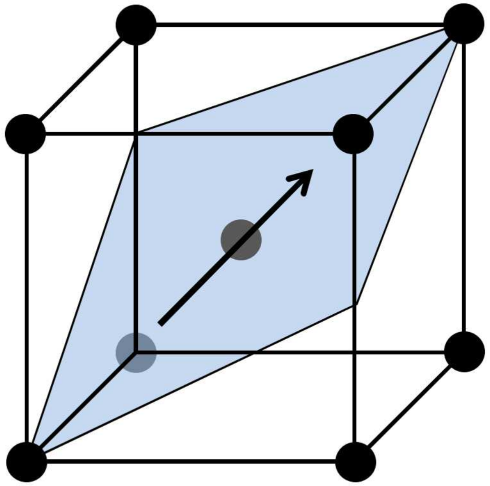
BCC



12 {110} slip systems
6 Planes each with two <111> Directions



12 {112} slip systems
12 Planes each with one <111> Direction

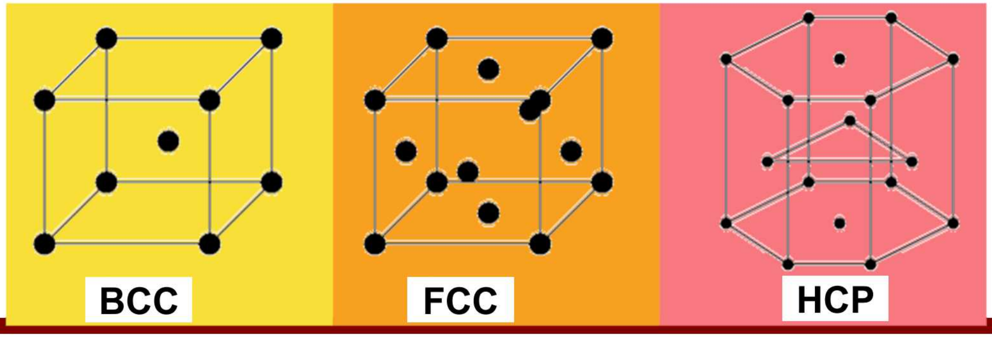


24 {123} slip systems
24 Planes each with one <111> Direction

Several important structural metals are BCC.

HCP BCC FCC

H																	He
453.69 Li bcc	1560 Be hcp											B	C	N	O	F	Ne
370.87 Na bcc	923 Mg hcp											933.47 Al fcc	Si	P	S	Cl	Ar
336.53 K bcc	1115 Ca fcc	1814 Sc hcp	1941 Ti hcp	2183 V bcc	2180 Cr bcc	1519 Mn	1811 Fe bcc	1768 Co hcp	1728 Ni fcc	1357.8 Cu fcc	692.68 Zn hcp	301.91 Ga	Ge	As	Se	Br	Kr
312.46 Rb bcc	1050 Sr fcc	1799 Y hcp	2128 Zr hcp	2750 Nb bcc	2896 Mo bcc	2430 Tc hcp	2607 Ru hcp	2237 Rh fcc	1828 Pd fcc	1235 Ag fcc	594 Cd	430 In	505 Sn	904 Sb	Te	I	Xe
301.59 Cs bcc	1000 Ba bcc	*	2506 Hf hcp	3290 Ta bcc	3422 W bcc	3186 Re hcp	3306 Os hcp	2446 Ir fcc	1768 Pt fcc	1337.33 Au fcc	234.32 Hg	577 Tl hcp	600.61 Pb fcc	544.7 Bi	527 Po	At	Rn
Fr	973 Ra bcc	**	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Uut	Fl	Uup	Lv	Uus	Uuo
	*	1193 La dhcp	1068 Ce fcc	1208 Pr dhcp	1297 Nd dhcp	1315 Pm dhcp	1345 Sm	1099 Eu bcc	1585 Gd hcp	1629 Tb hcp	1680 Dy hcp	1734 Ho hcp	1802 Er hcp	1818 Tm hcp	1097 Yb fcc	1925 Lu hcp	
	**	1323 Ac fcc	2115 Th fcc	1841 Pa	1405.3 U	917 Np	912.5 Pu	1449 Am dhcp	1613 Cm dhcp	1323 Bk dhcp	1173 Cf dhcp	1133 Es fcc	Fm	Md	No	Lr	



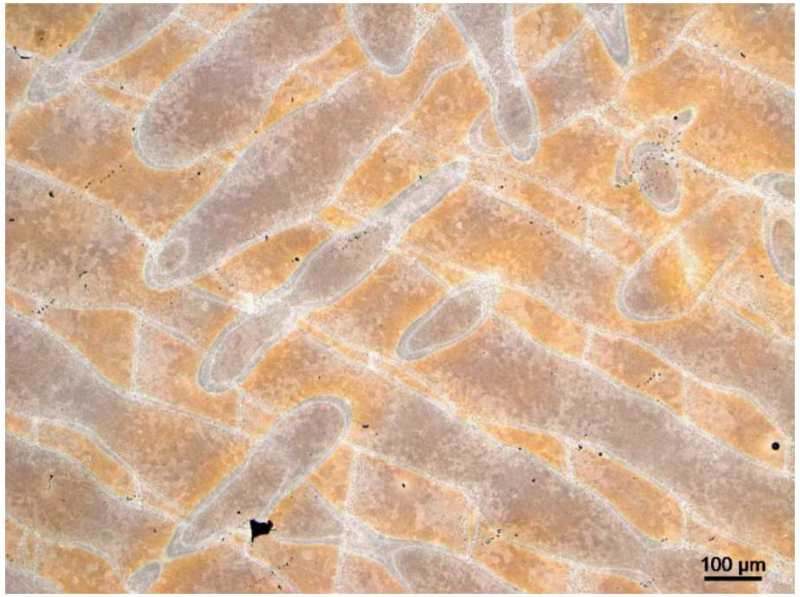
The top number in the cell is the melting point (in K)

- dhcp: double hexagonal close packed
- unusual structure
- nonmetal
- unknown or uncertain

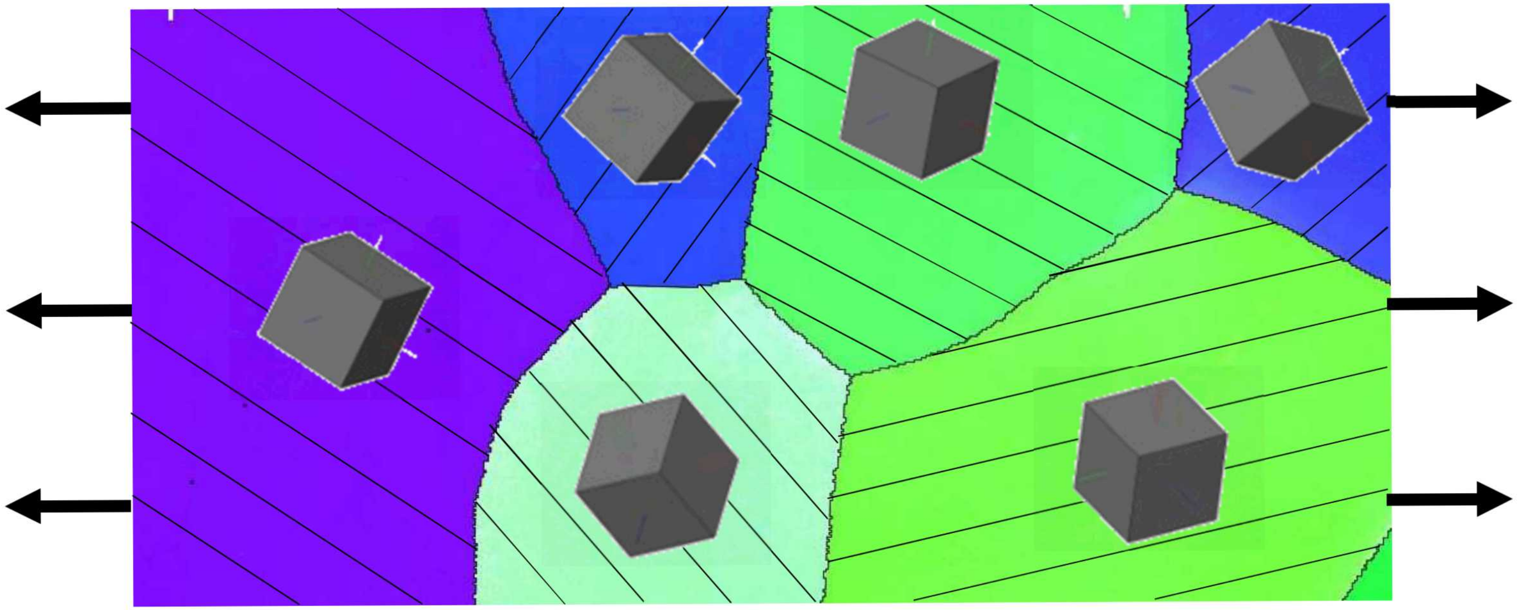
http://en.wikipedia.org/wiki/Periodic_table_(crystal_structure)

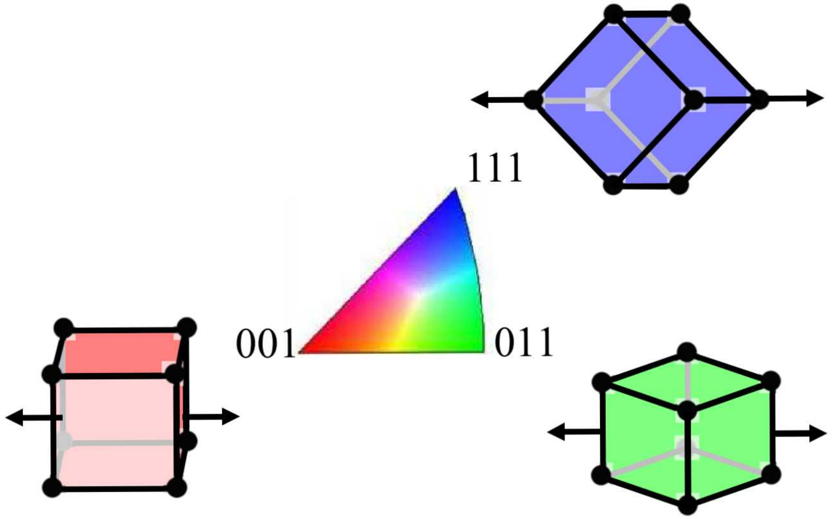
AlSi10Mg

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



Grains are regions with uniform orientation of the atomic unit cell.





Microstructure of AlSi10Mg- expect anisotropy?

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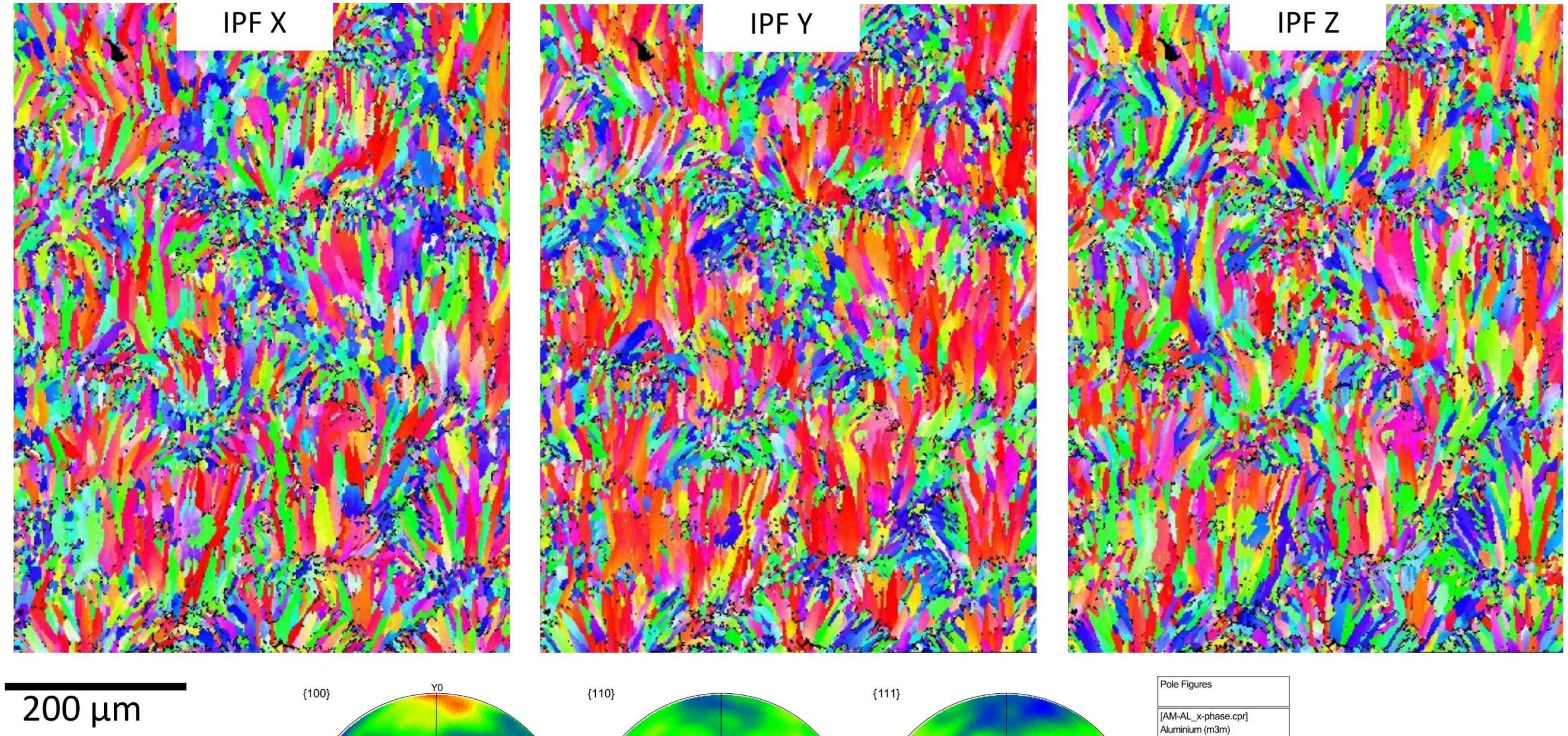
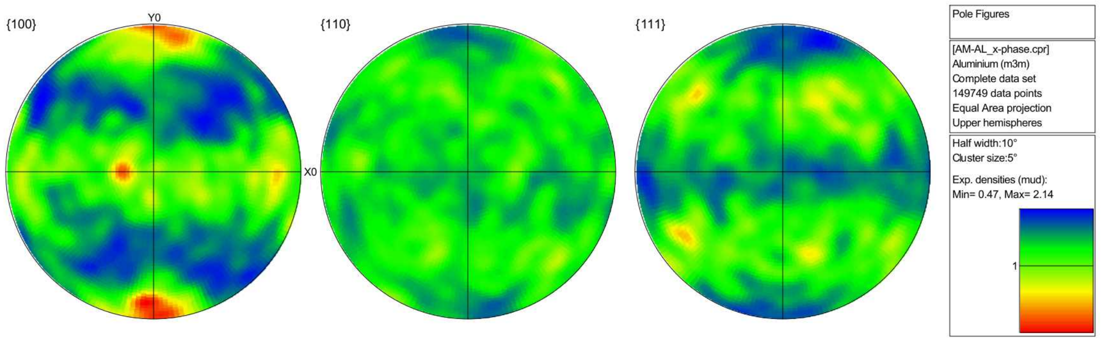
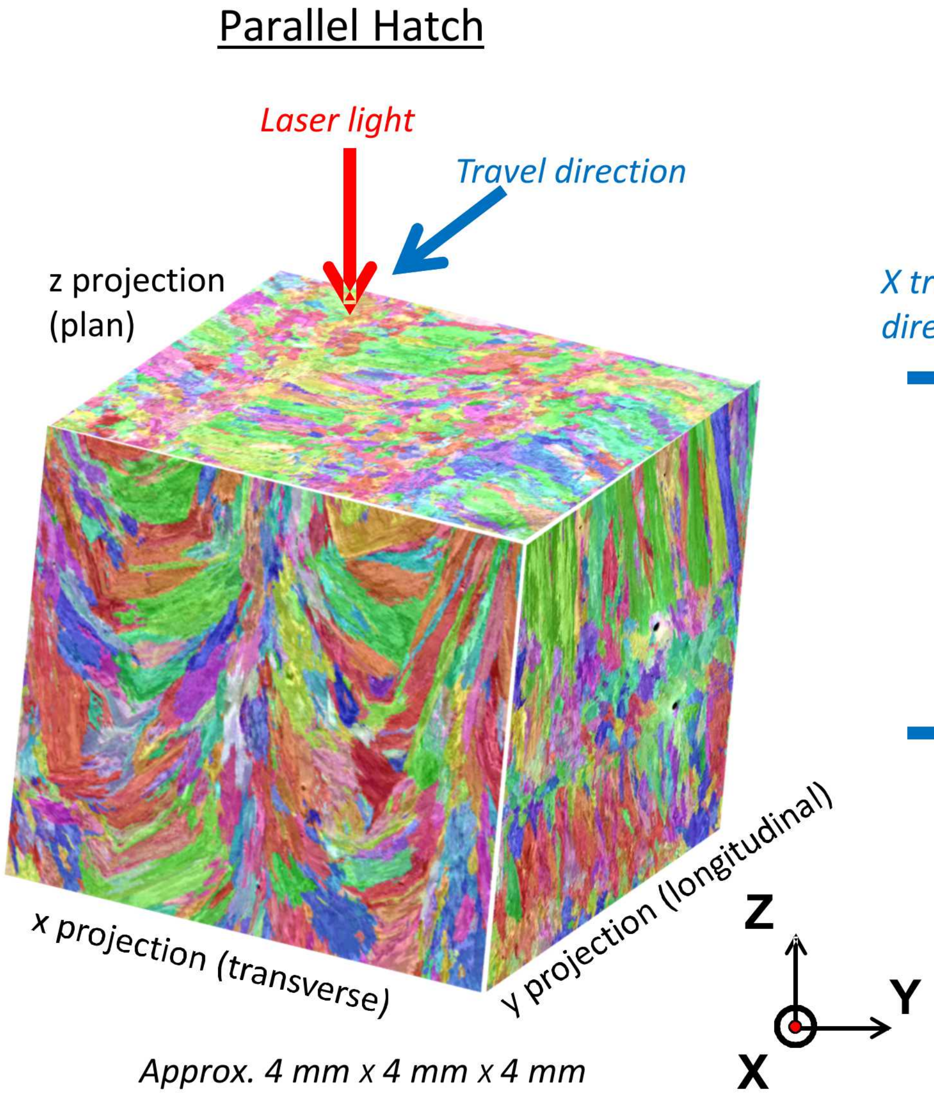
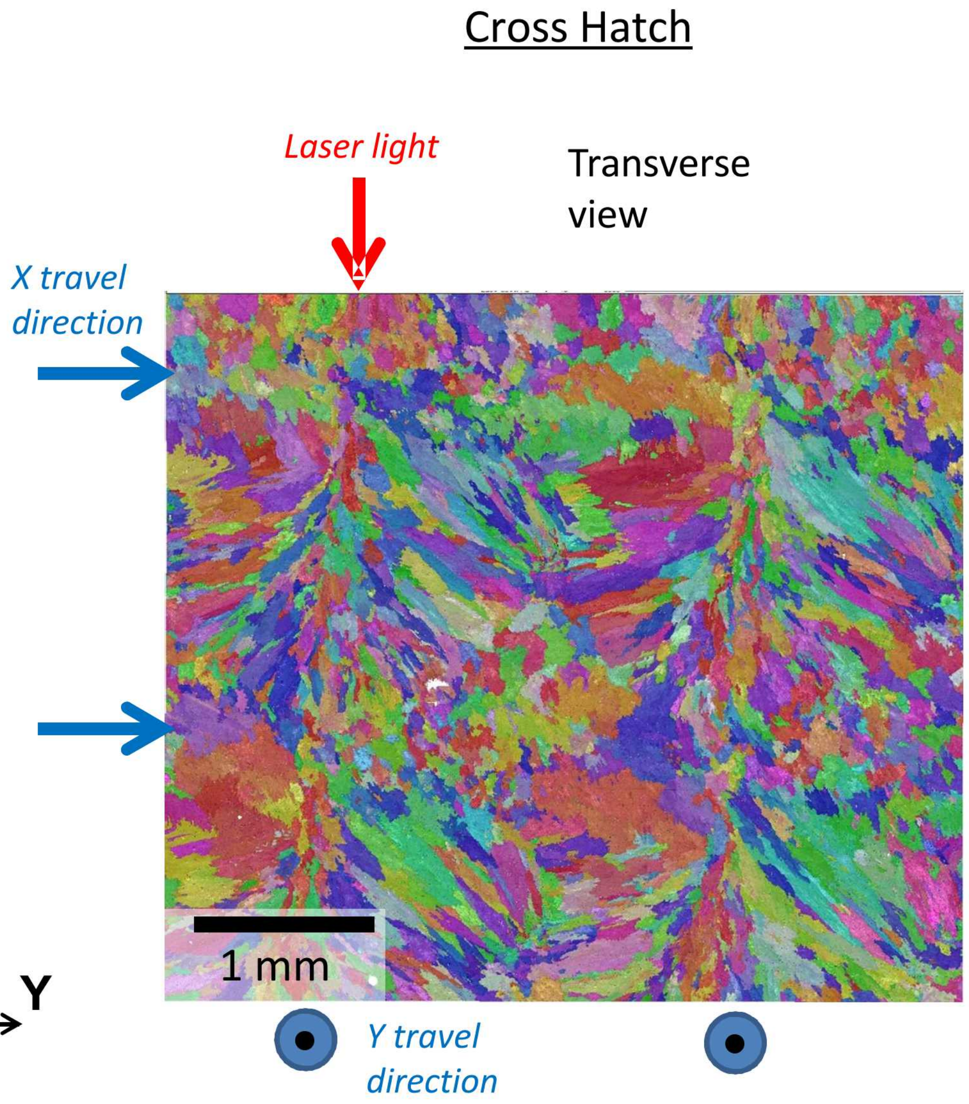




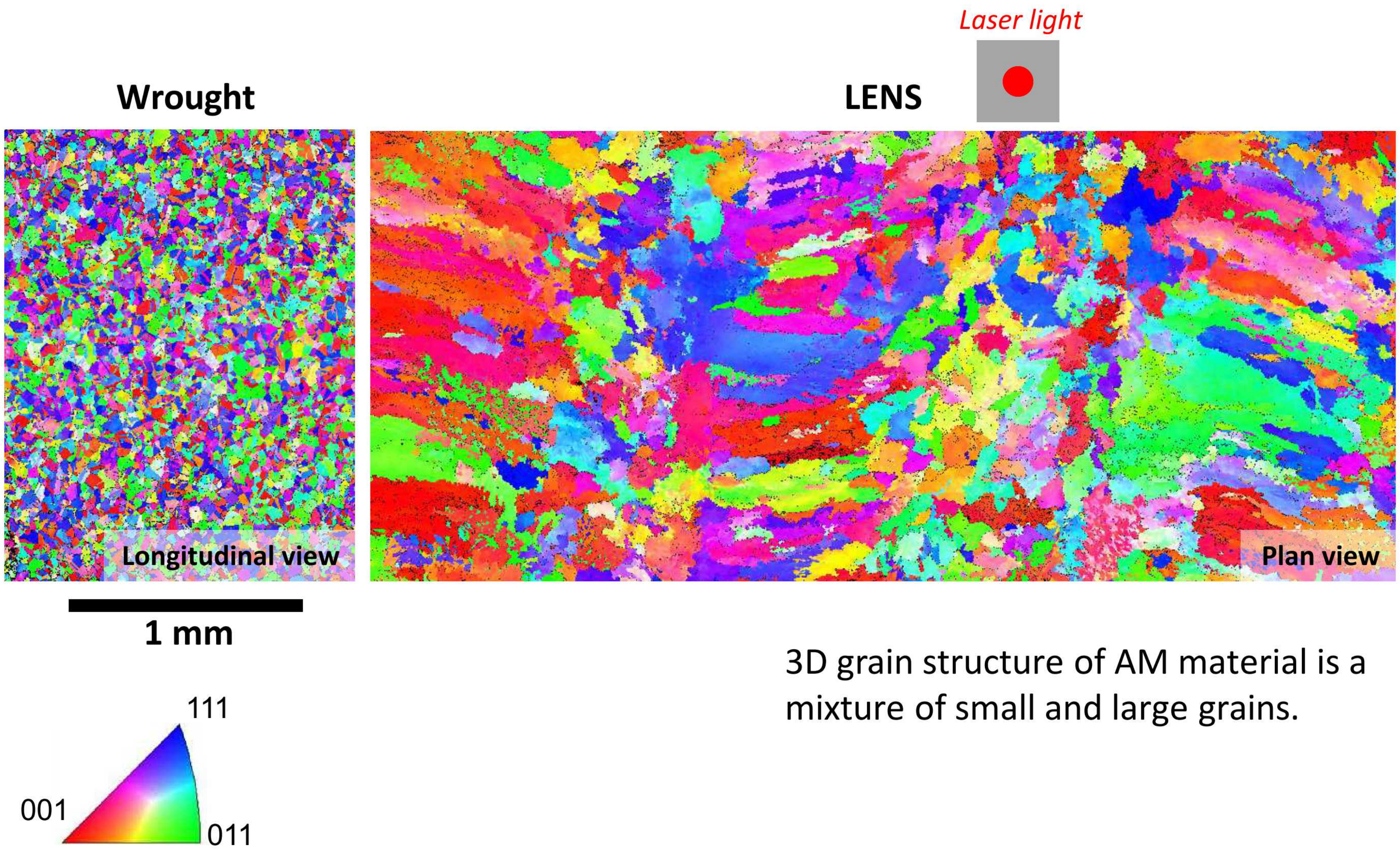
Pole figures - note some alignment of {100} with growth direction

3D grain structure of AM LENS material is a mixture of small and large grains.





AM grain size is much larger than wrought 304L SS.



3D grain structure of AM material is a mixture of small and large grains.