ICMAT, Singapore 6/25/2019

SAND2019-6956C

AM Flaws, Material Properties, and Component Performance

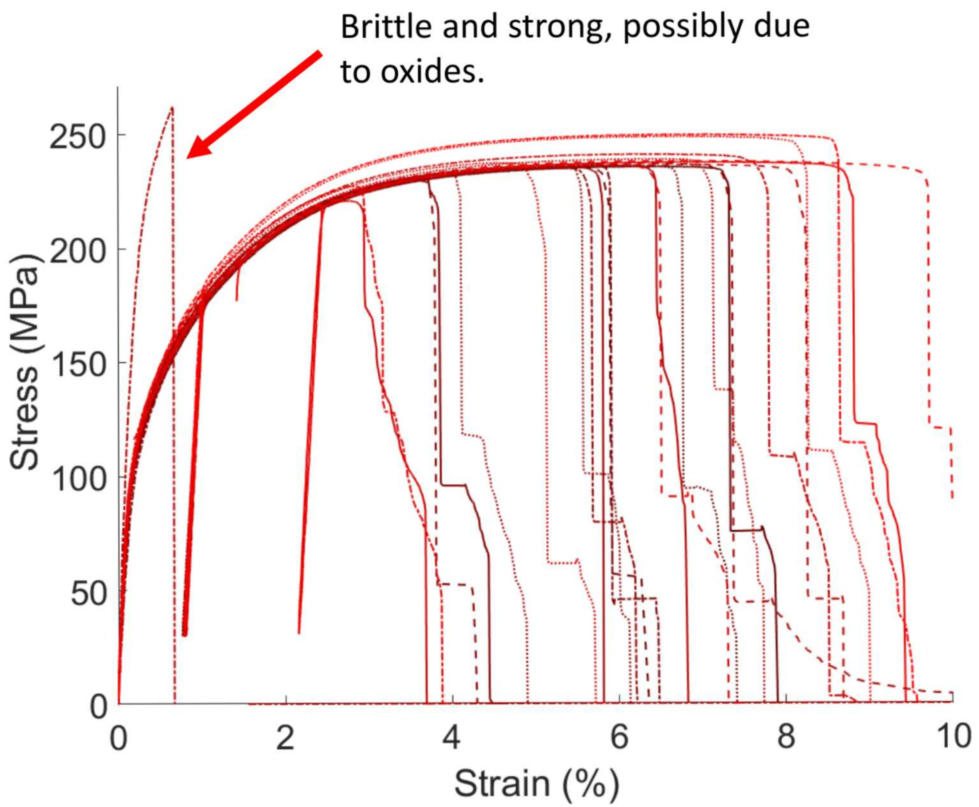
Jay Carroll[1], Christopher Laursen[1], Jody Bartanus[2], Benjamin Smith[2], Garrett Pataky[2], Stephanie DeJong[1], Lisa A. Deibler[1],

[1]Sandia National Laboratories, [2]Clemson University

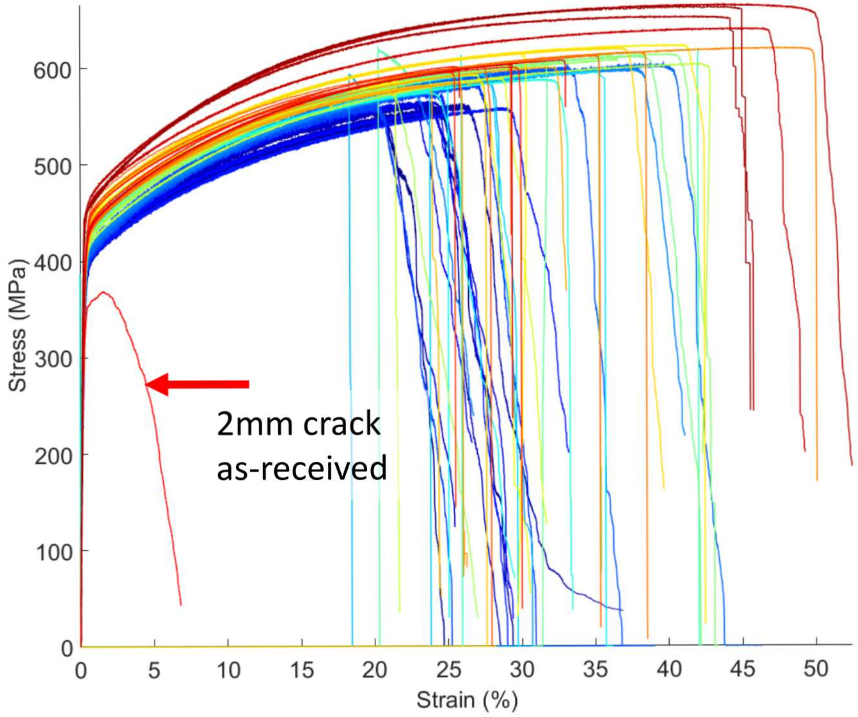
Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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

28 AM AlSi10Mg medium conventional tensiles



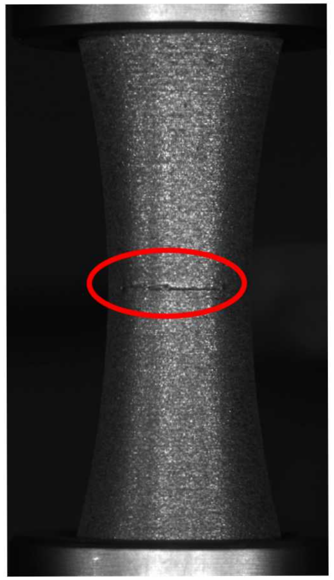
45 AM 304L medium conventional tensiles

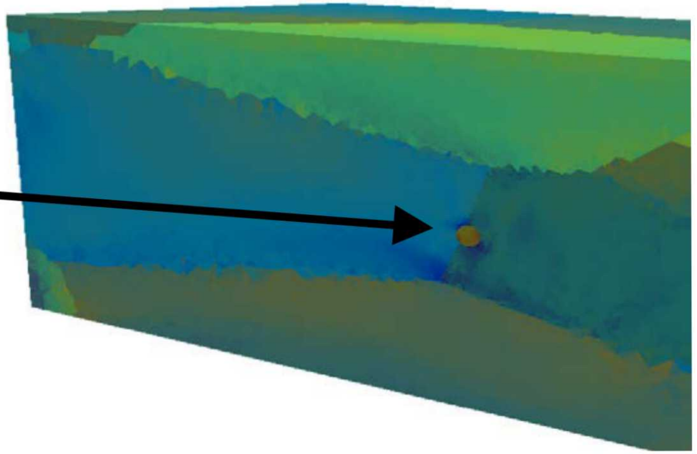


Is there a critical porosity-manufactured defect relationship which can be developed to qualify components for safe use?

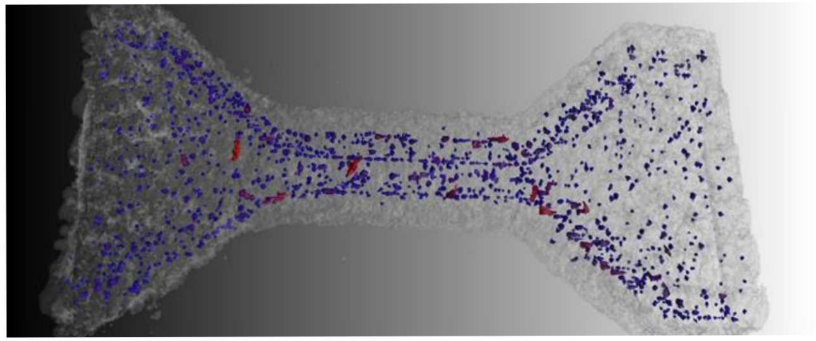
Damage tolerant approach

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



Additive Manufacturing Details

Sandia National Laboratories

Direct Metal Laser Sintering (DMLS)

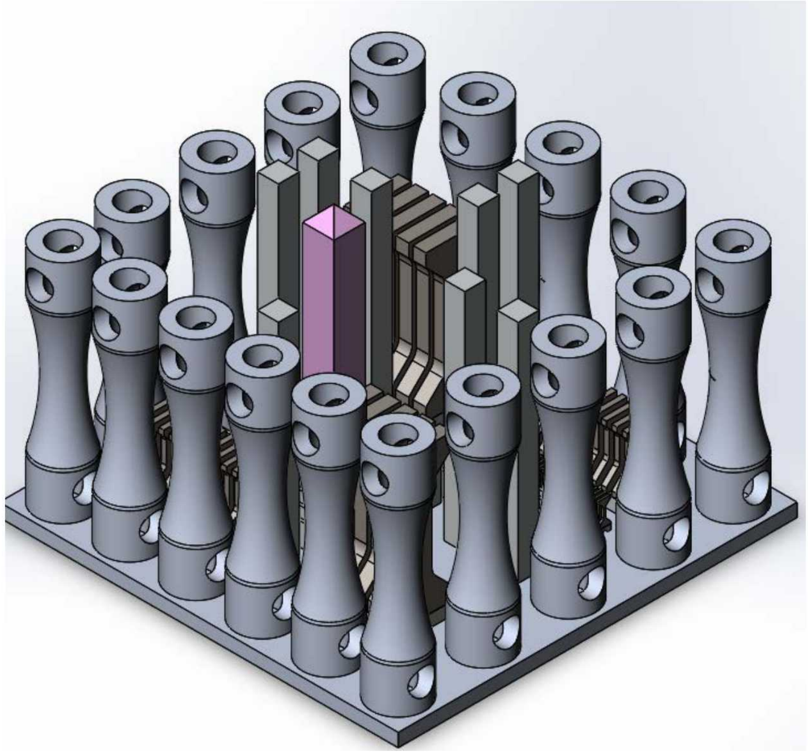
Powder Bed

Ductile: SS 316L

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

Relatively Brittle: AlSi10Mg

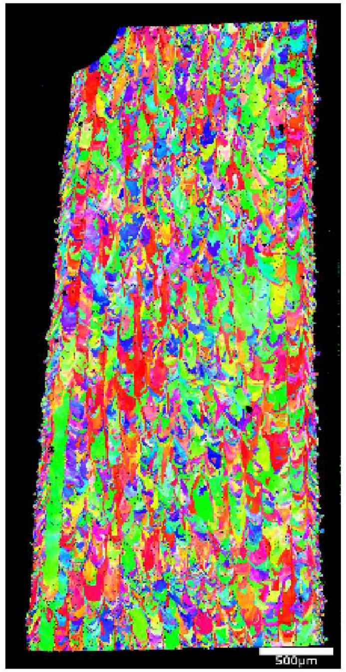
- EOS M290 Solid Laser Melting
- Build Plate A 370 W, 1300 mm/s, hatch 0.019 mm
- Build Plate B 277.5W, 1300 mm/s, hatch 0.019 mm
- Build Plate C 185 W, 1300 mm/s, hatch 0.019 mm



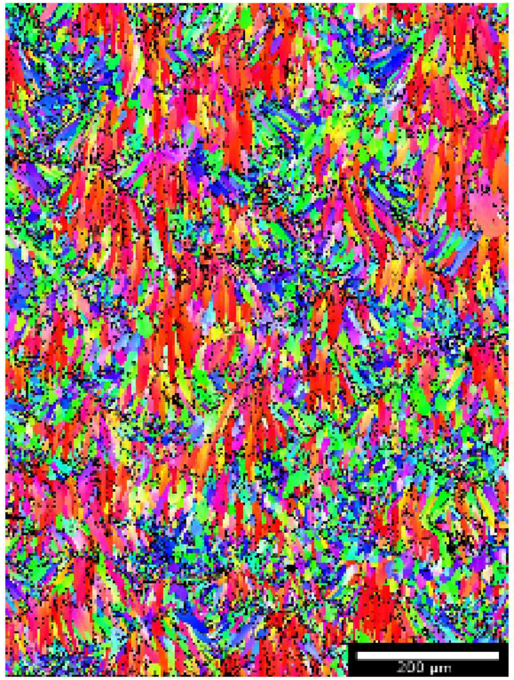
Build Plate Layout

Microstructural details affects material behavior less than flaws (porosity)
i.e. Steel is Steel, Aluminum is Aluminum

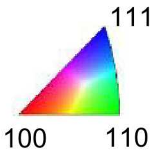
Representative Grain Structure



SS 316L
W.R.T build



AlSi10Mg
W.R.T build



AlSi10Mg

- Build Plate A Laser Power 370 W
- Build Plate B Laser Power 277.5 W
- Build Plate C Laser Power 185 W

Plate A

Plate B

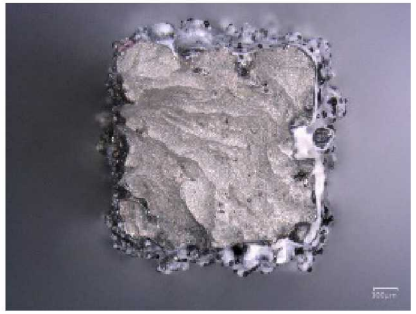


Plate C

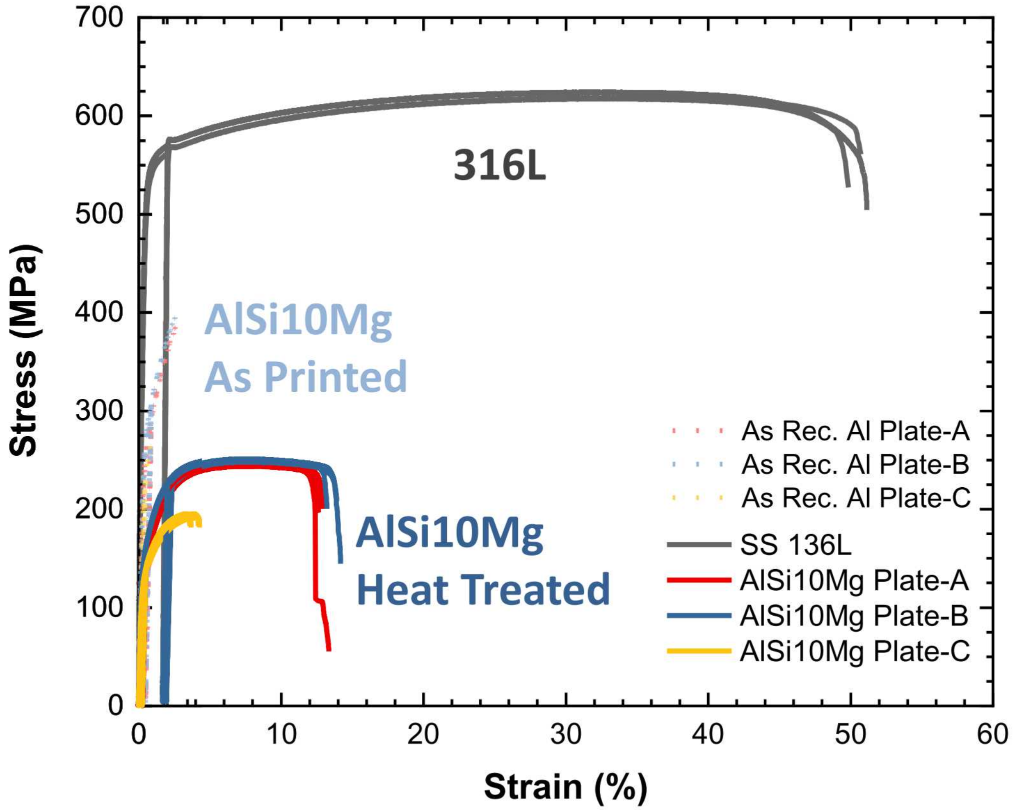
316 Stainless Steel vs. AlSi10Mg (Laser Powder Bed)

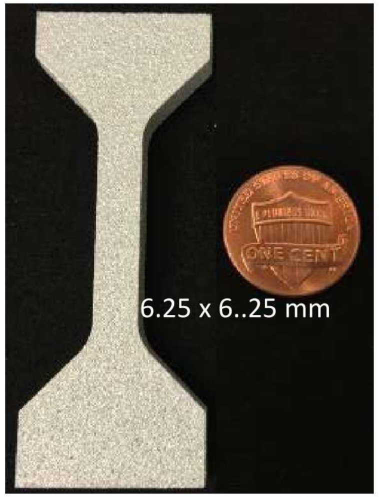
316 Stainless Steel

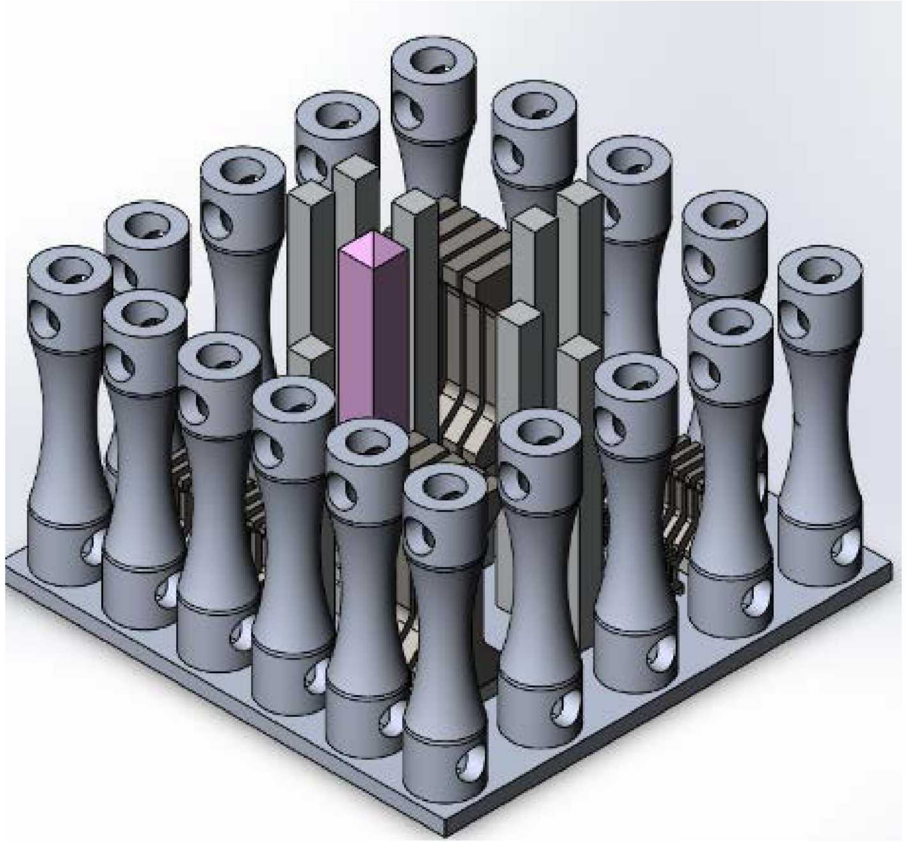
- K_{IC} > 120 MPa√m
- Charpy Impact toughness ~120 ft-lbs
- Ductility = 60%

AlSi10Mg (heat treated)

- K_{IC} ~ 15 MPa√m
- Charpy Impact toughness ~8 ft-lbs
- Ductility ~ 10%

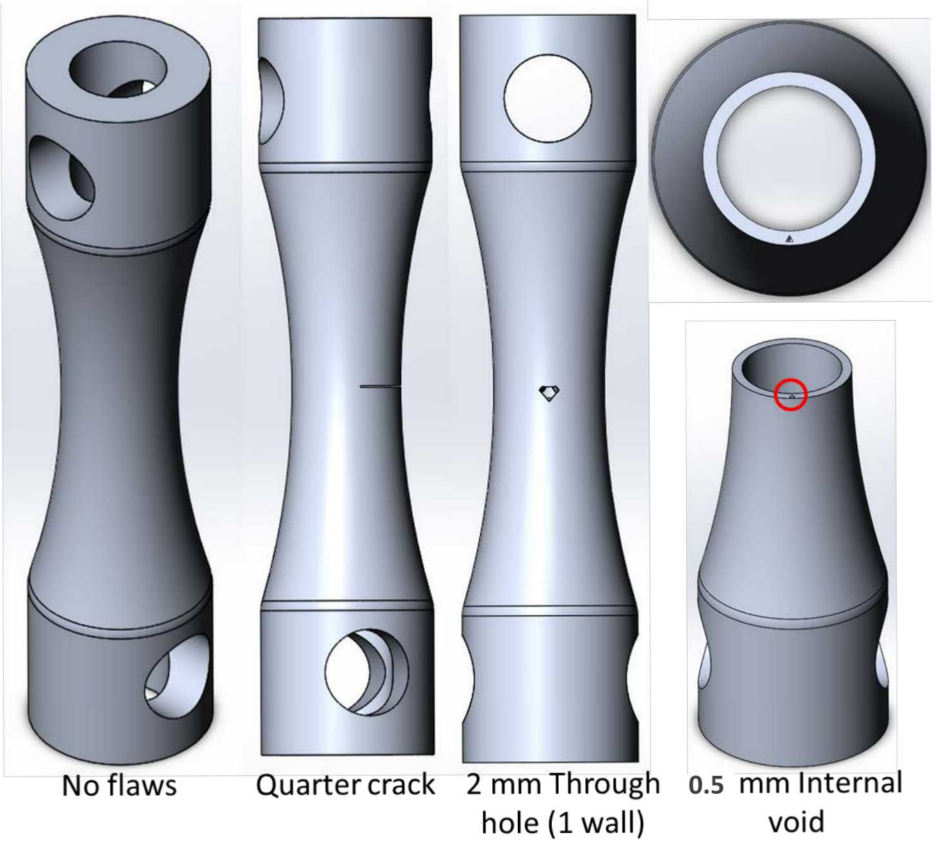






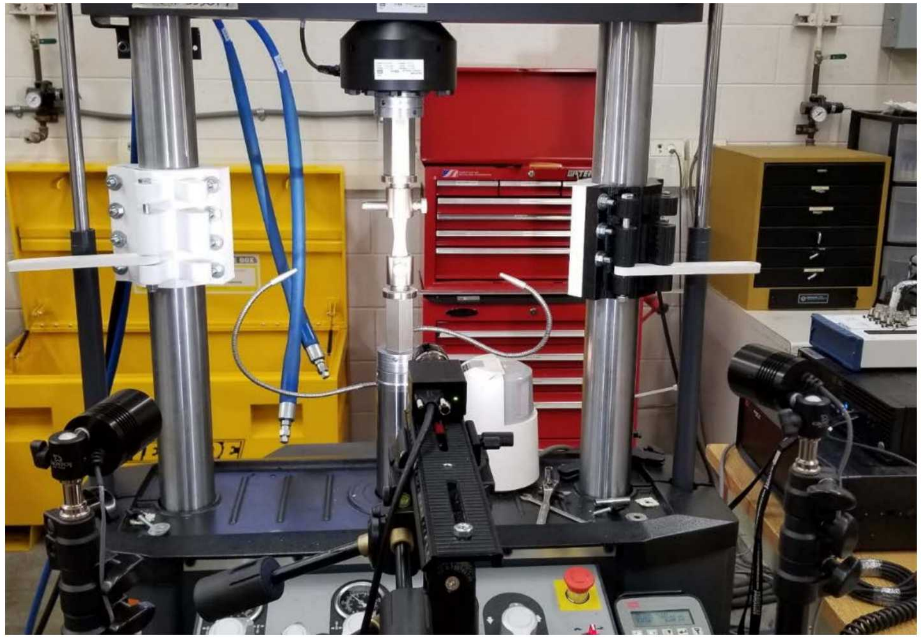
Tubular Specimens

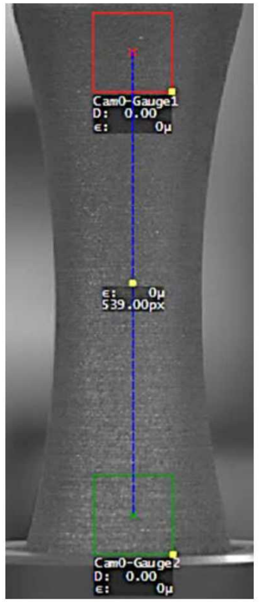
- **SS 316L and AlSi10Mg**
- **Pristine**
- **Manufactured Defects**
  - **Quarter Crack**
  - **Through Hole**
  - **Internal Void**

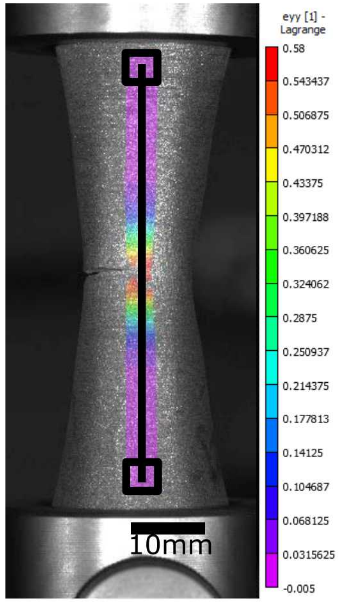


Experimentation

- **MTS Landmark Load Frame**
  - **Tension with clevis adaptors**
- **2D Digital Image Correlation**
  - **Vic Gauge 2D**
  - **Surface roughness for speckling**

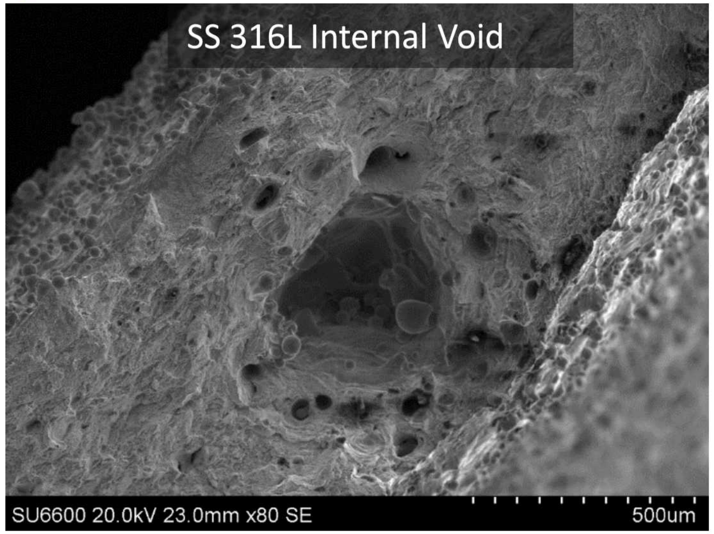


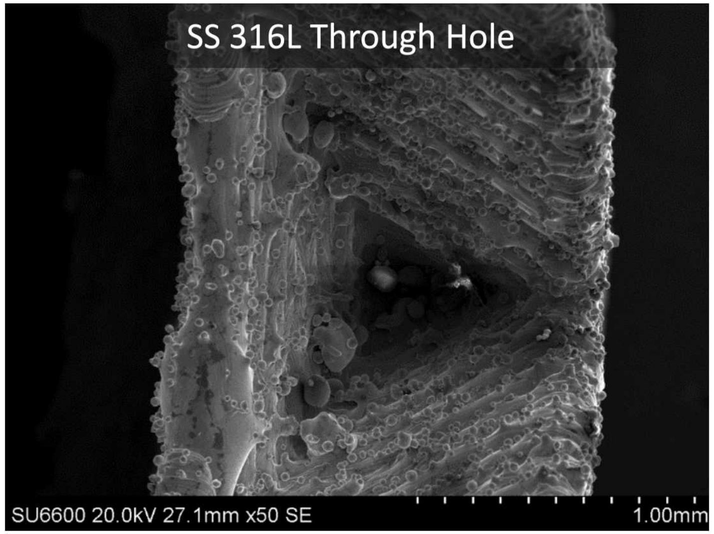


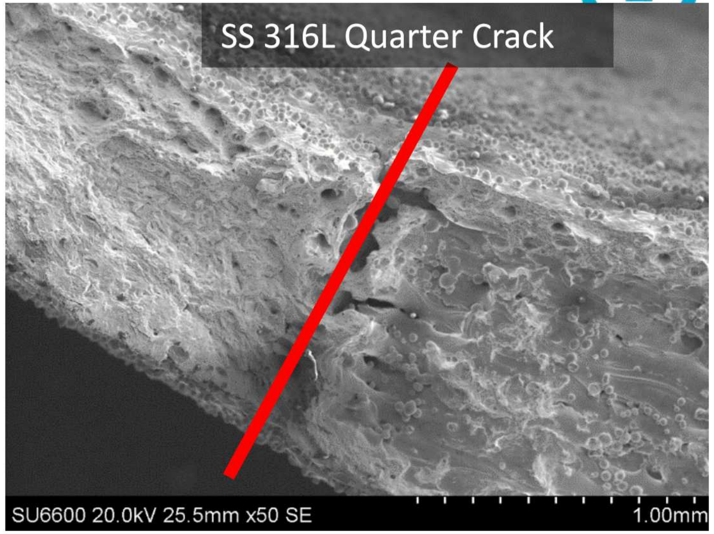


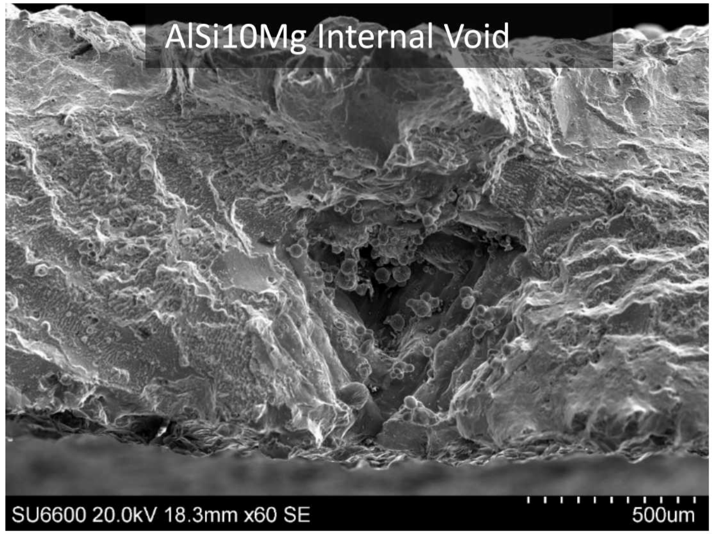
- Fractography at Clemson's Advanced Material Research Laboratory
  - Hitachi SU6600 SEM

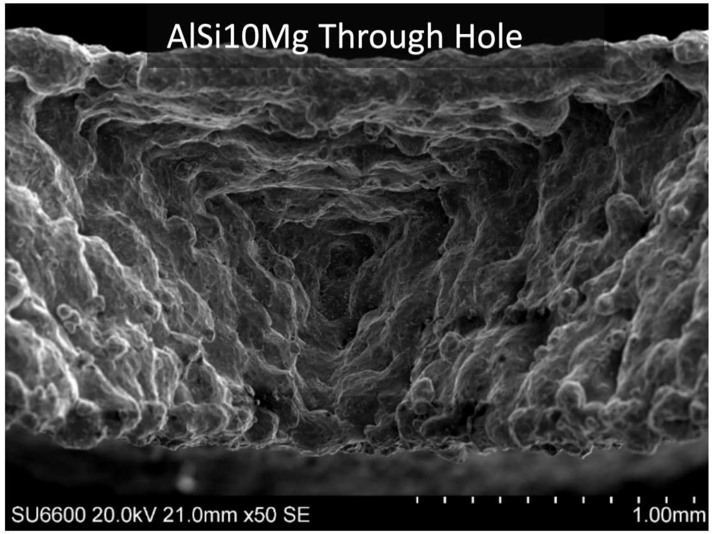
Defects

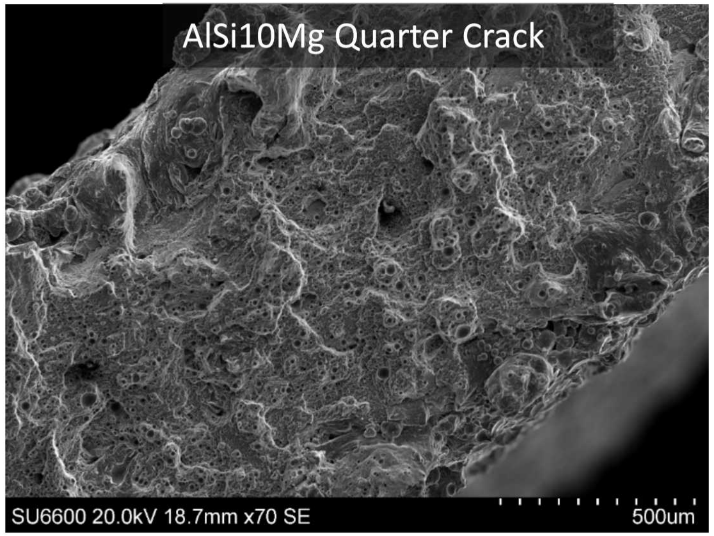

SS 316L Internal Void
SU6600 20.0kV 23.0mm x80 SE
500um


SS 316L Through Hole
SU6600 20.0kV 27.1mm x50 SE
1.00mm


SS 316L Quarter Crack
SU6600 20.0kV 25.5mm x50 SE
1.00mm

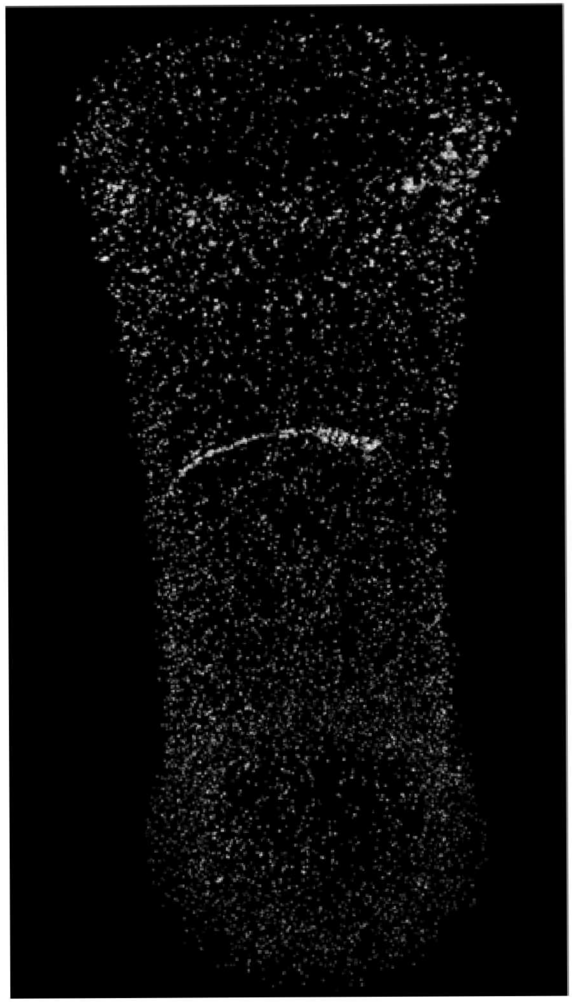

AlSi10Mg Internal Void
SU6600 20.0kV 18.3mm x60 SE
500um

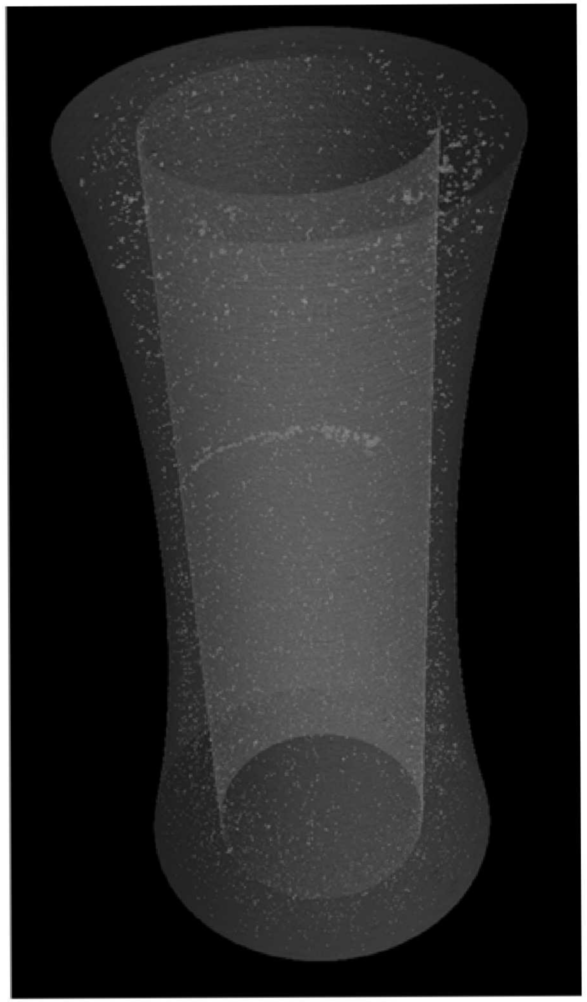

AlSi10Mg Through Hole
SU6600 20.0kV 21.0mm x50 SE
1.00mm


AlSi10Mg Quarter Crack
SU6600 20.0kV 18.7mm x70 SE
500um

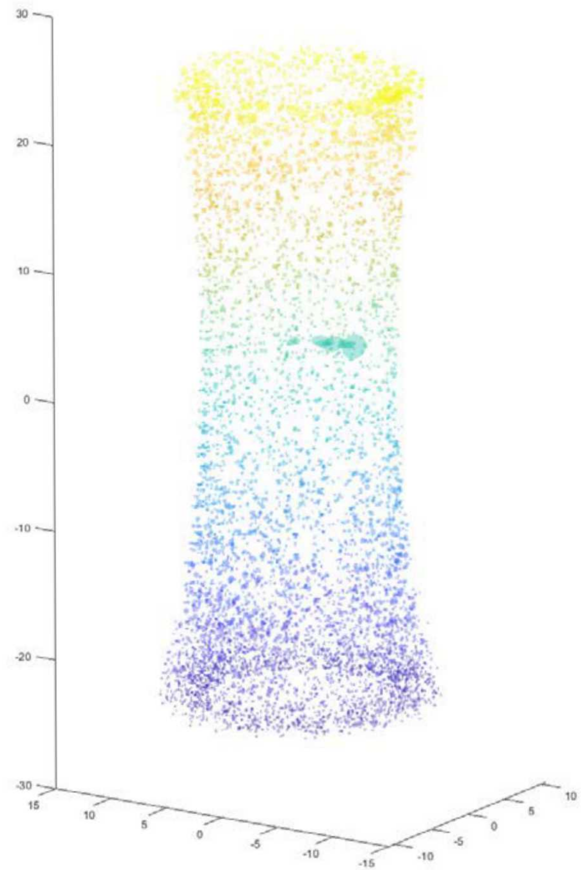
CT Images SS 316L

Sandia National Laboratories





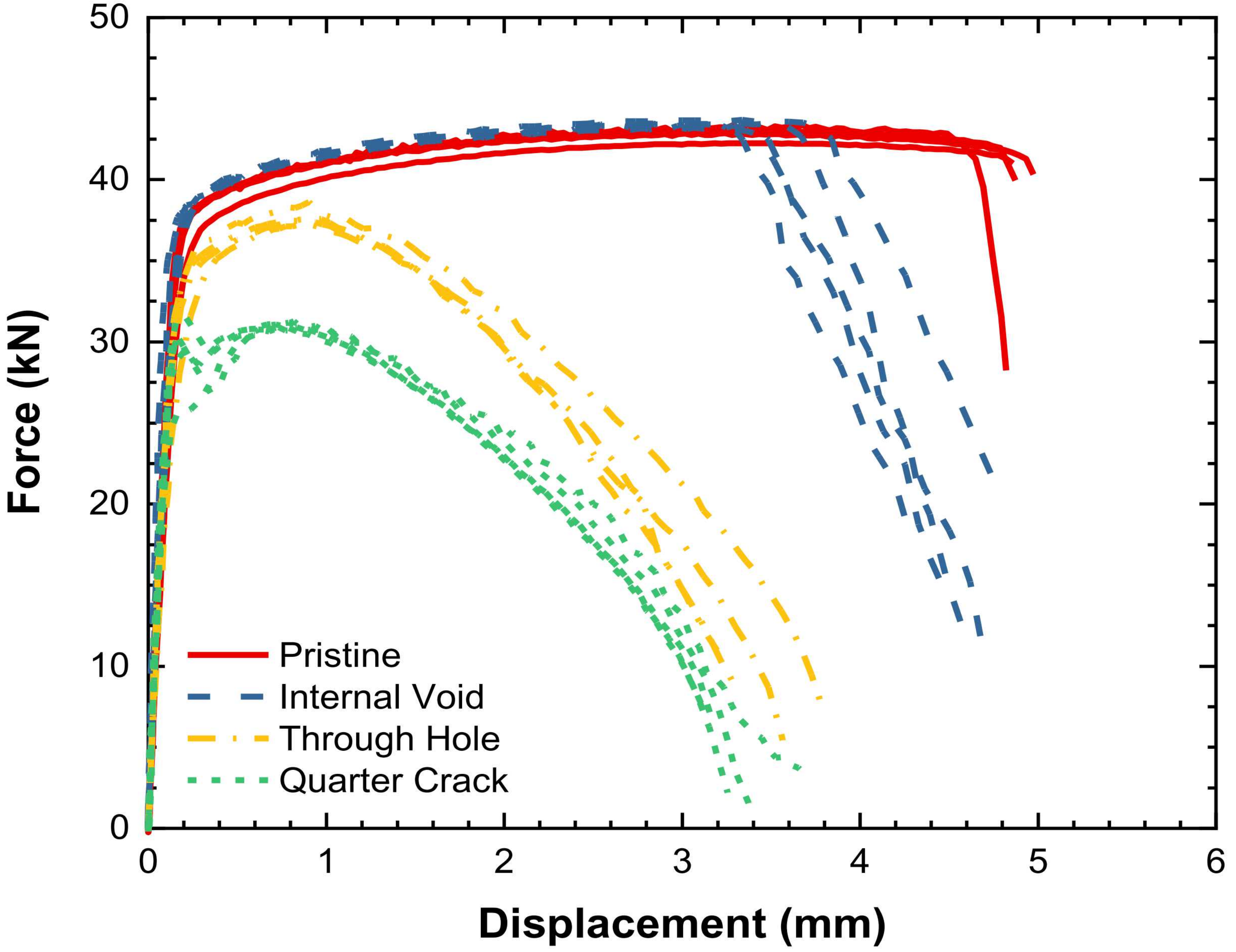
Quarter Crack



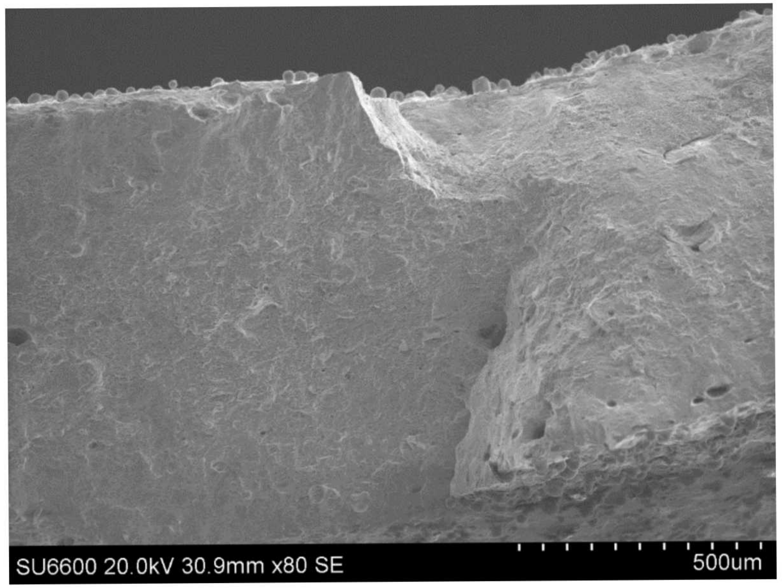
Through Hole

Voxel size: 30 μm x 30 μm x 30 μm

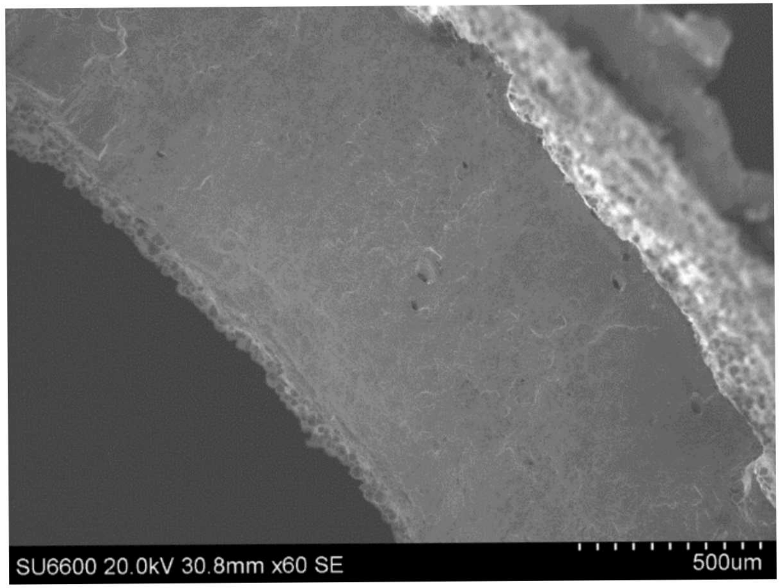
SS 316L Components. Flaws affect force proportionally.



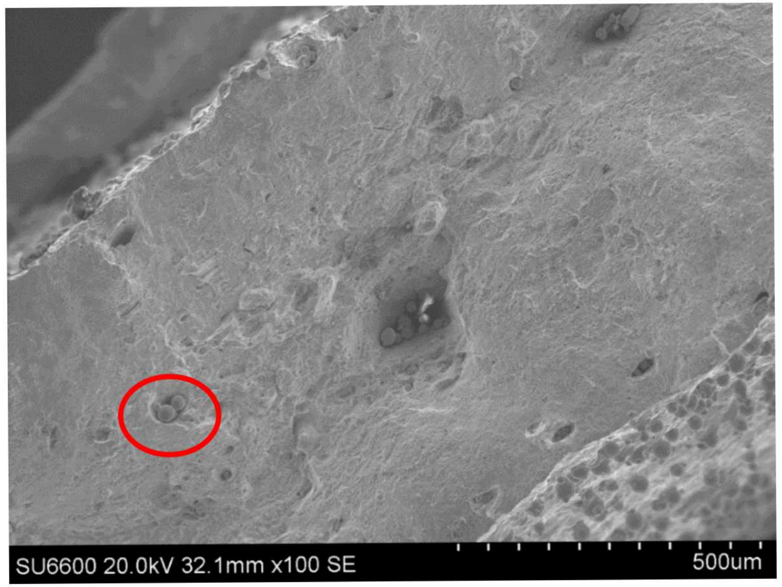
"Pristine" fractures appear smooth and more brittle looking.



Sharp, jagged edges on fracture surface, indicating brittle fracture. Not cup-cone ductile dimples

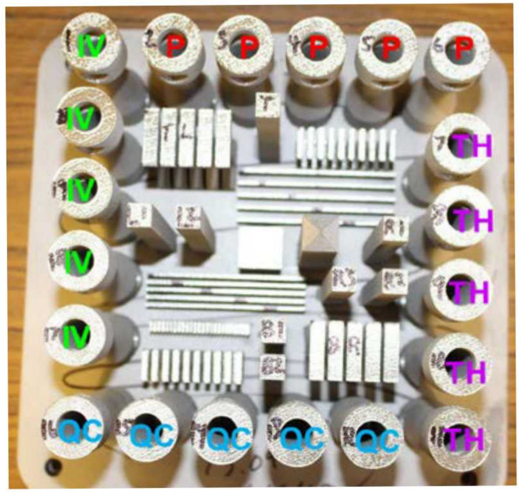


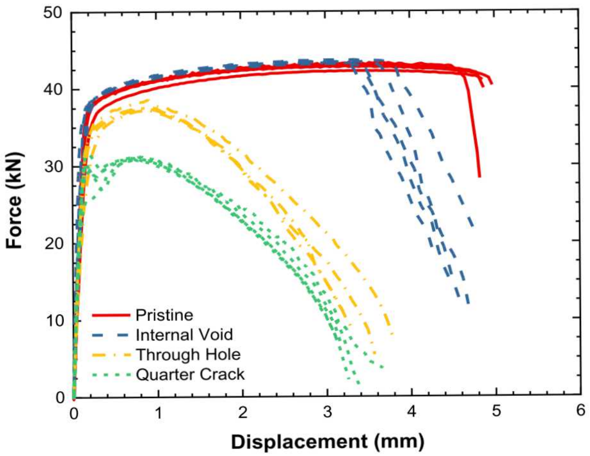
Flat surface indicative of brittle fracture



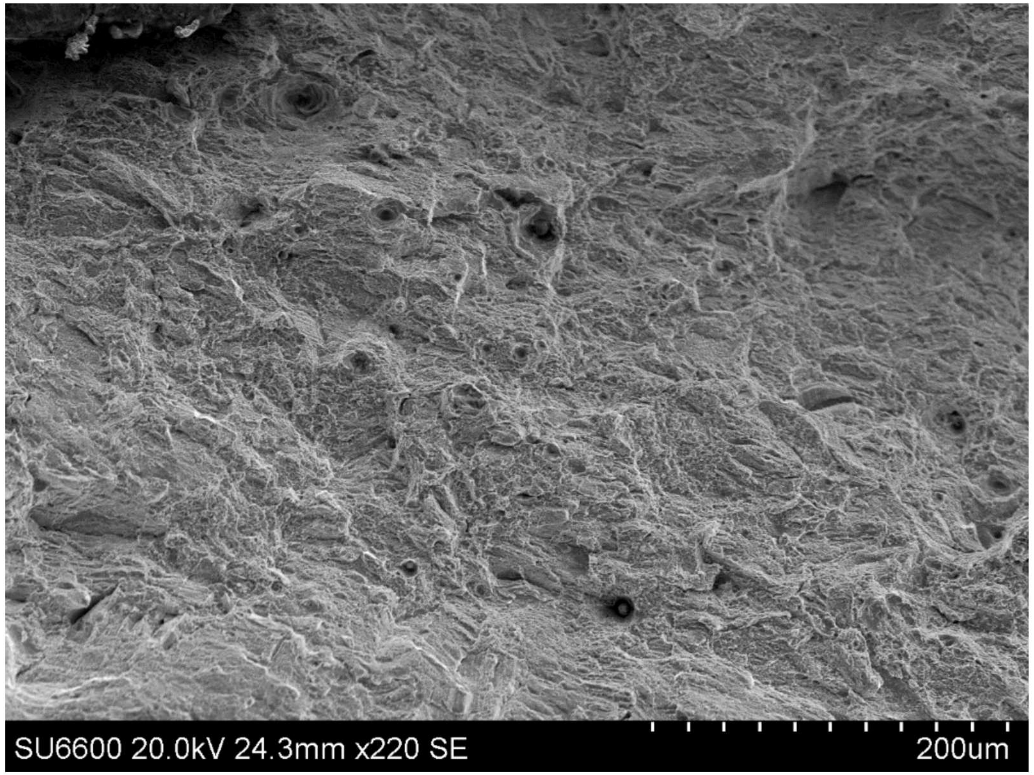
Unmelted particles on fracture surface

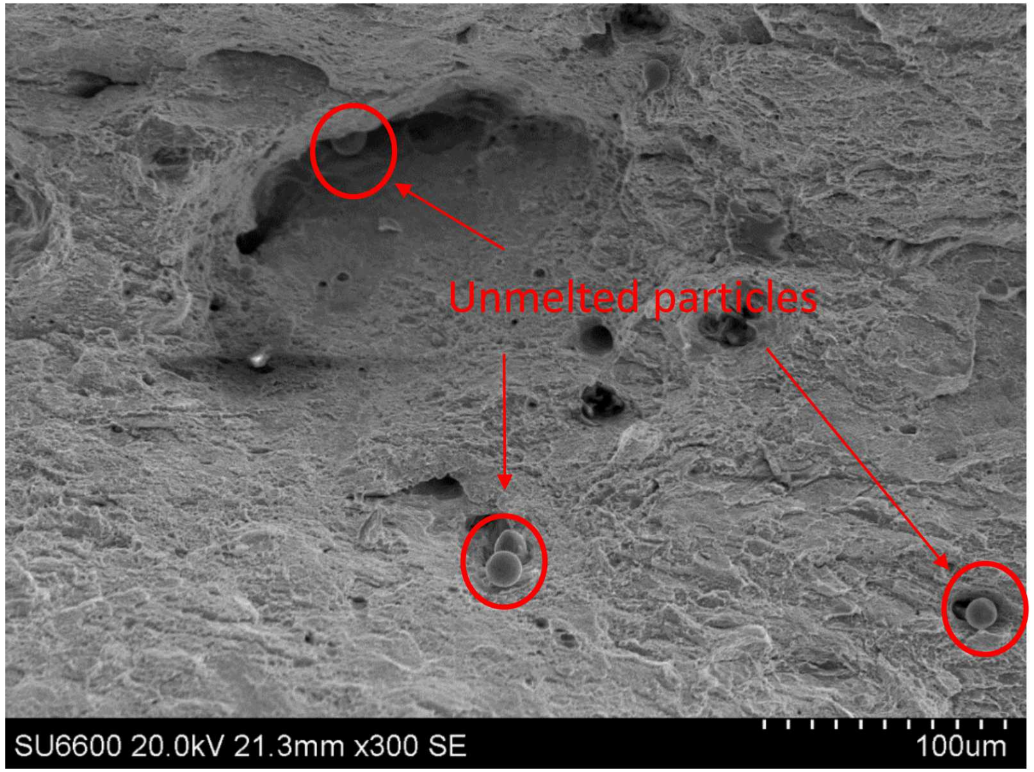
- **Consistent with low post-peak ductility.**
- **Print location effects?**



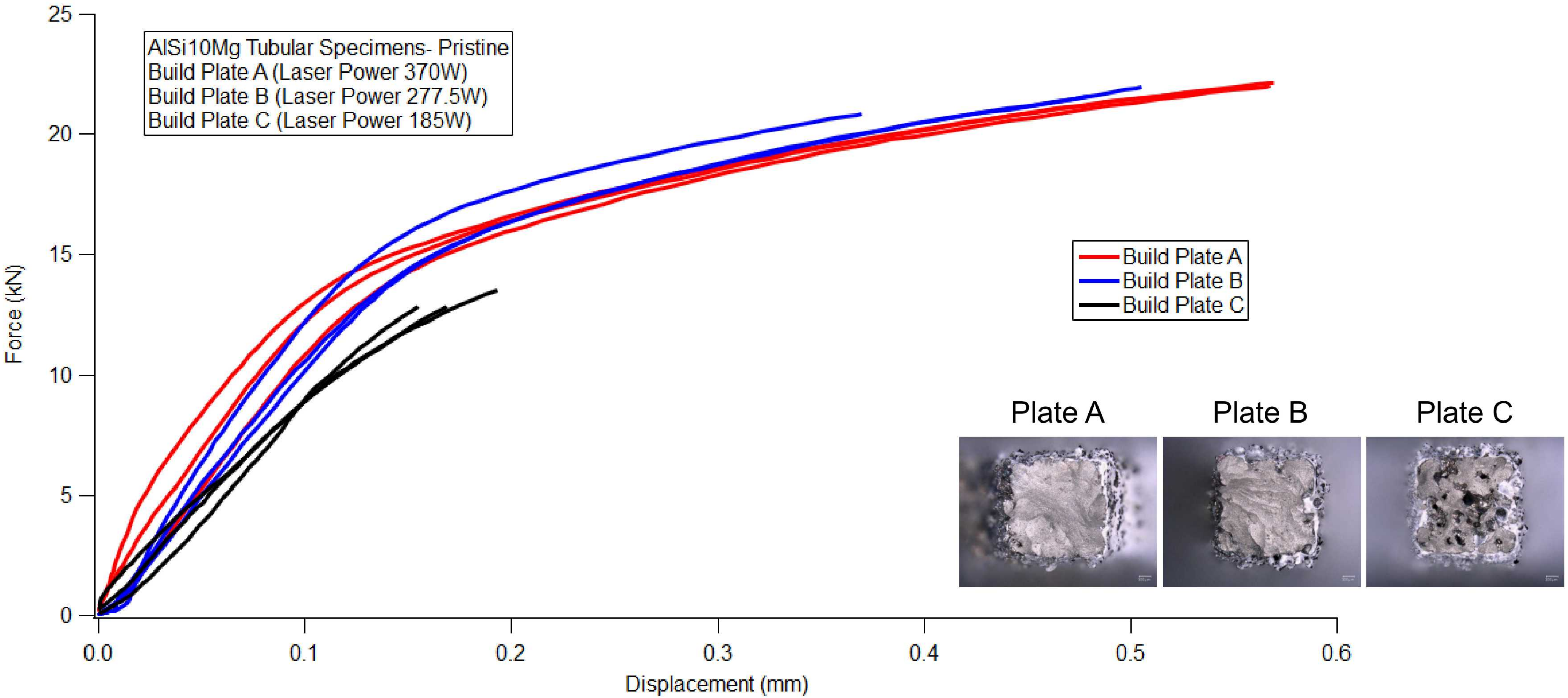


Defect Fractography Key Features





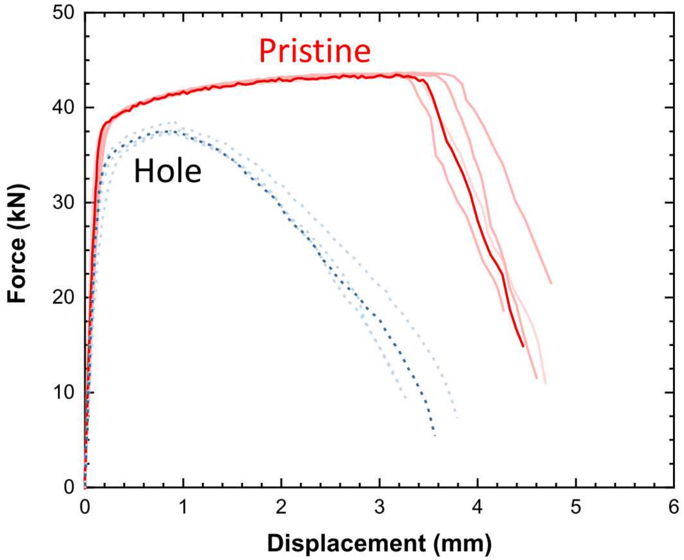
AlSi10Mg Build Plate Comparison of Pristine Tubular Specimens



Flaws impact AlSi10Mg more than 316L Stainless Steel

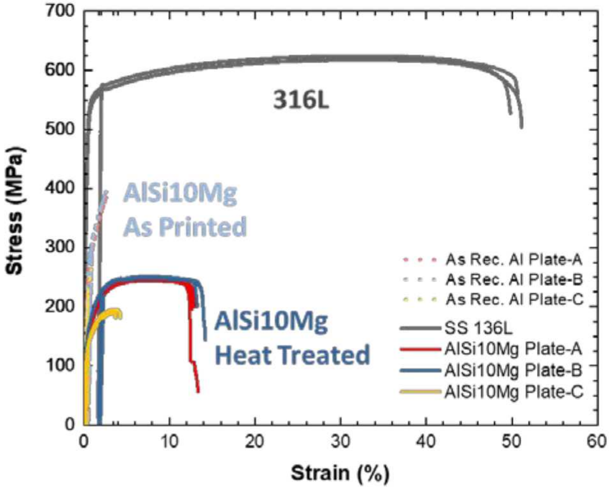
316 Stainless Steel

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



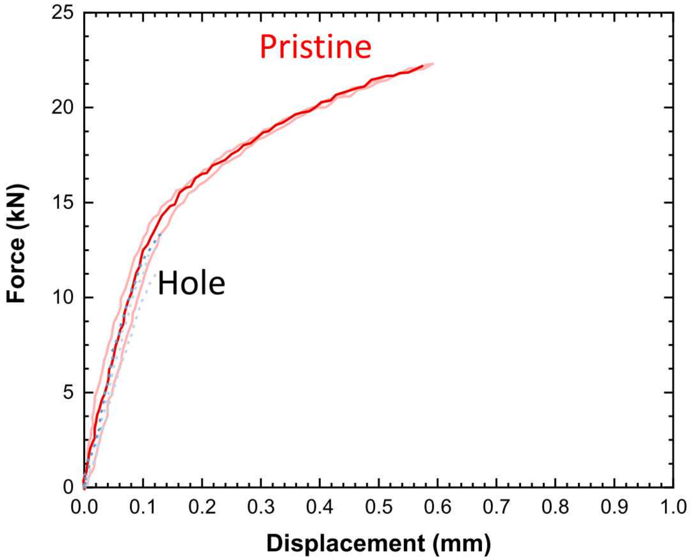
Hole reduces strength by 10% and ductility by 20%

2 mm Through-hole
Corner Cube Void



AlSi10Mg

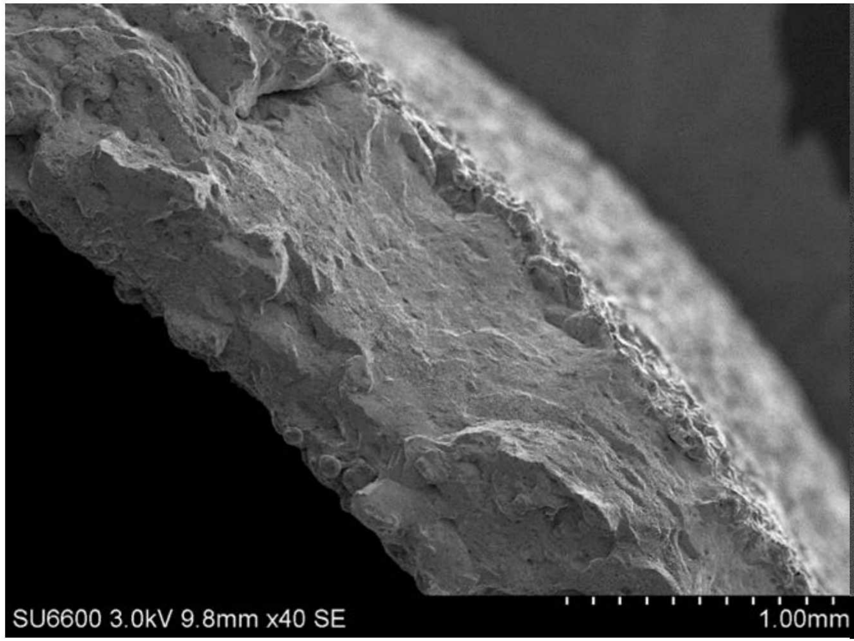
- **K = 20 MPa√m**
- **Charpy Impact toughness >8 ft-lbs**
- **Ductility = 10%**



Hole reduces strength by 40% and ductility by 65%

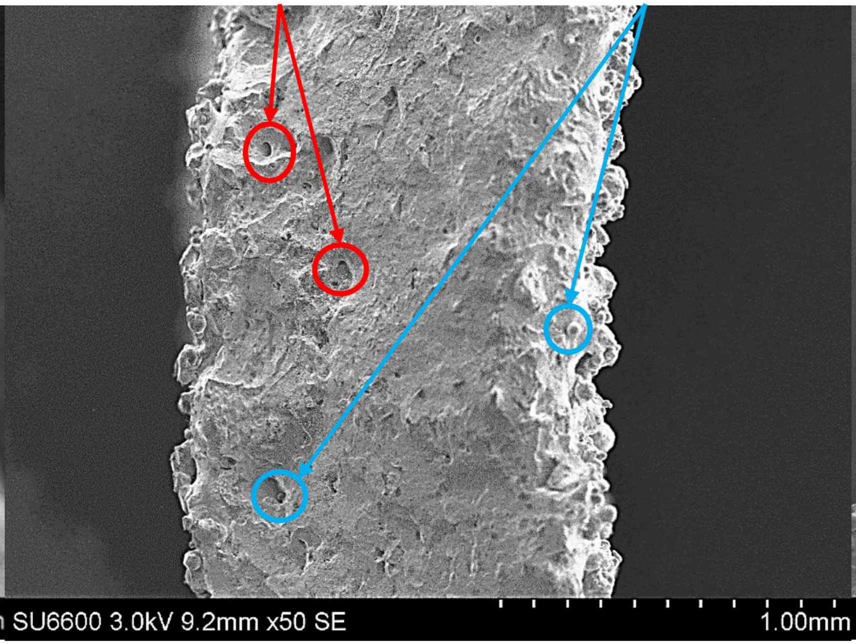
Fractography of AlSi10Mg Tubular Specimens

Build Plate A



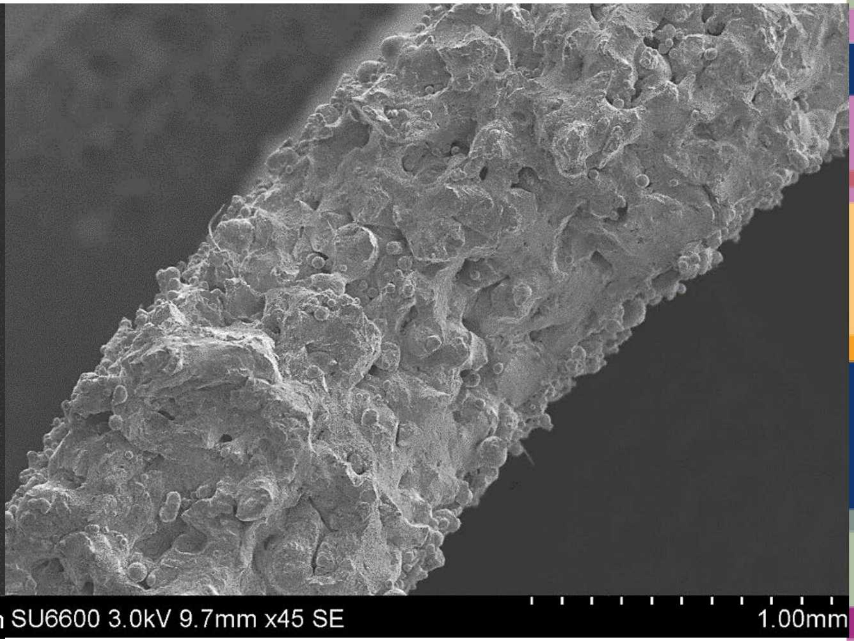
Build Plate B

Voids Unmelted particles



Build Plate C

Many voids and unmelted particles



Brittle fracture is seen in all AlSi10Mg tubular specimens

AlSi10Mg Tubular Results

Plate A
Defect-type driven

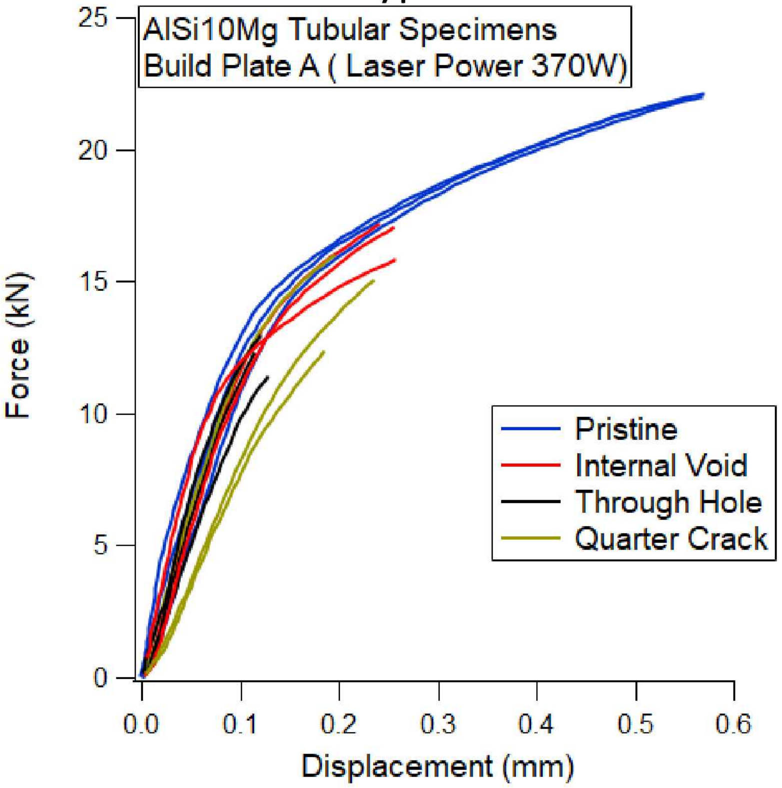


Plate B
Defect-presence driven

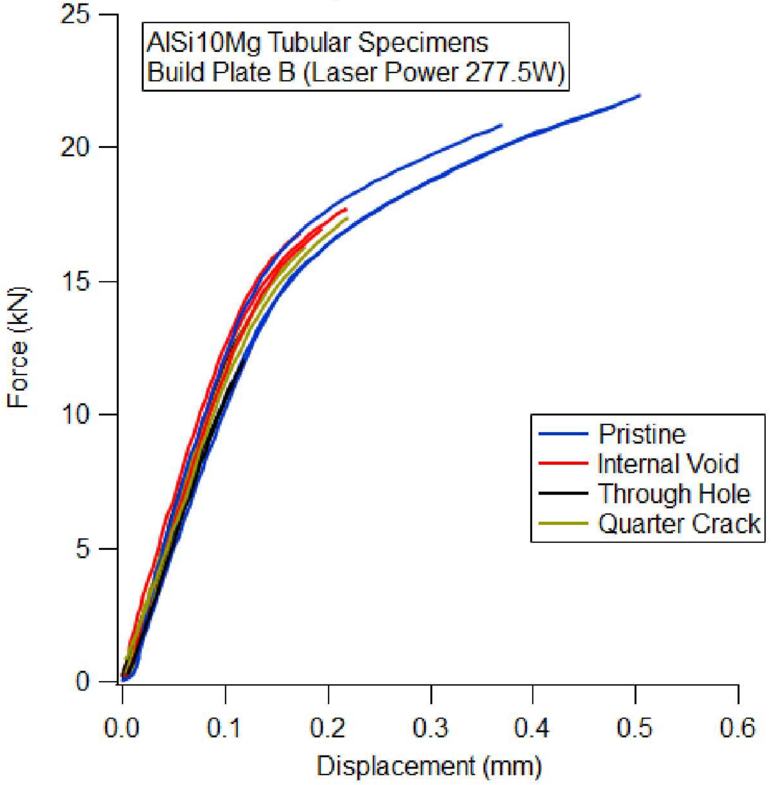
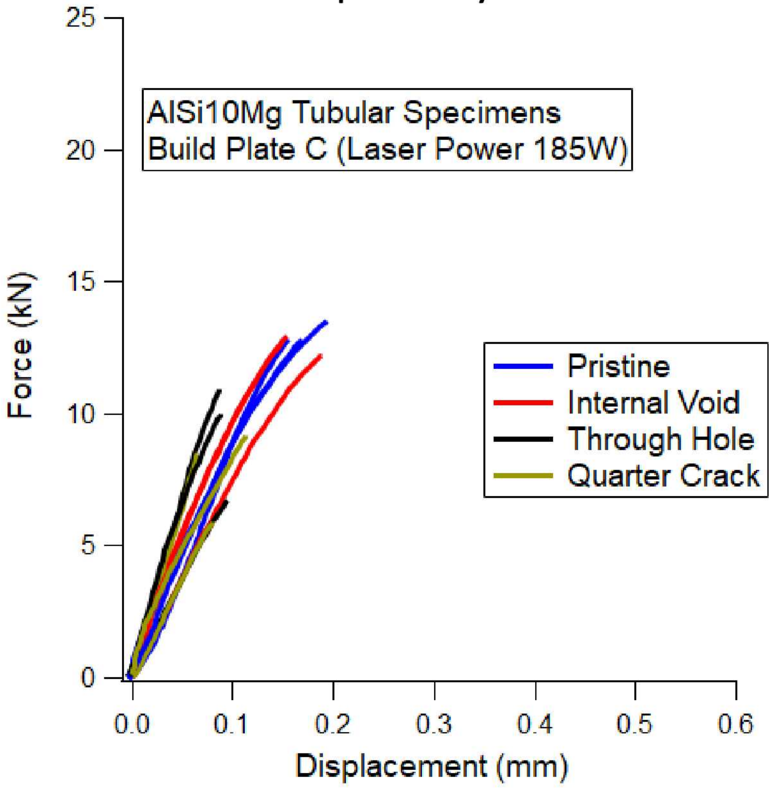
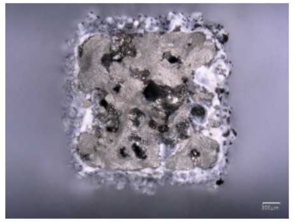


Plate C
Bulk porosity driven



- **Brittle fracture is seen in all AlSi10Mg tubular specimens (no post-peak ductility)**
- **Quarter crack was printed and may not be fully separated**
- **Distributed porosity can be more important than large discrete flaws.**

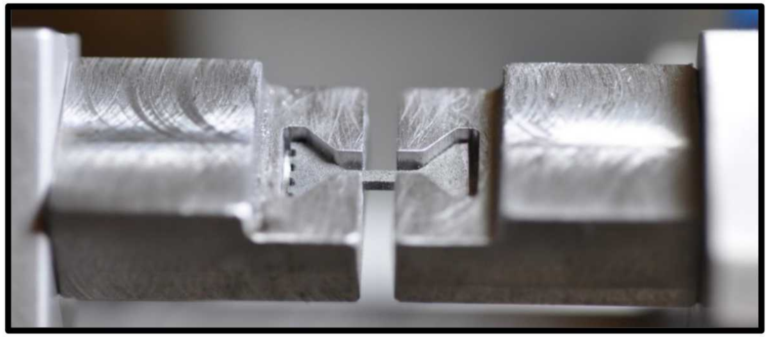


Bulk Porosity Defects

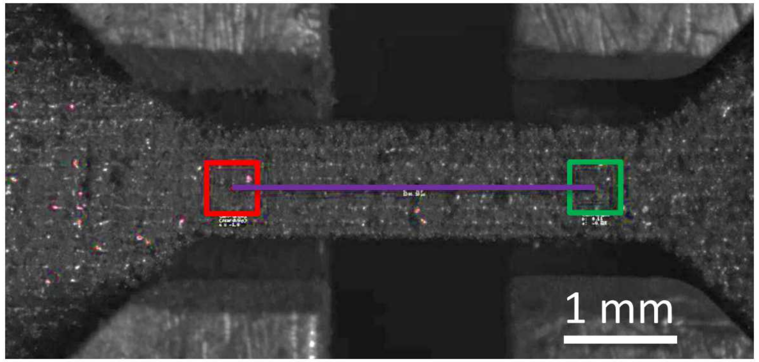
Multiple Defects Acting Together

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

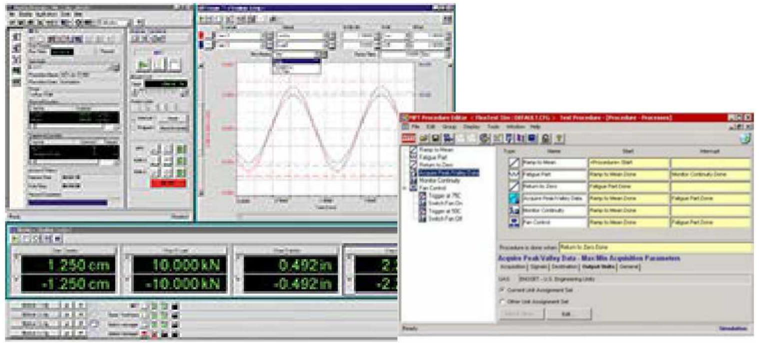
1. Self-aligning 'drop-in' grips

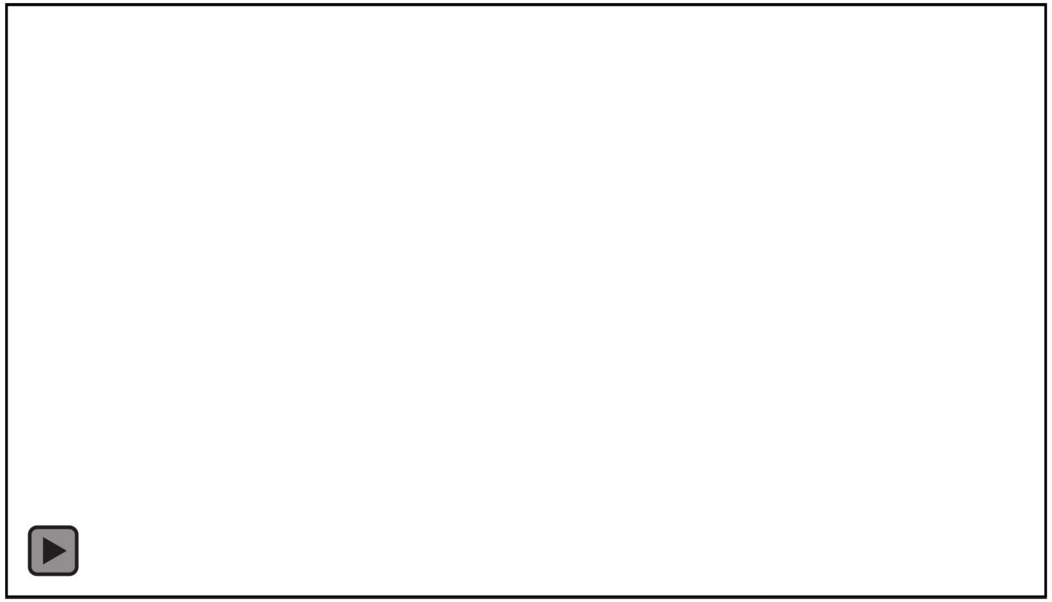


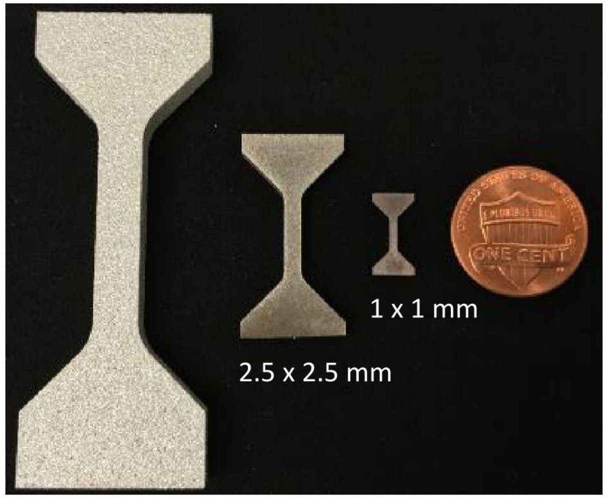
2. Non-contact virtual extensometer with "live" digital image correlation



3. Maximize software automation to reduce operator burden



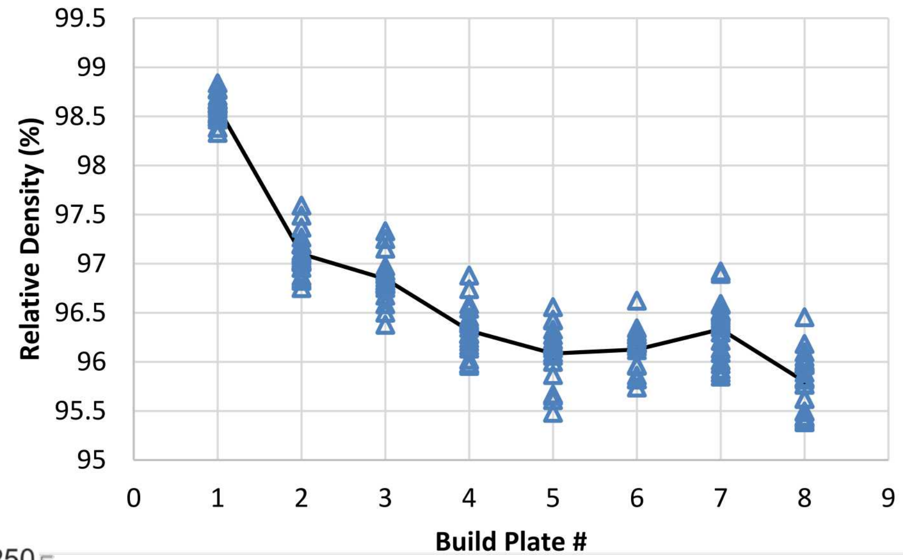


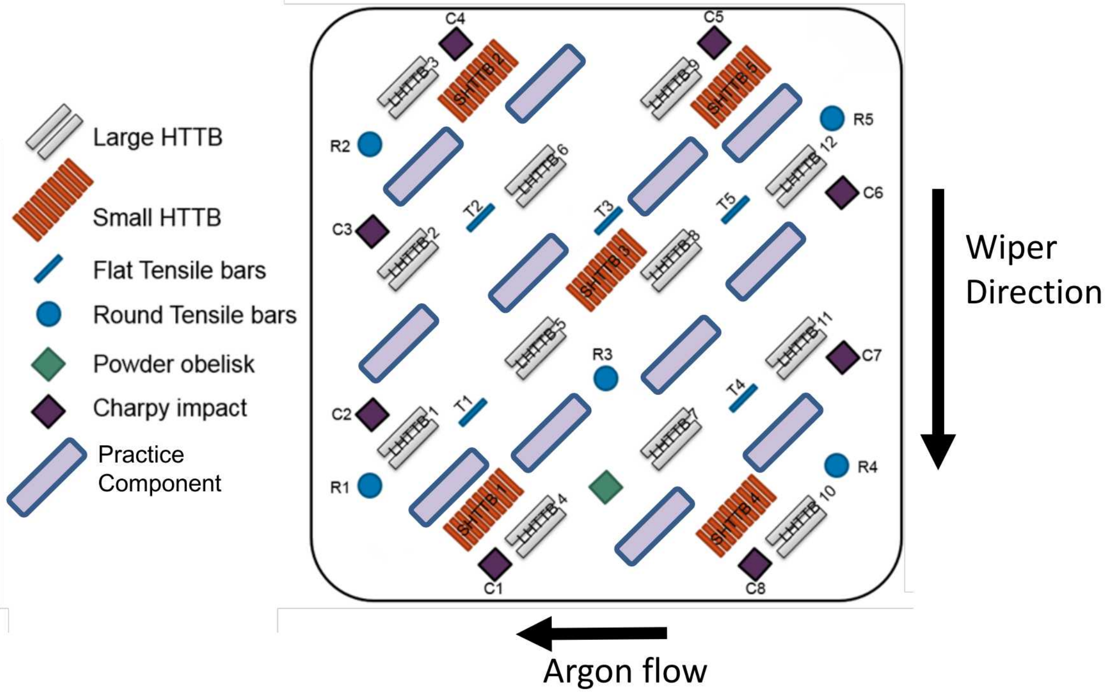


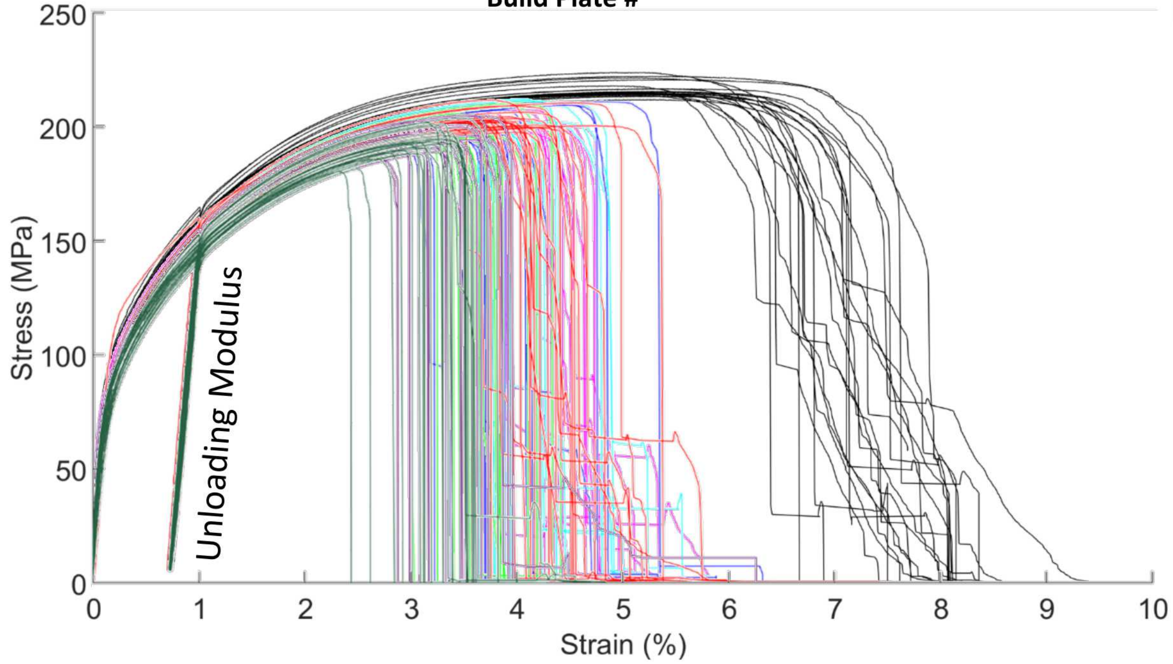
6.25 x 6.25 mm

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

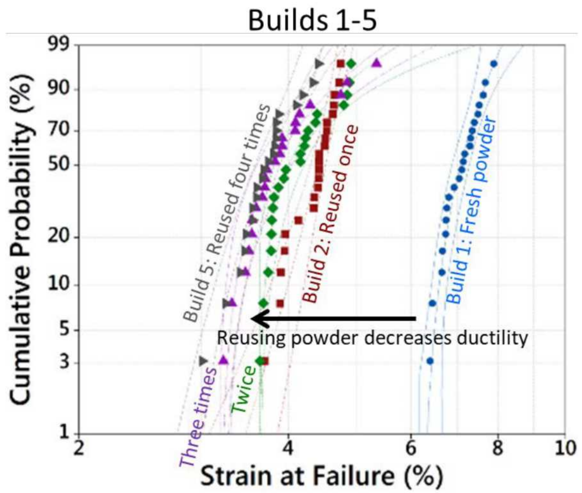
Powder reuse of AlSi10Mg gives different levels of porosity and tensile properties for each build plate.



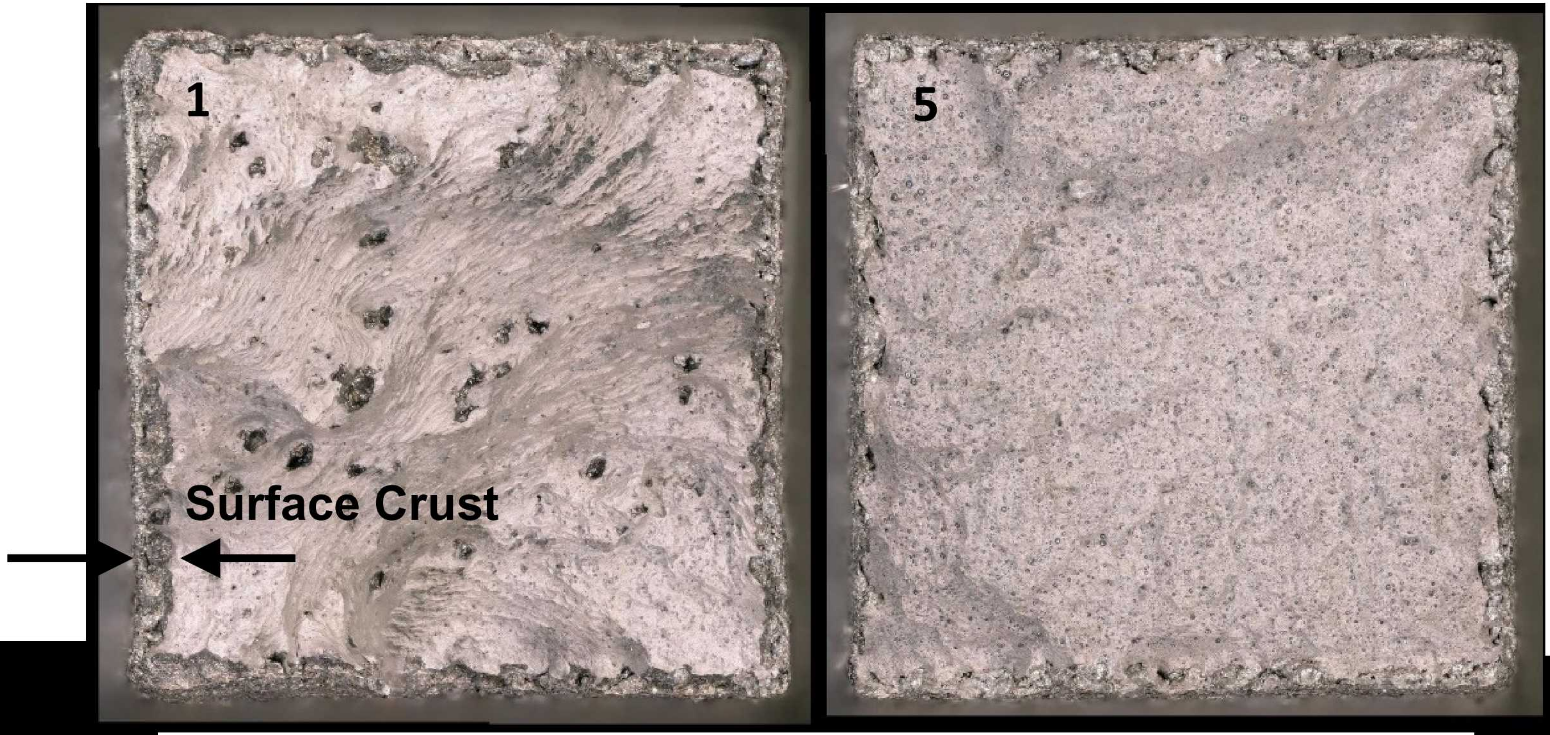


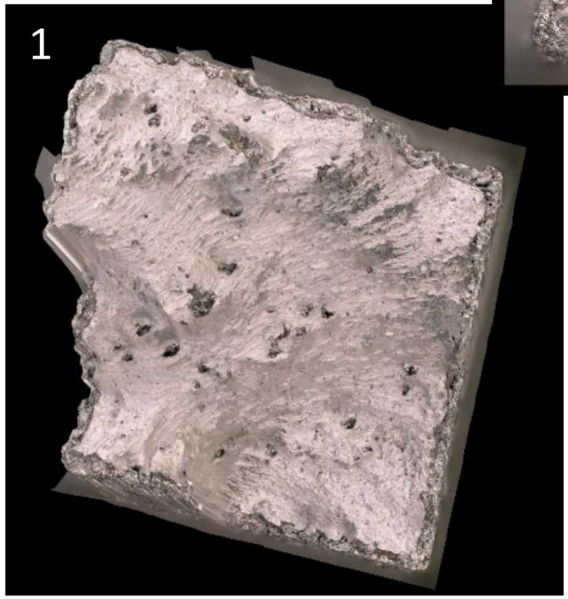


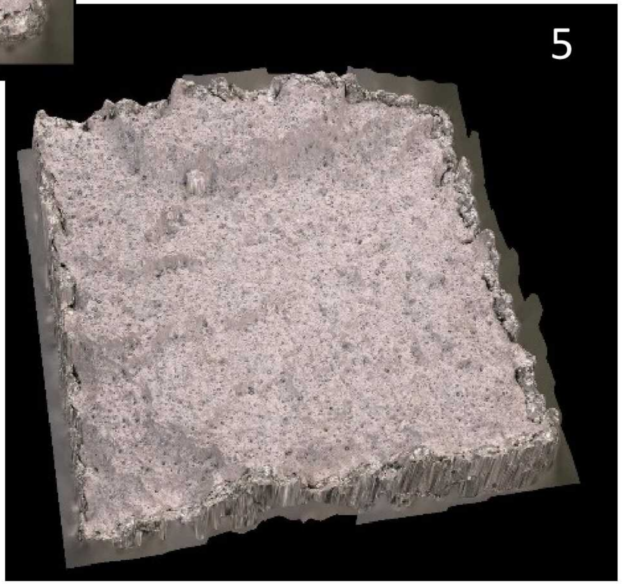
Build	Powder condition
1	**Fresh Powder**
2	Reused once
3	Reused twice
4	Reused 3 times
5	Reused 4 times
6	**Fresh (stored) Powder**
7	Reused once
8	Reused twice



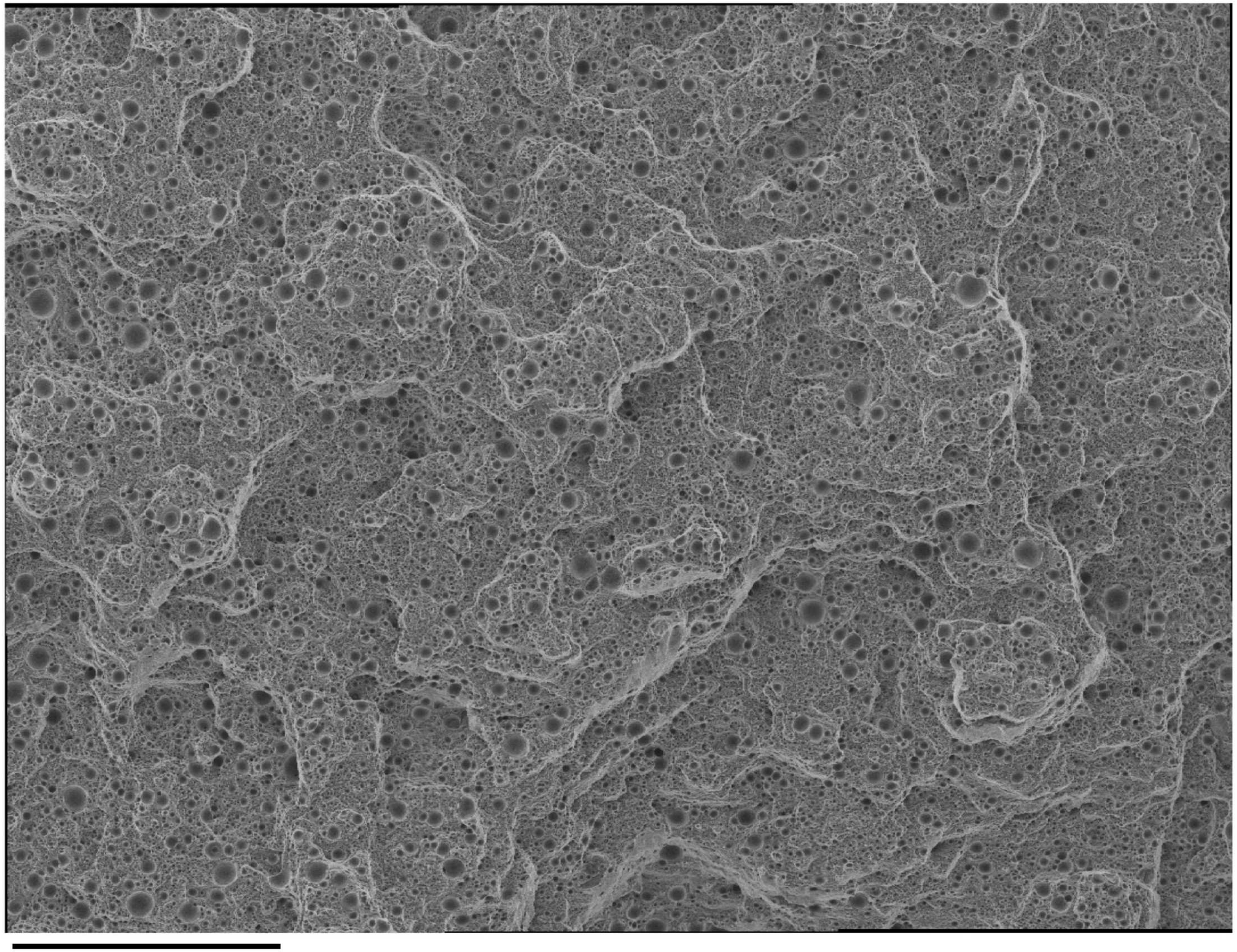
Lower strength specimens have substantially more small voids (20-50 µm).







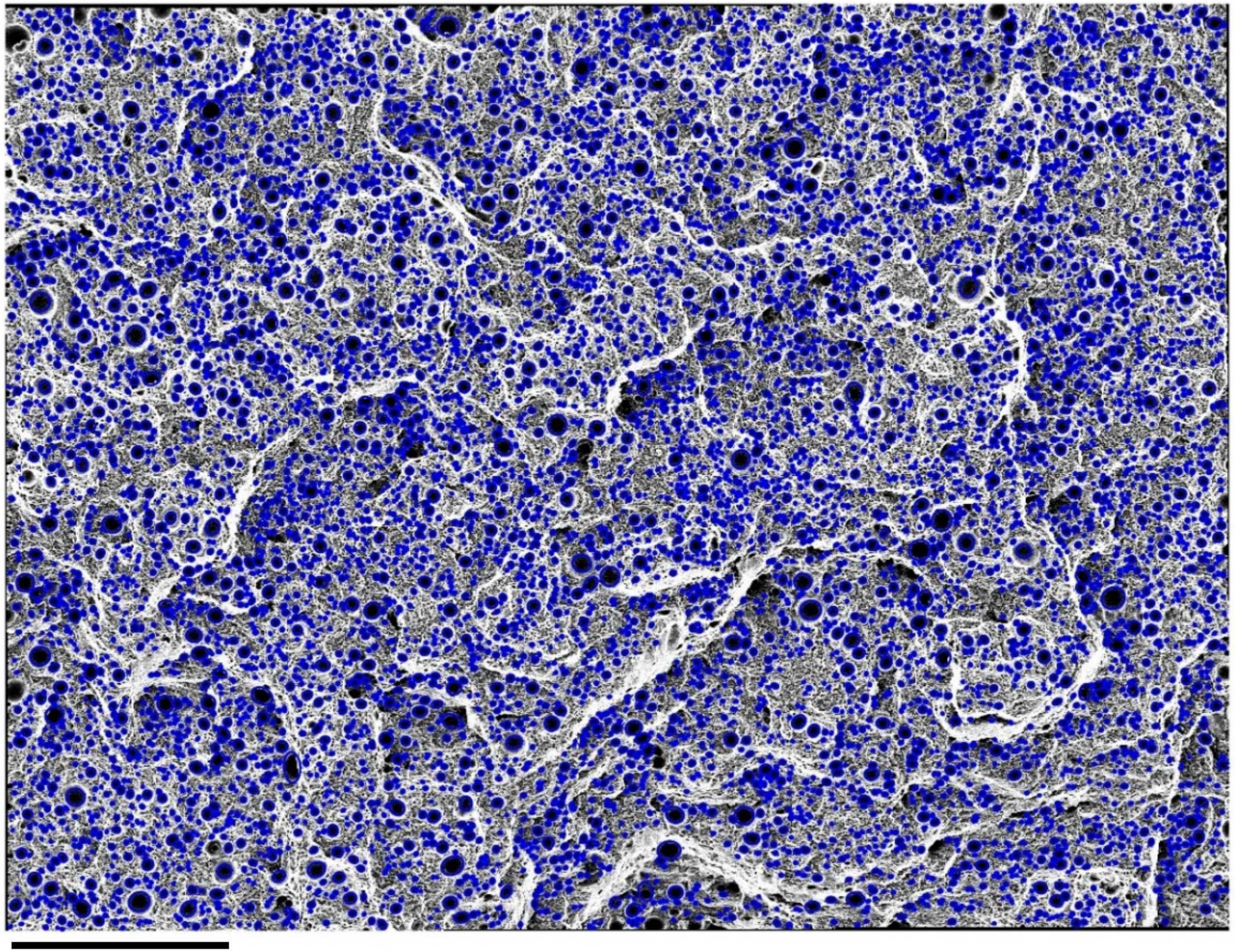
High throughput fracture surface imaging



Build Plate 3

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

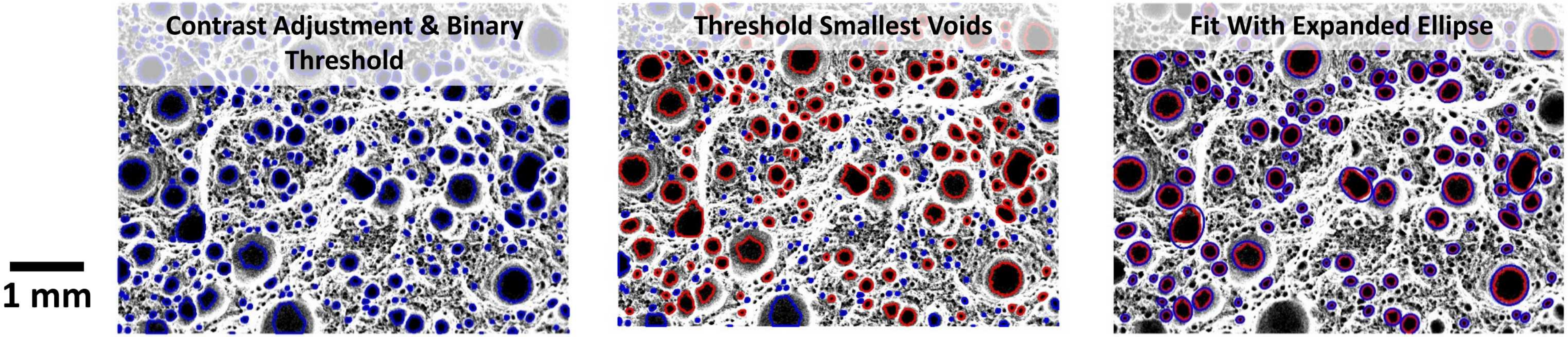
High throughput fracture surface imaging

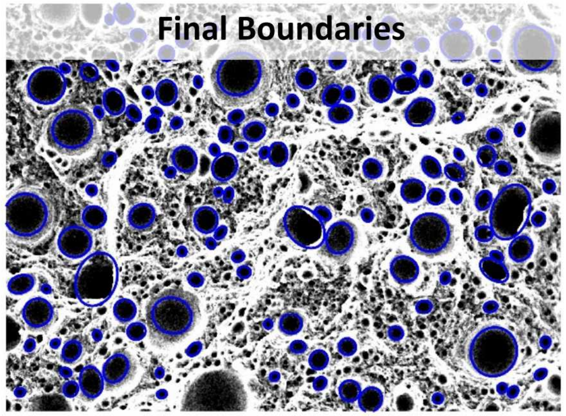


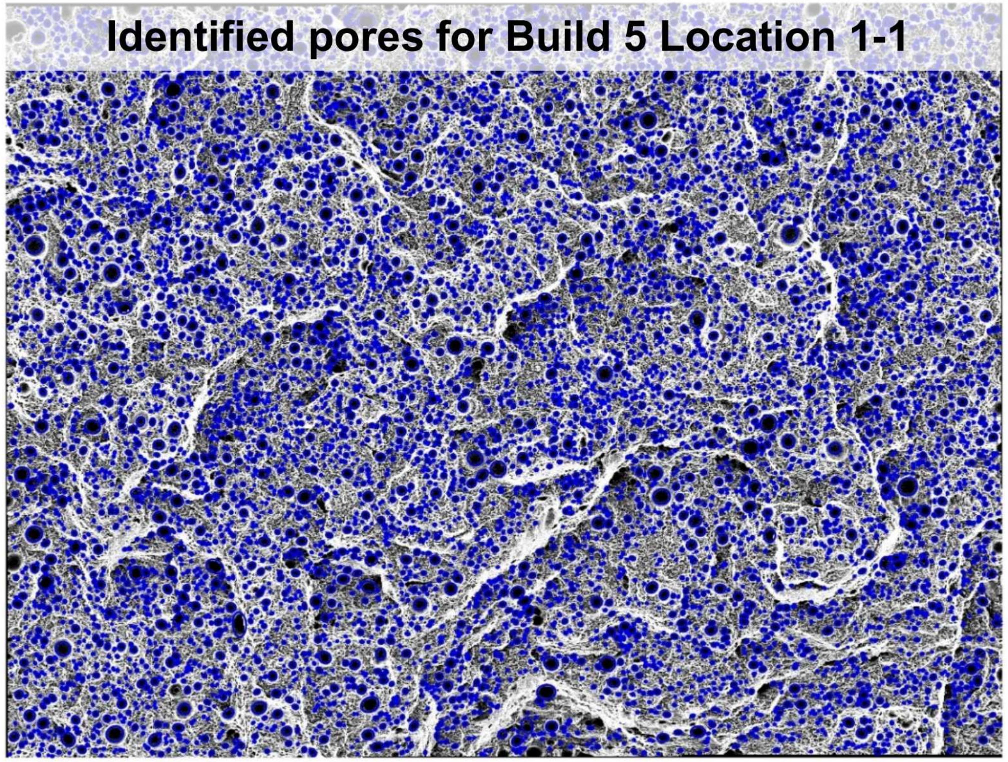
0.5 mm

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

Void identification algorithm to measure porosity on fracture surfaces

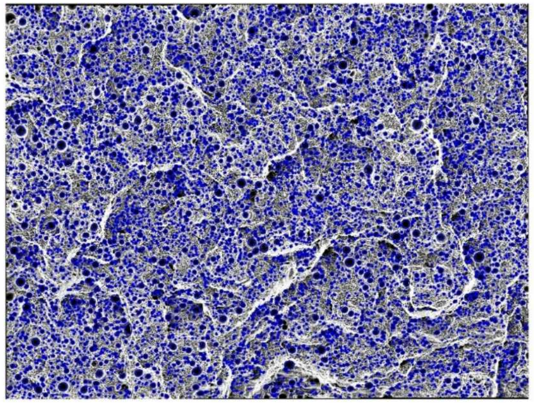


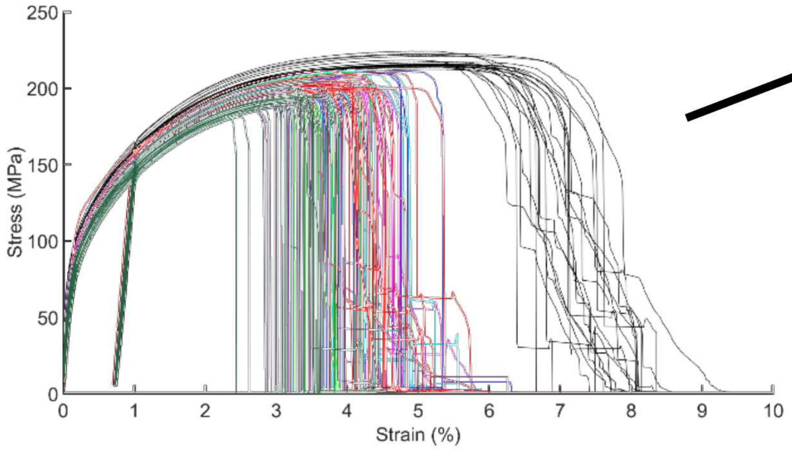


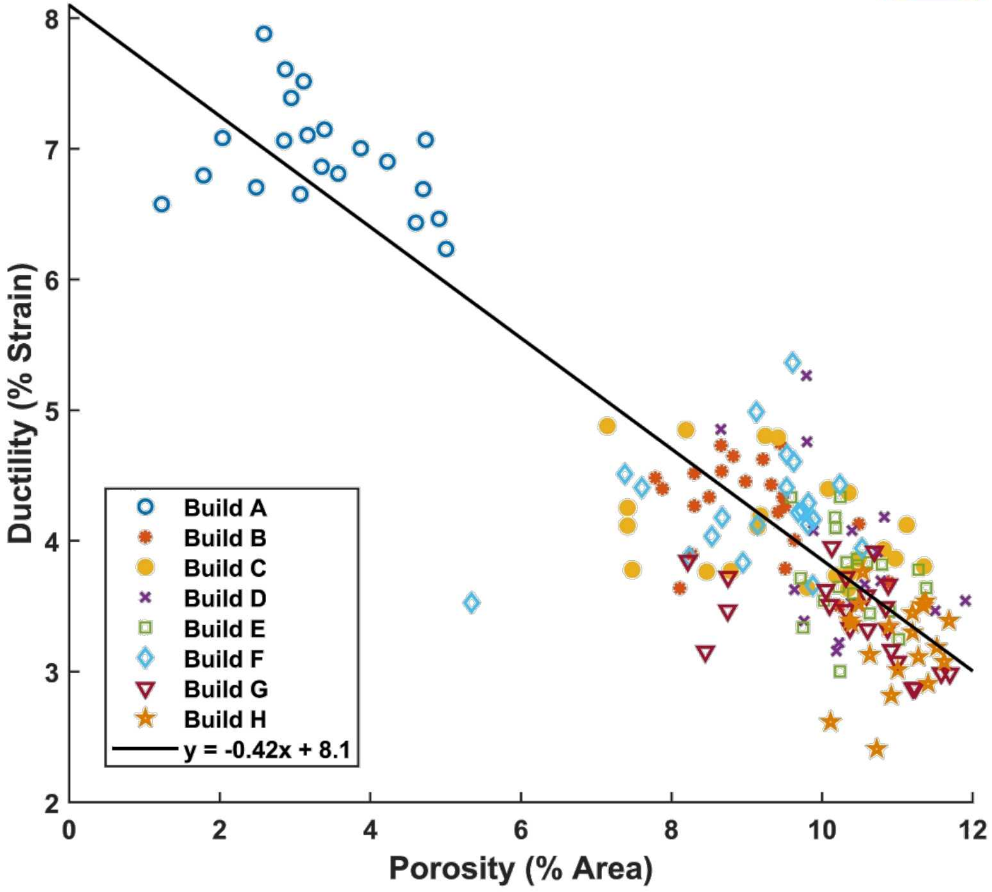


- **Identify voids on a fracture surface from high throughput SEM images.**
- **Multistep process does more than simple thresholding.**
- **Algorithm allowed ~172 fracture surfaces to be analyzed—about 10x more than was possible before.**

Compare ductility to fracture surface porosity



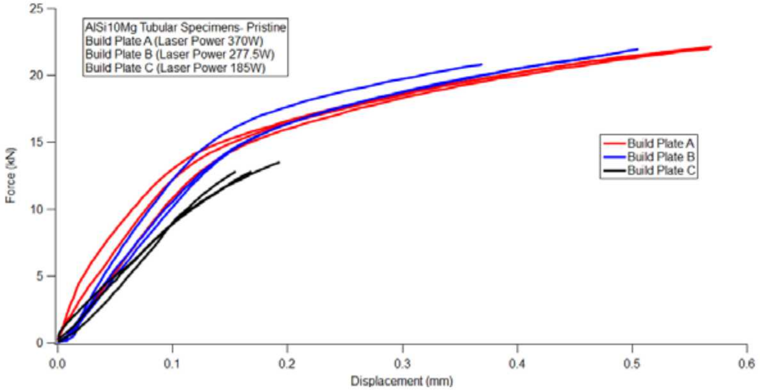


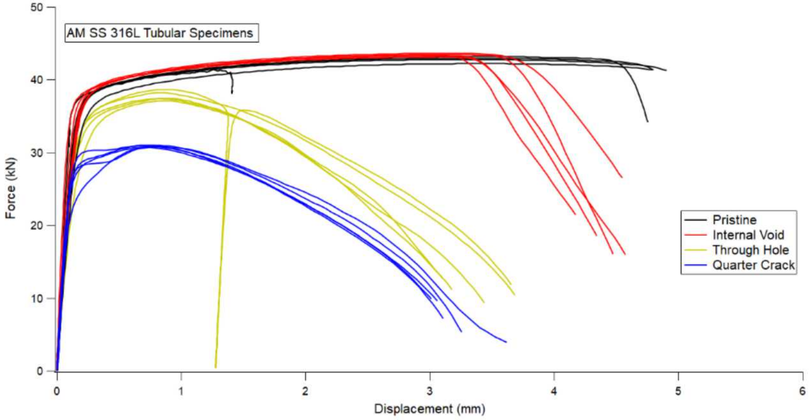


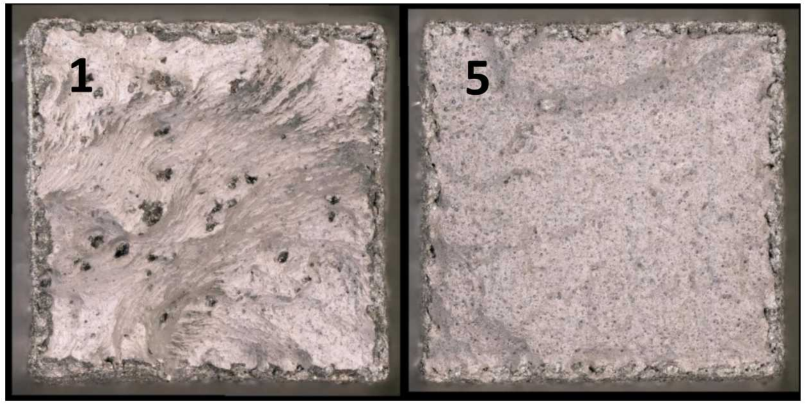
- **Increasing fracture surface porosity by 1% decreases ductility by 0.5%.**
- **Fracture porosity is NOT equivalent to density.**
- **Relationship between fracture surface porosity and density?**

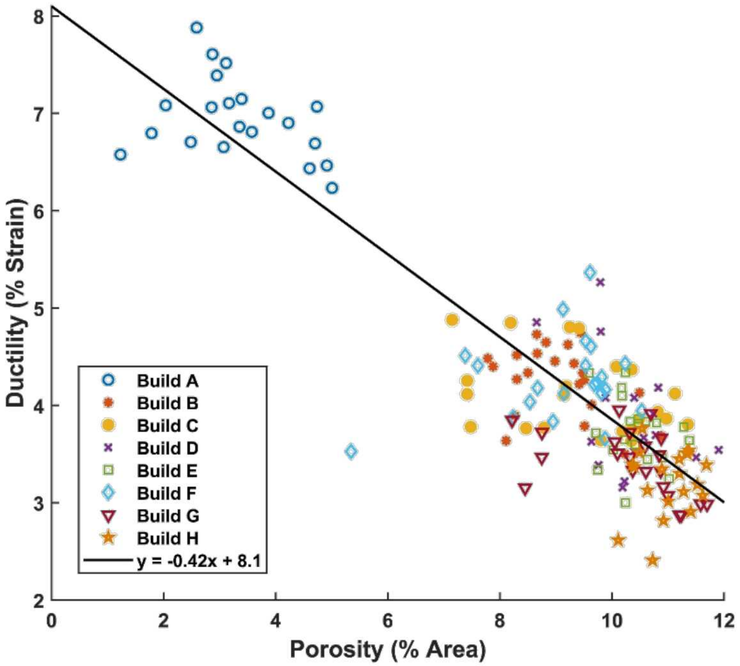
Conclusions

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 that regime.**



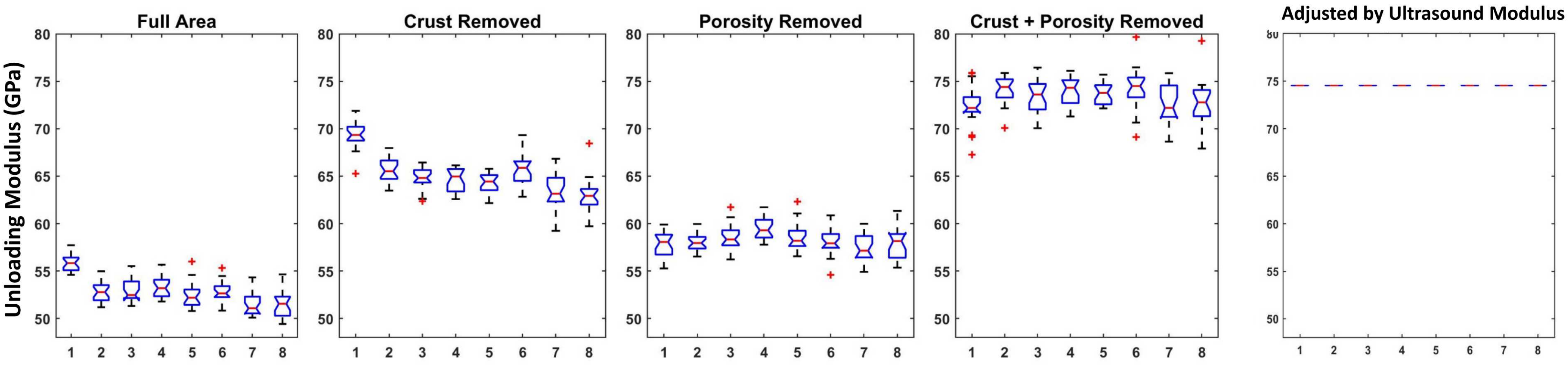




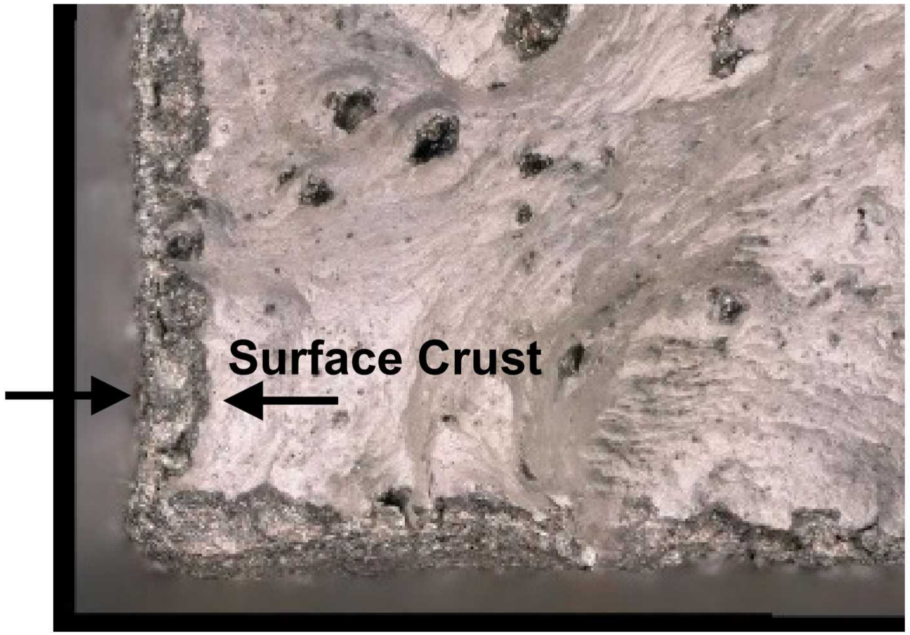


Thank You

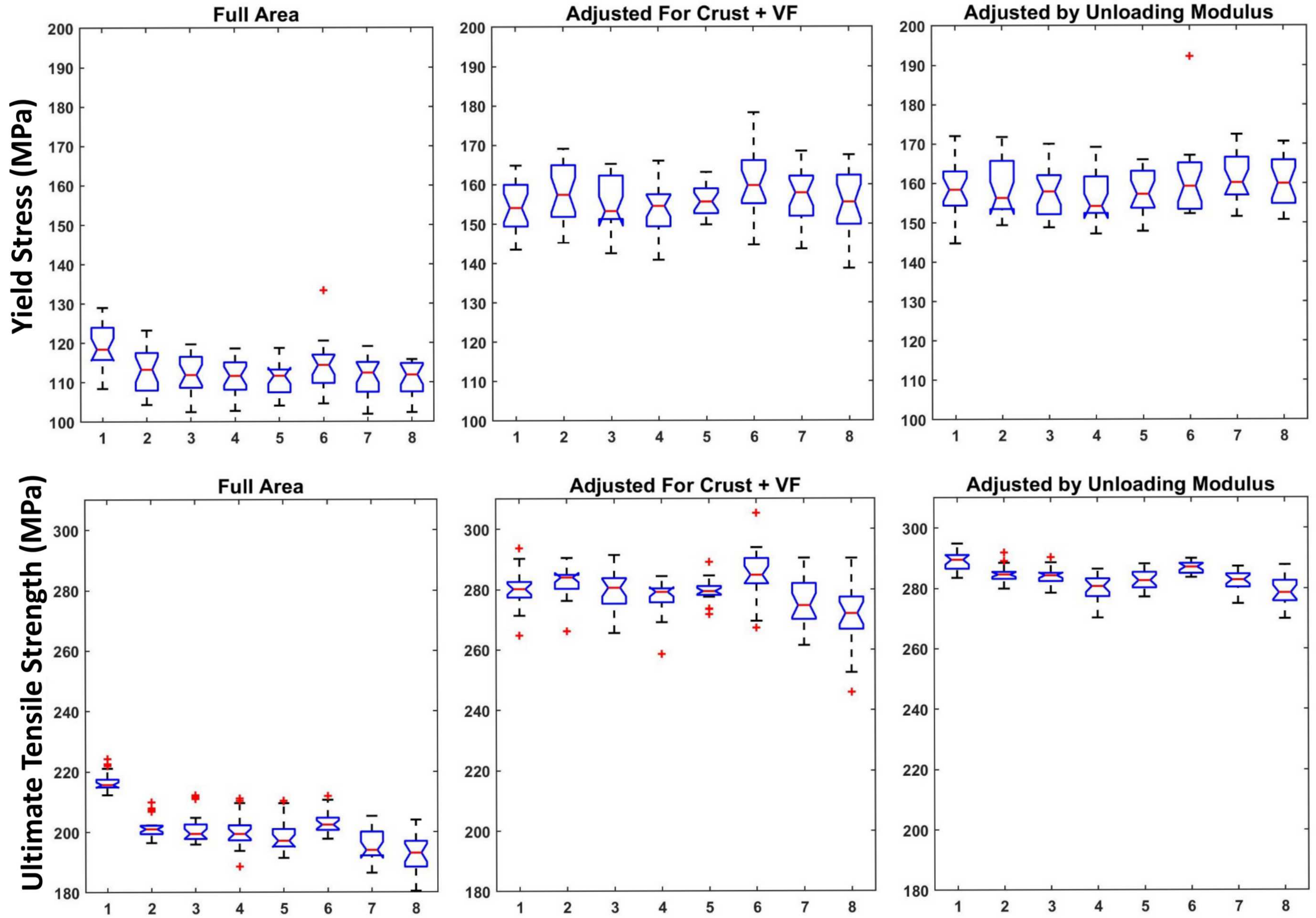
Crust and porosity effects on unloading modulus



- **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.**



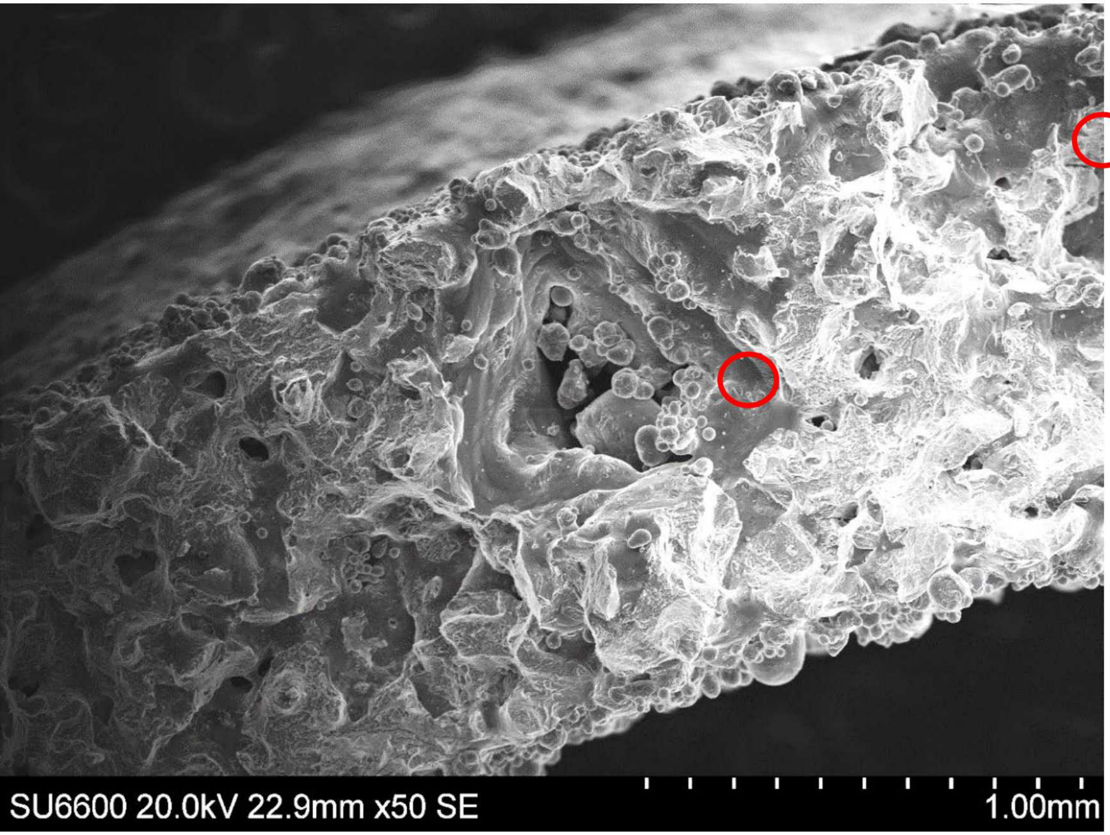
Crust and porosity effects on ultimate tensile strength



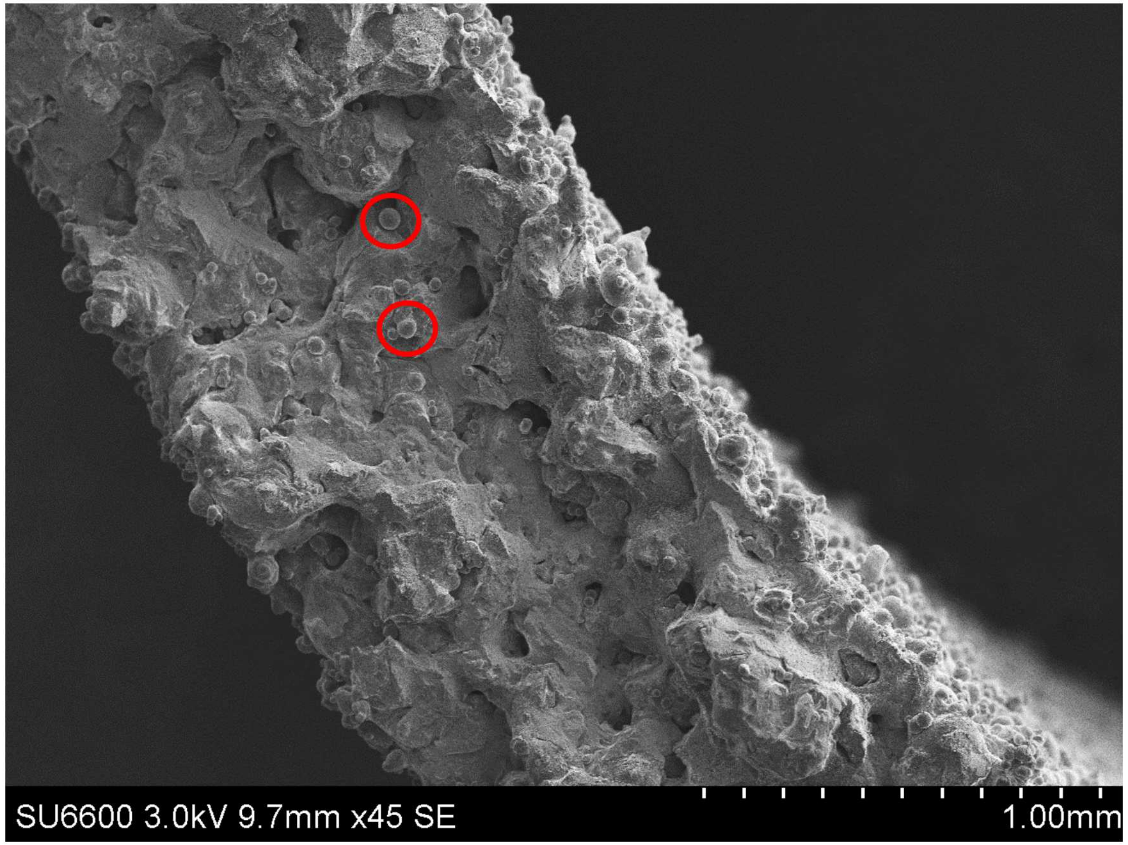
- **Inherent Yield stress is 160 MPa instead of 120 MPa.**
- **Inherent Tensile strength is 280 MPa instead of 200 MPa.**

Fractography of Al10MgSi Build Plate C

Internal Void



Pristine



Lack of fusion defects: Unmelted particles and voids are common in plate C specimens.