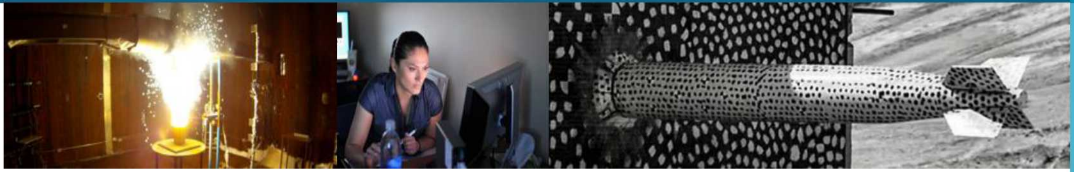
Sandia National Laboratories

SAND2019-11717C

Effect of Interactions Between Flaws and Material Properties on Component Performance



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LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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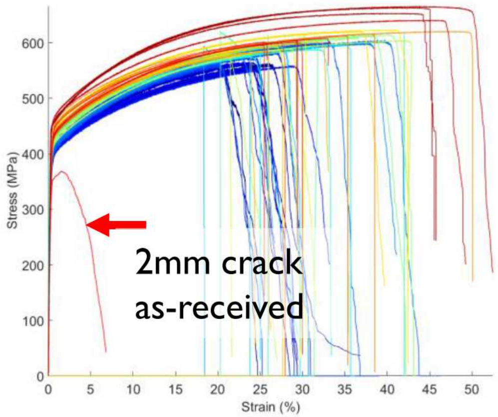
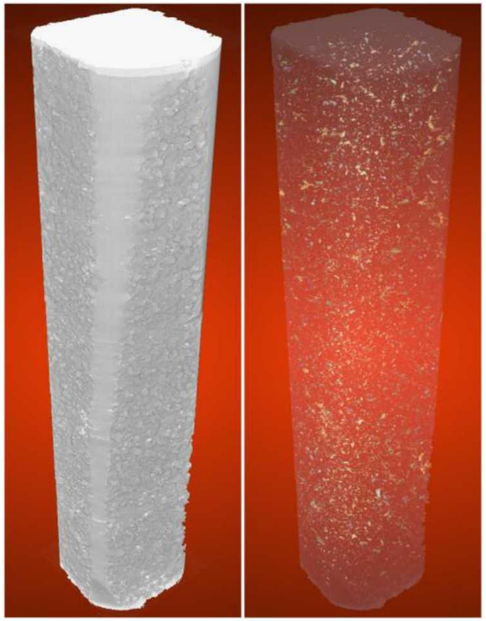
Importance of Flaws in Additive Manufacturing

- Additive manufacturing is known to have a variety of internal flaws
  - State of the art equipment and manufacturing processes reduce these flaws, but they are ever present
  - This results in high part rejection and/or avoidance of the technology
- Need alteration in paradigm: Consider a flaw tolerant approach
  - To do so we need to understand what parameters will be a threshold for acceptance/rejection
  - Potential Rejection Parameters
    - Flaw Size
    - Flaw Shape
    - Flaw Density/Proximity
    - Flaw Location
    - …
  - Once threshold parameters are determined, use non-destructive testing to detect the flaws

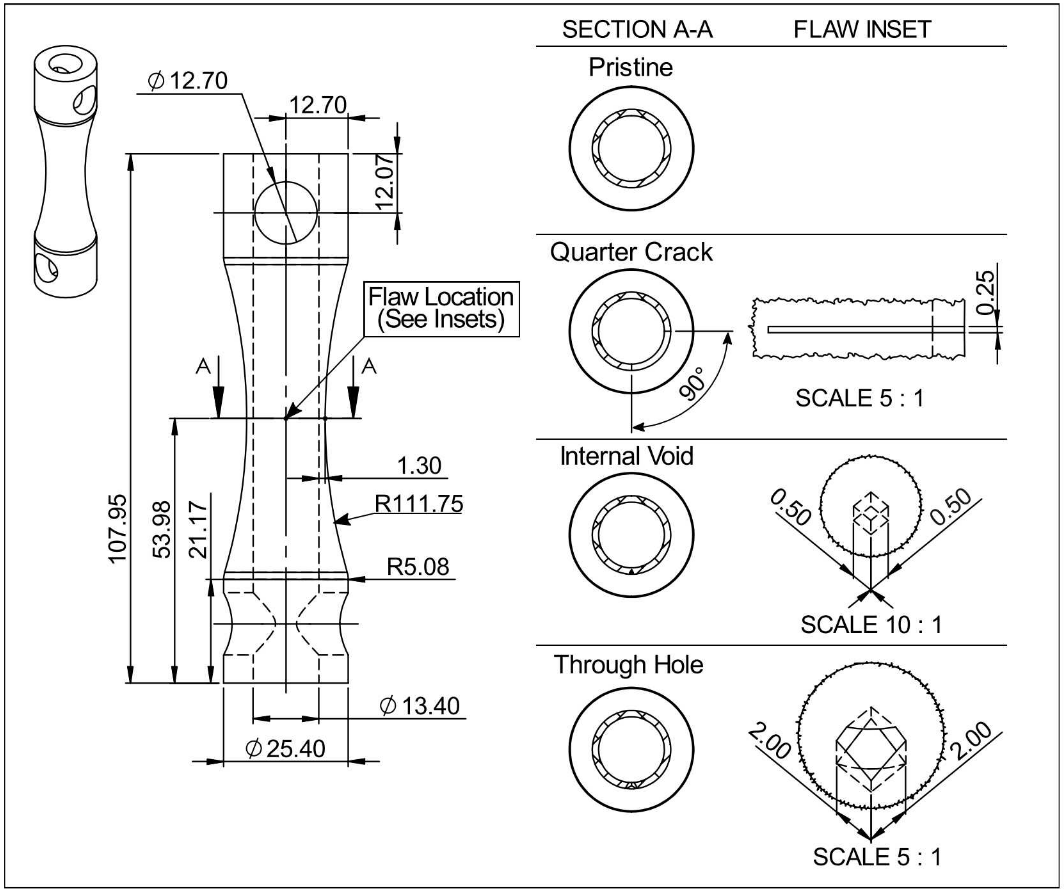
45 AM 304L medium conventional tensiles





Study Approach: Inclusion of Intentional Flaws

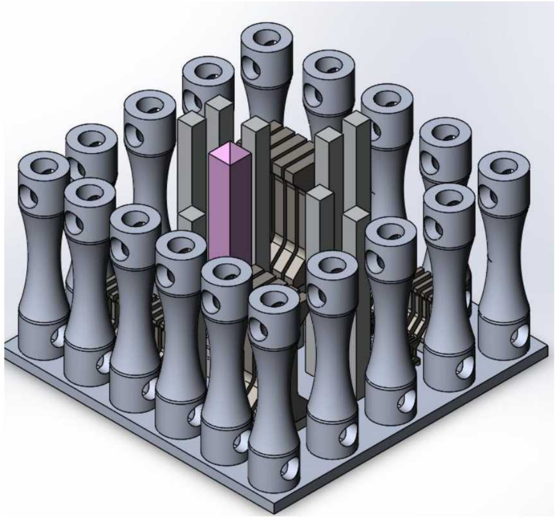
- Design an exemplar component with known failure region
- Add large geometrical flaws which will overshadow the effects of uncontrolled flaws



Materials

316L Stainless Steel

- Chosen for high dutility
- Commonly used in AM
- Build Condition:
  - Printer – Renshaw AM 400
  - Laser Power – 200 W
  - Hatch Spacing – 60 µm

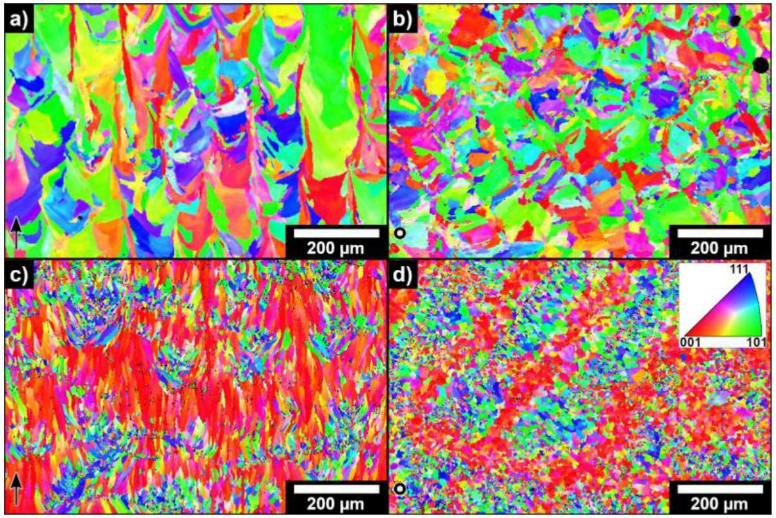


AlSi10Mg

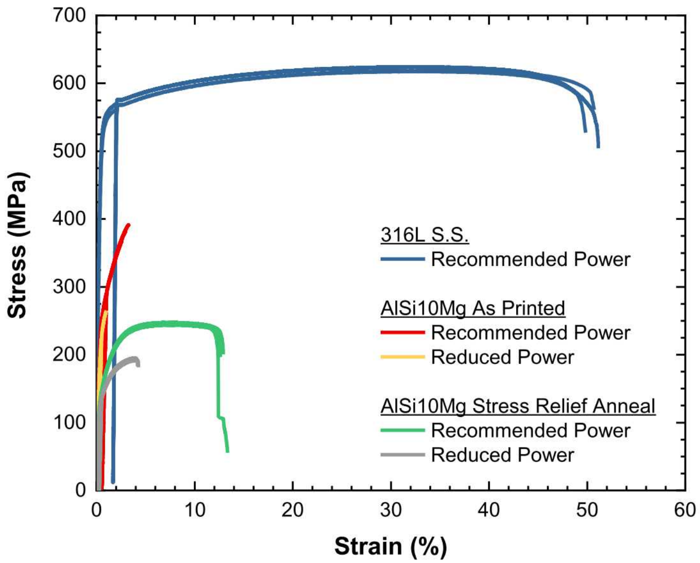
- Common casting alloy and gaining popularity in AM
- Usually used in Stress-relief-annealed condition
  - Majority of the work here is 'as-printed'
- Build Condition 1:
  - Printer – EOS M290
  - Laser Power – 370 W
  - Hatch Spacing – 190 µm
- Build Condition 2:
  - Printer – EOS M290
  - Laser Power – 185 W
  - Hatch Spacing – 90 µm

Material Characterization

- Need baseline material characterization before inclusion of flaws
- Testing performed on coupons adjacent to exemplar components on the build plate
- Experiments included:
  - Tensile testing
  - Compression testing
  - Fracture toughness
  - Charpy impact testing
  - Computed Tomography (CT)
  - Metallurgy/EBSD
  - Archimedes Density

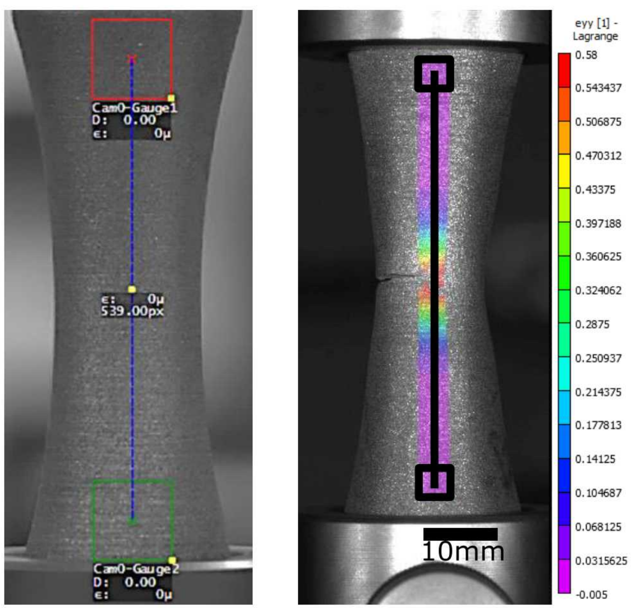


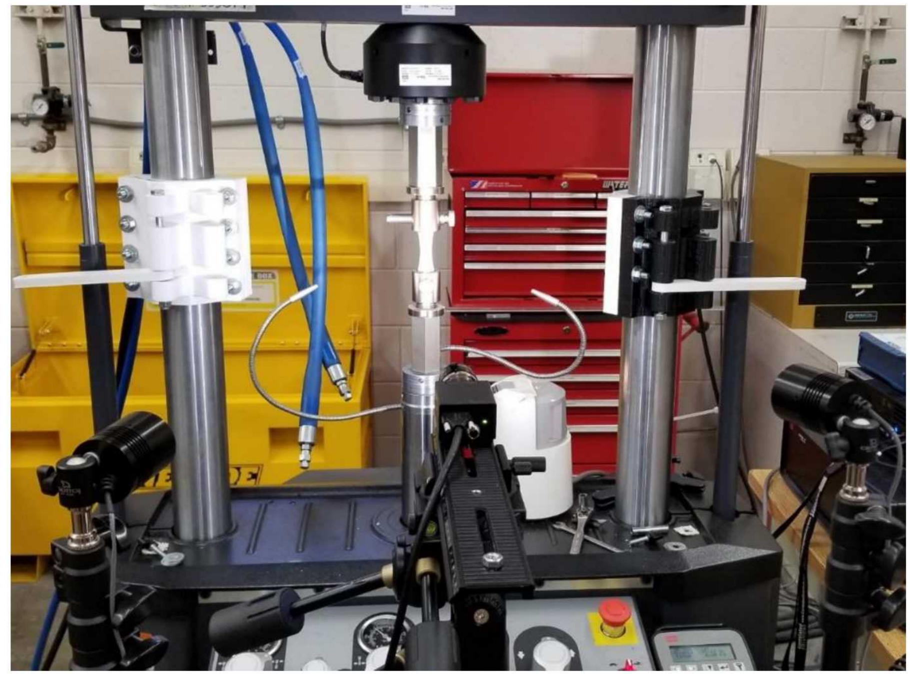
Material		ρ (%)	E (GPa)	σ_y (MPa)	σ_{UTS} (MPa)	ε_{tot} (%)
316L S.S.		99.2	161	511	620	50.6
AlSi10Mg As Printed	Rec.	99.4	63	260	380	3.0
	Red.	99.4	53	243	261	0.95
AlSi10Mg Stress Relief Annealed	Rec.	94.5	63	136	245	12.7
	Red.	94.5	53	130	194	4.1



Mechanical Testing Method

- Load in uniaxial tension until failure
- Displacement control at a rate of 50 μm/s
- Use in situ non-contact digital extensometery
- Post-process using full field digital image correlation

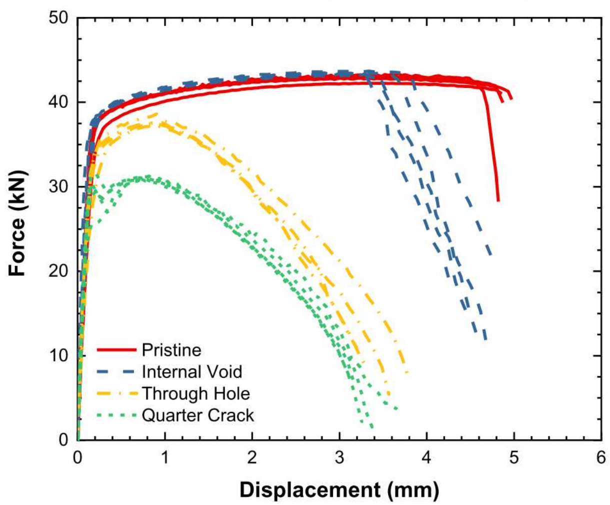


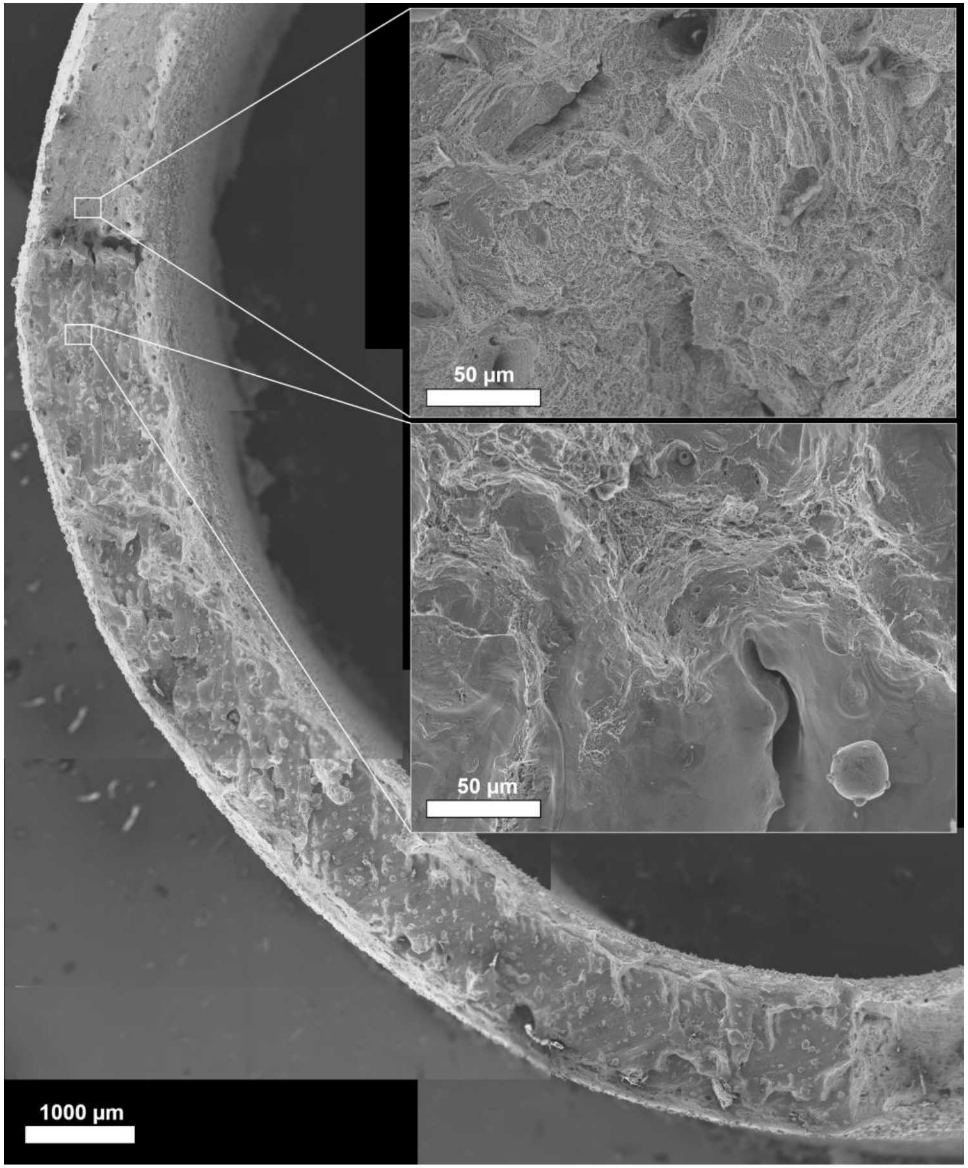


Stainless Steel 316L - Geometric Flaw Dependence

- Force/displacement curves show a significant amount of strain hardening
- Ductile dimples observed in fractography
- Pop-in event from quarter crack rupture
- Ductility and load closely follow area reduction

Geometric Feature	Area (%)	Peak Load (%)	Max Disp. (%)
Pristine	100.0	100	100
Internal Void	99.6	100	94
Through Hole	96.1	89	75
Quarter Crack	75.0	73	73

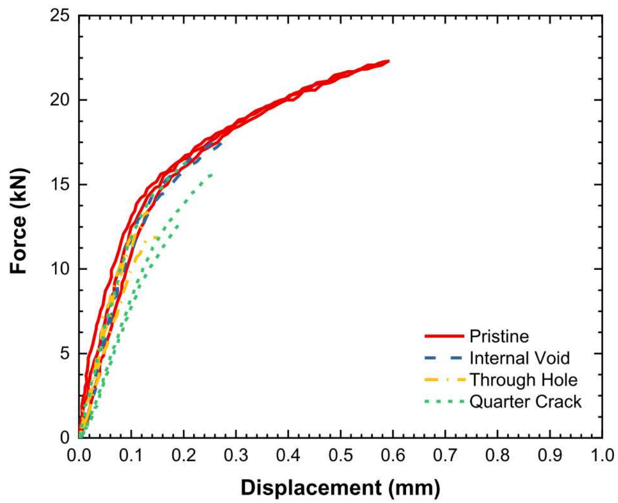


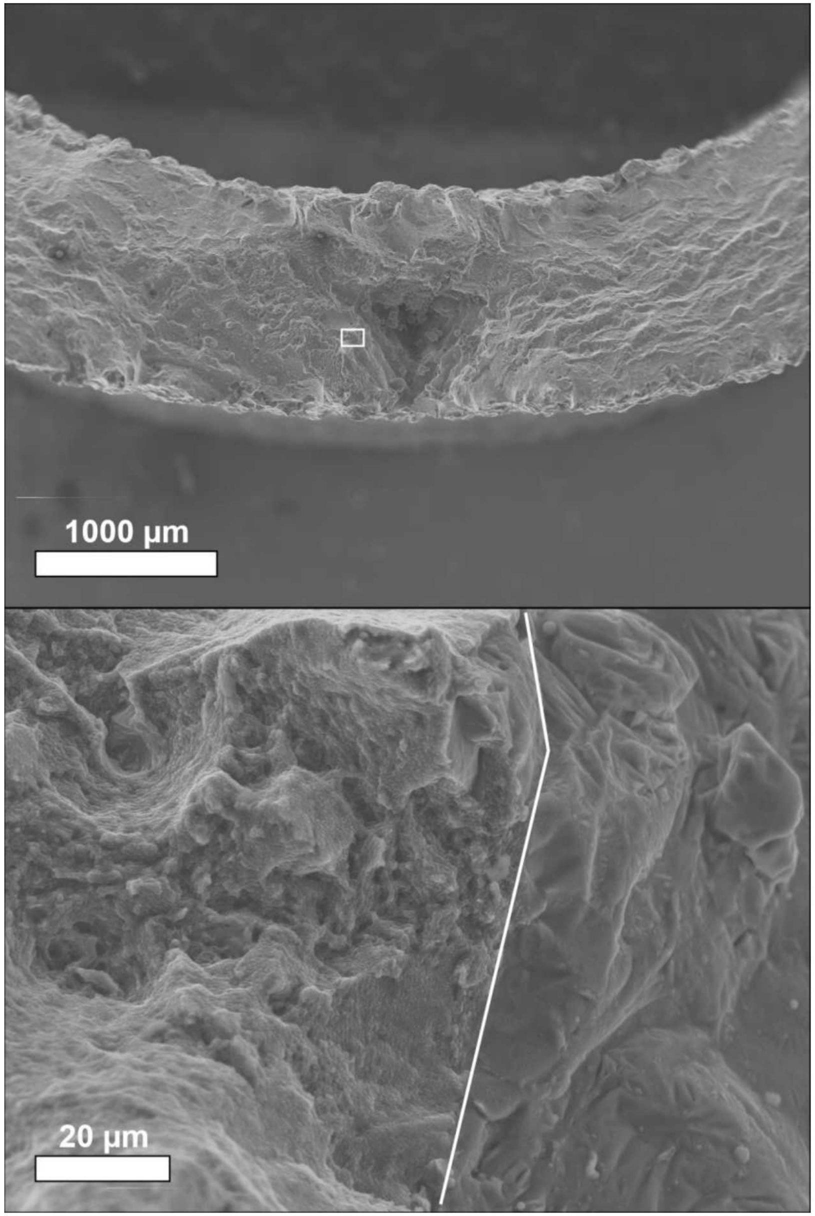


AlSi10Mg - Geometric Flaw Dependence

- Minimal strain hardening
- No signs of ductile dimples
- Adding a flaw (regardless of area) significantly weakens the part

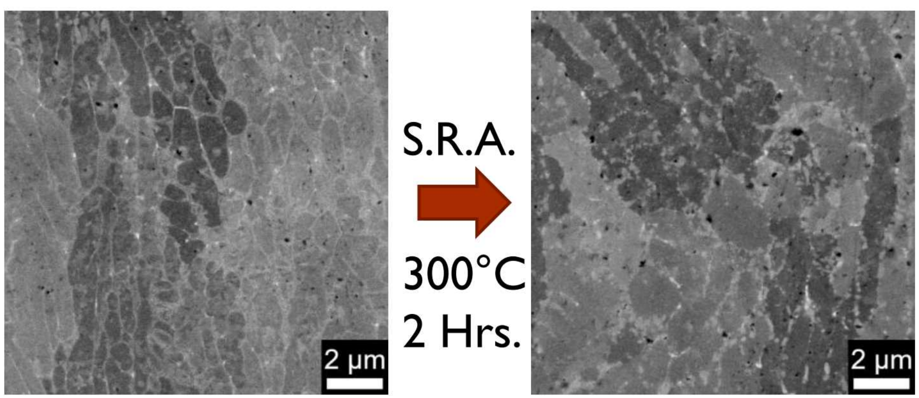
Geometric Feature	Area (%)	Peak Load (%)	Max Disp. (%)
Pristine	100.0	100	100
Internal Void	99.6	77	47
Through Hole	96.1	56	23
Quarter Crack	75.0	67	38



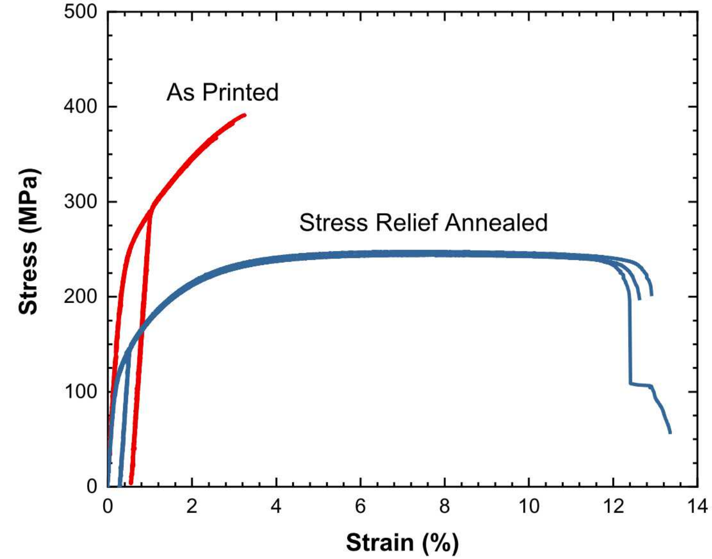


Stress-Relief Annealing of AlSi10Mg

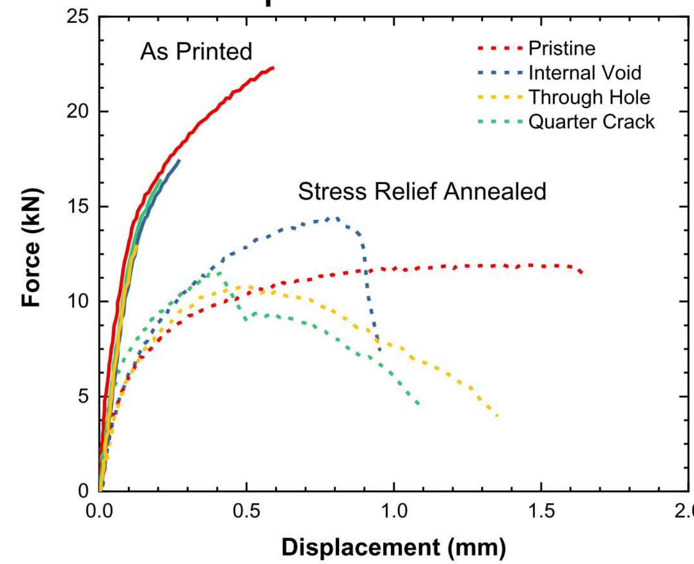
- Stress-relief annealing heat treatment breaks down silicon cellular network, increases ductility
- Material behavior transitions from brittle-like to ductile
- Flaw dependence begins to transition from geometry to cross-sectional area dependent



Material Behavior

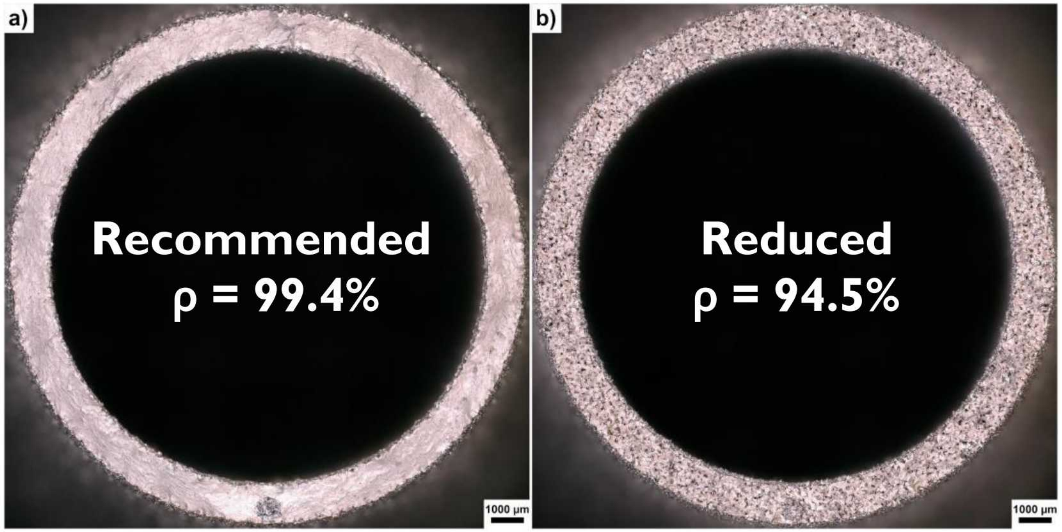


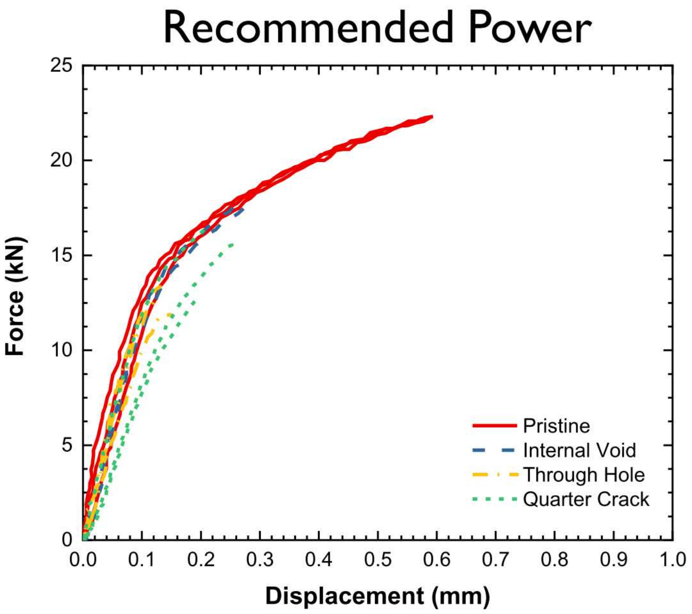
Component Behavior

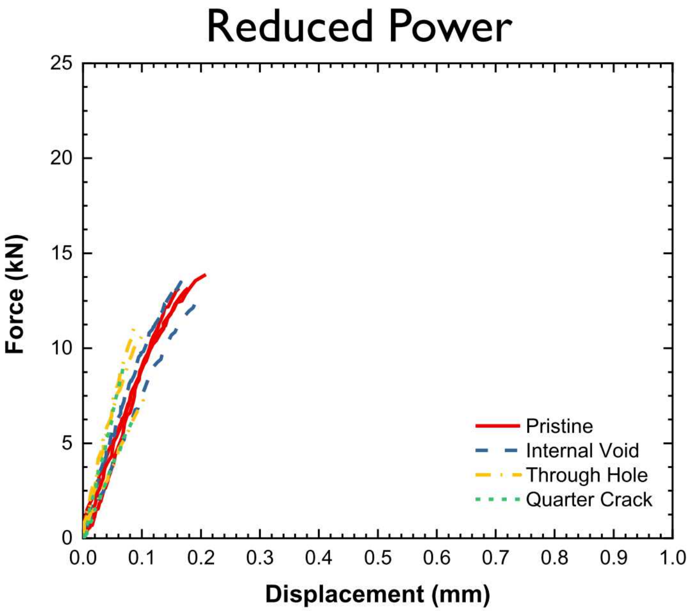


Bulk Porosity in Exemplar Components

- Build parameters have large effect on bulk porosity
- Observe two build plates of AlSi10Mg
  - Recommended power condition
  - Reduced power condition (50% of recommended power)
- High sample porosity will dominate over a single, large, geometrical flaw

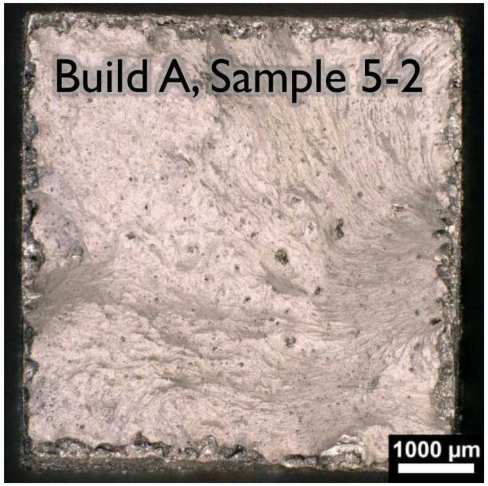


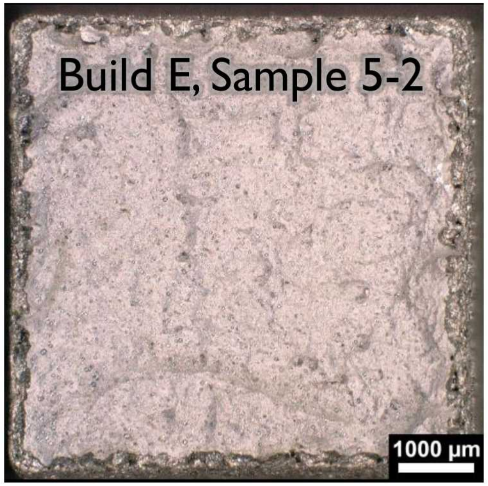


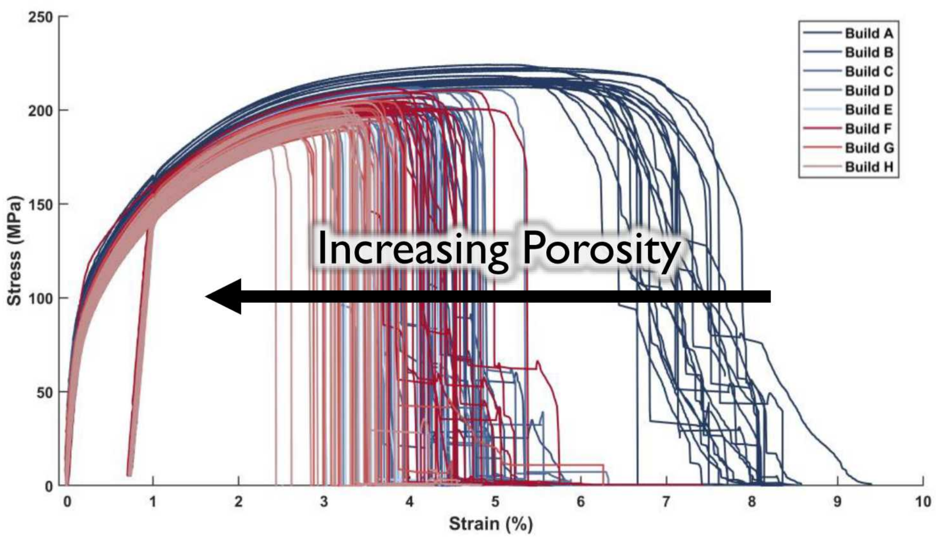


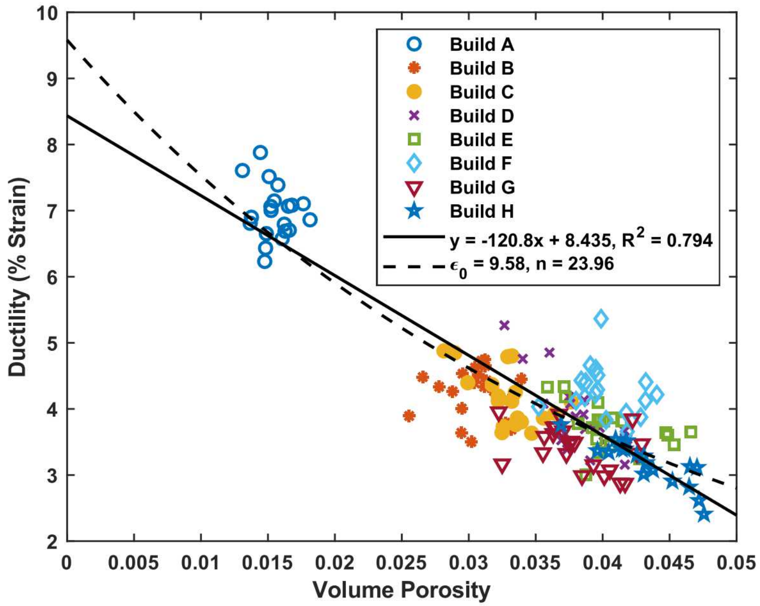
Bulk Porosity Effect on Mechanical Properties

- Compare mechanical results to a known decrease in porosity on tensile samples of eight AlSi10Mg build plates
  - Porosity increase due to powder re-use in subsequent build plates
- Strongest correlation: Ductility and Porosity



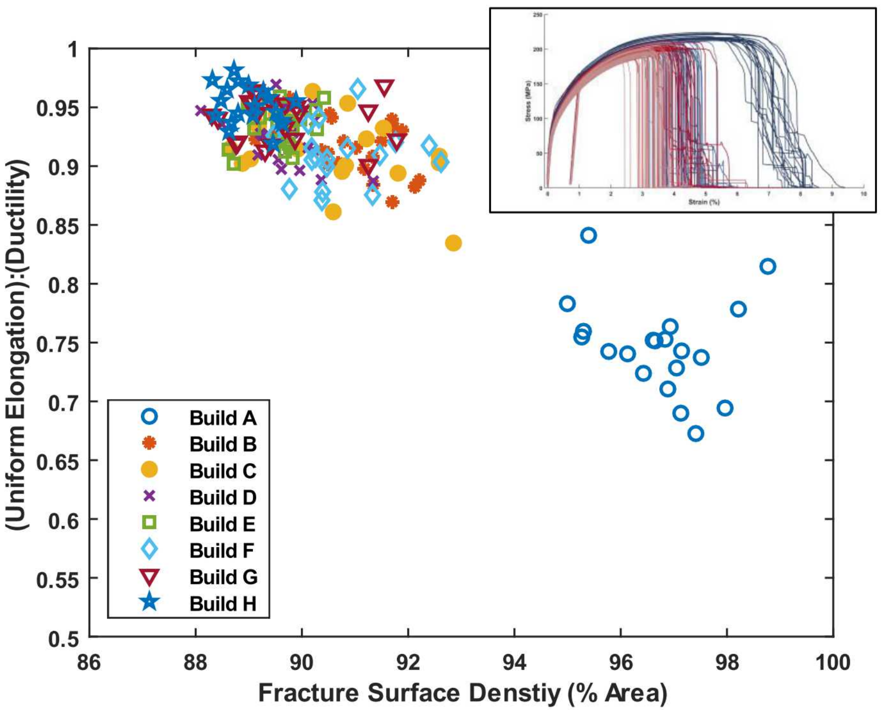


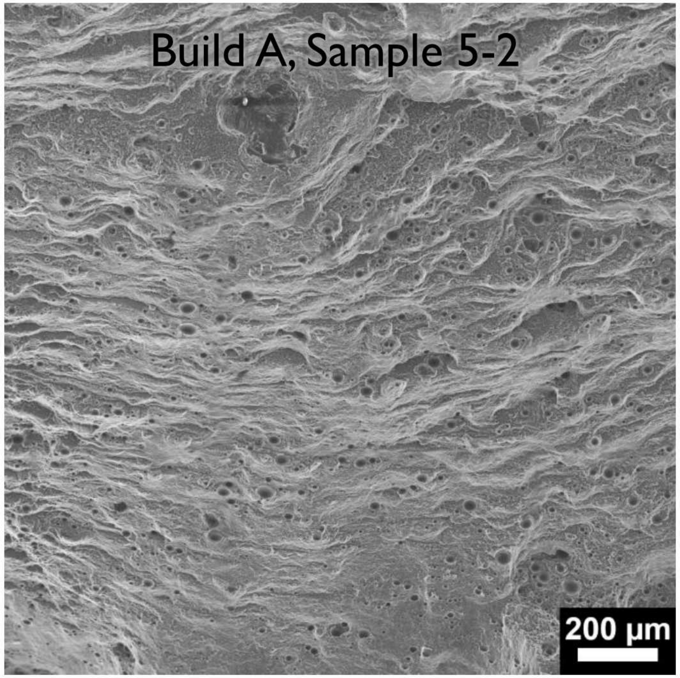


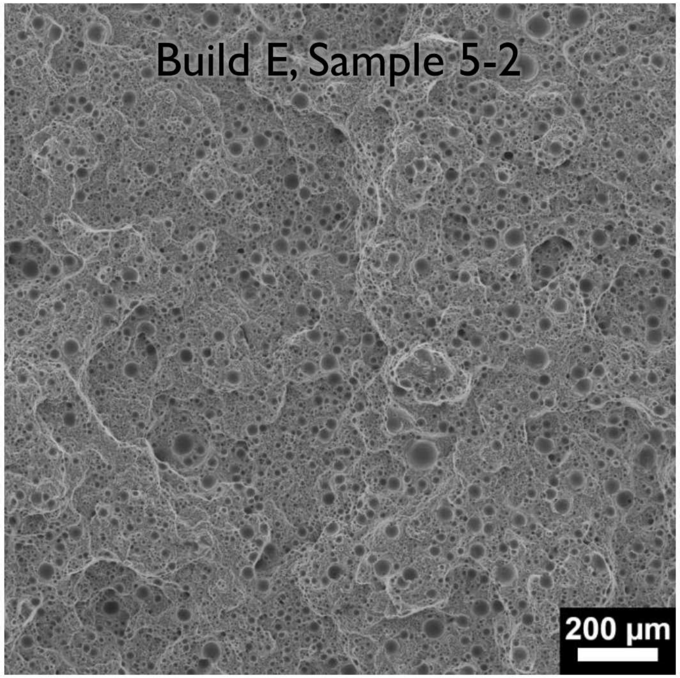


Reduction of Necking

- As part density decreases, ratio of uniform elongation to ductility approaches 1
  - Indicates no necking of parts
  - Attributed to transition in failure type from void nucleation, coalescence, and growth to coalescence of small voids

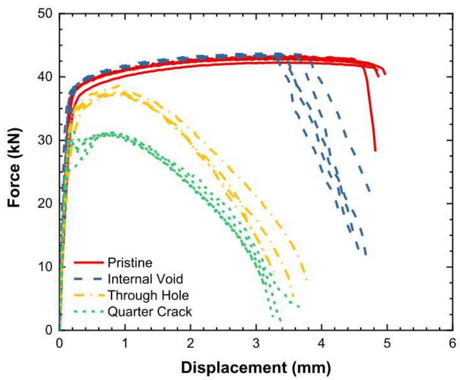


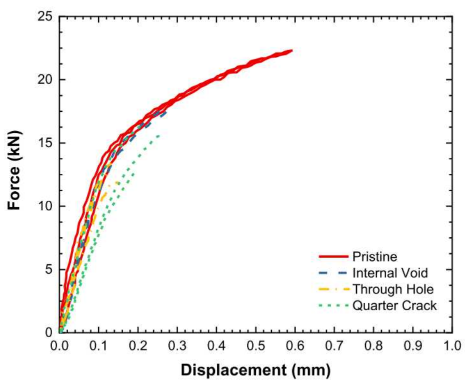


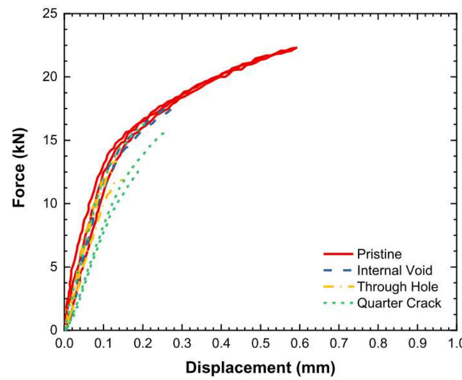


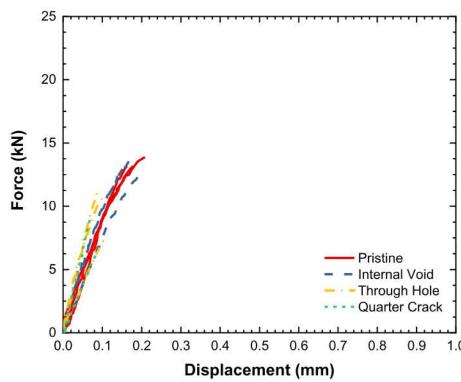
Conclusions

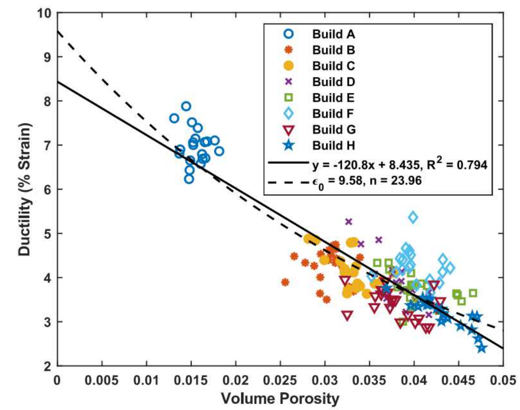
1. Inherent material ductility matters to flaw sensitivity in AM parts
   1. Ductile materials show dependence on area
   2. Brittle materials show a dependence on flaw shape (stress concentration)
2. A high concentration of small pores can dominate behavior over a single, large flaw
3. Ductility and failure type can be predicted by the porosity levels











Acknowledgements

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT
WHERE INNOVATION BEGINS

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David Moore

CLEMSON UNIVERSITY FRAME

FRacture And MEchanics laboratory

Garrett Pataky

Benjamin Smith

Jody Bartanus

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Extra Slides

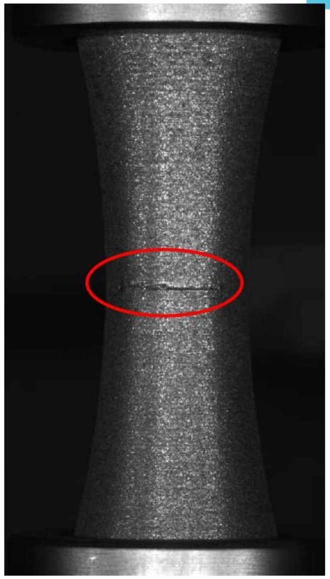
Damage Tolerant Approach

Assume all AM components have flaws

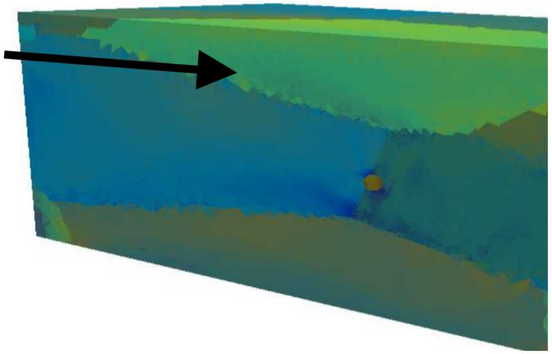
Which flaws matter?

Identify flaw types

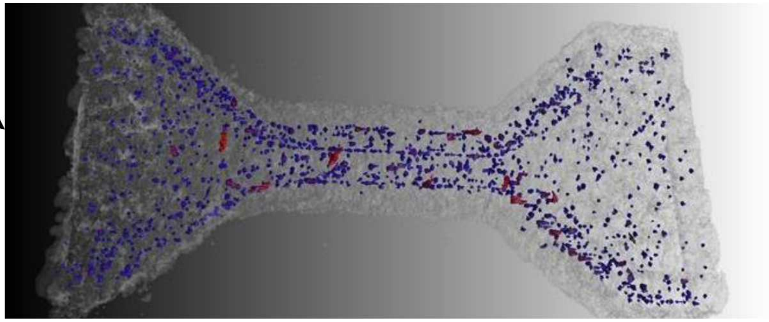
- Cracks
- Voids
- Bulk porosity
- Microstructure-based flaws



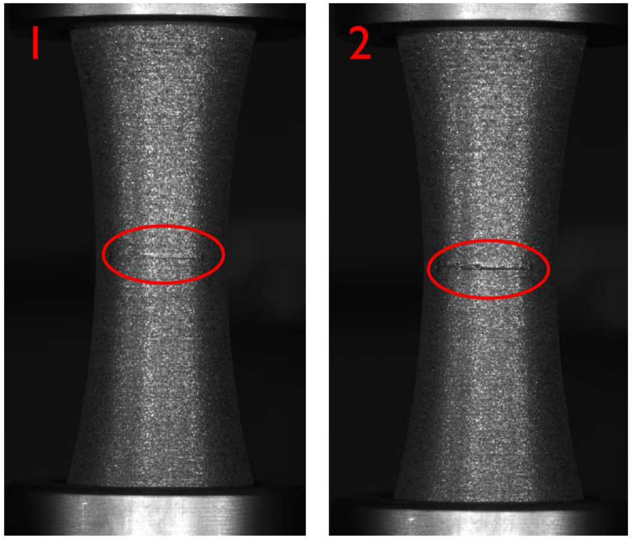
1. Print intentional flaws of varying sizes and types
2. Predict critical flaw sizes in different regions for each flaw type
3. Non destructively inspect each component for critical flaws
   - Critical flaw size is now defined for each region of the part.

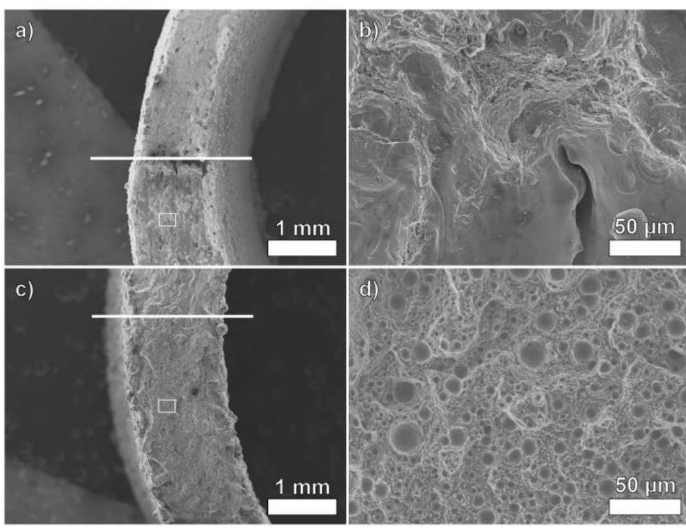


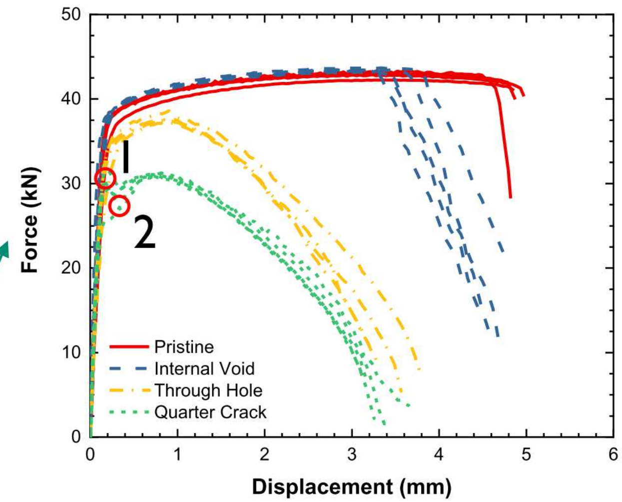
FE model including flaw with microstructure

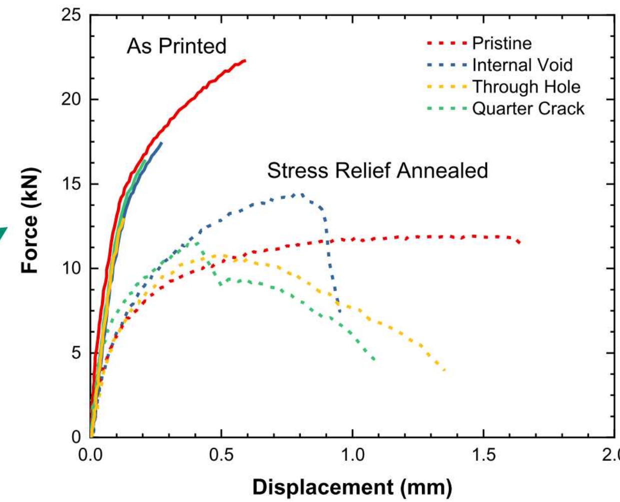


Quarter Crack Failure

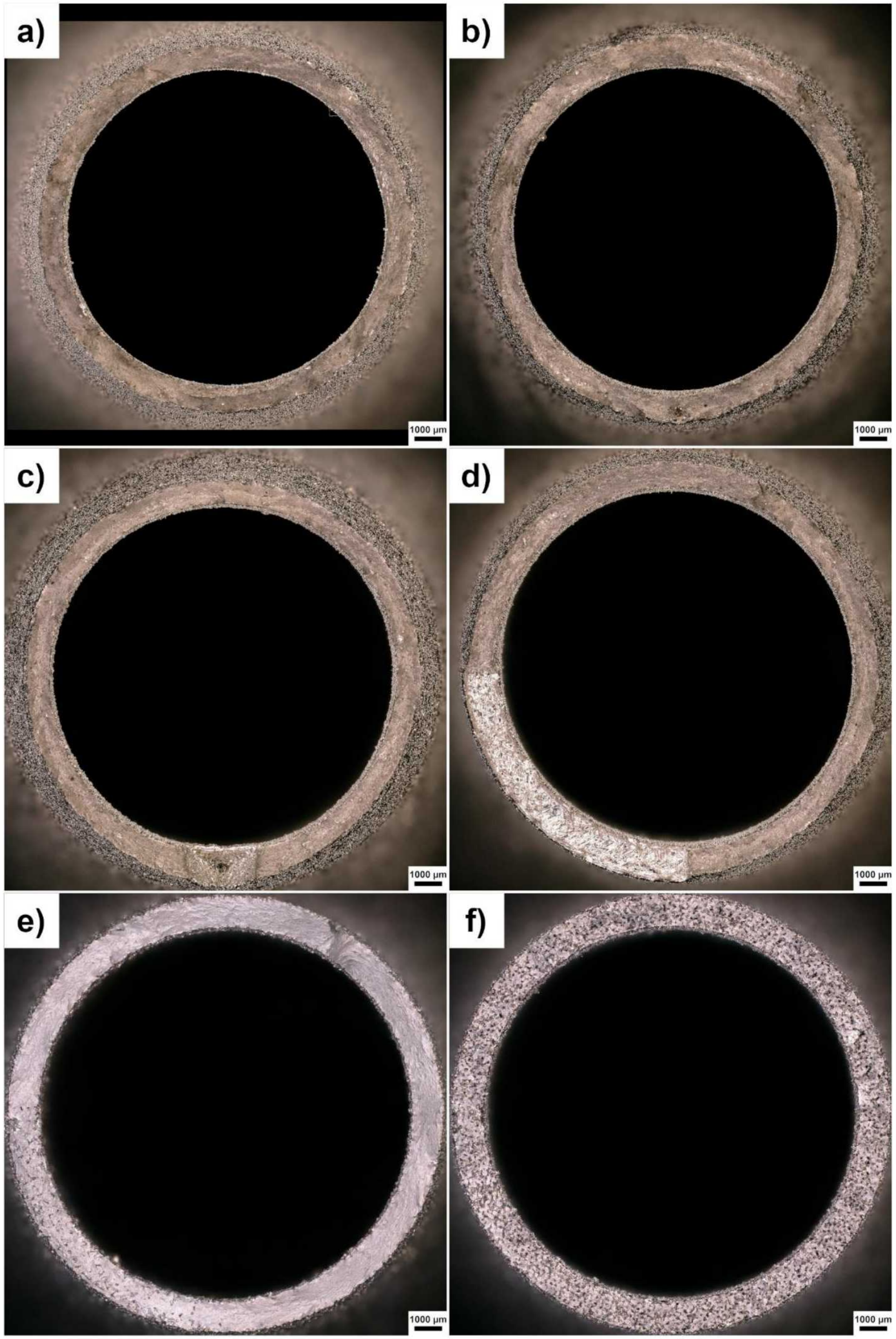




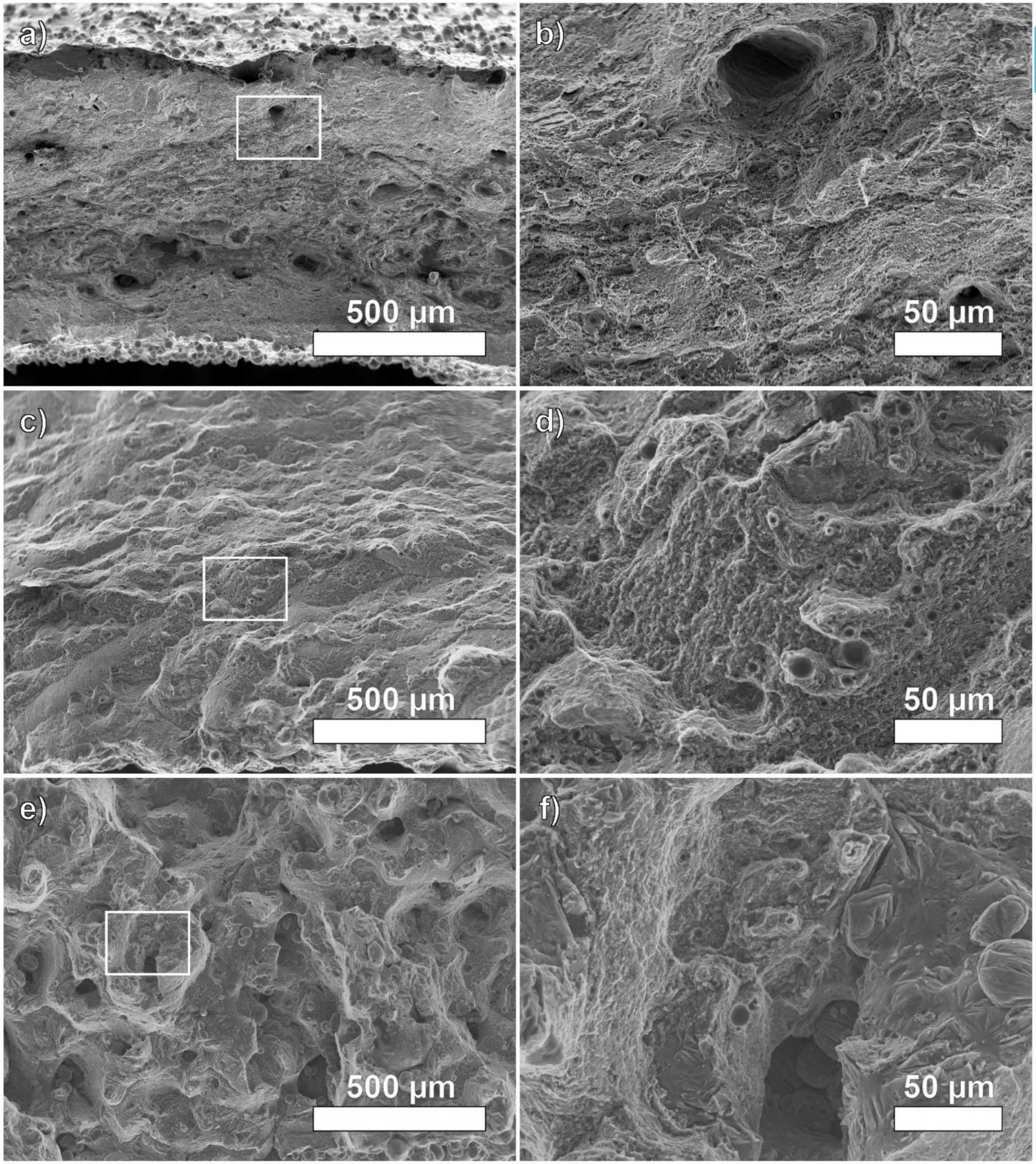




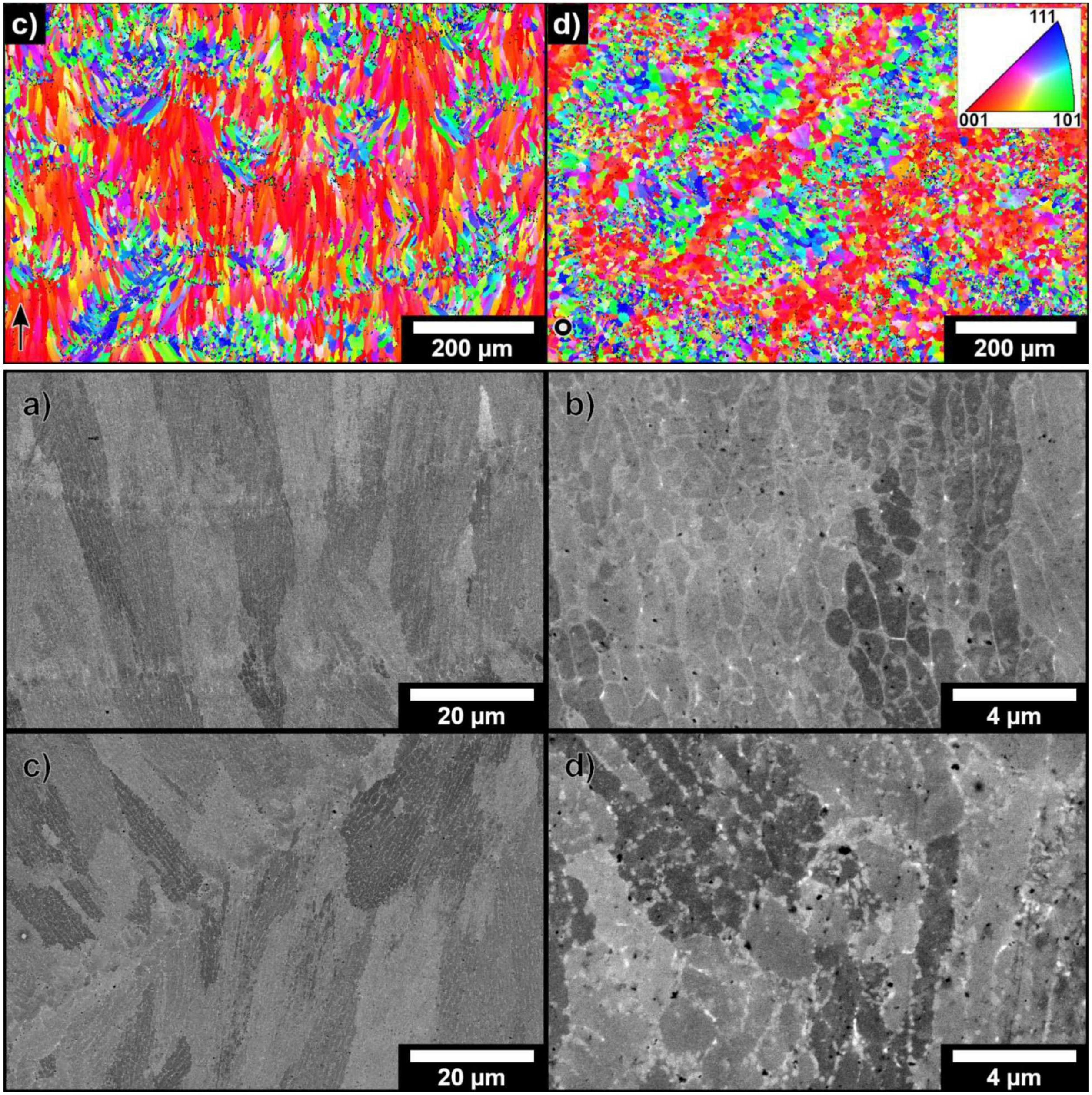
Optical Fractography



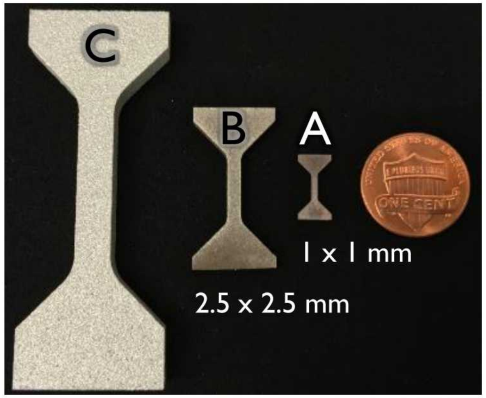
SEM fractography



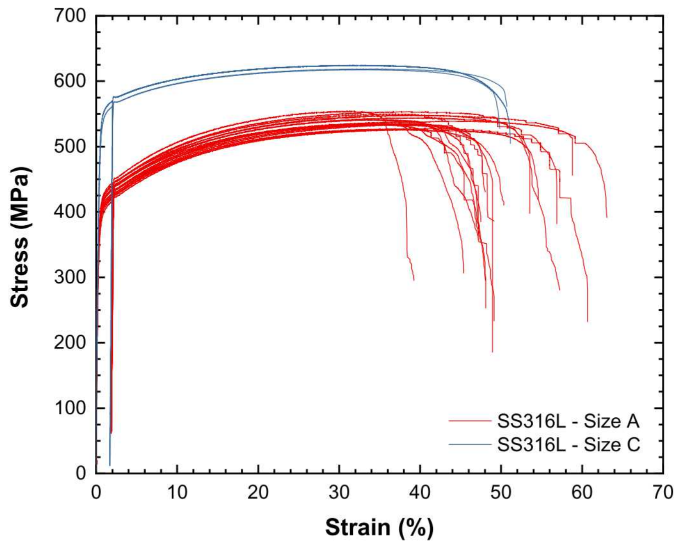
AlSi10Mg Microstructure

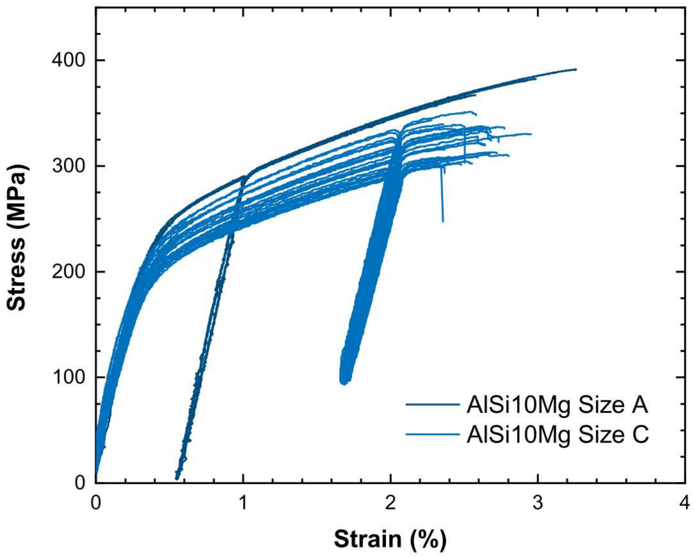


Size Effect



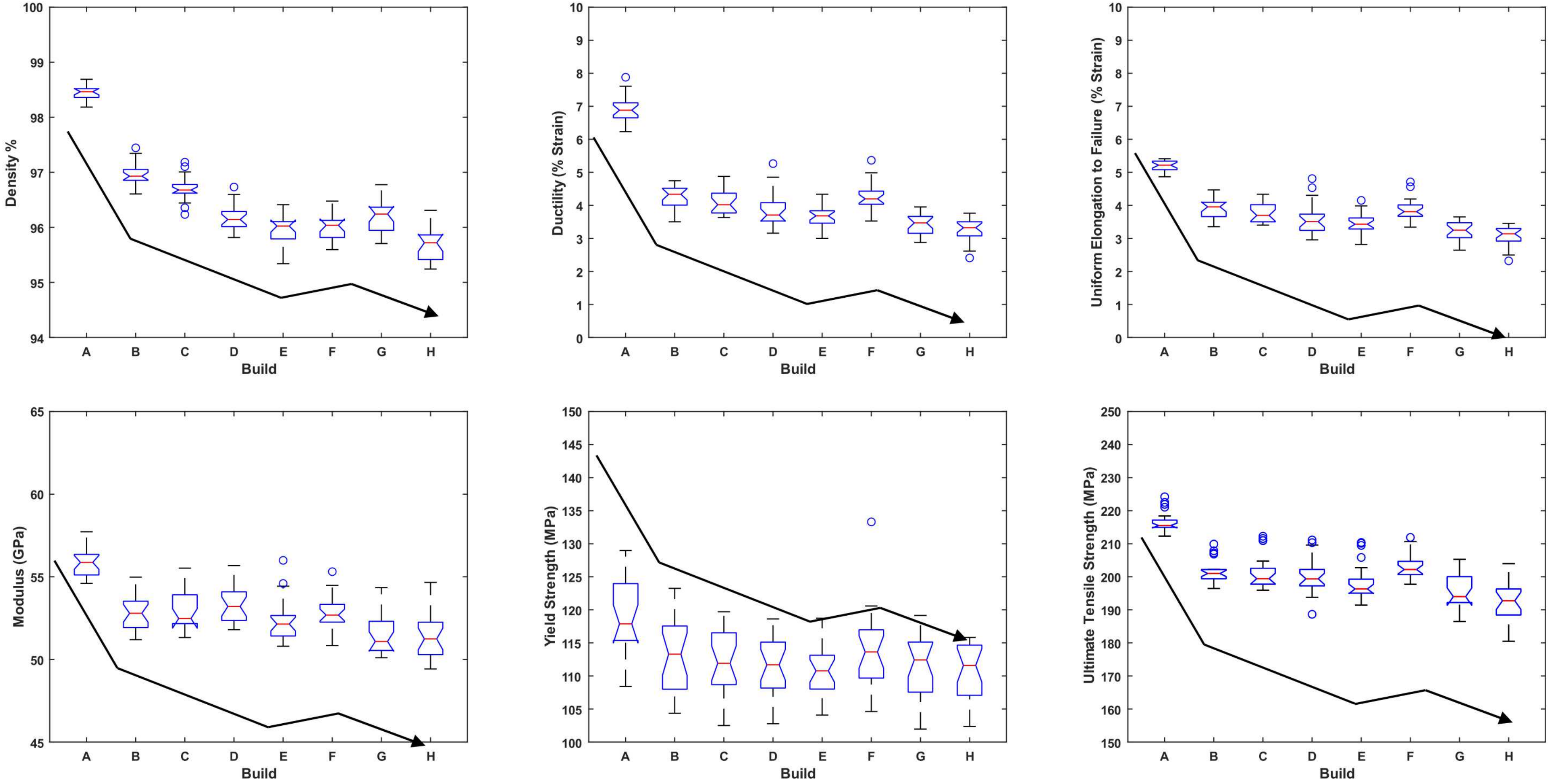
6.25 x 6.25 mm





Comparison of Build Plate Mechanical Properties

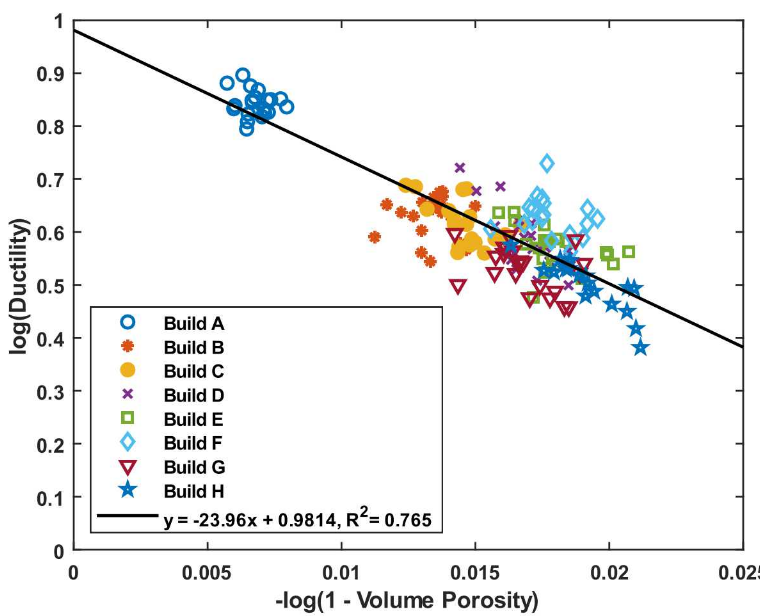
- Decrease in sample density (increase in bulk porosity) generally equates to a decrease in mechanical properties

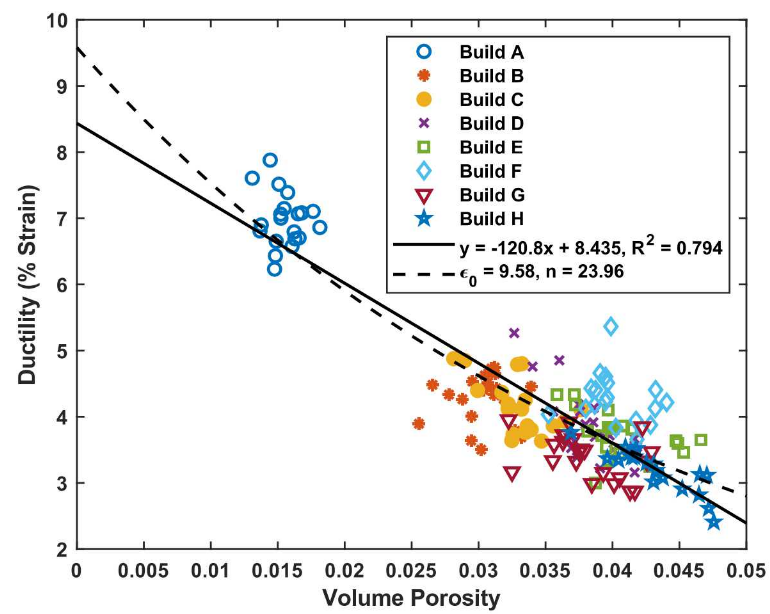


Data Fitting Density to Mechanical Results

- Perform linear regression analysis using two fitting methods
  - Linear Fit: $P = m(1 - \rho) - P_0$
  - Power Fit: $P = P_0(1 - \rho)^n$
  - Where P is the mechanical property of interest, P_0 is the fully dense property, ρ is the porosity, and m, n are fitting constants.
  - Coefficient of determination:

	ε_{tot}	σ_{UTS}	σ_y	E
Linear Fit	0.794	0.693	0.306	0.575
Power Fit (log/log)	0.765	0.683	0.297	0.569





Fracture Surface Correlation

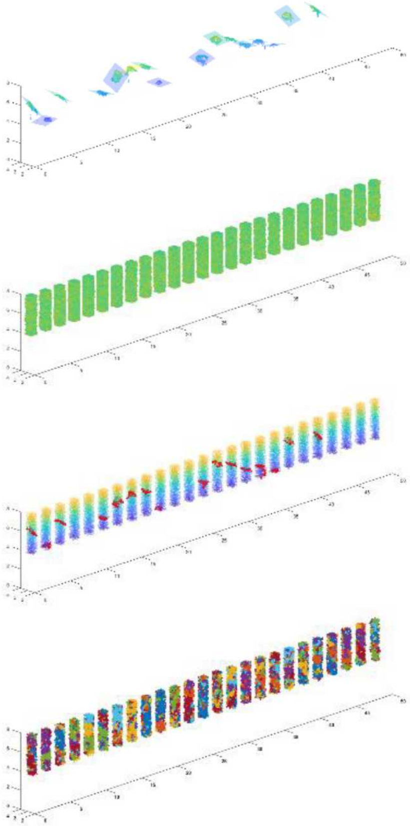
Measured

Fracture Surfaces (optical scans)

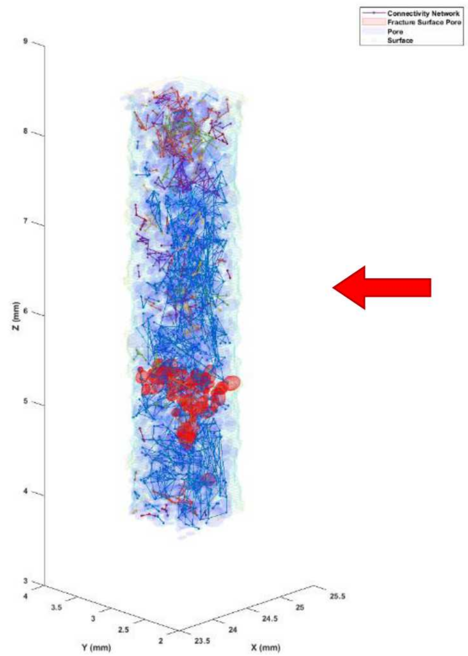
Surface Features (CT)

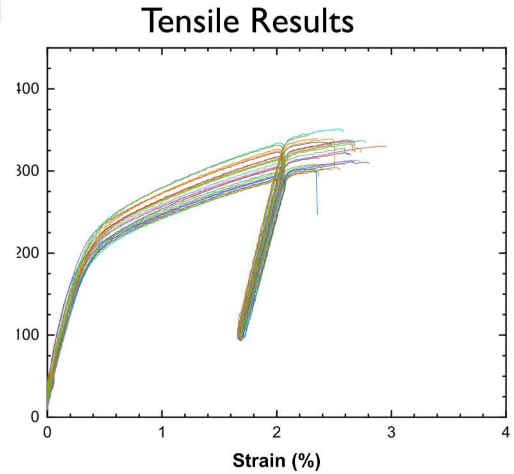
Internal Pores (CT)

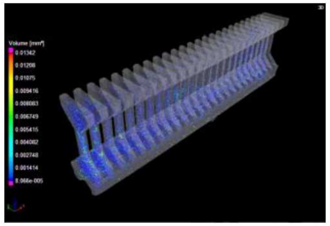
Pore Connectivity (Analysis)

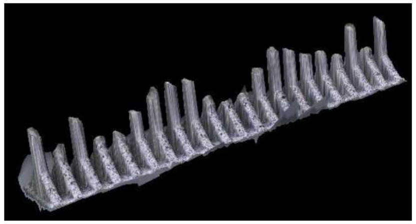


Predict fracture location and properties









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