The Qualification Response Envelope and The Scientific Foundation for Designing Additively Manufactured Structural Parts

Presenter: Sharlotte Kramer

Research Contributors: Thomas Ivanoff, Jonathan Madison, Andrew Lentfer, Chris Laursen, Jay Carroll, Zach Cassias, John Emery, Jonathan Pegues, Dale Cillessen, Bill Scherzinger, Paul Specht, Kyle Johnson, Nathan Brown, Colin Loeffler, and Bo Song

19 October 2021

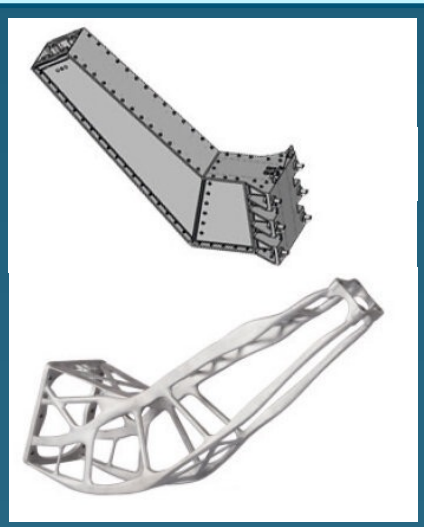
Penn State Additive Around the U.S. Seminar Series

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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.

Motivation: AM Structural Parts

Faster Realization of Parts (Reduction Design and Qualification Time)



https://www.eos.info/en/

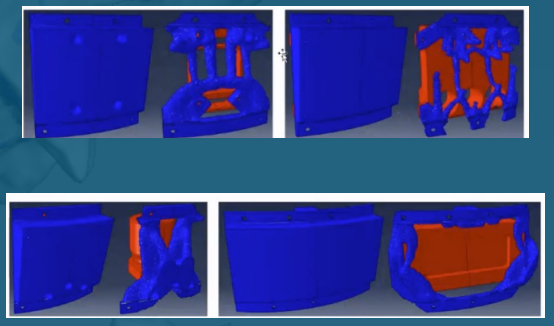
Time to Get Prototype

Conventional → **6-24 months**

AM → **0.5-3 months**

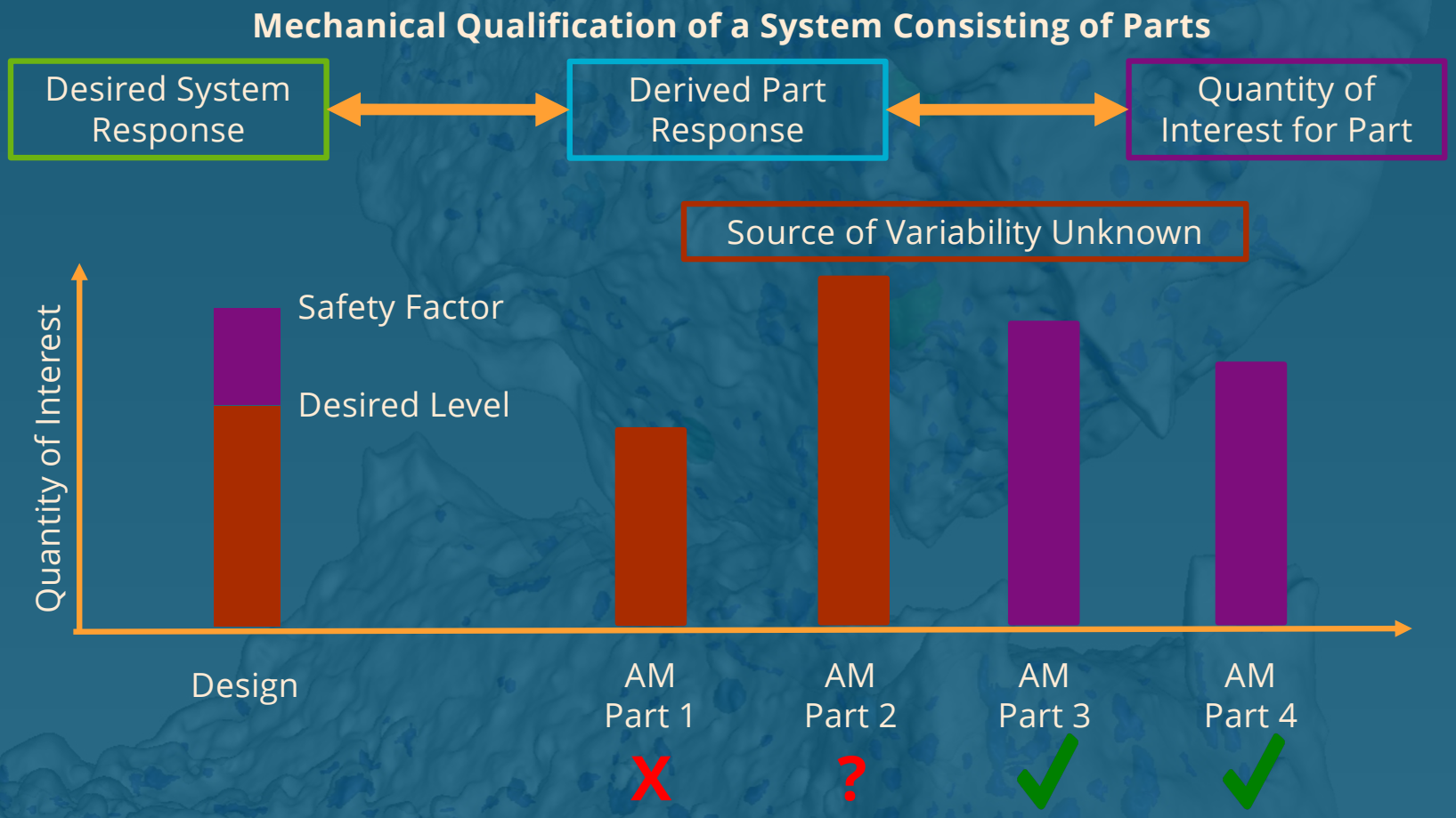
Smaller Manufacturing Facilities (Small Lots)

Novel Designs and Architectures and New Functionalities

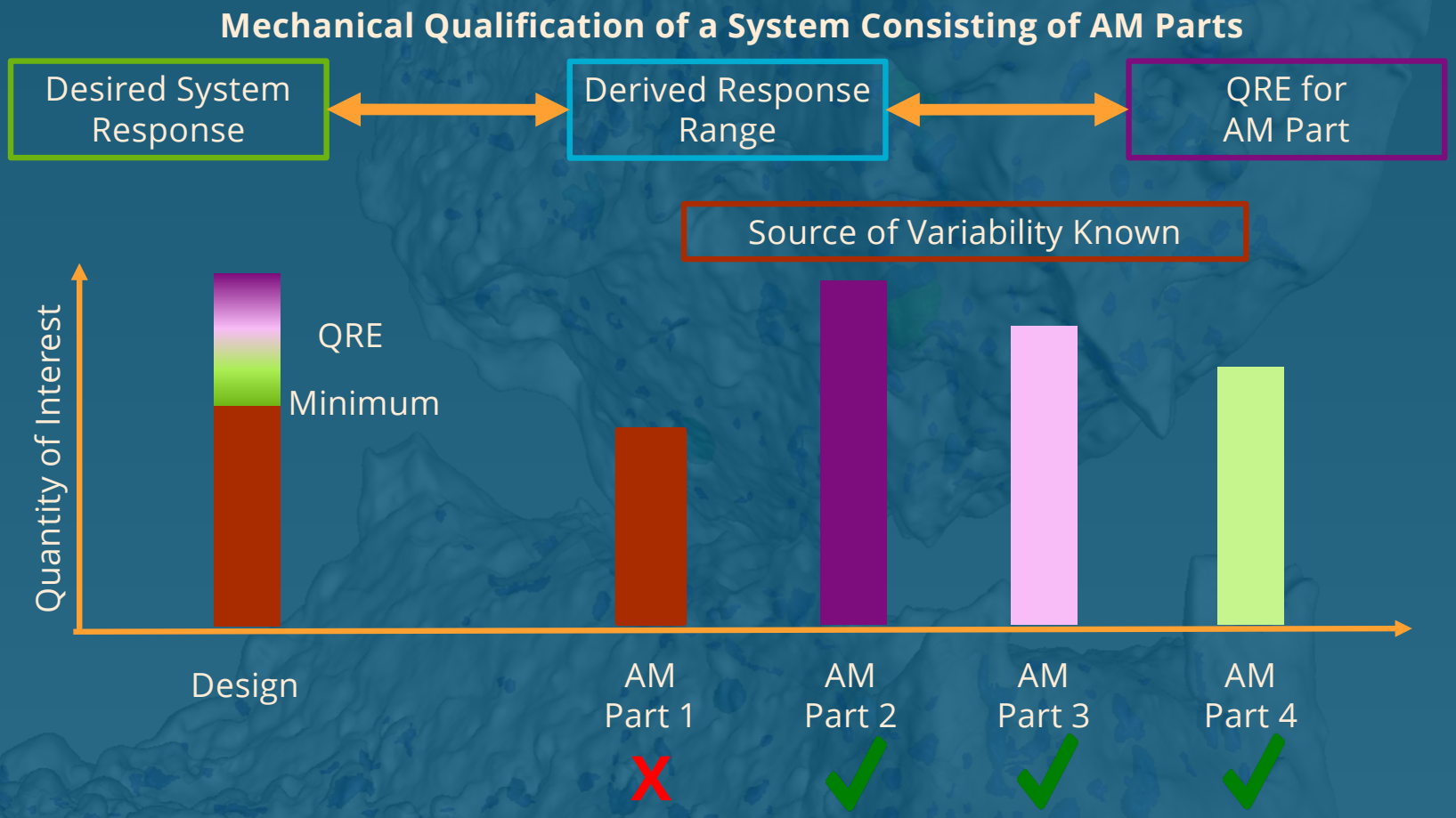


Conventional Vs Weight-Reduced AM Designs

Challenge: Current Design Paradigm



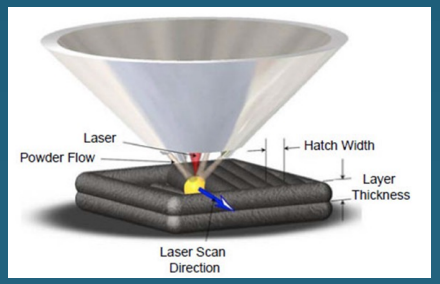
New Paradigm: Qualification Response Envelope (QRE)

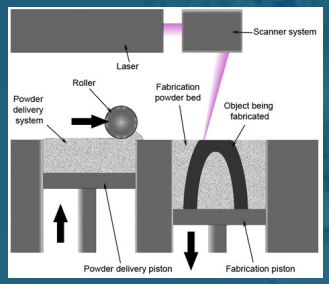


Foundational Research for QRE

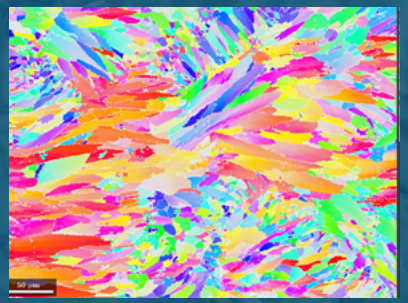
Explore Sources of Variability and Connections to Mechanical Response

Manufacturing Mode

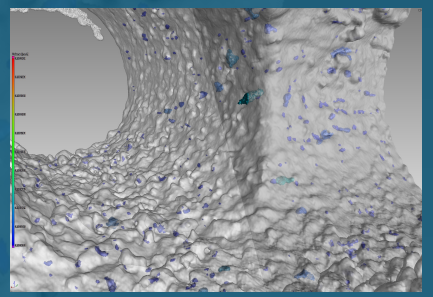




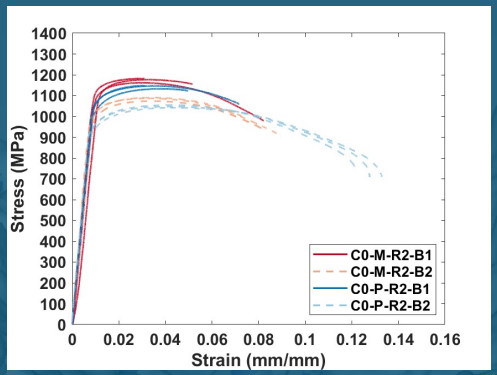
Microstructure



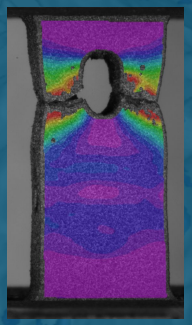
Flaws and Surface Effects



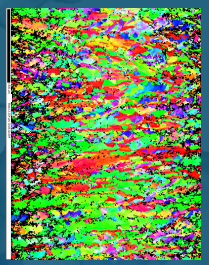
Material Behavior



Part Geometry



Different Alloys



Foundational Research for QRE: Mechanical Response

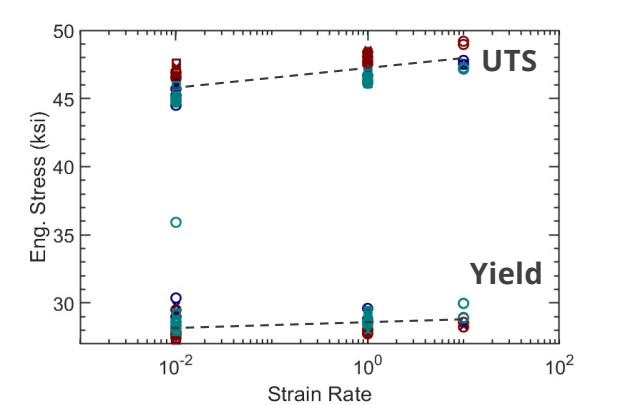
Strain Rate

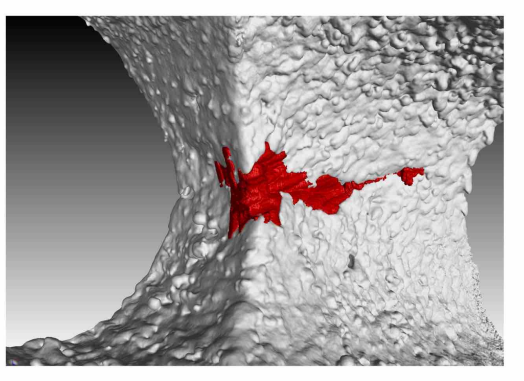
Yield Strength

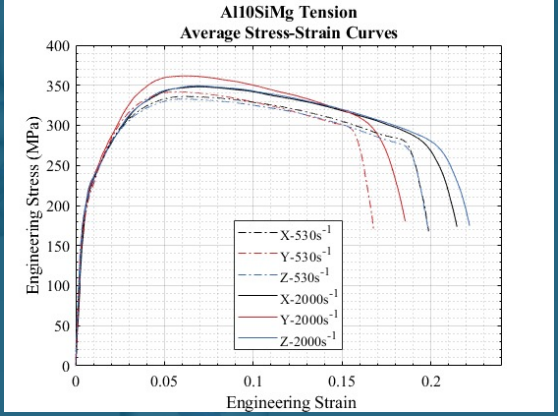
Fatigue

Fracture

Anisotropy

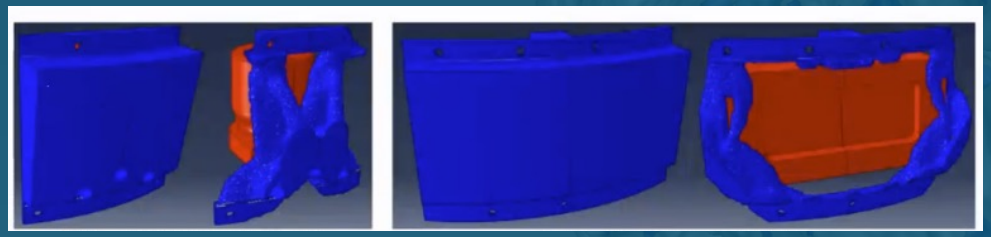




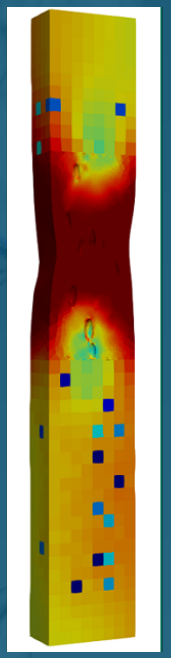


Foundational Research for QRE: Using Our Understanding

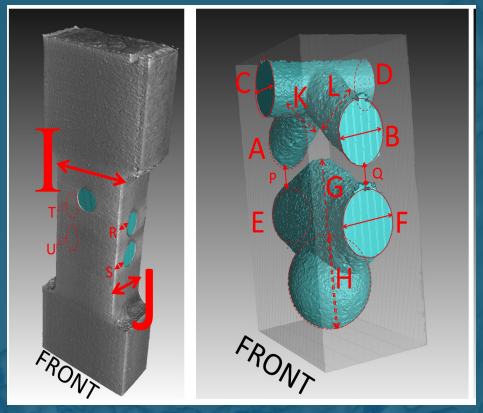
Topology Optimization



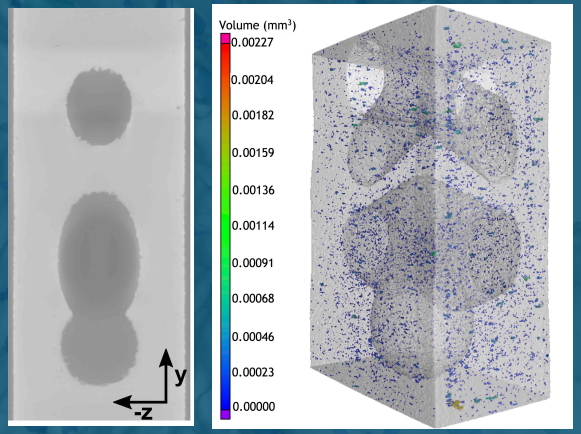
Computational Modeling



Design Guidance

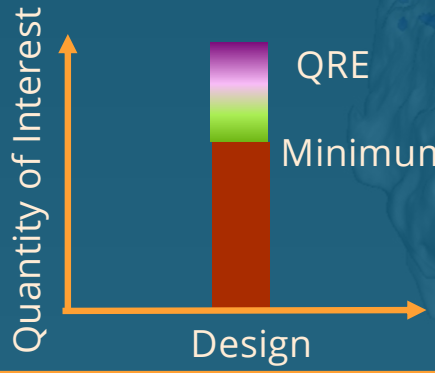


Inspection

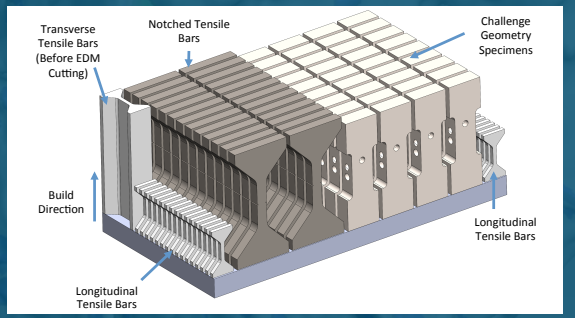


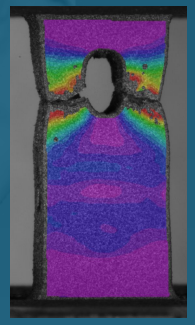
Sandia Research

Qualification Response Envelope (QRE)

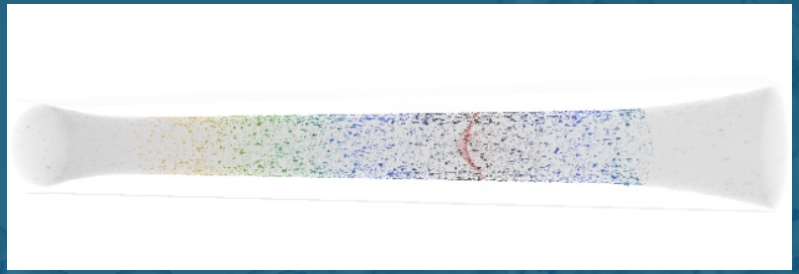


Fracture in AM Metal Parts

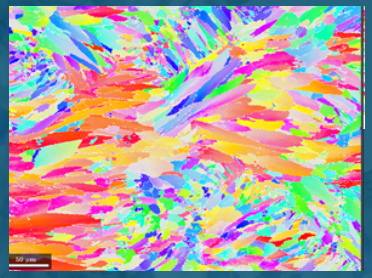


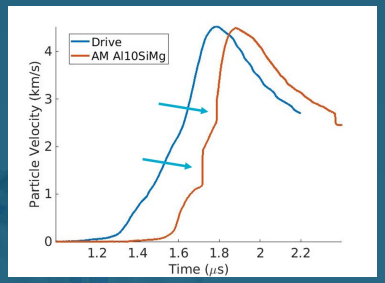


Fatigue in AM Metal



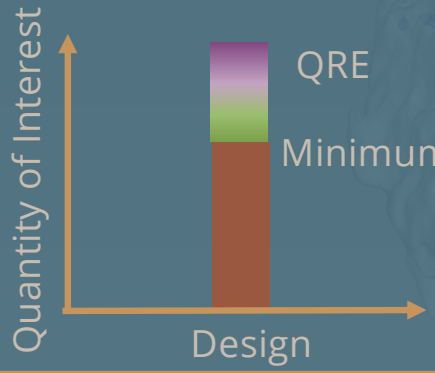
Strain-Rate Dependent Behavior of AM Metal



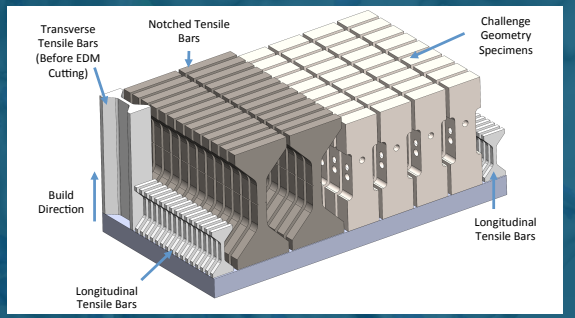


Sandia Research

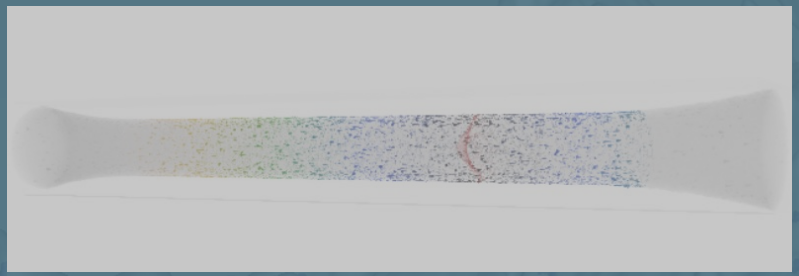
Qualification Response Envelope (QRE)



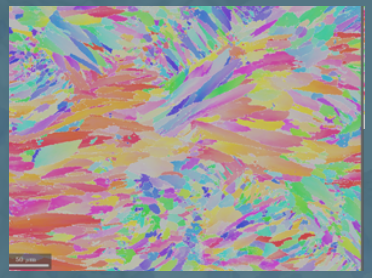
Fracture in AM Metal Parts

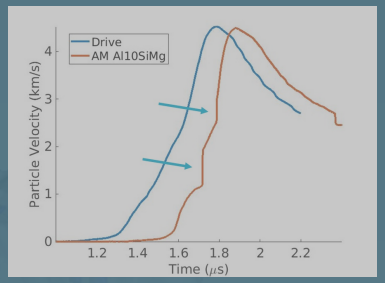


Fatigue in AM Metal

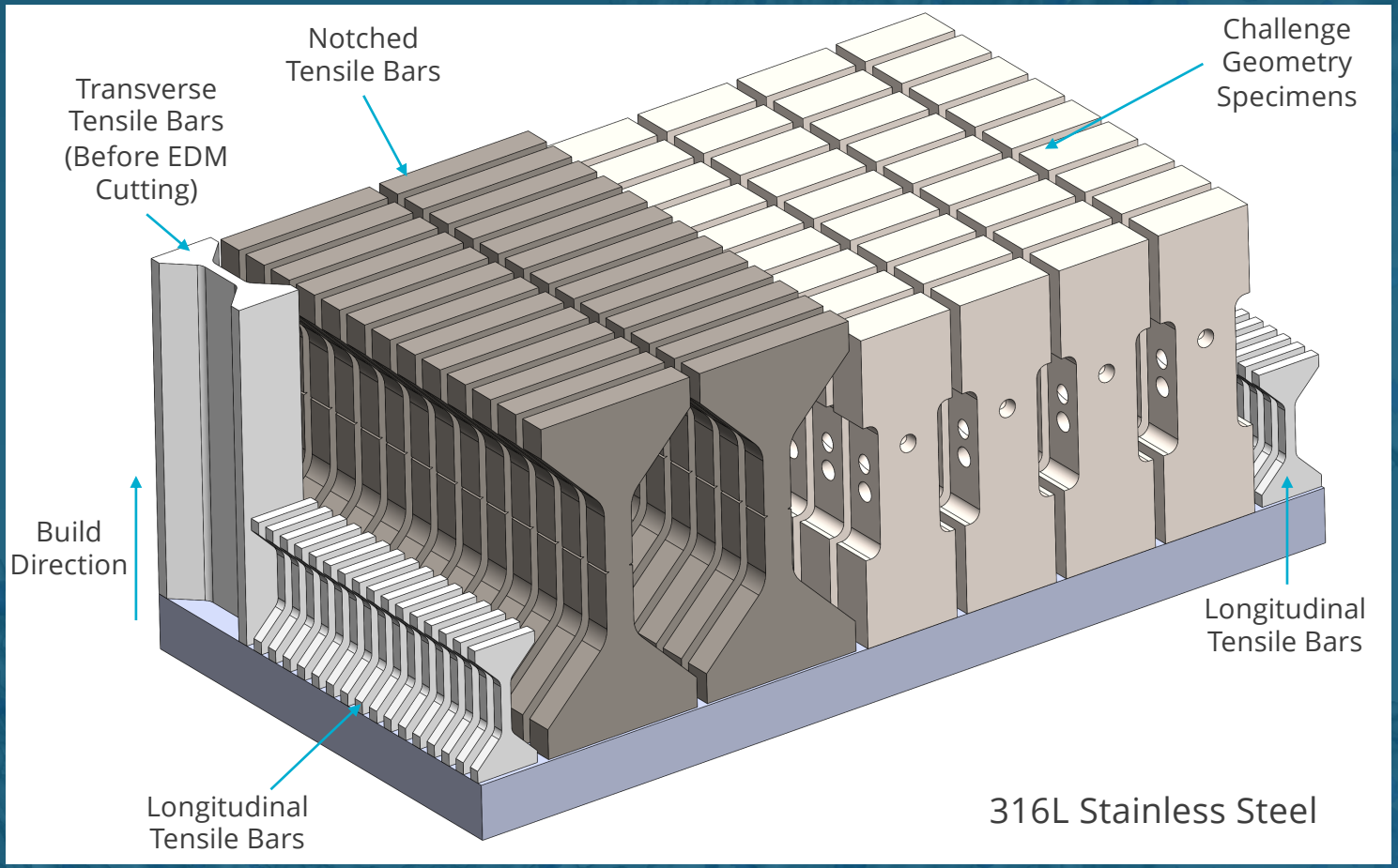


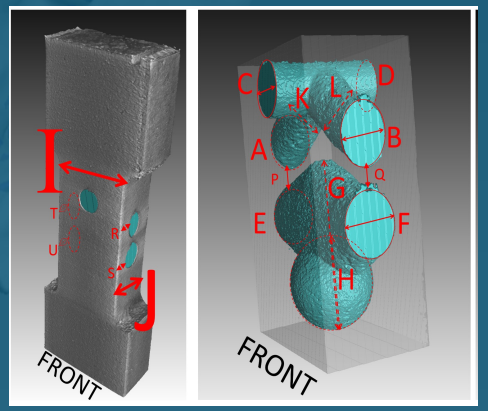
Strain-Rate Dependent Behavior of AM Metal



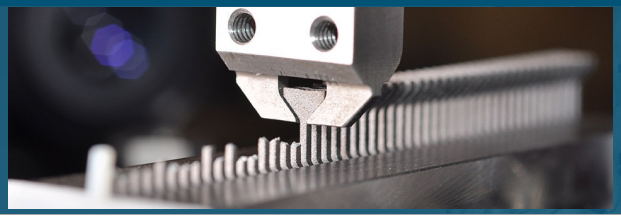


Third Sandia Fracture Challenge



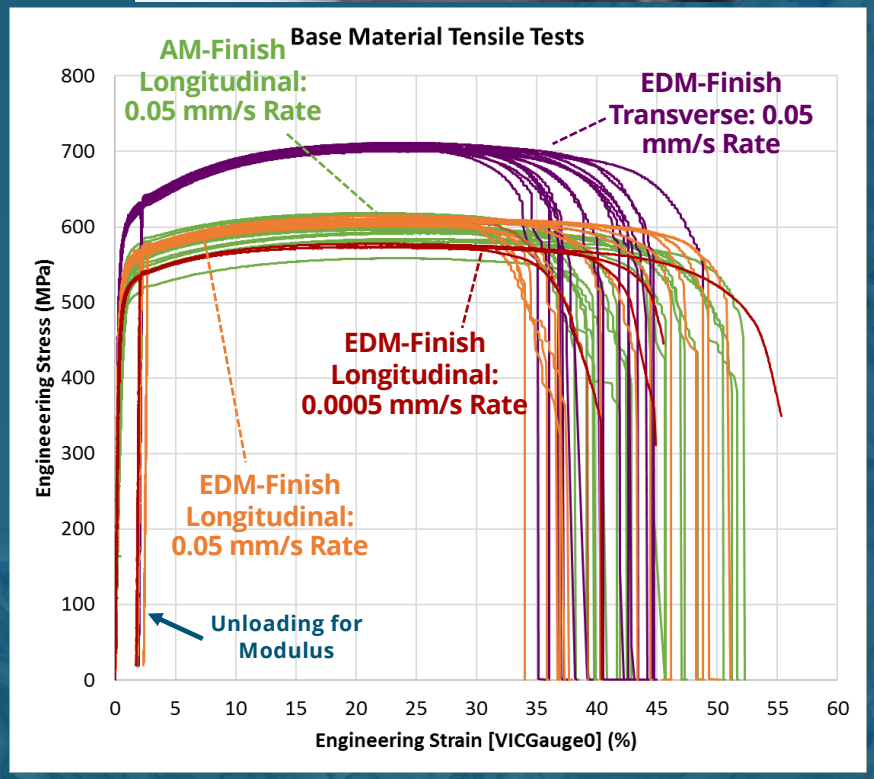


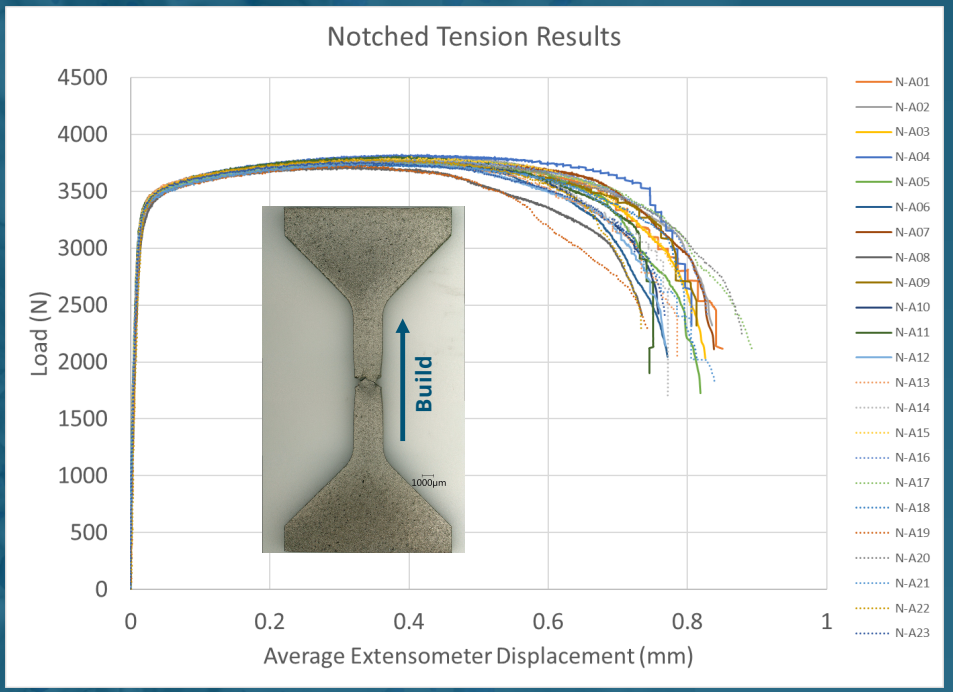
Variability in Mechanical Response of Base Material



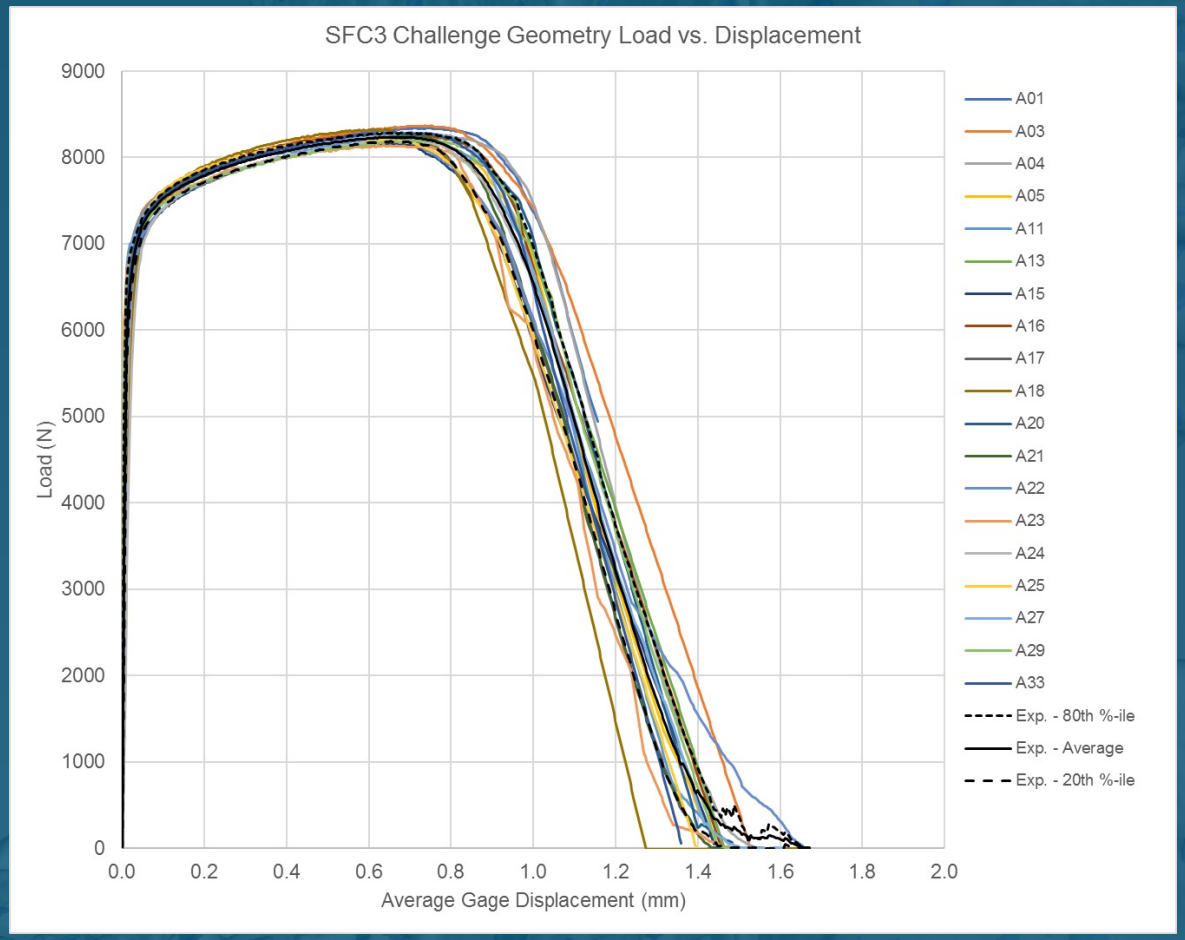
Uniform Cross-Section → Variability

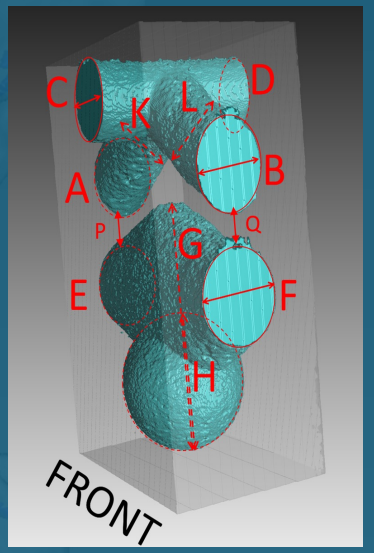
Notched Cross-Section → Less Variability





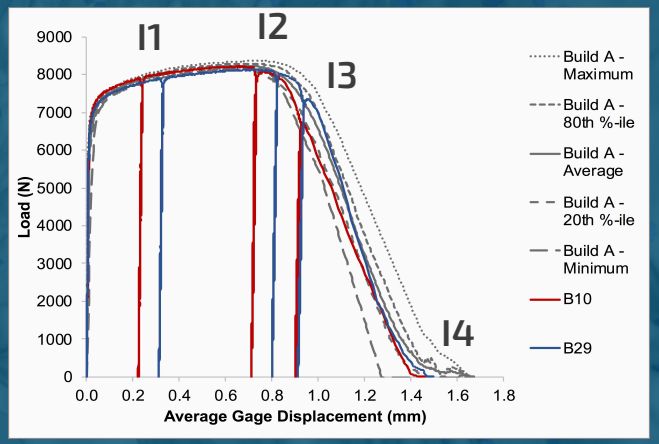
Global Mechanical Response of Structured Parts



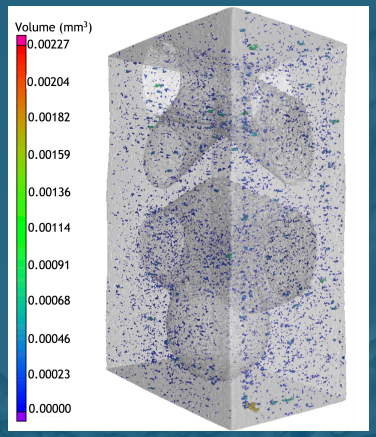


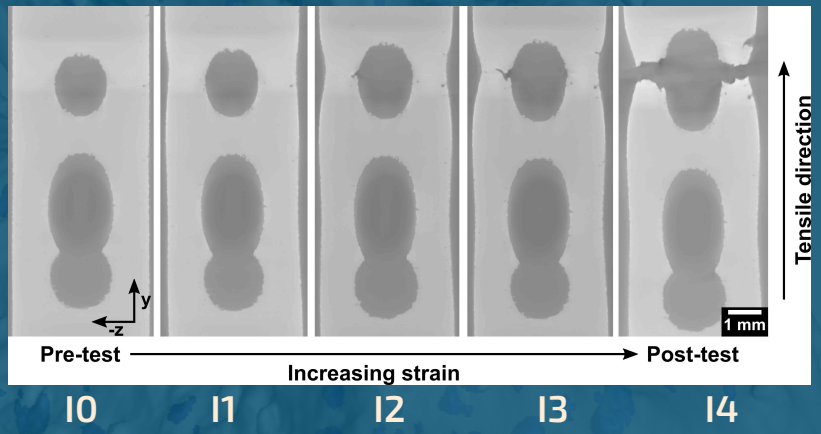
Interrupted Testing to Track Fracture Evolution

Interrupted Response



Pre-test data showing voids

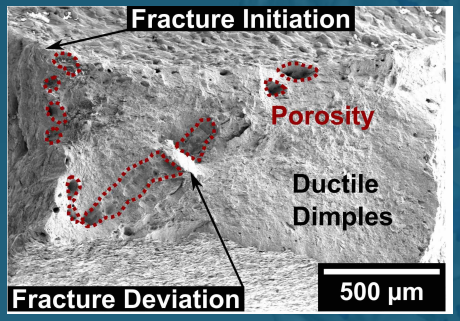




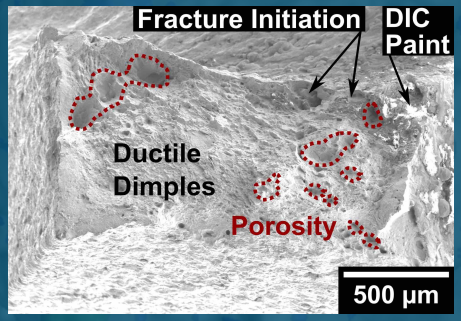
Ex situ micro-CT internal slices for Specimen B33

Local Fracture Variation in Structured Parts

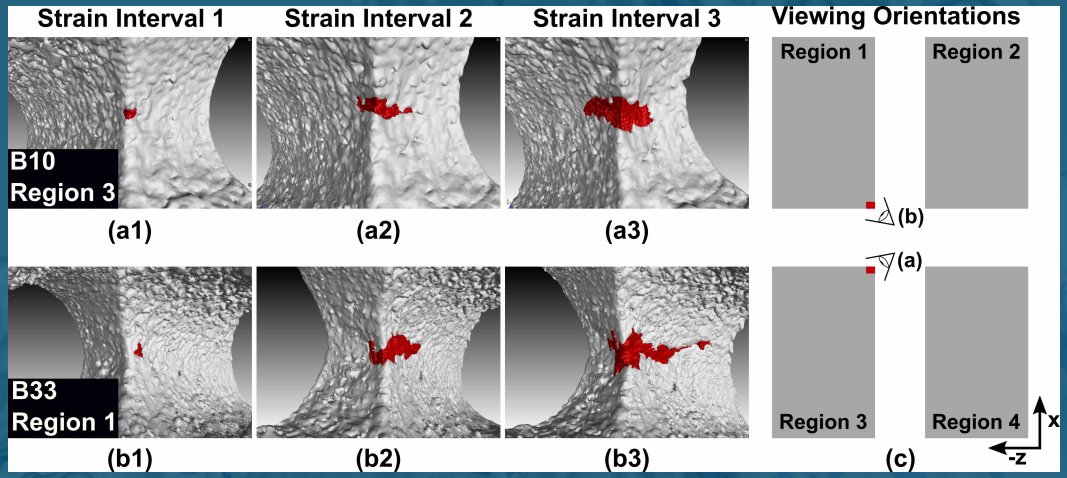
Specimen B10 Region 3



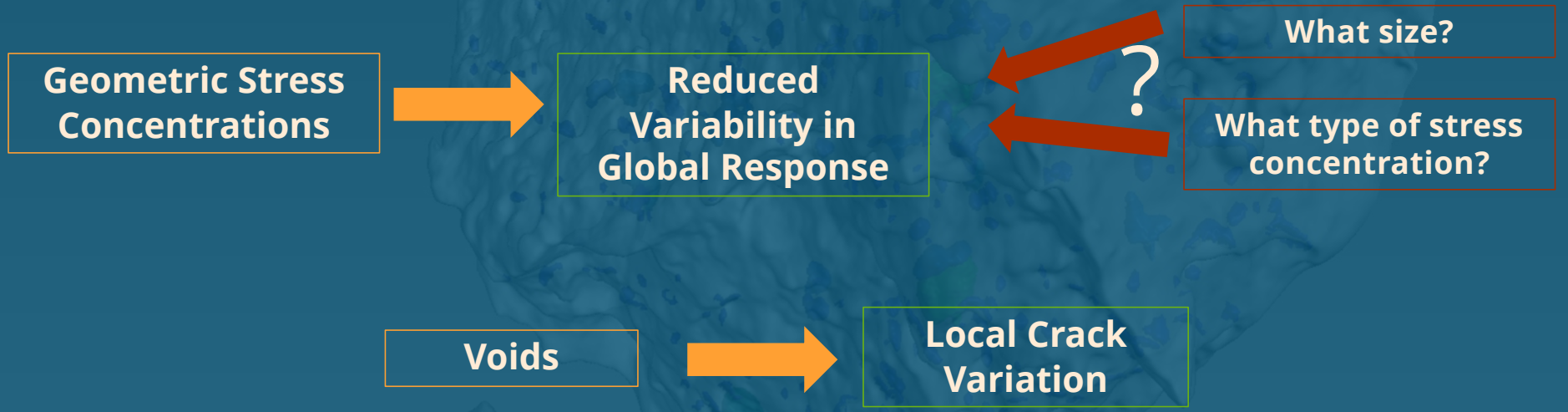
Specimen B33 Region 1



3D Reconstructions Highlighting Crack Volume



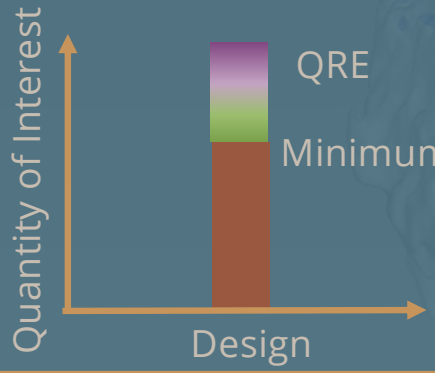
Lessons Learned and Open Questions



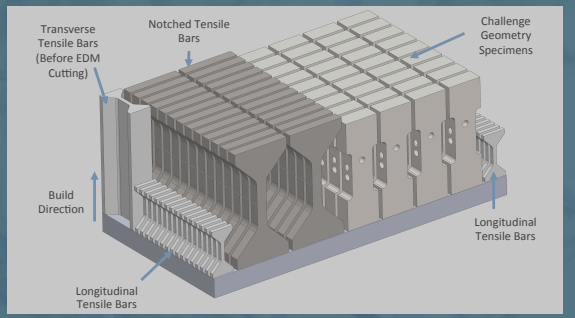
What Dominates Mechanical Response?

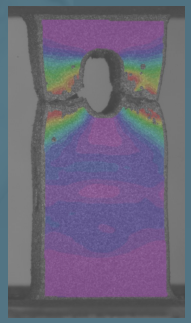
Sandia Research

Qualification Response Envelope (QRE)

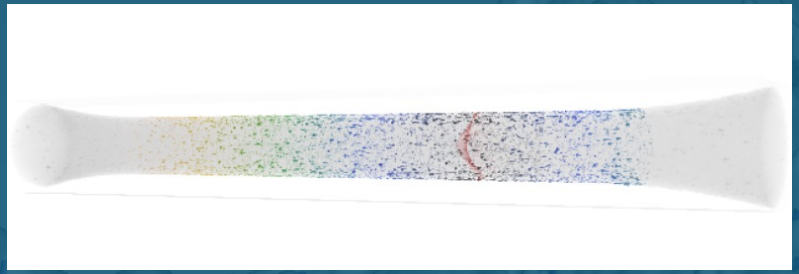


Fracture in AM Metal Parts

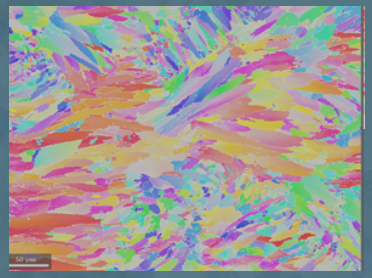


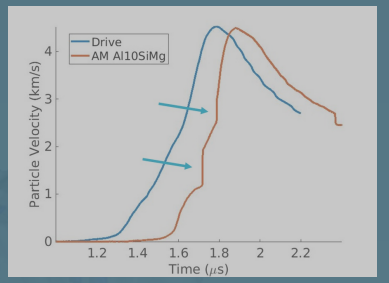


Fatigue in AM Metal



Strain-Rate Dependent Behavior of AM Metal

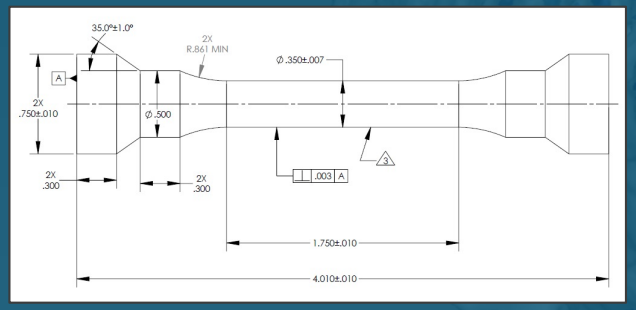




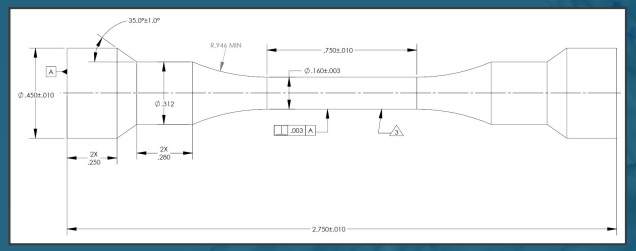
Fatigue in AM Ti-6Al-4V: Variables

AM Ligament Size

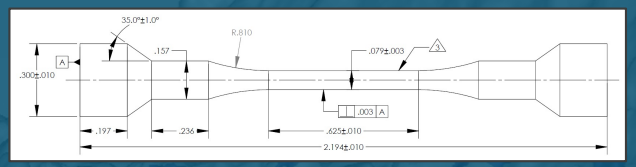
R2 Specimen
D = 8.89 mm



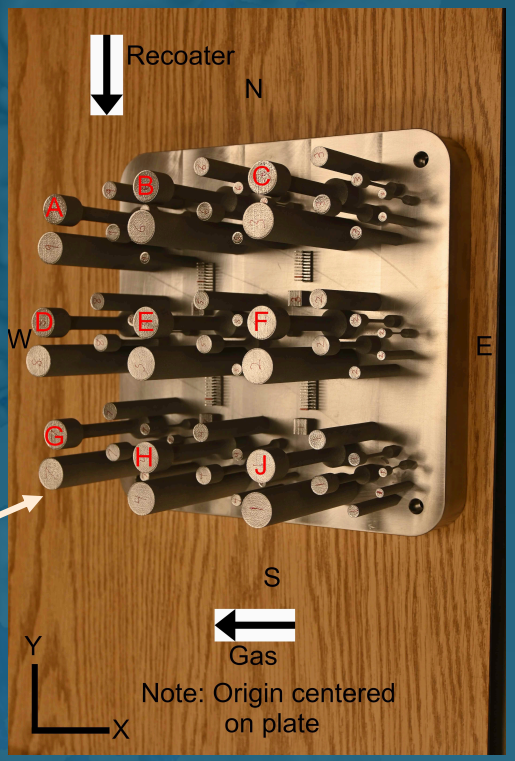
R4 Specimen
D = 4.06 mm



R6 Specimen
D = 2.01 mm



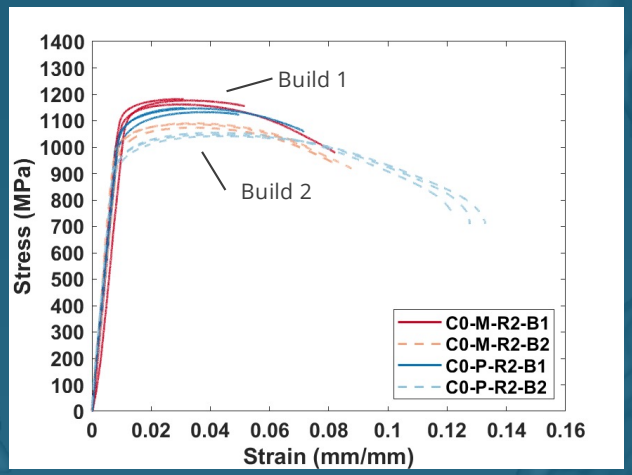
As-Printed vs. Post-Machined



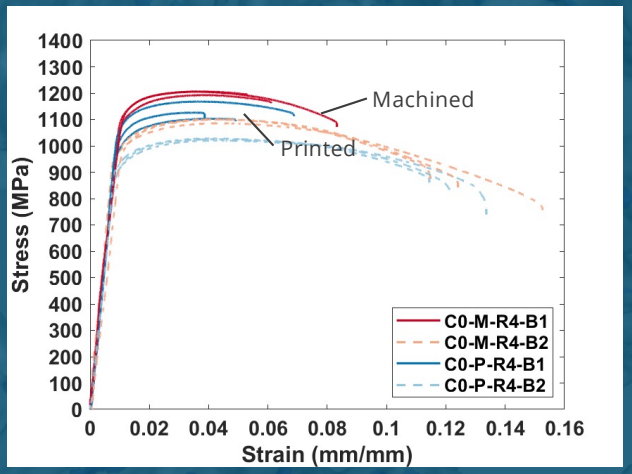
Printed Cylinders To Be Machined

Monotonic Tension Results

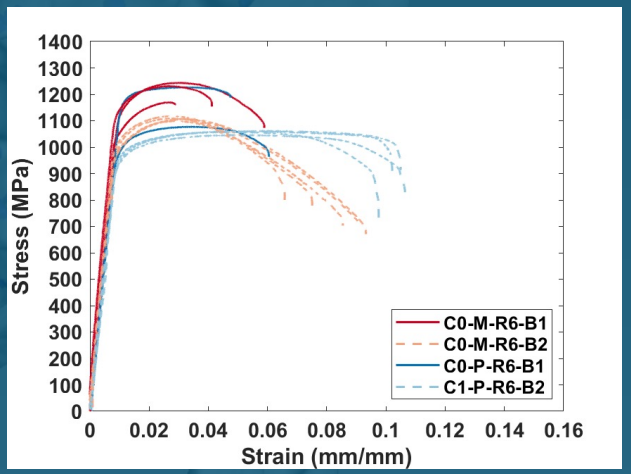
R2



R4

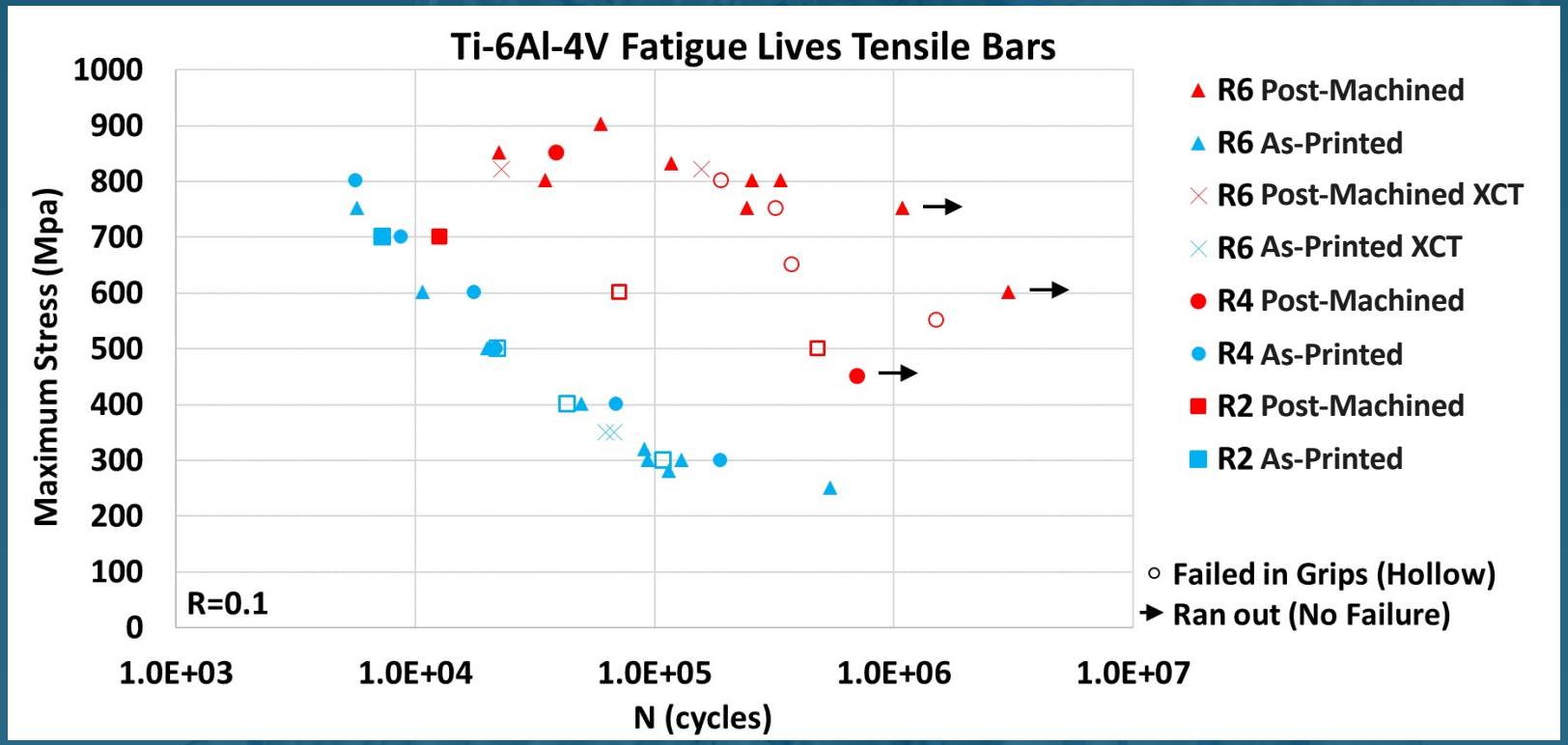


R6



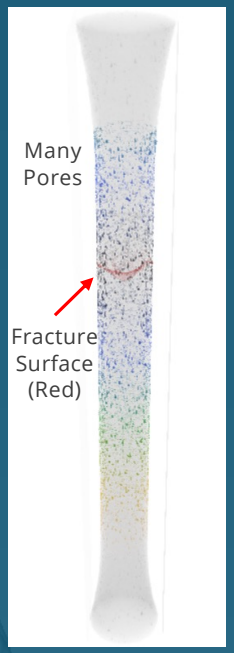
Decreasing Sample Size

Fatigue Results



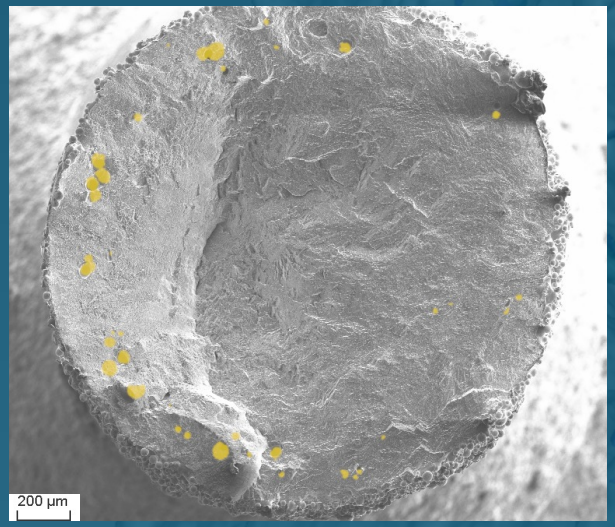
Fatigue Crack

As-Printed



XCT-identified Pores

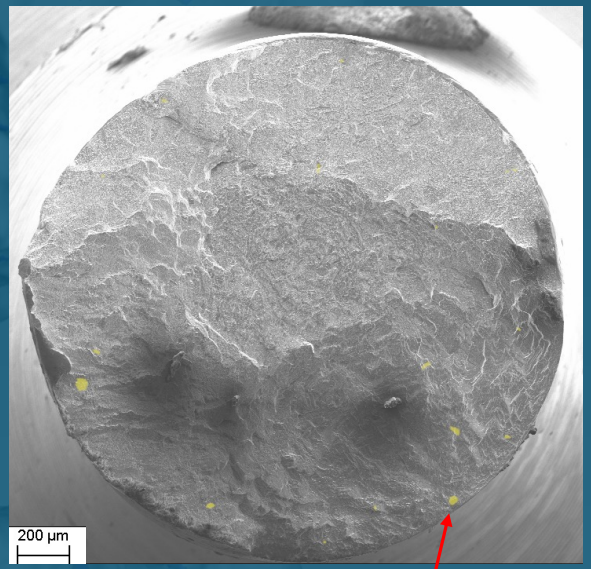
SEM Micrograph of Fracture Surface



Post-Machined

XCT-identified Pores

SEM Micrograph of Fracture Surface

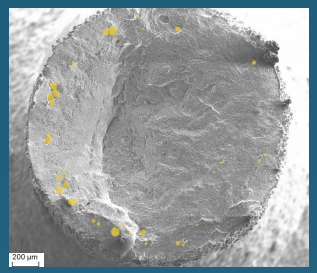


Failure Pore

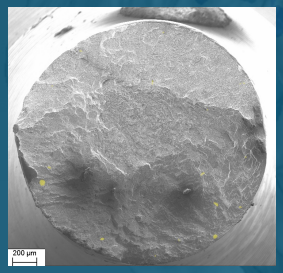
Fatigue: Future Variables of Interest

Different Post-Machining Methods

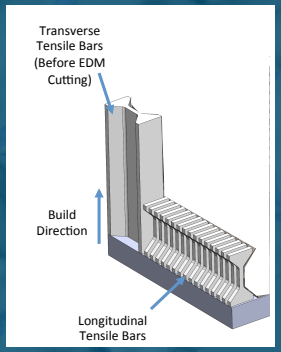
Remove Crust Only



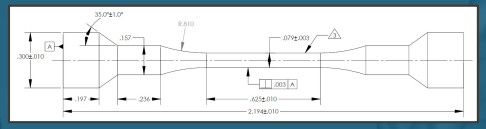
Polish Machining Marks

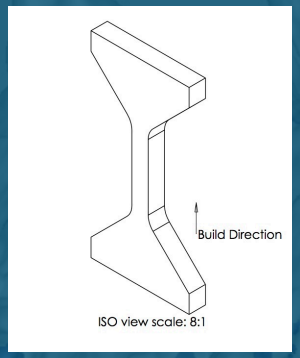


Build Orientation



Round vs. Flat Fatigue Specimens





Witness Fatigue Specimens

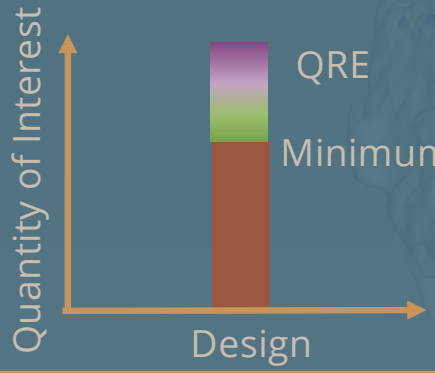
Compare to:

- Fatigue of specimen cut from part
- Fatigue of entire part

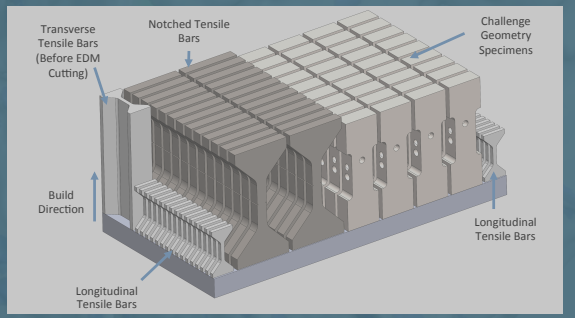
https://www.eos.info/en/

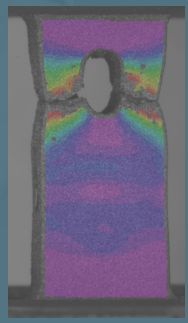
Sandia Research

Qualification Response Envelope (QRE)

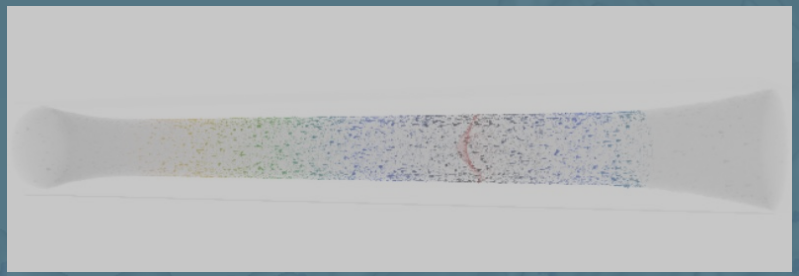


Fracture in AM Metal Parts

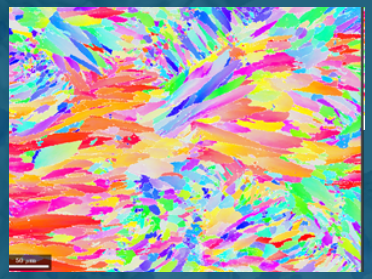


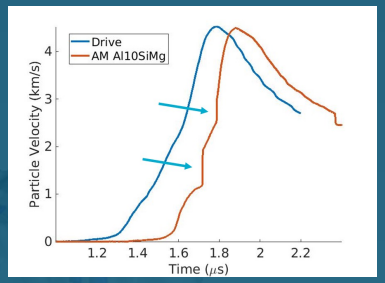


Fatigue in AM Metal

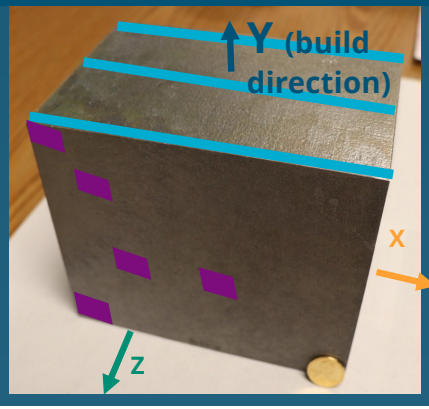


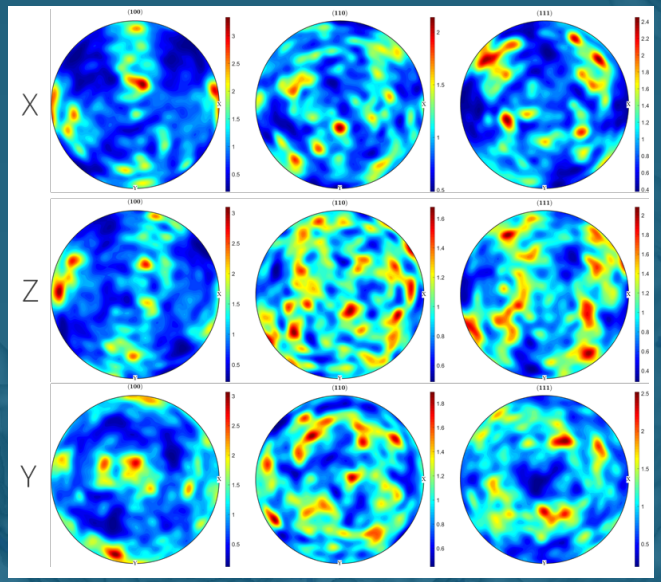
Strain-Rate Dependent Behavior of AM Metal

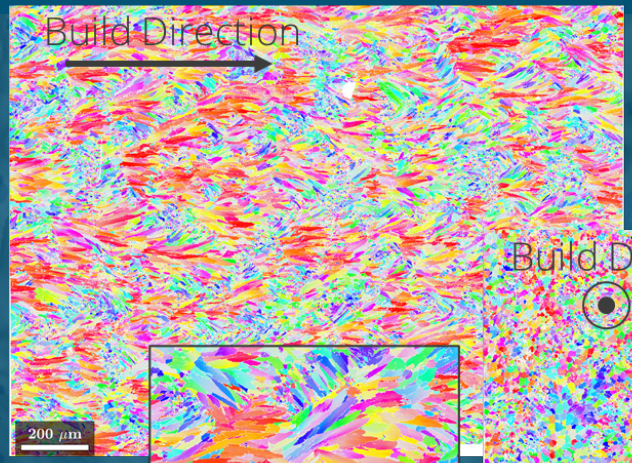


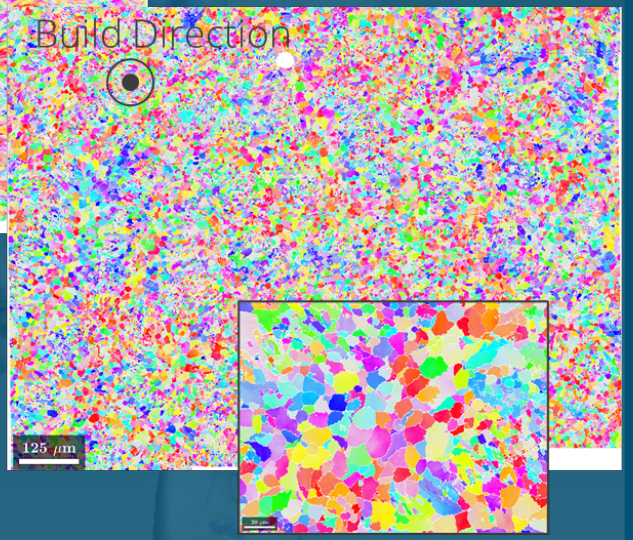


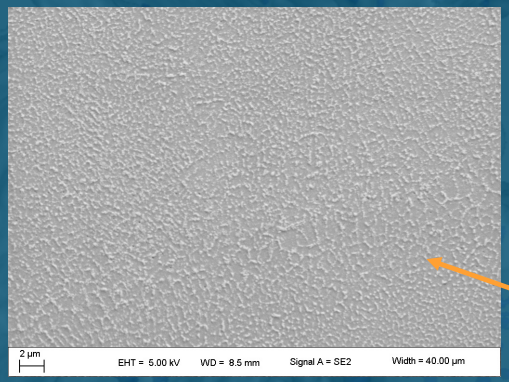
AlSi10Mg Microstructure





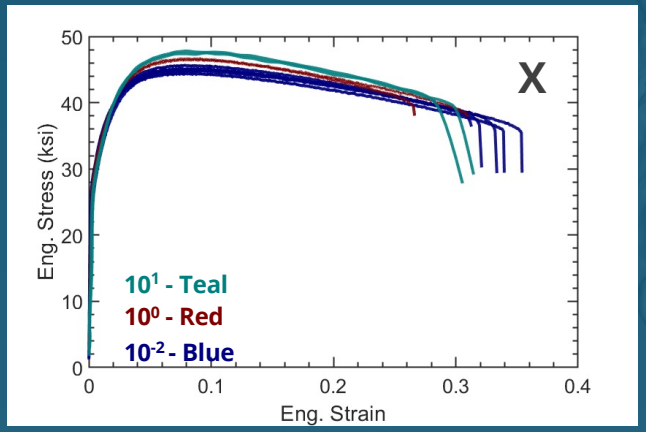


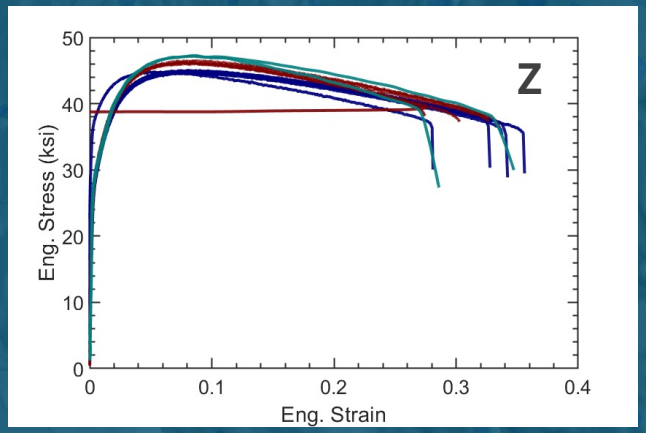


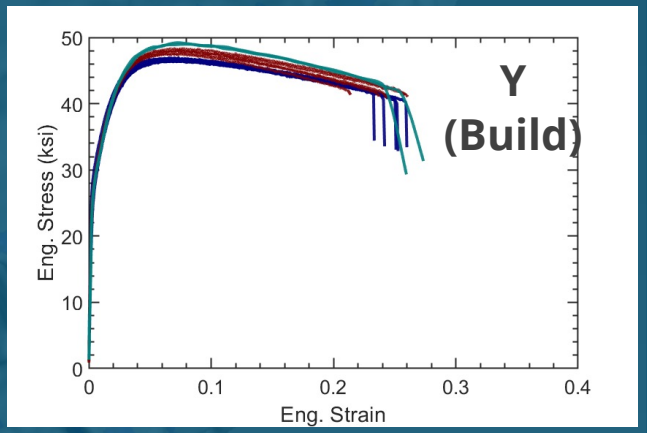


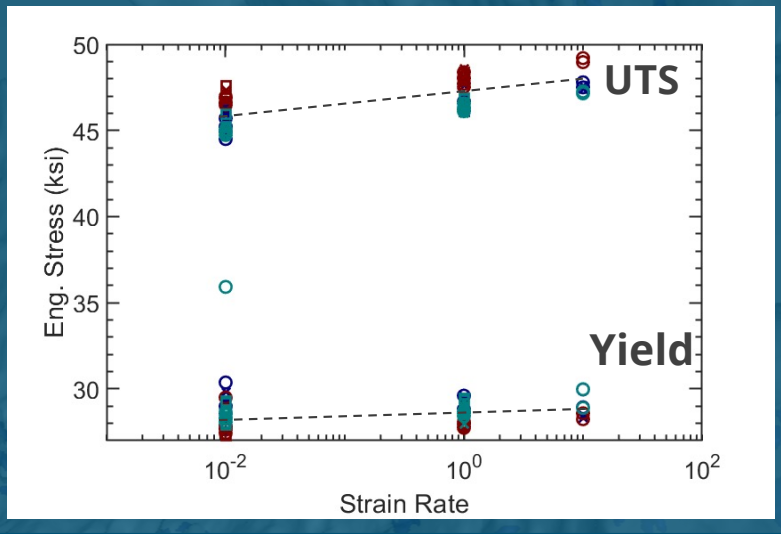
Si Intermetallic Precipitates

Tension for 10^{-2} to 10^{1}



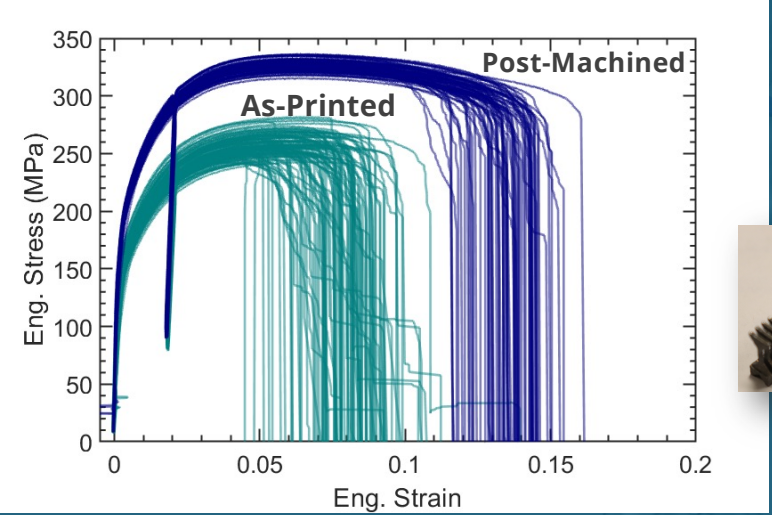




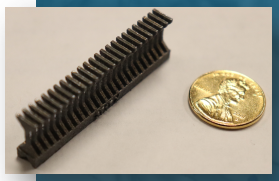


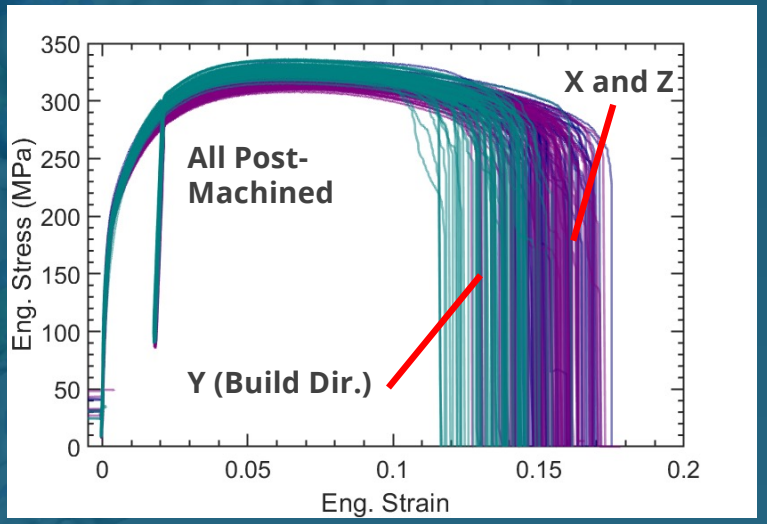
Colors represent the different testing directions, and the shapes represent the locations along the build height

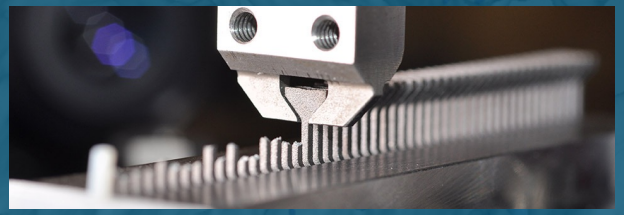
Effect of Processing History and Surface Finish



Evaluated using high-throughput tensile coupons



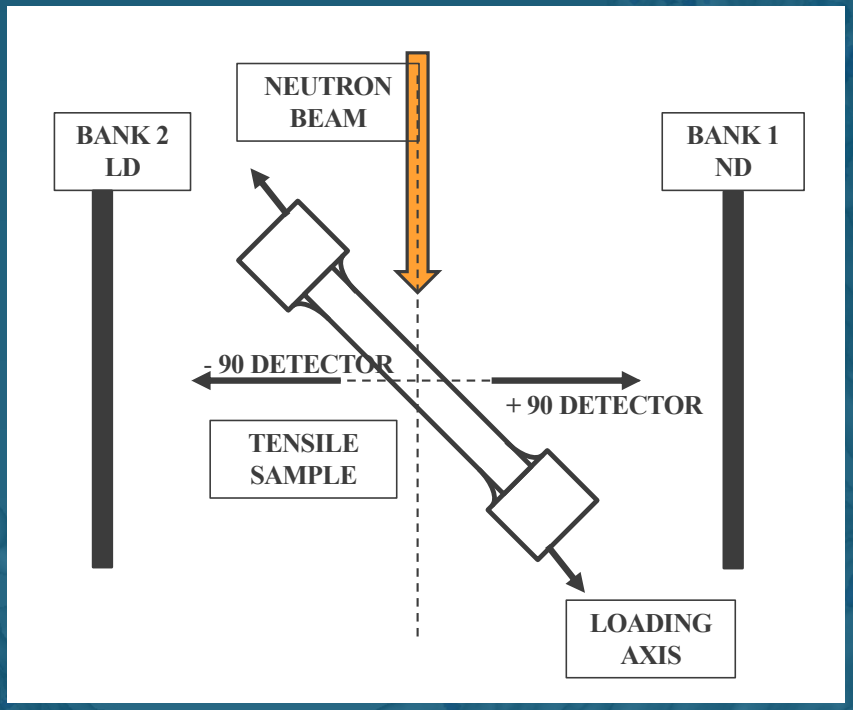




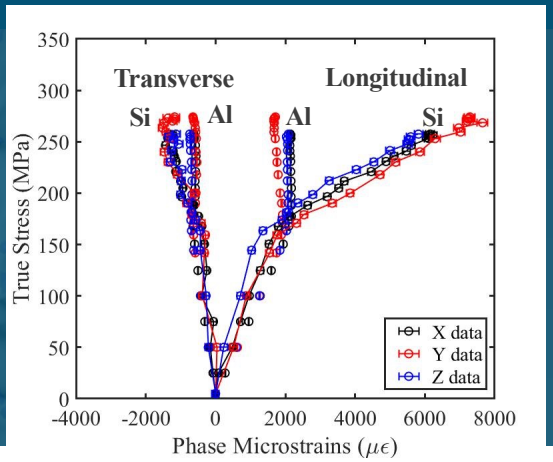
Surface roughness can be a significant driver of the material response

Stress-Partitioning Tensile Experiments

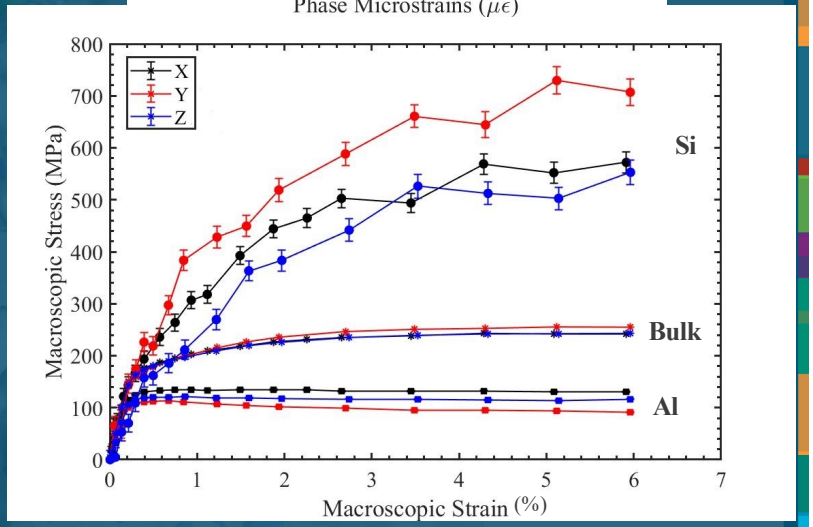
Schematic of tensile-loading stress partitioning experiment



Phase lattice stress vs. strain

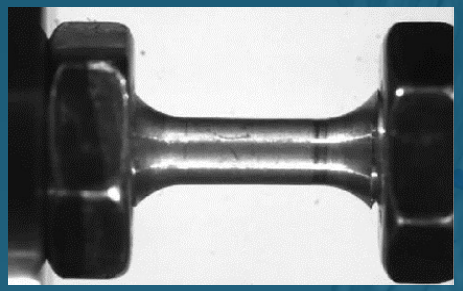


Stress partitioning

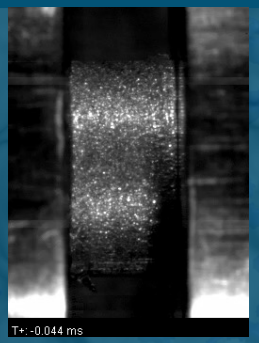


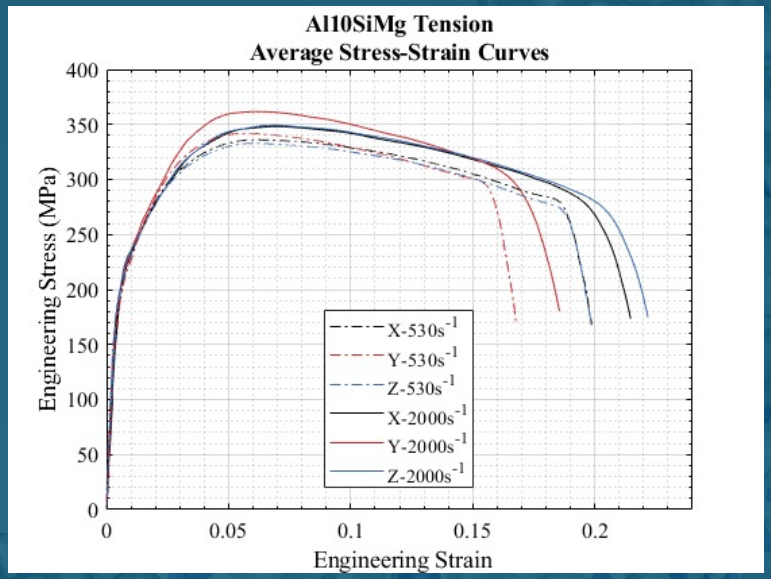
Collaborators: Bjørn Clausen (LANL), Don Brown (LANL), and Milan Agnani (Mines)

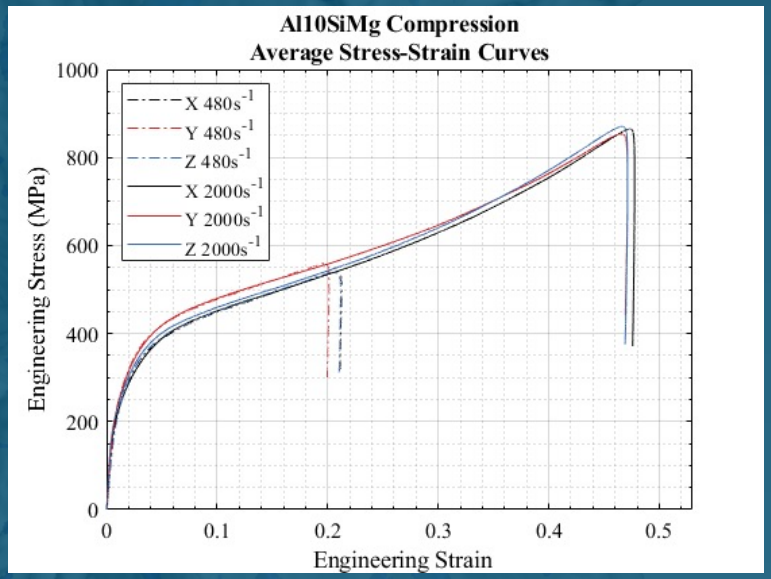
Tension and Compression for 10^2 to 10^3



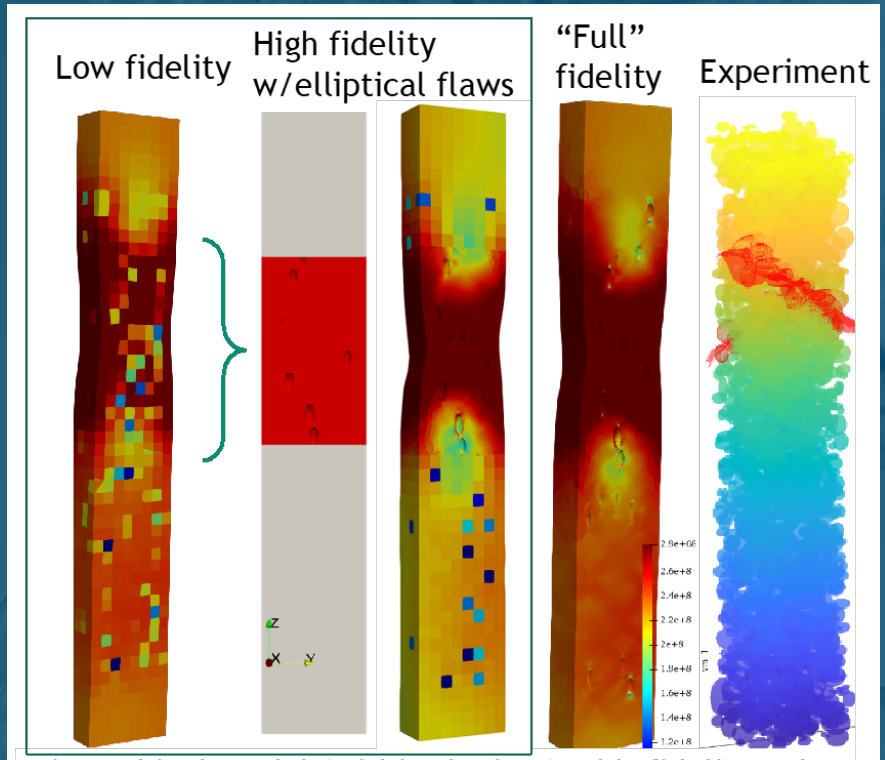
Split-Hopkinson Pressure Bar Testing







Solid Mechanics Modeling Approach



Hierarchical model (within the box) adds fidelity only in hotspot regions where its needed.

High-Rate Material Modeling

EOS model

pressure: p

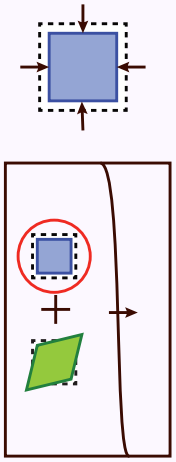


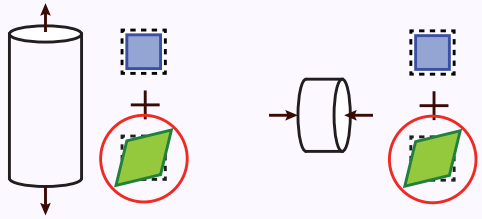
plate impact

$p >> \tau$

$\dot{\varepsilon} \sim 10^{6}\ s^{-1}$

strength model

shear: τ



uniaxial tension

$\tau \sim p$

$\dot{\varepsilon} \sim 10^{-3}$ to $10^{1}\ s^{-1}$

Hopkinson bar

$\tau \sim p$

$\dot{\varepsilon} \sim 10^{2}$ to $10^{3}\ s^{-1}$

failure model

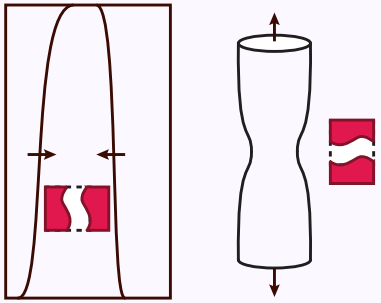


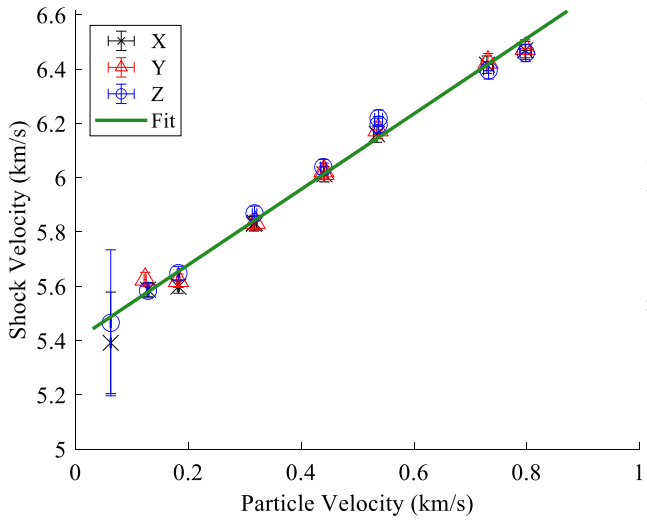
plate impact

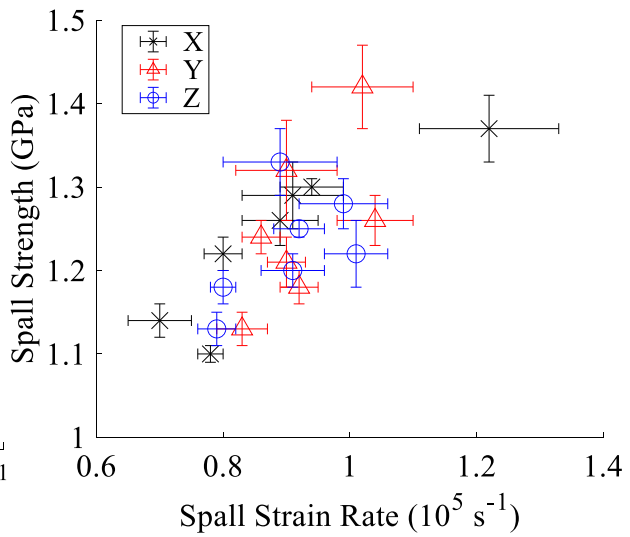
spall

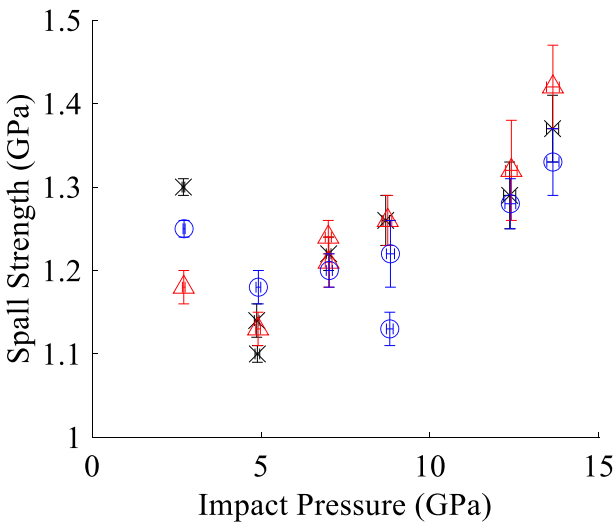
uniaxial tension

ductile failure

EOS and Spall Response





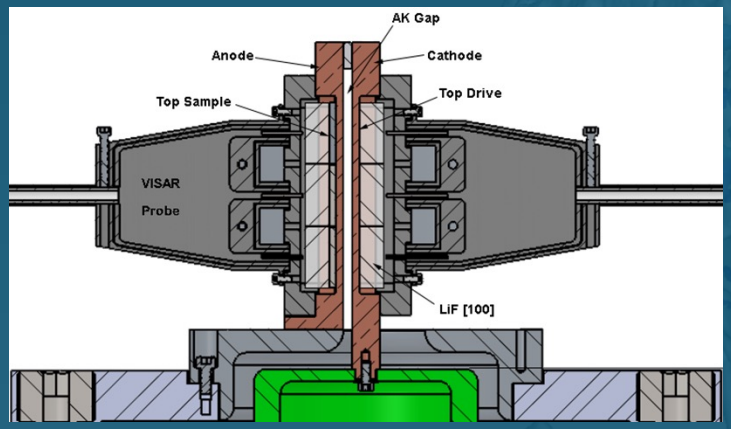


EOS for AlSi10Mg Like That for Al 6061 up to ~13GPa

Isotropic Spall Strength
(Anisotropic response disappears at high strain-rates)

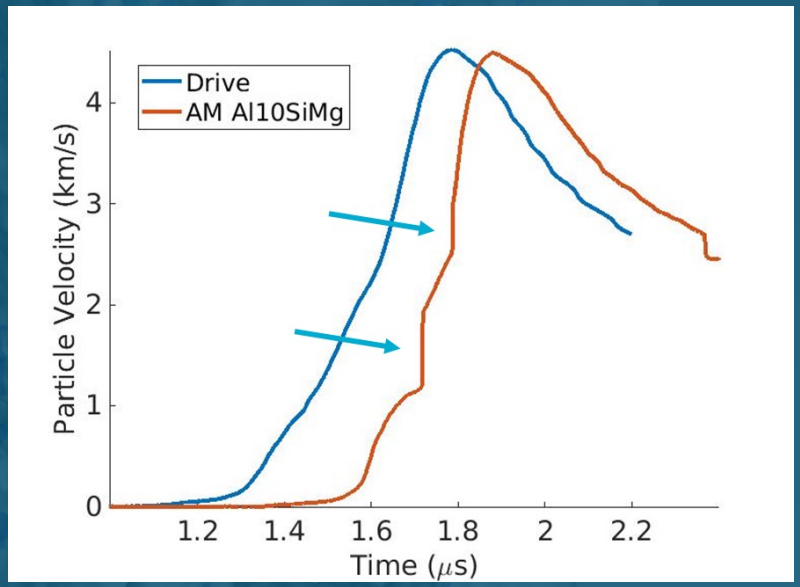
Quasi-Isentrope Experiments on Z-Machine

Ramp-Release Experiments at Mega-Bar Stresses

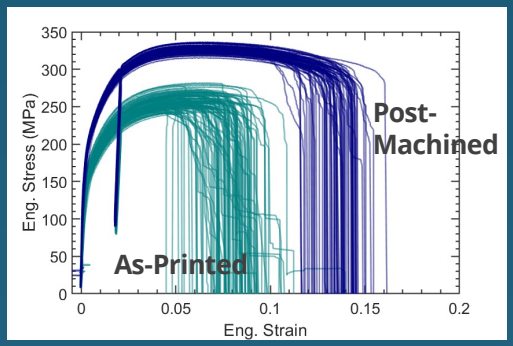


Z3615 Target

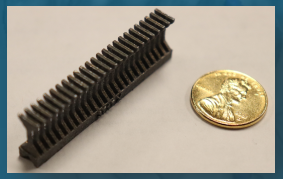
AM AlSi10Mg exhibits two low pressure phase changes

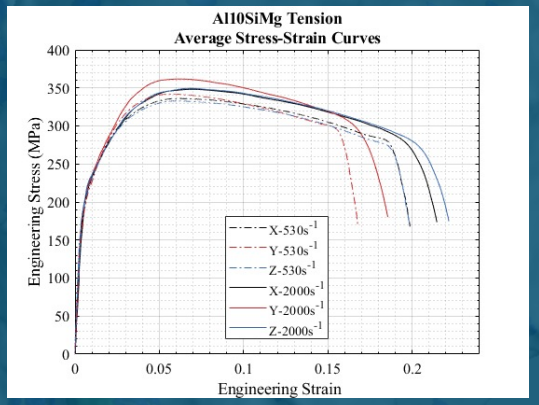


Key Insights from AlSi10Mg Study

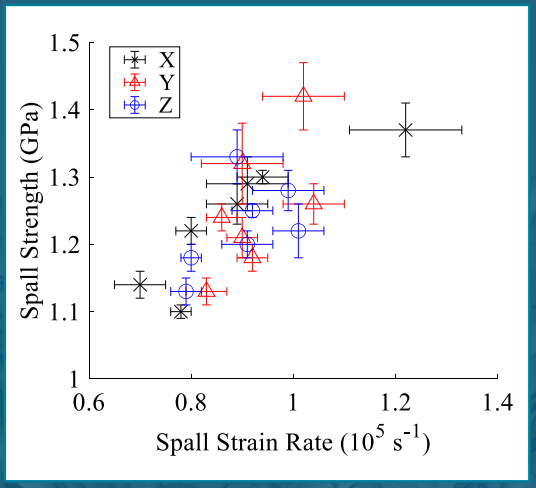


Size of Printed Part and Surface Finish Matter

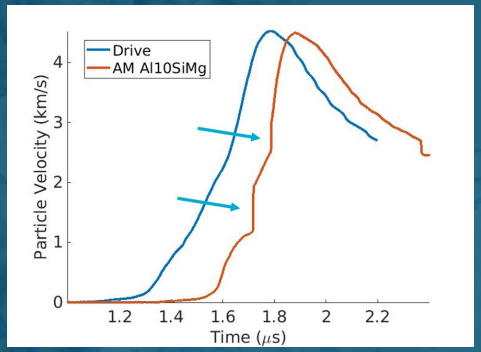




Strain Rate-Dependent and Anisotropic Behavior at Q.S. and intermediate Strain Rates



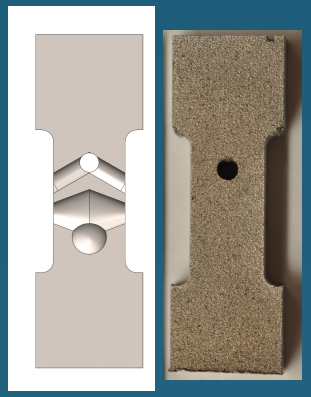
Strain Rate-Dependent and Behavior at High Rates, but Anisotropic Response Disappears



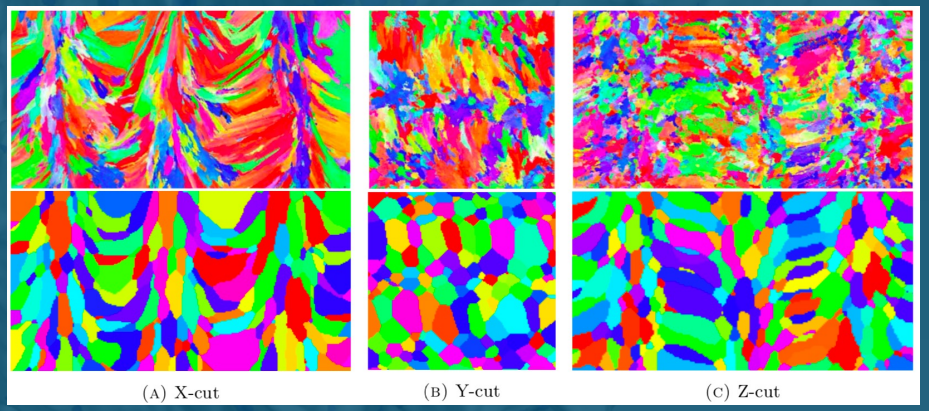
Unexpected Phase Changes in an Al Alloy at High Pressures

Future Work on Strain-Rate Dependent Behavior

Effect of Geometry



Improved modeling at all rates



EBSD

SPPARKS

Topology Optimization

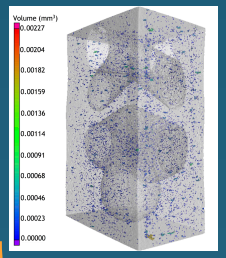
https://www.eos.info/en/

Design Guidance

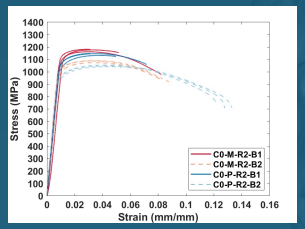
- Stress Concentrations
- Ligament Sizes
- Machining Considerations

Summary of Foundational Research for QRE and Future Work

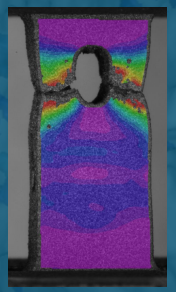
Role of Inspection



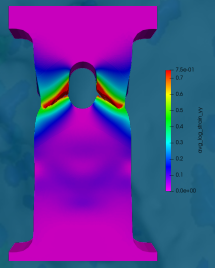
Further Material Characterization



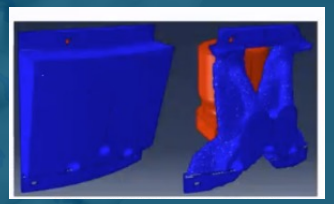
Part Geometry Effects



Part Performance Predictions



Topology Optimization



Future Work for QRE

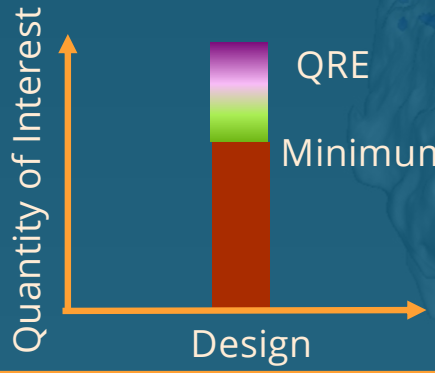
Sources of Variability in Mechanical Response

- Flaw Structure
- Surface Finish
- Part Geometry
- Build History (Thermal History)
- Microstructure / Anisotropy

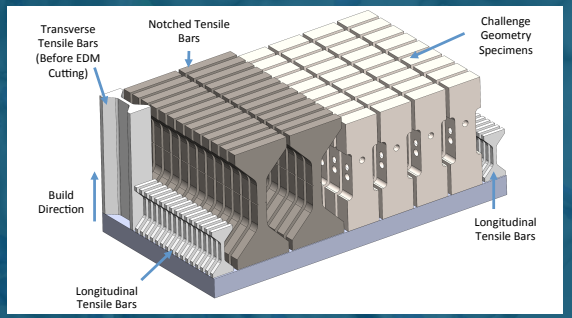
Complex Relationship Between Part Geometry and Flaw Structure

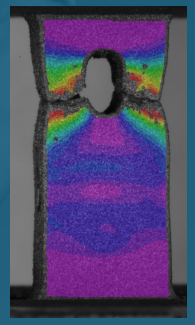
Sandia Research to Support Development of AM Structural Parts

Qualification Response Envelope (QRE)

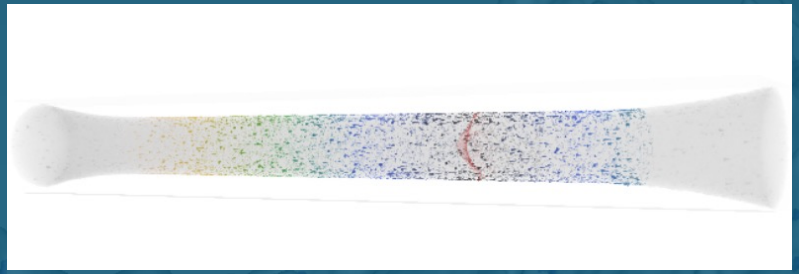


Fracture in AM Metal Parts

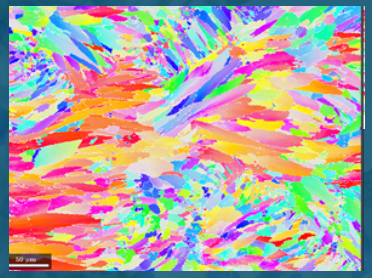


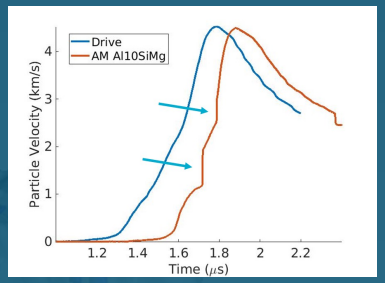


Fatigue in AM Metal



Strain-Rate Dependent Behavior of AM Metal





Questions