SAND2022-13835C

Sandia National Laboratories

Scientific Foundations and Approaches for Qualification of Additively Manufactured Structural Components

Sharlotte Kramer, Tyler LeBrun, and Jonathan Pegues

MS&T2022 Conference

Pittsburgh, PA

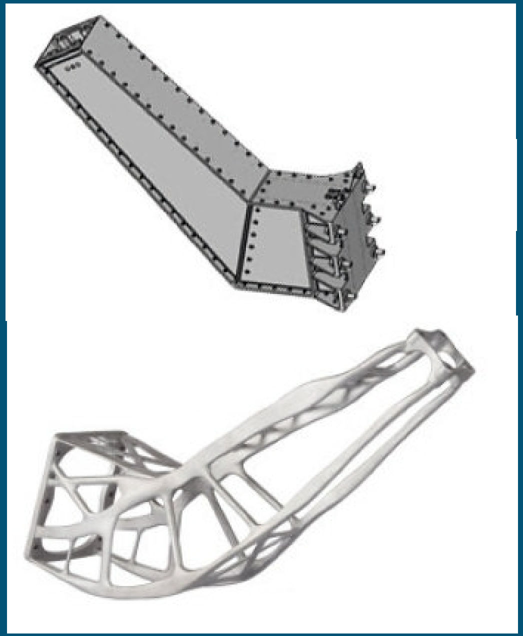
10 October 2022

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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.

End Goal: Quickly Fabricated, Tailored AM Metal Structures

Faster Realization of Parts (Reduction Design and Qualification Time)



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

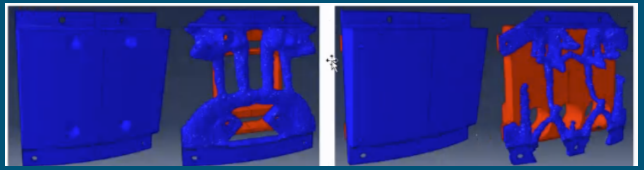
Time to Get Prototype

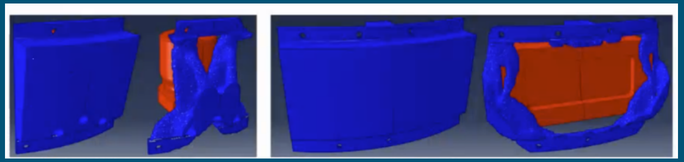
Conventional → **6-24 months**

AM → **0.5-3 months**

Smaller Manufacturing Facilities (Small Lots)

Novel Designs and Architectures and New Functionalities

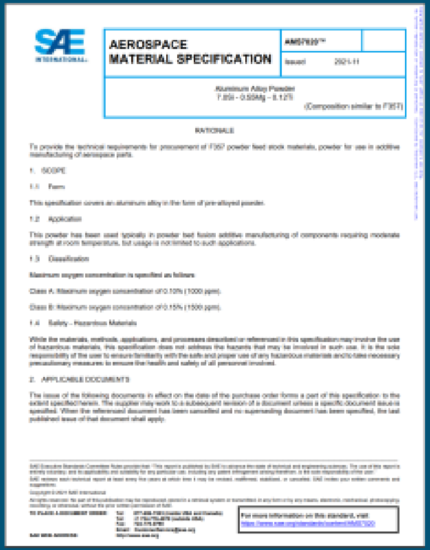




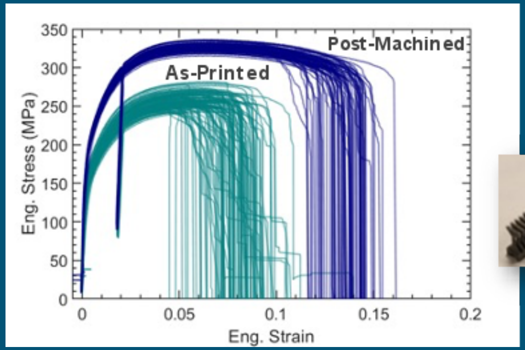
Conventional Vs Weight-Reduced AM Designs

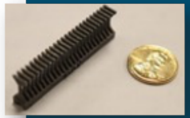
Path to End Goal

Development of AM Material Specifications

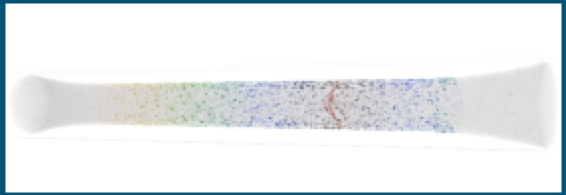


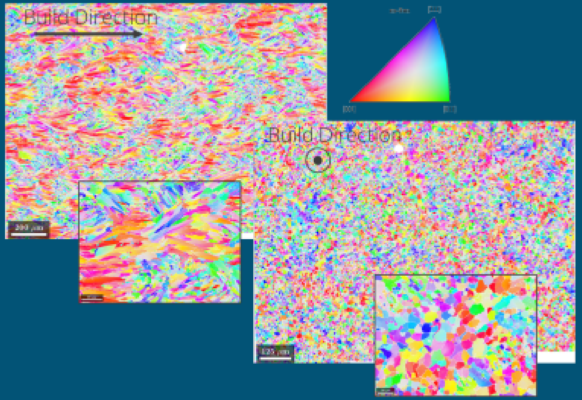
Accelerated Build Health Inspection Approach



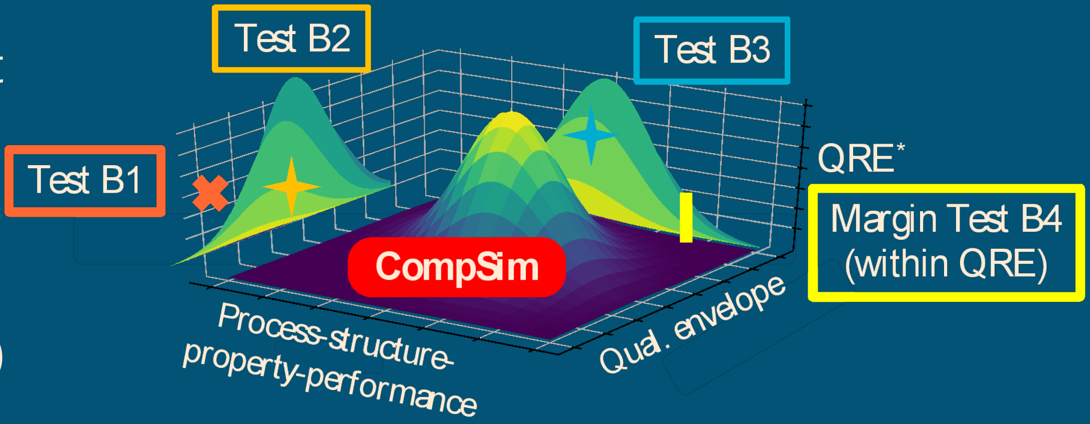


Foundational Science of AM Variables Affecting Performance





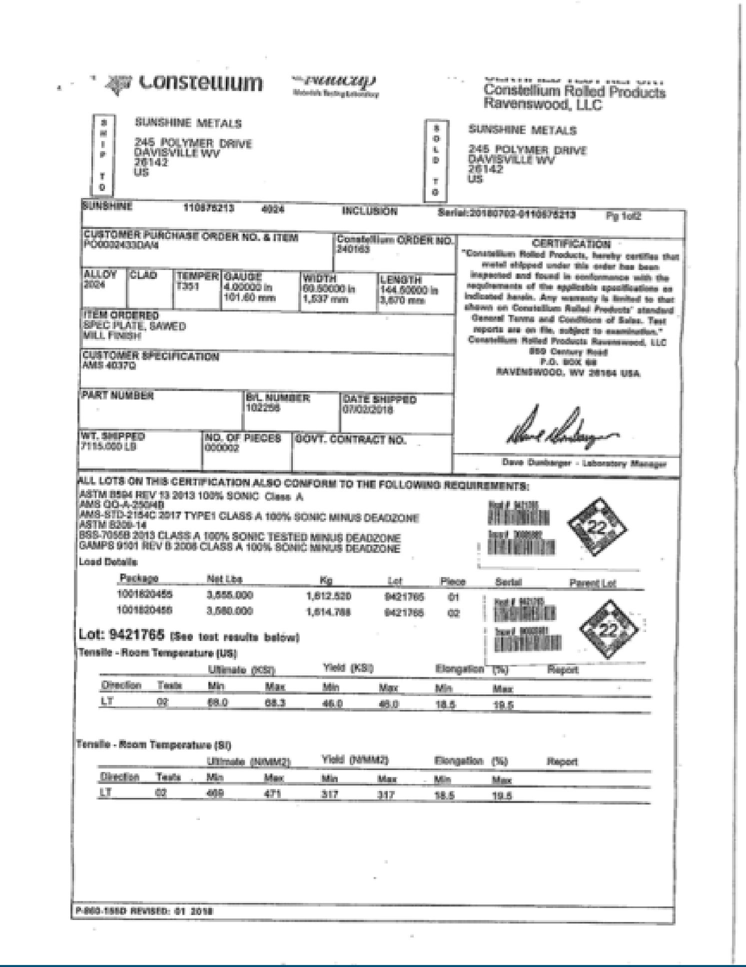
Enveloped Part Qualification Approach: Qualification Response Envelope (QRE)



Materials Specification (MS) Approach(es)

Precedent for Material Specifications

- **Volumetric** forming processes
- **Single-document material specifications** with monolithic properties
- **Testing** of stock represents material and subsequent parts
- **Wide applicability** for forms used in subtractive manufacturing



Constellium

Constellium Rolled Products
Ravenswood, LLC

SHIP TO: SUNSHINE METALS, 245 POLYMER DRIVE, DAVISVILLE WV 26142 US

SOLD TO: SUNSHINE METALS, 245 POLYMER DRIVE, DAVISVILLE WV 26142 US

SUNSHINE 110875213 4024 INCLUSION Serial:20180702-0110875213 Pg 1of2

CUSTOMER PURCHASE ORDER NO. & ITEM: PO0002433DA/4

Constellium ORDER NO.: 240163

ALLOY	CLAD	TEMPER	GAUGE	WIDTH	LENGTH
2024		T351	4.00000 in 101.60 mm	60.50000 in 1,537 mm	144.50000 in 3,670 mm

ITEM ORDERED: SPEC PLATE, SAWED, MILL FINISH

CUSTOMER SPECIFICATION: AMS 4037Q

PART NUMBER:

B/L NUMBER: 102256

DATE SHIPPED: 07/02/2018

WT. SHIPPED: 7115.000 LB

NO. OF PIECES: 000002

GOVT. CONTRACT NO.:

CERTIFICATION

"Constellium Rolled Products, hereby certifies that metal shipped under this order has been inspected and found in conformance with the requirements of the applicable specifications as indicated herein. Any warranty is limited to that shown on Constellium Rolled Products' standard General Terms and Conditions of Sales. Test reports are on file, subject to examination." Constellium Rolled Products Ravenswood, LLC, 859 Century Road, P.O. BOX 68, RAVENSWOOD, WV 26164 USA

Dave Dunbarger - Laboratory Manager

ALL LOTS ON THIS CERTIFICATION ALSO CONFORM TO THE FOLLOWING REQUIREMENTS:
ASTM B594 REV 13 2013 100% SONIC Class A
AMS QQ-A-250/4D
AMS-STD-2154C 2017 TYPE1 CLASS A 100% SONIC MINUS DEADZONE
ASTM B209-14
BSS-7056B 2013 CLASS A 100% SONIC TESTED MINUS DEADZONE
GAMPS 9101 REV B 2006 CLASS A 100% SONIC MINUS DEADZONE

Load Details

Package	Net Lbs	Kg	Lot	Piece	Serial	Parent Lot
1001620455	3,555.000	1,612.520	9421765	01		
1001620456	3,560.000	1,614.788	9421765	02		

Lot: 9421765 (See test results below)

Tensile - Room Temperature (US)

		Ultimate (KSI)		Yield (KSI)		Elongation (%)		Report
Direction	Tests	Min	Max	Min	Max	Min	Max	
LT	02	68.0	68.3	46.0	46.0	18.5	19.5	

Tensile - Room Temperature (SI)

		Ultimate (N/MM2)		Yield (N/MM2)		Elongation (%)		Report
Direction	Tests	Min	Max	Min	Max	Min	Max	
LT	02	469	471	317	317	18.5	19.5	

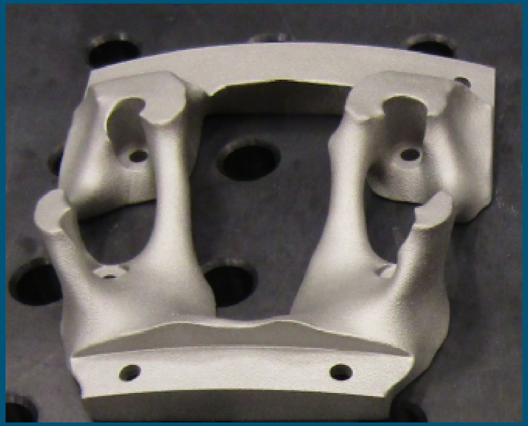
P-860-155D REVISED: 01 2018

Problems with AM Paradigm

- ✗ **Lack of volumetric consistency**
- ✗ **Material specifications** need large safety factors with uncertainty
- ✗ **Witness coupons** may not represent part
- ? **Where is a material specification appropriate or useful?**

Process Control Verification via MS

Developed AM Part



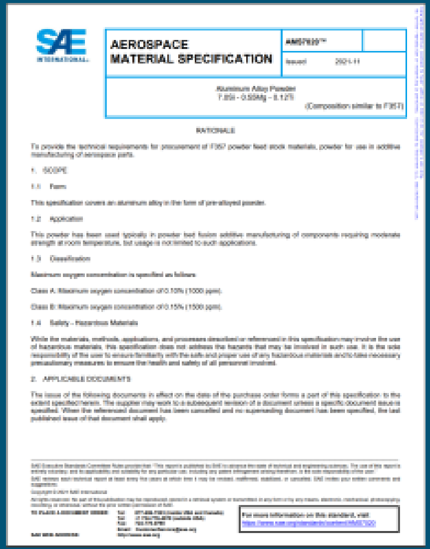
Need to Verify
Process Health and Reproducibility
During Production

Production AM Parts

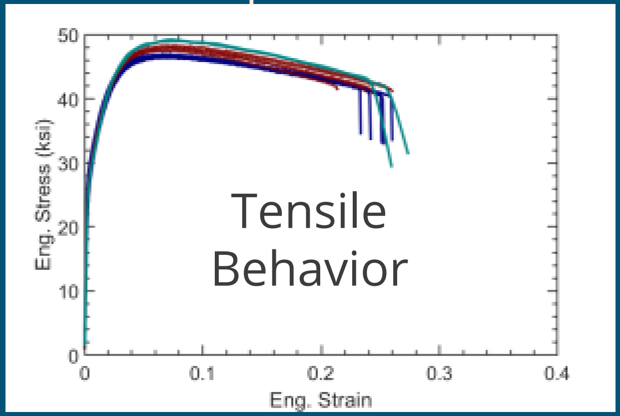
Performance Requirements

- No Yield with Applied Force of 500 N
- Deflection no Greater than 10 mm During Service

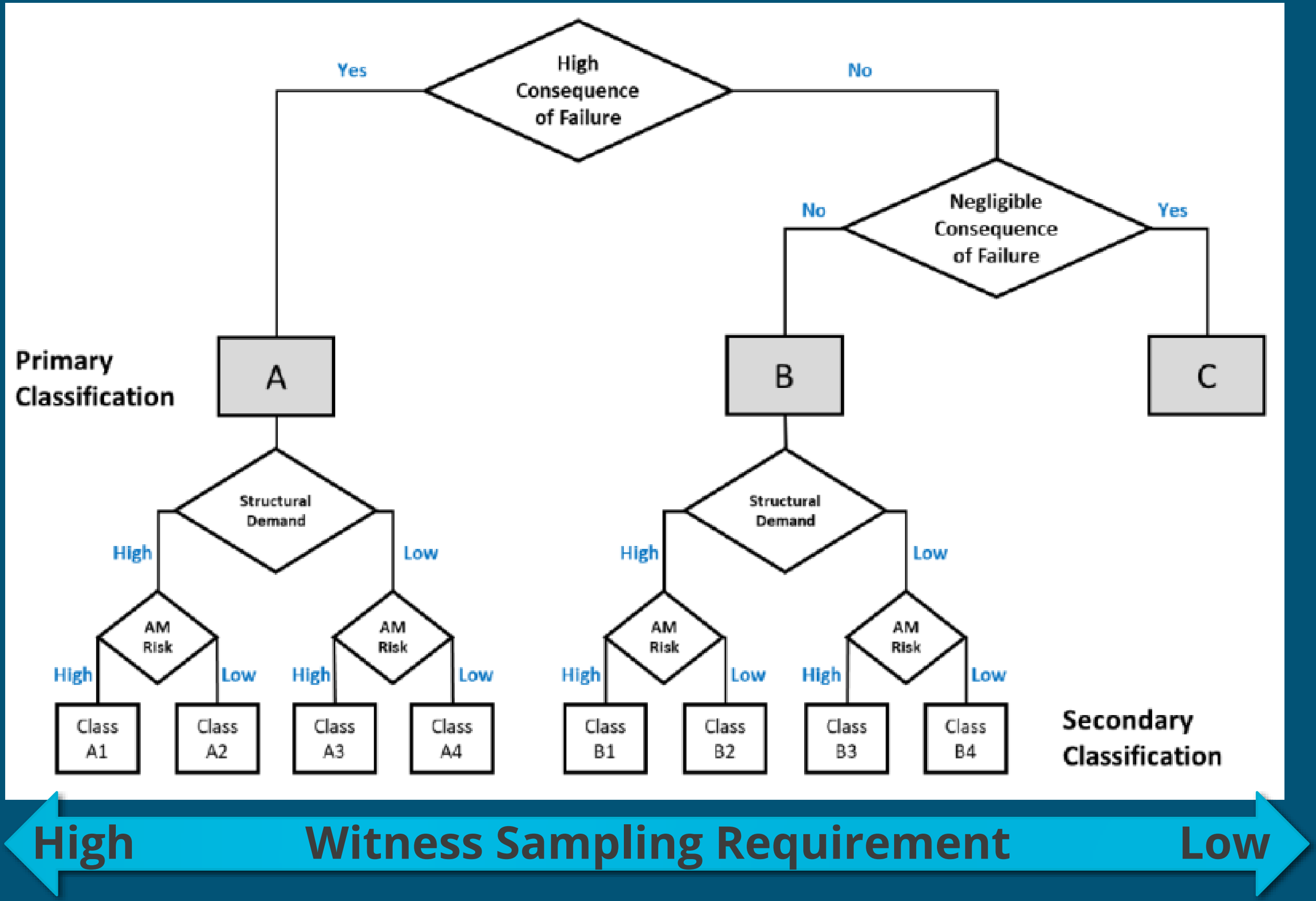
AM MS Gate



Required Witness Coupon Tests



NASA-STD-6030: Quantifiable AM Risk Metric



Risk metric guides witness sampling strategies, but testing burden can be time-inefficient, which is being addressed.

Class	A1	A2	A3	A4
Tensile	6	6	6	6
FH Contingency	1	1	1	1
Metallography	2	2	1	1
Chemistry	1	1	-	-
HCF	2	2	2	2
Low Margin Point	A/R	A/R	-	-
Witness sub-article	A/R	-	A/R	-
Witness article	1 for 6	-	-	-
CQMP	A/R	A/R	A/R	A/R

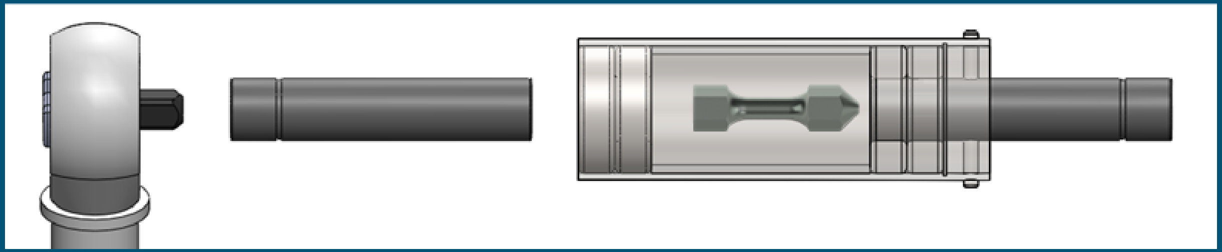
Notes:

FH Contingency = Full-height contingency specimen

A/R = As required when specified in the PPP/QPP

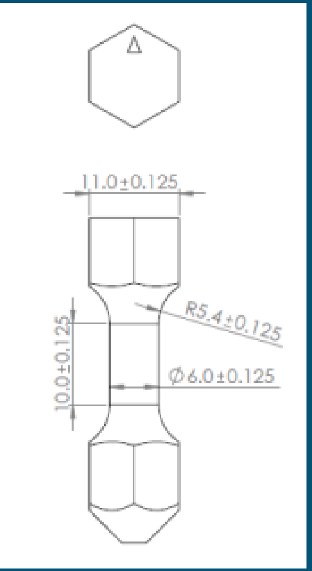
	B1	B2	B3	B4
Tensile	6	6	6	6
FH Contingency	1	1	-	-
Metallography	1	1	-	-
Chemistry	-	-	-	-
HCF	2	-	-	-
Low Margin Point	-	-	-	-
Witness sub-article	A/R	-	-	-
Witness article	-	-	-	-
CQMP	A/R	A/R	-	-

Accelerated Build Health Inspection



- Torsion witness coupon design for testing immediately after build completion
- Designed to monitor build health and intervene post-processing by identifying major build health issues
- Early detection of build corruption
- Provides minimal acceptance criteria for post-processing

Example Torsion Coupon



ASTM INTERNATIONAL Standards Worldwide
AUBURN UNIVERSITY
JABIL
NASA
Sandia National Laboratories

Impact of Unrecognized Build Corruption

Where is the most efficient point in the production cycle to detect build corruption?

Feedstock & Machine Prep	Fabricate Parts	Cycle Machine & Depowder	Stress Relief & Removal	Heat Treat	Test Coupons
4 – 8 hrs	1 – 30 days	4 -8 hrs	3 – 7 days	3 – 10 days	10 – 20 days

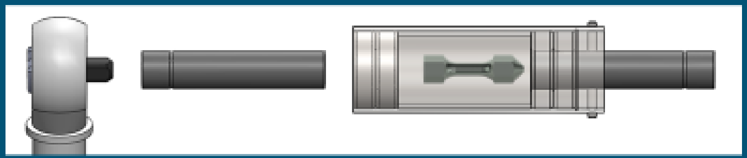
~2 – 32 days (Feedstock & Machine Prep through Cycle Machine & Depowder)

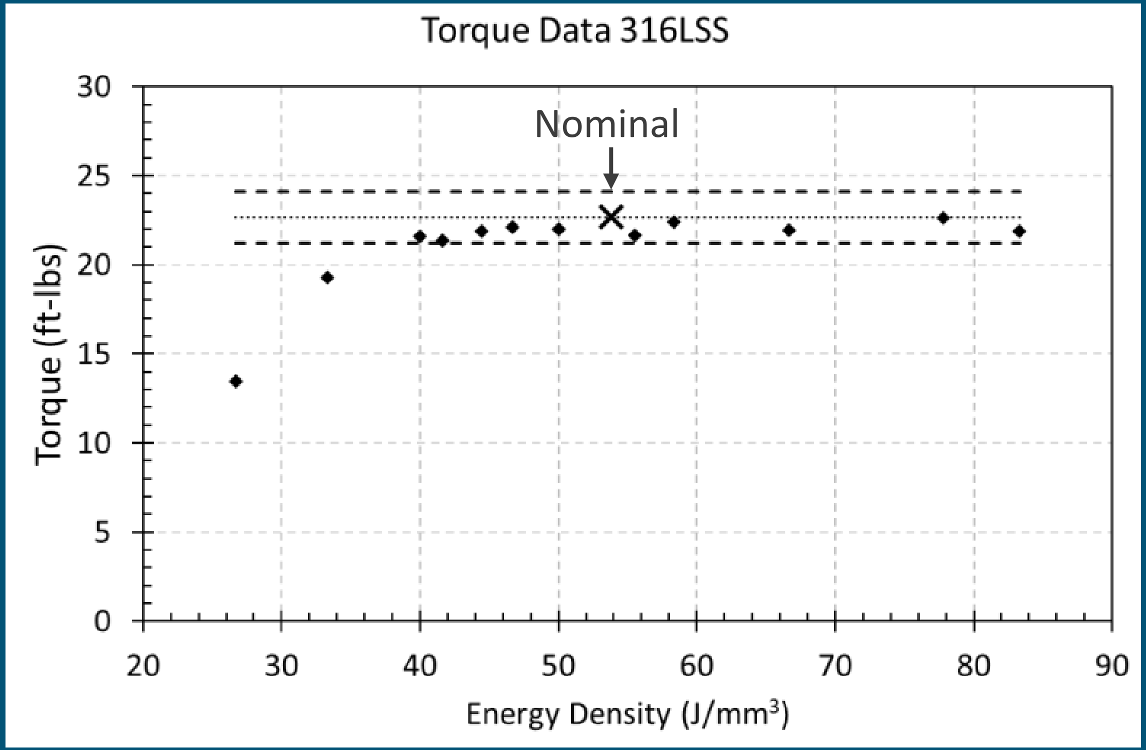
~18 – 70 days (all steps)

1 Build /day ✖ **10 Parts /build** ✖ **2 Machines** = **20 Parts /day**

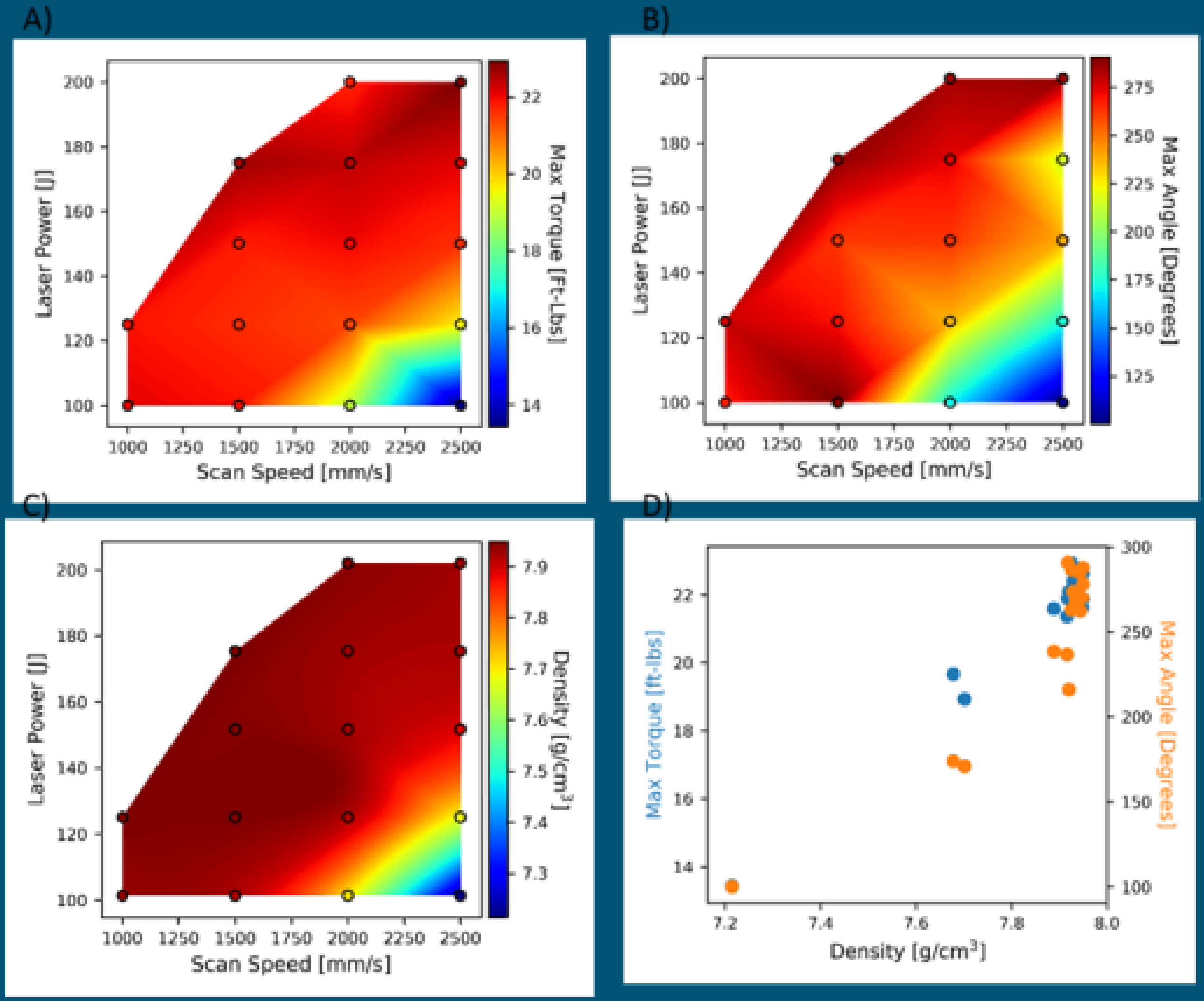
With Production Cycle Interruption ($1,000/part)	Without Production Cycle Interruption ($1,000/part)
20 parts/day X 1 day → 20 scrapped parts	20 parts/day X 42 days → 840 scrapped parts
$20,000 in scrapped parts	**$840,000 in scrapped parts**

Process Data for 316LSS: ProX 200

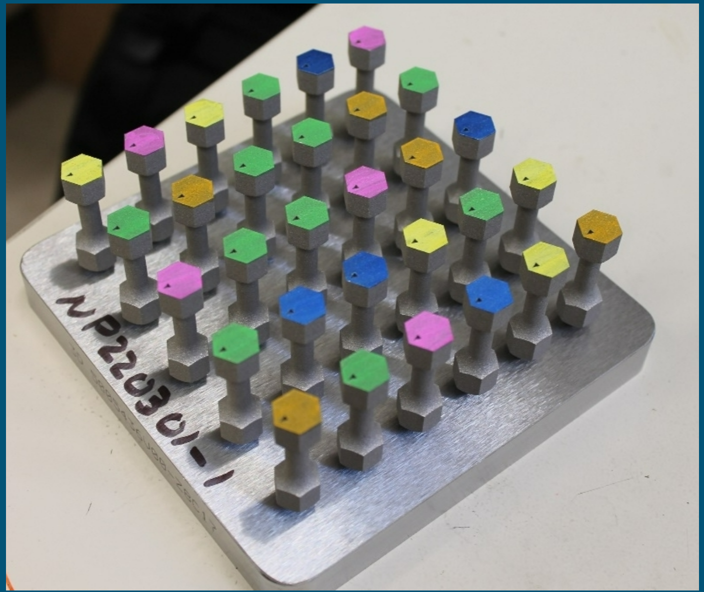




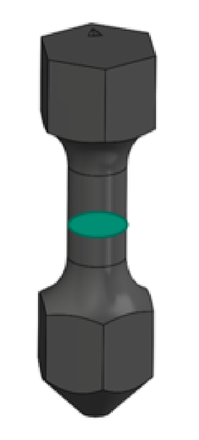
- Low energy conditions rapidly fall below 3 standard deviations from nominal mean
- Both max torque and angle of twist follow trends for density within similar process window



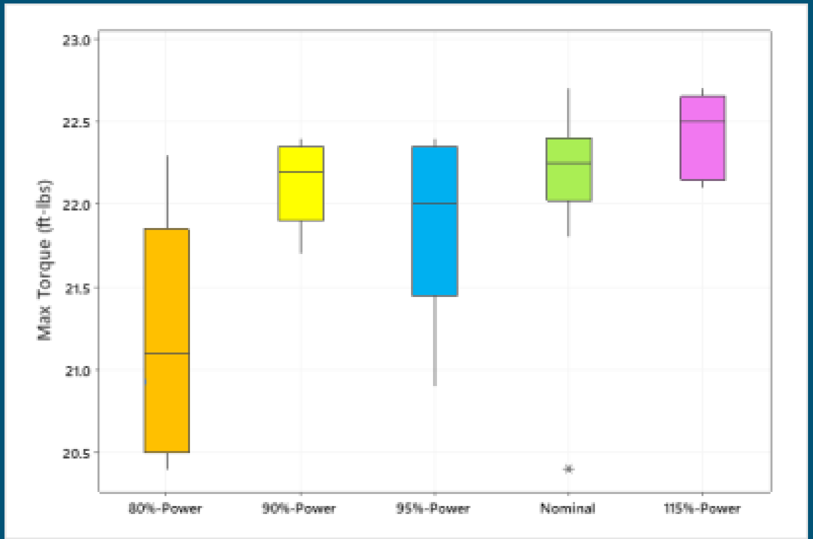
Single Layer Corruption Detection

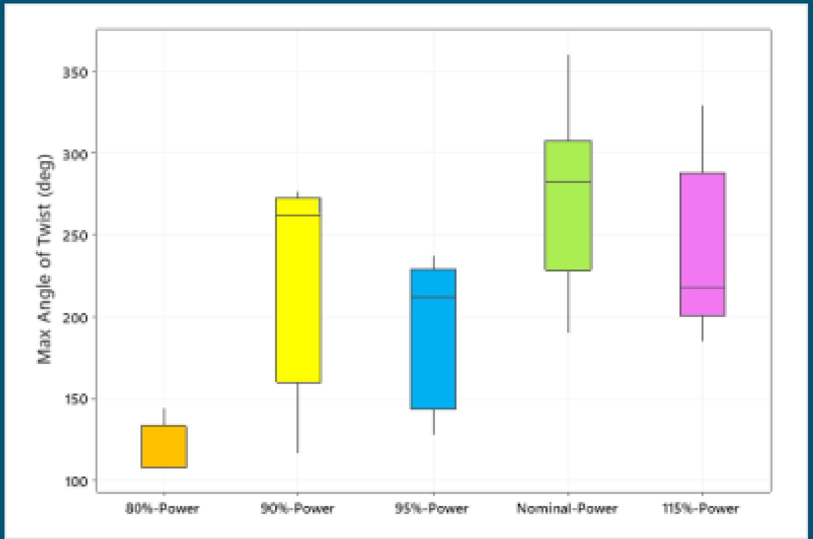


Single Layer Corruption



Color	Power
Pink	115%
Green	Nominal
Blue	95%
Yellow	90%
Orange	80%





Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
115%-Torque	5	22.420	A	
90%-Torque	5	22.140	A	B
Nominal-Torque	10	22.080	A	
95%-Torque	5	21.920	A	B
80%-Torque	5	21.160		B

Tukey Method and 95% Confidence

Factor	N	Mean	Grouping	
Nominal-Twist	10	273.8	A	
115%-Twist	5	239.0	A	
90%-Twist	5	225.4	A	
95%-Twist	5	191.2	A	B
80%-Twist	5	118.00		B

Means that do not share a letter are significantly different.

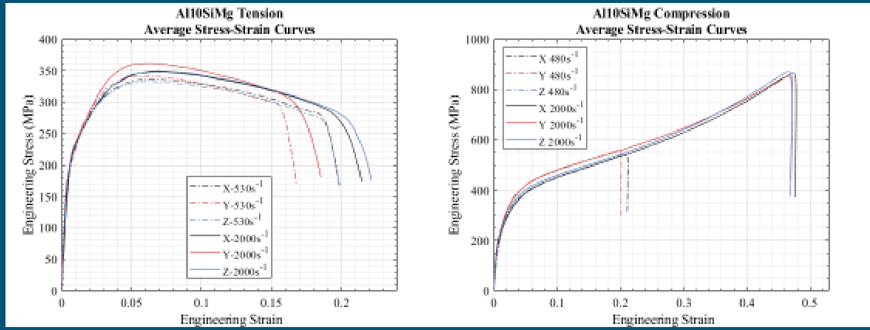
Foundational Science of AM Variables That Affect Performance

AM Variables

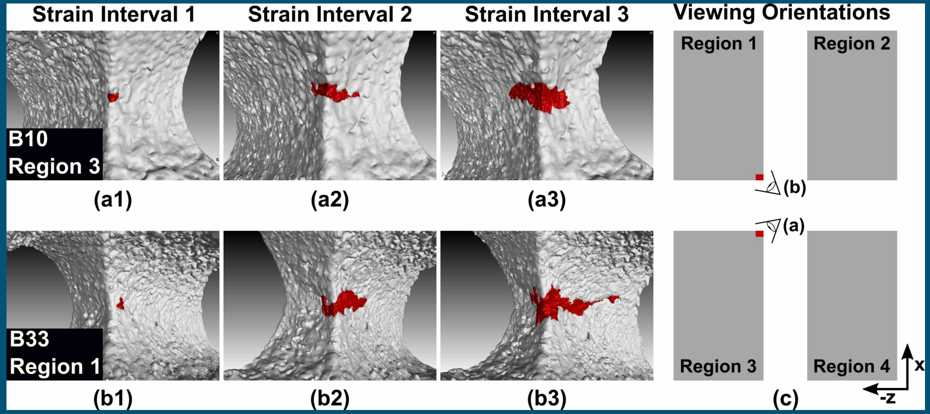
- Process
- Microstructure
- Flaws
- Geometry
- Heat Treatment
- HIP
- Post-machining
- Anisotropy
- Strain-Rate
- Mode of Deformation
- Damage
- Fatigue
- Fracture

Process-Structure-Property-Performance (PSPP) Relationships

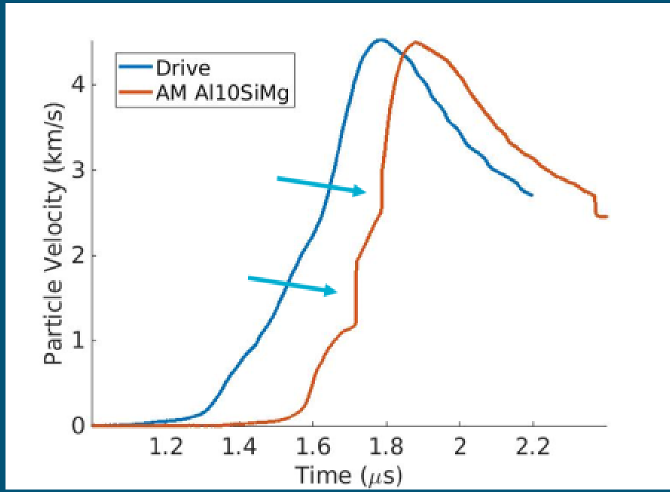
Strain-Rate Dependence in Tension But Not In Compression for AM AlSi10Mg



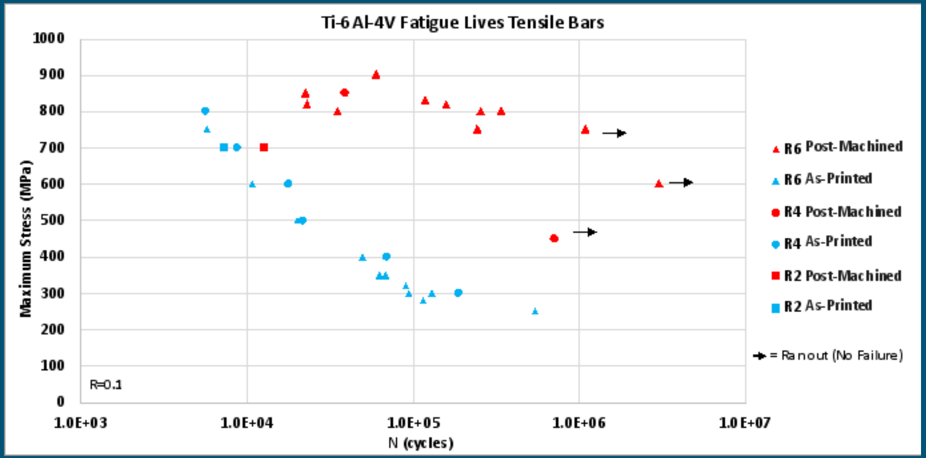
Fracture Evolution, Geometry, Pores, and Surface Roughness in AM 316L SS



High-Pressure Phase Changes in AM AlSi10Mg Not Present in Al 6061

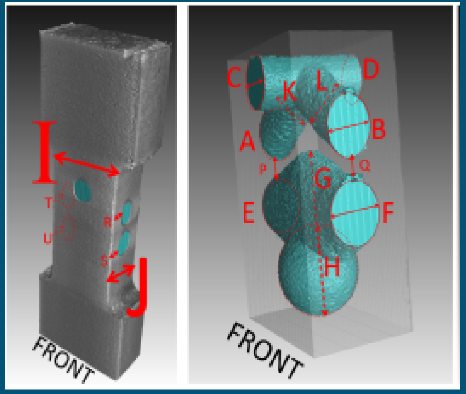


Effect of Post-Machining and Size on Fatigue Life in AM Ti-6Al-4V

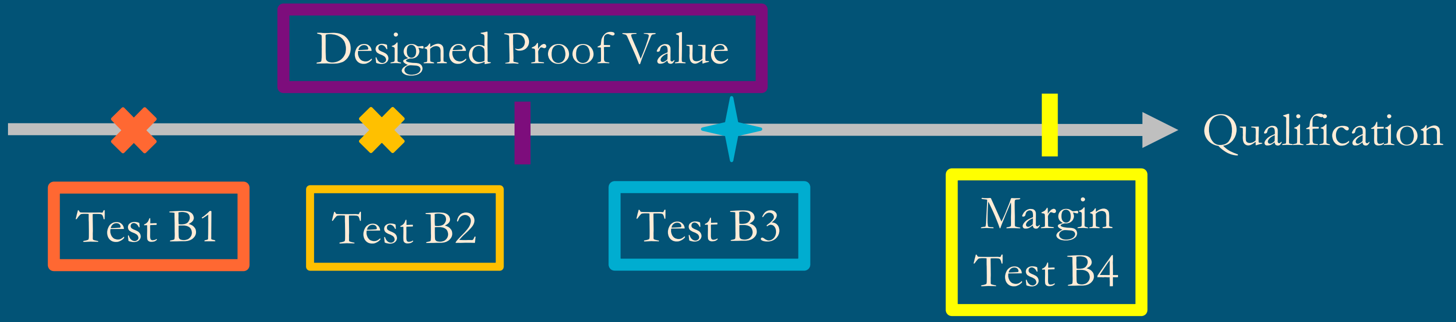


New Paradigm for Designing and Qualifying AM Parts

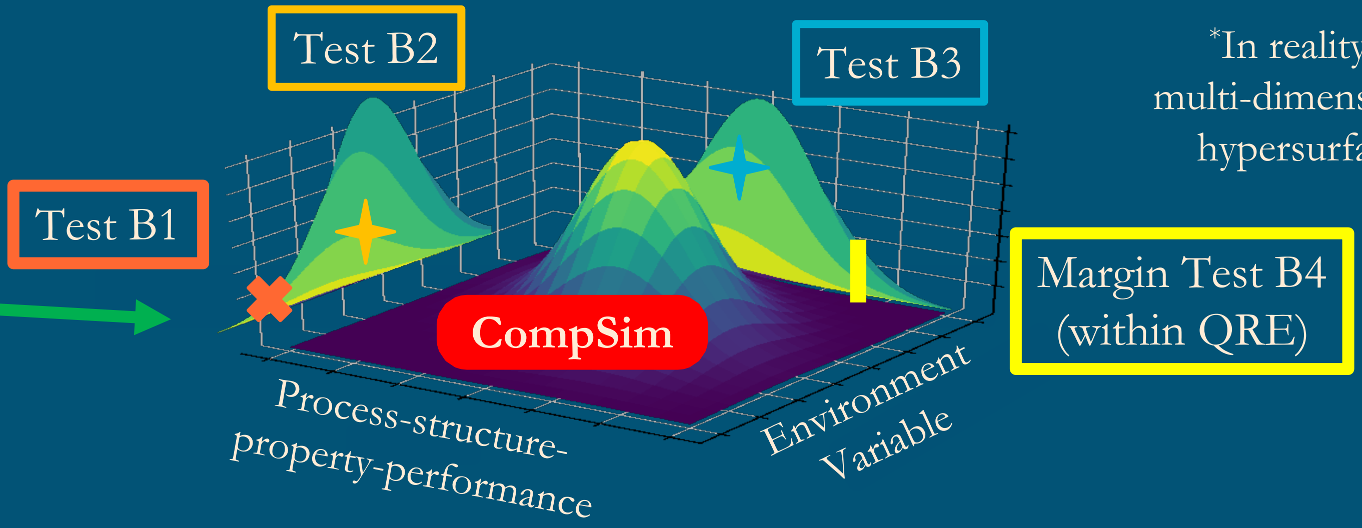
Prototype
Builds B1-B4



Current Paradigm



New Paradigm: Qualification Response Envelope (QRE)*

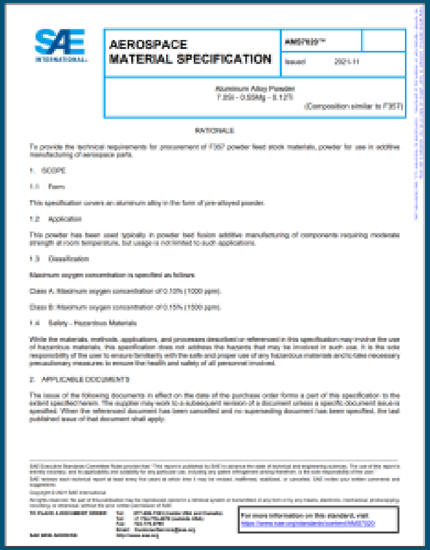


*In reality a multi-dimensional hypersurface

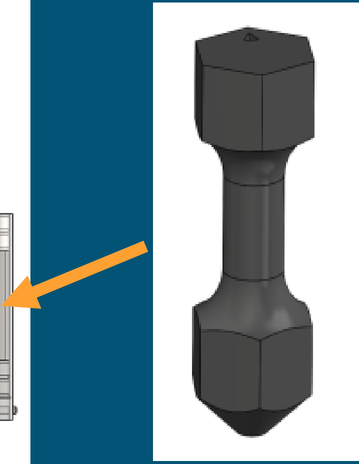
Future
Production
Builds BA-BZ

Path to End Goal

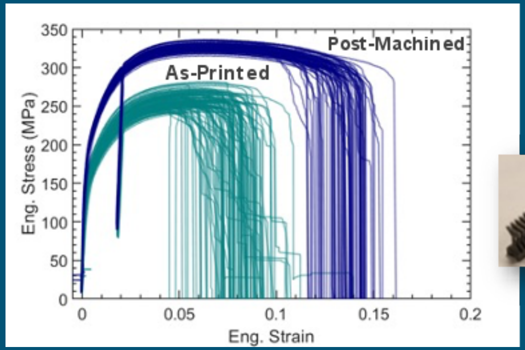
Development of AM Material Specifications

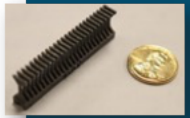


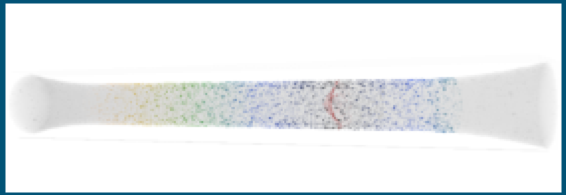
Accelerated Build Health Inspection Approach

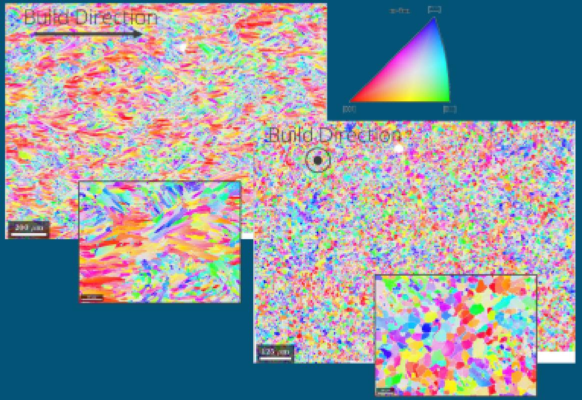


Foundational Science of AM Variables Affecting Performance

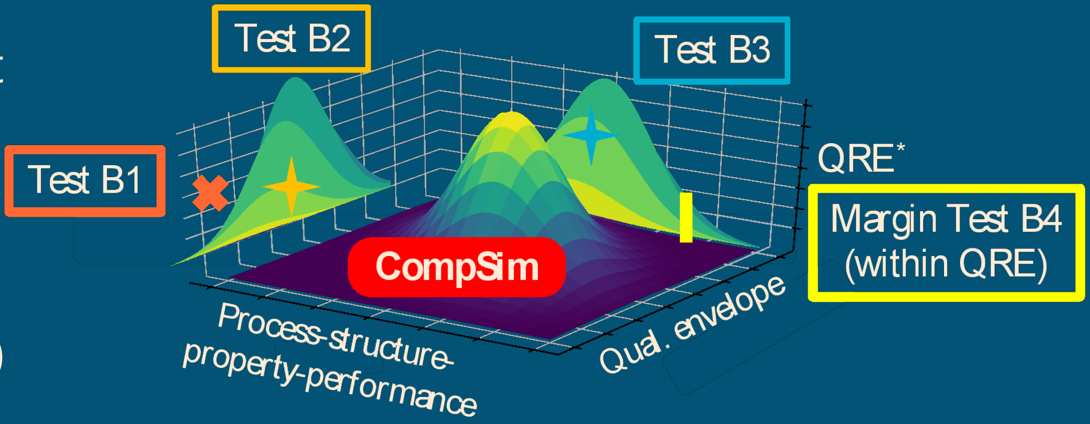








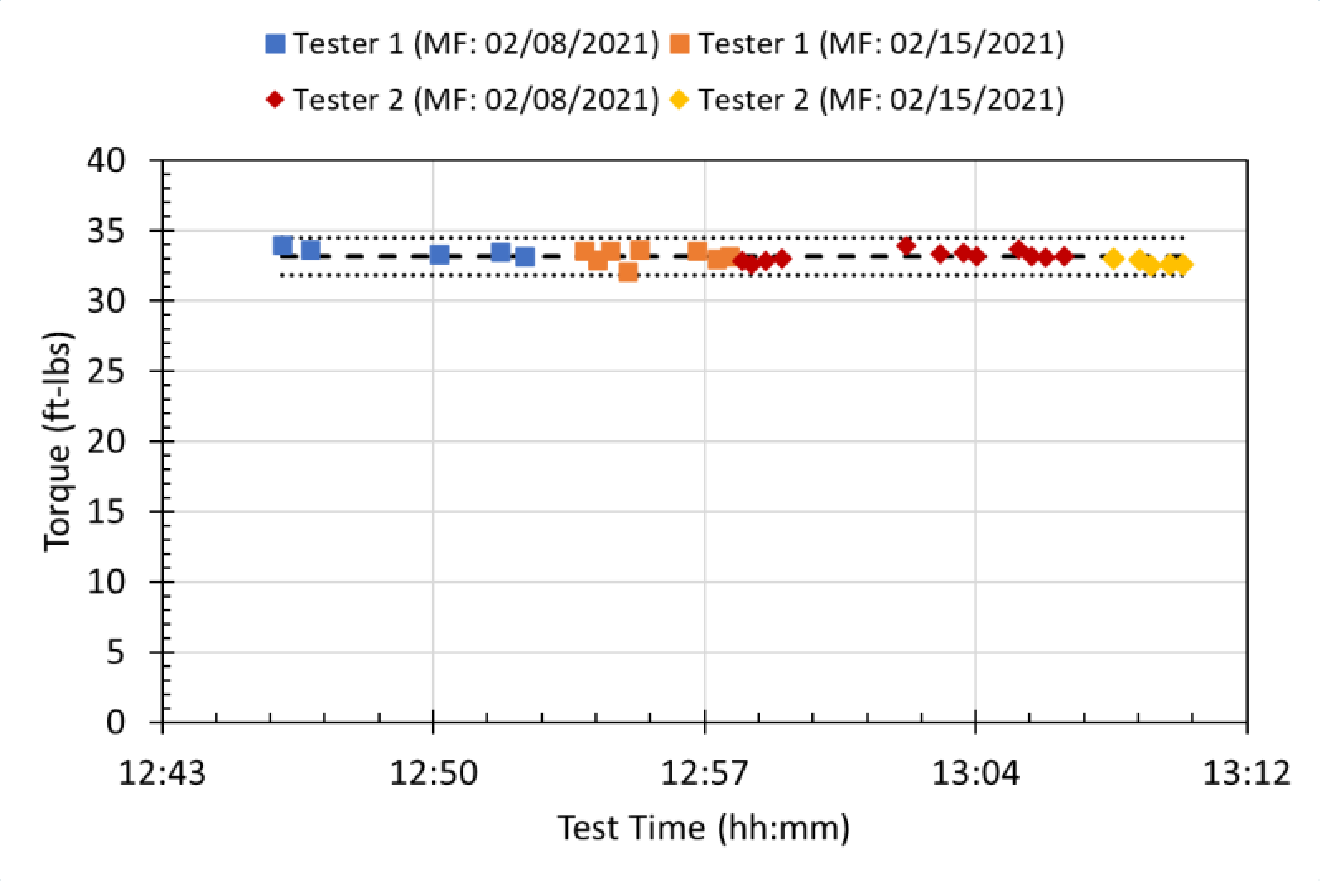
Enveloped Part Qualification Approach: Qualification Response Envelope (QRE)



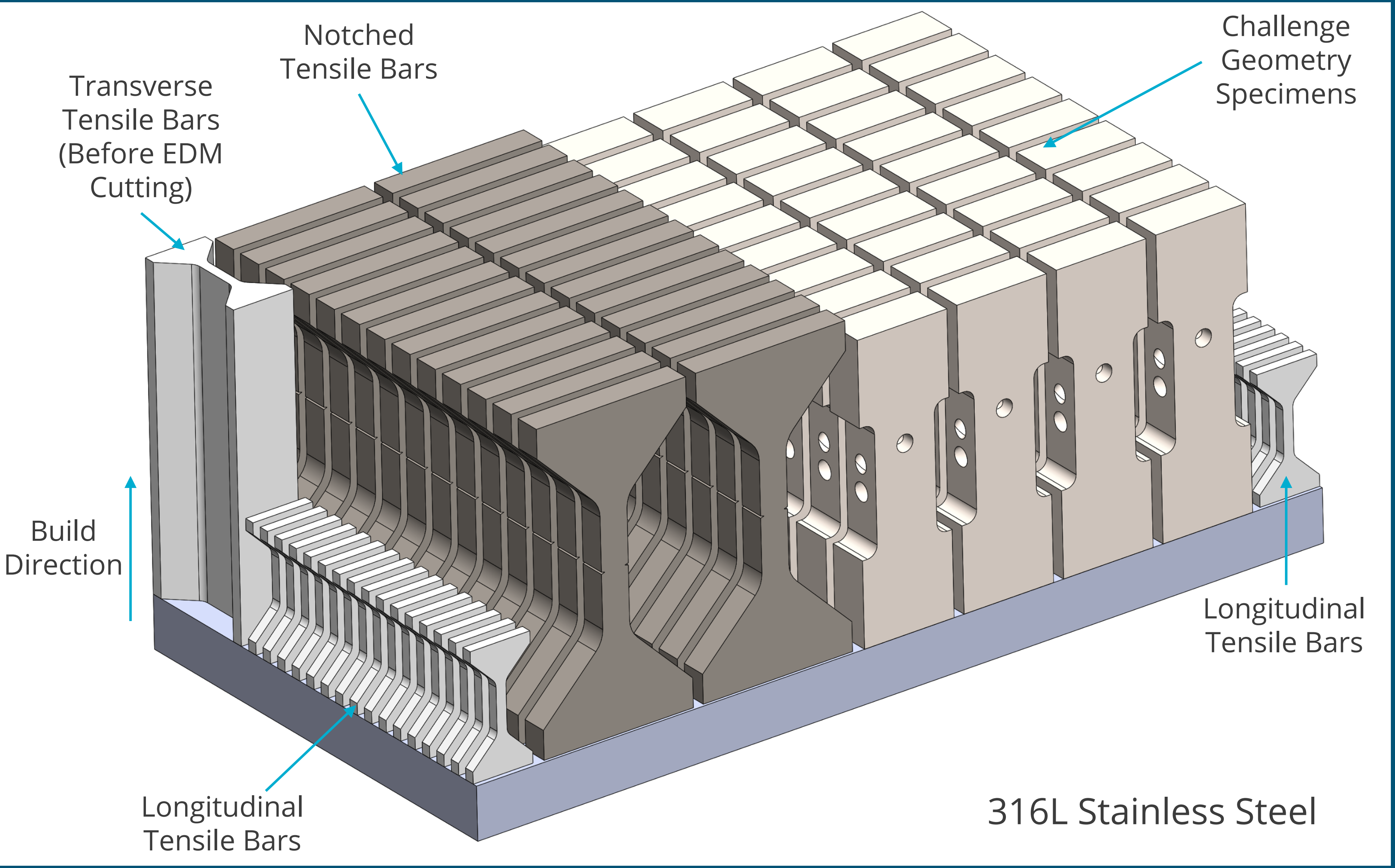
Backups

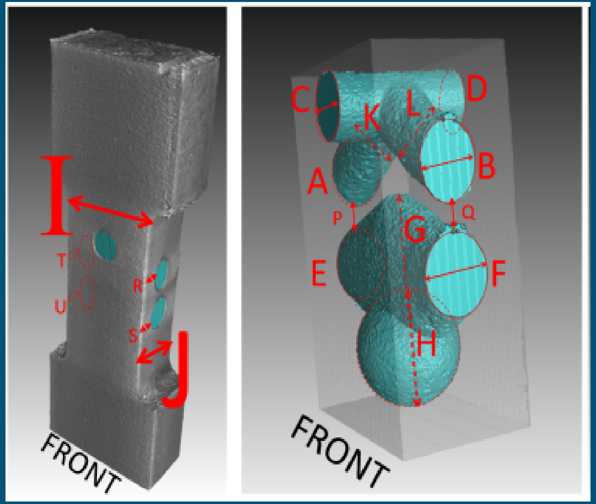
Cross-site & Tester Repeatability: 15-5 PH SS

- Tests conducted by two users covering two different manufacture dates
- Test specimens were torqued to failure using "high" and "low" twist rates
- Ongoing efforts to compare consistency across different materials, manufacturer dates, testers, and test devices



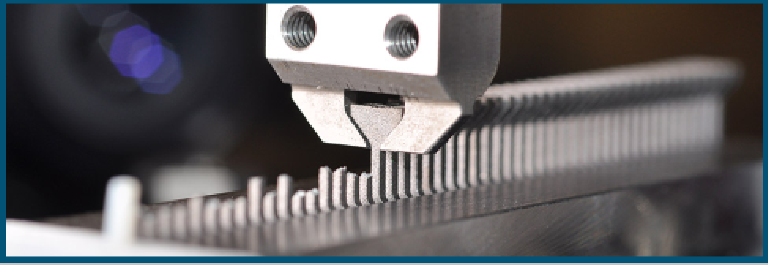
Third Sandia Fracture Challenge





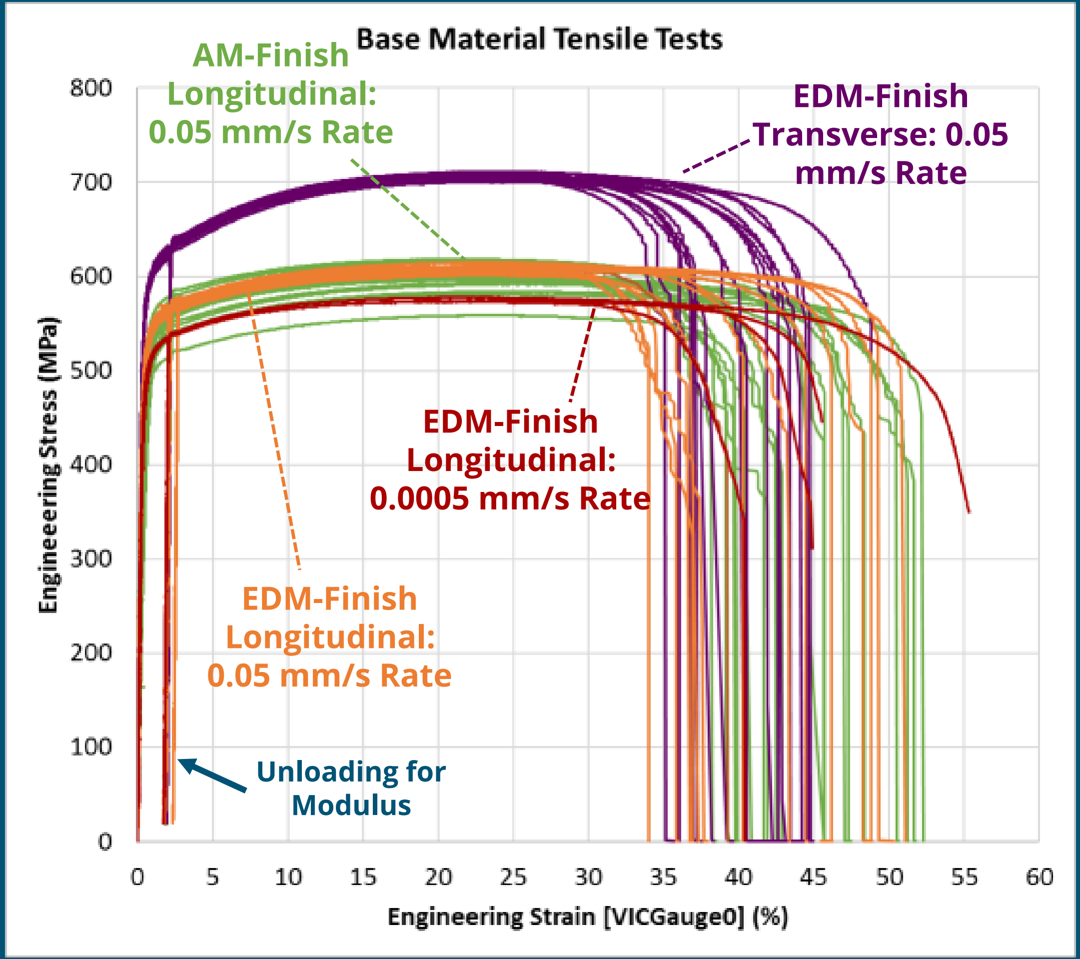
Kramer, S.L.B., *et al.* The third Sandia fracture challenge: predictions of ductile fracture in additively manufactured metal. *Int J Fract* **218,** 5–61 (2019). https://doi.org/10.1007/s10704-019-00361-1

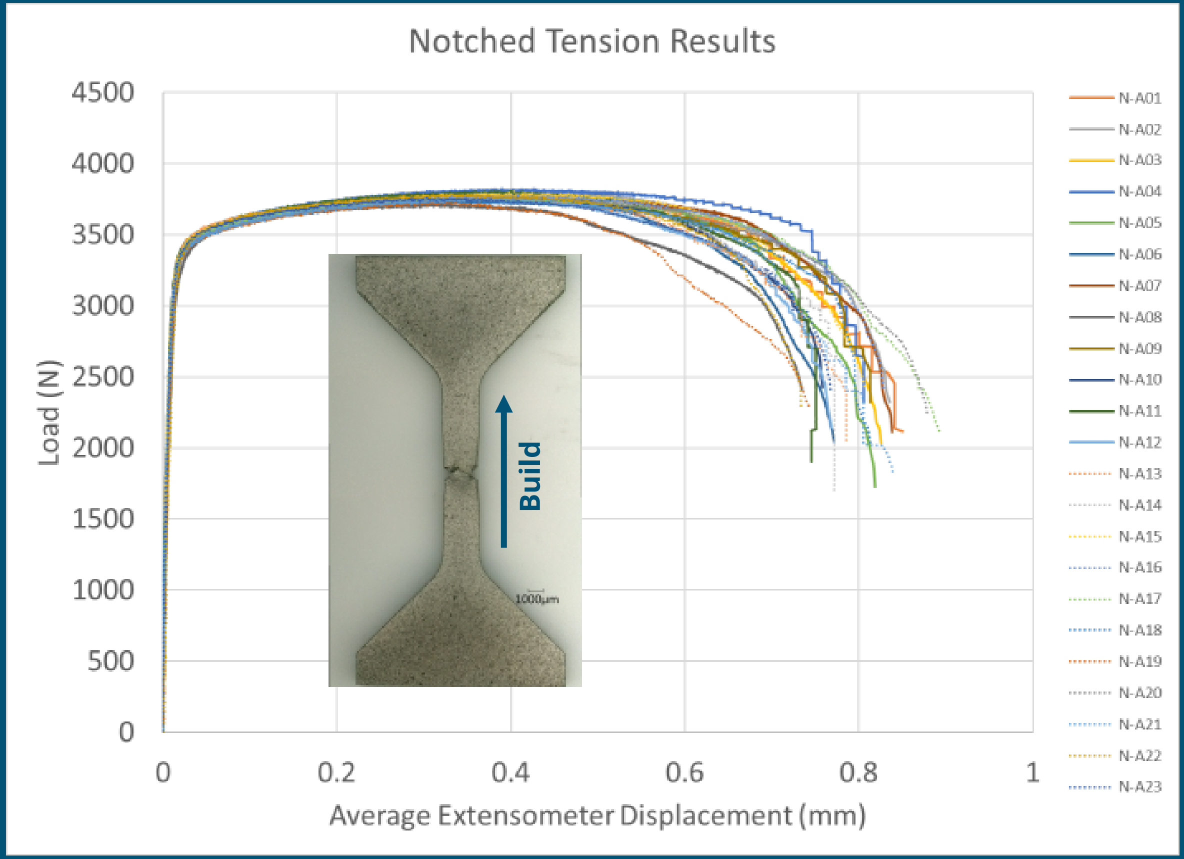
Variability in Mechanical Response of Base Material



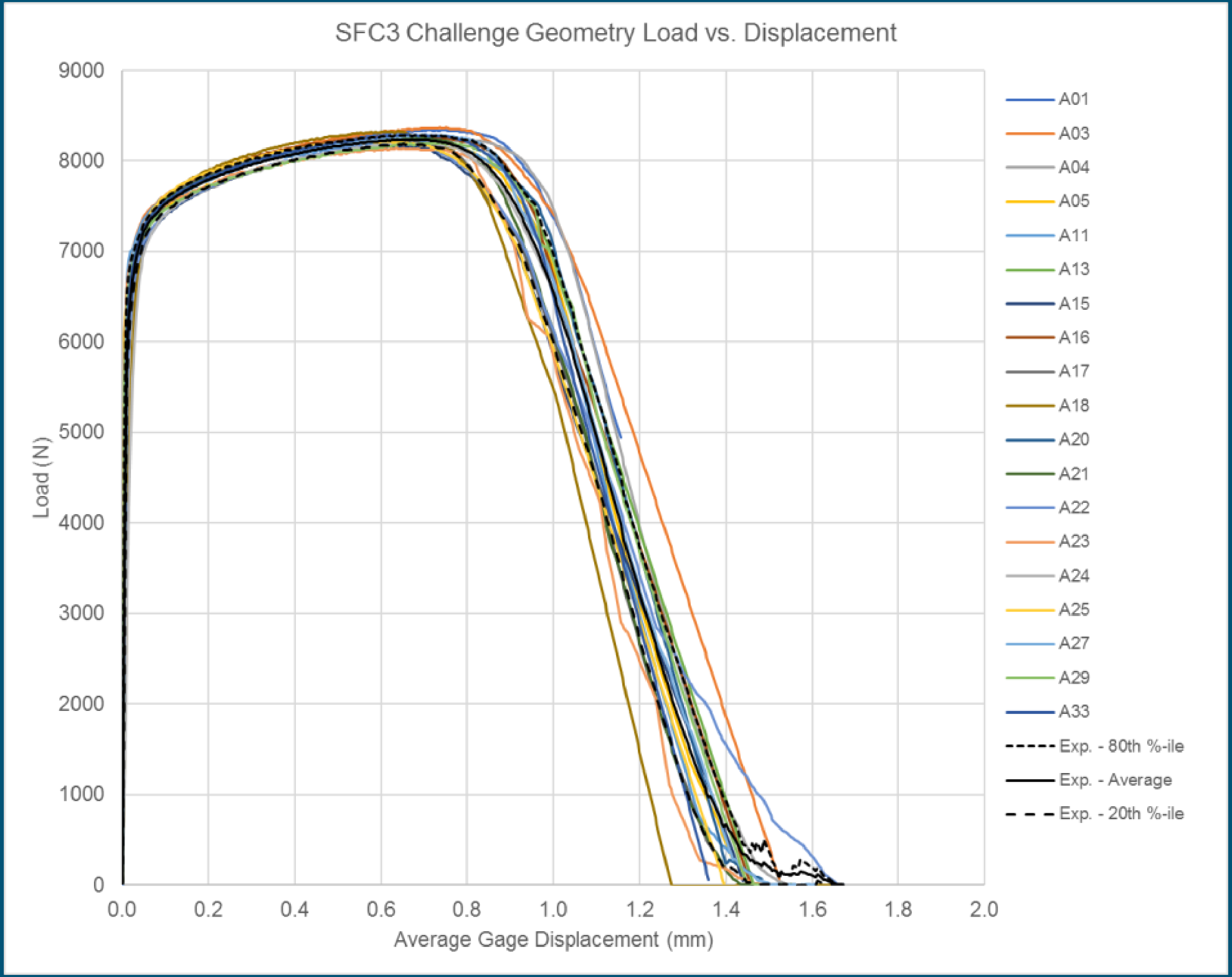
Uniform Cross-Section ➜ Variability

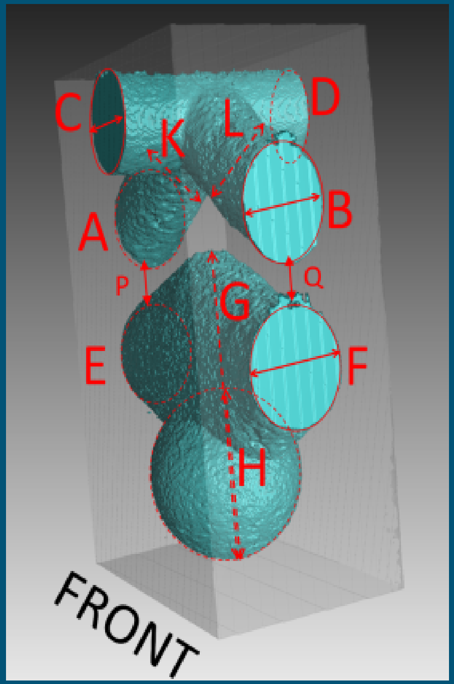
Notched Cross-Section ➜ Less Variability





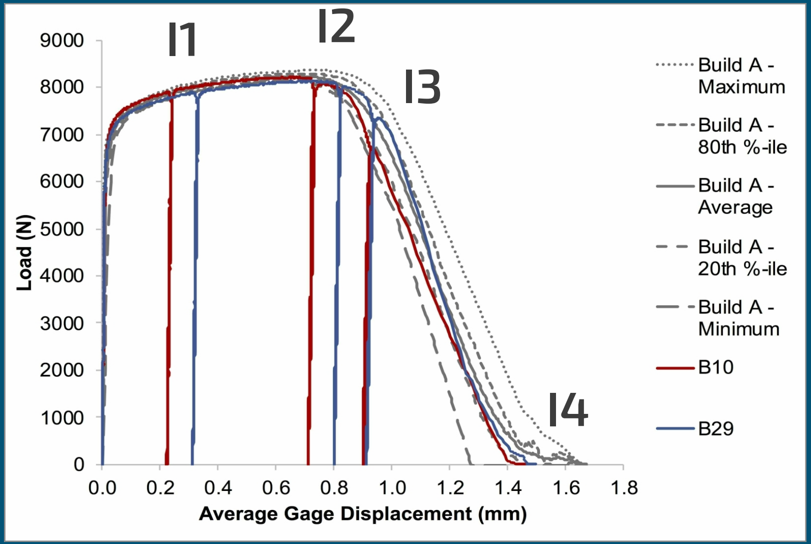
Global Mechanical Response of Structured Parts





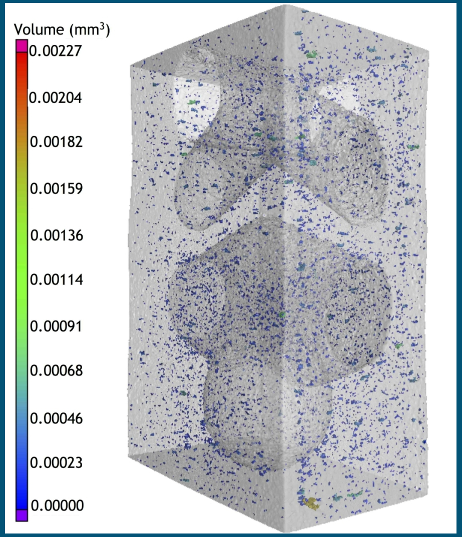
Interrupted Testing to Track Fracture Evolution

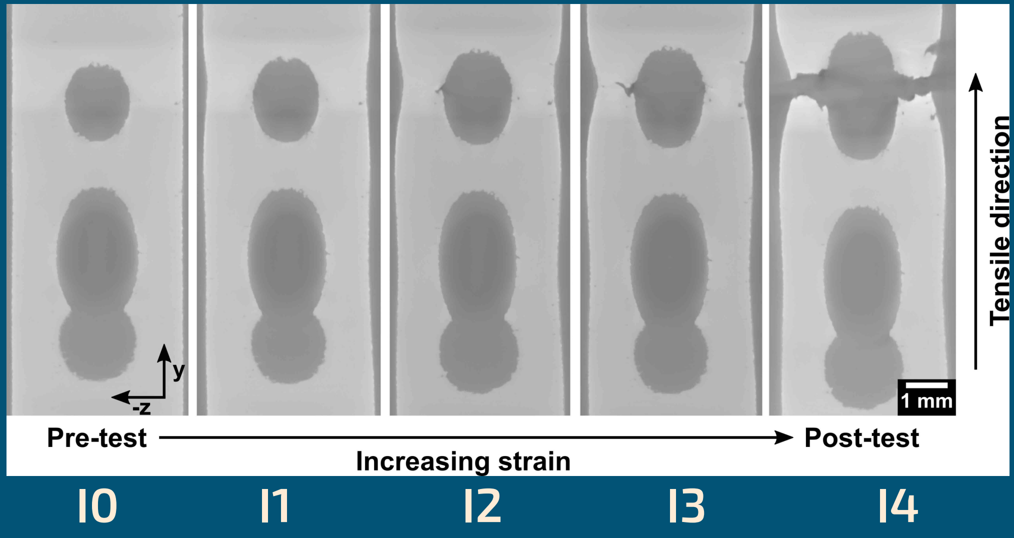
Interrupted Response



Kramer, S.L.B., Ivanoff, T.A., Madison, J.D. *et al.* Evolution of damage and failure in an additively manufactured 316L SS structure: experimental reinvestigation of the third Sandia fracture challenge. *Int J Fract* **218,** 63–84 (2019). https://doi.org/10.1007/s10704-019-00357-x

Pre-test data showing voids

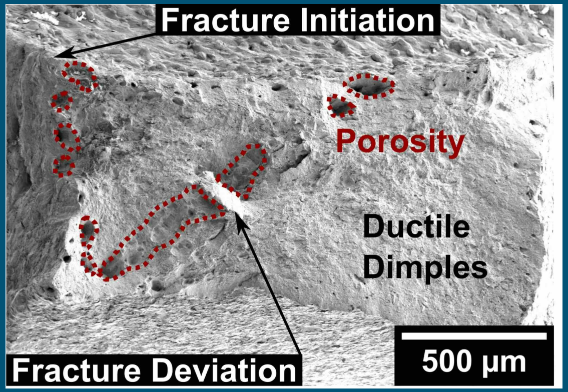




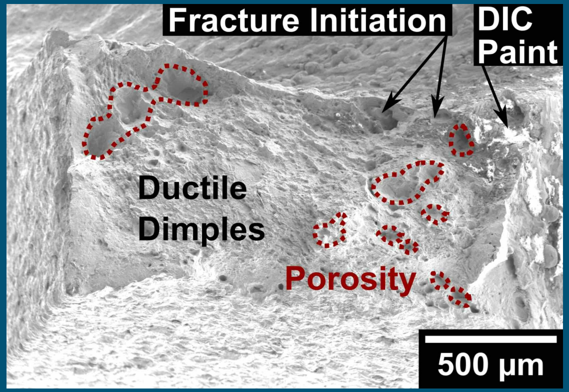
Ex situ micro-CT internal slices for Specimen B33

Local Fracture Variation in Structured Parts

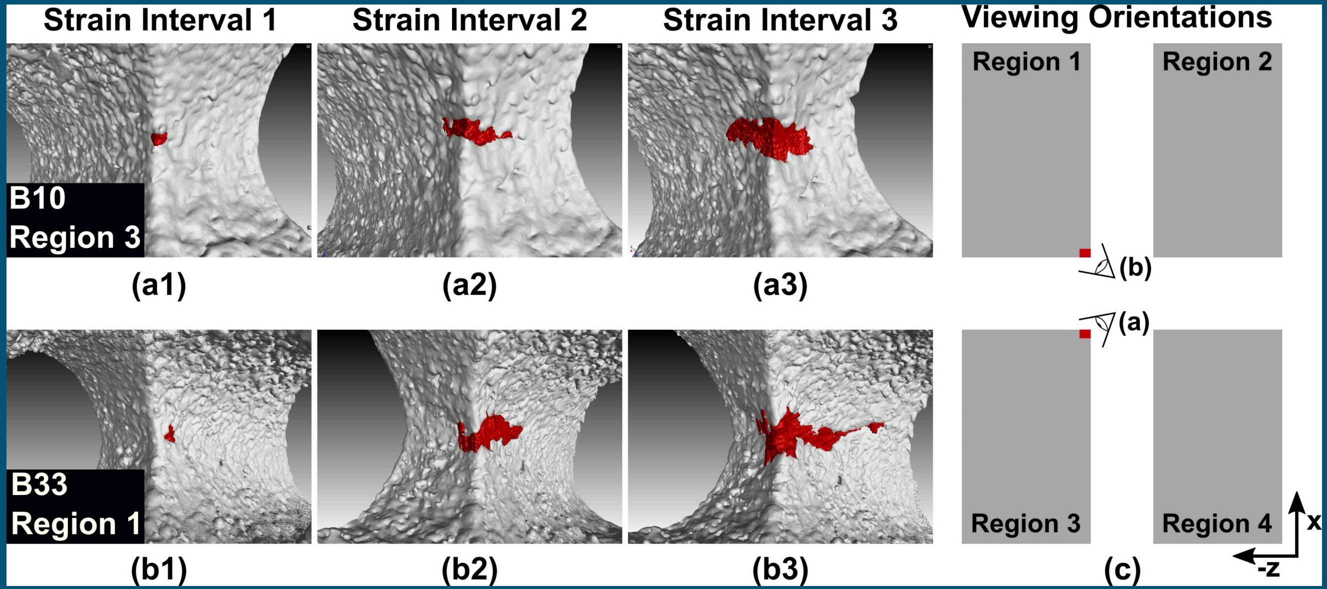
Specimen B10 Region 3



Specimen B33 Region 1



3D Reconstructions Highlighting Crack Volume



Lessons Learned and Open Questions

Geometric Stress Concentrations → Reduced Variability in Global Response

? ← What size?

? ← What type of stress concentration?

Voids → Local Crack Variation

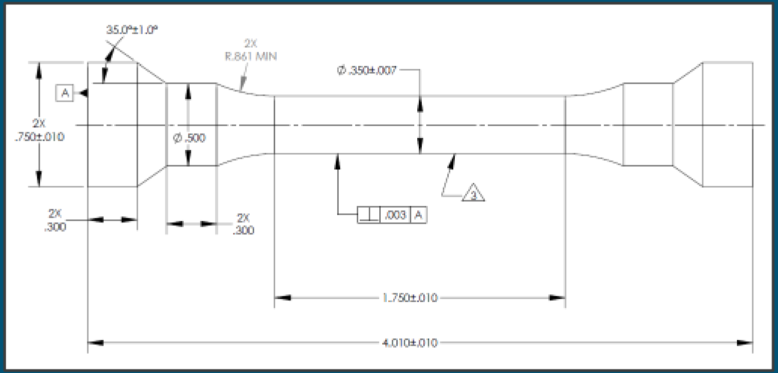
What Dominates Mechanical Response?

Geometry-Dominant | Transition / Overlap | Flaw-Dominant

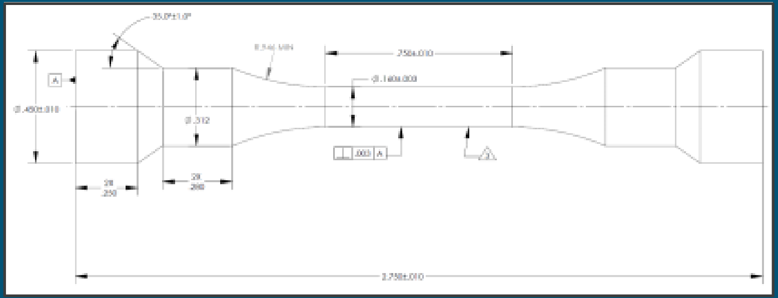
Fatigue in AM Ti-6Al-4V: Variables

AM Ligament Size

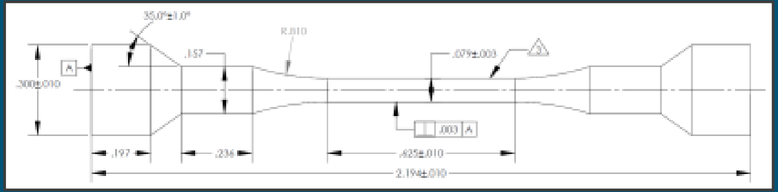
R2 Specimen
D = 8.89 mm



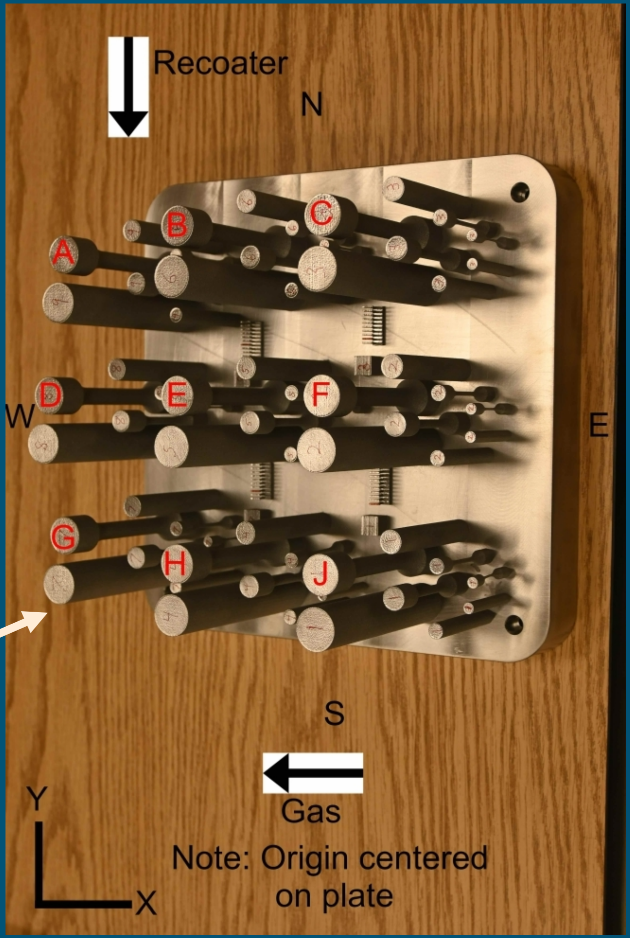
R4 Specimen
D = 4.06 mm



R6 Specimen
D = 2.01 mm



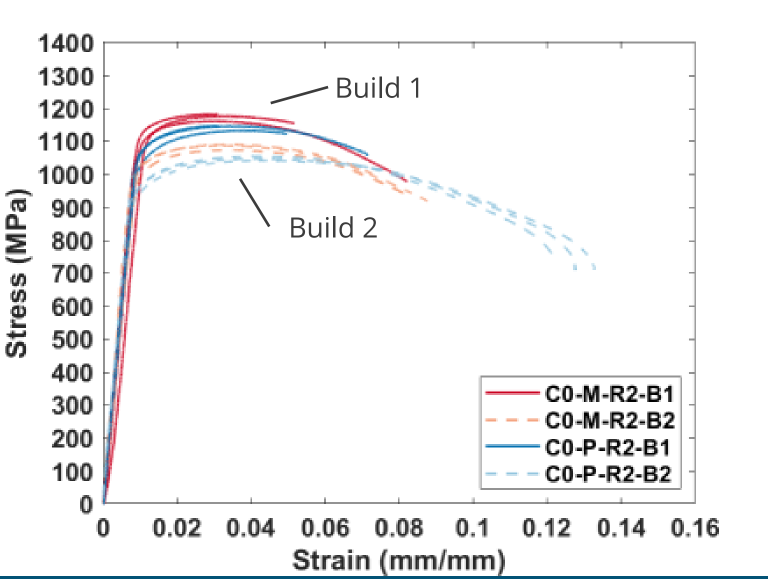
As-Printed vs. Post-Machined



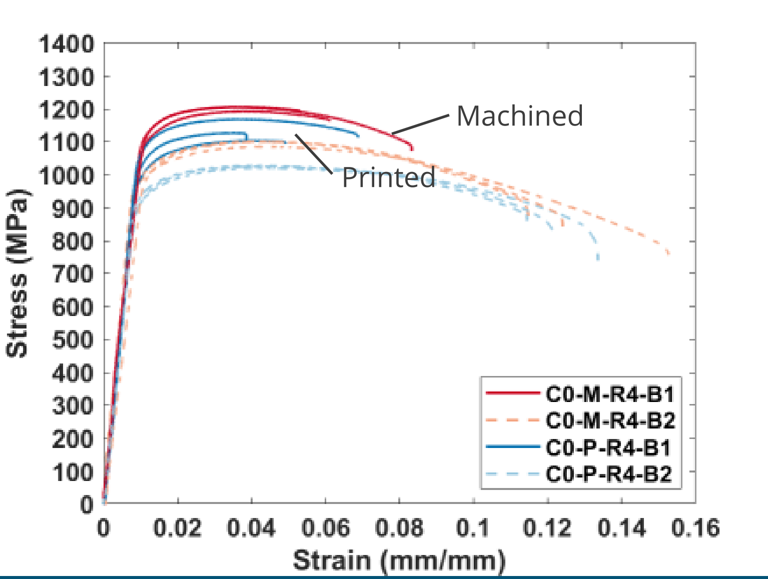
Printed Cylinders To Be Machined

Monotonic Tension Results

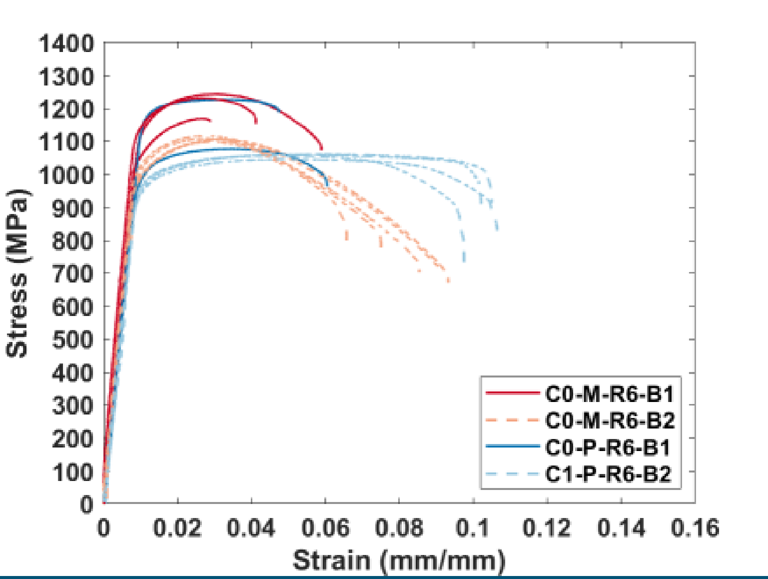
R2



R4

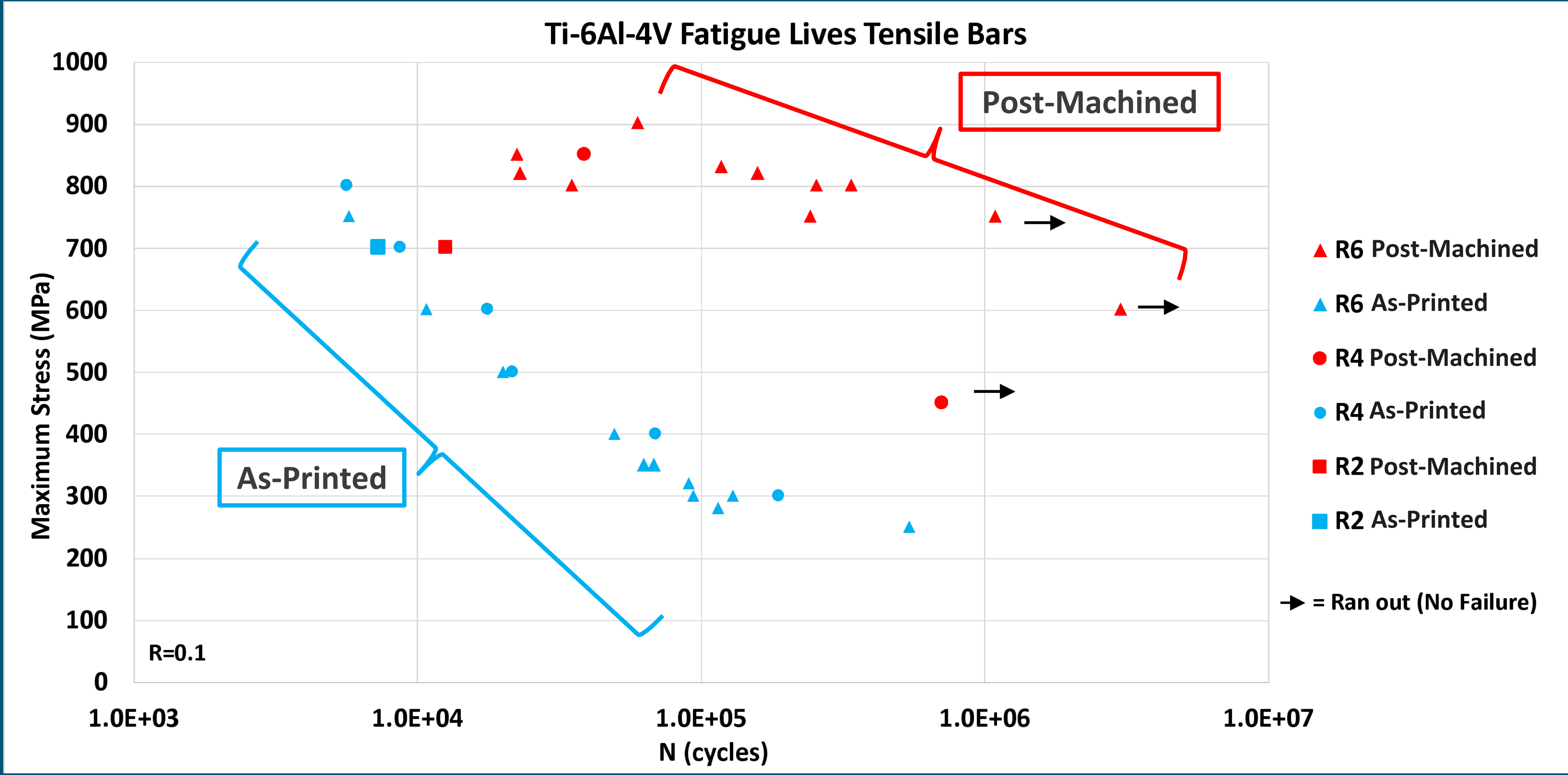


R6



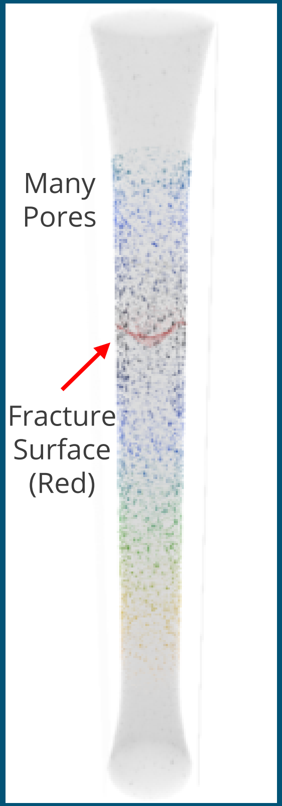
Decreasing Sample Size

Fatigue Results



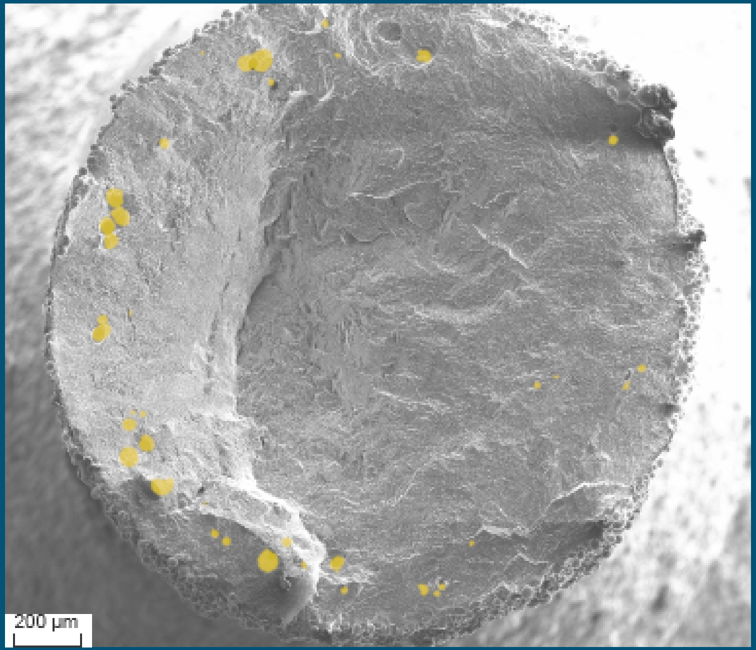
Fatigue Crack

As-Printed



XCT-identified Pores

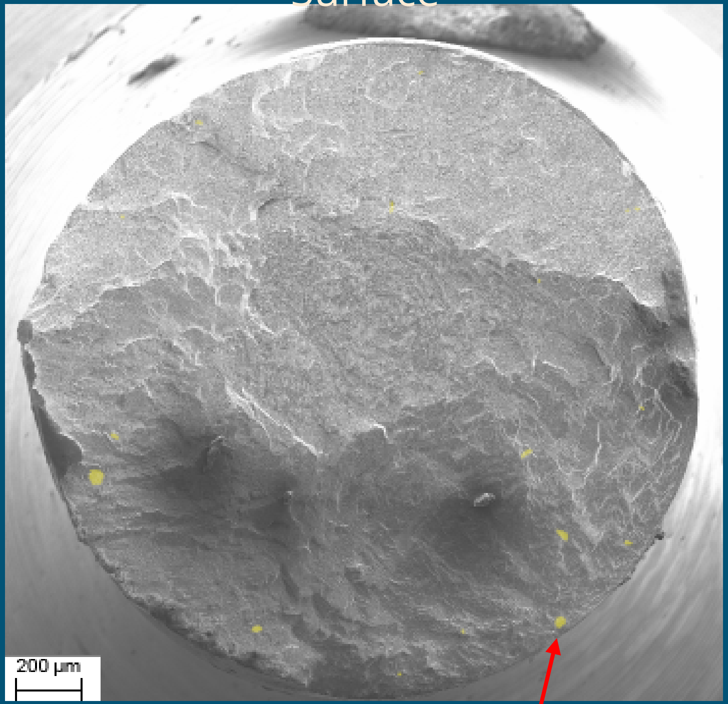
SEM Micrograph of Fracture Surface



Post-Machined

XCT-identified Pores

SEM Micrograph of Fracture Surface

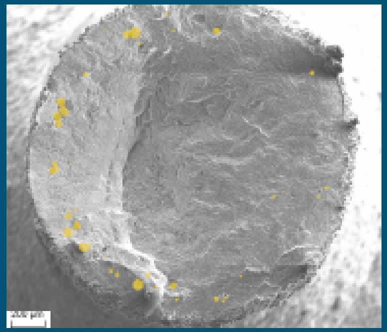


Failure Pore

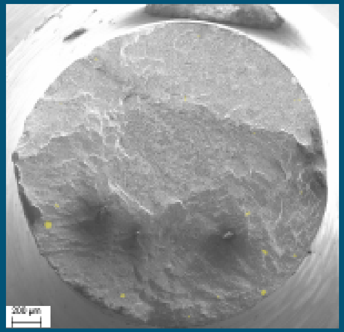
Fatigue: Future Variables of Interest

Different Post-Machining Methods

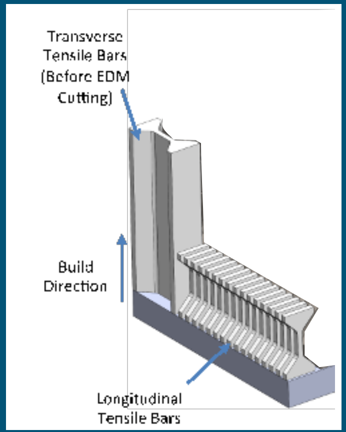
Remove Crust Only



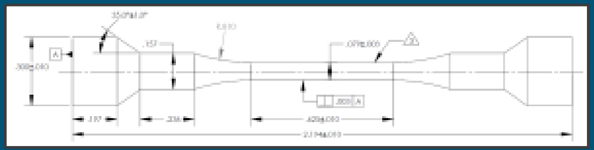
Polish Machining Marks

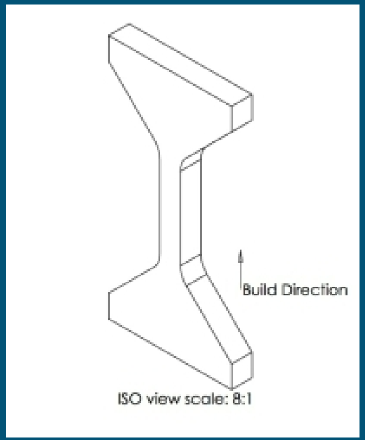


Build Orientation



Round vs. Flat Fatigue Specimens





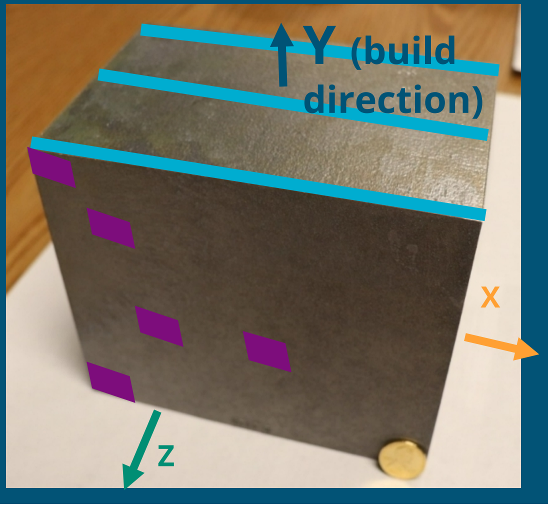
Witness Fatigue Specimens

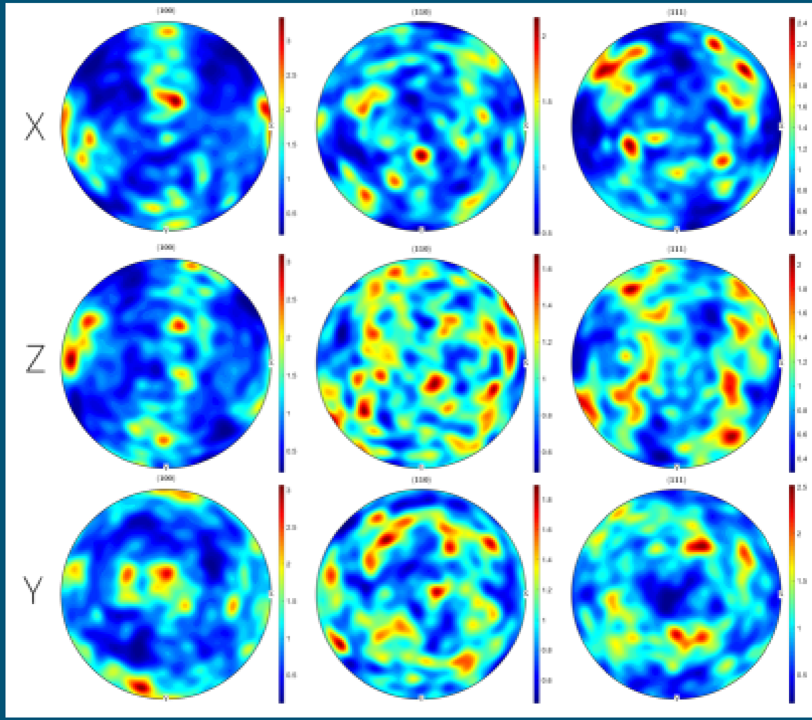
Compare to:

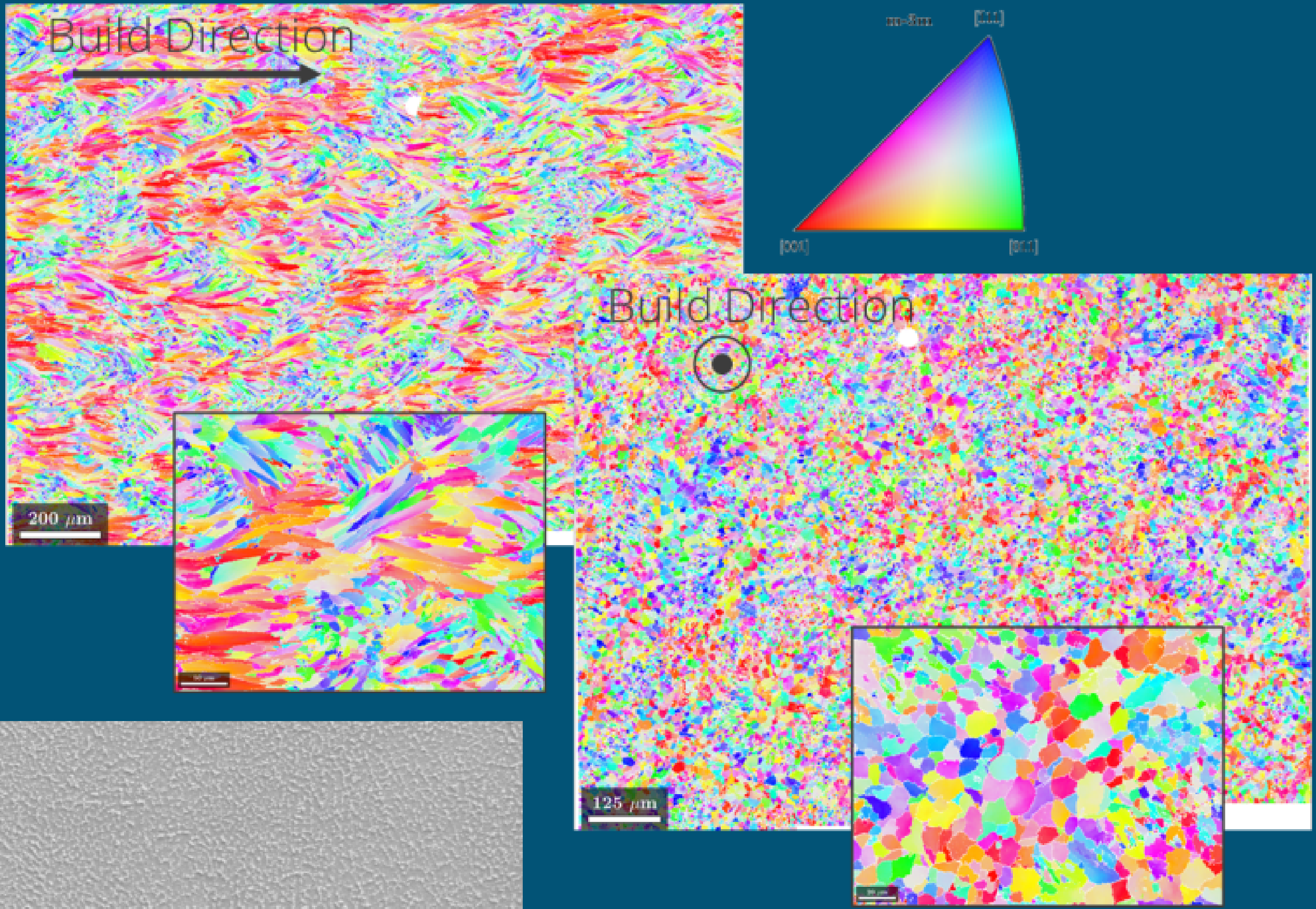
- Fatigue of specimen cut from part
- Fatigue of entire part

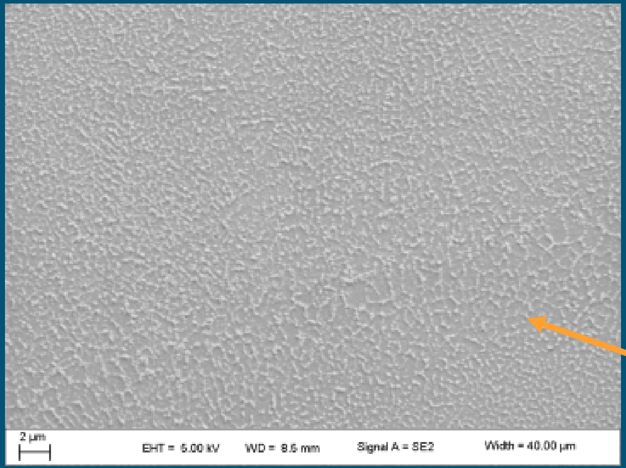
https://www.eos.info/en/

AlSi10Mg Microstructure



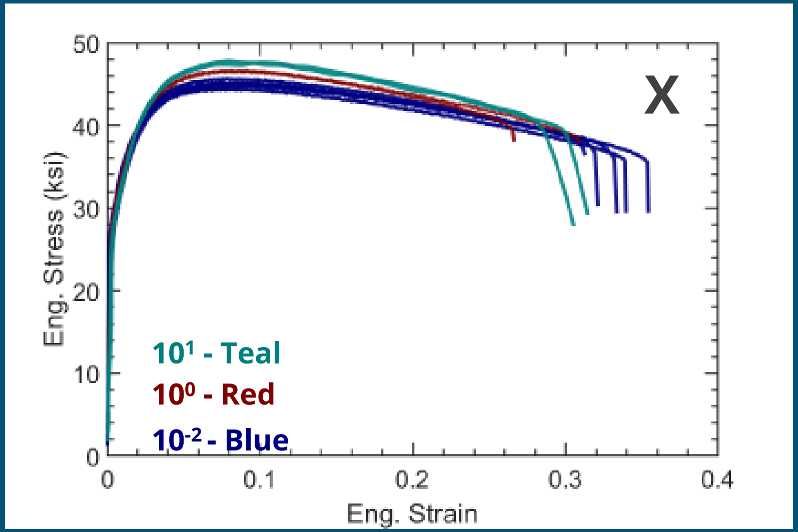


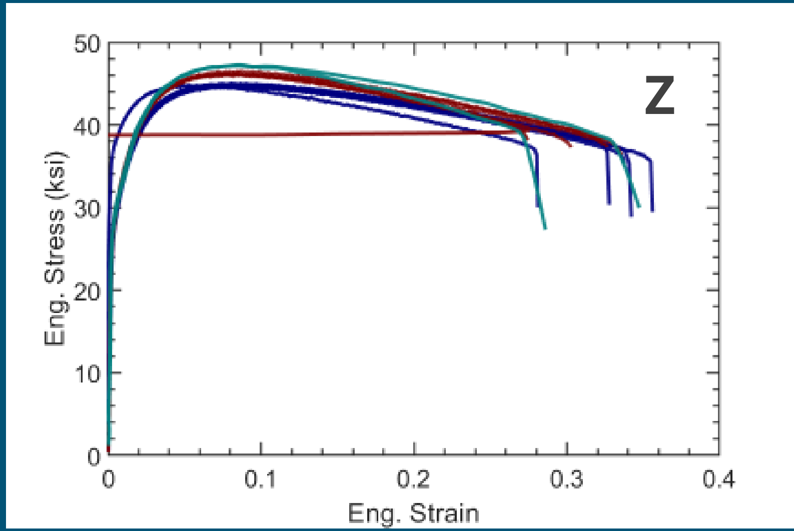


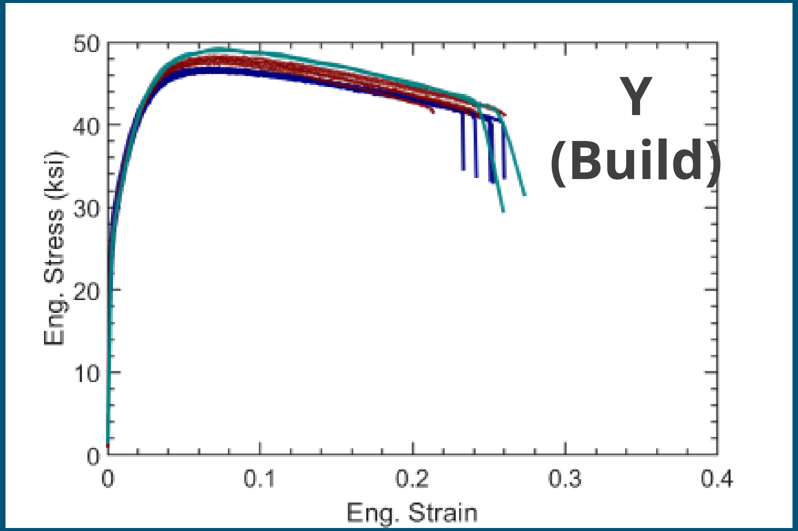


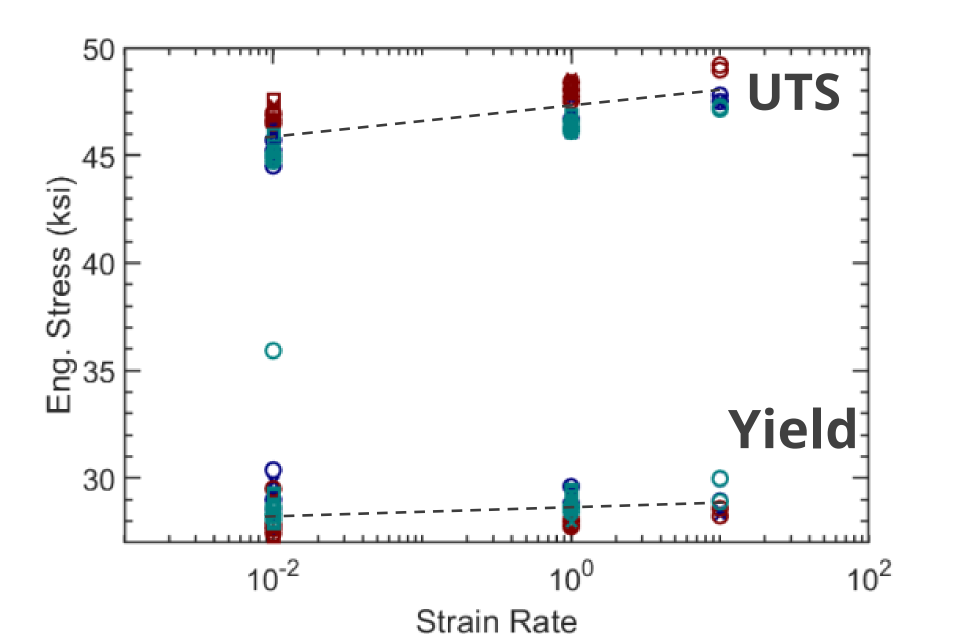
Si Intermetallic Precipitates

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



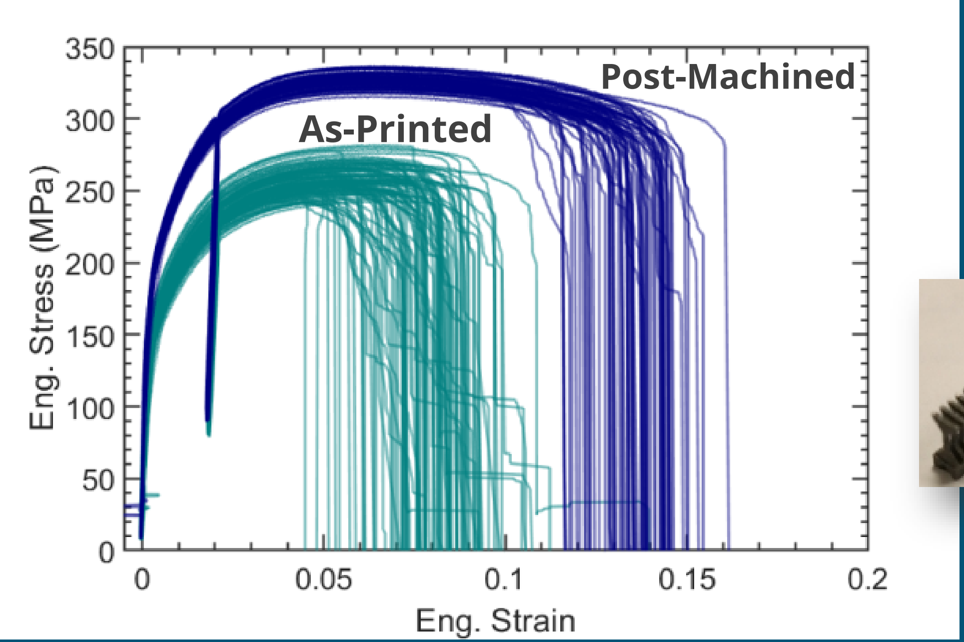




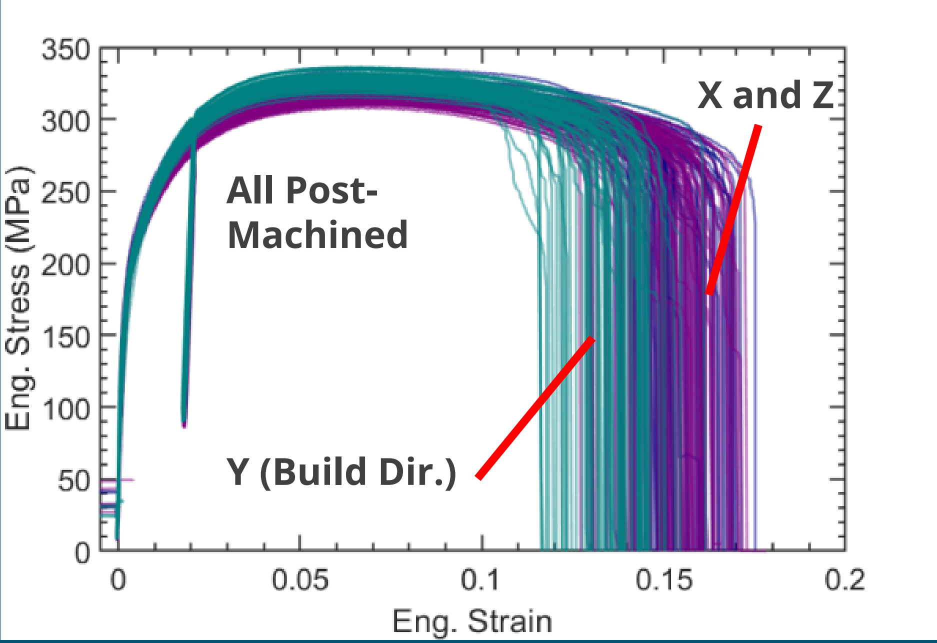


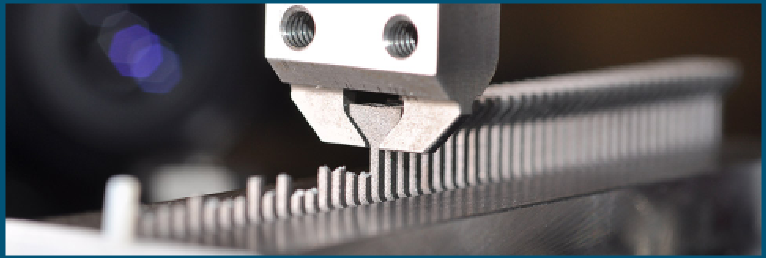
Colors represent the different testing directions, and the shapes represent the locations along the build height

Effect of Processing History and Surface Finish



Evaluated using high-throughput tensile coupons

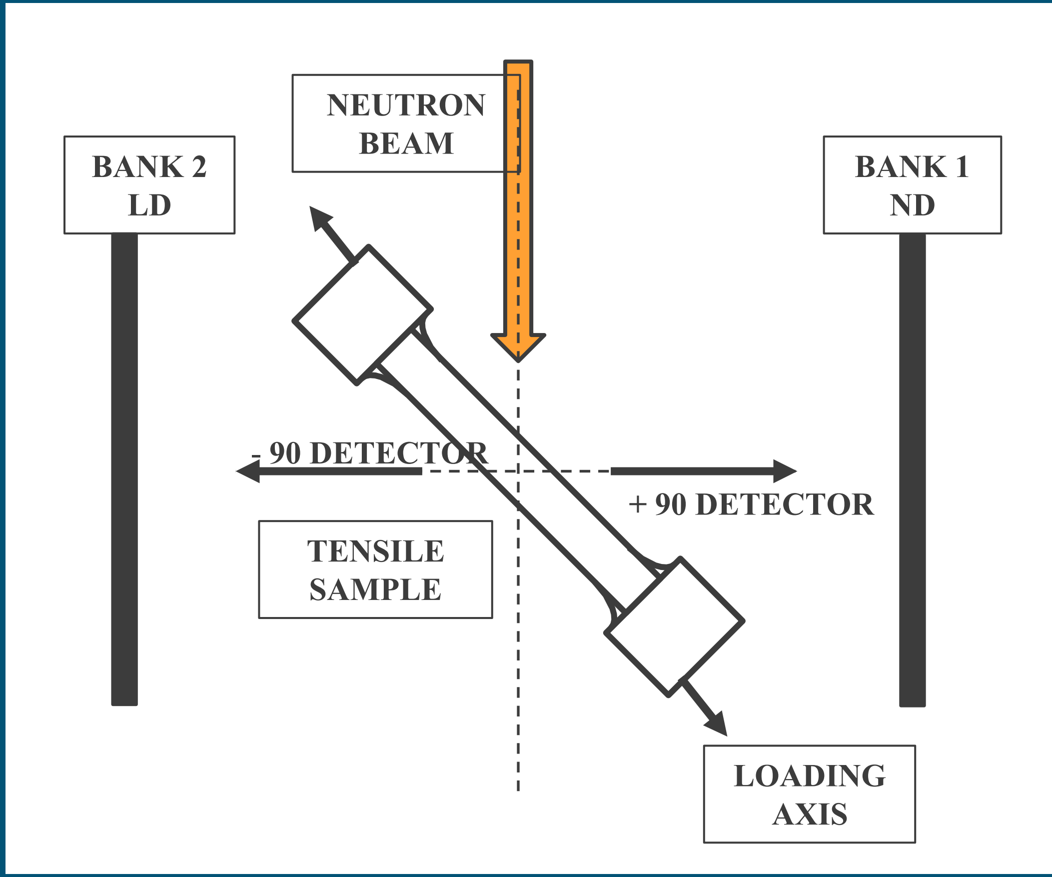




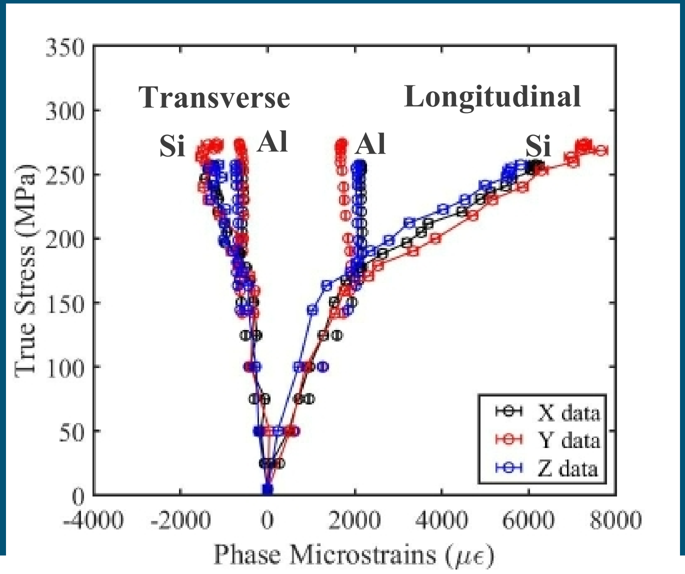
Surface roughness can be a significant driver of the material response

Stress-Partitioning Tensile Experiments

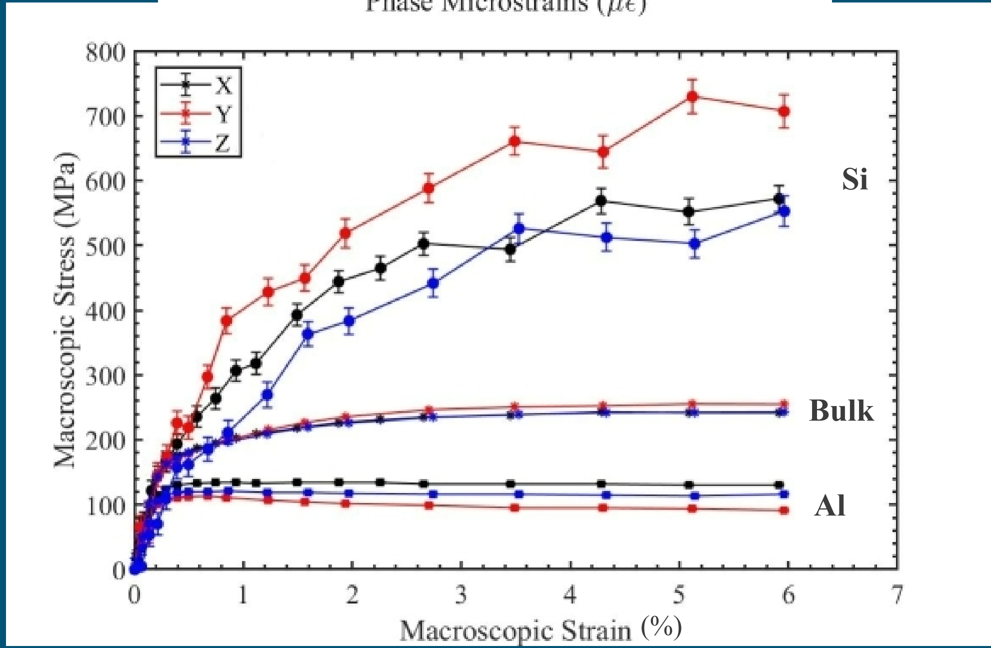
Schematic of tensile-loading stress partitioning experiment



Phase lattice stress vs. strain

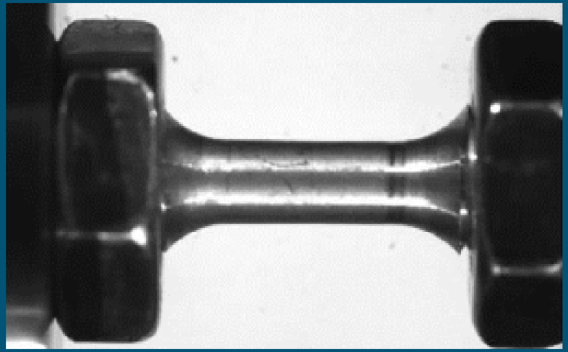


Stress partitioning

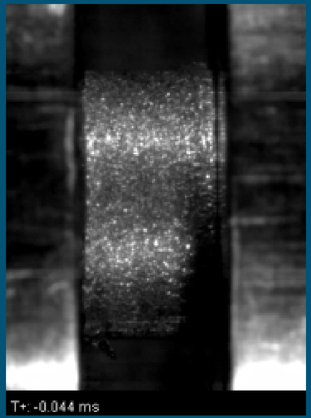


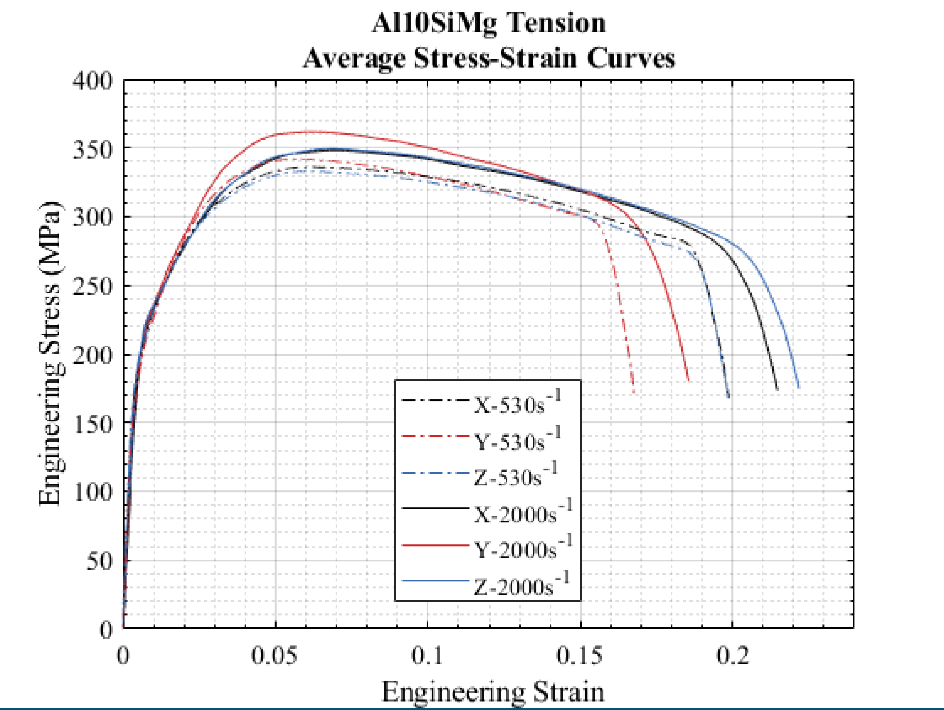
Collaborators: Bjørn Clausen (LANL), Don Brown (LANL), and Milan Agnani (Mines)

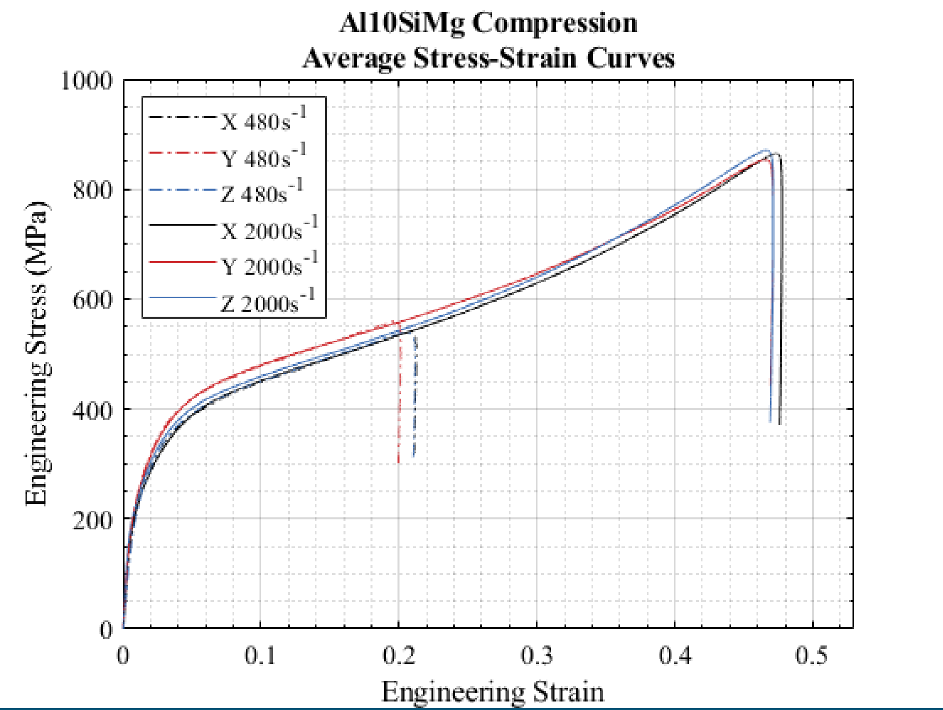
Tension and Compression for 10^2 to 10^3



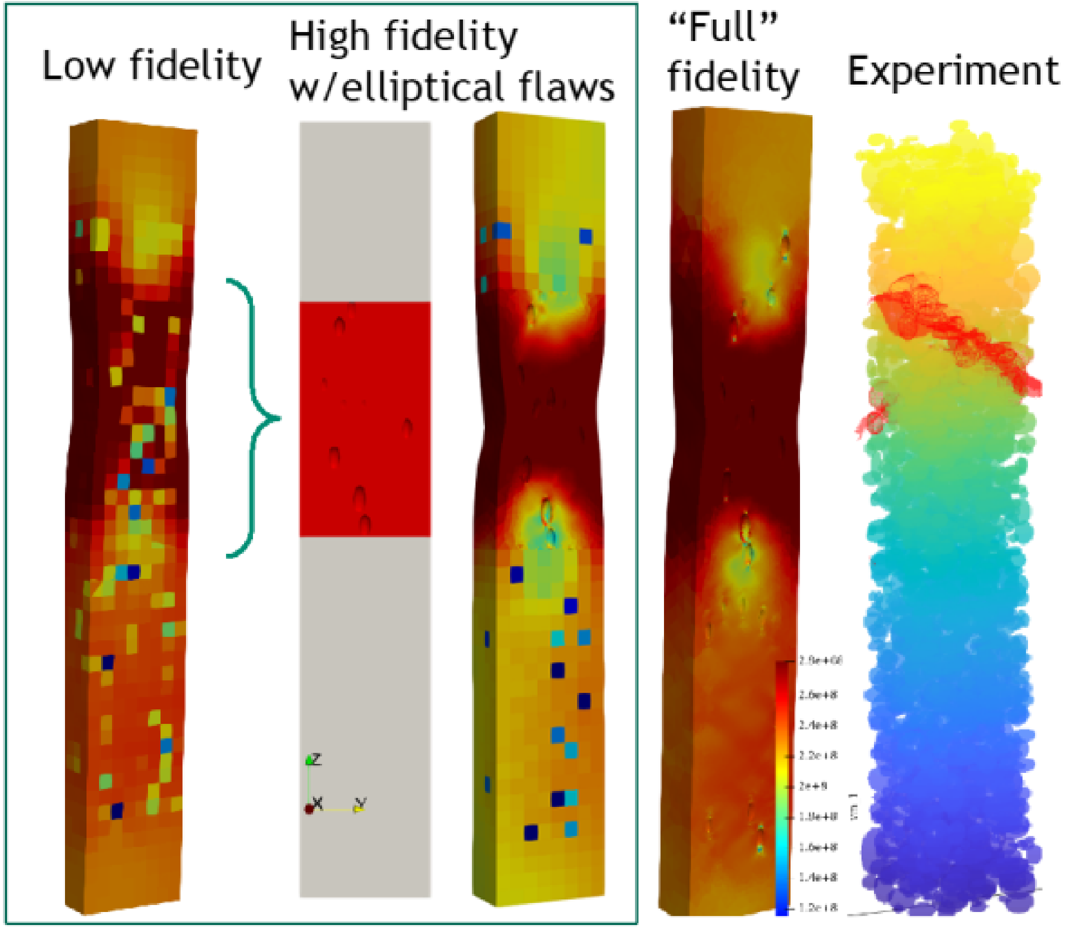
Split-Hopkinson Pressure Bar Testing





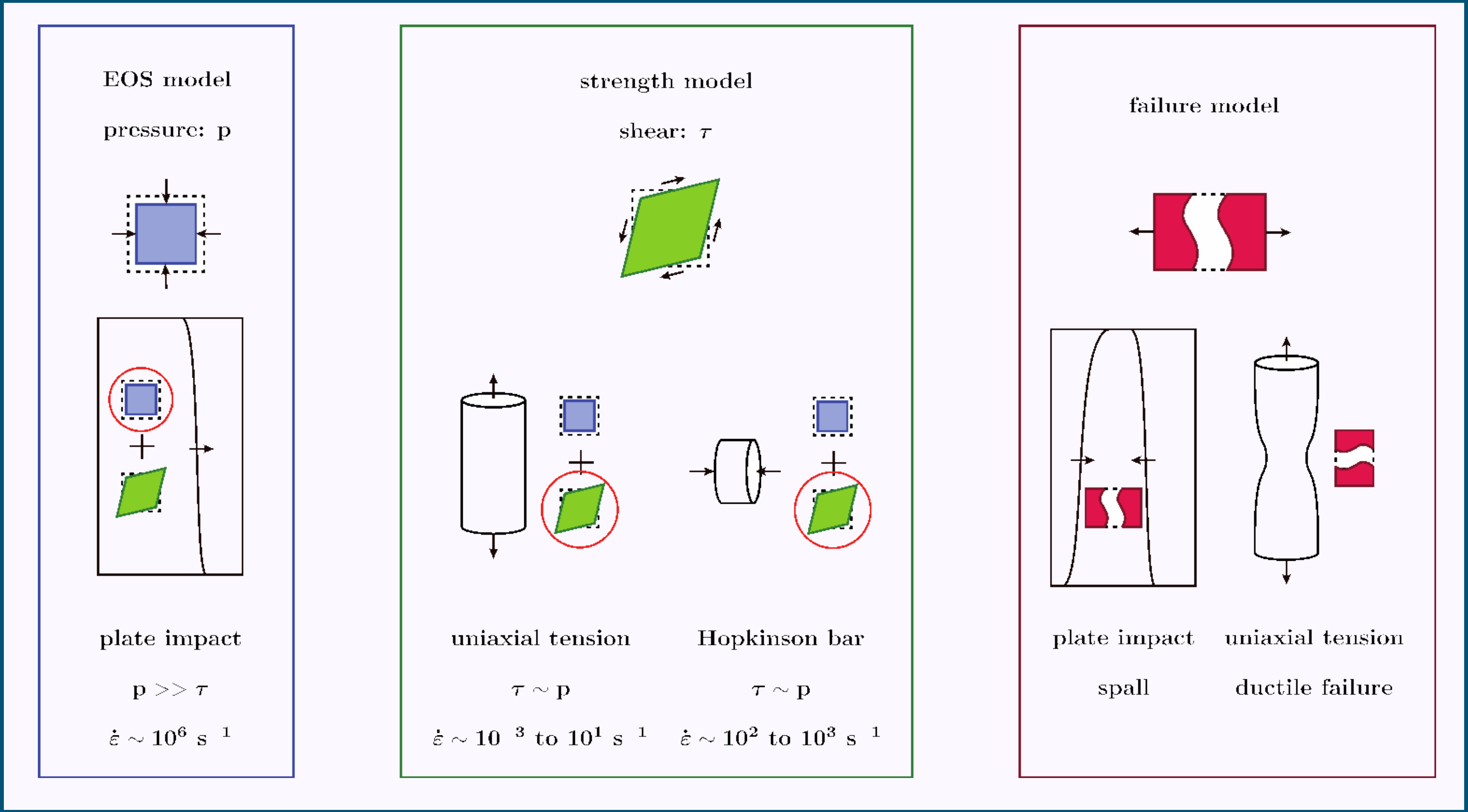


Solid Mechanics Modeling Approach

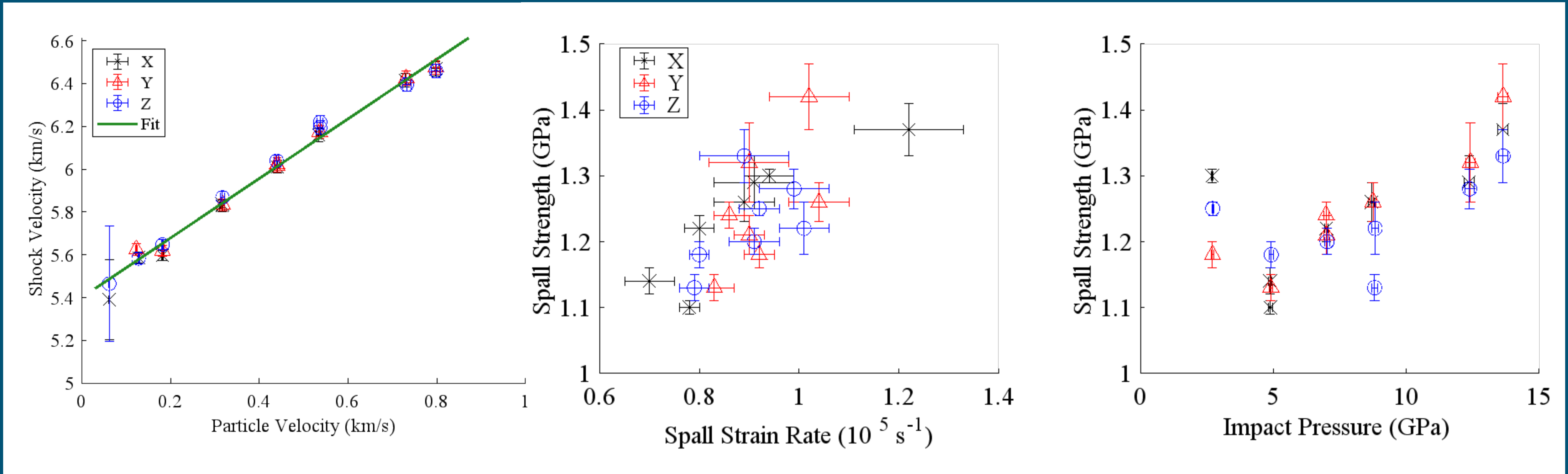


Hierarchical model (within the box) adds fidelity only in hotspot regions where its needed.

High-Rate Material Modeling



EOS and Spall Response

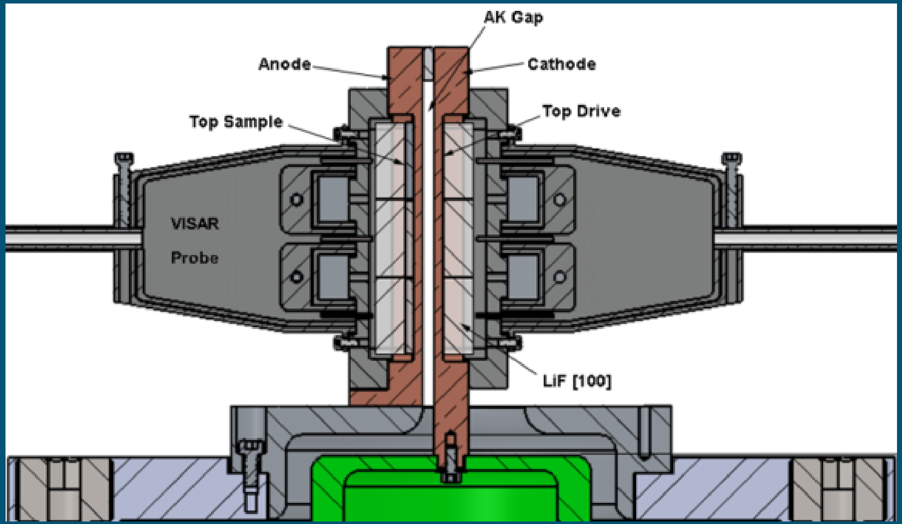


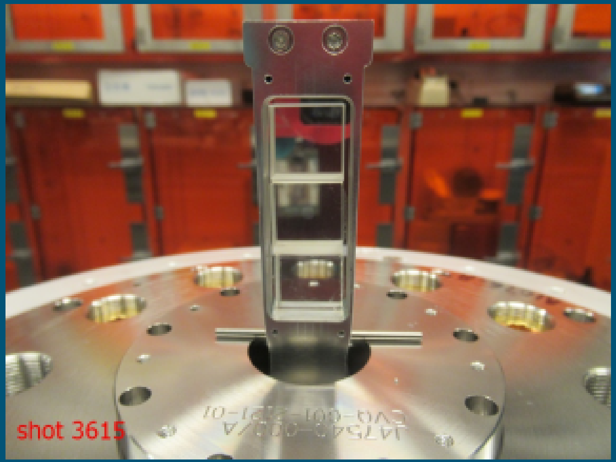
EOS for AlSi10Mg Like That
for Al 6061 up to ~13GPa

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

Quasi-Isentrope Experiments on Z-Machine

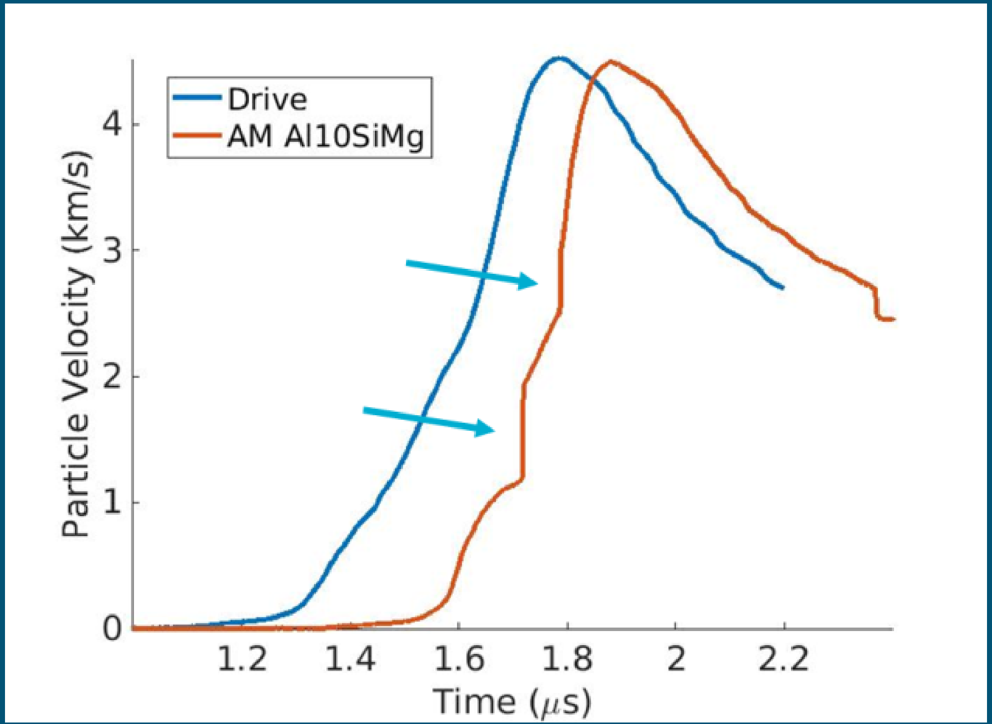
Ramp-Release Experiments at Mega-Bar Stresses



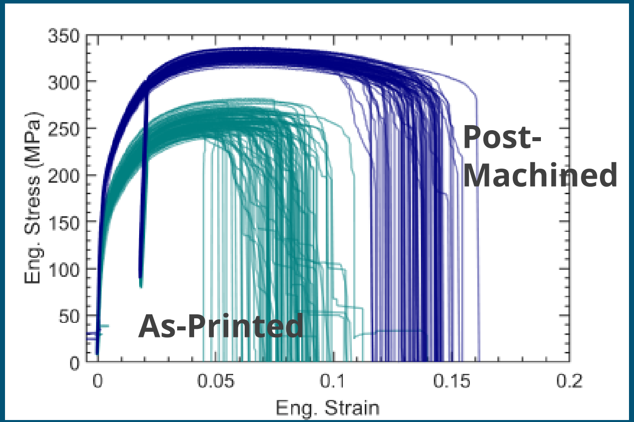


Z3615 Target

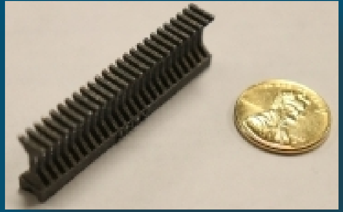
AM AlSi10Mg exhibits two low pressure phase changes

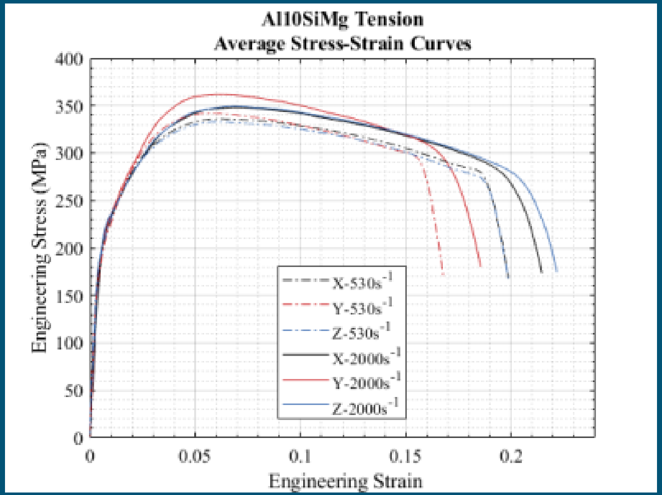


Key Insights from AlSi10Mg Study

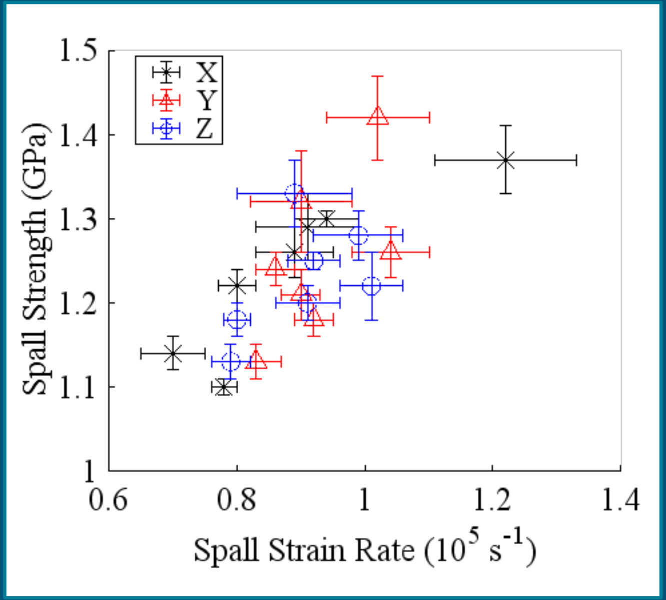


Size of Printed Part and Surface Finish Matter

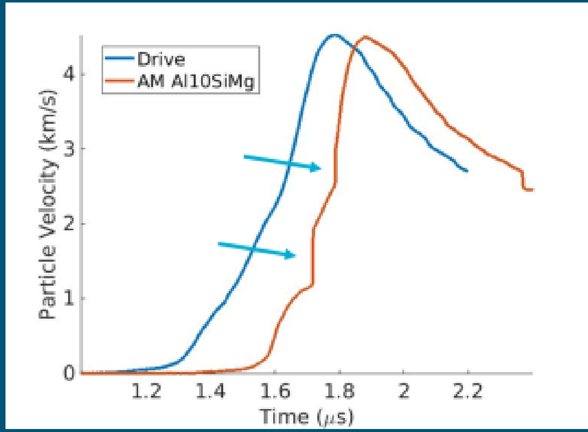




Strain Rate-Dependent and Anisotropic Behavior at Q.S. and intermediate Strain Rates



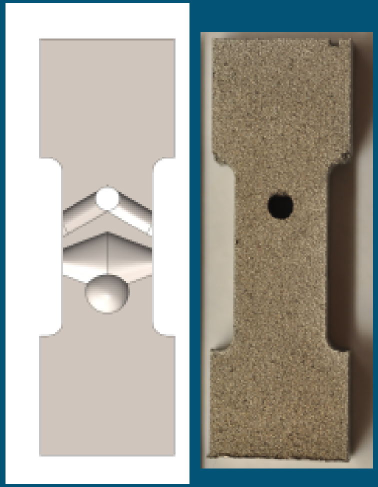
Strain Rate-Dependent and Behavior at High Rates, but Anisotropic Response Disappears



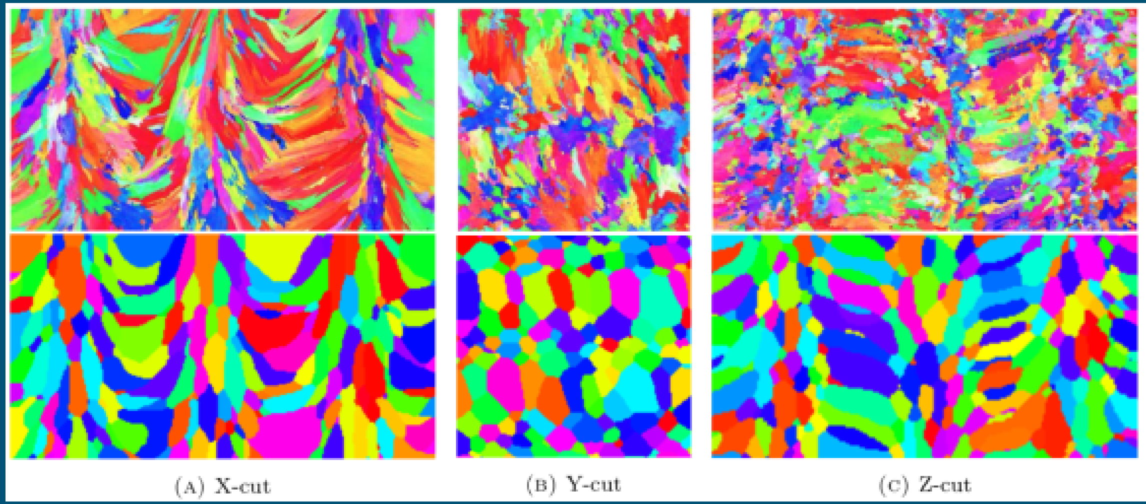
Unexpected Phase Changes in an Al Alloy at High Pressures

Future Work on Strain-Rate Dependent Behavior

Effect of Geometry



Improved modeling at all rates



EBSD

SPPARKS

Topology Optimization

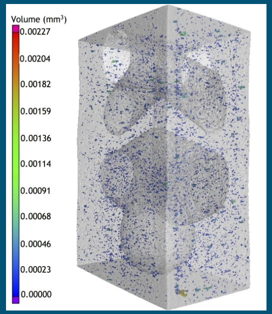
https://www.eos.info/en/

Design Guidance

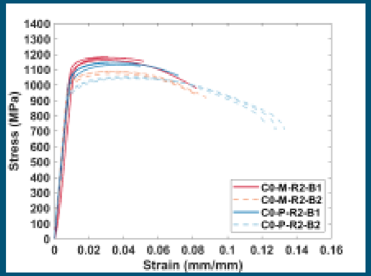
- Stress Concentrations
- Ligament Sizes
- Machining Considerations

Summary of Foundational Research for QRE and Future Work

Role of Inspection

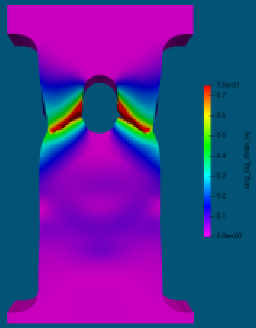


Further Material Characterization

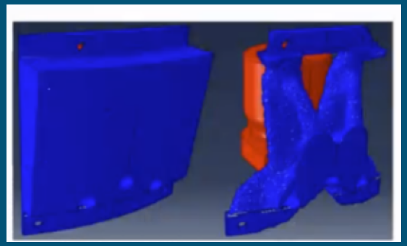


Part Geometry Effects

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