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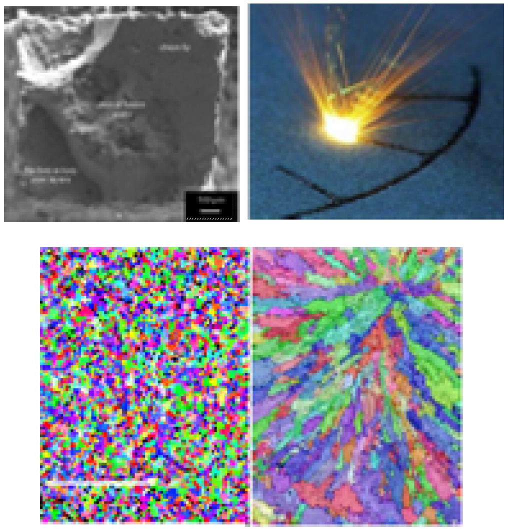

Changing the Engineering Design & Qualification Paradigm in Component Design & Manufacturing (Born Qualified)

R. Allen Roach, Principal Investigator

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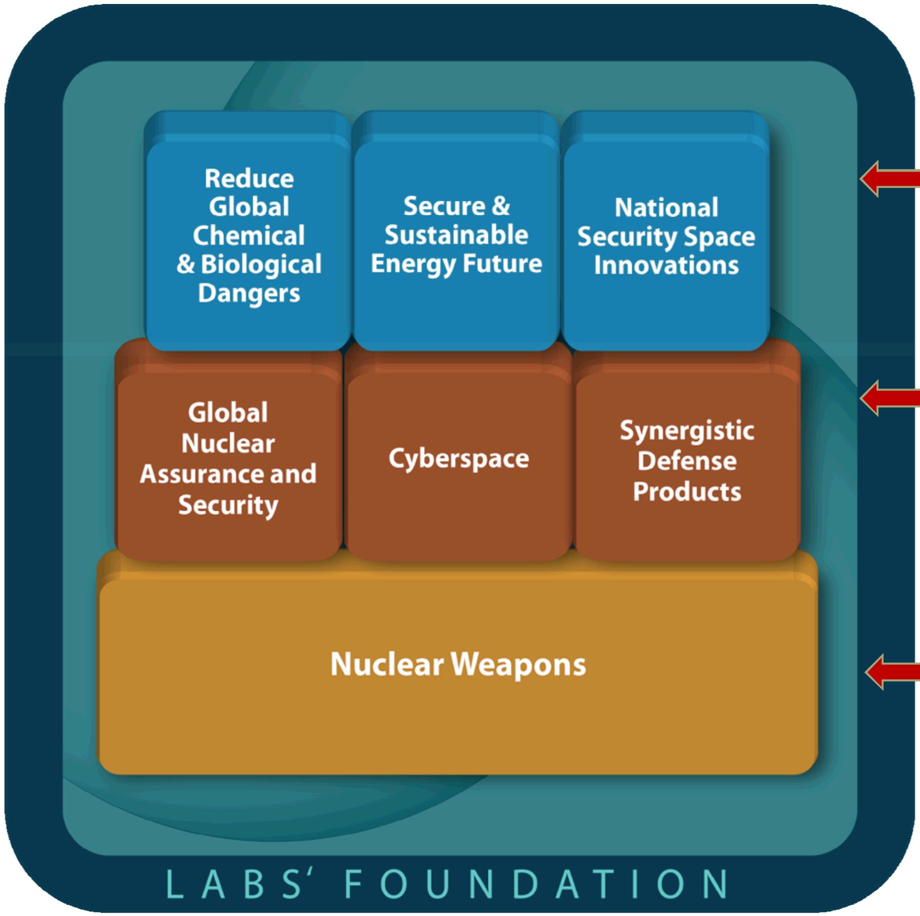
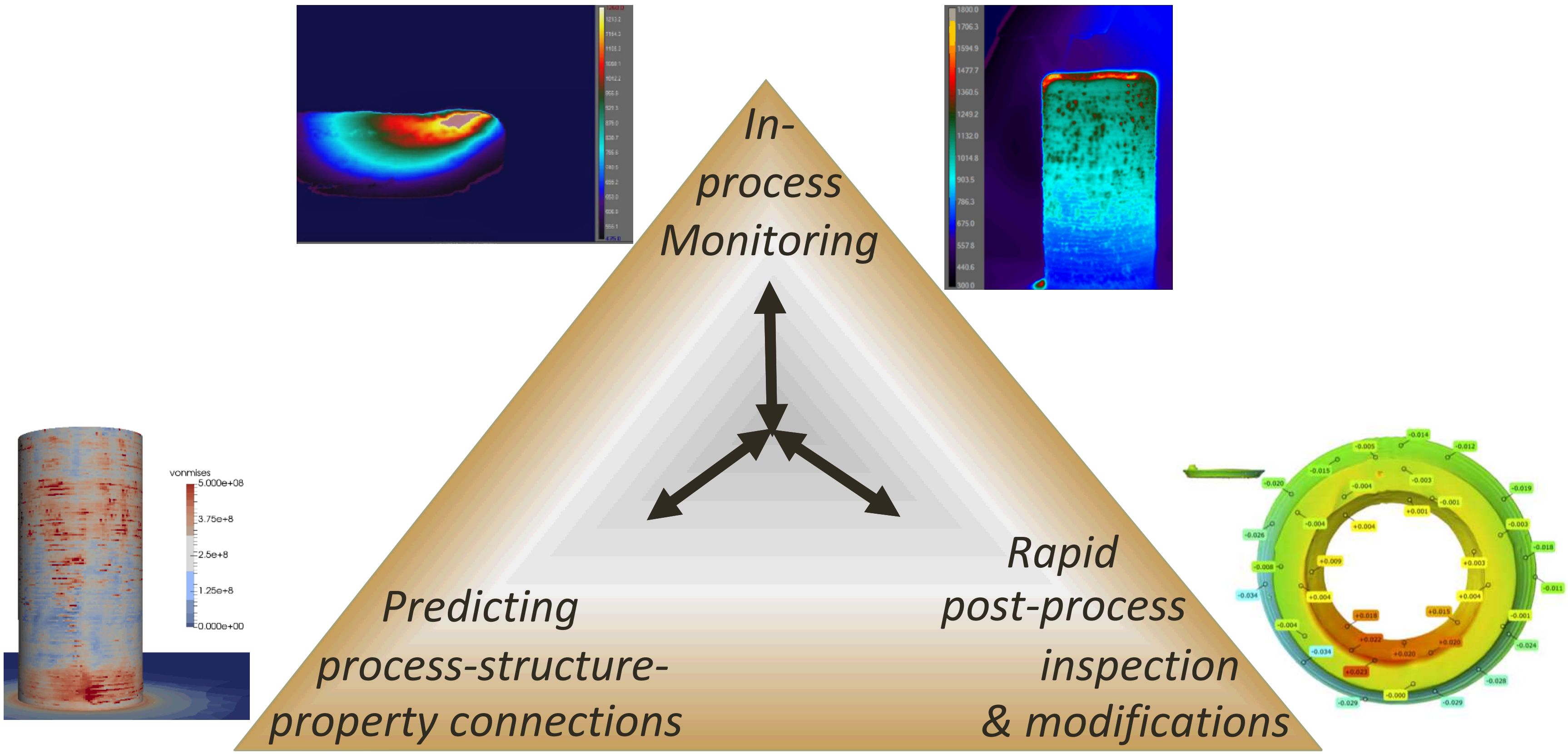
Sandia National Security Mission Areas



- Top row: Critical to our national security, these three mission areas leverage, enhance, and advance our capabilities.
- Middle row: Strongly interdependent with NW, these three mission areas are essential to sustaining Sandia's ability to fulfill its NW core mission.
- Bottom row: Our core mission, nuclear weapons (NW), is enabled by a strong scientific and engineering foundation.

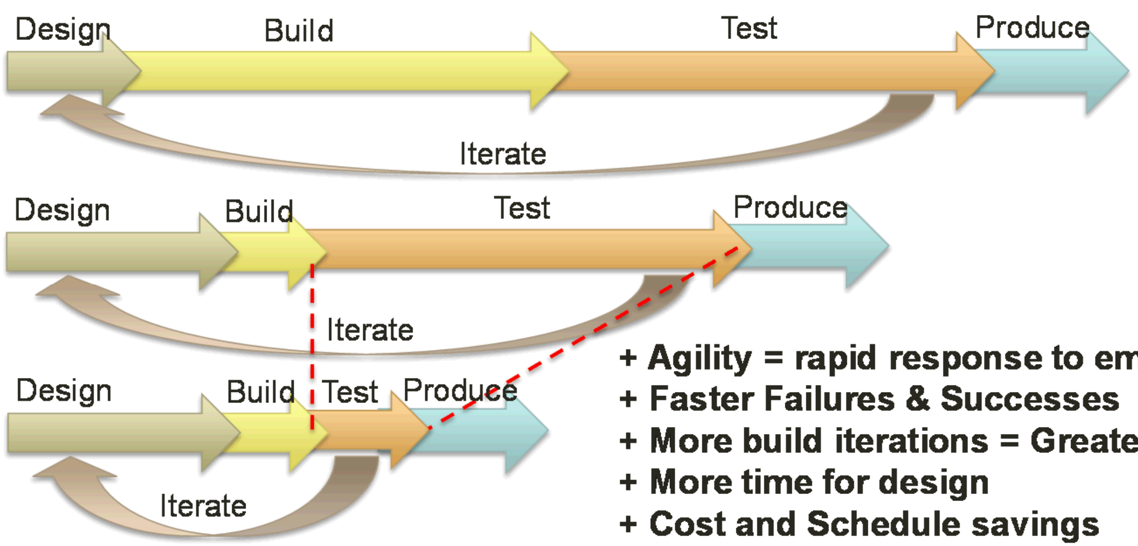
Approach to Paradigm Change

- Sandia is developing an assurance capability that is rapid, flexible, and practical that exploits disruptive capabilities of Additive Manufacturing
- Develop deep materials & process understanding by integrating validated, predictive capability with real-time and ex-situ diagnostics to realize Uncertainty Quantification driven qualification of design and process



Approach to Paradigm Change

- Drive Qualification revolution by
  - Predicting Performance Probabilistically
  - Tightly Controlling Process
  - Utilizing Accelerated Cycles of Learning



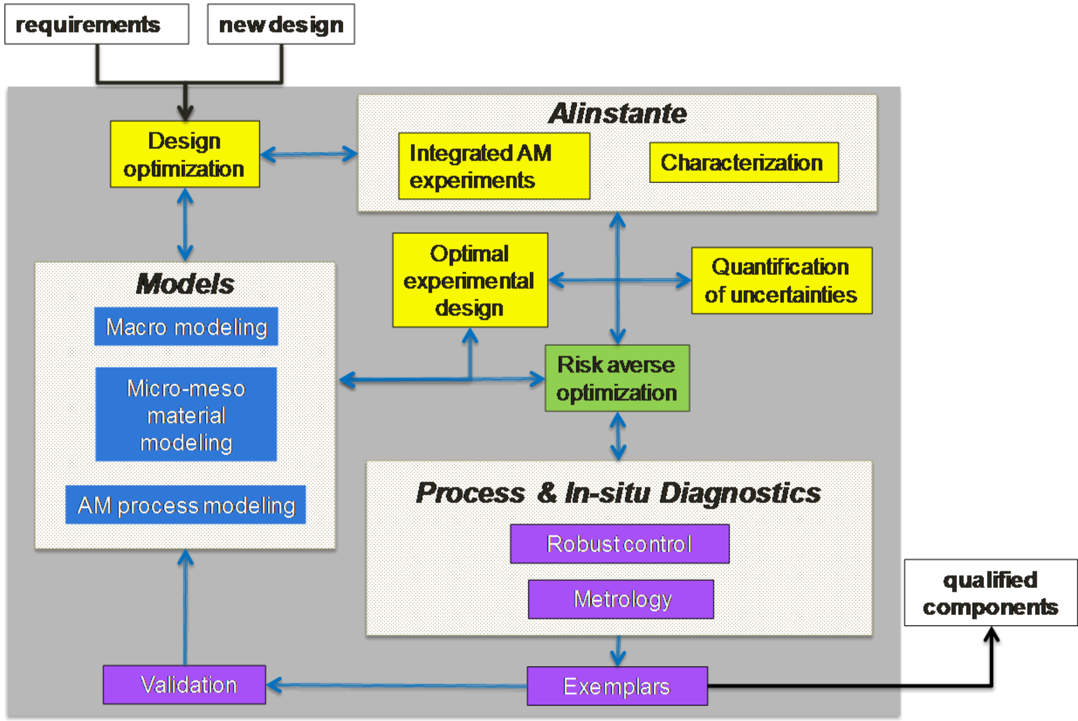
+ Agility = rapid response to emerging threats
+ Faster Failures & Successes
+ More build iterations = Greater confidence
+ More time for design
+ Cost and Schedule savings

- At the end of FY18, test with 3 Exemplars to evaluate progress and future investment needs

FY16-18 Plans

Project Area	FY16-18 Focus
AM Process	material stock & process capabilities
In-situ Diagnostics	process measurements
AIinstante	rapid characterization
Process models	T, geometry
Material models	microstructure, properties/defects
Exemplar models	structural performance
Optimization & UQ	capabilities for optimization under uncertainty

New Qualification Strategy



Alinstante

Alinstante = Rapid Characterization

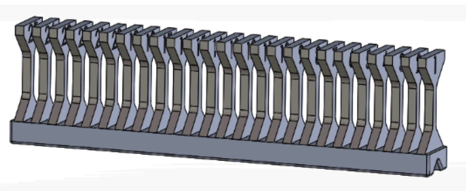
- Wishlist…

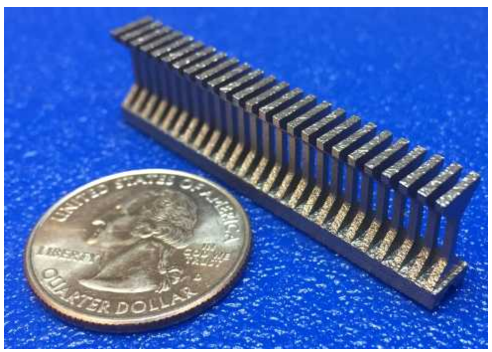
Properties	**Structure**	**Process**
Tensile strength	Geometry	Surface remediation
Ductility	Roughness	Heat treatment
Toughness	Porosity	Subtractive machining
Hardness	Chemistry	Coating
Wear & friction	Phase content	Joining
Permeability	Grain Size	Integration
Thermal expansion	Crystal Texture	etc.
Reactivity/corrosion	Residual stress	
Electrical conductivity	Dislocation content	
Resonance	etc.	
etc.		

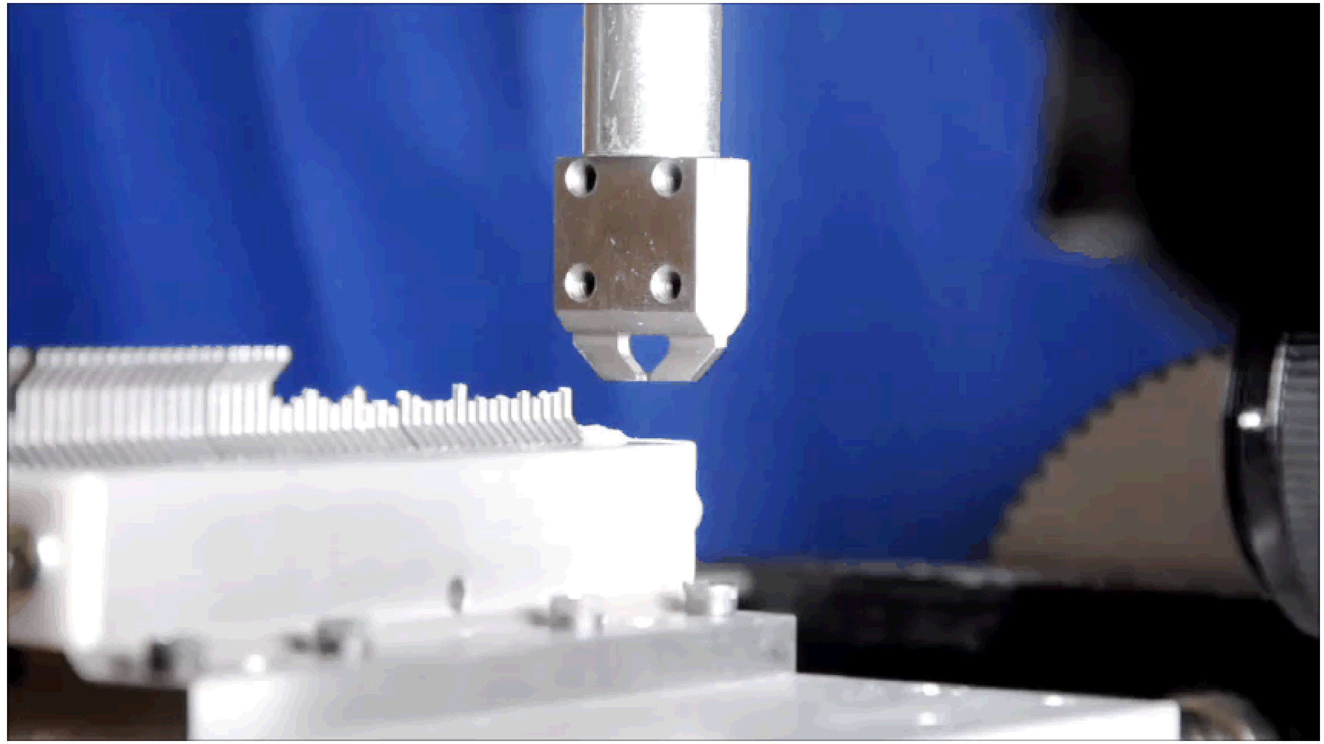
- Can we automate?

* Some measurements, like resonance testing, can be used to infer multiple aspects (geometry, density, modulus, residual stress, etc)

High-Throughput Testing





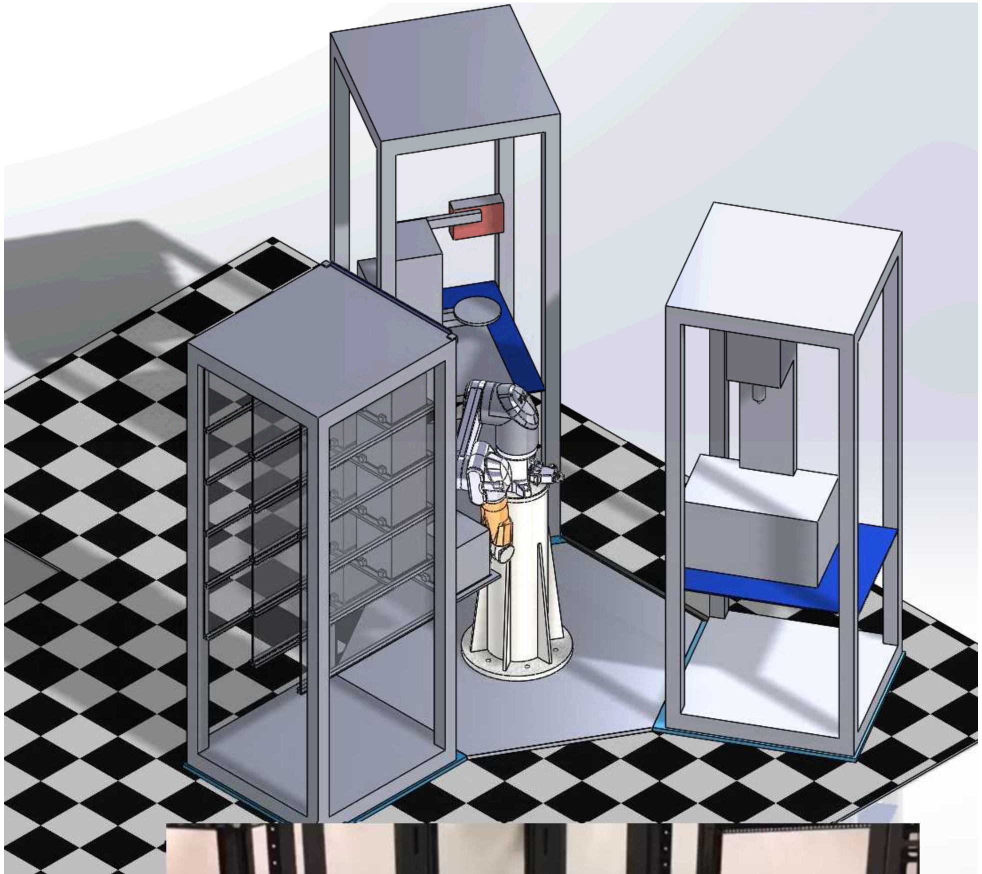


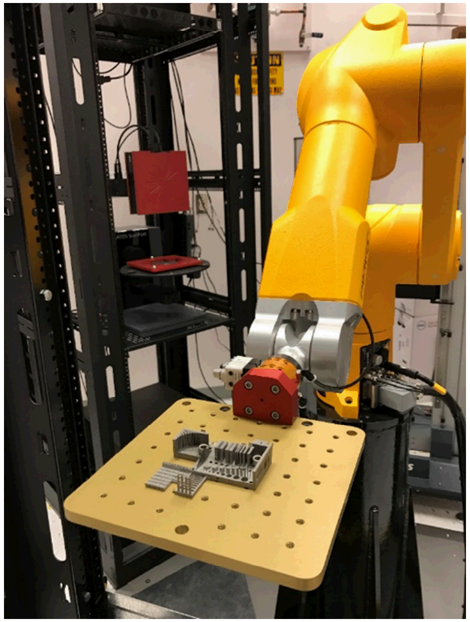
>100 tensile tests/hr with minimal operator burden

Published results from our capability:

- B.L. Boyce, B.C. Salzbrenner, J.M. Rodelas, A.M. Roach, L.P. Swiler, J.D. Madison, B.H. Jared, Y.-L. Shen, “Extreme-value statistics reveal rare failure-critical defects in additive manufacturing”, *Advanced Engineering Materials*, 2017.
- B.C. Salzbrenner, J.M Rodelas, Y-L Shen, J.D. Madison, B.H. Jared, L.P. Swiler, B.L. Boyce, “High-throughput stochastic tensile performance of additively manufactured stainless steel”, *Journal of Materials Processing Technology*, 2017.

Alinstante Modular Pedal Concept

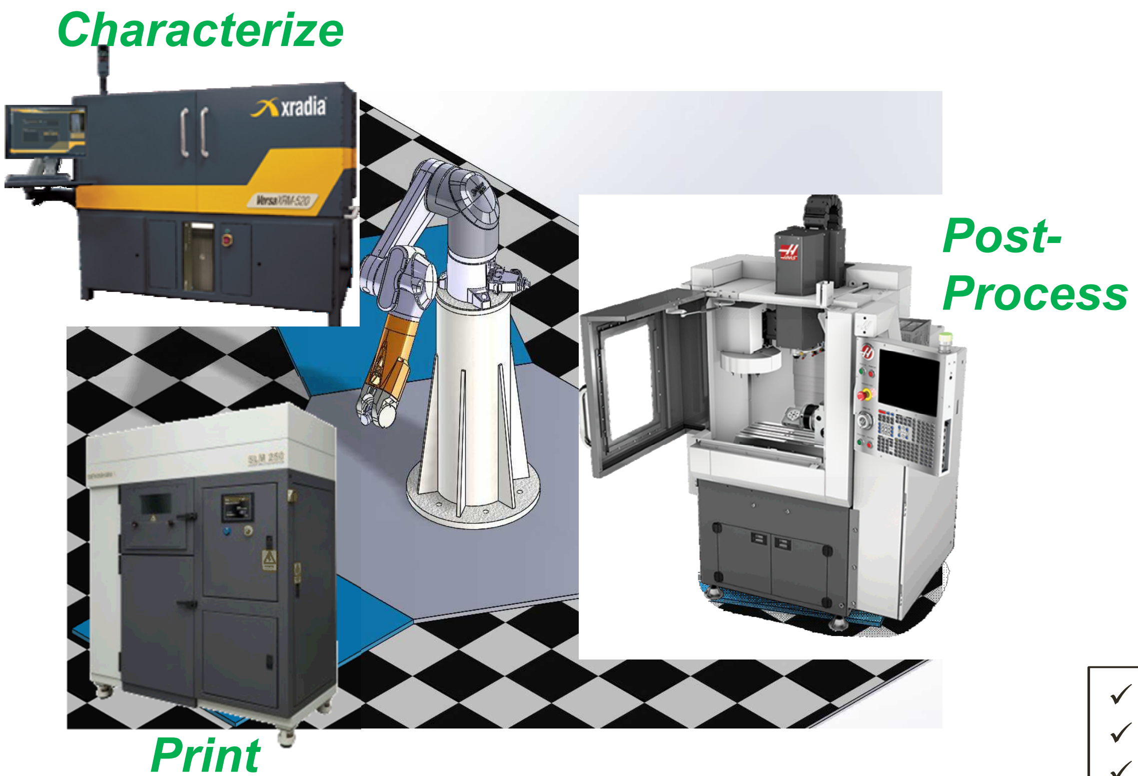


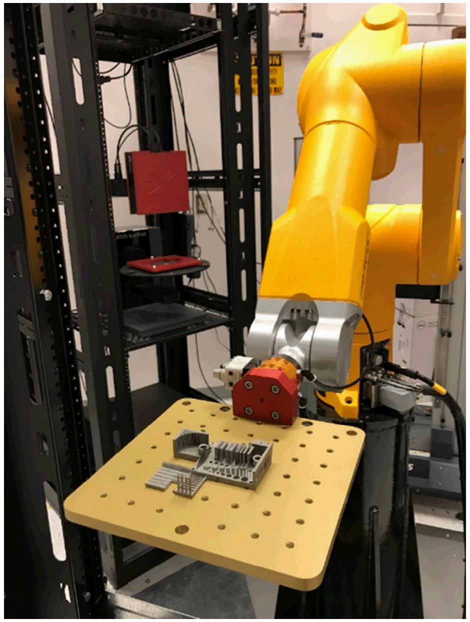


- ✓ Electrical, Pneumatic Supply
- ✓ Robot installed
- ✓ Robot Control Hardware & Software
- ✓ 3 Module racks installed
- ✓ Light curtain interlocks activated
- ✓ Safety Authorization
- ✓ Part Trays Fabricated
- ✓ GOM 3D Scanner Installed
- ✓ Mechanical Loadframe Installed
- ✓ Tray Receiver Installed
- ✓ Tray Racks Installed
- ✓ Direct Communication Robot-Scanner

  Mechanical test integration

Alinstante Modular Pedal Concept





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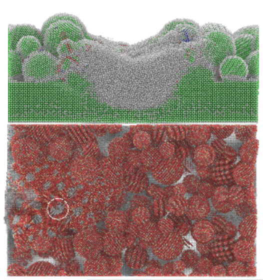
- ✓ Direct Communication Robot-Scanner
  Mechanical test integration

Models

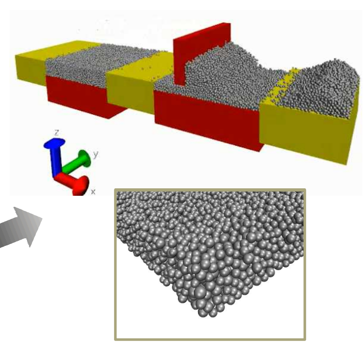
SNL Modeling Work – Metal AM

Codes
LAMMPS, SPPARKS, Sierra/Aria, Sierra/Adagio

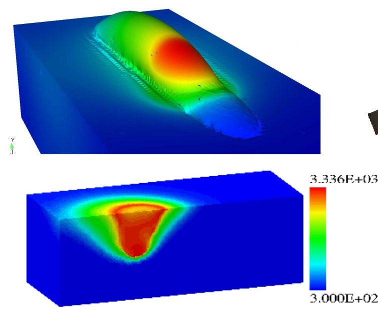
Powder Behavior
Mark Wilson



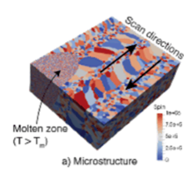
Powder Spreading
Dan Bolintineanu



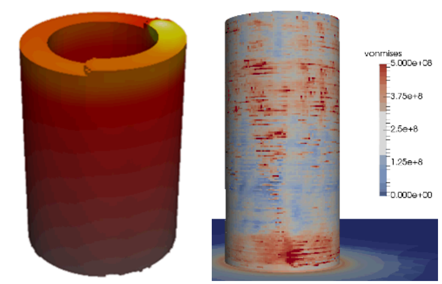
Mesoscale Thermal Behavior
Mario Martinez & Brad Trembacki



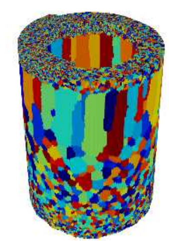
Mesoscale Texture/Solid Mechanics/CX
Judy Brown, Theron Rodgers and Kurtis Ford



Part Scale Thermal & Solid Mechanics
Kyle Johnson, Kurtis Ford & Joe Bishop



Part Scale Microstructure
Theron Rodgers



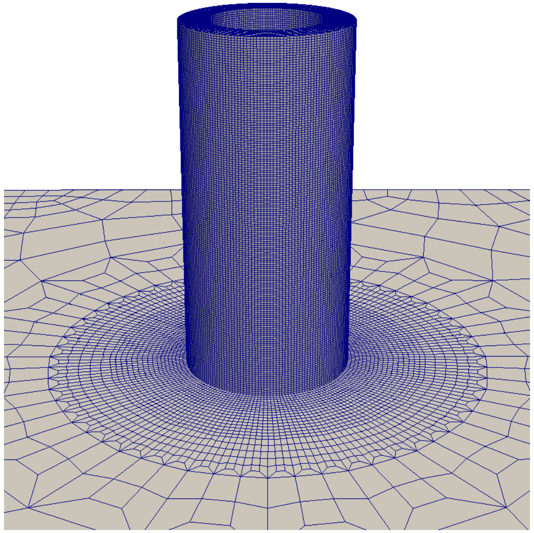
10^{-6} — 10^{-3} — 1

Length Scale (m)

304L Cylinder Example

Process	Structure	Property	Performance (Future)
Thermal Model in Aria	Microstructure Model in SPPARKS	Residual Stress in Adagio	Behavior using as-built microstructure, residual stress, and properties

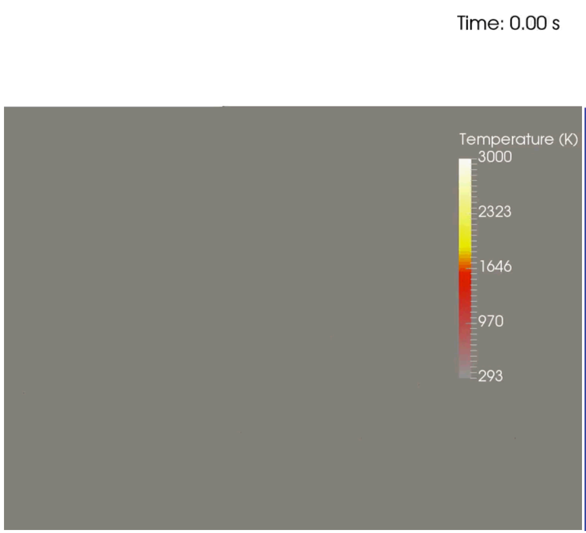
- Cylinder built using LENS process
- Laser diameter = 4 mm
- Laser Speed = 8.46 mm/s
- Layer Thickness = 0.9 mm
- Laser Power = 2000 > 1750 > 1500 > 1250 W

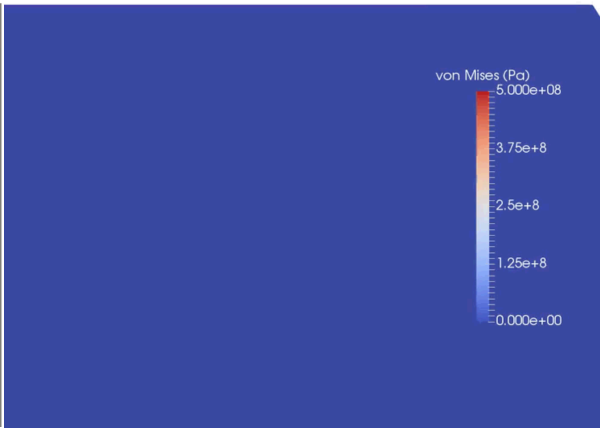


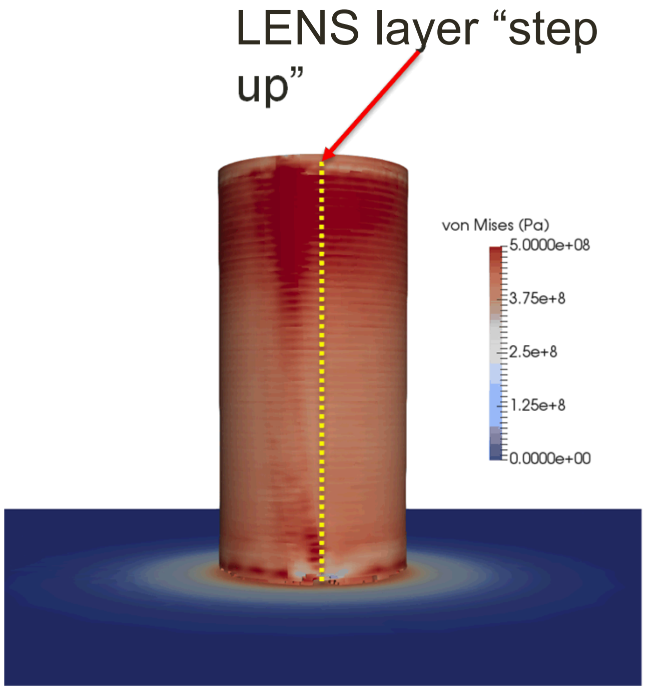
Contact – Kyle Johnson, Kurtis Ford, Theron Rodgers, Joe Bishop

Microstructure Demonstrates Equiaxed to Columnar Grain Transition

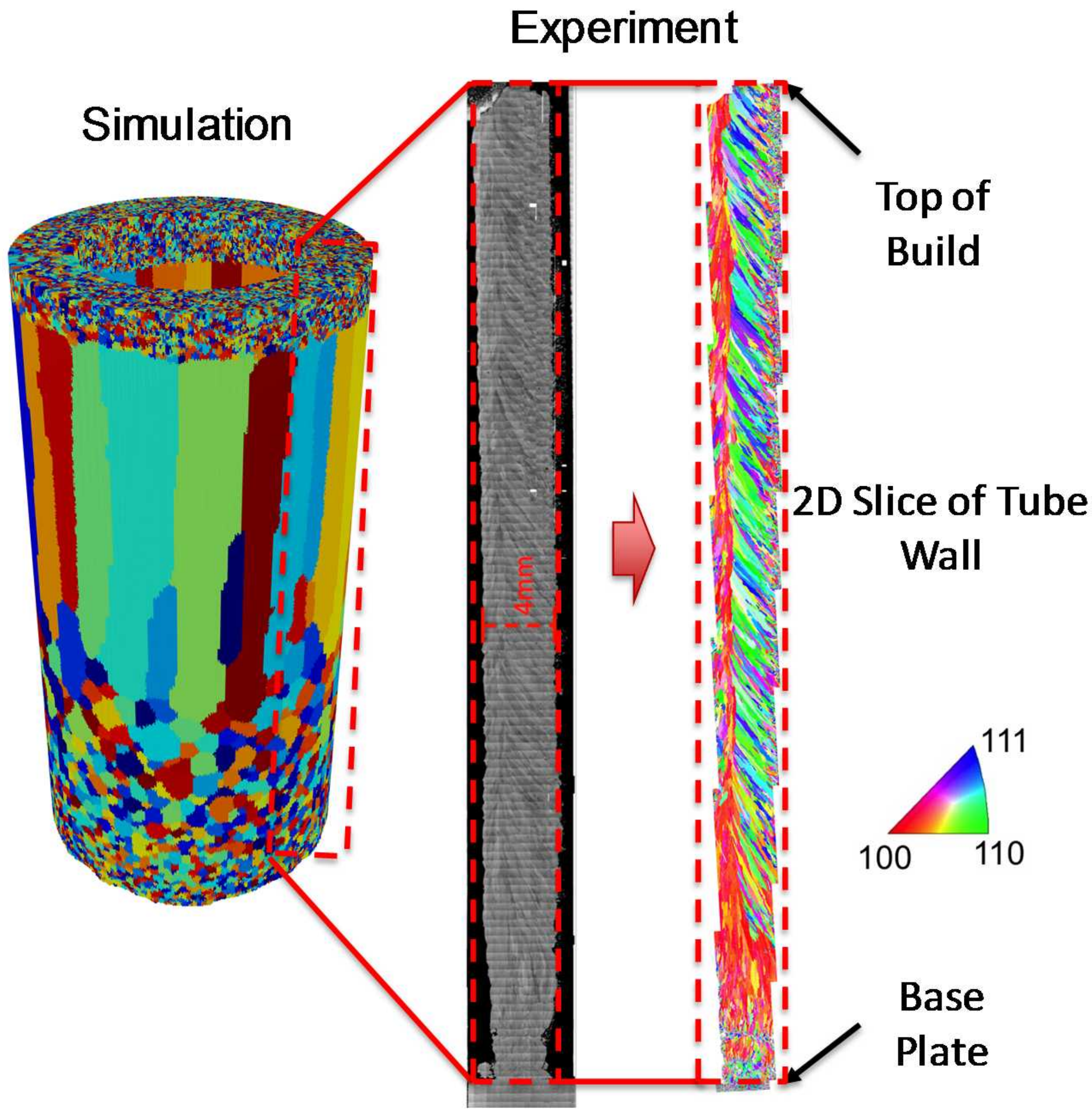
- Thermal history file directly imported into SPPARKS
- Plan to use thermal and microstructure histories in conjunction with crystal plasticity model in order to predict Type II (grain-specific) residual stresses as part is built







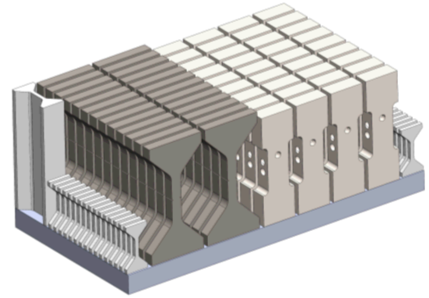
Experimental Comparison

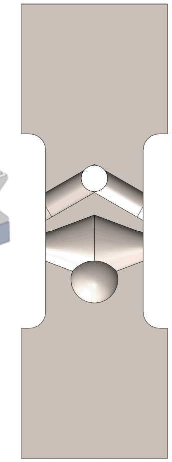


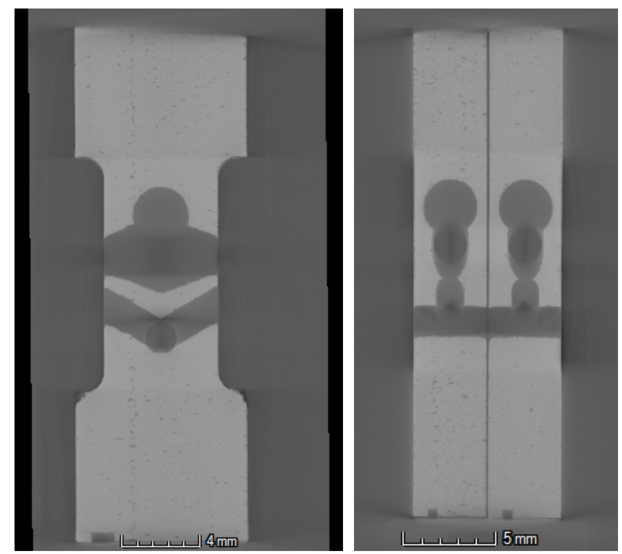
EBSD: O. Underwood, J. Madison, A. Kilgo, J. Michael, S. Dickens

Sandia Fracture Challenge

- 316L Stainless Steel LPBF Part
- Complex geometry with internal channels and spherical cavity
- Loaded in tension
- Given CT data along with smooth tension and notched tension data
- Challenge Questions:
    - Force at four different displacements
    - Force and log strain at four points on front face
    - Total force-displacement curve
    - Force and log strain along four horizontal lines on front face
    - Images of front surface at crack initiation and complete failure

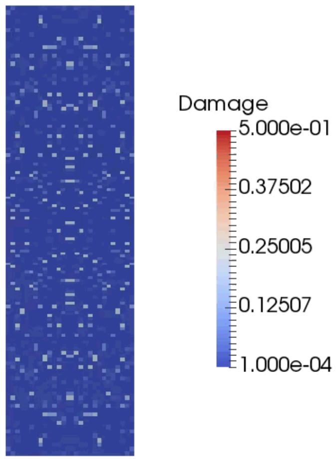


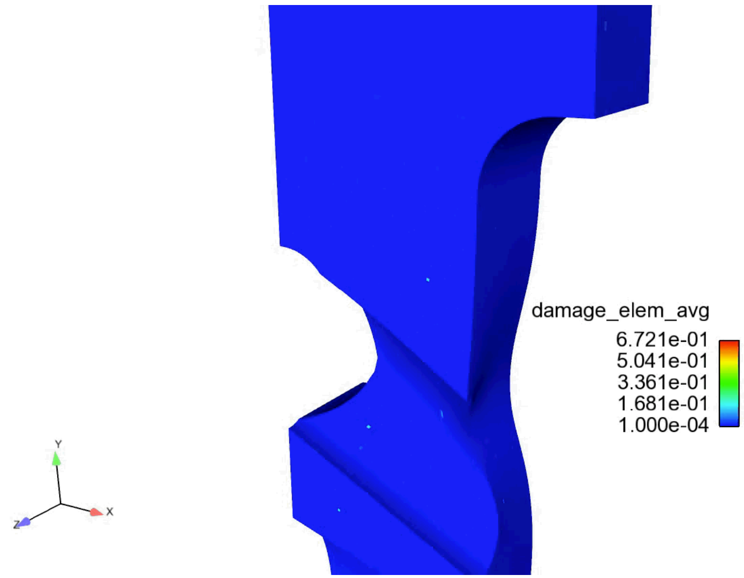


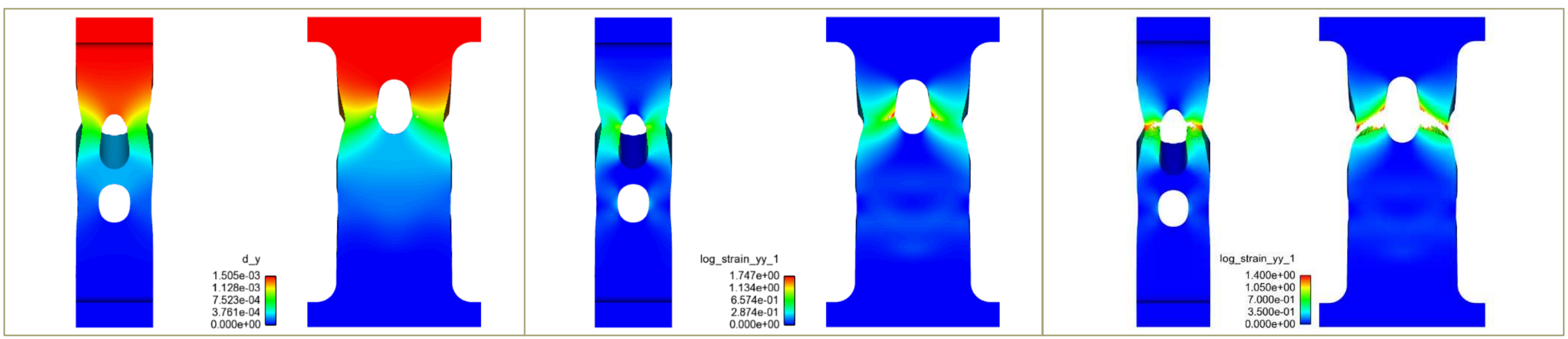


Contact – Brad Boyce, Sharlotte Kramer, Judy Brown

Predictive Approach – Simulations for Many Porosity Realizations



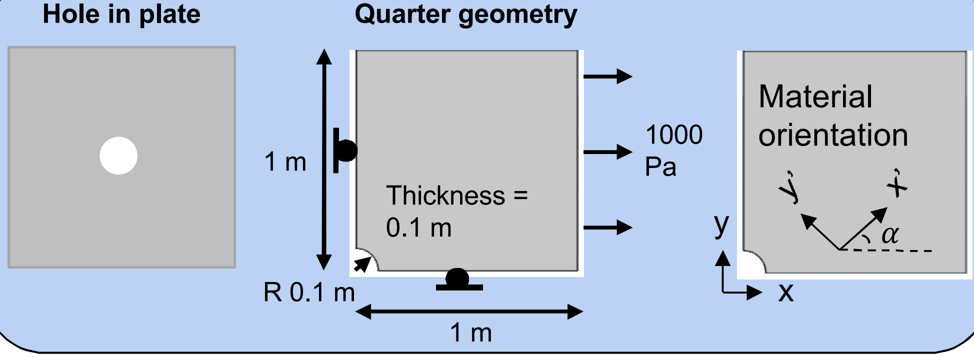




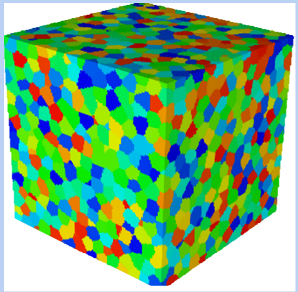
Contact – Kyle Johnson, Kurtis Ford, Bradley Jared, Joe Bishop

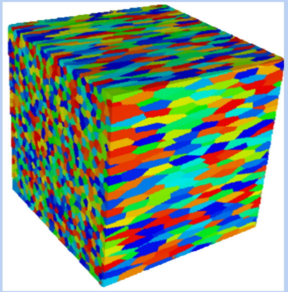
Optimize Microstructure of Metallic AM Structures

Model set-up



Rep. vol. elements (RVE)


Isotropic


Pure Fiber

Effective material properties

Material: 304L Stainless Steel

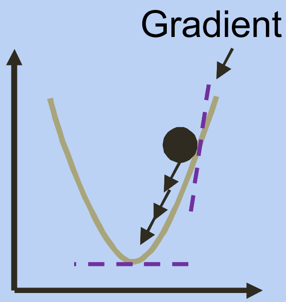
	Elastic mod [GPa]			Poisson's ratio			Shear mod [GPa]		
	E_{11}	E_{22}	E_{33}	ν_{12}	ν_{23}	ν_{13}	G_{12}	G_{23}	G_{13}
Isotropic	198			0.29			76.5		
Pure Fiber Texture	143	143	90.9	0.11	0.62	0.62	58	126	126

Gradient Optimization

$$\min Q = Q(u(\alpha))$$

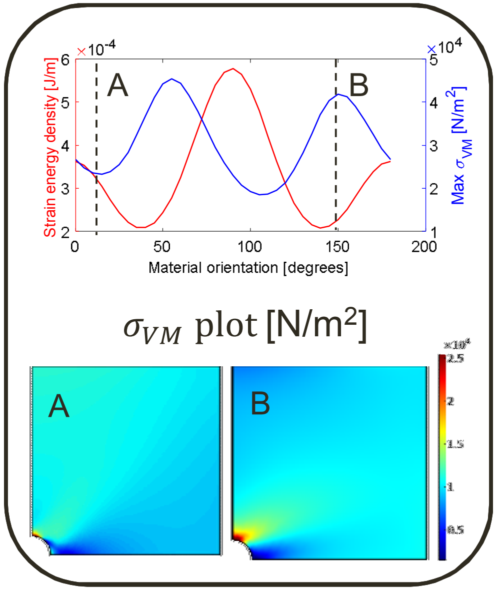
$$Q_1 = \frac{1}{V(\Omega)} \int_{\Omega} W_S \, d\Omega$$

$$Q_2 = \sigma_{VM}$$



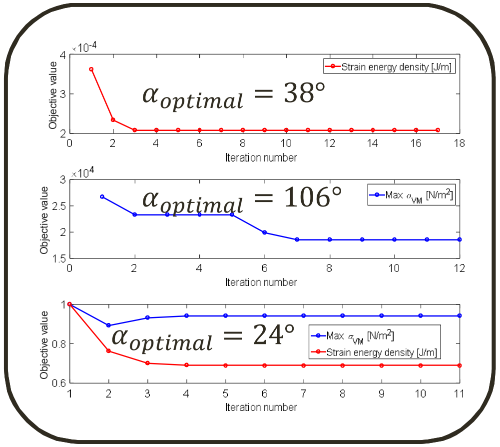
Contact – Judy Brown, Grace Gu (MIT), Joe Bishop

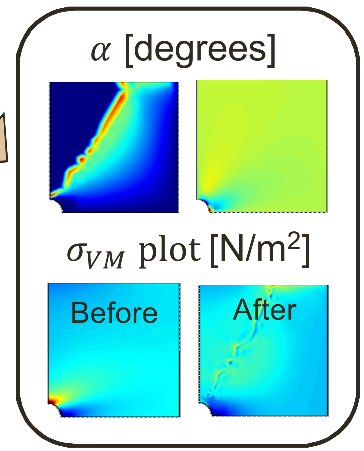
Progress to Date



2D model: Parametric study

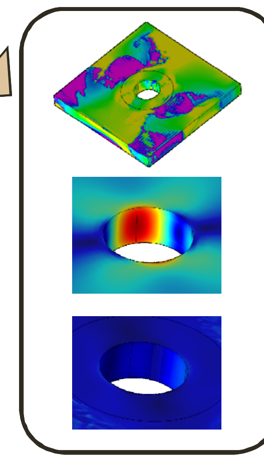
Opt. of spatially uniform properties





Opt. of spatially varying properties

3D model

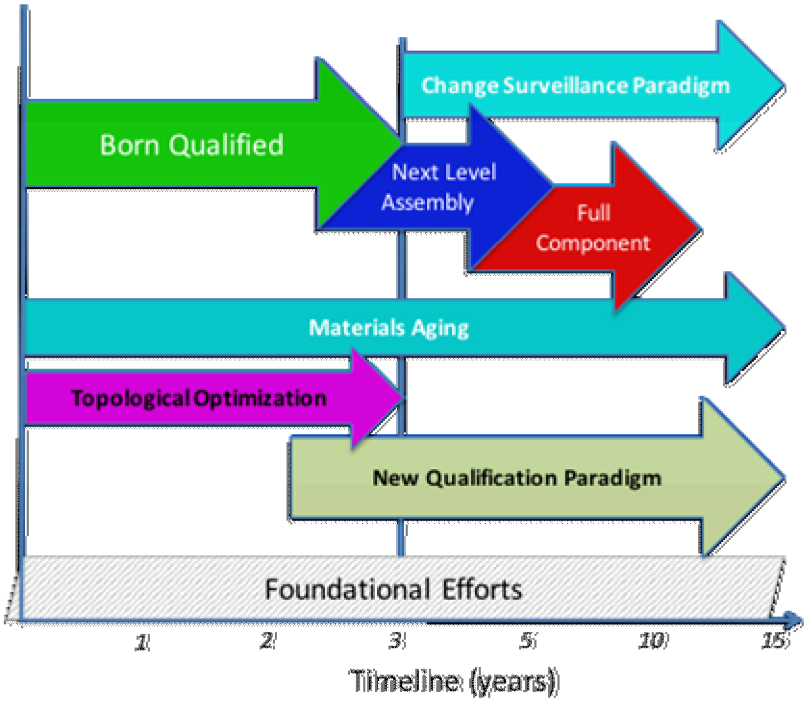


Closing Slide

3 Yrs

FY16-FY18 Main Deliverables

1. Deliver capability (models, in-situ and Alinstante measurements, Optimization, UQ) to predict AM part performance
2. Produce, test, and evaluate 3 single material exemplars where performance was predicted during manufacture



5 - 15 Years

- Science-Based & Born Qualified Design
  - Identify critical performance parameters, enhance design flexibility & agility
- Science-Based & Trusted Manufacturing
  - Verify manufacturing is the same every time
- Cost Effectiveness & Agility
  - Reduce number of builds by re-inventing component testing to validate, not discover, performance
- Improved Surveillance & Confidence in Lifetime Performance
  - Quantified birth data on all materials, track every material through its lifetime

Backups

Accelerate Qualification