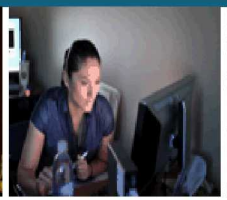
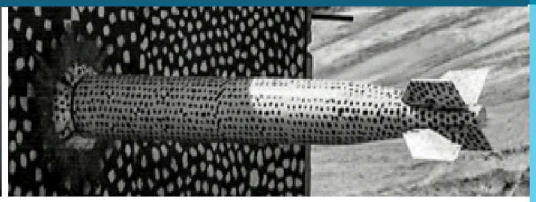
SAND2019-4242PE

Overview of Sandia's Efforts in AM & Born Qualified Project





PRESENTED BY

R. Allen Roach
Engineering Sciences Center

SAND201????

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.

Born Qualified Project Details

- 3-year Grand Challenge Laboratory Directed Research & Development Project (FY16-18)
- ~$13M total funding
- ~70 staff, students, and Post Docs

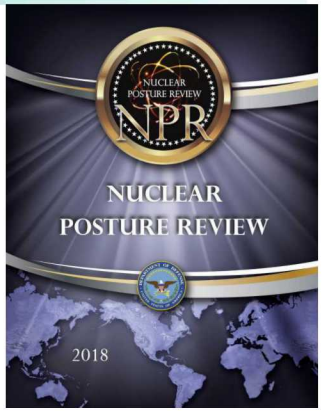
Collaborators

- LANL
- LLNL
- ORNL
- KCNSC
- University of Texas at Austin
- Georgia Tech
- MIT
- CMU
- Clemson
- University of New Mexico
- Missouri S&T
- Rochester Institute of Technology

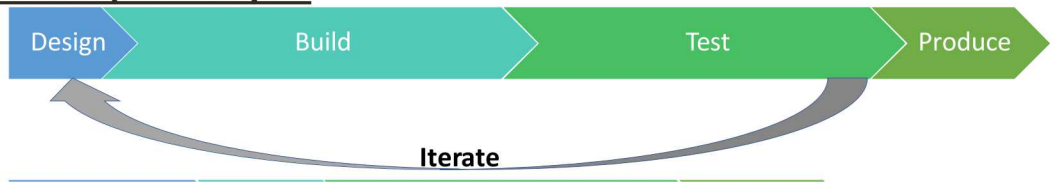
Accelerating Design to Production

Moving beyond the current paradigm of 10+ years to insert technologies into the stockpile will benefit from the use of advanced materials and advanced manufacturing

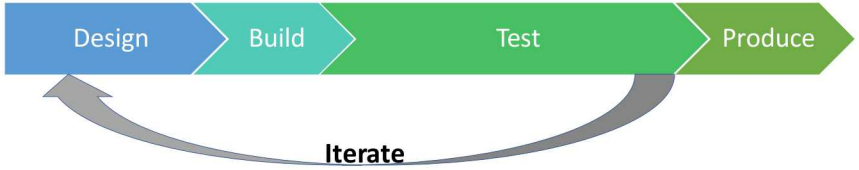
- A responsive, agile, and flexible deterrent requires capability and infrastructure innovation to increase efficiency and responsiveness of material/part development cycle
- Developing an assurance capability for high value, high consequence, low volume products that exploits Additive Manufacturing (AM)



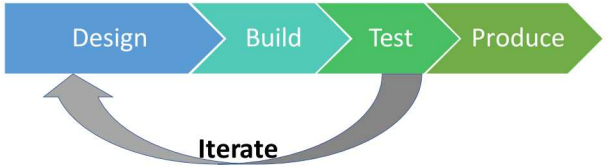
★**Typical Development Cycle**



★**Reduced Build Cycle with AM**



★**Reduced Test Cycle by Predicting Performance**



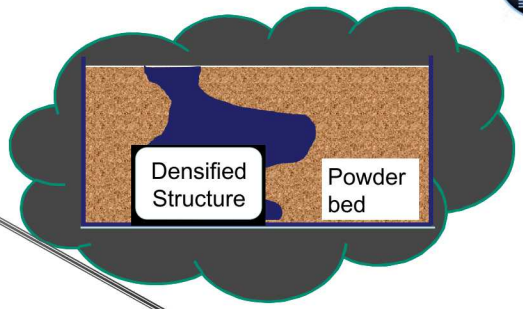
+ Agility = rapid response to emerging challenges
+ Faster failures & successes
+ More build iterations = greater confidence
+ More time to design
+ Cost & schedule savings

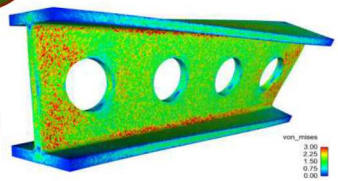
Overview of Born Qualified

Using Metal AM Examples

Quantify & Optimize

AM Process





material / part performance simulation

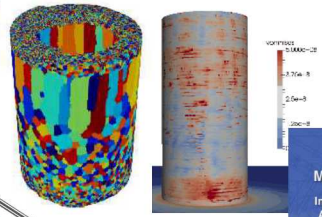
thermal history during bi-directional metal deposition

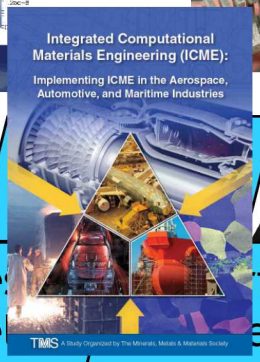
Performance Predictions

Exemplar Performance

In-Situ Measurements

Alinstante Properties

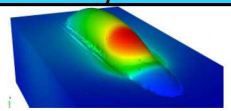




Data Analytics:
- ✓ *Regression*
- *Classification*
- ✓ *Density Estimation*
- ✓ *Statistical Estimation*
- ✓ *Dim reduction*

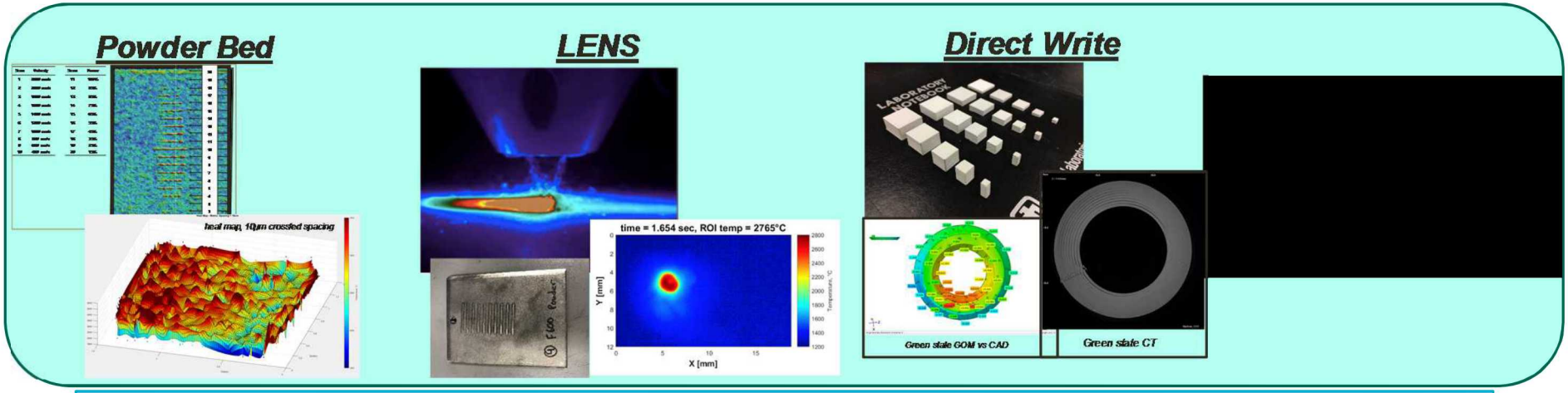
Proce… Mode… …ials …els

Property Aware Processing



Predicting Performance

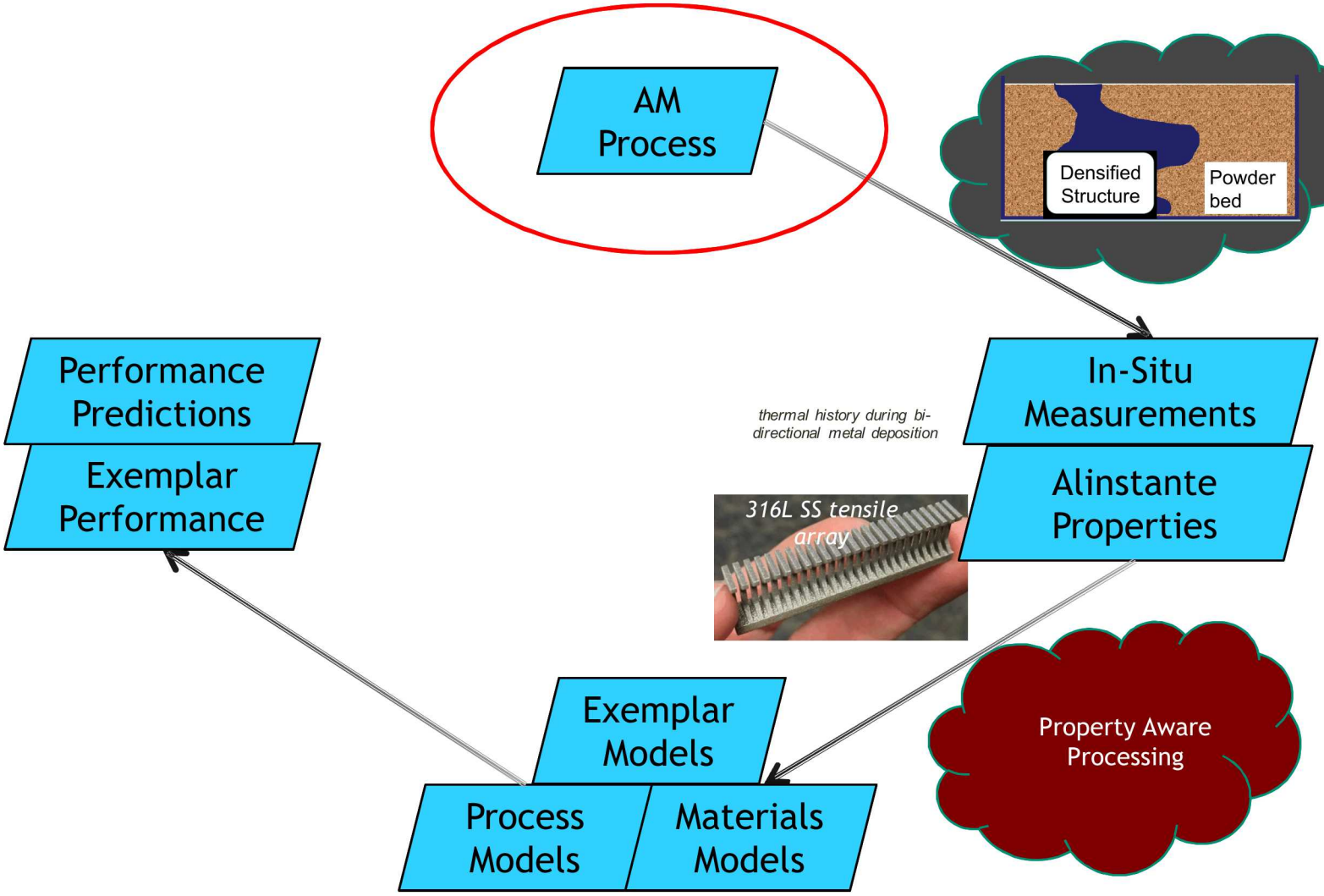
- The first 2 years focused on development, evaluation and down-selection of capabilities to predict part performance
- Year 3 focused on executing integration plan to drive the performance predictions using our 3 Exemplars to evaluate our progress
- Process-Structure-Properties-Performance **PSPP**



FY18 Focus for Performance Predictions

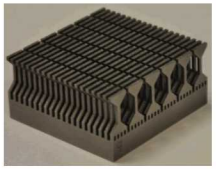
- Direct Write: bead D,T,P⇔interfaces+porosity⇔density+local strain
- LENS & Powder Bed: melt pool+T⇔microstructure⇔residual stress

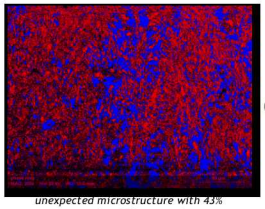
Review Progress to Date



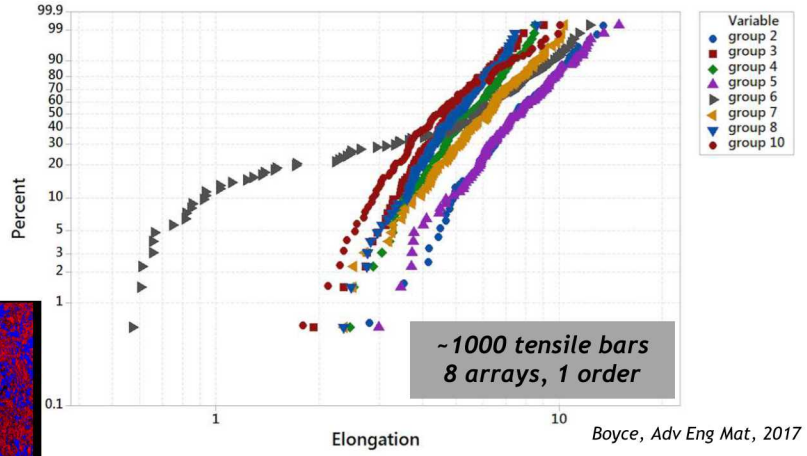
Process Control

- Material Uncertainty in Early AM Metals
  - 17-4PH parts requested from external vendor in 2015, 1x1mm gage x-section
  - Sandia did not know or control: feedstock pedigree, machine, build environment, process inputs or post-processing steps
  - Not-surprisingly, extensive material variability observed



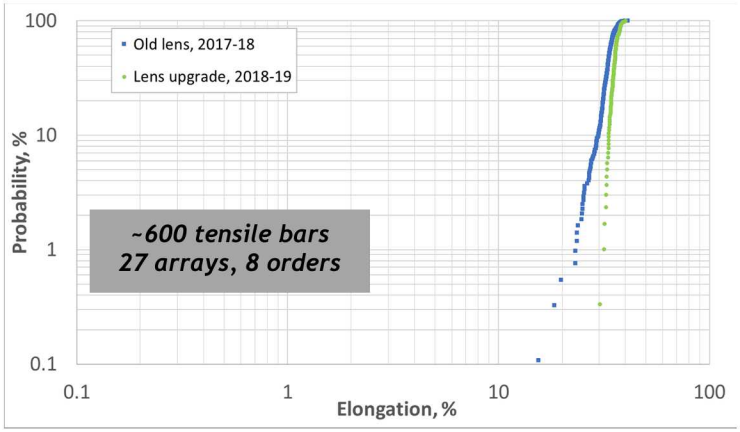


unexpected microstructure with 43% austenite, 57% martensite



Boyce, Adv Eng Mat, 2017

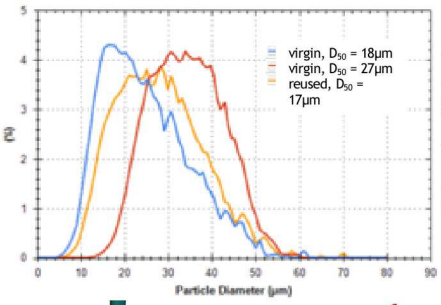
- Process Knowledge & Control Reduces Material Variability
  - 316L stainless steel from 1830's 3D Systems ProX 200
  - Sandia now controlling & logging every part, build & powder cycle
    - process space mapped & machine performance characterized
    - feedstock pedigree, build environment, process inputs, post-processing
    - printing & testing artifacts w/build cycles
    - storing feedstock, process & printed material data in GRANTA
    - capabilities for in-situ machine & process monitoring

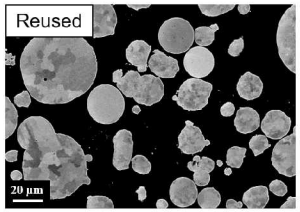


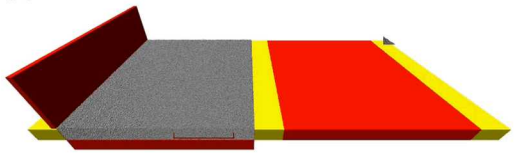
Contact Bradley Jared, Brad Boyce

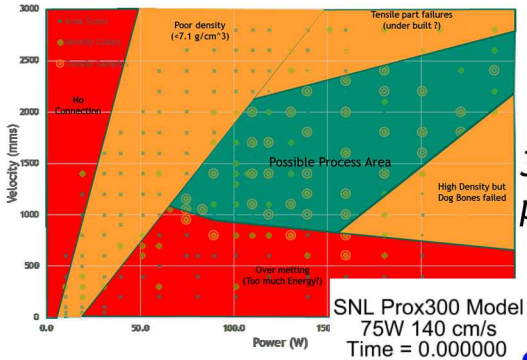
Process & Machine Characterization

316L SS powder particle size

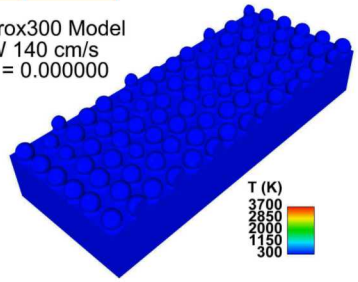




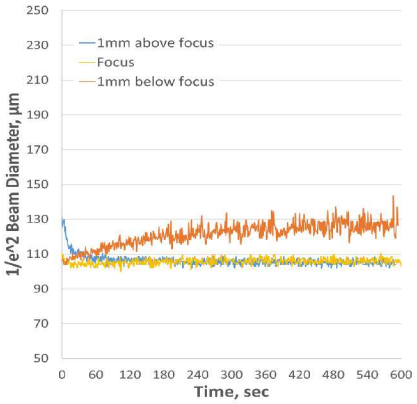


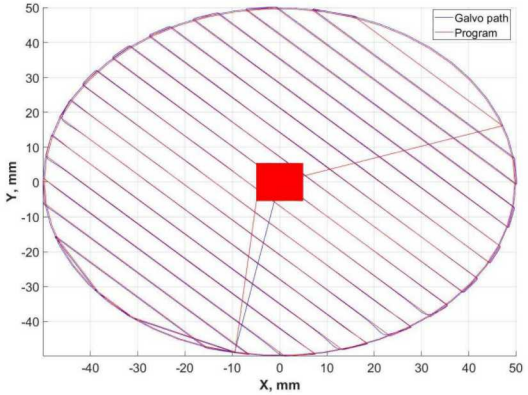


ProX 200 316L SS process map



beam diameter w/upgraded f-theta lens



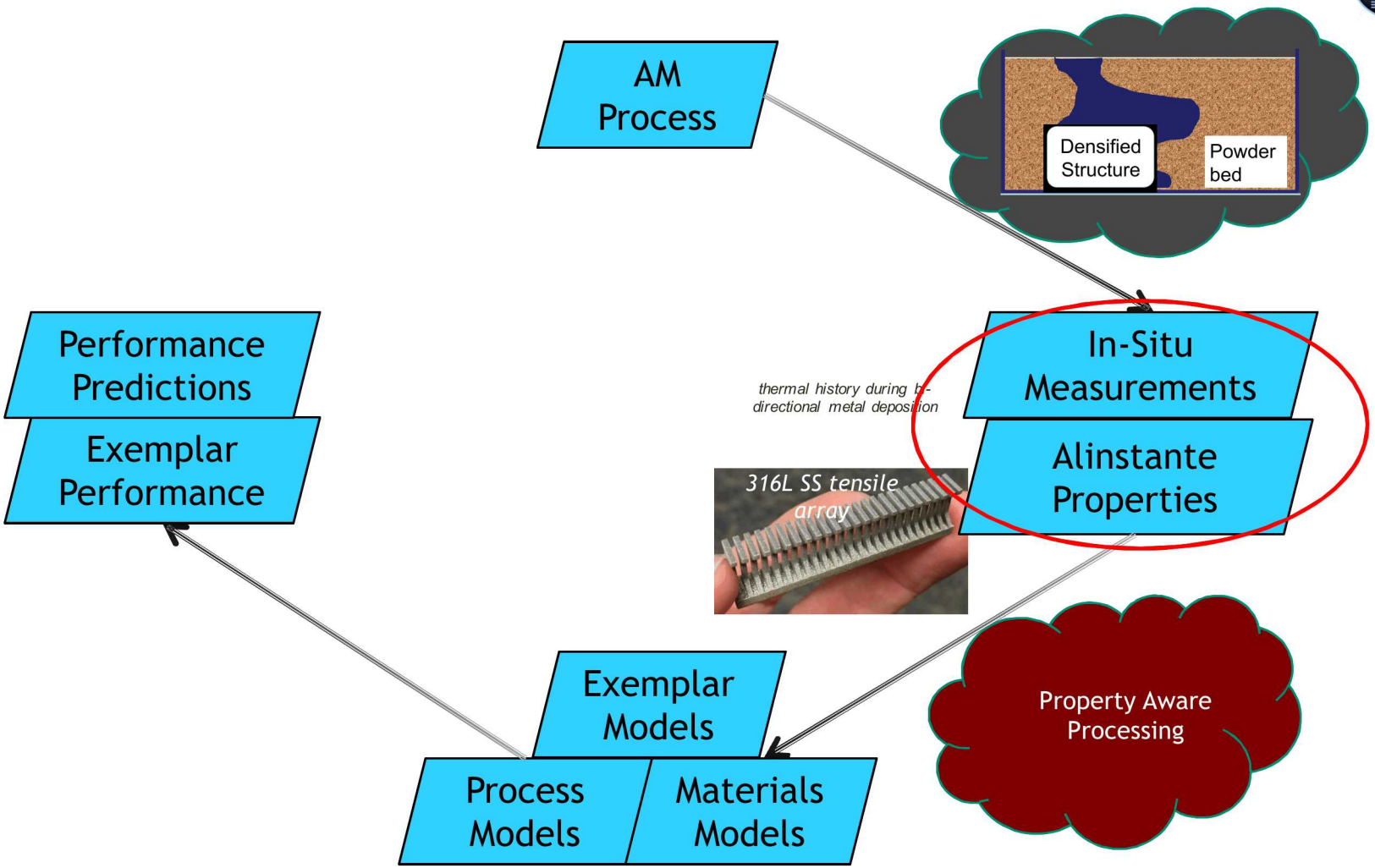


ARCS output for a simple test pattern

Working to agree on artifacts that can be built with every build to measure materials properties that capture process control information which can be an indicator of build quality

Contact Bradley Jared, Jeremy Lechman, Mario Martinez

Review Progress to Date

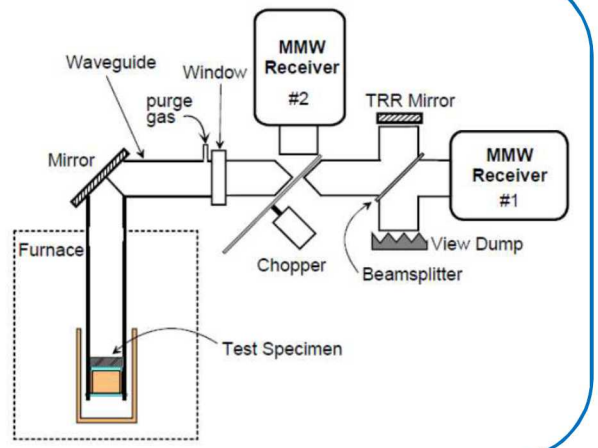


PSPP

In-situ Measurements

- Investigating passive mm-wave thermal emission for non-contact temperature measurement in additive manufacturing applications.
- Initial use is IR Camera calibration
- Linear relationship between radiated power and temperature enabling *single-point black body calibration*.
- Thermal Return Reflection (TRR) technique enables real-time measurement of emissivity.

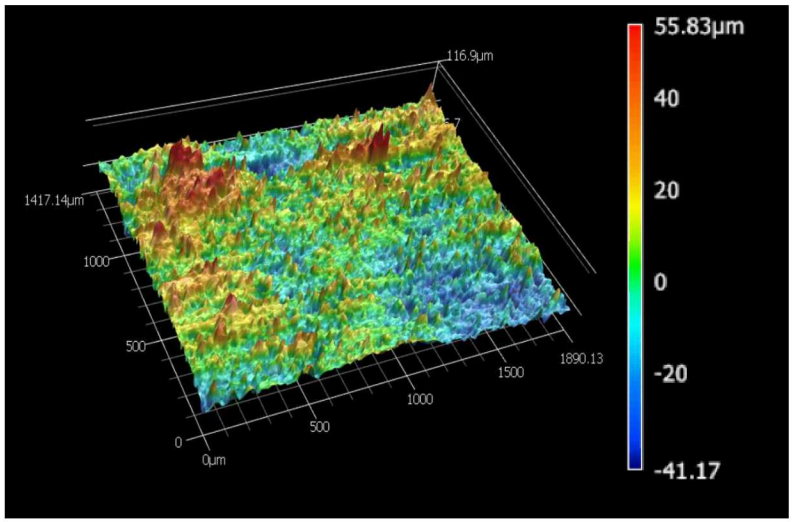
Schematic of mm-Wave Radiometer System.

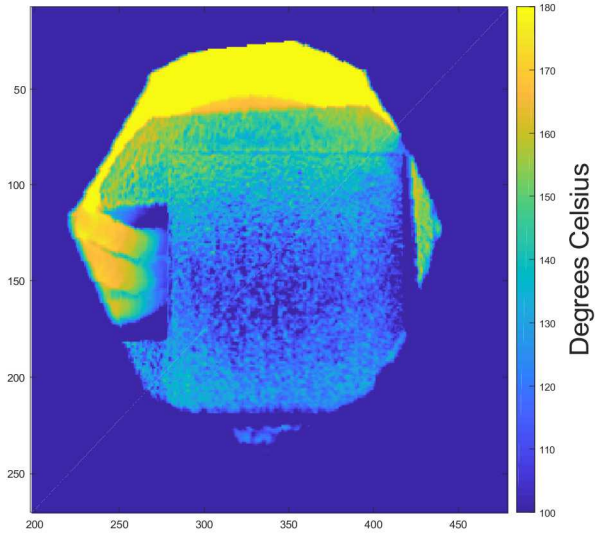


Contact Eric Forrest

In-situ Measurements

- Investigating effects of view angle and surface texture on emissivity for metallic additively manufactured parts
- Focusing on emissivity for common infrared camera wavelength ranges
- Results will be used to improve the accuracy of thermal monitoring of metal AM processes
- MM-wave setup leveraged to simulate in build conditions for measurement environment





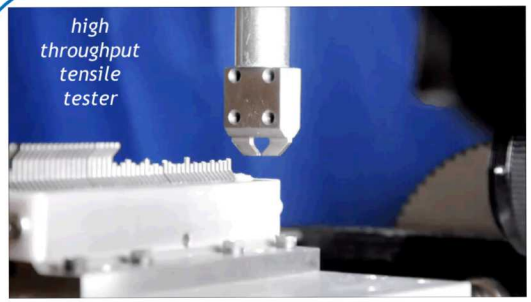
Contact Samantha Taylor

Alinstante

- Wishlist… In an Instant?

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.		

https://youtu.be/6UKxxU3ukoQ



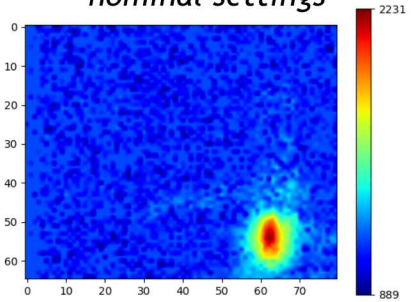
- High throughput automation using robotic workcell
- Consistent, rapid, & efficient
- Eliminate human factor
- Integrate with manufacturing process

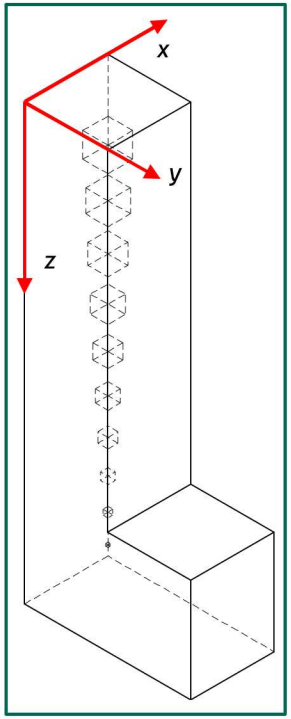
Contact Brad Boyce

Defect Detection

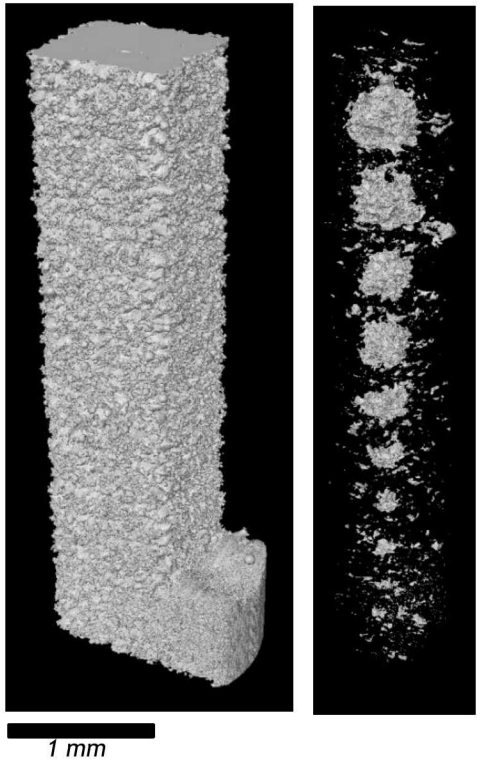
ThermaViz installed in the 3D Systems ProX 200

Melt pool motion, nominal settings

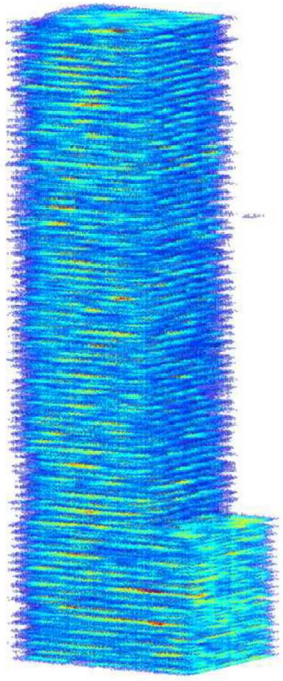




captured hole structure design



µCT reconstruction



pyrometer data reconstruction

Analytical tools used for material reconstruction and mapping pore locations to diagnostic signals

Data processing streams are crucial, complex and not optimized

VOLUME GRAPHICS
Micro-computed tomography

MATLAB
Interactive Data Language
IDL

ImageJ

Adobe Photoshop
batch processing
16bit > 8bit conversion
lossless filetype conversion

FIJI
alignment & registrat
cropping
grayscale matchin
autoleveling
image filtering
thresholding

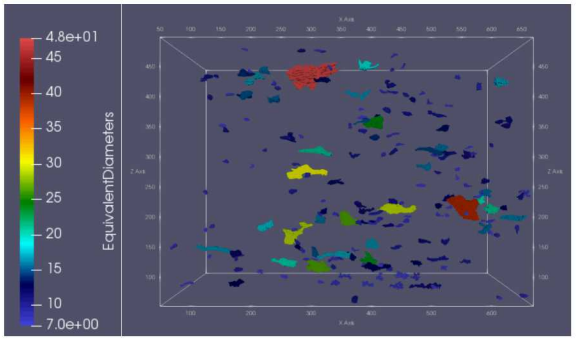
3D reconstruction
3D quantification

python
ParaView
Parallel Visualization Application

DREAM.3D
image processing & quantification. 3D reconstructions

BlueQuartz Software
Specializing in Software Tools for the Scientist
http://dream3d.bluequartz.net

ROBO-MET.3D
Serial-sectioning

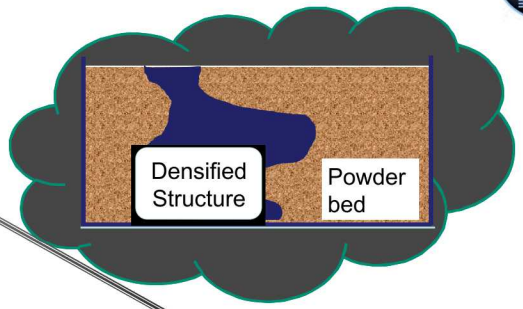


porosity map generated using DREAM.3D near the 10 & 20μm pores

Contact Bradley Jared, Laura Swiler

Review Progress to Date

AM Process



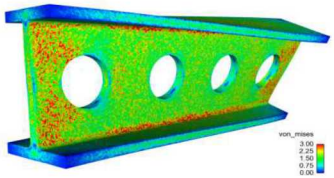
In-Situ Measurements

thermal history during bi-directional metal deposition

Alinstante Properties

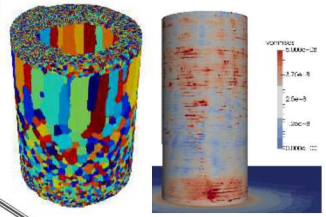
Property Aware Processing

Performance Predictions



material / part performance simulation

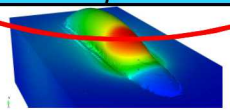
Exemplar Performance



Exemplar Models

Process Models

Materials Models



PSPP

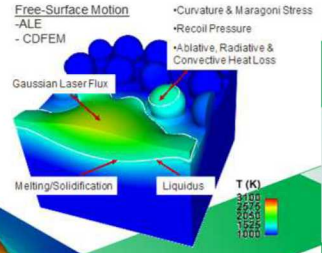
Materials Reliability - Metals

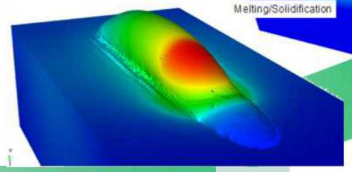
Bridging Length Scales – Informed Relevance

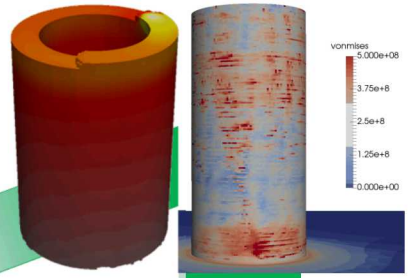
LAMMPS
ARIA
ADAGIO
SPPARKS

Build Scale Thermal + Mechanics
K. Johnson, K. Ford, L. Beghini, M. Stender & J. Bishop

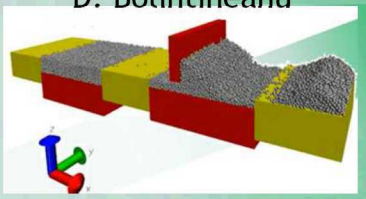
Solidification Scale Thermal
M. Martinez, B. Trembacki, D. Moser



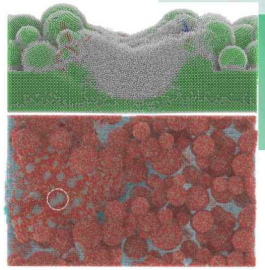




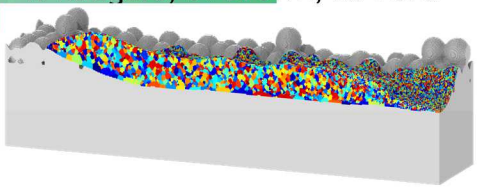
Powder Spreading
D. Bolintineanu



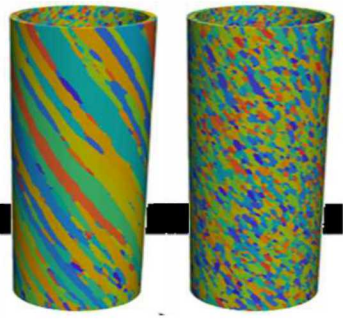
Powder Behavior
M. Wilson



Mesoscale Texture/Solid Mechanics
T. Rodgers, J. Brown, K. Ford



Build Scale Microstructure
T. Rodgers, J. Madison

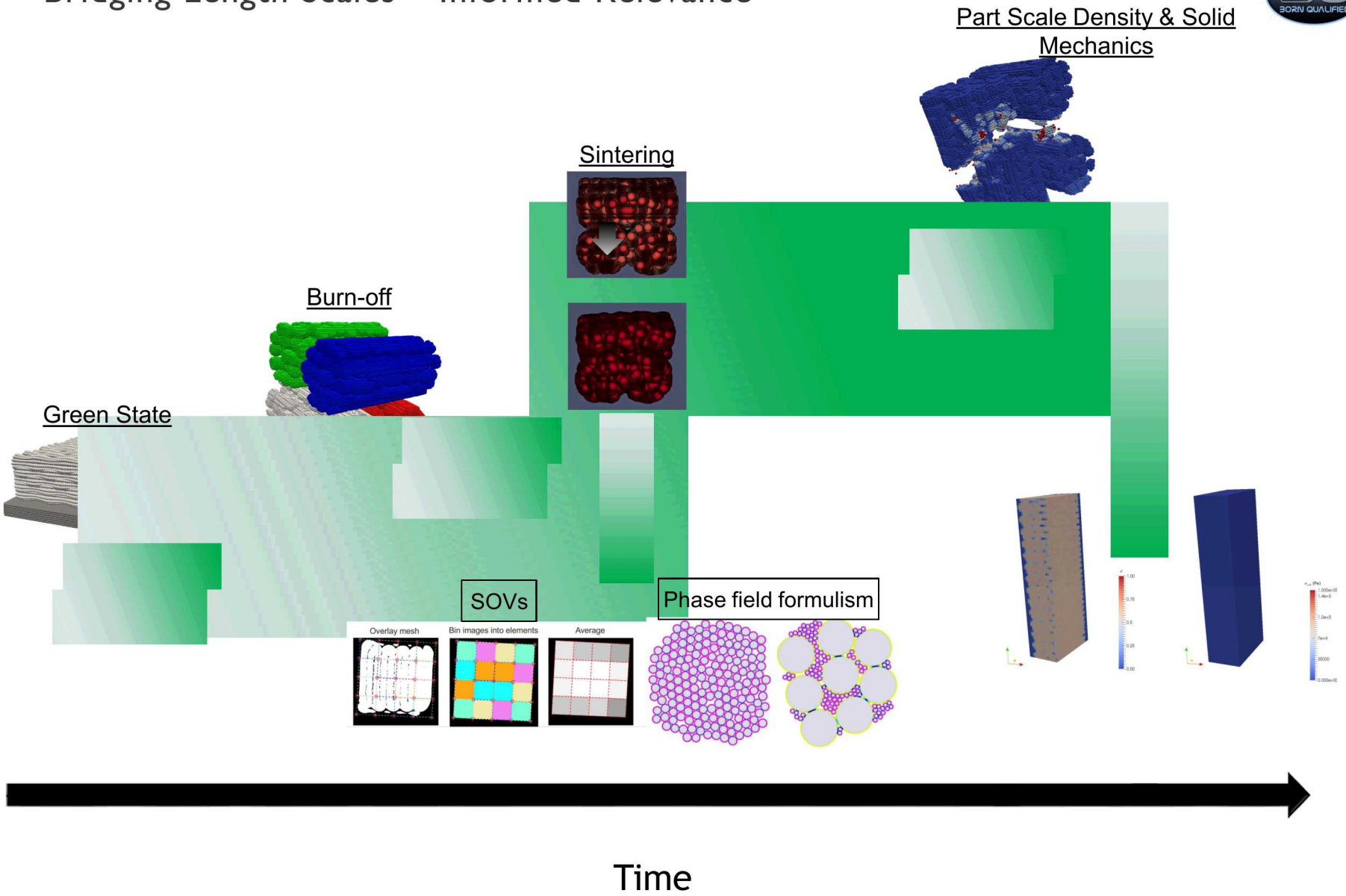


10^{-6} 10^{-3} 1

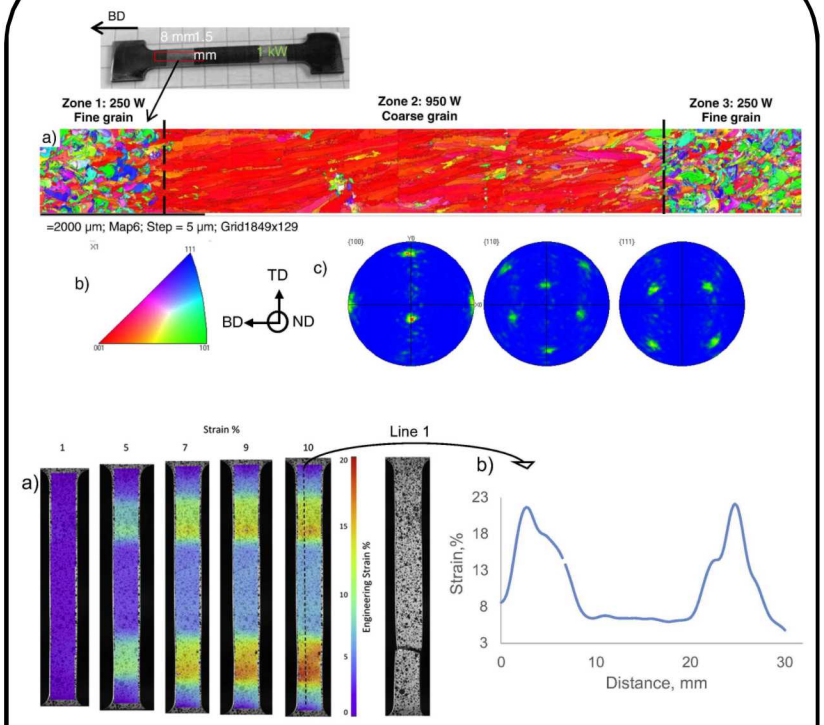
Length Scale (m)

Materials Reliability - Ceramics

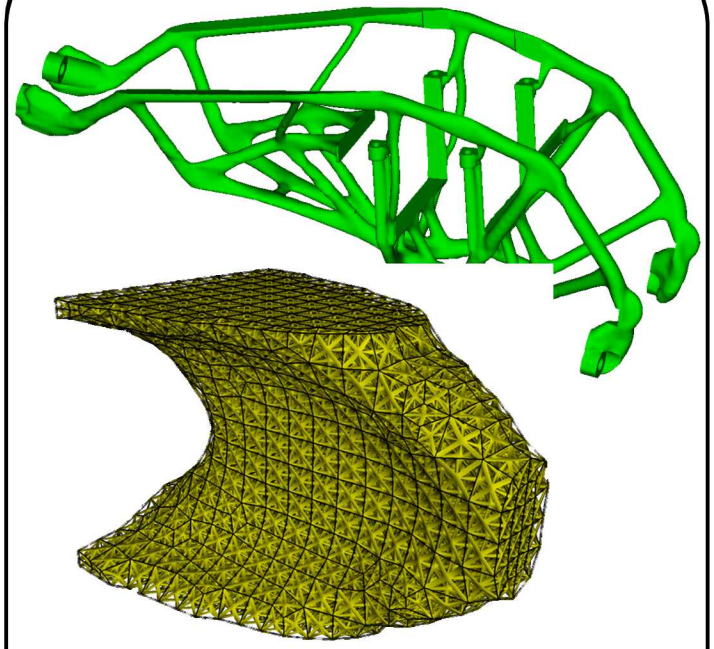
Bridging Length Scales – Informed Relevance



Microstructure By Design



Process-dependent Microstructure (Popovich *et al.*, Materials & Design, 2017



Design Optimization Code Such as PLATO

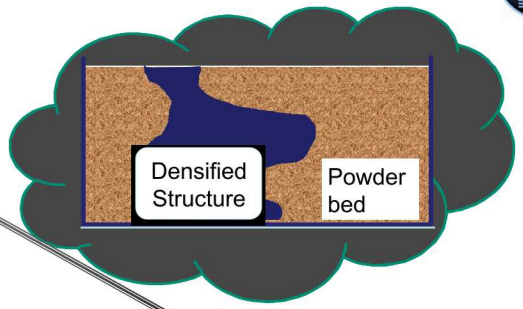
Site-specific optimized microstructure through process control

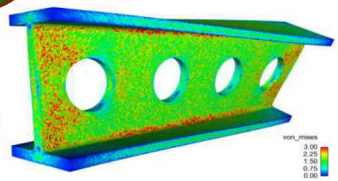
Contact Brett Clark, Theron Rodgers

Review Progress to Date

Quantify & Optimize

AM Process





material / part performance simulation

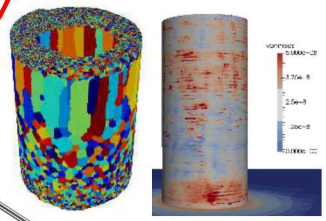
Performance Predictions

Exemplar Performance

thermal history during bi-directional metal deposition

In-Situ Measurements

Alinstante Properties

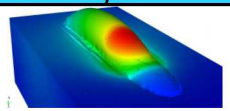


Data Analytics:
- ✓ *Regression*
- *Classification*
- ✓ *Density Estimation*
- ✓ *Statistical Estimation*
- ✓ *Dim reduction*

Exemplar Models

Process Models

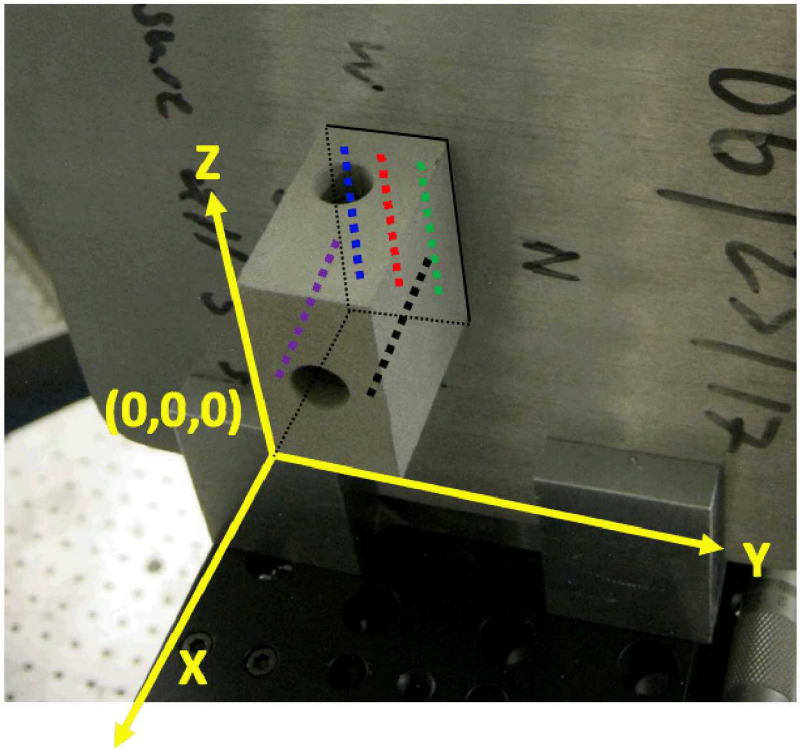
Materials Models



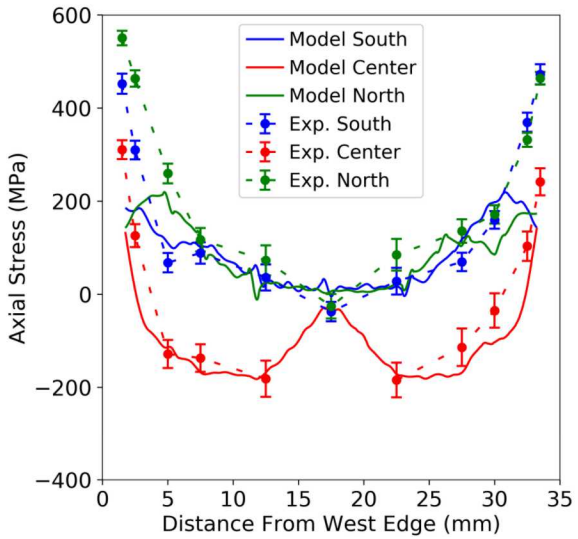
Property Aware Processing

PSPP

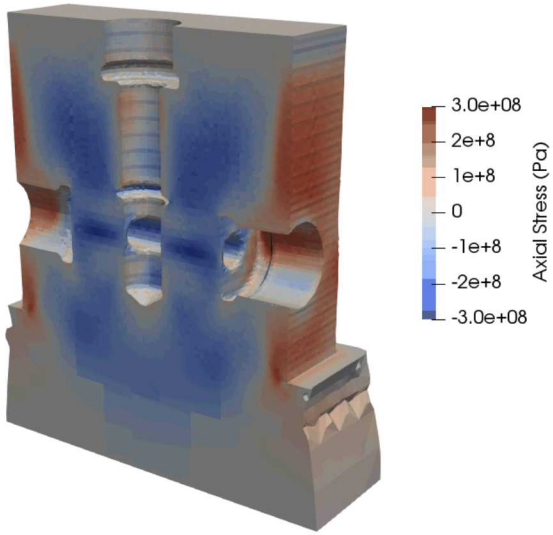
Integration Example
Using Metal AM Exemplar



Neutron Diffraction Measurements (LANL)

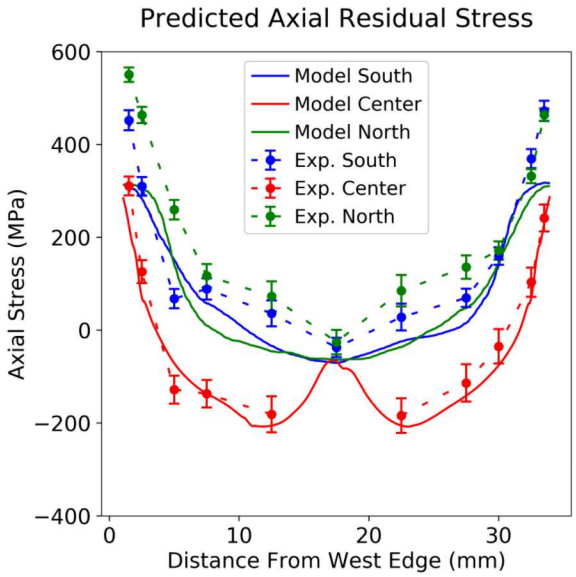


Cross-Section Stresses & Distortion

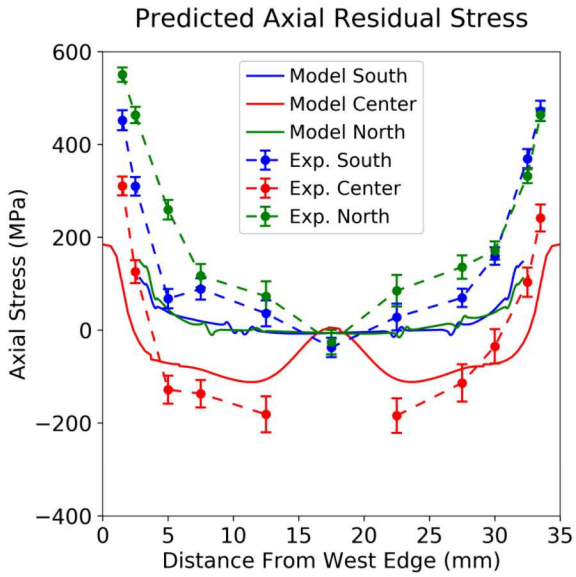


Contact Kyle Johnson, Bradley Jared

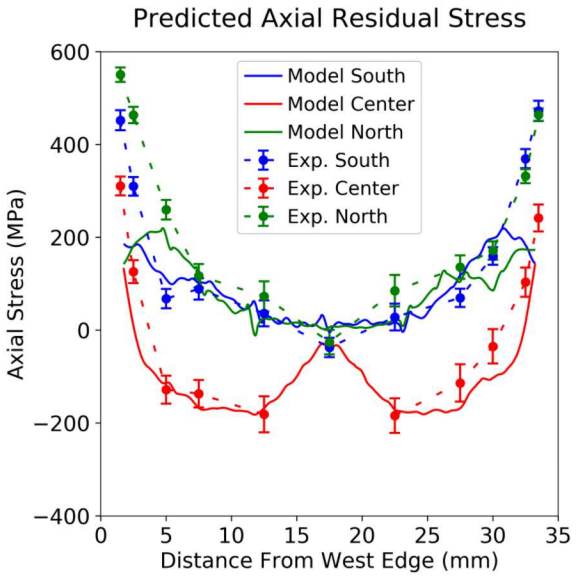
Comparison of Approximation Methods



Inherent Strain with Quiet Elements
30 mins on 60 cpus



Multiscale Inherent Strain with Inactive Elements
8 mins on 60 cpus



Lumped Laser with 40 Layers and ~0.4mm Elements
6 hours on 100 cpus

*Physical build time ~6 hours

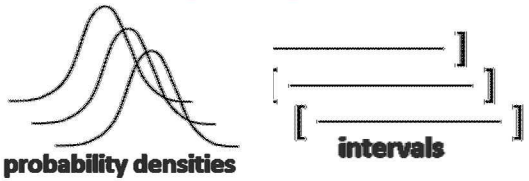
Contact Kyle Johnson

Uncertainty Quantification (UQ)

Goals: Account for material and process variability in model predictions (forward UQ) to understand margins, use experimental data across scales to calibrate model parameters (inverse UQ), and integrate optimization with UQ for robust control.

Forward UQ: propagate uncertainties to put error bars on simulation predictions

Uncertainty in input variables *u*



physical parameters / properties, initial/boundary conditions, numerical accuracy, geometry, data

Simulation Model *s(u)*

Statistics or intervals on output *s(u)*

Observations: experimental or upstream model

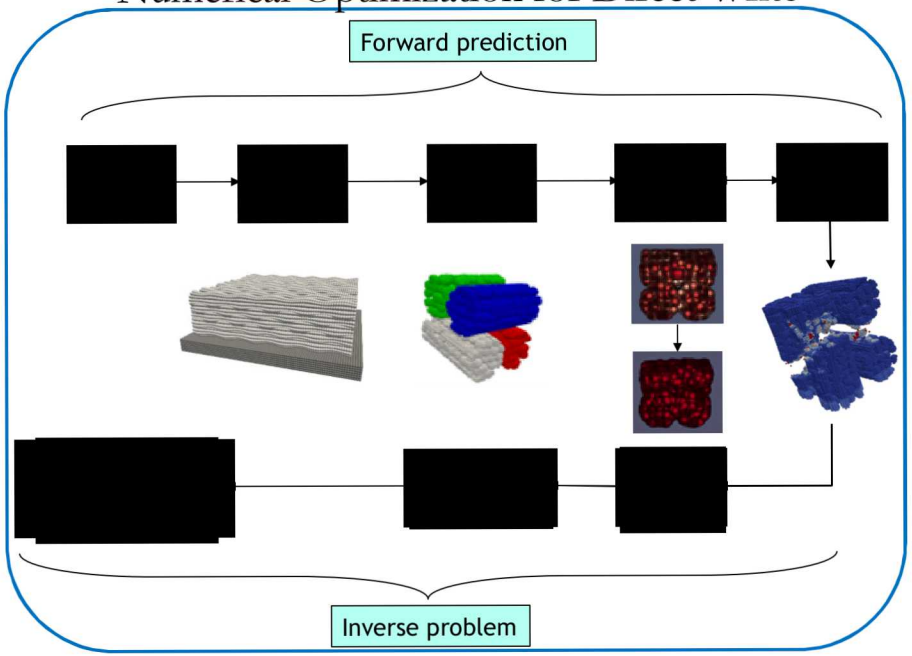
Inference / Inverse UQ: characterize parameter uncertainty from observations

Robust Control: Integrate optimization with uncertainty for process and property design

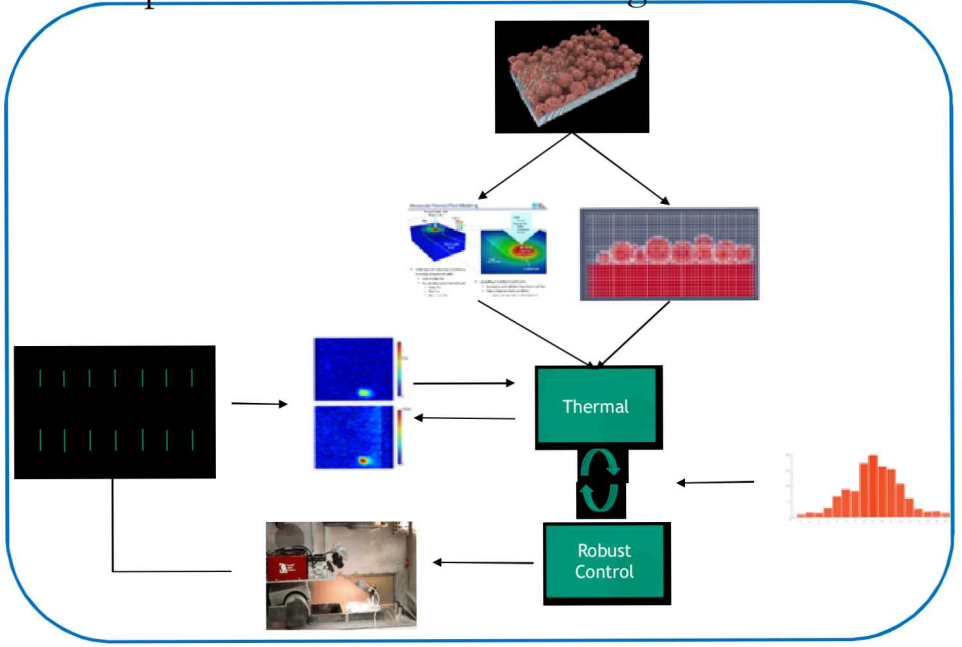
Contact Laura Swiler, Bart van Bloemen Waanders

Optimization & Control

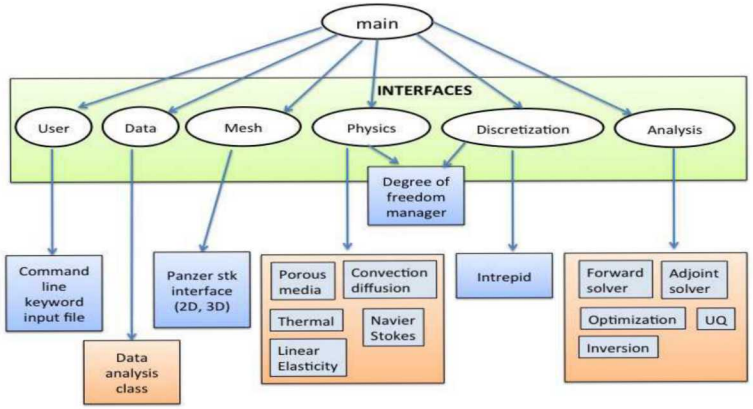
Numerical Optimization for Direct Write



Optimal Control of LENS using Line Scans

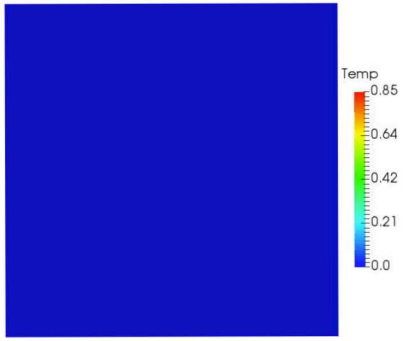


Multiscale/physics Interface for Large scale Optimization (MILO)



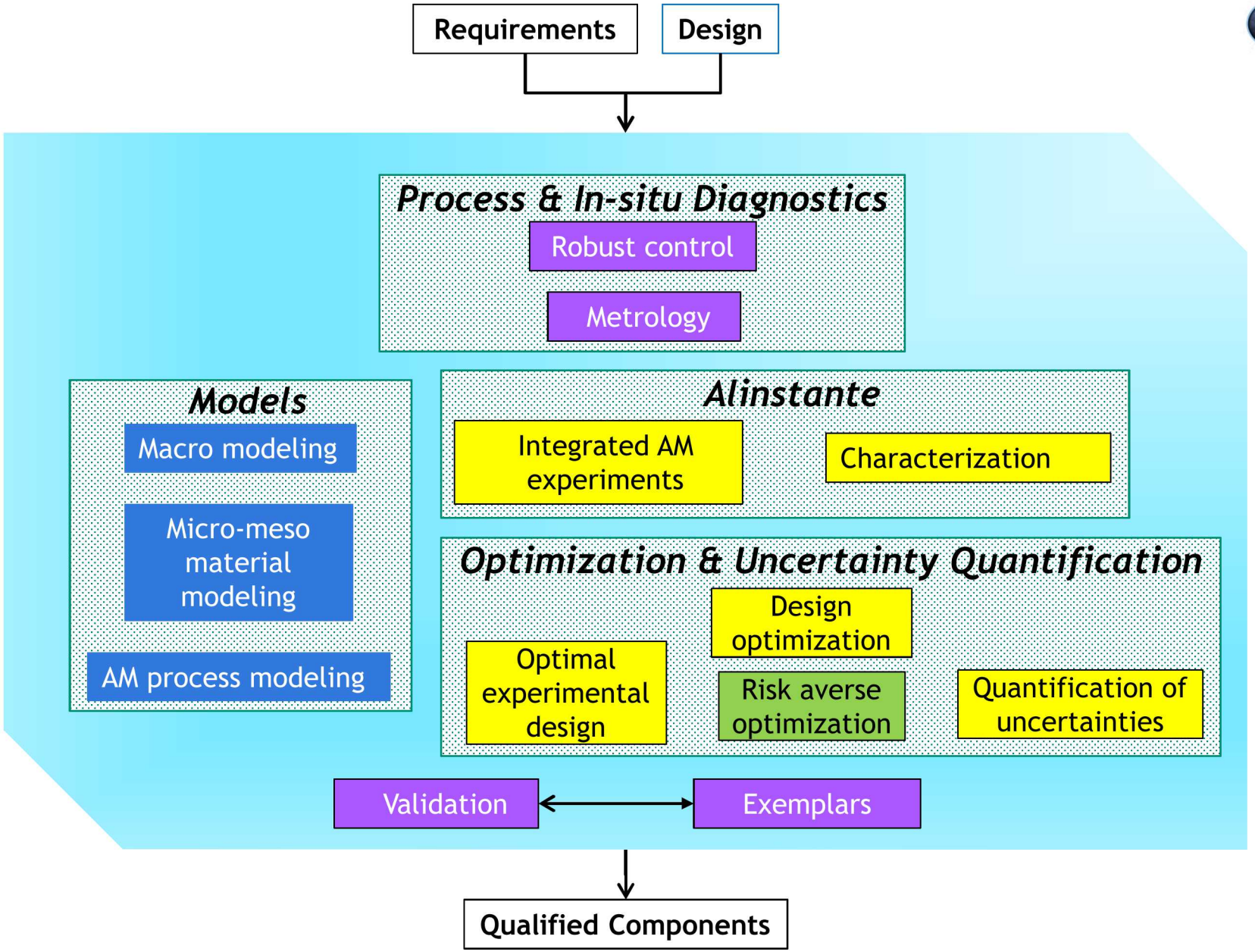
Automates:

- 2D/3D Parallel
- Adjoints
- Opt under uncertainty
- Unstructured
- Multiscale
- Multiphysics



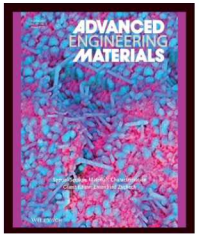
Contact Bart van Bloemen Waanders

Qualification Strategy



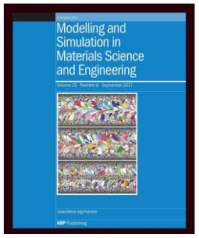
Project Impact

20+ Journal publications, 25+ Invited Talks, 5 Patents, 4 Journal Covers, 2 Editor assignments



Extreme-Value Statistics Reveal Rare Failure-Critical Defects in Additive Manufacturing

- Brad Boyce, Bradley Jared, Jeff Rodelas, Jonathan Madison

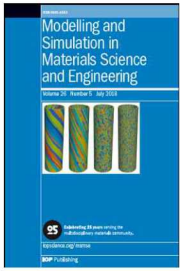


A Monte Carlo Model for 3D Grain Evolution During Welding

- Theron Rodgers

Direct numerical simulation of mechanical response in synthetic additively manufactured microstructures

- NV Sahinidis, M Ulbrich, Bart van Bloemen Waanders



Direct numerical simulation of mechanical response in synthetic additively manufactured microstructures

- Theron Rodgers, Joseph Bishop, Jonathan Madison

Modeling mechanical behavior of an additive manufactured metal structure with local texture variations: a study on model form error

- Judy Brown, Joseph Bishop

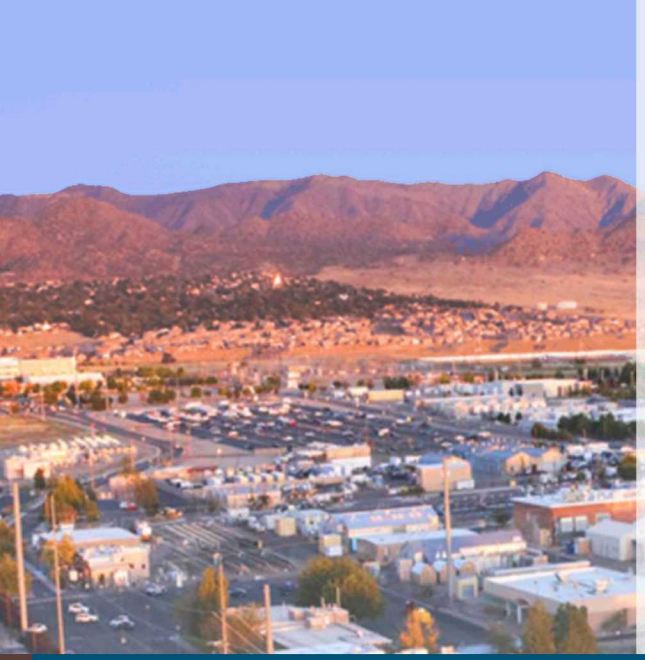
Focus on commercializing additive manufacturing and other emerging materials manufacturing technologies in an IOT world

- O Belousova, G Dillon, S Gardner, Y Marinakis, RA Roach, D Tolfree, S Walsh

Sandia Impact: Changing culture and approach to qualification of high value, high consequence, low volume products AM parts

Next Steps (short list)

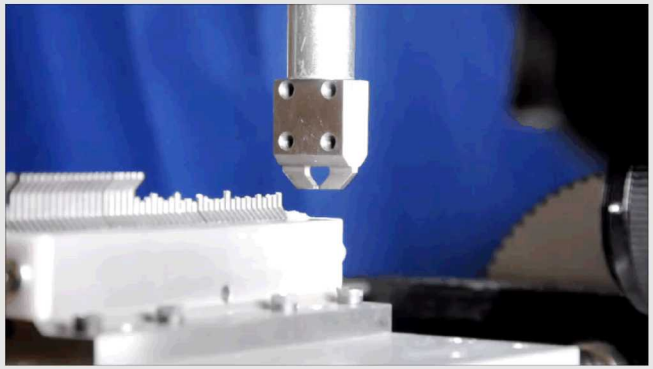
- Integrate microstructure predictions into exemplar models
  - Representing local microstructure (nm to μm) on full size parts (cm) is both a computing power and data storage issue. Exascale? What about designers?
- Fully automate Alinstante
  - Need advanced high throughput testing capability coupled with Machine Learning algorithms
- Artificial Intelligence based product acceptance
- Explore novel alloy development
- Integrate optimization with uncertainty for process and property design
  - Efficient concurrent multiscale modeling and UQ when material statistical homogeneity does not apply using techniques such as multigrid and error estimation
  - Crystal Plasticity models need to account for as-built dislocation structures and other microstructural characteristics unique to AM



Questions?

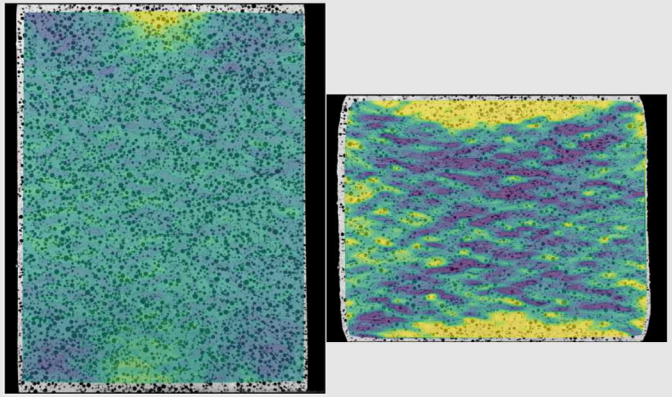
raroach@sandia.gov
(505) 844-6112

Full Field High Throughput Testing + Machine Learning / Deep Learning



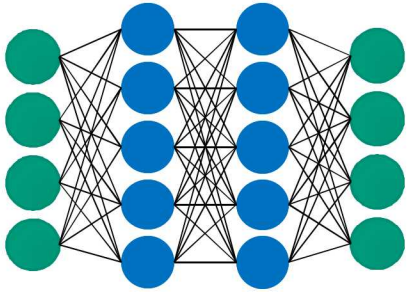
Boyce et al. 2017

High Throughput Testing with Full Field Digital Volume Correlation (DVC)

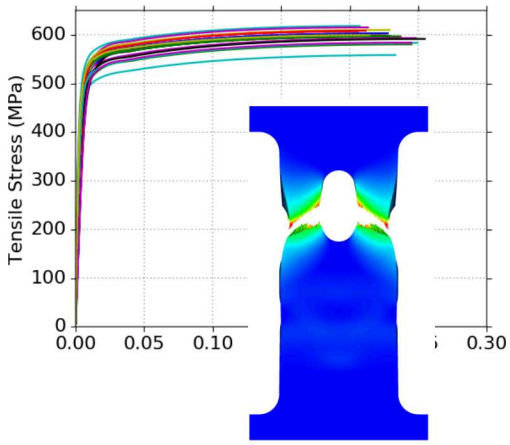


H. Jin and K. Long (SNL)

$\varepsilon, \boldsymbol{F}, \emptyset$

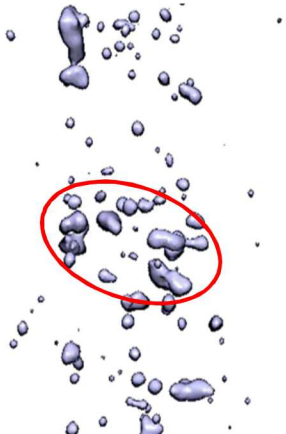


Neural Network



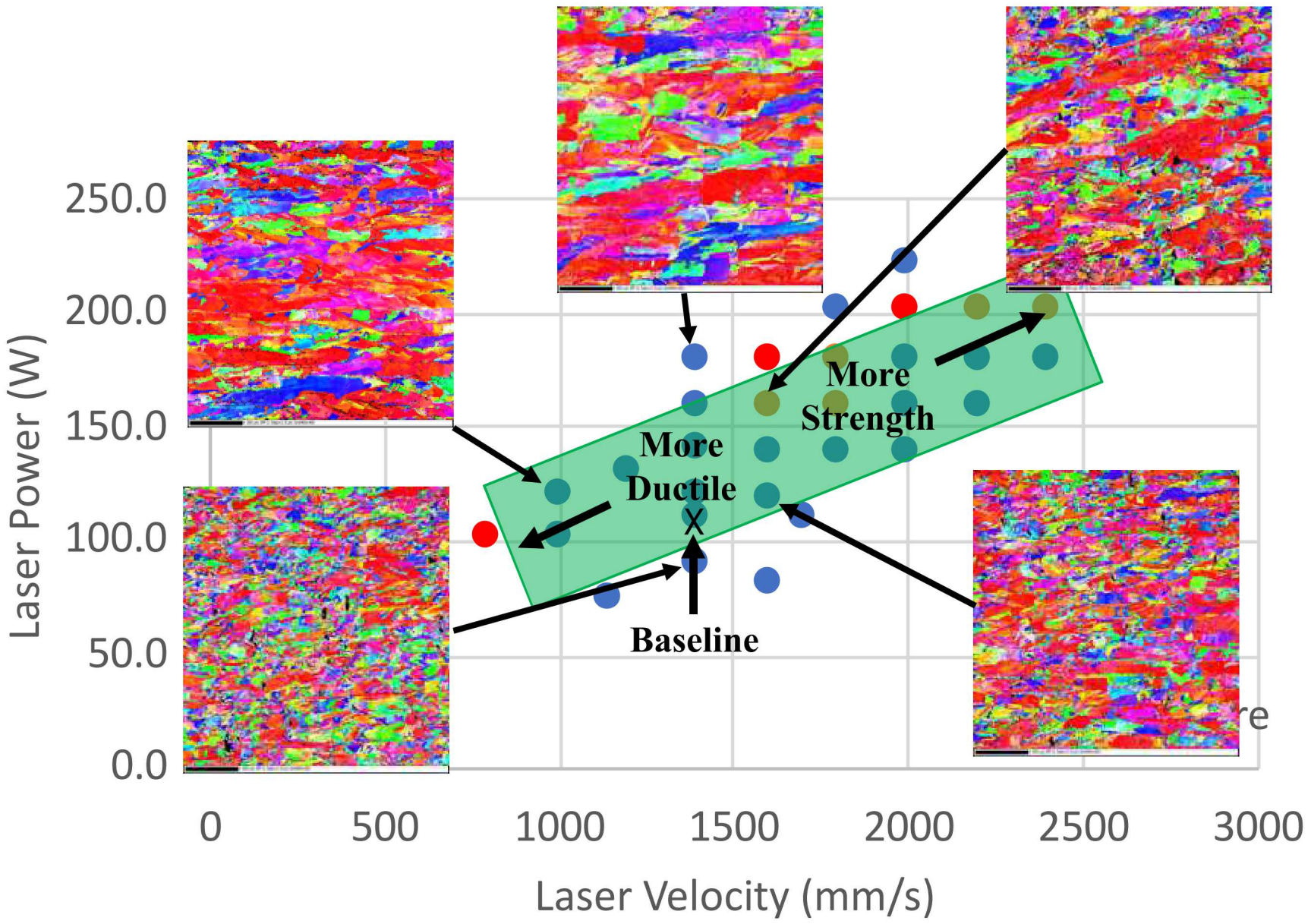
Failure?

Critical Defect Structure?



J. Madison (SNL)

Varying Microstructure & Properties w/Process Inputs



Realtime Machine Monitoring

ARCS (Archive, Research, Control, Synchronization)

- developed by Penn State & 3D Systems
- installed on ProX 200
- records galvo & laser @ 100kHz
  - compare programmed motion w/actual galvo motion, laser triggering
  - PSU multi-spectral sensor installed for high rate melt pool monitoring

Exploring data streams to insure part quality

- large data files for full part builds
- intermittent galvo motion errors observed
  - systematic occurrence has not been demonstrated