Analysis of Highly Correlated Datasets to Establish Processing-Structure-Property Relationships for Additively Manufactured Metals

Workshop on Predictive Theoretical and Computational Approaches for Additive Manufacturing

National Academies

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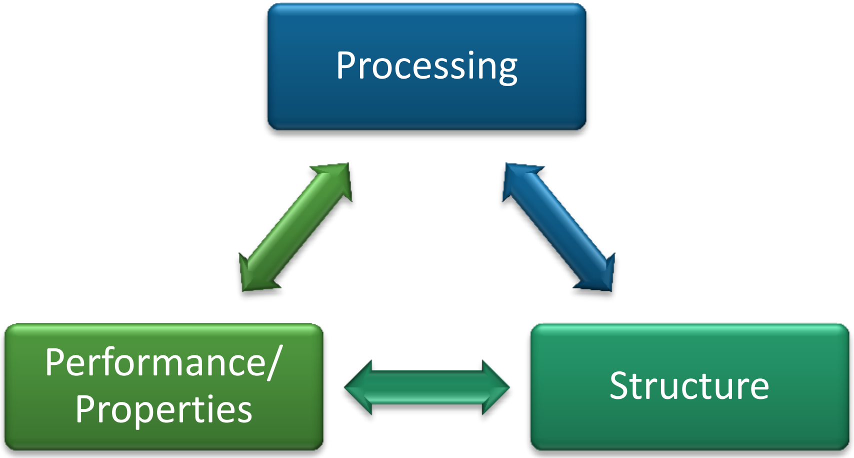
Integrity ★ Service ★ Excellence

Why AM?

- Additive Manufacturing (AM)
  - Fabrication of net or near-net shape components from digital representation and feed-stock, typically layer by layer fashion
  - A.K.A “3D-printing”, DLMS, DMLM, EBM, etc.
- *Potential benefits*
  - *Near*: short lead time, little tooling required, small lots
  - *Far*: complex shapes, graded or tailored structure & properties, hybrid structures; *not possible* via conventional processing
- *Challenges*
  - Immature understanding of processing – structure – property links due to process complexity
  - Design rules, process specs lacking or non-existent

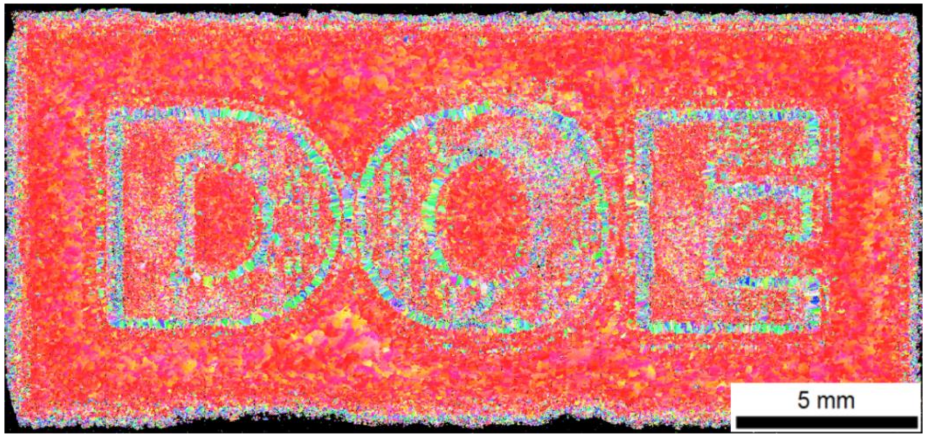
Transition of AM requires fundamental understanding of process – structure – performance links

Motivation & Overview



- Paradigm allows for engineering & design of materials
- Same principals apply to Additive Manufacturing (AM)
- What's new: degree to which *local* processing state is controlled

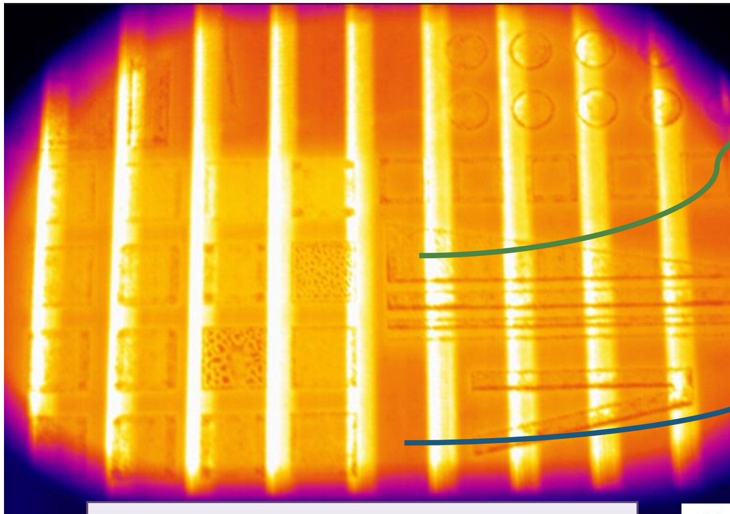
- AM complexity necessitates Integrated Computational Material Science & Engineering approach

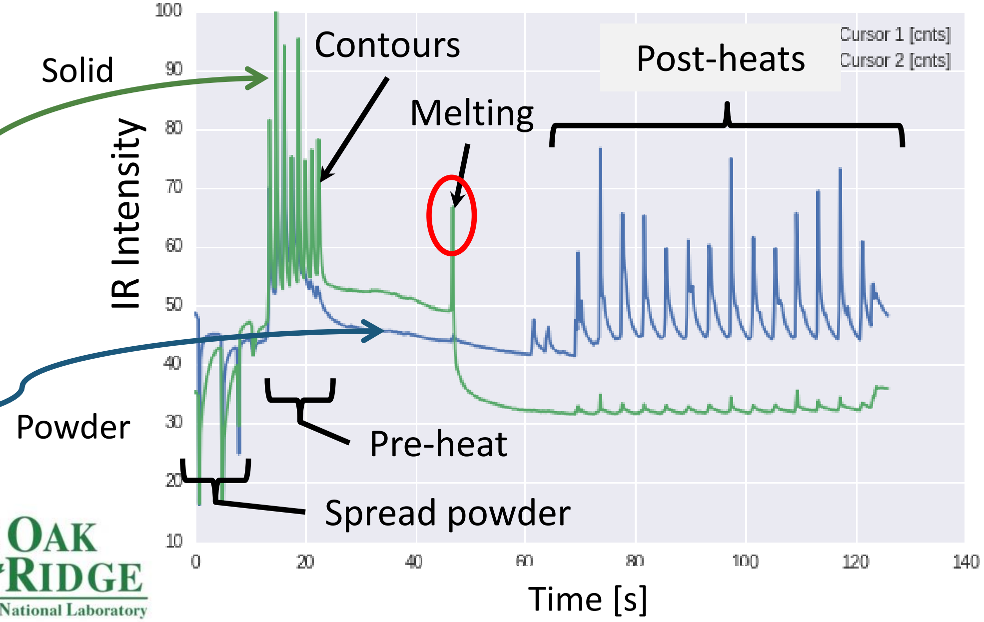


Dehoff, Kirka, Sames, Bilheux, Tremsin, Lowe, Babu. *Mat. Sci. & Tech.* 31(8), 931-938 (2015).
Dehoff, Kirka, List, Unocic, Sames. Mat. Sci. & Tech. 31(8), 939-944 (2015).

Complexity of Metals AM

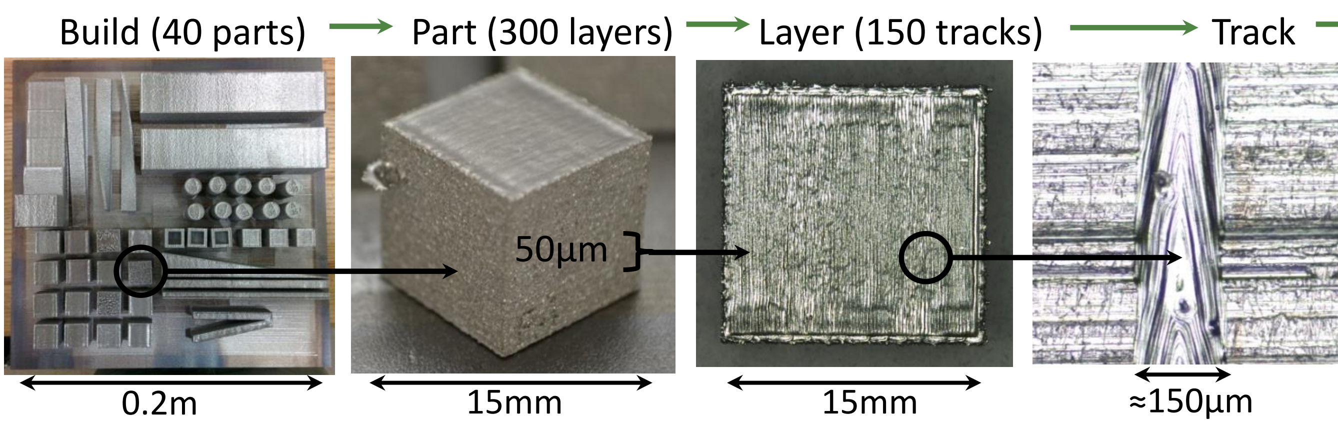
Temporal





Complex energy input & resulting thermal history

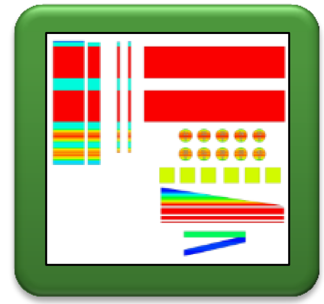
Spatial



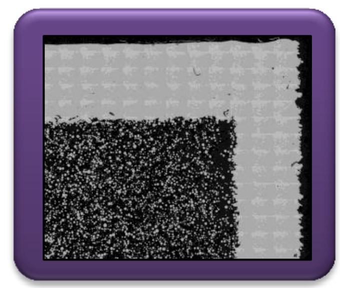
Wide range of spatial scales, complex build can easily have *10km* of track

Research Vision

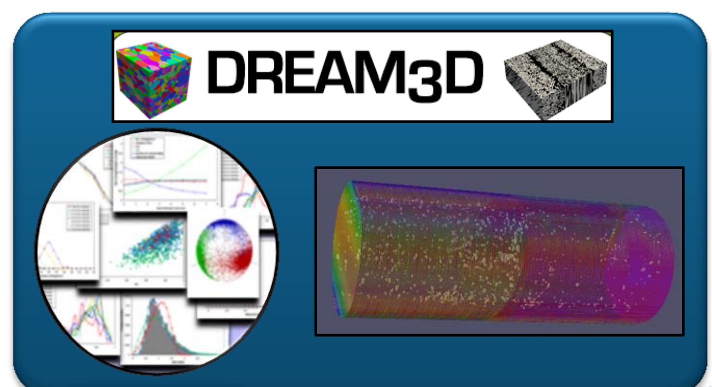
1. Pedigreed process data generation
   – Accurate & complete description



2. Advanced material characterization
   – Describe process outcome



3. Data analysis & reduction:
   – From (terabytes of) data to actionable *information*

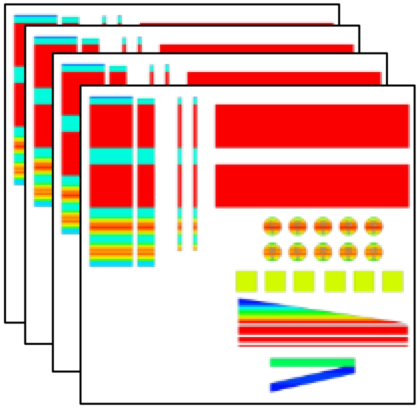


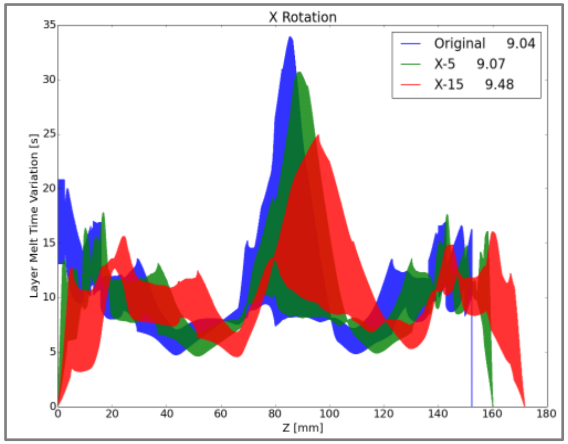
Process Data

Planning: process intent

Geometry (CAD)

Process Condition Maps

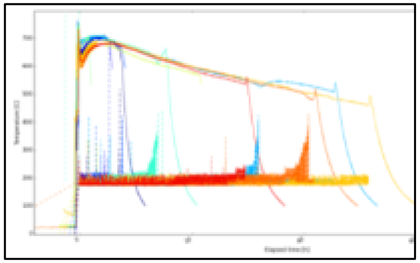




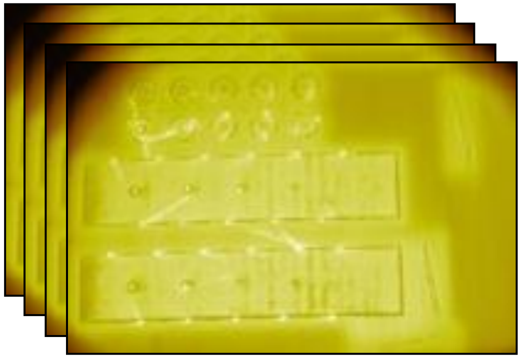
2D to 3D

Execution: process reality

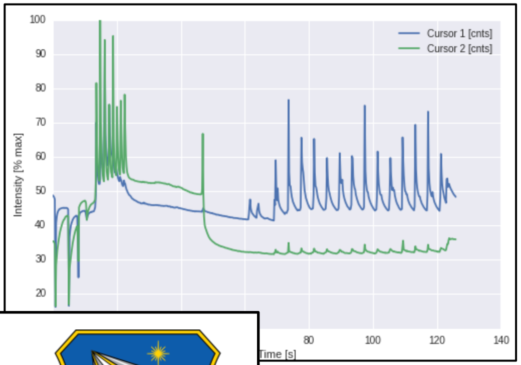
Log-files



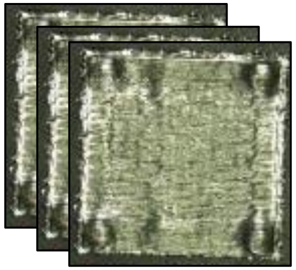
IR videos



Thermal Histories



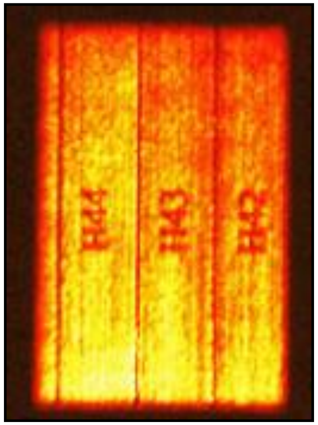
In situ imaging for porosity



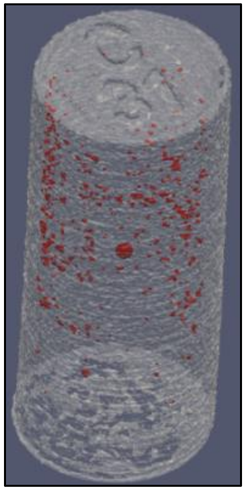
Detailed understanding and pedigreed description of the process; beyond 'knob settings'

Characterization

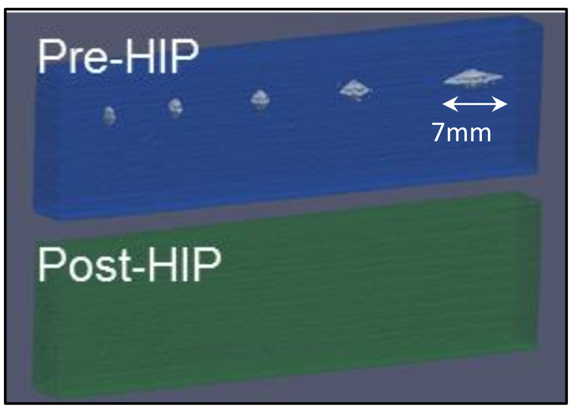
← **Non-destructive** →



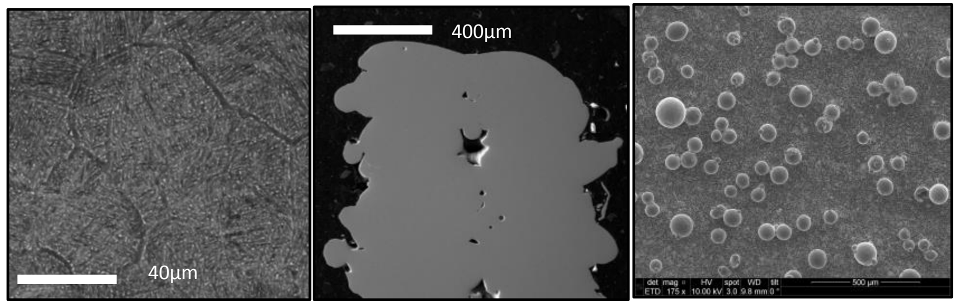
Ultrasound



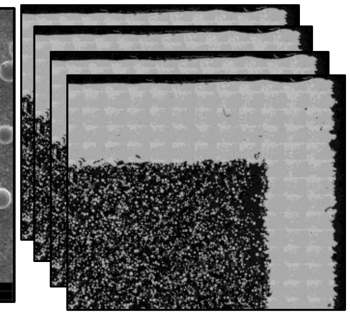
X-ray, 2D & CT



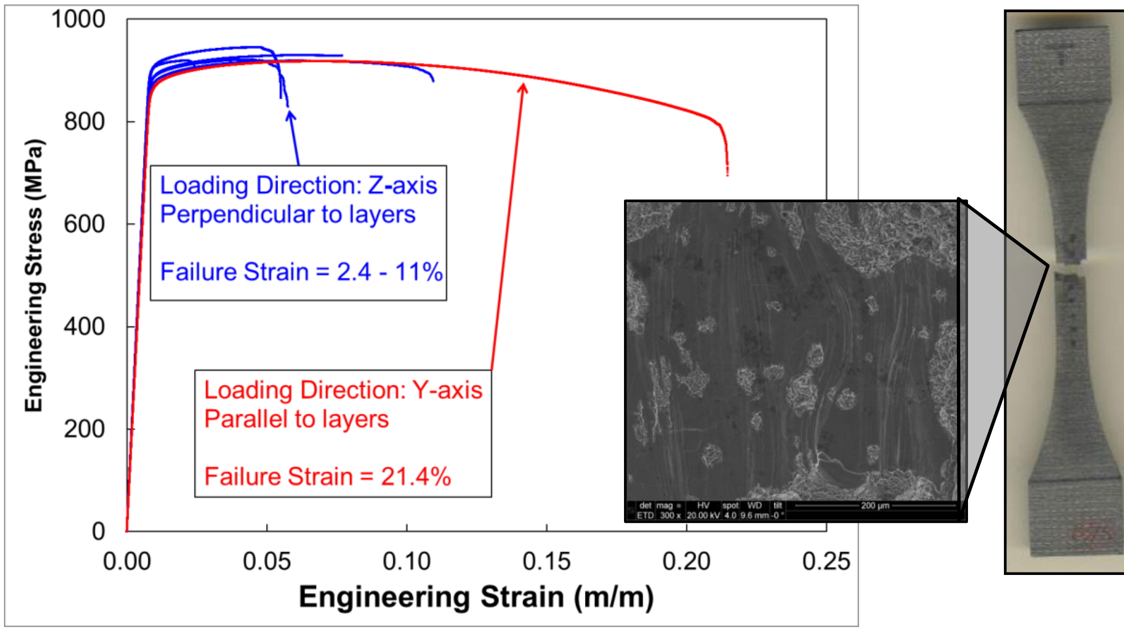
← **Destructive** →



Conventional Microscopy



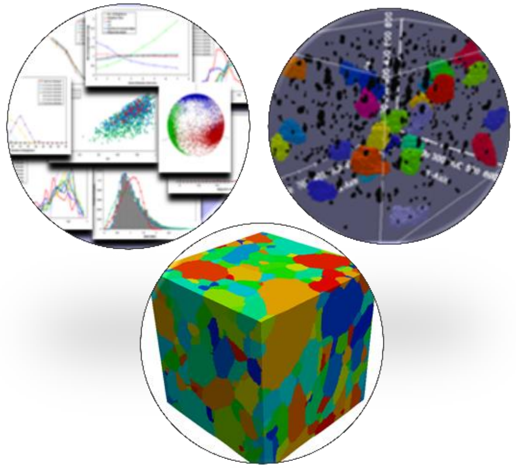
Serial Sectioning



Capture material structure & properties

Data Analysis & Reduction

- Combine/register planning, execution, & characterization data sets, model outputs
  - Establish processing → structure → properties correlations
  - “Zone” parts based on processing conditions
- Challenges:
  - Range of data modalities
  - Disparate spatial and temporal scales
  - Large datasets: 1TB per build
- *SIMPL:* open-source software library for dynamic, hierarchical management of spatial data
  DREAM.3D: extensible tool suite for analytics of the internal state of materials, built on SIMPL
- Infrastructure useful for other materials problems

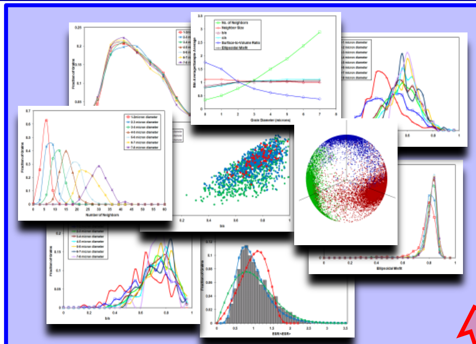


From data to actionable information

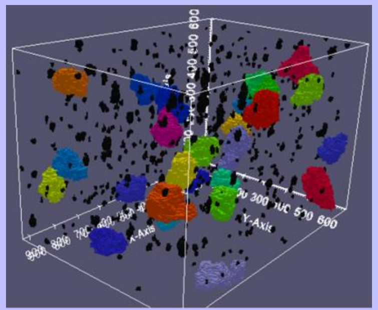
DREAM.3D: An App Suite for Materials

* Central box represents SIMPL as a broker/manager between applications

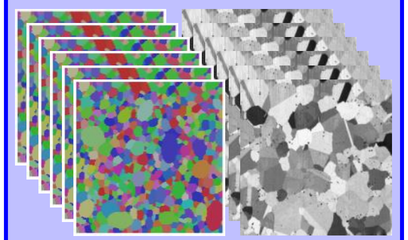
* Blue boxes represent a suite of applications for specific processes



Quantification Application(s)



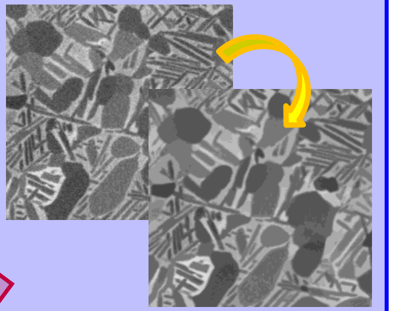
Identification Application(s)



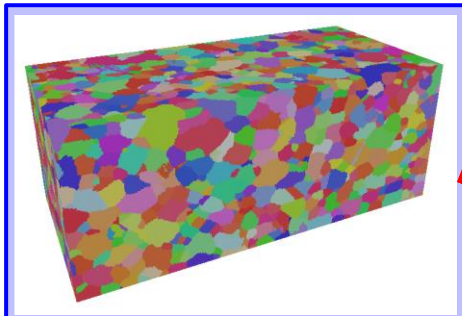
Archival Application(s)

SIMPL: Spatial Information Management Protocol Library

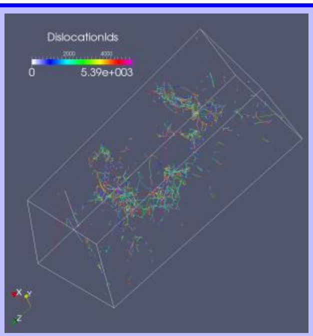
- Manages Current Object Versions
- Brokers Application Interaction
- Controls I/O
- Manages Digital History of Data



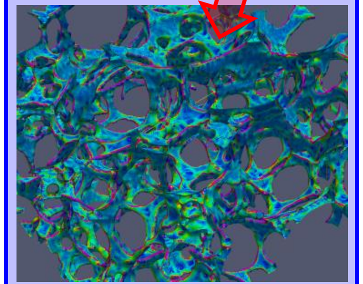
Processing Application(s)



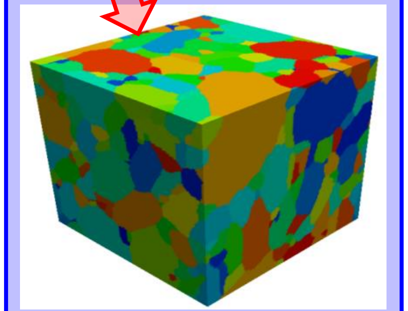
Reconstruction Application(s)



Simulation Application(s)



Meshing Application(s)



Instantiation Application(s)

* Images are example outputs from existing applications for specific processes

* Red arrows represent the transfer of information to/from SIMPL to Application

SIMPL is material independent; Apps may be material & data-type dependent

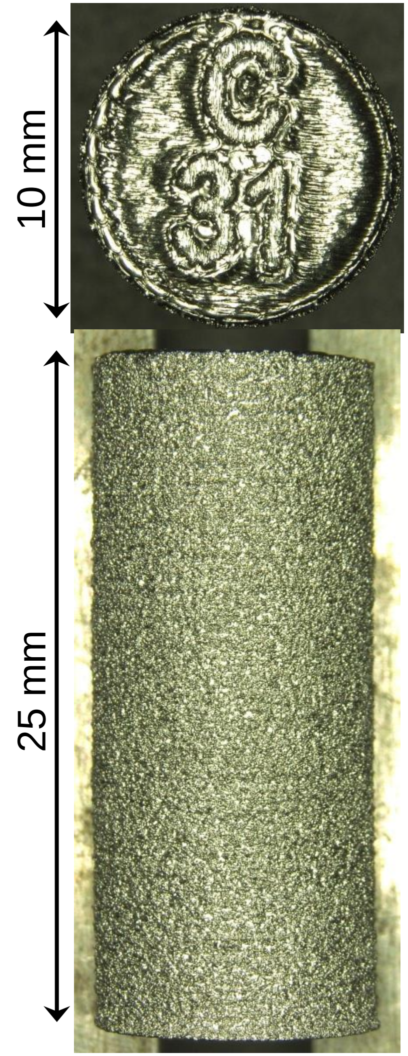
Data Fusion Example

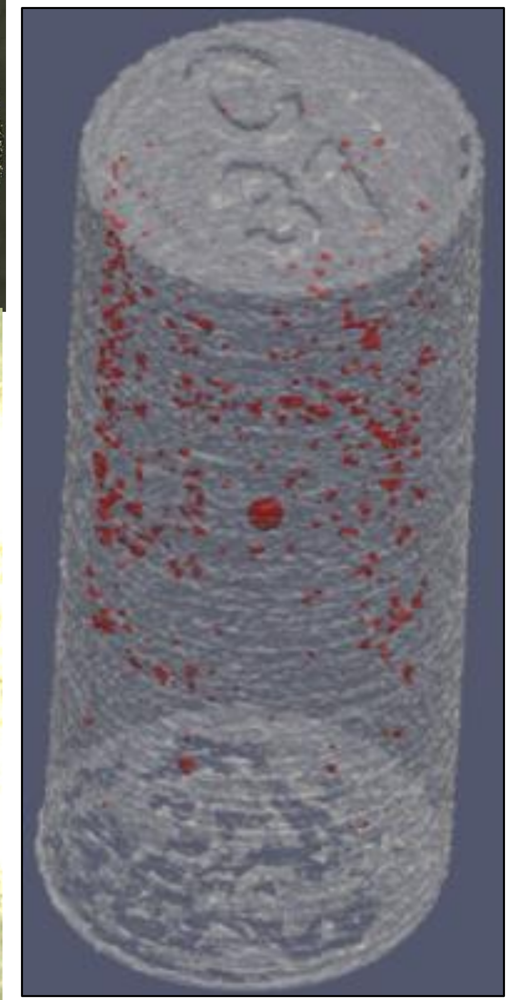
- Preliminary analysis
  - Motivating problem
  - Significant manual efforts for data registration

- Example of data fusion across
  - Processing parameter maps
  - Machine log-files
  - X-ray computed tomography

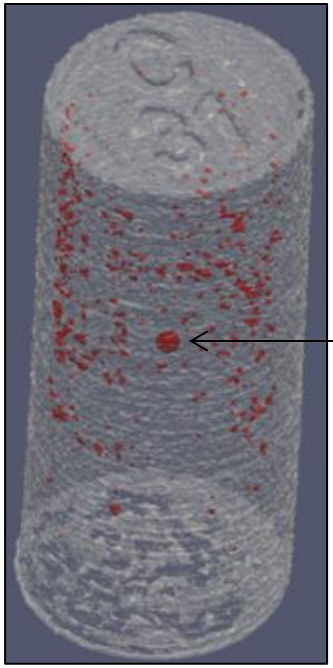
- Titanium-6Al-4V e-beam powder bed fusion @

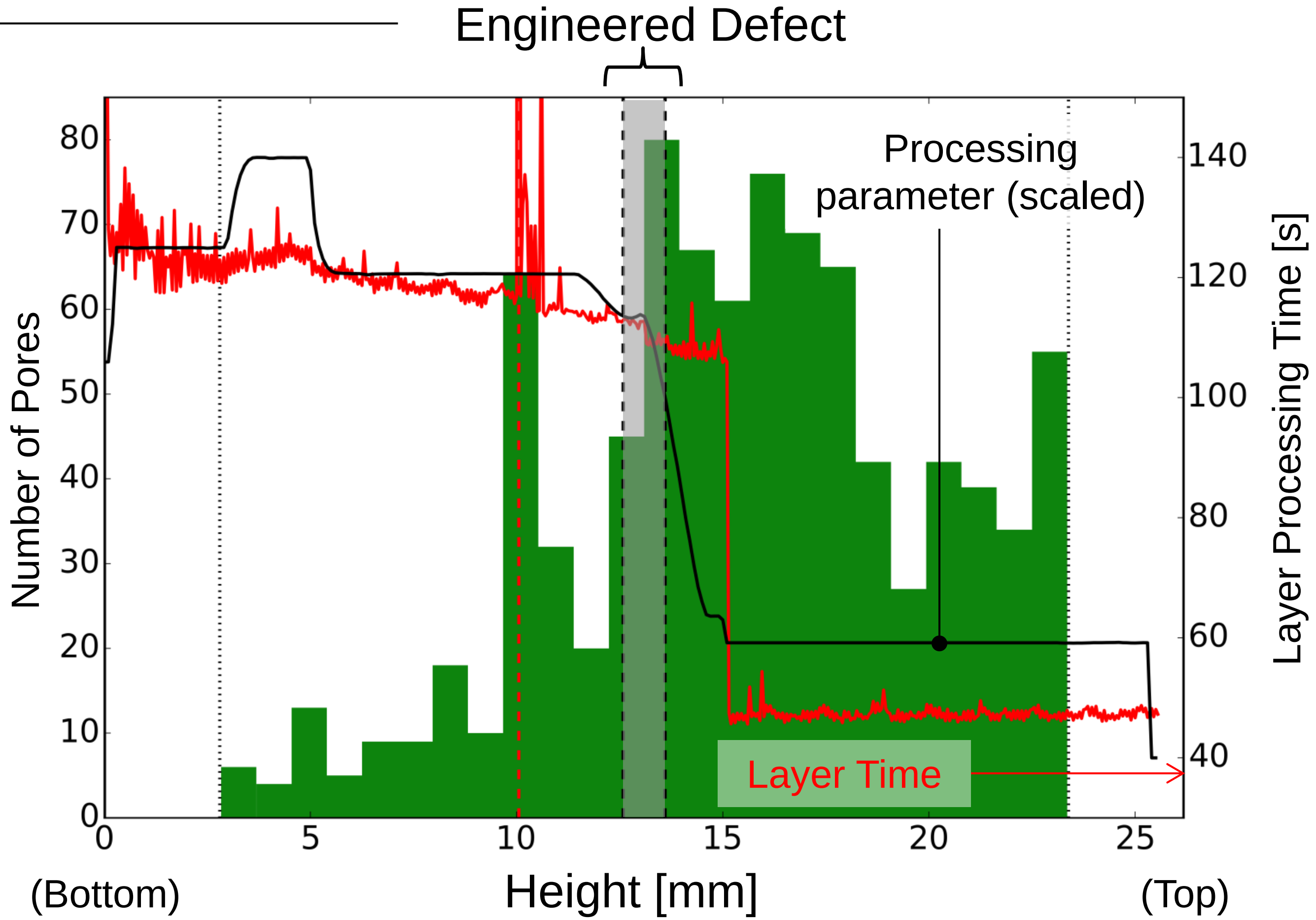
OAK RIDGE
National Laboratory





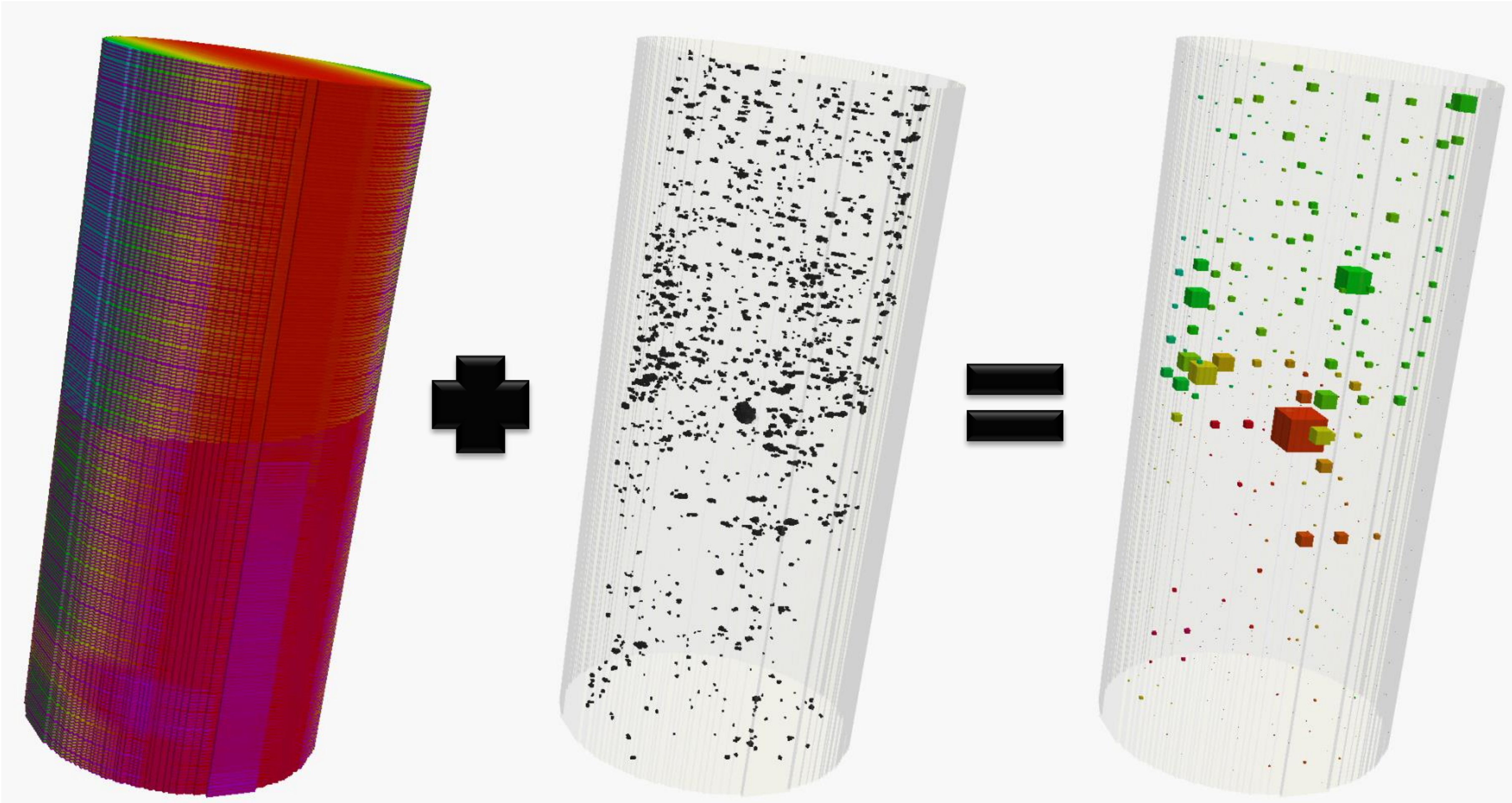
Data Fusion Example





1. X-ray CT: Outcome, actual structure: porosity
2. Log-file: Execution, process anomaly
3. Parameter Maps: Planning, parameter changes

Fully Fused Data



Melt Current

CT data

Size → Pore vol. frac.
Color → Average current

Summary

- Establishing ICMSE tools for digital data management for AM
- Establish process-structure-property links to:
  - Enable "Design for AM"
  - Digital data to address process specification challenges

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