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
8 October 2015

Edwin Schwalbach¹, Michael Groeber¹, Ryan Dehoff², Vincent Paquit²

1.) Air Force Research Laboratory, Materials & Manufacturing Directorate
2.) Oak Ridge National Laboratory, Manufacturing Demonstration Facility

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

Complexity of Metals AM

Temporal

Complex energy input & resulting thermal history

Spatial

Build (40 parts) → Part (300 layers) → Layer (150 tracks) → Track

Solid

Powder

IR Intensity

Contours

Pre-heat

Melting

Post-heats

Spread powder

Time [s]

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

0.2m

15mm

15mm

≈150µm

50µm

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

Execution: process reality

Log-files

IR videos

Thermal Histories

In situ imaging for porosity

2D to 3D

Detailed understanding and pedigreed description of the process; beyond ‘knob settings’
Characterization

Non-destructive

Ultrasound
X-ray, 2D & CT

Destructive

Capture material structure & properties

Conventional Microscopy

Pre-HIP

7mm

Post-HIP

Serial Sectioning

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.

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

* Images are example outputs from existing applications for specific processes.

SIMPL: Spatial Information Management Protocol Library

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

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 @
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
# Acknowledgements

<table>
<thead>
<tr>
<th>Materials &amp; Processing Team</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Jonathan Miller</td>
<td>Dr. Reji John</td>
</tr>
<tr>
<td>Dr. Lee Semiatin</td>
<td>Dr. William Musinski</td>
</tr>
<tr>
<td>Dr. Adam Pilchak</td>
<td>Dr. Dennis Buchanan</td>
</tr>
<tr>
<td>Lt. Andrew Nauss</td>
<td>William Porter</td>
</tr>
<tr>
<td>Dr. Michael Groeber</td>
<td>Norman Schehl</td>
</tr>
<tr>
<td>Dr. Michael Uchic</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>UT Inspection</th>
<th>X-ray CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dr. Eric Lindgren</td>
<td>John Brausch</td>
</tr>
<tr>
<td>Norman Schehl</td>
<td>Nicholas Heider</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Students</th>
<th>ORNL Manufacturing Demo. Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jordan Danko</td>
<td>Dr. Ryan Dehoff</td>
</tr>
<tr>
<td>Austin Harris</td>
<td>Dr. Vincent Paquit</td>
</tr>
<tr>
<td>Brandon Pfledderer</td>
<td>Dr. Brett Compton</td>
</tr>
<tr>
<td>Tyler Weihting</td>
<td>Larry Lowe</td>
</tr>
<tr>
<td>Capt. Evan Hanks (AFIT)</td>
<td>Michael Goin</td>
</tr>
<tr>
<td></td>
<td>Ralph Dinwiddie</td>
</tr>
</tbody>
</table>
