Developing a Robust 3D Representation Framework for 3D Printed Materials

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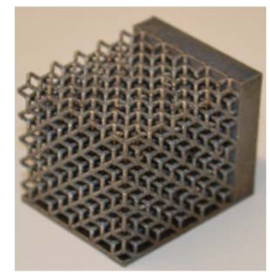
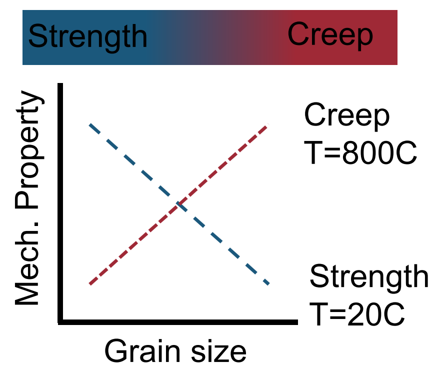
Integrity ★ Service ★ Excellence

Background

- Potential benefits of AM include:
  - Rapid turn-around & short lead times
  - Component complexity enabler
    for topology optimized, organic, & lattice structures
  - Tailored or graded performance & properties, competing requirements





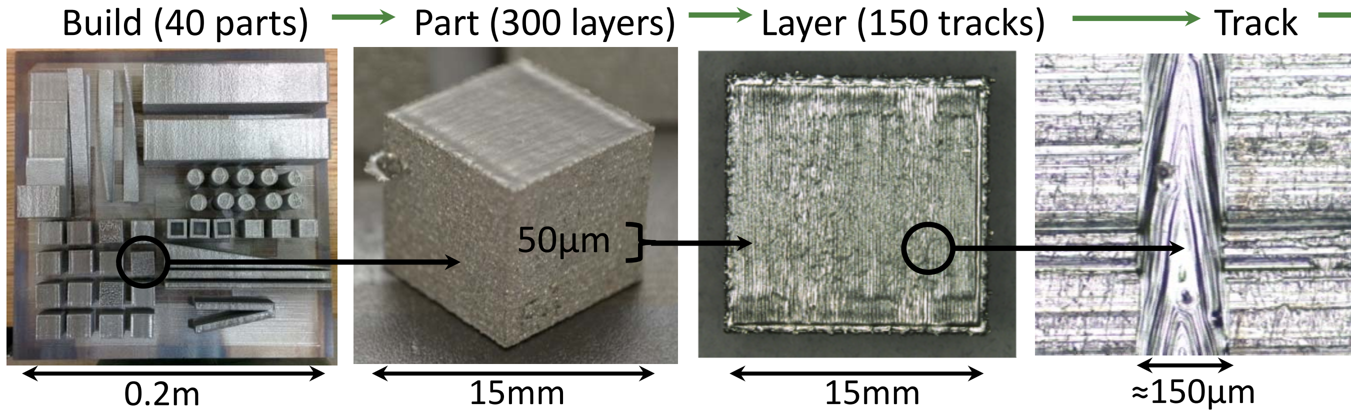
Form – Fit – Function

- Additive manufacturing (a.k.a. AM, 3D Printing) grew from rapid prototyping – *form and fit* were initial focus
- Use of AM in service requires getting *function* right

Structural applications have stringent requirements on *function*

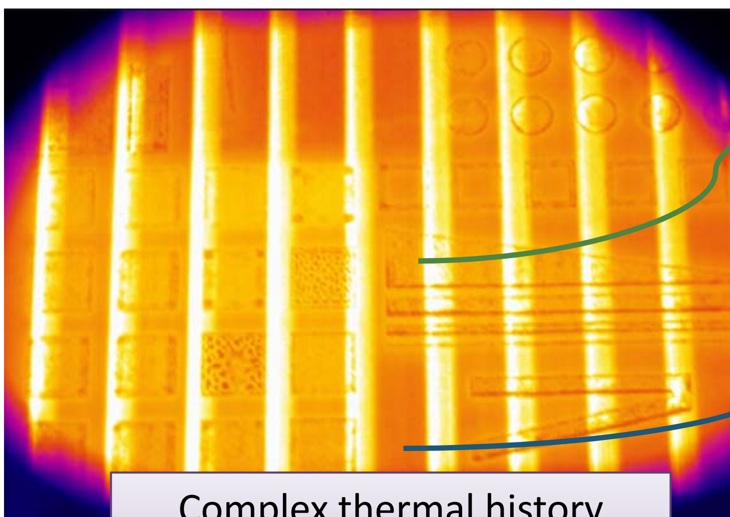
Powder Bed Fusion of Metals

Spatial

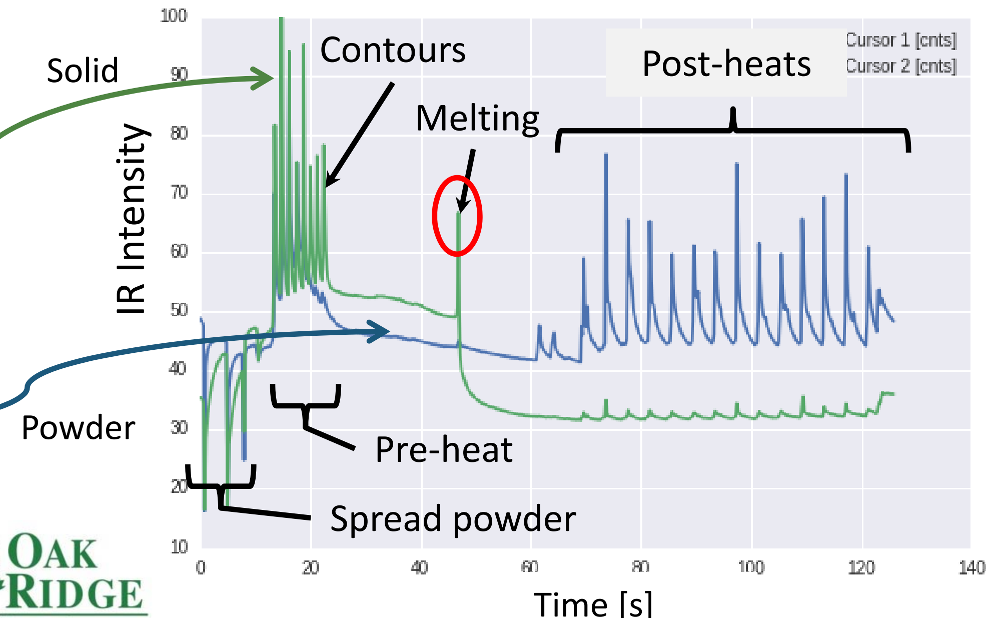


Wide range of spatial scales, complex build can easily have *10km* of track

Temporal



Complex thermal history
Solidification event ≈1 µs
Full build ≈1 day

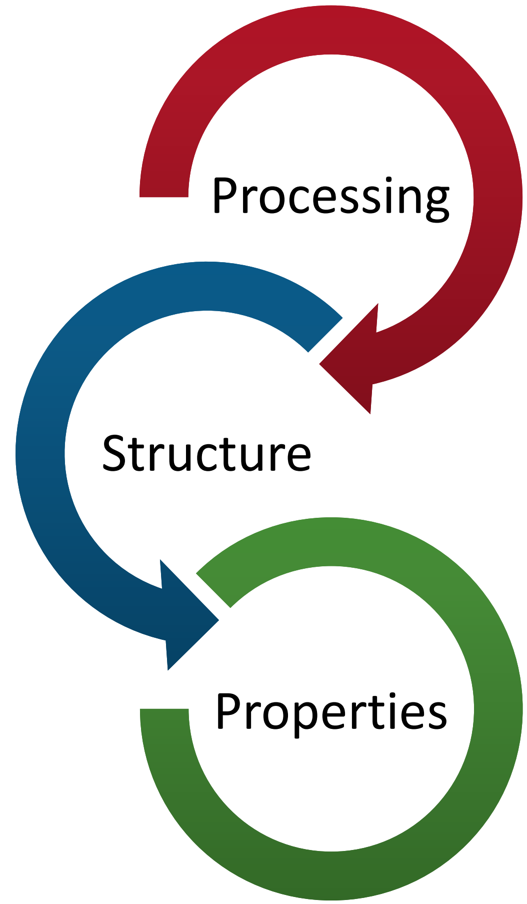


AM is spatially and temporally complex

Materials Science Primer

- Core Concept:
  Processing – Structures – Properties (PSP)
  - Performance & properties are dictated by (micro)structure, e.g.: $\text{strength} \propto \text{size}^{-\frac{1}{2}}$
  - Structure is controlled by processing history/pathway:
    $\text{size} = f(\text{cooling rate})$

- Materials *engineering* – manipulate processing pathway to obtain desirable structure and therefore performance



AM provides unique opportunity to *locally influence* this chain of relationships

Heterogeneous Nature of Materials

Conventional Cast Structure

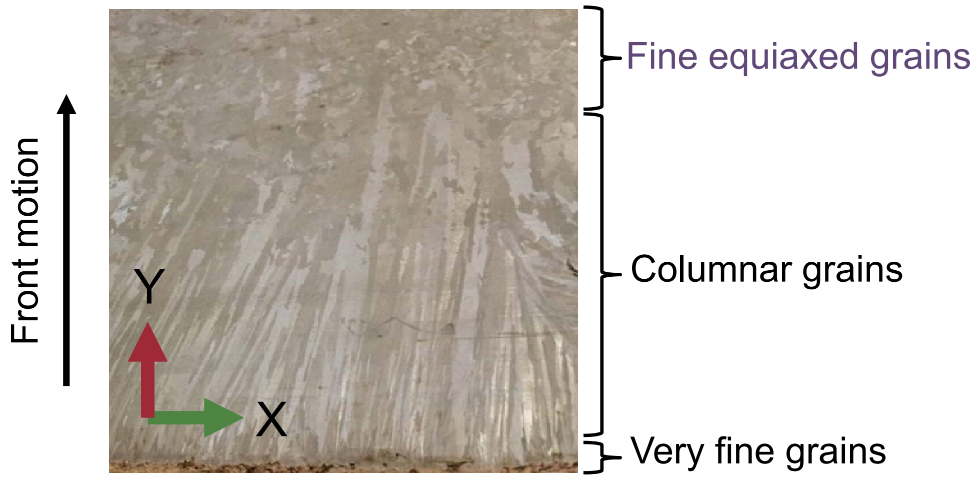
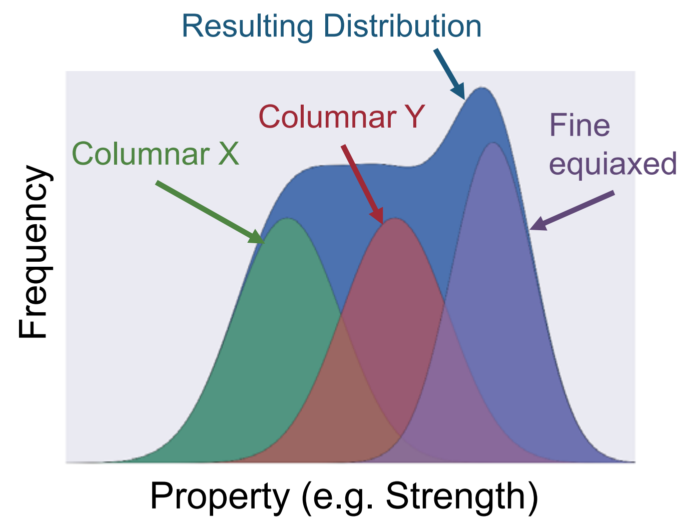
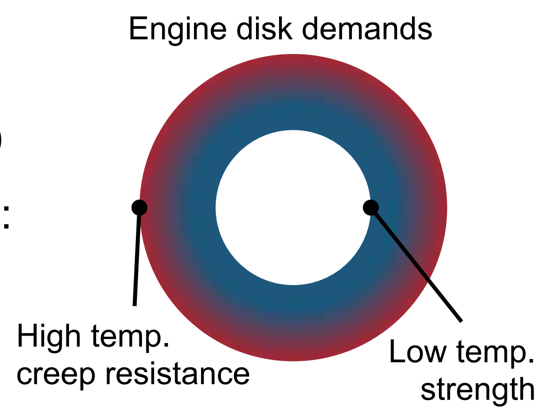
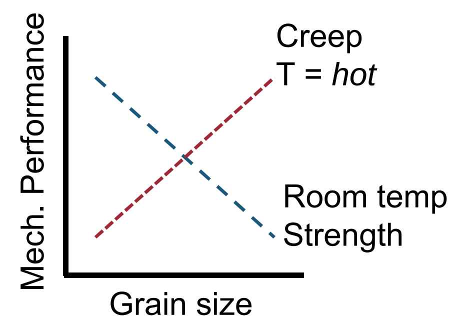


Image courtesy Kevin Chaput



- Heterogeneity & anisotropy are "the norm"
- Can be desirable! (extra degree of freedom)
- However, with most *conventional* processes:
  - Tightly *coupled* to part geometry
  - Influenced by *global* process parameters
  - Little/no *site-specific* control



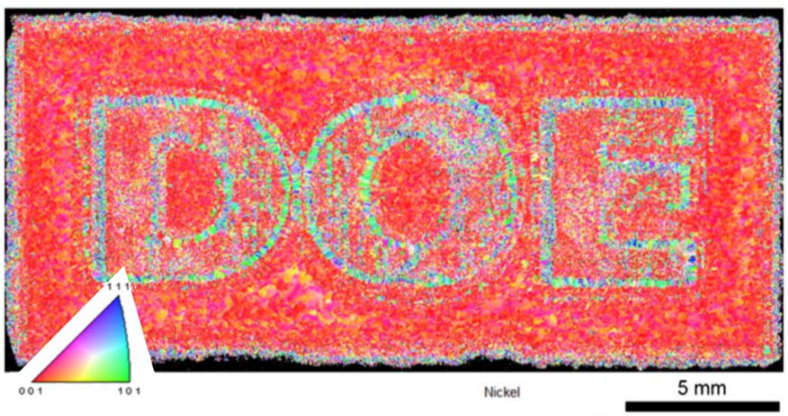


AM can *relax* (not eliminate) these constraints

Site Specific (for Better or Worse)

Purposeful or Explicit

IN718 (Nickel) *electron beam powder bed*
Careful manipulation of process sequence (and thus thermal history) to achieve grain size & orientation control



OAK RIDGE National Laboratory

Site specific control of crystallographic grain orientation through electron beam additive manufacturing

R. R. Dehoff*[1,2], M. M. Kirka[1,2], W. J. Sames[1,3], H. Bilheux[4], A. S. Tremsin[5], L. E. Lowe[1,2] and S. S. Babu[1,6,7]

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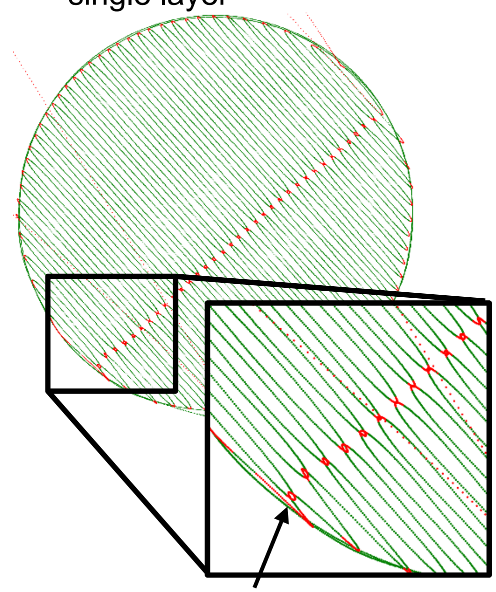
Unintended or Implicit

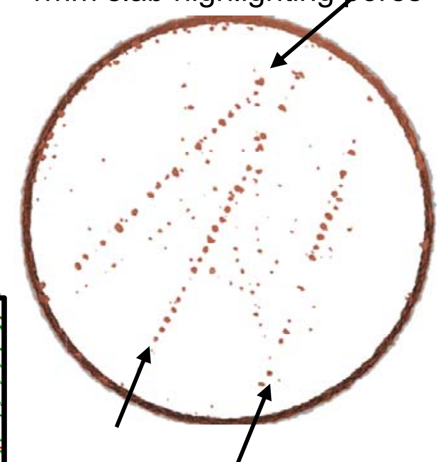
Ti-6Al-4V (Titanium) cylinder – *laser powder bed*
Interaction of complex scan strategy and part geometry introduces ‘artificial’ inhomogeneity, Defects frequency varies spatially in accordance

Measured scan path – single layer



Beam off at internal boundary

X-ray CT data
1mm slab highlighting pores



Cylinder diam.=10mm
Typical pore 100μm

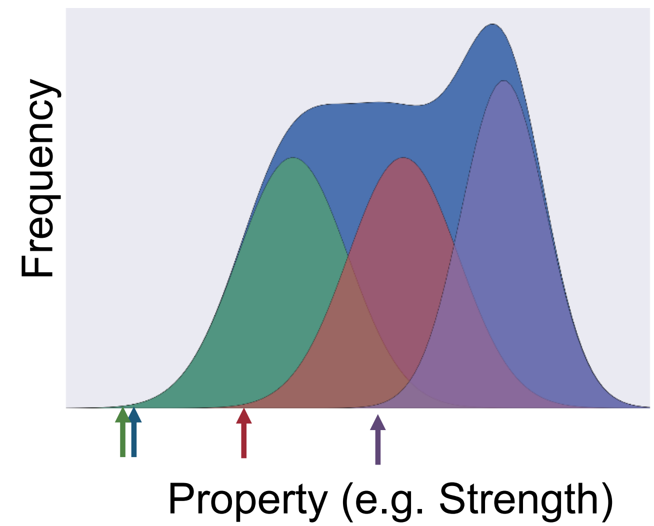
AM is site-specific in both purposeful & unintended fashions (typically both!)

Aerospace Design Practice

- Mechanical design accounts for 'worst case' behavior, property mins.
- *Accepted properties* for aerospace materials from "Metallic Materials Properties Development and Standardization" handbook (MMPDS) (maintained by Battelle Memorial Institute for FAA, DoD)
  - A-basis: 99% of pop. exceeds w/ 95% confidence
  - B-basis: 90% of pop. exceeds w/ 95% confidence
- Expensive to generate sufficient test data, design with handbook data to avoid case-by-case qual.

Example data header for Ti-6Al-4V

Processing →	Specification	AMS 4911[a]					
Proc. & Geo. →	Form	Sheet		Plate			
Processing →	Condition	Annealed					
Geometry →	Thickness, in.	≤ 0.1874		0.1875-2.000		2.001-4.000	
	Basis	A	B	A	B	A	B



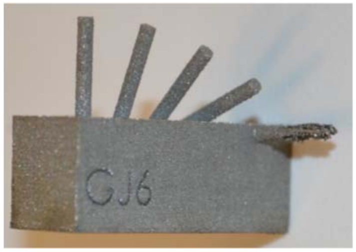
Break out sub-populations

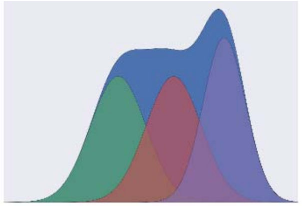
AM Challenge: coupling between site-specific processing & complex geometries → SOA for AM is point design

Recap

- What have we established?
  - Process – structure – properties relationships critical to ensure *function*
  - Process varies spatially in 3D
  - Variation can be explicit, implicit, *or likely both*
- Where do we want to be?
  - Routinely exploit PSP relationships during design of complex parts (think “AM process sensitive Top.Opt.”)
  - Be sensitive to qualification processes/requirements
- What do we need to get there?
  - A robust 3D framework to capture/describe PSP:
    - Intent/planning information: location specific conditions
    - Execution record: in-situ monitoring data
    - Outcome: post build characterization data
  - Analytics/learning tools to extract actionable information from that data
  - Pathway to feed this info back to design/fab. process

D=500μm





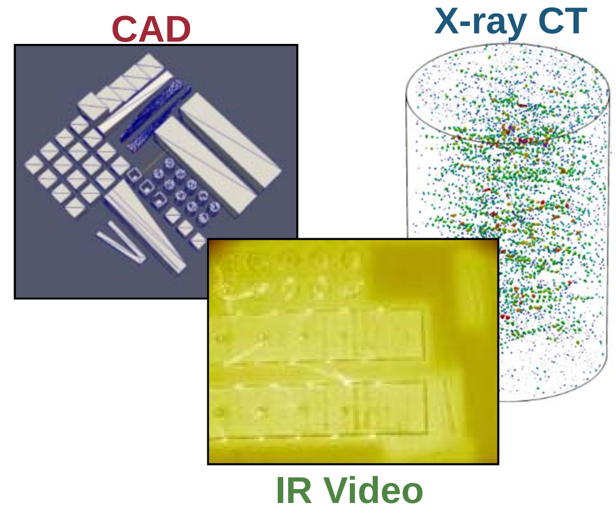
3D Framework & Analytics

- Combine/register **planning**, **execution**, & **characterization** data sets, model outputs
- 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

Michael Groeber: AFRL
Mike Jackson, Sean Donegan: BlueQuartz

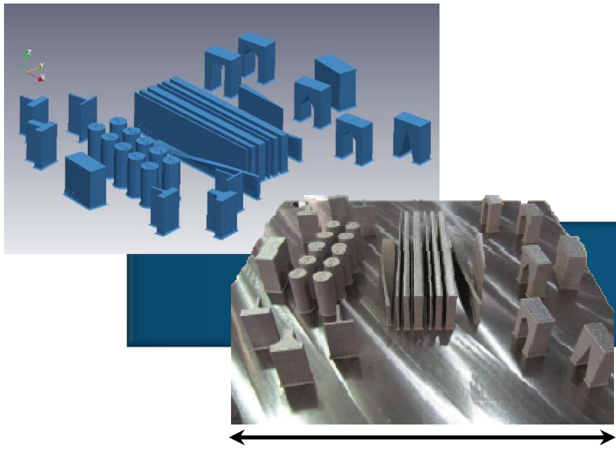
http://dream3d.bluequartz.net/

From data to actionable information

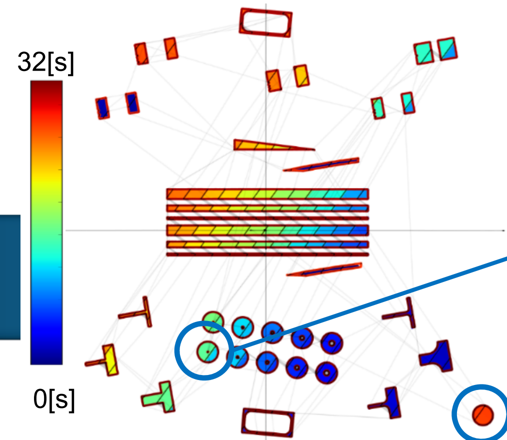


Example Analytics Pathway

CAD Geometry

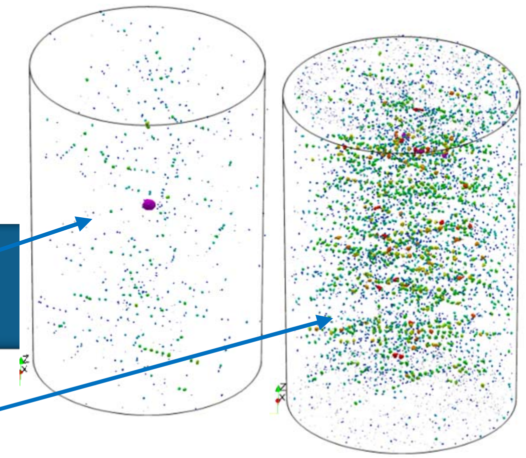


Energy Source Position & Properties

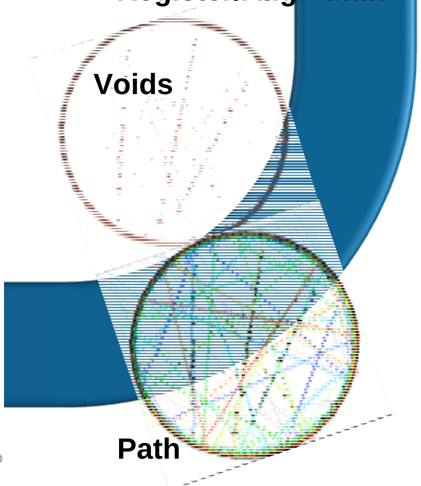


Experiments w/ T. Spears, J. Gockel GE Aviation
EOS M280 w/ Sigma Labs PrintRite3D

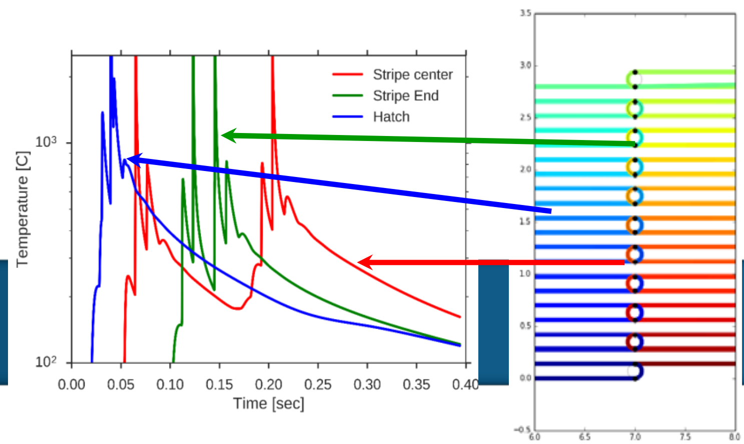
Post-Build Defect Characterization



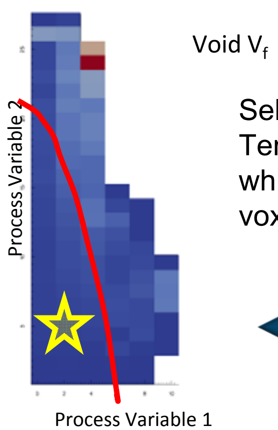
Register/Align data



Generate Loc. Specific Temp vs. Time



Generate Processing-Structure Maps



Select attributes of the Temp vs. Time history which are unique to void voxels.

Open Questions

- What are sufficient *reduced order representations* of the local processing state?
  - Brute force: one (small) part has 10^8 location specific histories with 10^7 entries each
  - Opportunities for: intelligent/sparse sampling, signal processing techniques, symbolic aggregate approximation, genomics, …
- How do we establish *which features* of the spatially varying energy input or thermal histories are *relevant* to particular micro and defect structures?
  - Combination of existing processing knowledge/experience with learning techniques
  - Opportunities for: dimensionality reduction, correlation analysis, PCA, CCA, topological data analysis, …
- How to describe the spatial component of the correlations
  - Describe continuous variation in manageable number of 'zones'
  - Clustering techniques, spatial statistics,

- Given answers to the above, how do we suggest *new* processing pathways that yield desirable spatial variation in processing state/history?

Acknowledgements

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