Air Force Research Laboratory

Data Fusion and Mining of In Situ Monitoring Sensors, Process Modeling, and Defect Characterization in Powder Bed Fusion Additive Manufacturing

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Integrity ★ Service ★ Excellence

AFRL HERITAGE | 1917–2017

100 YEARS OF U.S. AIR FORCE SCIENCE & TECHNOLOGY

Contributors & Acknowledgements

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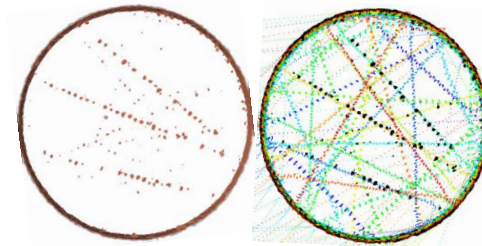Thomas Carmody

Outline

0[s]   32[s]

Overview of Additive Manufacturing

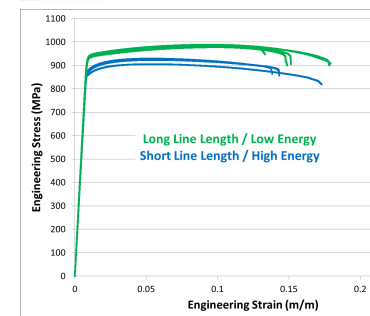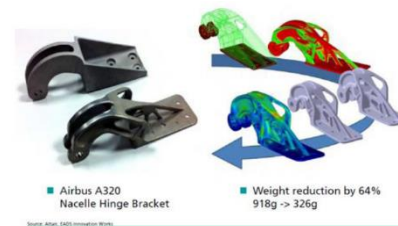Process, Design, & Qualification Complexity
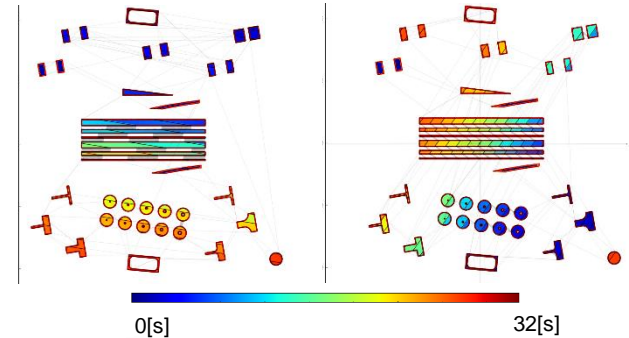
Process, Structure, Properties Linkages: DMLS

Voids in DMLS Ti-64

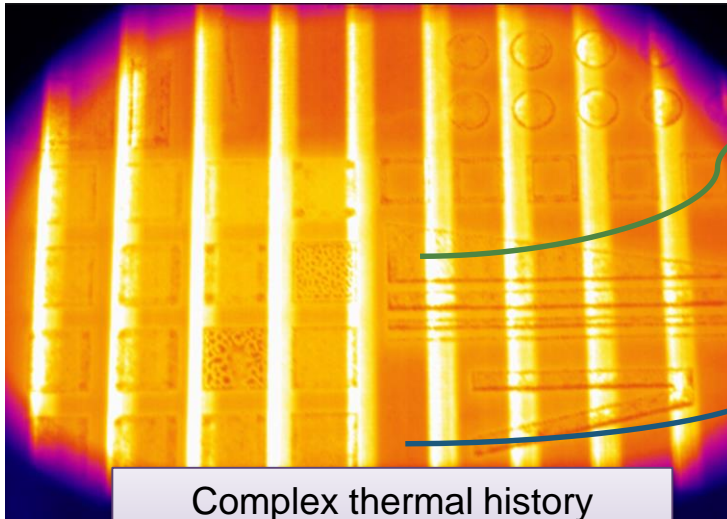## Process, Structure, Properties Linkages: EBM

Mechanical Response in EBM Ti-64

- Airbus A320 Nacelle Hinge Bracket
- Weight reduction by 64% 918g -> 326g

Source: Airbus EADS Innovation Works

Long Line Length / Low Energy
Short Line Length / High Energy

Forward Vision

Forecasting, Optimization, & Design for AM

Powder Bed Fusion of Metals

Temporal

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

Solid

Powder

Contours

Melting

Post-heats

Cursor 1 [cnts]
Cursor 2 [cnts]
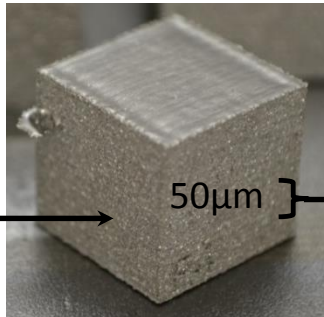
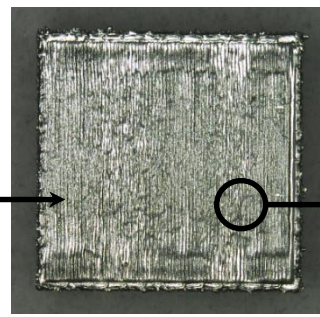IR Intensity

Pre-heat

Spread powder

Time [s]

OAK RIDGE National Laboratory
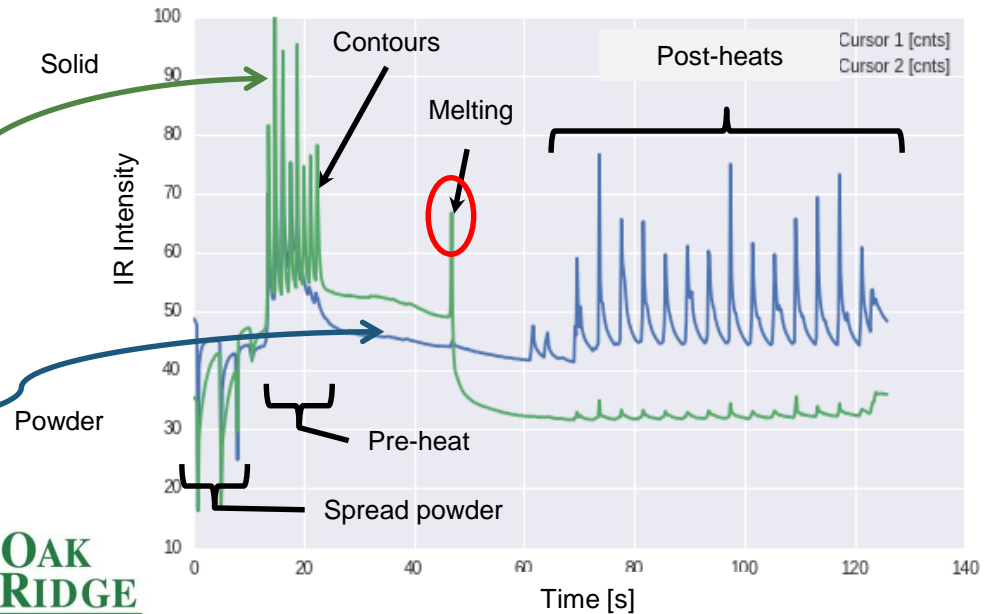
Spatial

Build (40 parts) → Part (300 layers) → Layer (150 tracks) → Track
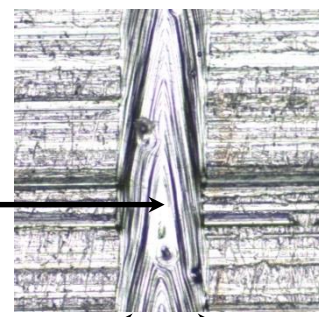
50μm

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

0.2m   15mm   15mm   ≈150μm

AFRL Vision Overview

Vision Requirements

Challenge: *Form, Fit, & Function* will require*:*
- A robust 3D framework to capture/describe build intent and process quality assurance
- Analytics/learning tools to extract *actionable information* from that data
- Pathway to feed this info back to design/fabrication

> What are the *"essential process variables"* for AM?

> What is the *quality* of in situ characterization for AM?

How do we quantify the above to:
- Establish processing equivalency between coupons, features, parts, etc.?
- Link defects & microstructure (thus performance) to local processing state?
- Design future (unconventional?) processes to achieve desired location specific defect & microstructures

> Need an approach that incorporates *geometry & scan path*

Capabilities Needed

Establish process equivalency
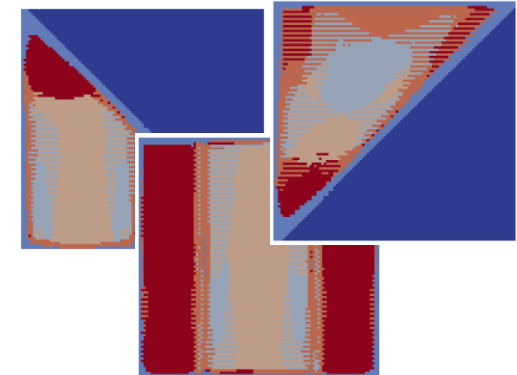
Link defects & microstructure to processing
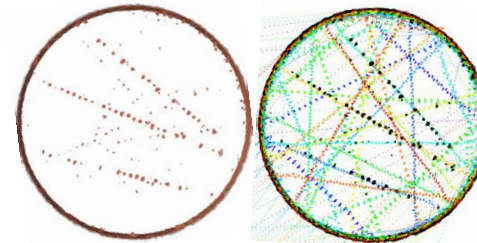
Design future processes
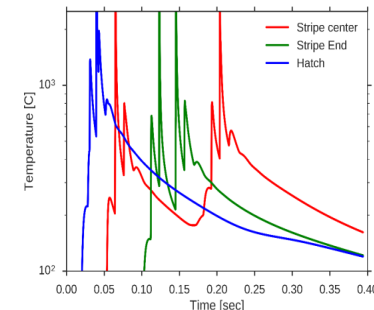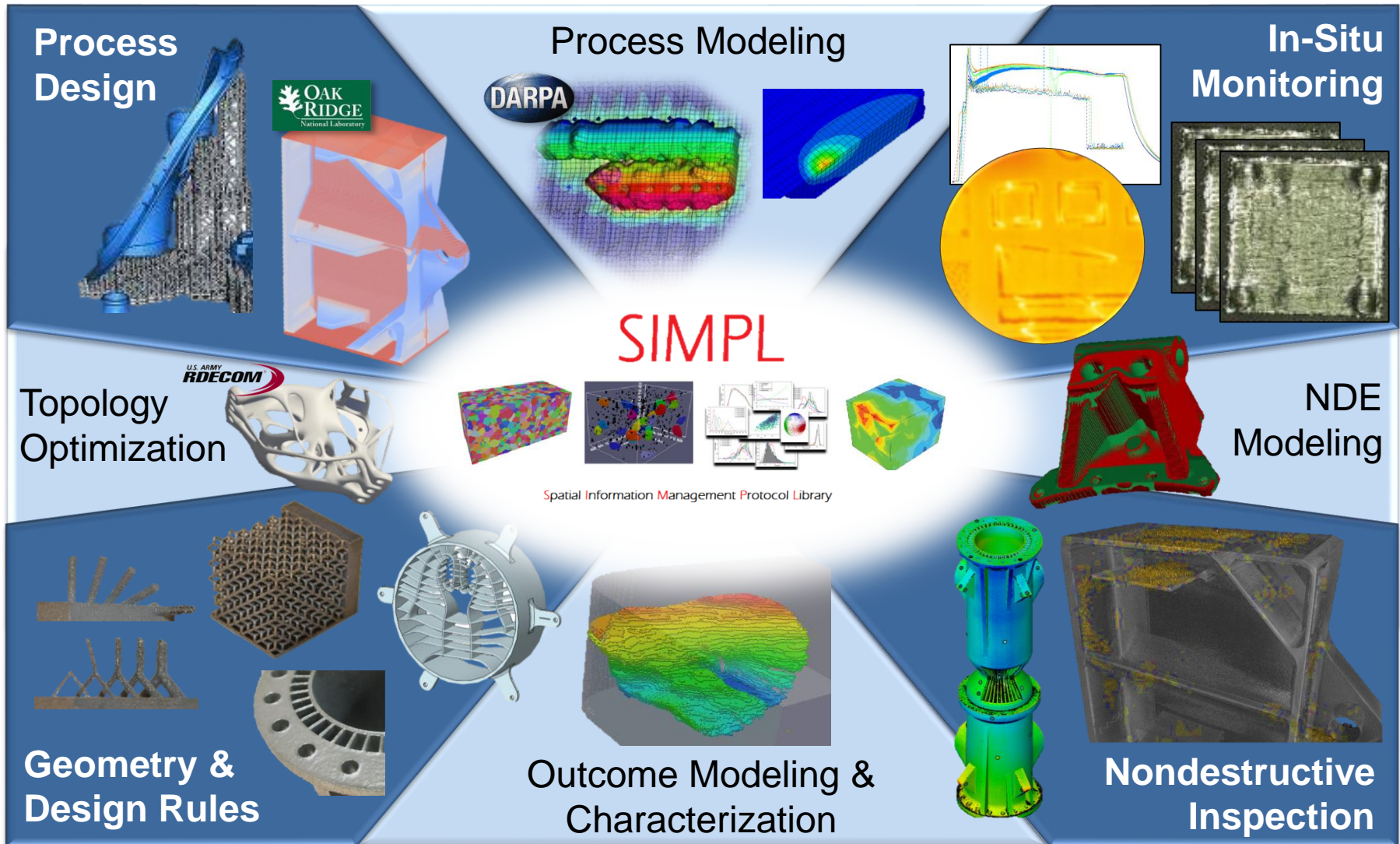
Additive Manufacturing (AM) at 30,000 Feet

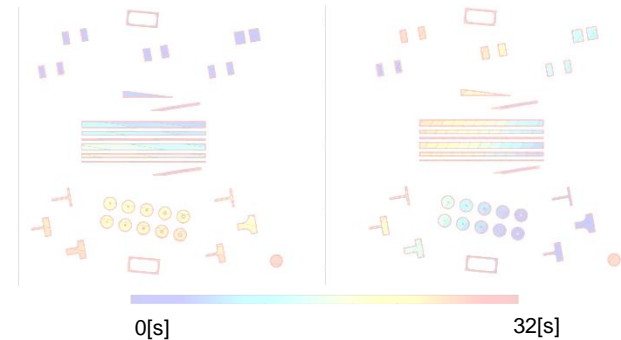*A Century of Scientific Excellence for our Airmen*

Process Design

Process Modeling

In-Situ Monitoring

SIMPL

Spatial Information Management Protocol Library

Topology Optimization

NDE Modeling

Geometry & Design Rules

Outcome Modeling & Characterization

Nondestructive Inspection

Outline

Overview of Additive Manufacturing

Process, Design, and Qualification Complexity

0[s]   32[s]

Process, Structure, Properties Linkages: DMLS

Voids in DMLS Ti-64
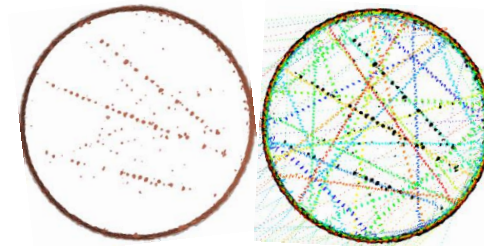
Process, Structure, Properties Linkages: EBM

Mechanical Response in EBM Ti-64
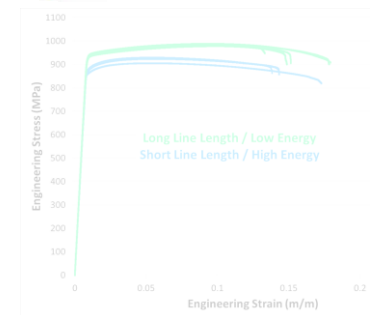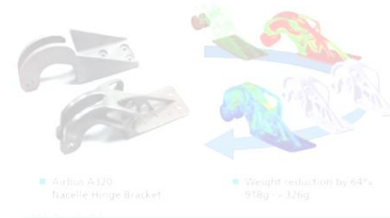
Forward Vision

Forecasting, Optimization, and Design for AM

Process Complexity: DMLS

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Direct Metal Laser Sintering (DMLS)
EOS M280 Machine
Striping & Hatching Enabled
Stripes Rotate 67° Per Layer

Stripes Typically 1s-10s of mm
Stripes Processed in Serpentine Manner
Laser Moves ~1 m/s
Laser Crosses Stripe in ~1/200 s

0[s]   32[s]
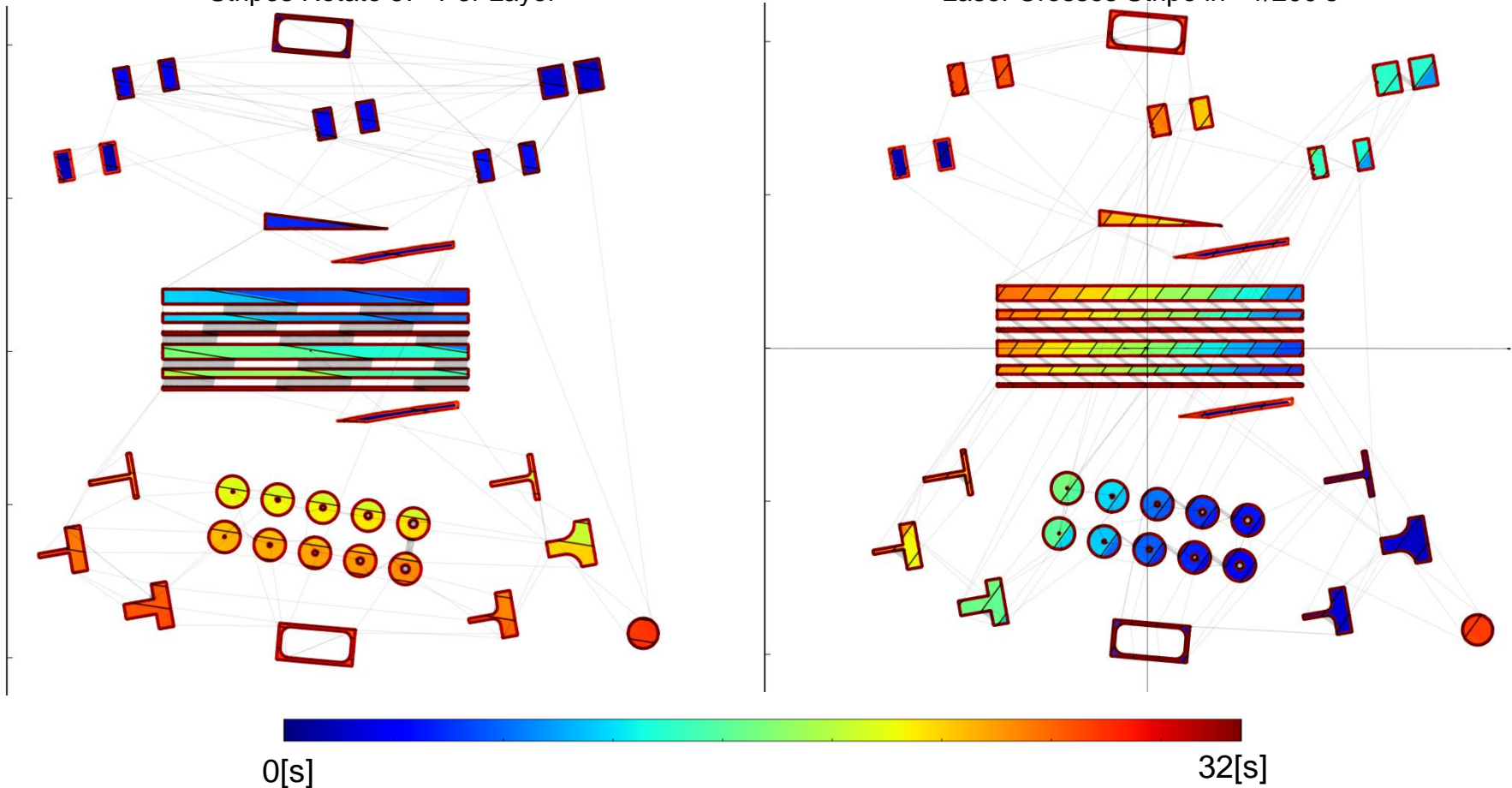
Bottom-Line Up Front (BLUF)
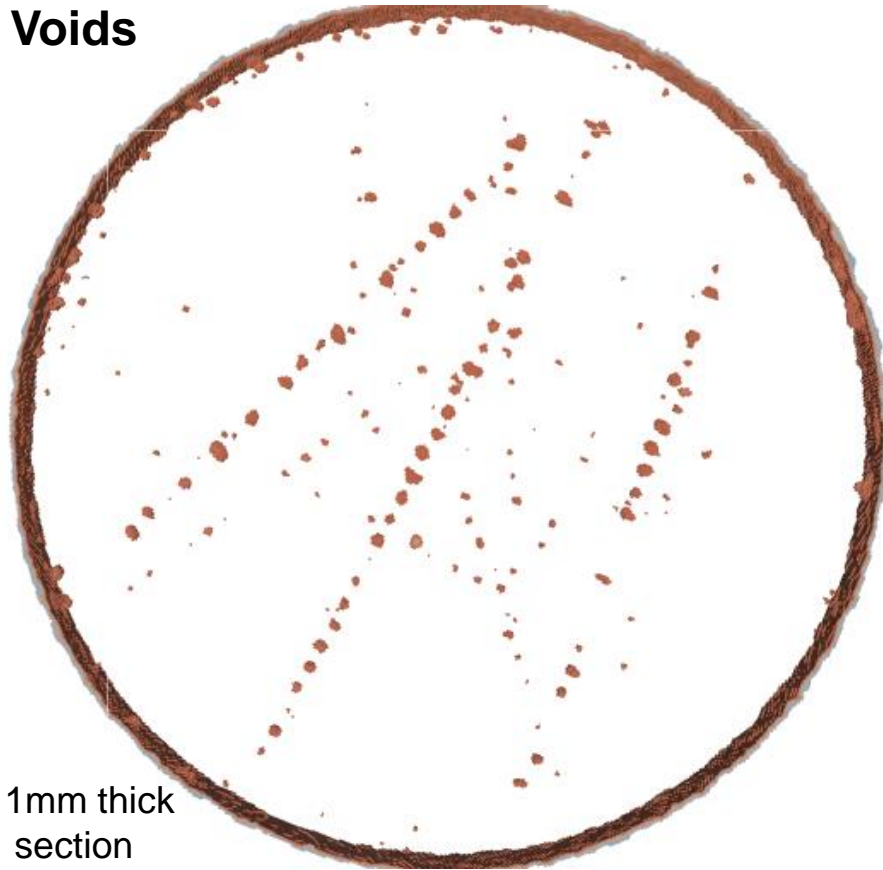
Voids

~ 1mm thick
section

**Voids &
Stripes**
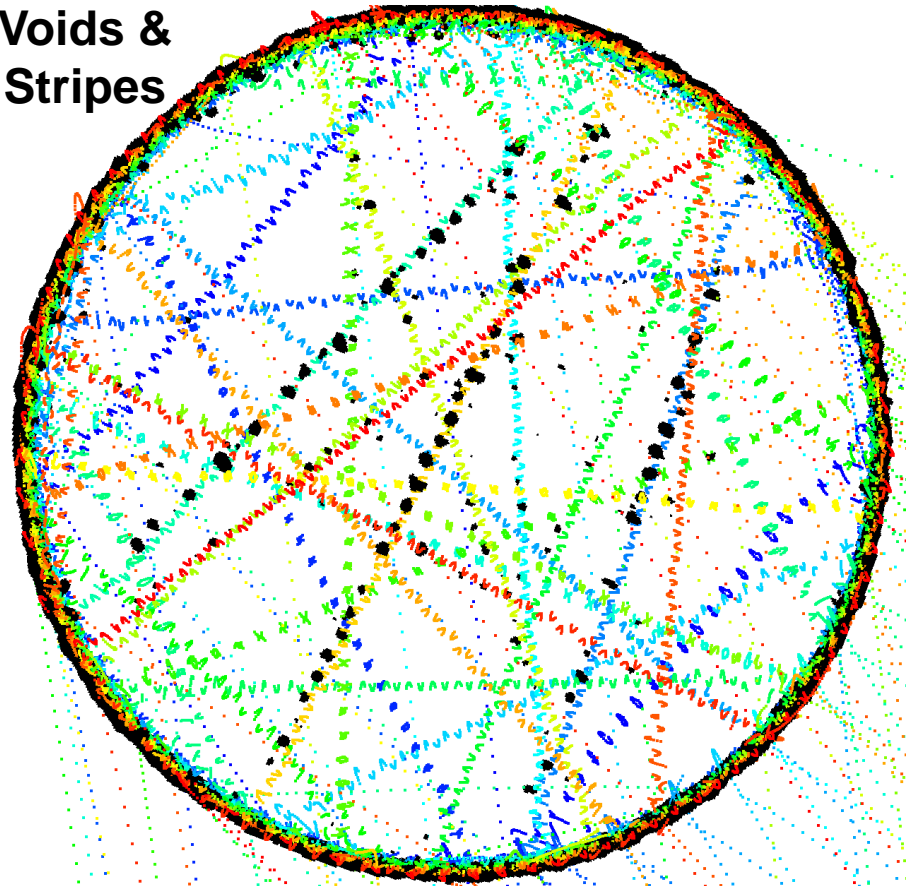
What makes a 'bad' stripe boundary? – Need correlative analysis to answer

**Visually apparent that voids align with stripe boundaries
– *Not all stripes though!***

Processing–Defect Correlations: DMLS Ti-64

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CT at 25 μm voxel size:
Void location, approximate size
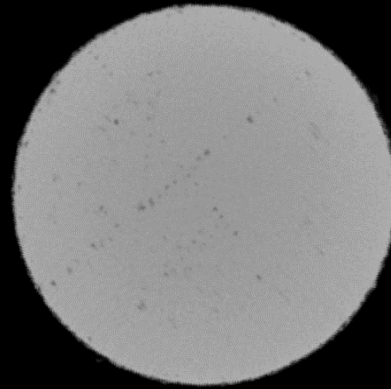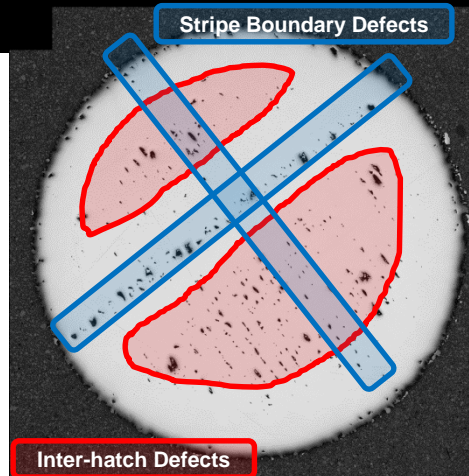
CT at 2 μm in plane, 1-5μm z:
location, size, *shape*
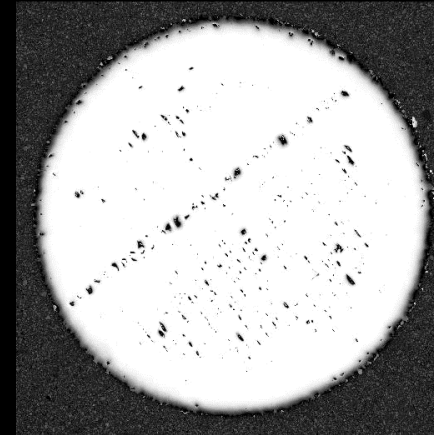
Second stripe

Preferential defect orientation

θ°

X, 0°, horizontal
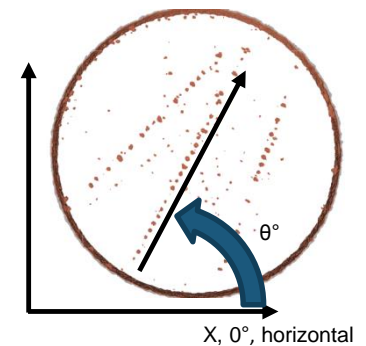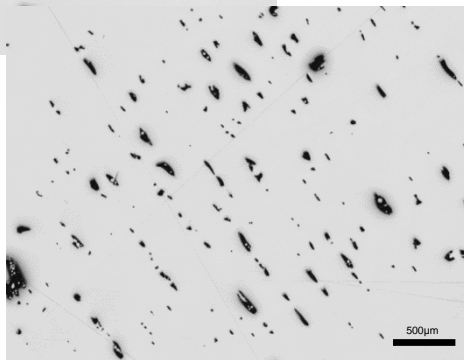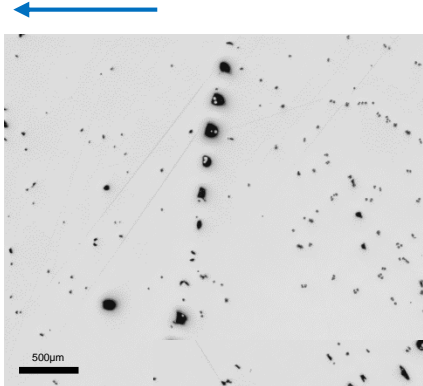
Stripe Boundary Defects

Inter-hatch Defects

Stripe Boundary Void Orientations

No linear arrays 130 ° to 180°

No linear arrays, 0 ° to 30°

Angle from Horizontal (degrees)

Slice Number

500μm

500μm
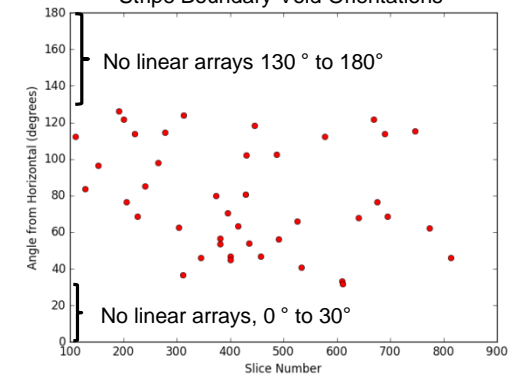
CT not sufficient to elucidate defect types & mechanisms

Overview of Datasets

Process Intent & Monitoring – point cloud of laser position & properties w/ additional in-situ sensors

Laser Position(t)

CAD Geometry – triangulated surface representation of parts to be built
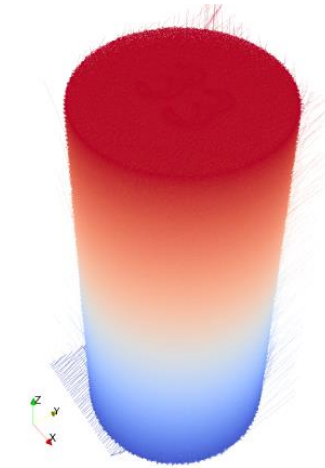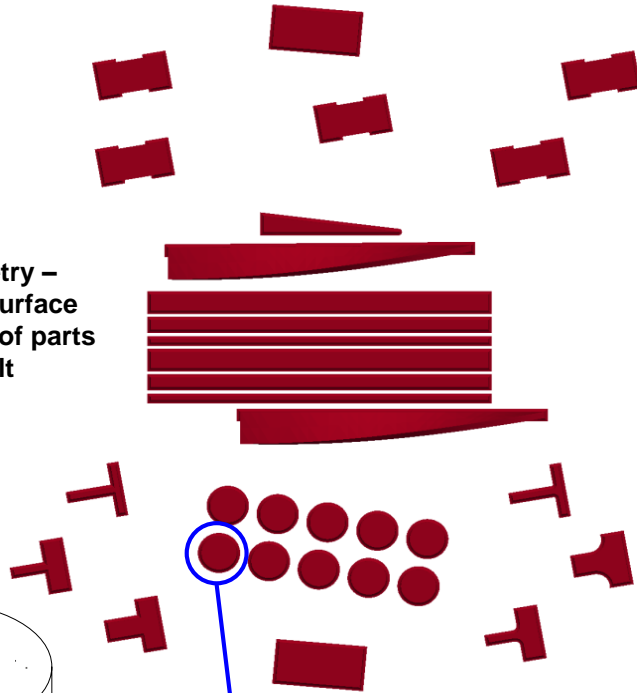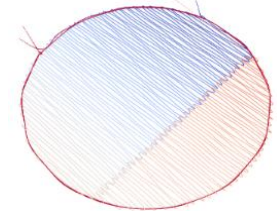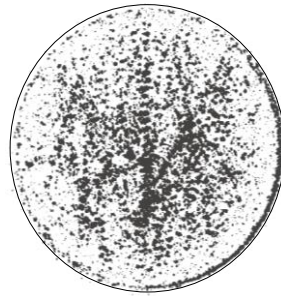
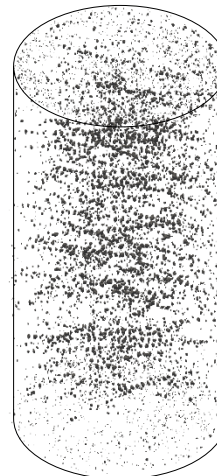**Other sensor data - Often not spatially located**

Laser Properties

GC1

GC0
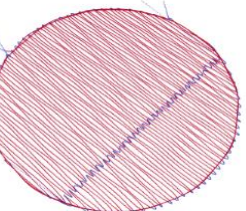
Computed Tomography (CT) – voxelized representation of defects/voids

Multi-Modal Registration & Fusion

Process Intent & Monitoring

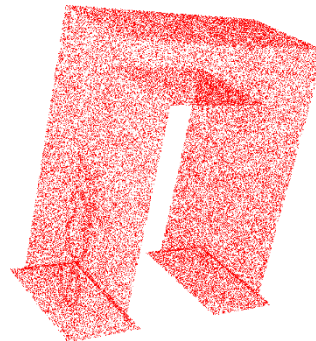Remove points where the beam is off
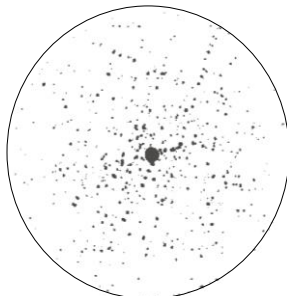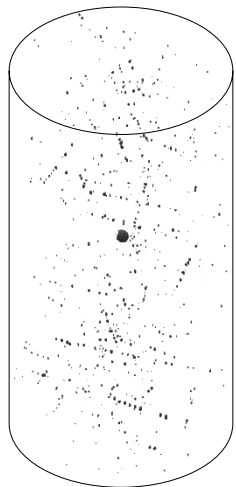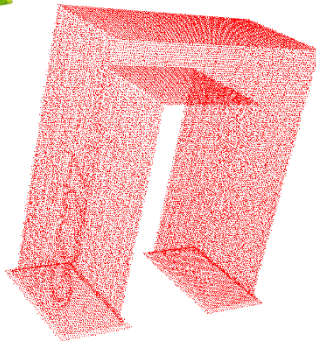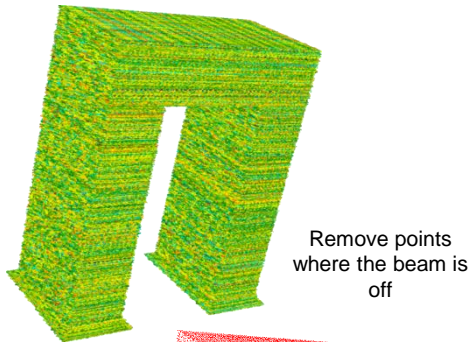
Compute 3D Delaunay triangulations to extract a concave hull
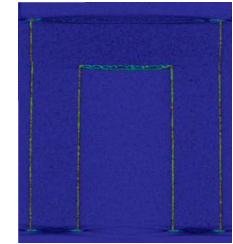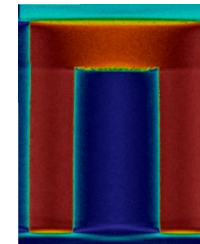
$\mathcal{A}?$

CAD
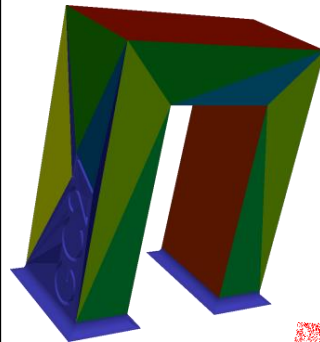
Nodes do not uniformly sample surface

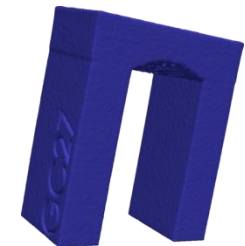Compute triangle areas & construct piecewise constant distribution weighted by areas

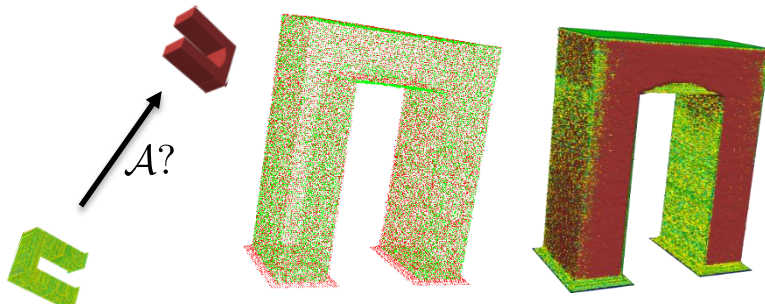Sample triangles from distribution and pick points uniformly within triangles

Automatically registered to CAD geometry with ICP using affine transformation only

CT

Density   Gradient magnitude

Automatically compute threshold – weighted by gradient

$$T = \frac{\sum_p G(p) I(p)}{\sum_p G(p)}$$

Auto-threshold   Surface mesh of threshold

Sample triangles in same manner as CAD

Spatially-Resolved Processing Histories

'Simple' Green's function analytical solution for Gaussian point source – apply superposition to approximate moving source

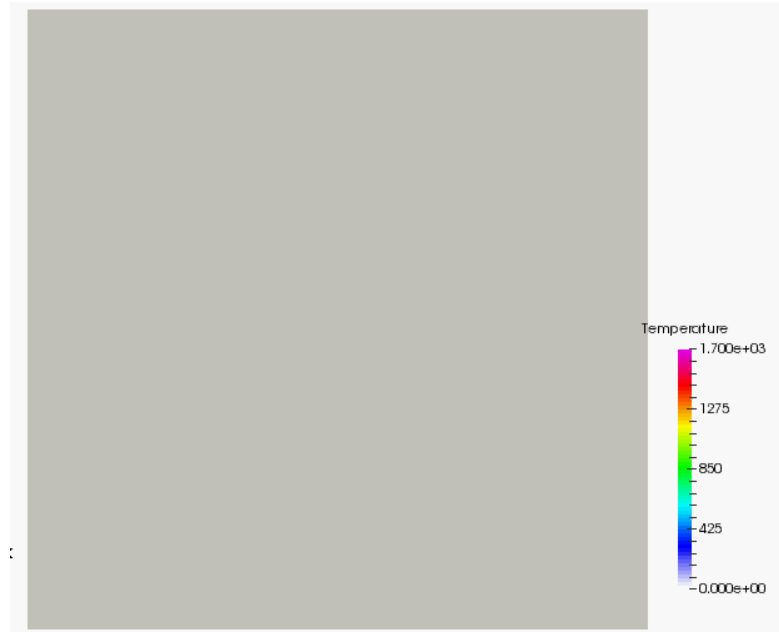$$Q_i = \frac{A_i}{\left[2\pi\left(\sigma^2 + 2\alpha(t - \tau_i)\right)\right]^{3/2}} \exp\left[-\frac{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2}{2\sigma^2 + 4\alpha(t - \tau_i)}\right]\Theta(t - \tau_i) \qquad A_i = \eta\frac{P\Delta t}{\rho_m c_p}$$

considers only conduction

4-dimensional kernel
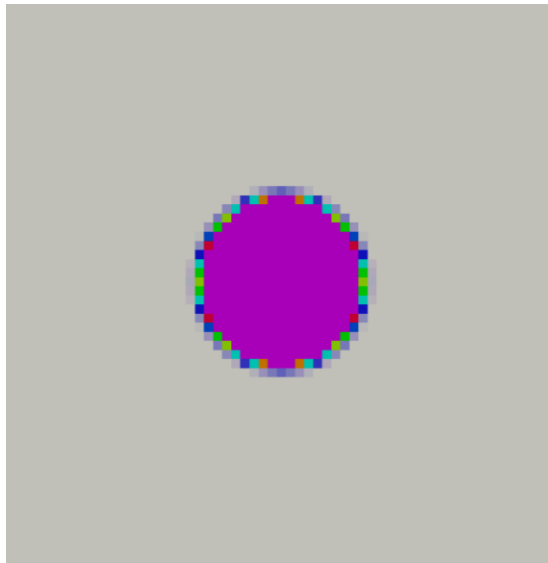
Thermal kernel from analytical Green's function solution at some time, t > 0

Temperature
- 1.700e+03
- 1275
- 850
- 425
- -0.000e+00

Superposition of all point sources active prior to time, t

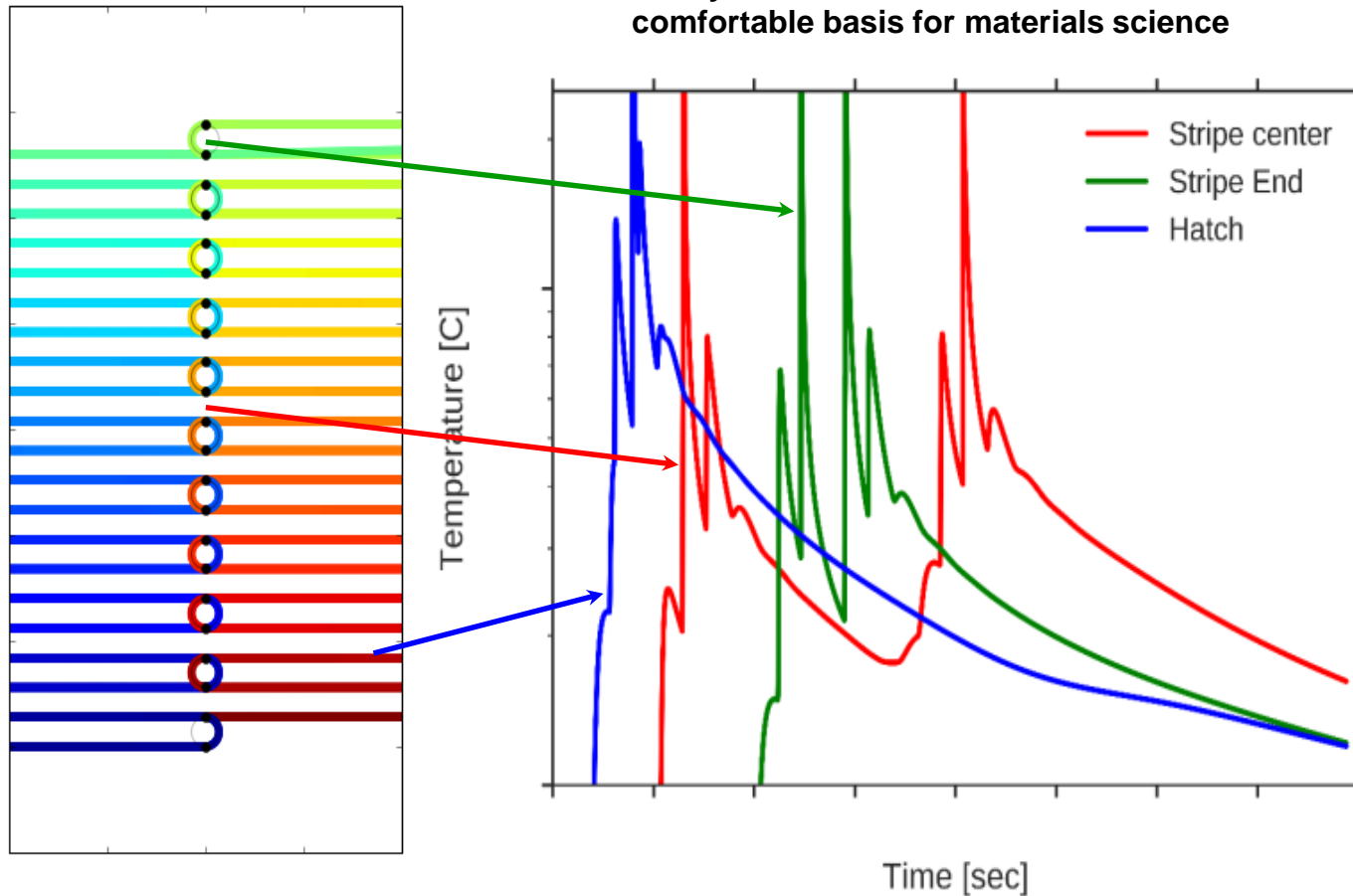**Number & time between melting events – *influenced by geometry***
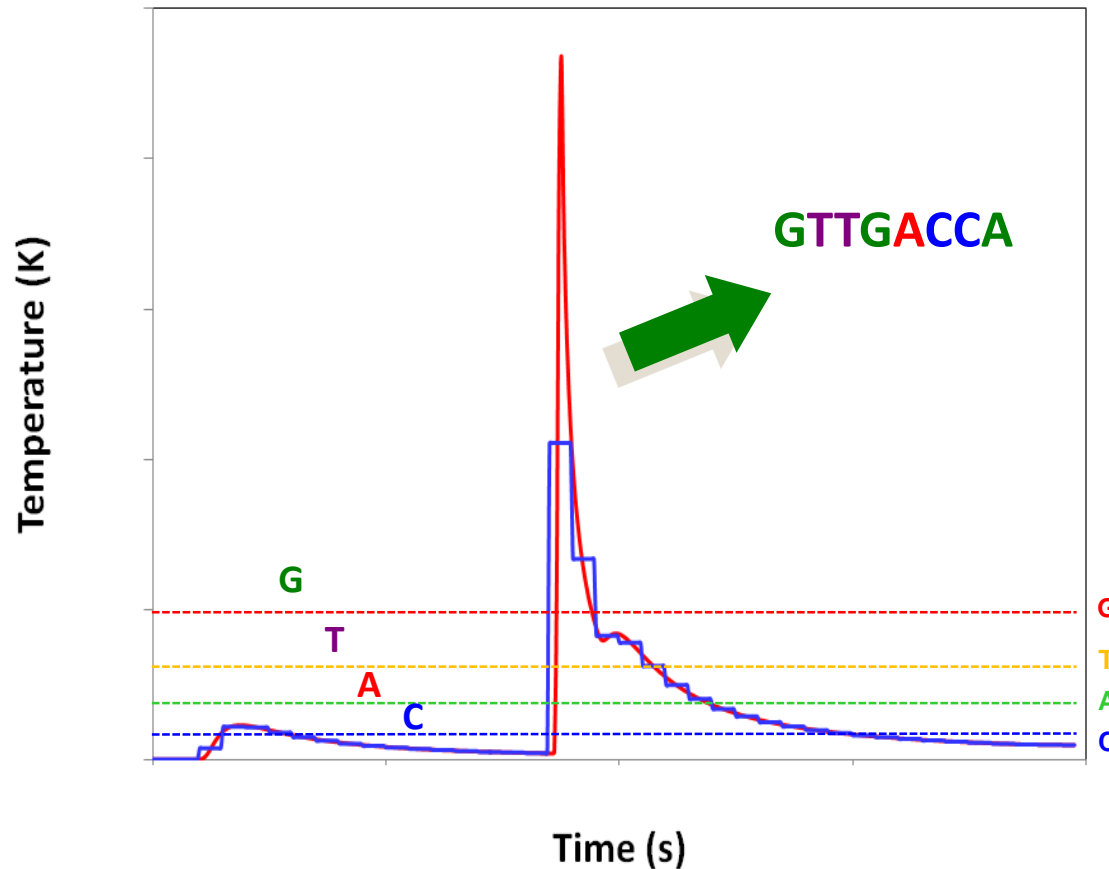
Spatially-Resolved Processing Histories

Locally-resolved thermal histories – more comfortable basis for materials science

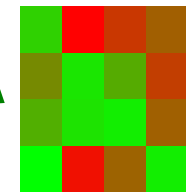**Number & time between melting events – *influenced by geometry***

Dimensionality Reduction

Perform Symbolic ApproXimation (SAX) to reduce histories to strings – further reduces strings to 'images' counting pairwise substrings
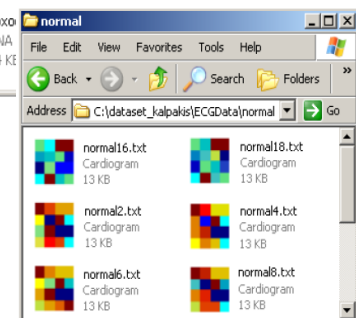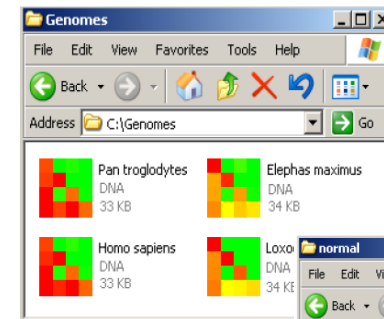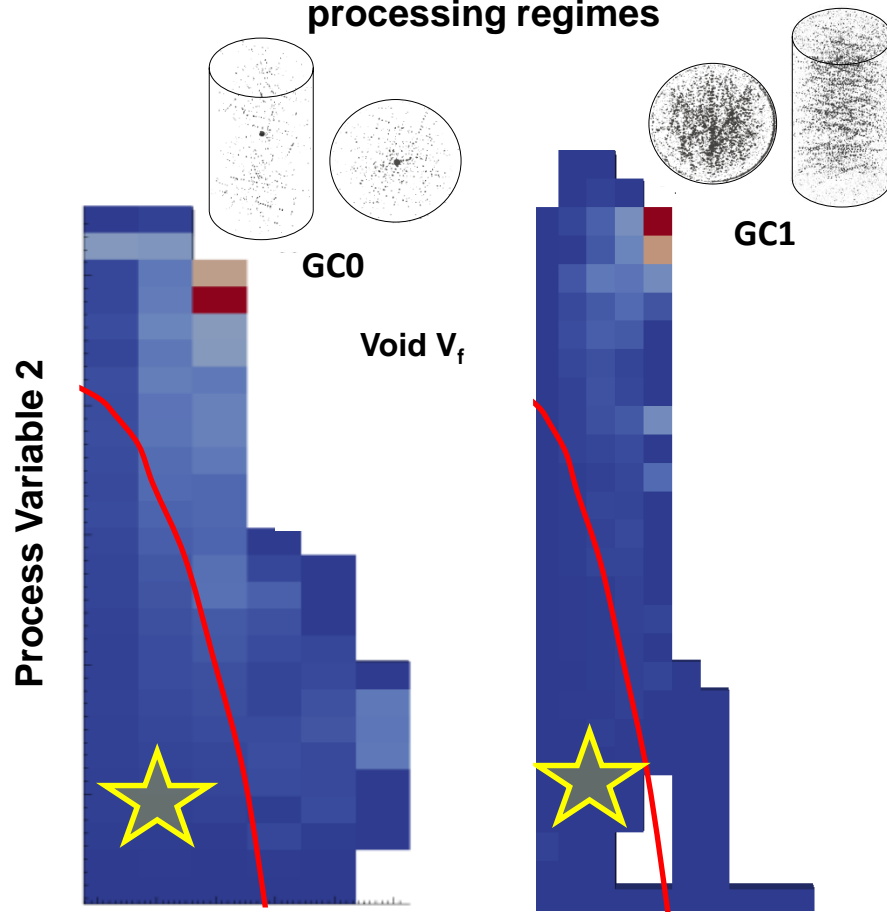

GTTGACCA

adapted from E. Keogh, UC-Riverside

AA	AC	CA	CC
AG	AT	CG	CT
GA	GC	TA	TC
GG	GT	TG	TT

Time Series Bitmap

Correlative Analysis

Mapping local volumes into 'processing space' shows voids systemic in certain processing regimes

Processing-Microstructure relationships are analogous to genotype-phenotype association & can utilize machine learning techniques
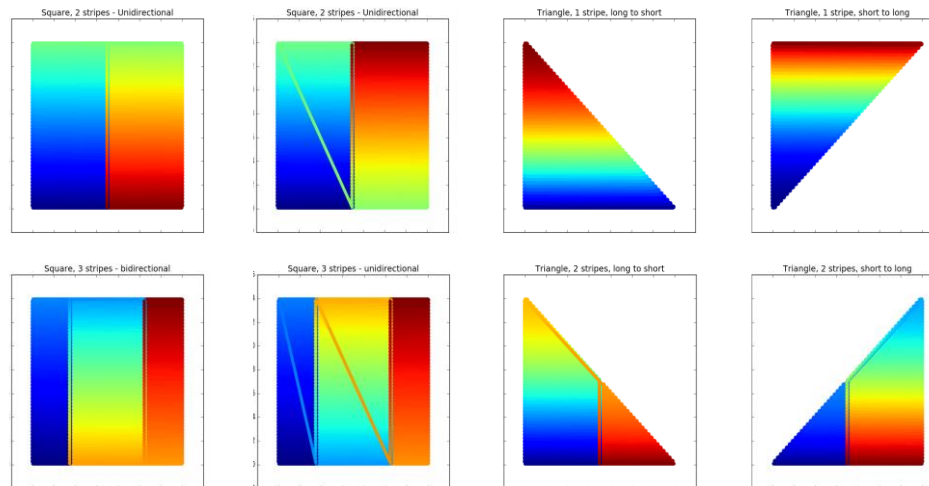

GC0

GC1

Void V_f
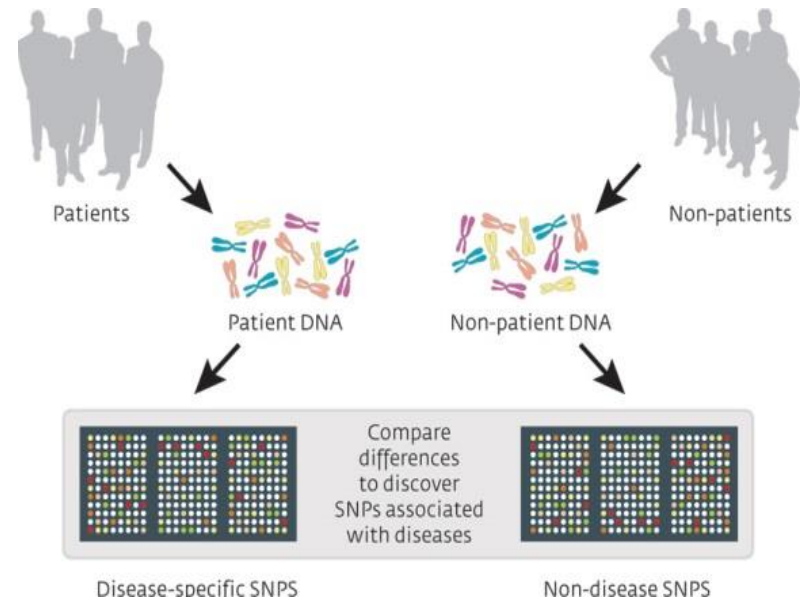
Process Variable 2
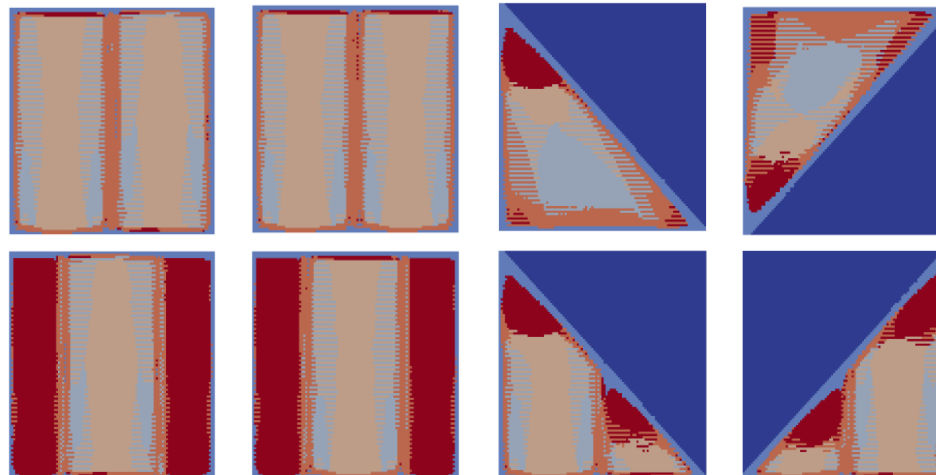
Process Variable 1

Correlative Analysis

Zone/Cluster regions of common processing – Tunable to 'SNPs' linked to specific structures/'diseases'

Phantoms

Zoned Phantoms

Outline
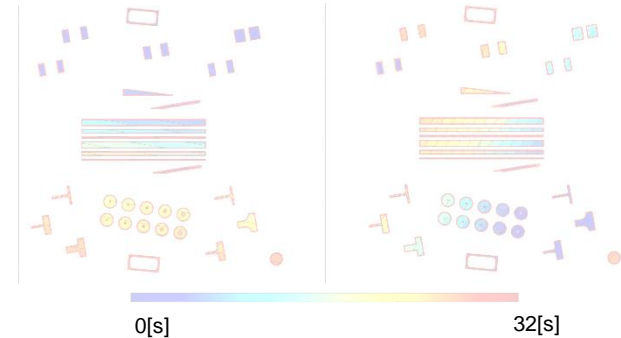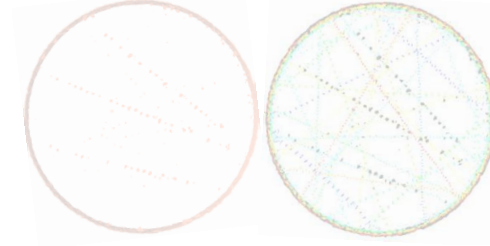
0[s]   32[s]

Overview of Additive Manufacturing
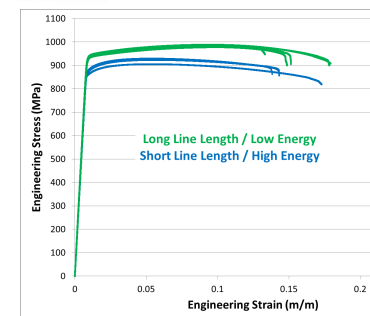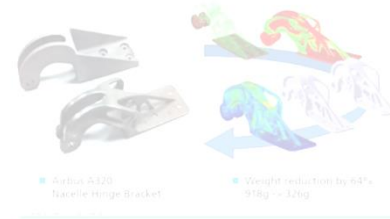
Process, Design, and Qualification Complexity

Process, Structure, Properties Linkages: DMLS

Voids in DMLS Ti-64

Process, Structure, Properties Linkages: EBM

Mechanical Response in EBM Ti-64

Long Line Length / Low Energy
Short Line Length / High Energy

Forward Vision

Forecasting, Optimization, and Design for AM

Processing–µStructure Correlations: EBM Ti-64

Arcam A2 e-beam powder bed fusion: Ti-6Al-4V

Parameters (Normalized to Region A)

	HED REGION	LED REGION
Length [mm]	20	107.6
Power / P_{HED}	1	4.67
Spot Velocity / V_{HED}	1	8.10
Line Velocity / V_{HED}	1	1.5
Scan time / t_{HED}	1	0.636
Energy Density / E_{HED}	1	0.556

- **Notional parameters uniform throughout bed**
- **Local processing parameters changed by system in response to geometry**

OAK RIDGE
National Laboratory

Z (build) normal to page

Long Line Length

HED Region

LED Region

Short Line Length

Y

X

20 mm
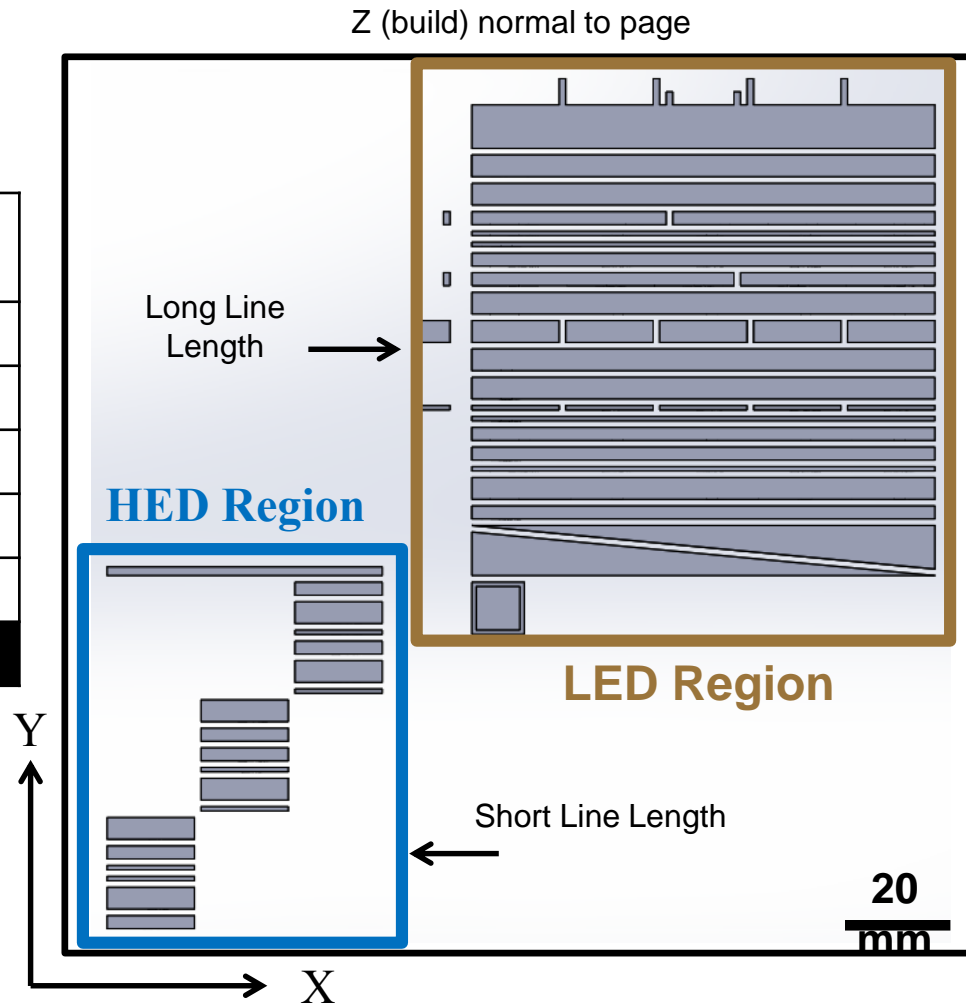
'Process Design' through collaboration & deep knowledge of system

Variation in As-Built Mechanical Response

Arcam A2 EBM powder bed fusion: Ti-6Al-4V

Z (build) normal to page

HED Region

LED Region

20 mm

Tensile Tests (Load // Build Direction)

LED (Long Line Length)
HED (Short Line Length)
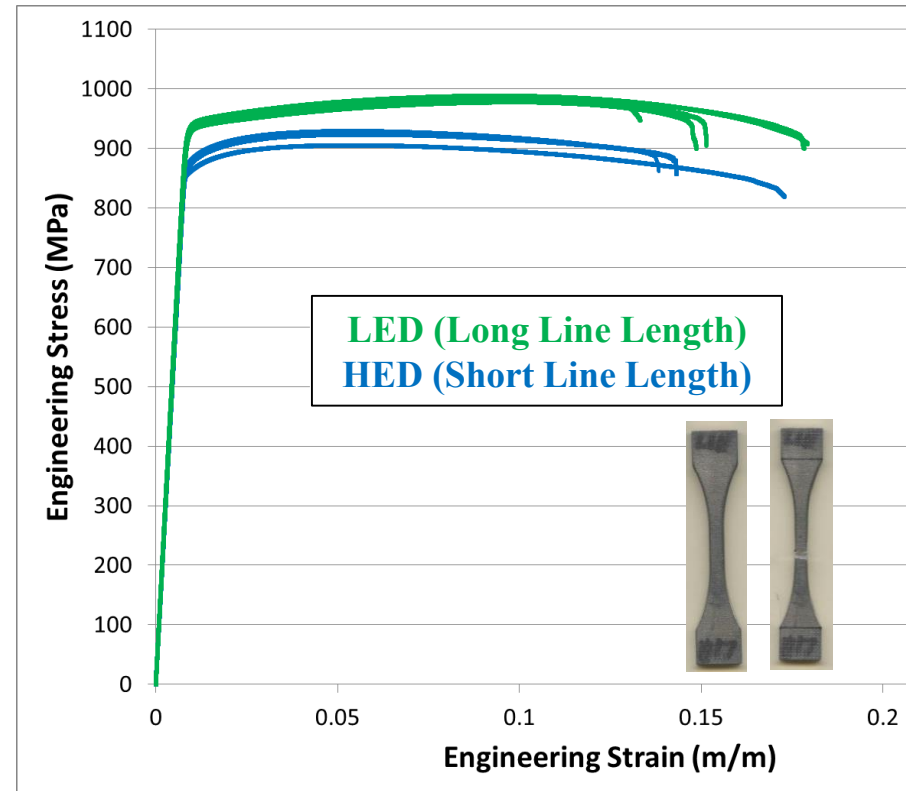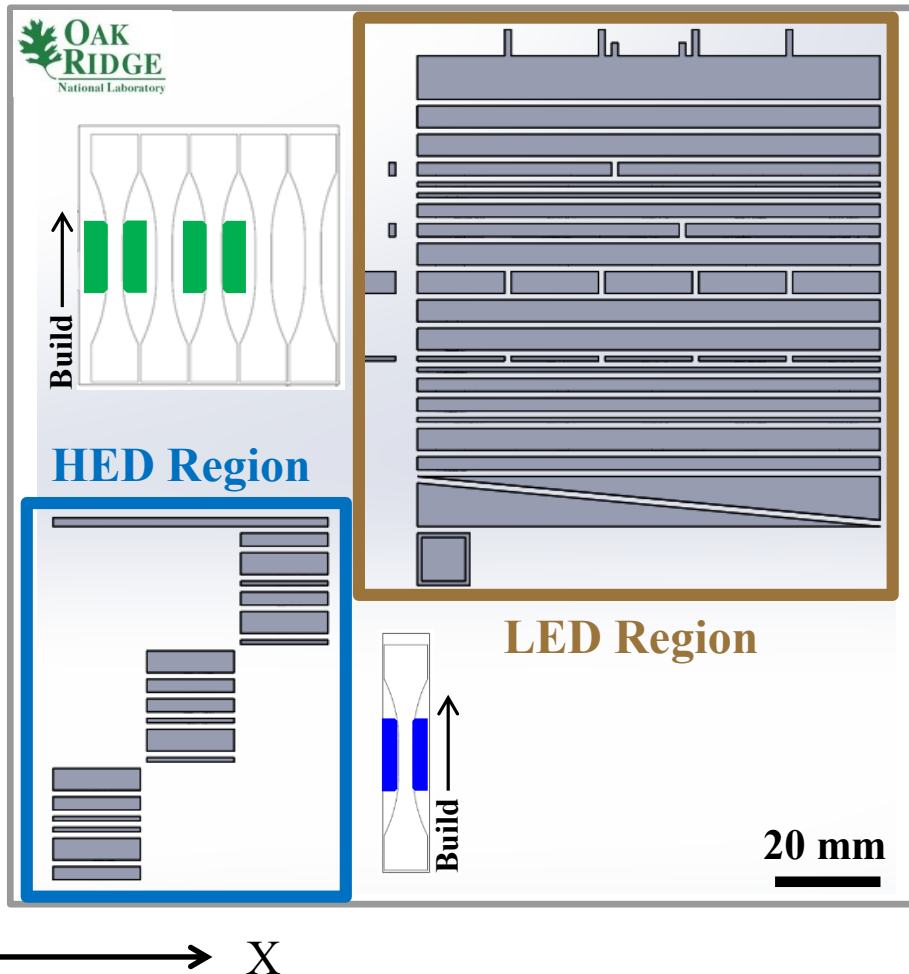
HED to LED Samples

- **10% Increase in YS, UTS**
- **Uniform strain and hardening**
- **Similar Ductility**

As-Built Microstructures

HED Region — XY — 5 μm

LED Region — XY — 5 μm

Alpha IPF (Build // ND) — 5 μm — YZ — 50 μm

Alpha IPF (Build // ND) — 5 μm — YZ — 50 μm
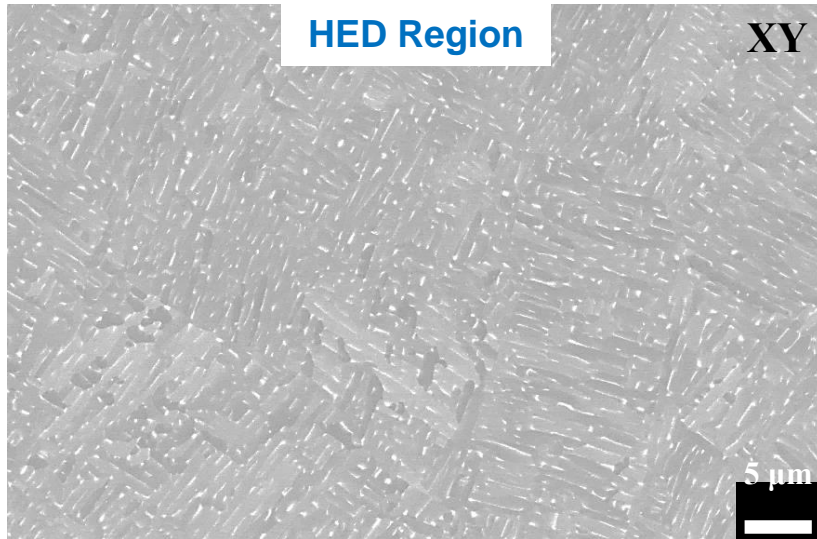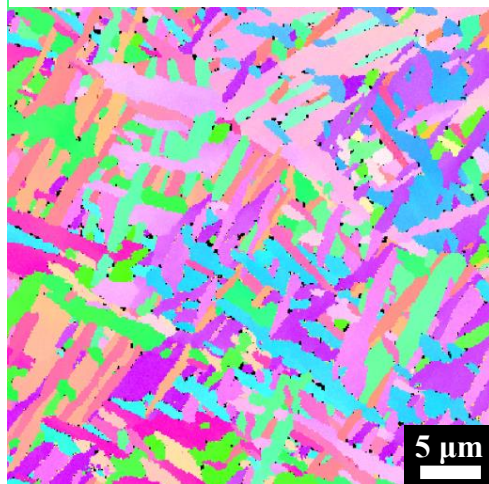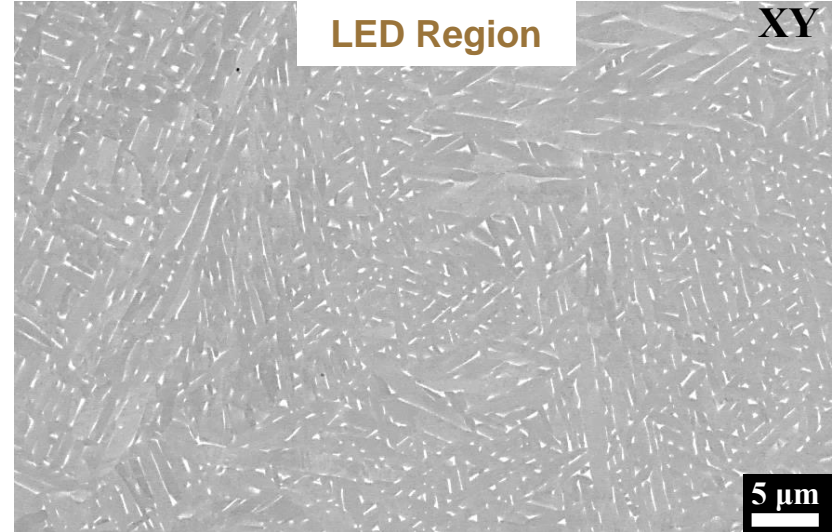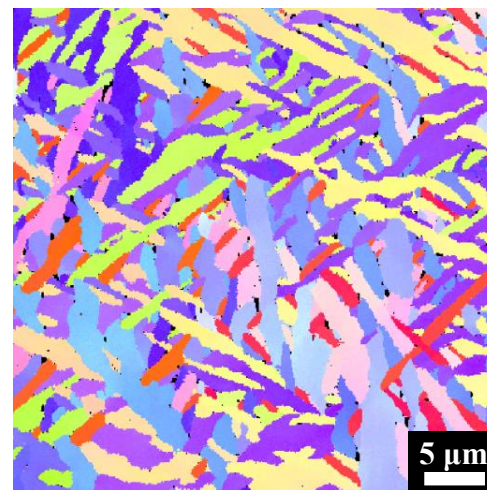
Crystallographic Texture

HED Region

Alpha ND IPF Map [Build (Z) // ND]

Max: 9.5
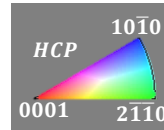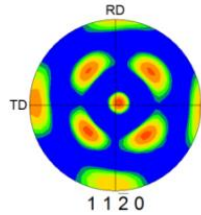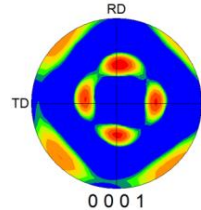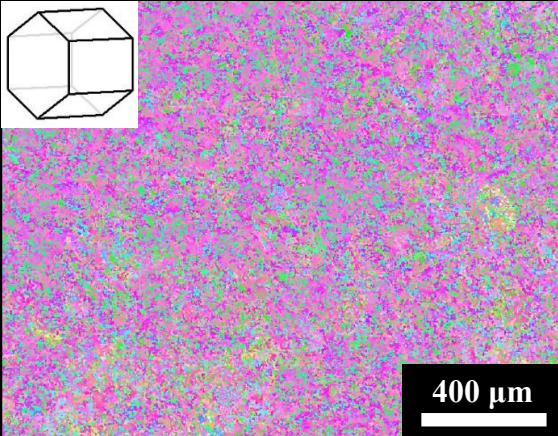
Beta ND IPF Map [Build (Z) // ND]

Max: 23.3

LED Region

Alpha ND IPF Map [Build (Z) // ND]
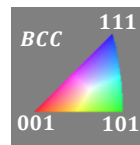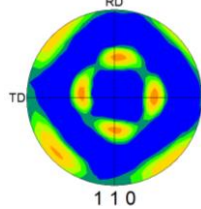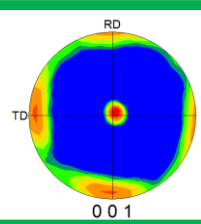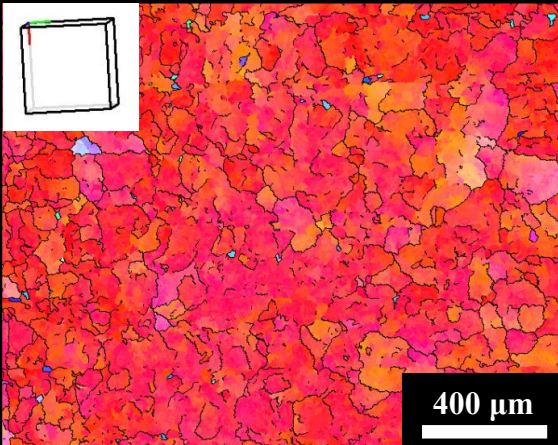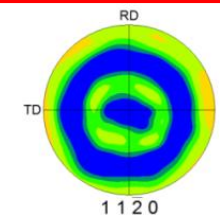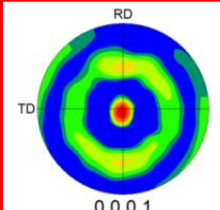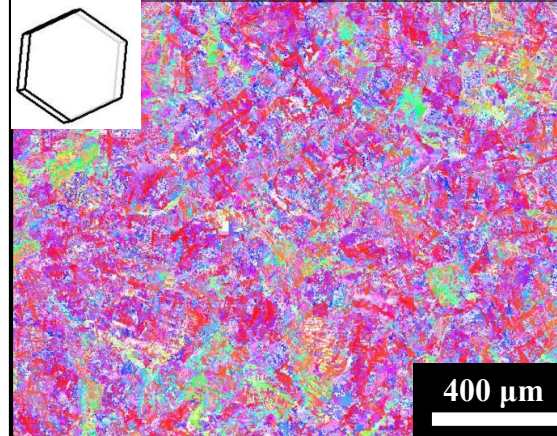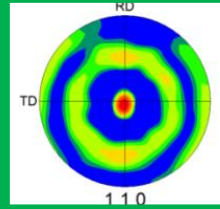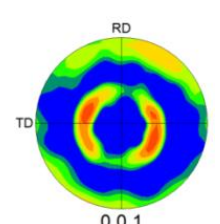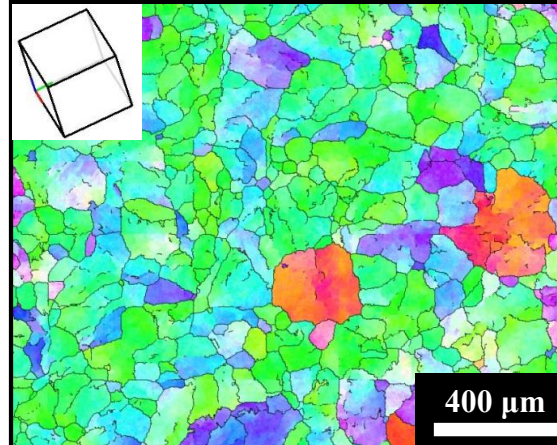
Max: 10.6
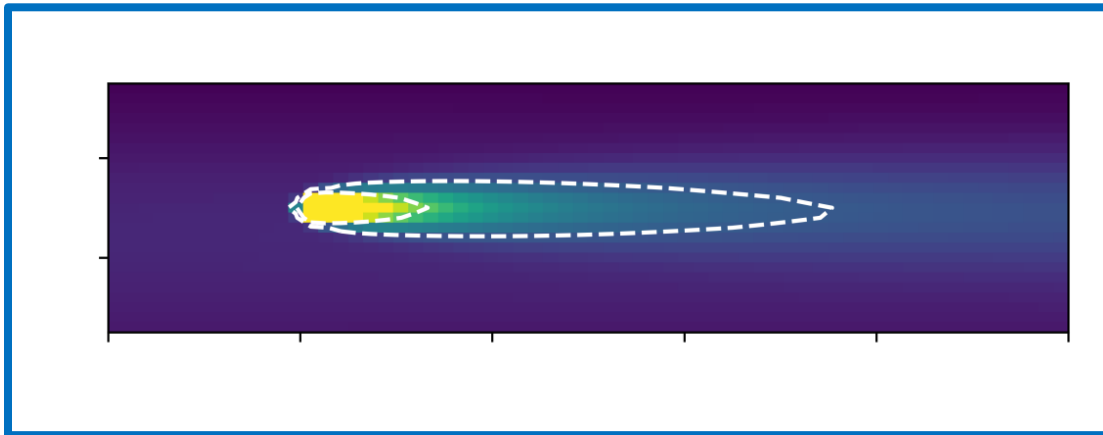
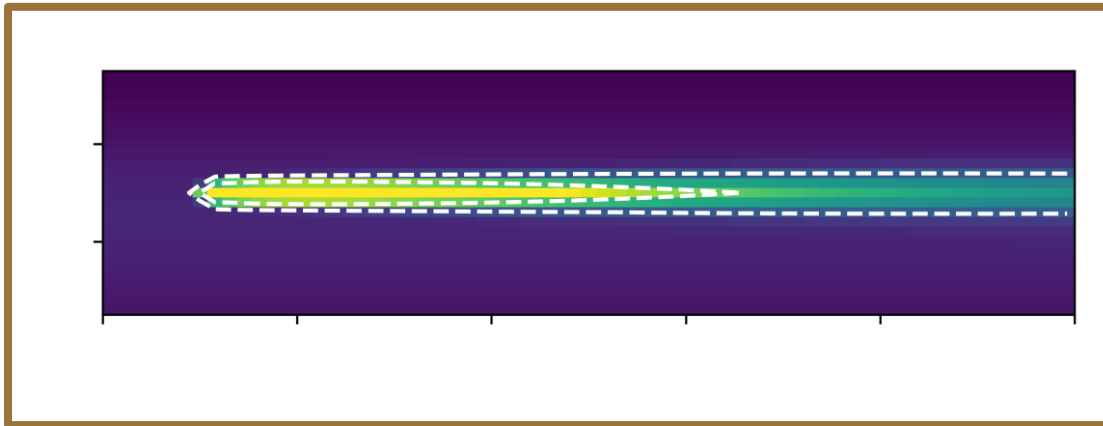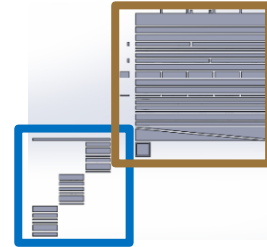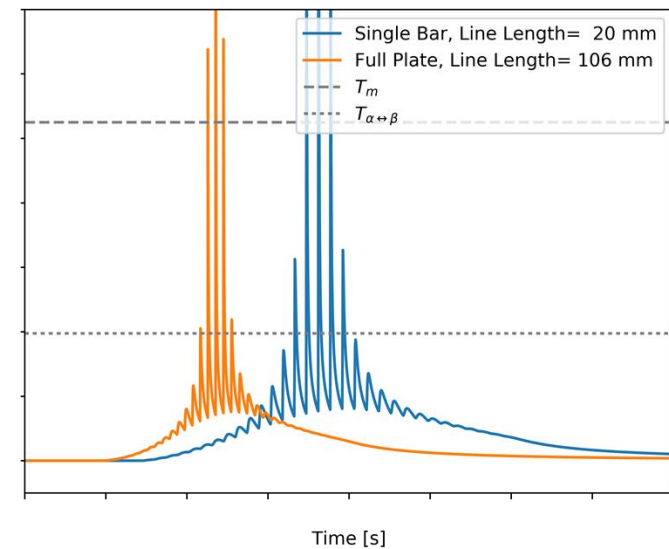Beta ND IPF Map [Build (Z) // ND]

Max: 6.9

A Century of Scientific Excellence for our Airmen

Single Bar, Line Length= 20 mm
Full Plate, Line Length= 106 mm
T_m
$T_{\alpha \leftrightarrow \beta}$

Temperature [C]

Time [s]

Thermal model shows solidification differences → explains textures

Outline

Overview of Additive Manufacturing

Process, Design, and Qualification Complexity

0[s]   32[s]

Process, Structure, Properties Linkages: DMLS

Voids in DMLS Ti-64

Process, Structure, Properties Linkages: EBM

Mechanical Response in EBM Ti-64

- Airbus A320 Nacelle Hinge Bracket
- Weight reduction by 64% 918g -> 326g

Source: Altair, SM3D Innovation Works
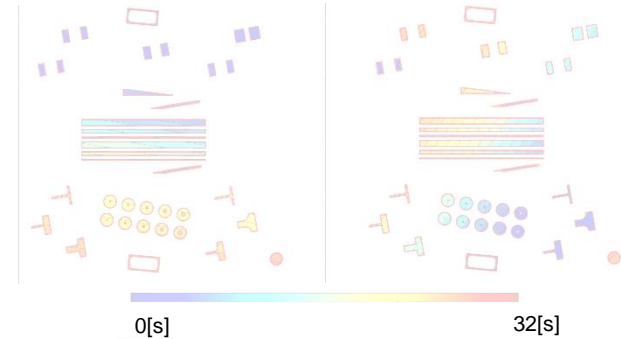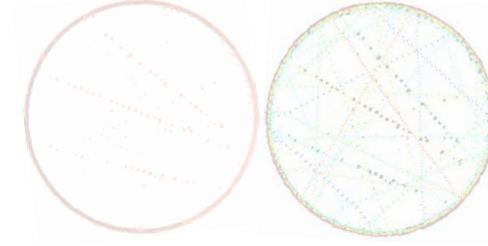
Forward Vision

Forecasting, Optimization, and Design for AM

Path Sensitive Process Maps

Control Spatial Processing Variation → Control Structure
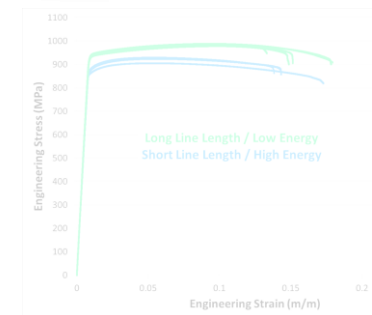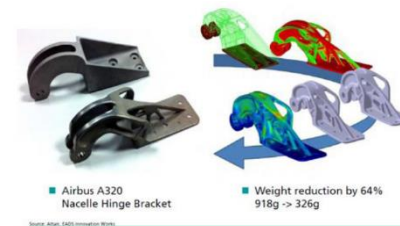
Voids

Voids & Stripe Boundaries

CAD Geometry

Data collected at GE (AFRL contract)
EOS M280   Ti-64

Processing-Structure Maps

Process Variable 2

Void V_f

Process Variable 1

Post-Build Defect Characterization

Temp v. Time Profiles

- Stripe center
- Stripe End
- Hatch

Temperature [C]

Time [sec]
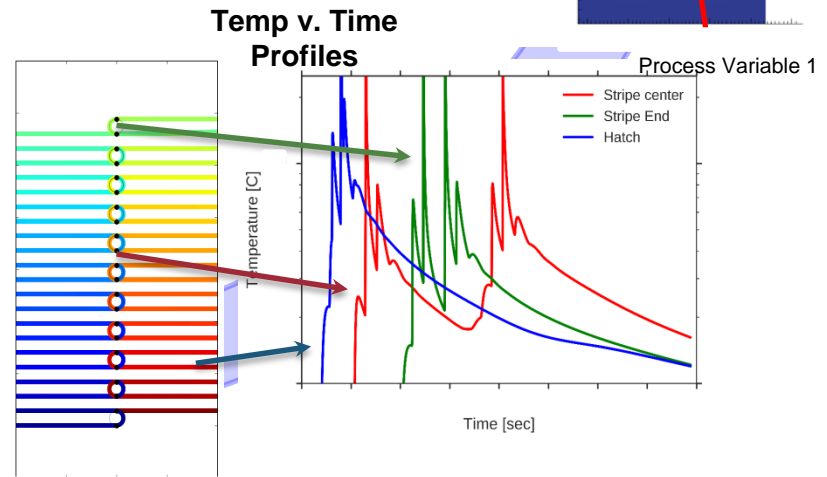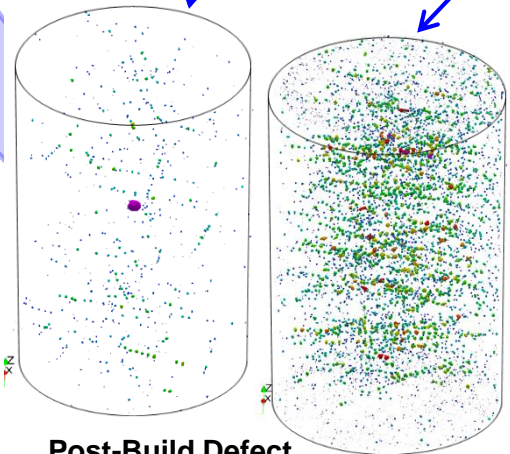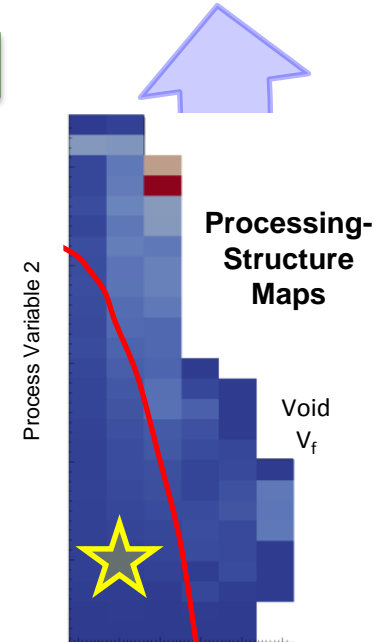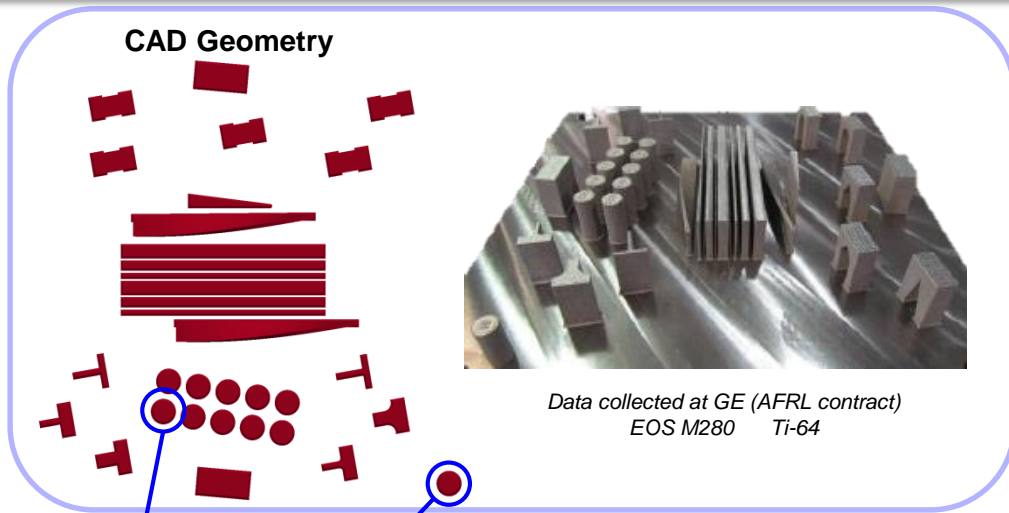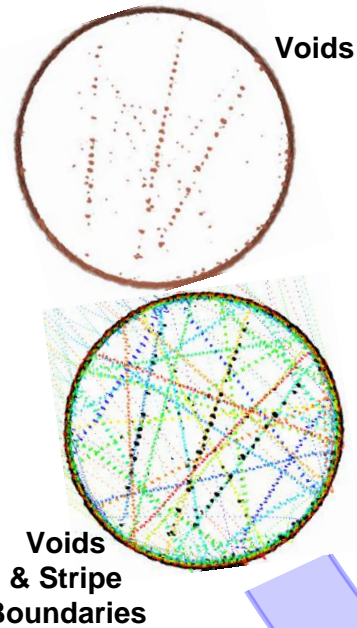
Transitioning to Industry Programs

Automated Registration of Intent, In-situ, & Post Build Characterization Data

CAD (.stl)   PrintRite Point Cloud   CT Scan   Registered Data

MAI, NG-7

Automatic keypoint extraction, mapping computation, and transformation application for all geometry types, within DREAM.3D

Fully automatic, one-click registration
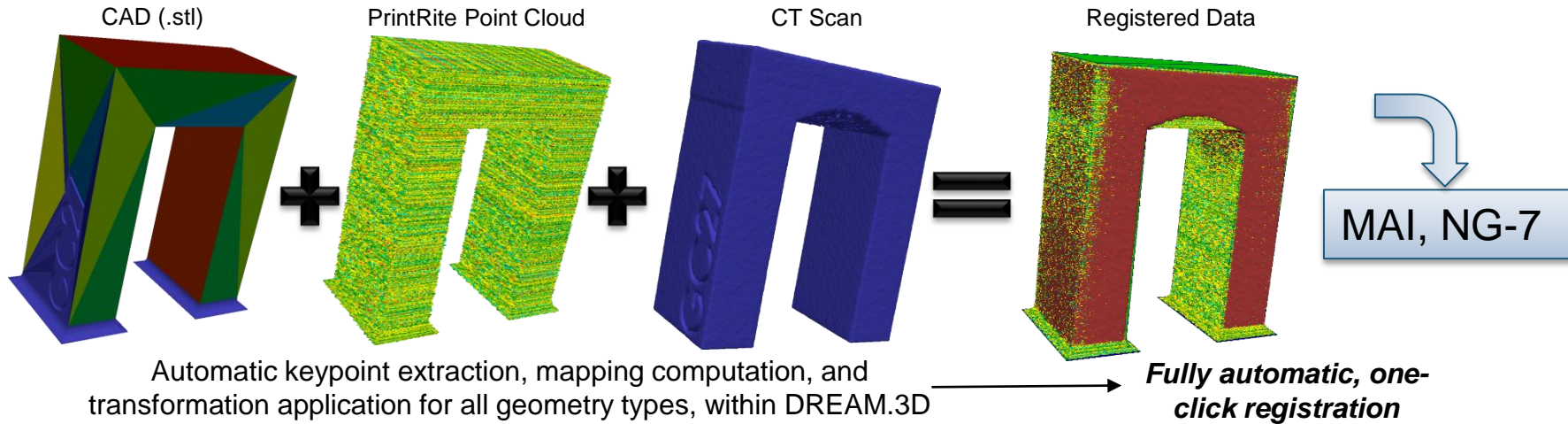
Cone Beam CT, Model Based Iterative Reconstruction
Thilo Balke & Charles A. Bouman

PURDUE UNIVERSITY
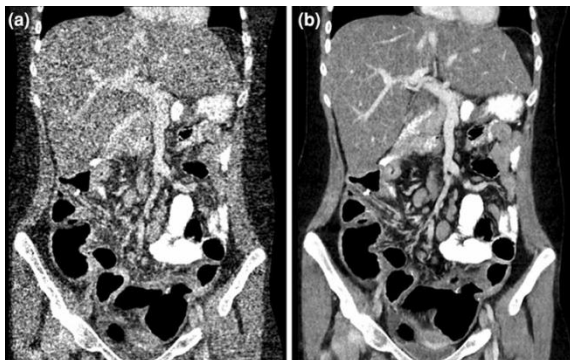
Experimental Data   Model Projection

MAI, NG-8
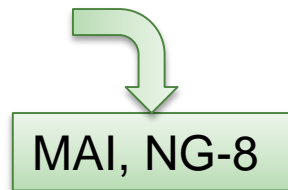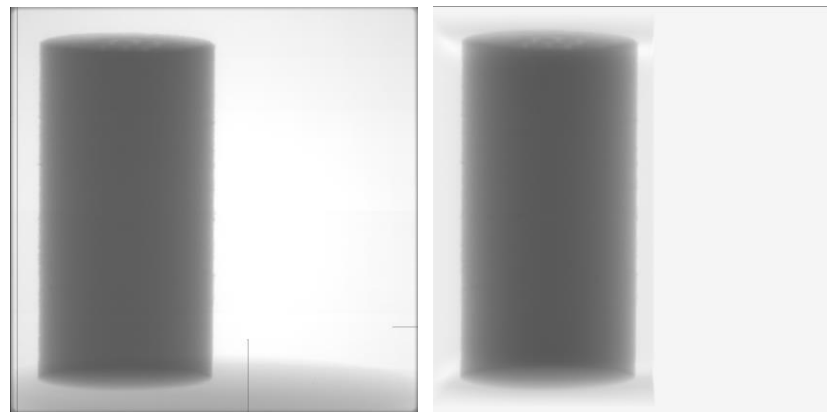
Reconstruction techniques on GE medical scanners

AM & Topology Optimization Tools

- **Inputs – envelope, boundary conditions, figure of merit**

- **Assumptions – isotropic, homogeneous nominal properties**

    – does not consider processing, inspection, μ-structure

- **Model – 1,000s of iterations, compare to figure of merit**

- **Present voxelized representation of best solution**

GE Bracket Challenge

- Airbus A320 Nacelle Hinge Bracket
- Weight reduction by 64% 918g -> 326g

Source: Altair, EADS Innovation Works
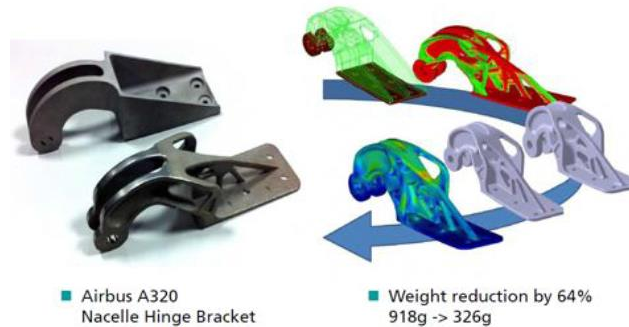
Must account for processing influences on material properties

Forecasting Material Heterogeneity

Microstructure - Texture

Highly-Pedigreed AM Builds

High-fidelity Detailed Processing, Structure & Property Characterization

Experiment

Simulation

Axial Strain

Transverse Strain

Validation & Benchmarking of Current Forecasts

Community Challenges
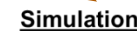
Actionable Materials Forecasts

Build framework to assess data streams & models → build surrogates models to forecast zones for topology optimization

Questions?