

Advanced Materials & Manufacturing Technologies

Digital Thread: The Multi-Dimensional Data Correlation (MDDC) Framework

Vincent Paquit
Lead – Energy Systems Analytics group

AMMT Industry Workshop - May 23rd & 24th 2023
ORNL Manufacturing Demonstration Facility

The Multi-Dimensional Data Correlation (MDDC) Framework: Multi-length scale data integration

Lead Lab and contributing Lab(s):

Mark Messner (ANL), Andrea Jokisaari (INL), Laurent Capolungo (LANL), Vincent Paquit (ORNL), Ayoub Soulami (PNNL)

Scope:

Establish a discipline common to all participants of the AMMT program that defines the protocol for data collection and processing at every step of the manufacturing process, but also during the subsequent characterization and testing phases, and ultimately during operation

End-of-project goal

Digital platform supporting the certification and qualification of AM components for nuclear applications

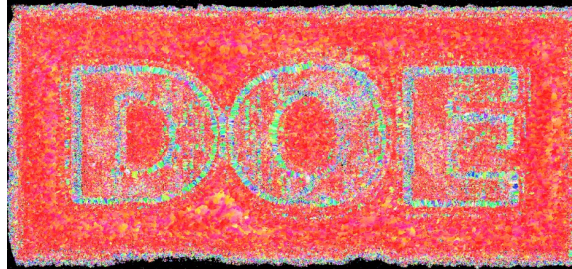
Objectives:

- Develop a unified software architecture for AMMT data management and processing
- Deploy digital platform across AMMT participants' facilities
- Generate pedigree datasets across multiple labs and facilities



Data Analytics Framework for Advanced Manufacturing

Scientific drivers

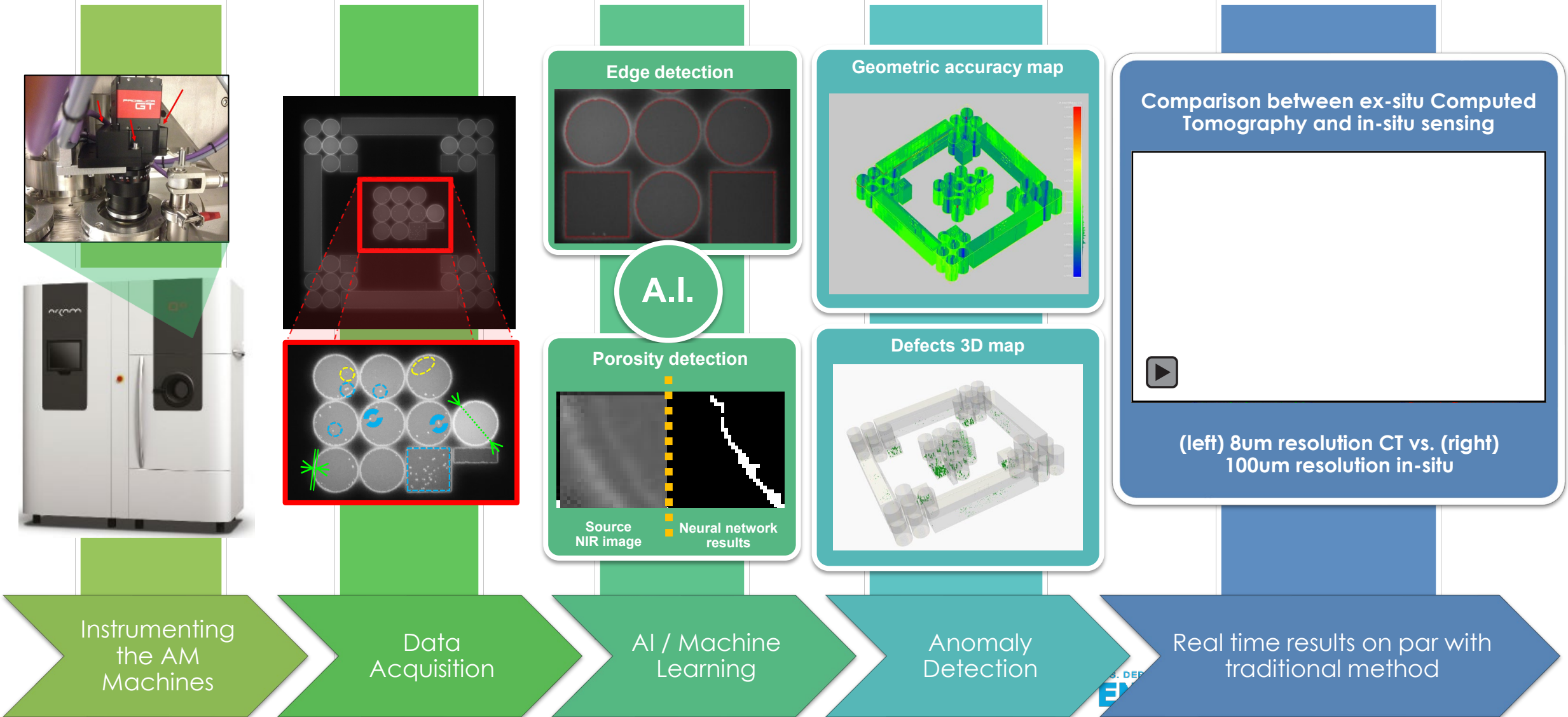


Develop new certification methodologies

Accelerate production of complex components

Improve manufacturing technologies

In-Situ Quality Control of AM Processes using AI



Smart Manufacturing Approach

A technology-agnostic data analytics framework for manufacturing: a four-step data-driven approach toward processes optimization, qualification, and certification of manufactured parts.

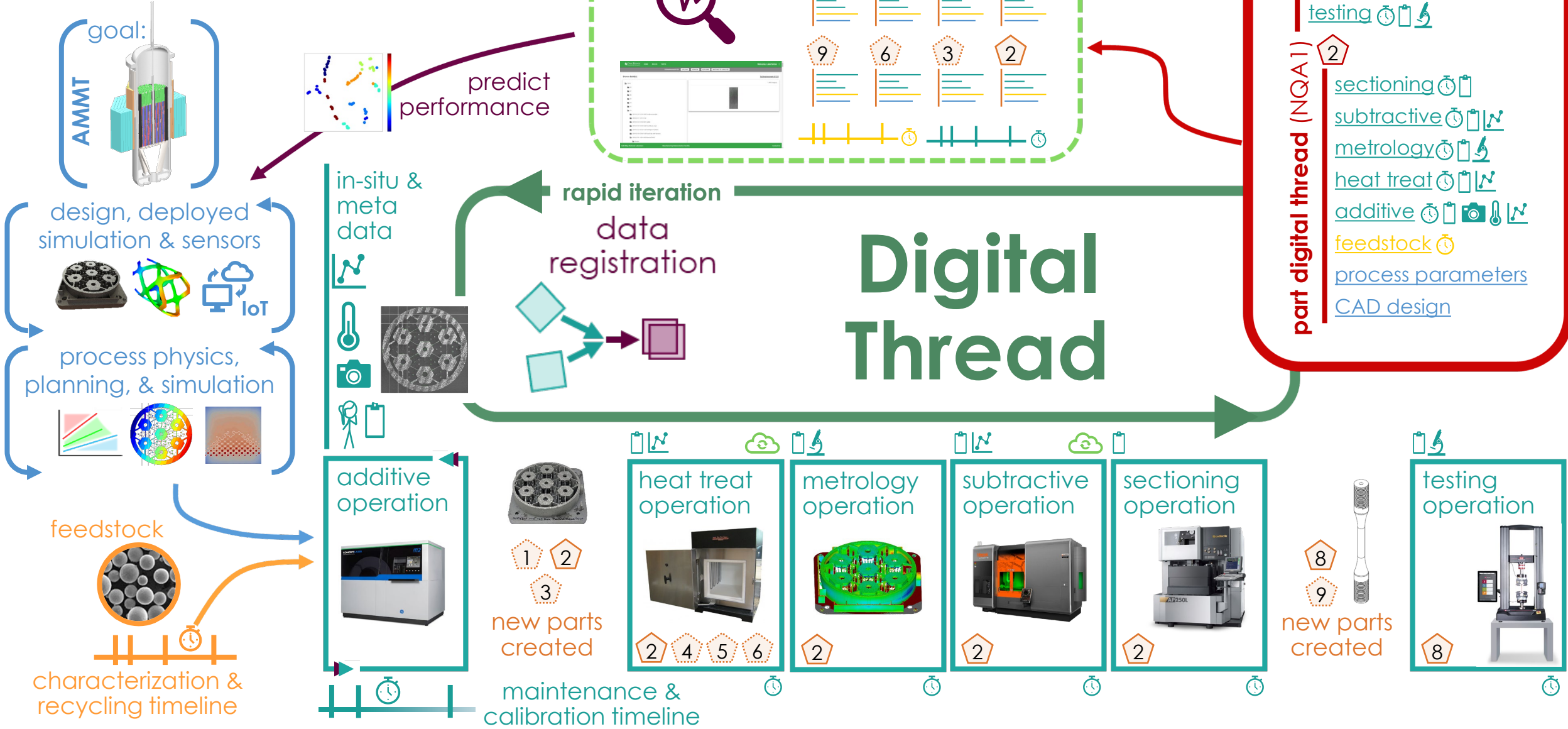
Step 1: Understand the process

Step 2: Optimize the process

Step 3: Create feedback loop for self-optimization/ correction

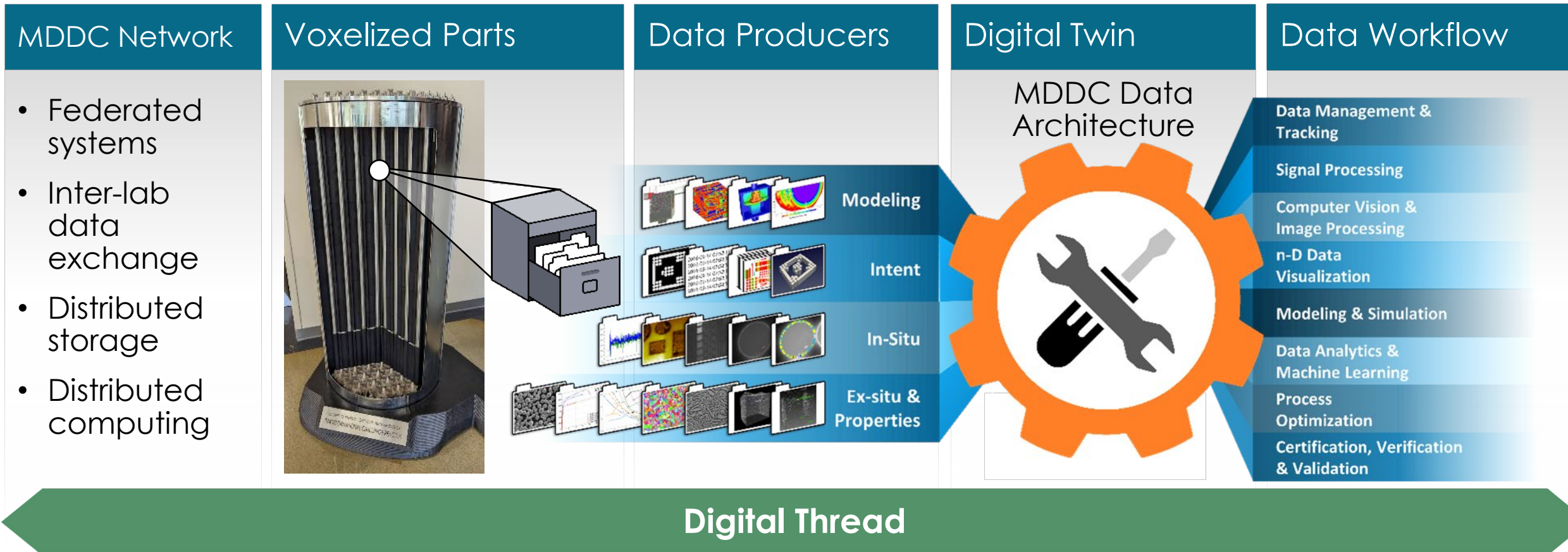
Step 4: Certify and qualify components

Digital Discipline



Unified Software Architecture for AMMT Data Management and Processing

Advanced manufacturing technologies produce valuable datasets at every stage of the manufacturing workflow. Collecting, structuring, and analysis such data is paramount to understanding, optimizing and validating the manufacturing process.



Data Management and Digital Discipline



Web-based Digital Tool

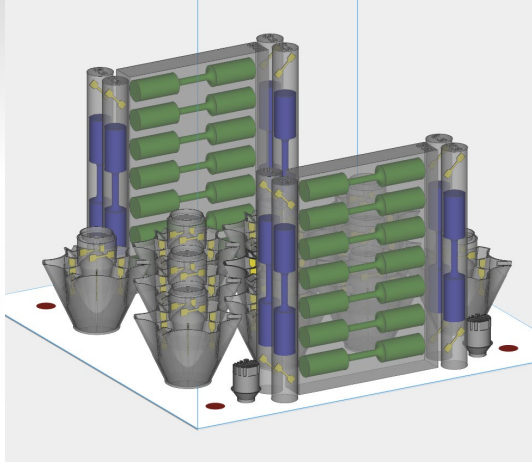
OAK RIDGE National Laboratory | HOME OPERATIONS PARTS

ConceptLaserM2-ORNL1 | UPLOAD SEARCH EXPLORE WAITING TO ANALYZE

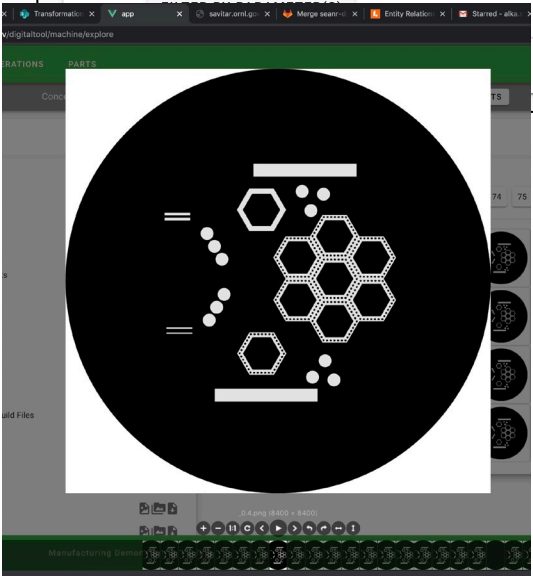
Build(s): ConceptLaserM2-ORNL1

Action	Name	Start Date	End Date	Status	Material
<input checked="" type="checkbox"/>	Framatom Arch	2020-02-04	2020-02-04	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	Airfoils & TCR Moderator Pieces	2020-02-07	2020-02-07	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	Kairos Impeller	2020-02-12	2020-02-12	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	MDF Framatome Fasteners 01	2020-02-26	2020-02-26	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	Fastener Assembly	2020-02-06	2020-02-06	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	Framatome Fastener Components	2020-02-14	2020-02-14	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	TCR Moderator Pieces	2020-02-03	2020-02-03	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	Framatom Middle Section	2020-02-05	2020-02-05	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	Inner Mask Mold Bottom Section	2020-04-08	2020-04-08	Successful	316L/Praxair/27
<input checked="" type="checkbox"/>	Theta Impeller and TCR Endcaps	2020-03-12	2020-03-12	Successful	316L/Praxair/27

Physical and Digital Traceability



Physical and Digital Traceability



OAK RIDGE National Laboratory | HOME PARTS | Welcome, Alka Singh

Part Timeline: PART THREAD REPORT RESET

2021

Jul Aug Sep Oct Nov Dec

Heat Treatment (Aug)

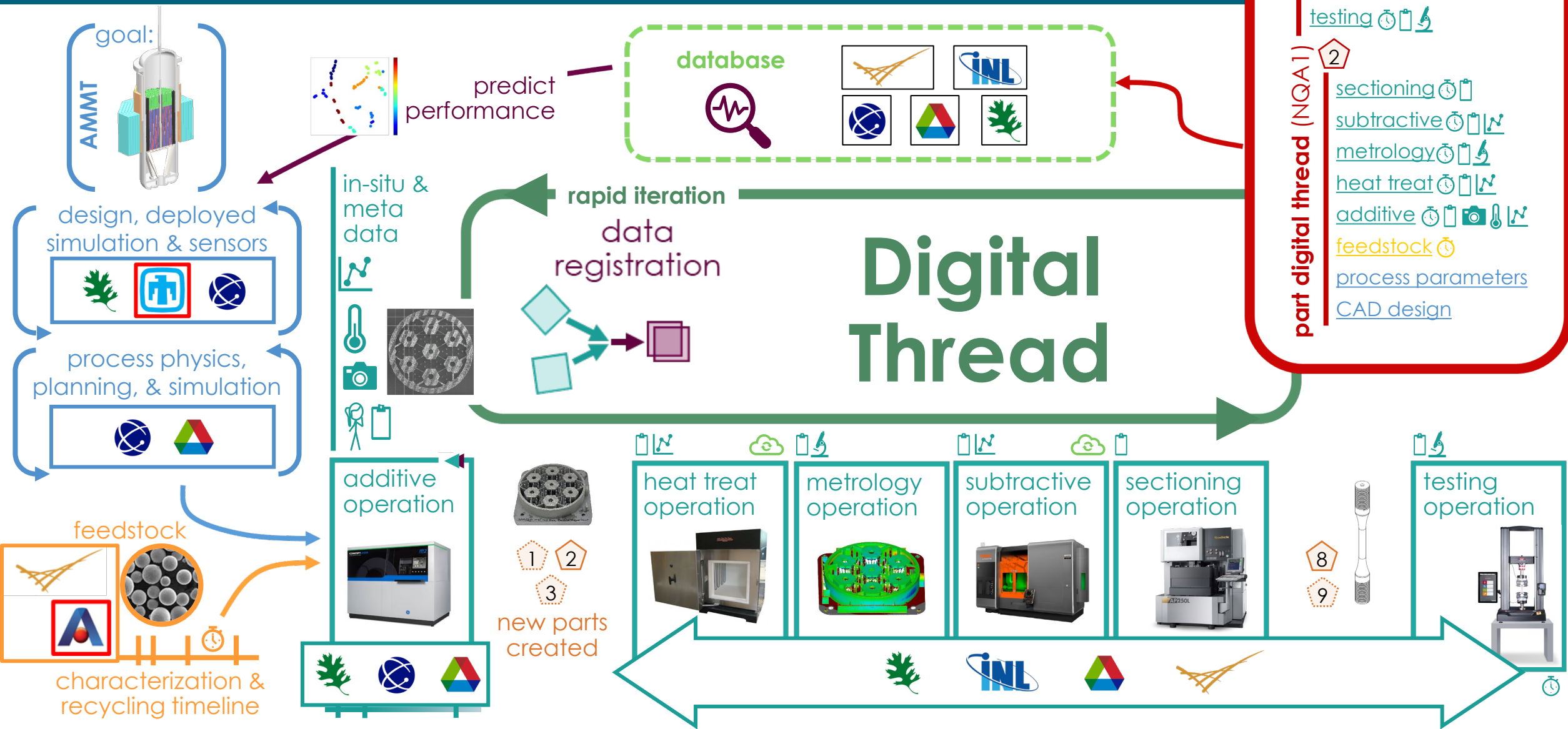
Additive Manufacturing (Aug)

Wire EDM (Nov)

Tensile Testing (Dec)

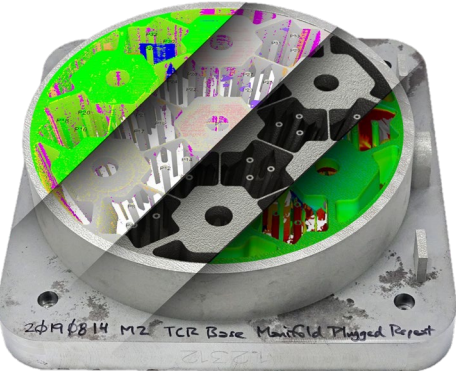
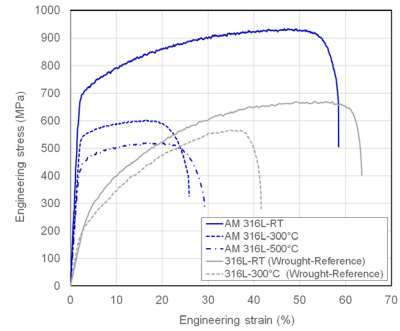
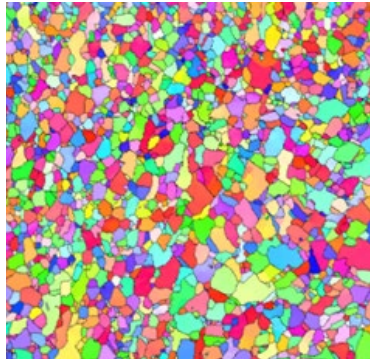
Content: Wire EDM
Machine: SodickAQ750LH-T0981
Global parts: 6132
Operation Date: 2021-11-15 09:14:28
Technician: Ryan Duncan

Complexity of a Multi-Site MDDC Platform



Digital Tool : Database structure

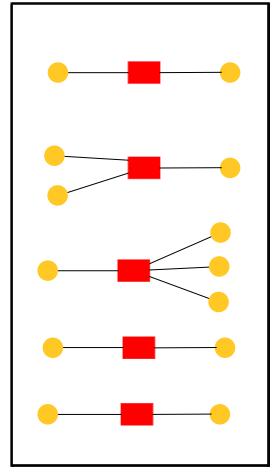
Reference to Data
[files, time series, etc.]



Operations

Printing
Testing
X-Ray CT
Wire EDM
Scans
SEM
...
Recycling

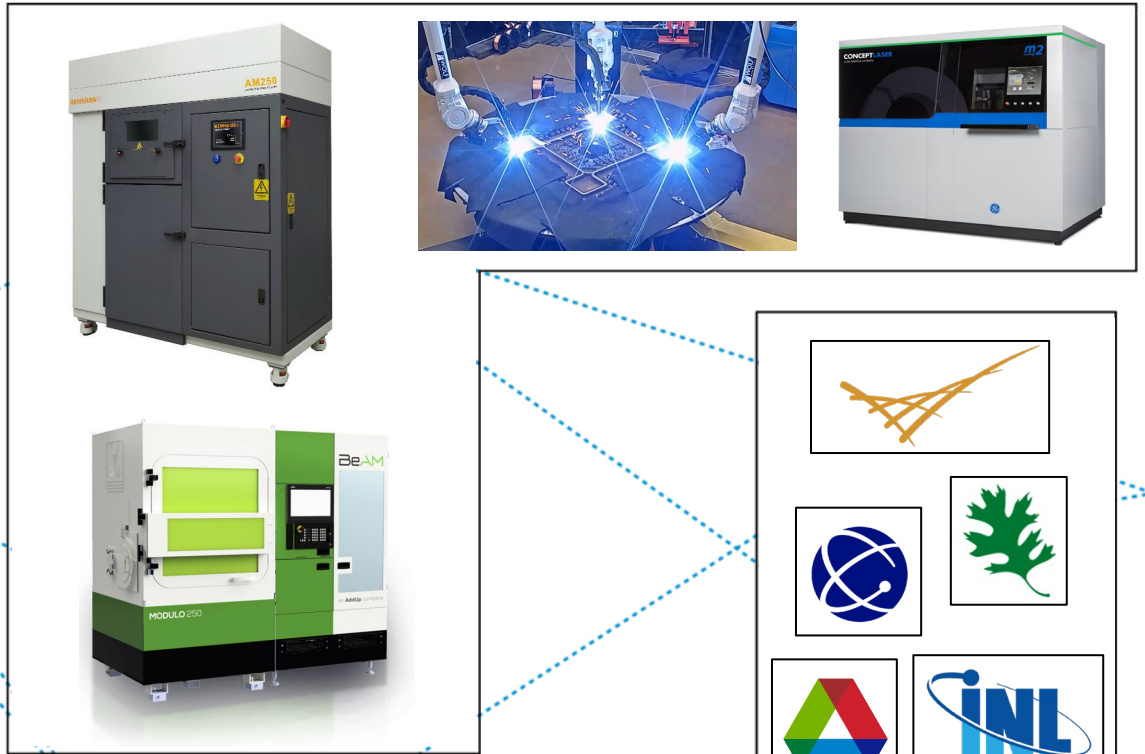
Association tables



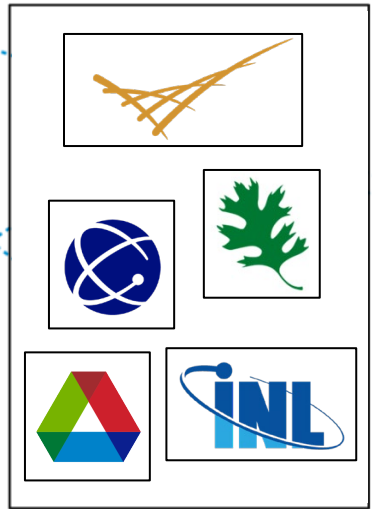
Materials
Part
Tensile
Batch
Specimen
Build
...
Digital Model

Trackables

Machines

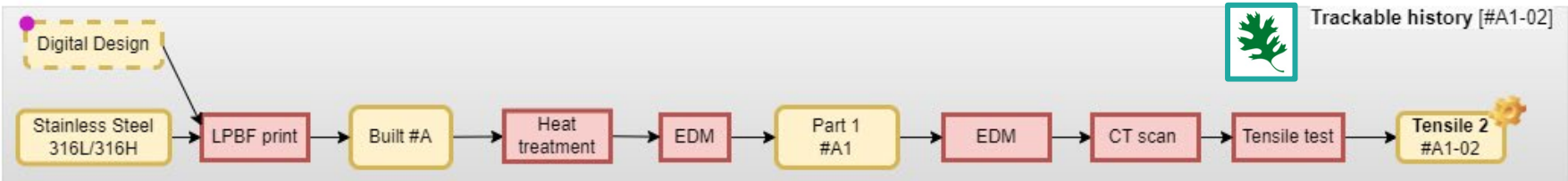
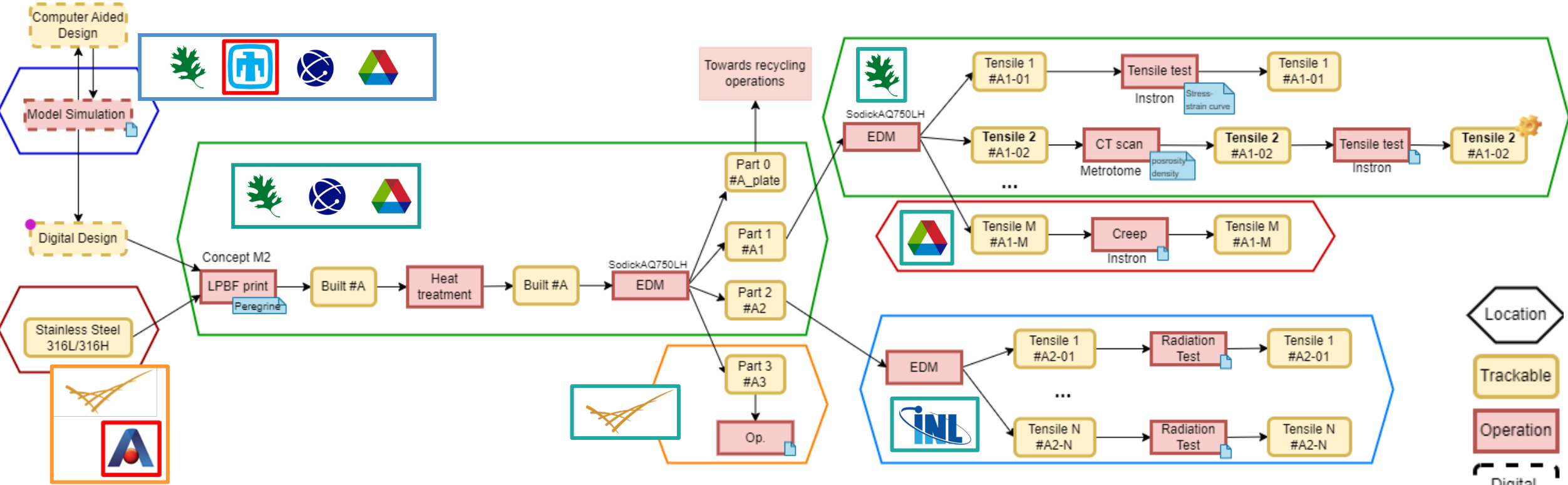


People



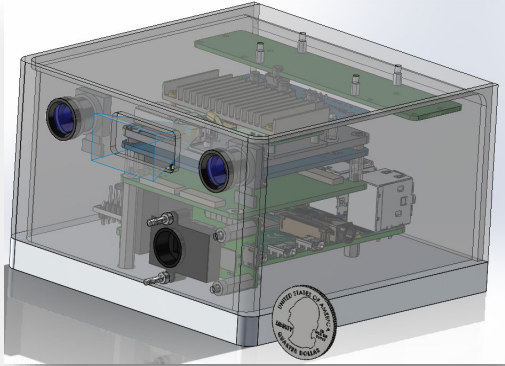
Organization / Location

Life Cycle Data Integration

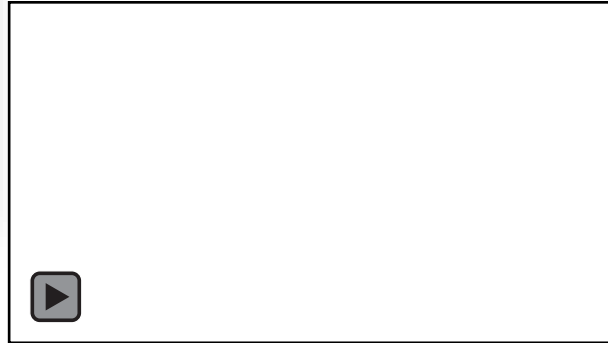


In Situ Monitoring, Sensor Development and Integration

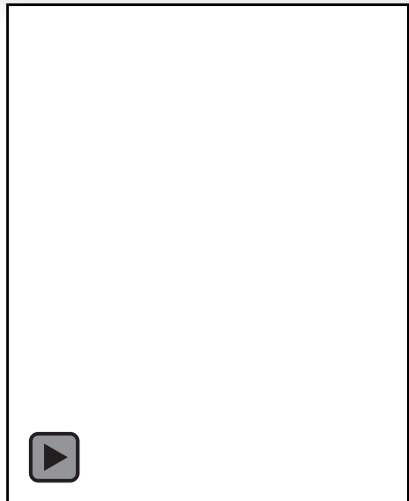
SCOPS



- Compact multimodal imaging technology



Shape measurement
(Okuma – Hybrid)



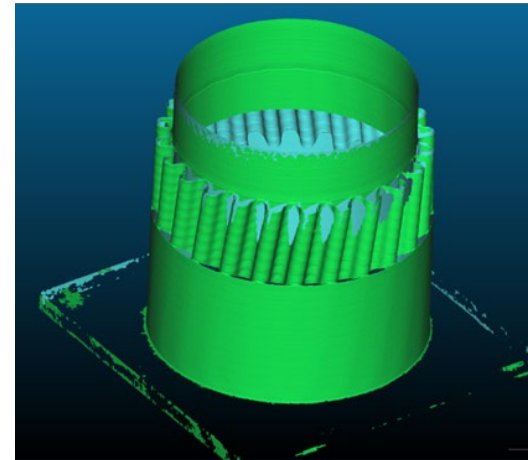
Thermal
(BeAM – blown powder)



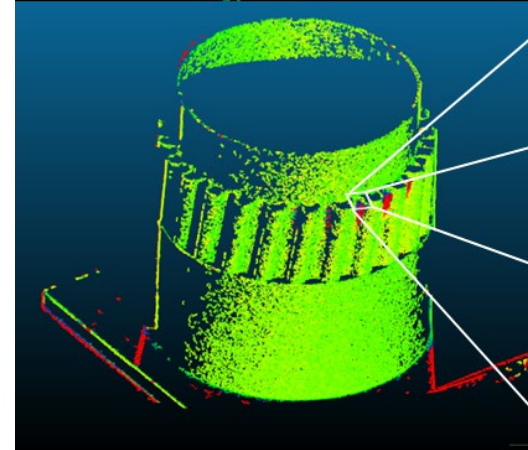
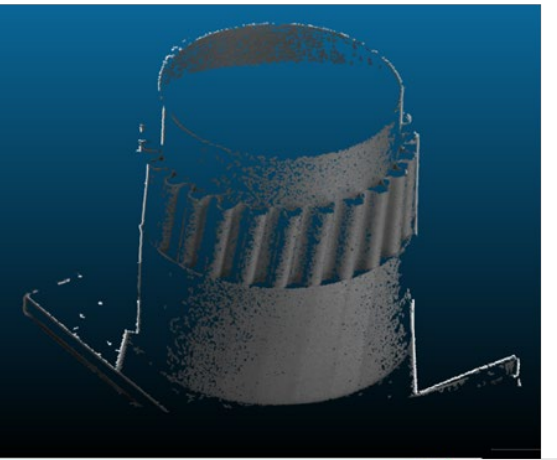
Strain measurement
(GKN – Laser wire)

Performance

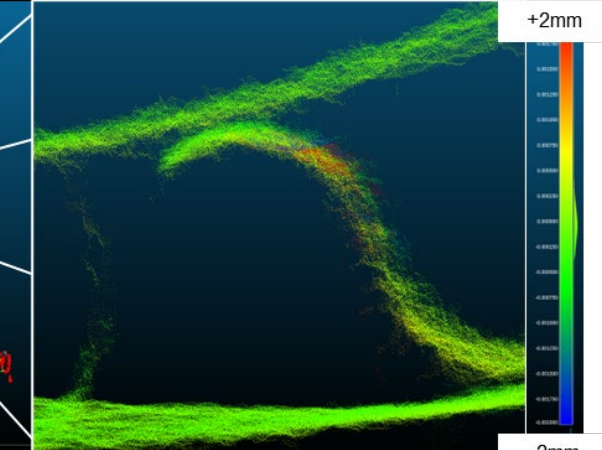
White light scan



SCOPS 3D scan

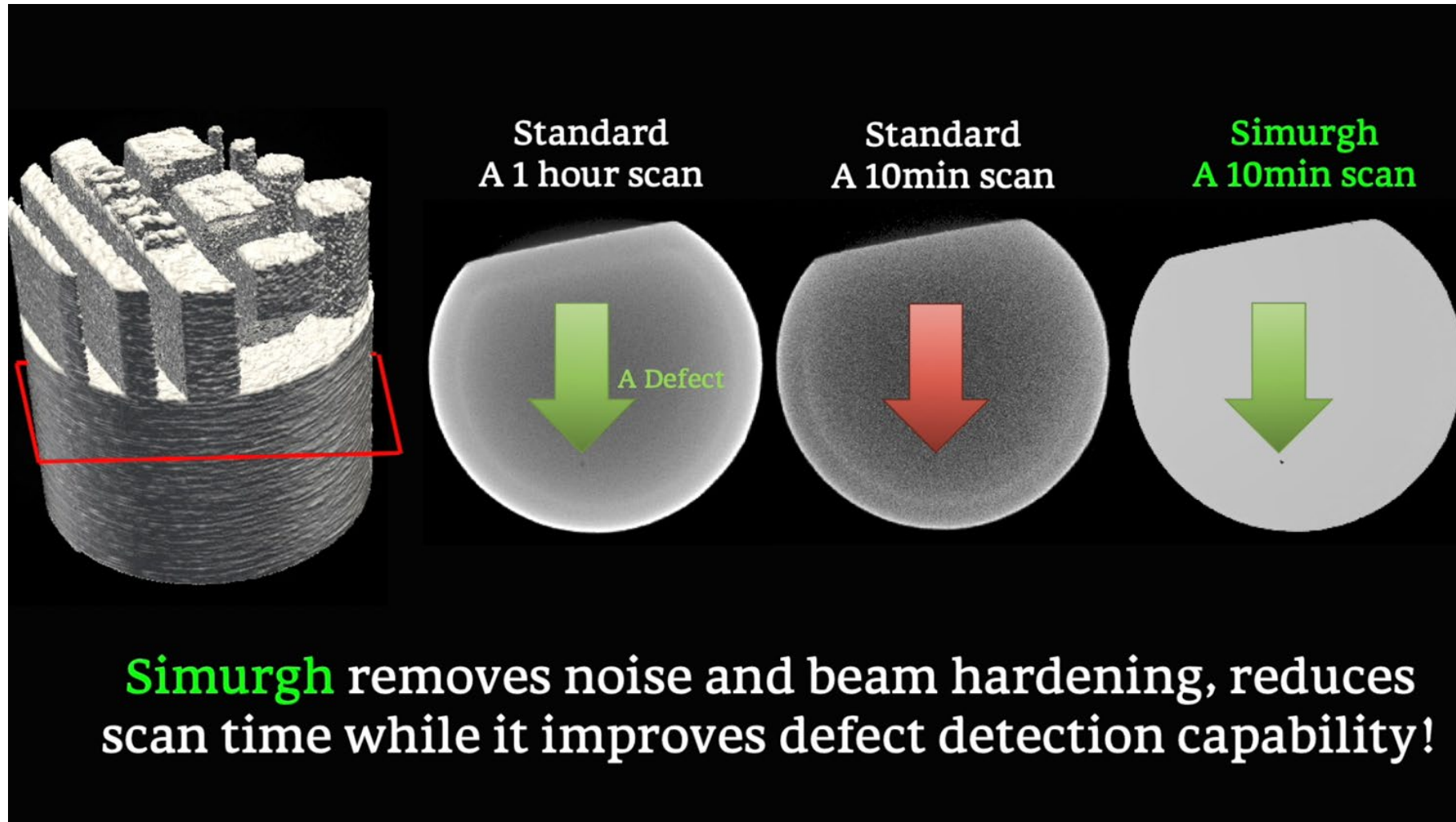


Comparison



Corrugation Detail

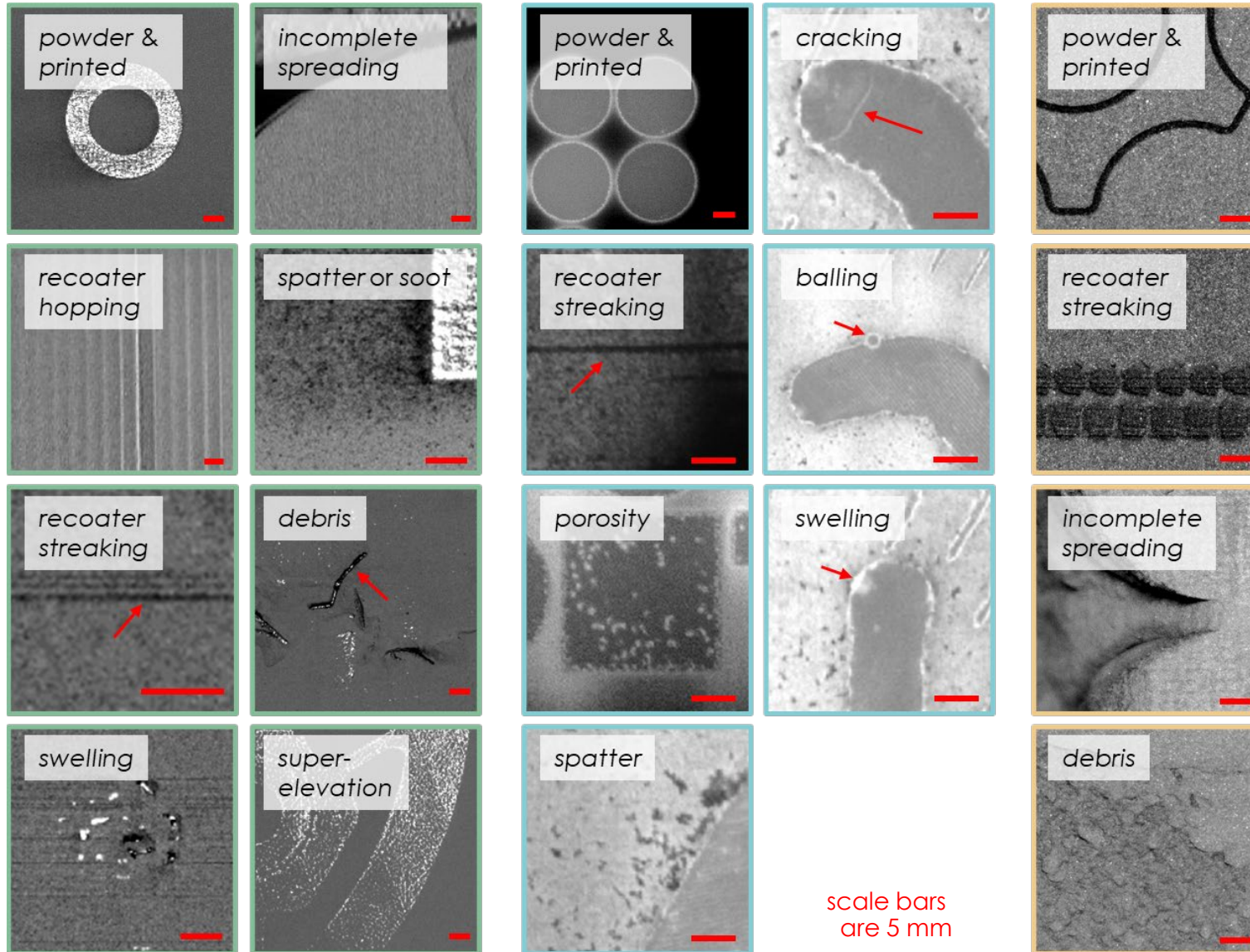
Simurgh AI-based X-ray CT reconstruction



Simurgh removes noise and beam hardening, reduces scan time while it improves defect detection capability!

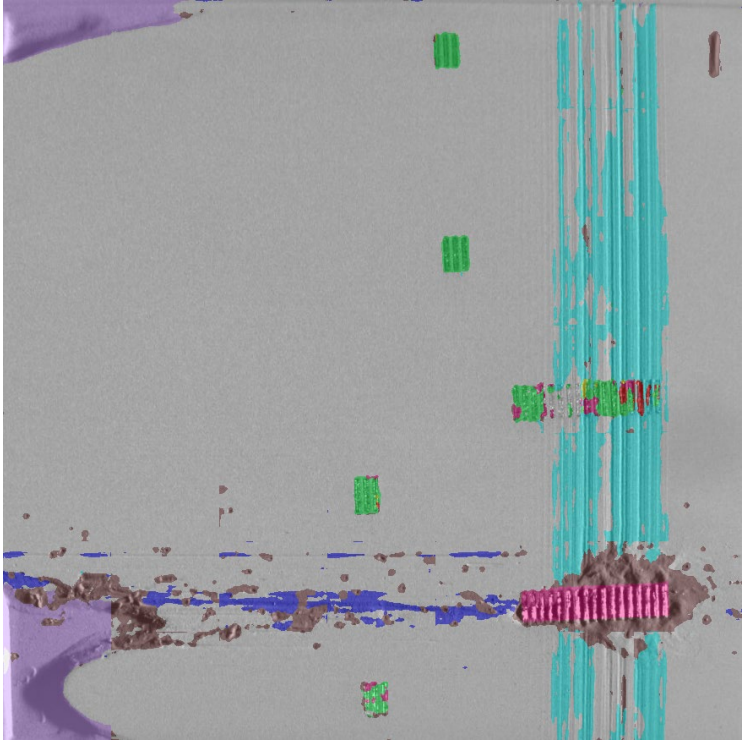
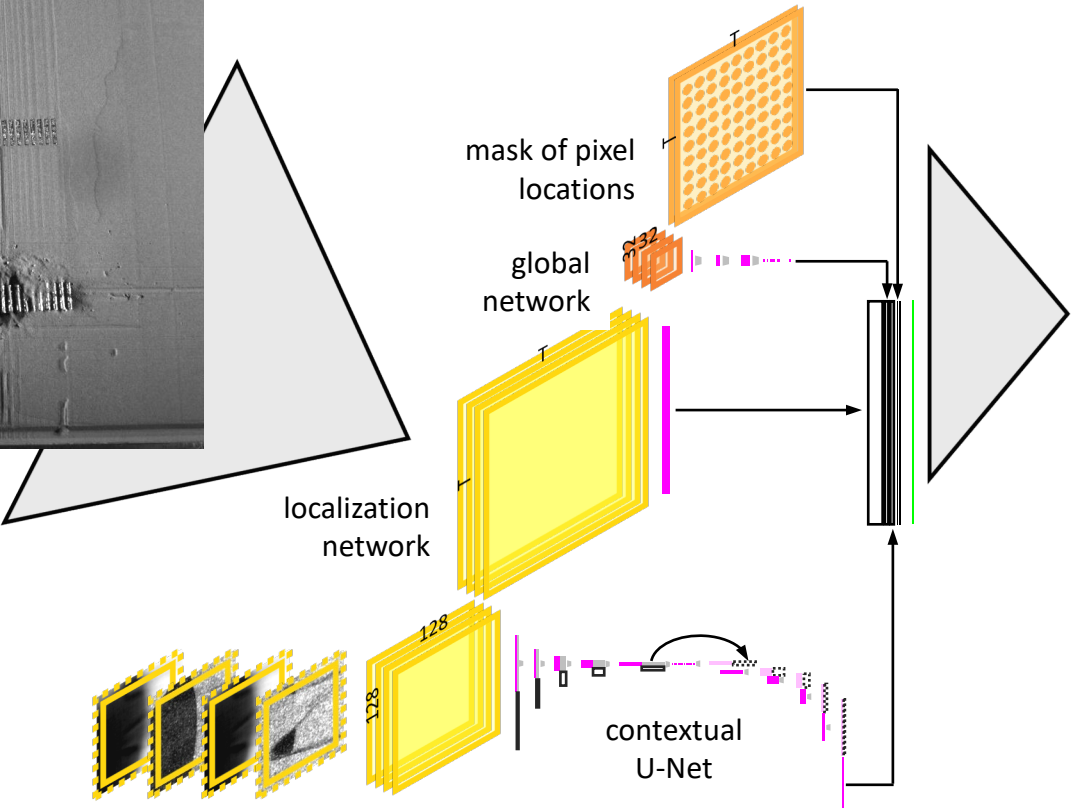
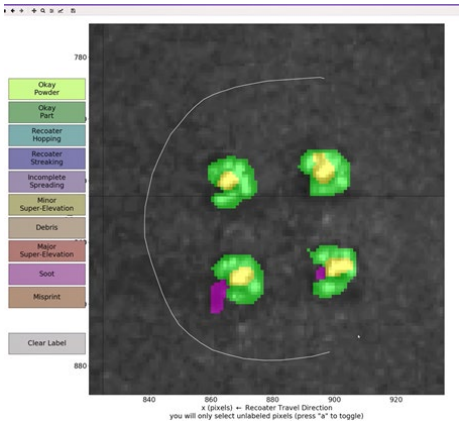
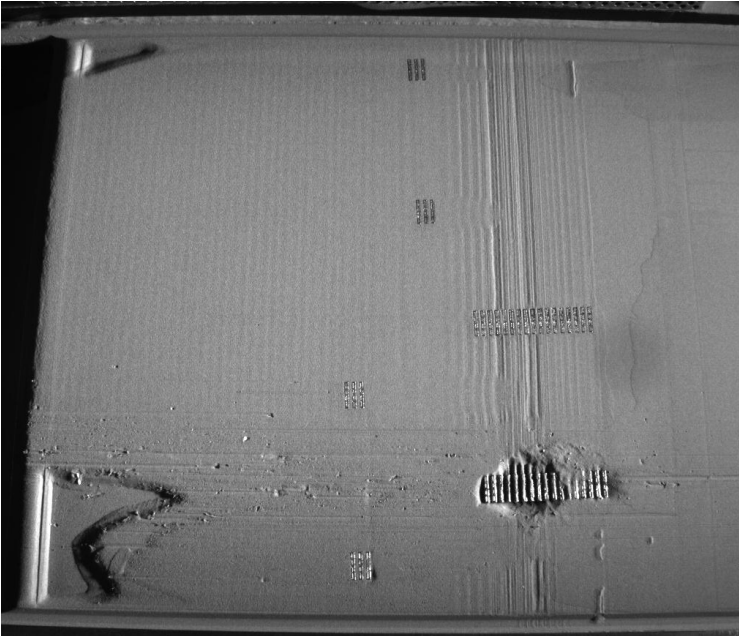
- Technology provides:
 - 10X improvement in feature resolution
 - 12X improvement in characterization time
- Commercial copyright license available
- Provisional patent
- **Licensed by Zeiss**
- Publication DOI: 10.1115/IMECE2020-23766

Available Data and Common Process Anomalies



- **Laser Powder Bed Fusion (L-PBF)** printers usually have visible-light and infrared cameras
- **Electron Beam Powder Bed Fusion (EB-PBF)** printers usually have near-infrared cameras
- **Binder Jet** printers usually have visible-light and infrared cameras
- Most systems record health data
 - oxygen concentration
 - motor current draws
 - temperatures
 - etc.
- Heat source scan path data can be used to transform **temporal** data into the **spatial** domain

Defect detection AI workflow and transfer learning



- Okay
- Recoater Hopping
- Recoater Streaking
- Incomplete Spreading
- Major Super-Elevation
- Debris
- Minor Super-Elevation
- Part Damage
- Part Outlines

Dynamic Segmentation Convolutional Neural Network

Peregrine

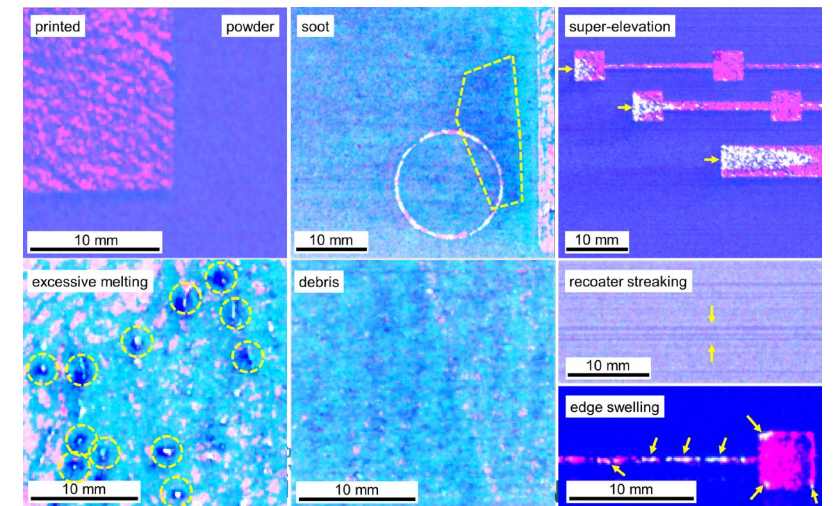
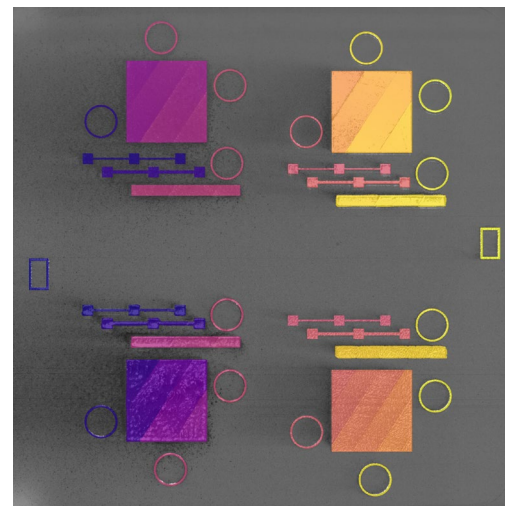
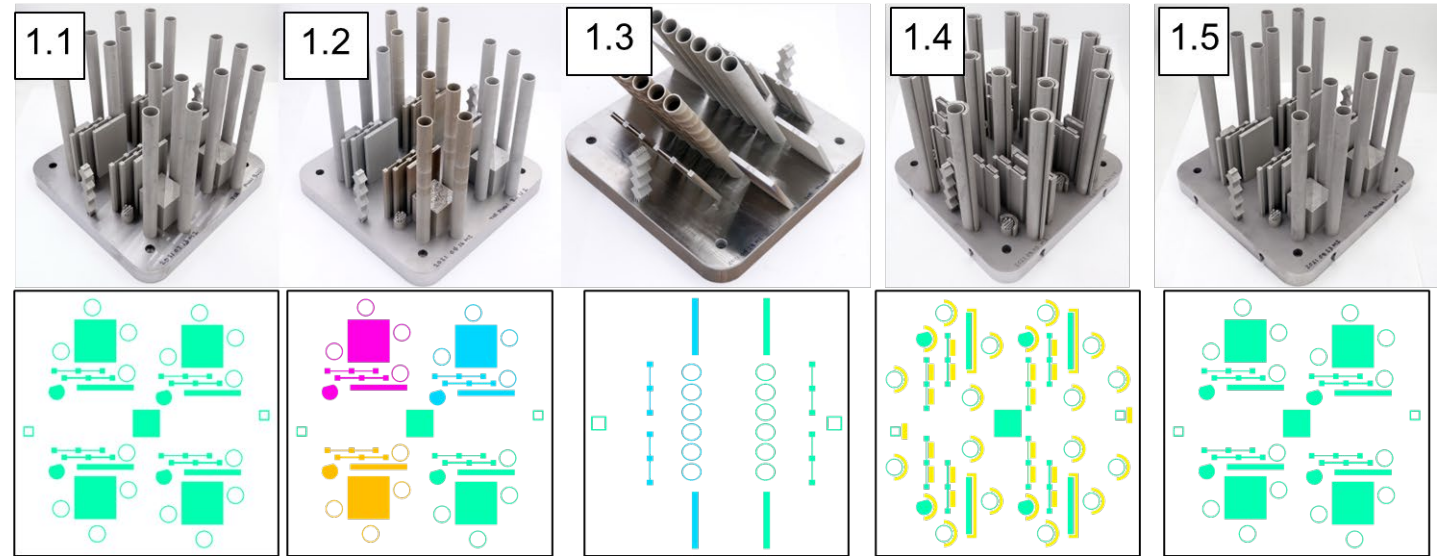
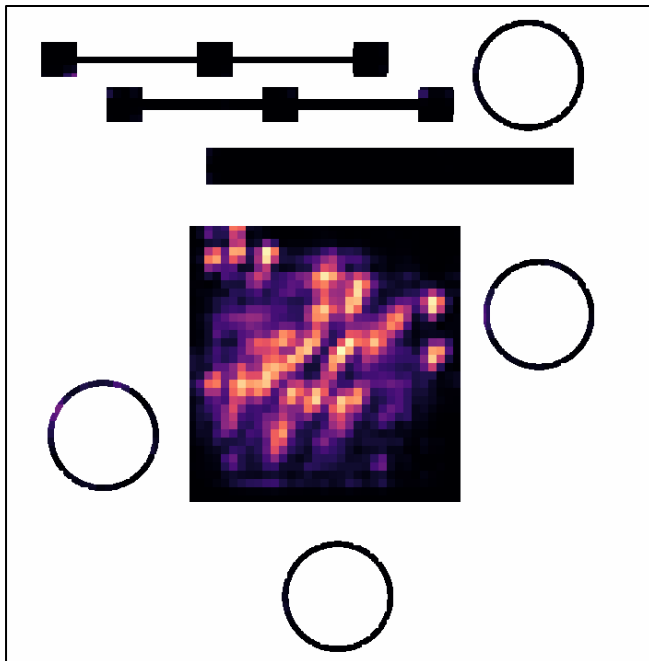


- AI software for real-time 3D print monitoring
- Main platform for most of the TCR data analytics activities
- Commercial copyright license available
- **>35 Licenses**
- **2022 FLC Excellence in Technology Transfer Award**
- Publication DOI:
10.1016/j.addma.2020.101453



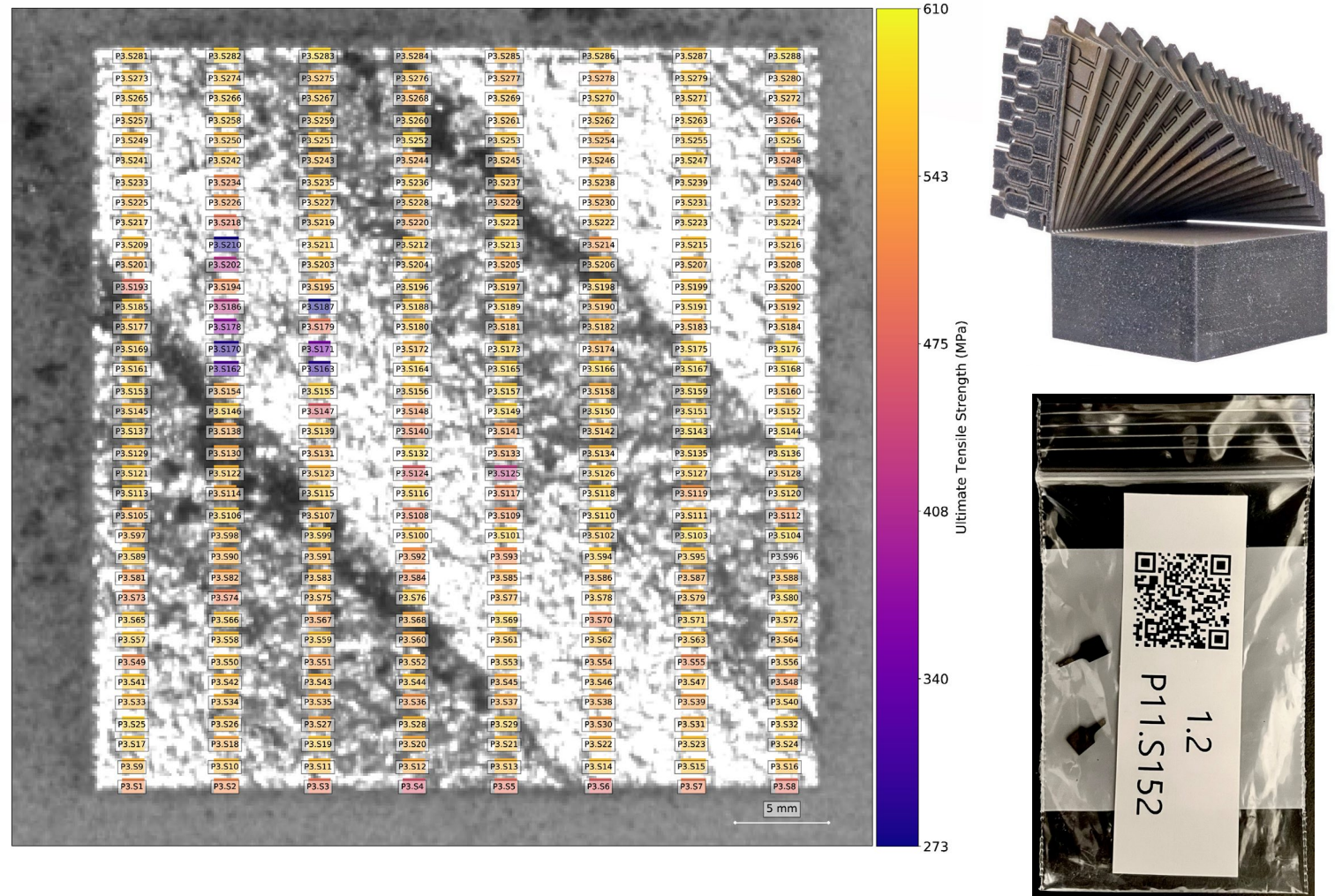
In Situ Data Collection

- Data collected from **5** builds with varying process **parameters**, part **geometries**, and process **conditions**
- Data from a 5 MP **visible-light** camera, the laser **scan path**, and printer **health monitoring** sensors
- Data are broken into sub-volumes call **super-voxels**



Tensile Testing

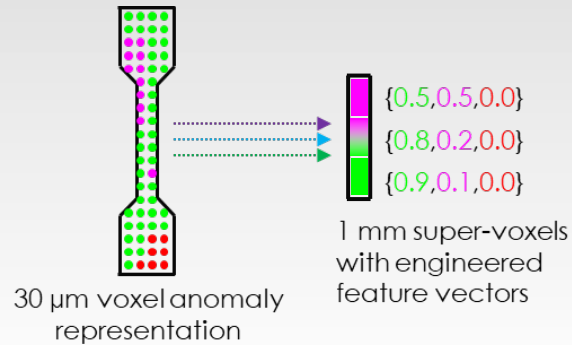
- Spatially tracked **6,299** unique SS-J3 tensile specimens
- Automated the analysis of the load-displacement curves to extract **yield strength, ultimate tensile strength, uniform elongation, and total elongation**
- As a side effect this produces a massive database of L-PBF **SS 316L** material properties



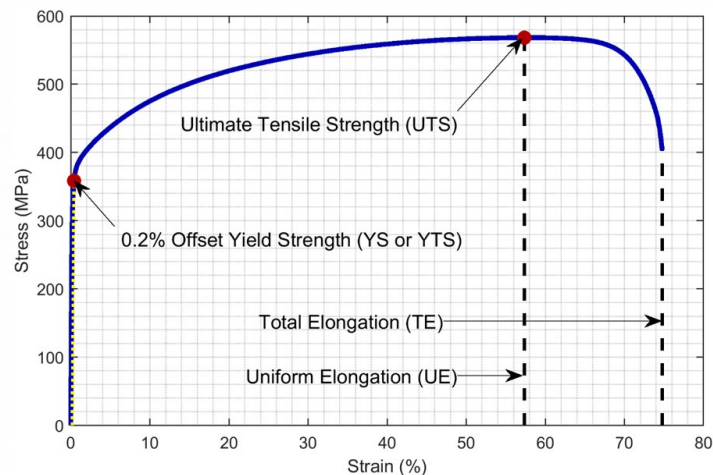
Validation Performance

Input Data

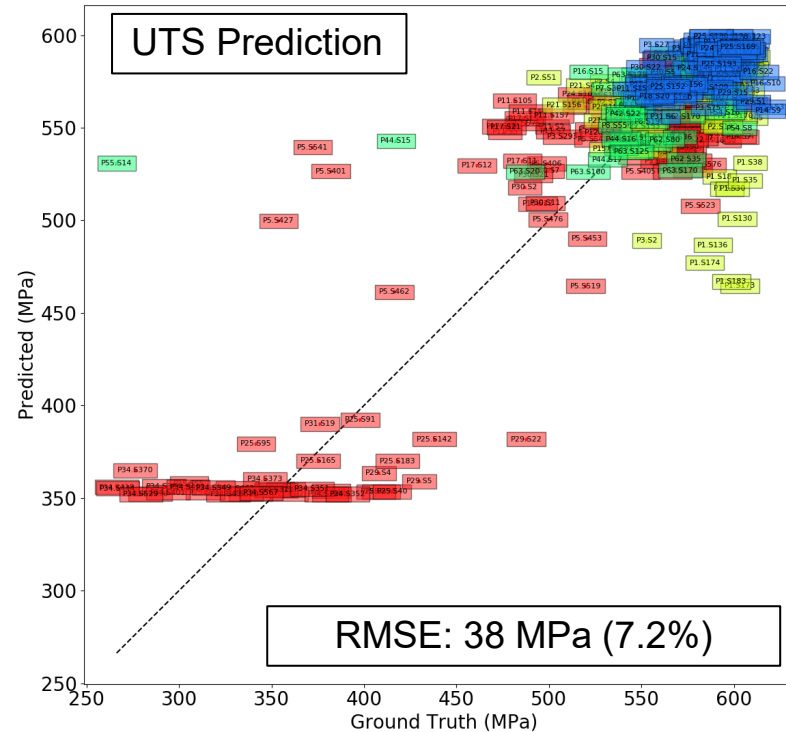
- Intent + in-situ + modelling data



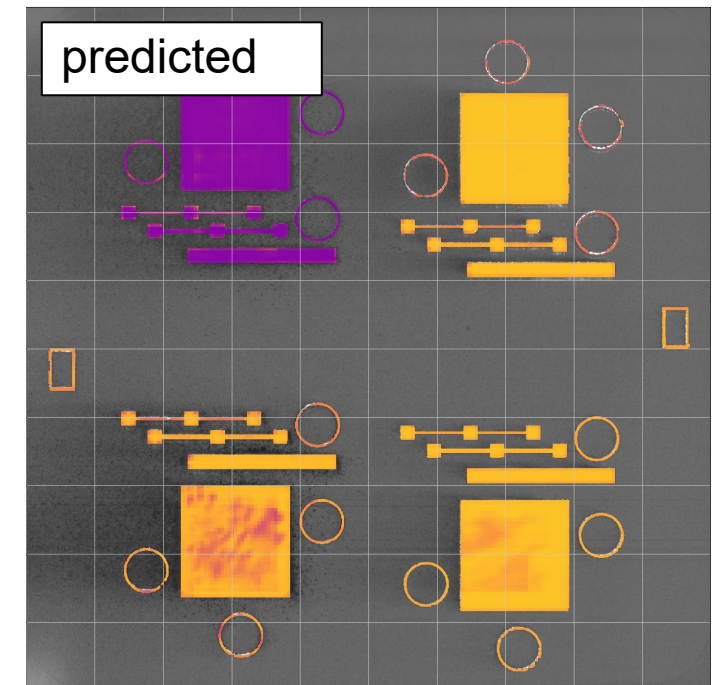
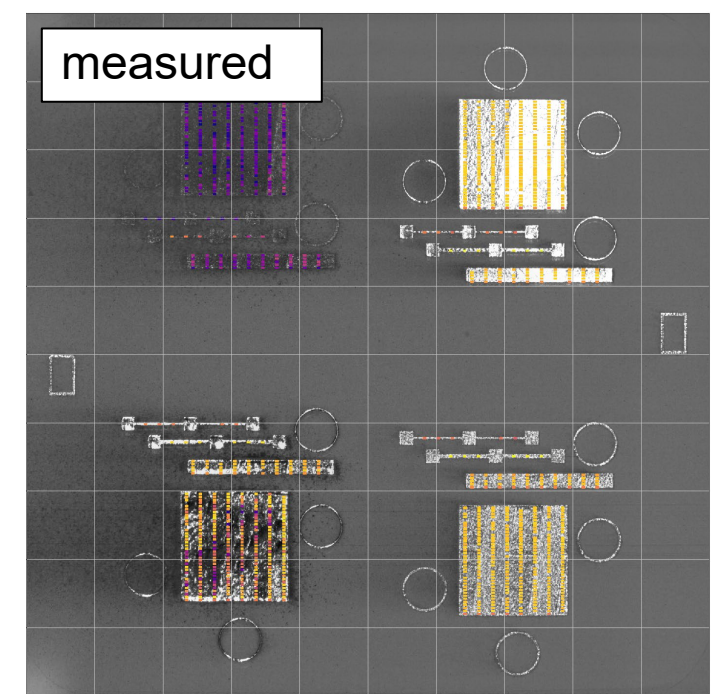
- Characterization data



Prediction Model Results



- The UTS RMS error is **38 MPa** over an observed range of 80 MPa – 610 MPa
- This represents a **61% reduction** in the extrinsic RMS error compared to the naive estimate of the material properties



Digital Handbook

3. ADVANCED MANUFACTURING TECHNOLOGIES

3.1 POWDER BED

3.1.1 Renishaw AM 250

The Renishaw AM 250 is a single-laser, Laser Powder Bed Fusion printer with a build volume of 250 mm x 250 mm x 365 mm. This Additive Manufacturing operation acts on powdered metal feedstock and may instantiate new parts within the Digital Platform in the future. The MDF typically prints a wide range of metal alloys on this system.



Category	Value
Digital Platform Tag(s)	RenishawAM250-008W73
Digital Point of Contact	
Approximate Data Volume per Operation (GB)	50 MB per layer
Approximate Number of Operations per Year	20
Associated Software Tools	Peregrine

3.1.1.1 Data Collection and Transfer

Peregrine is installed at the edge on a local compute node with a user display (desktop computer on a rolling cart). The Peregrine computer is able to communicate with the printer control computer through WinSCP, open-source SSH File Transfer Protocol, allowing the Peregrine computer to directly access folders on the printer control computer to distribute build files and retrieve log files. The Peregrine computer is connected via USB to cameras (a 20 MP Basler - acA5472-17um and a 4.2 MP Pixelink - PL-D734MU-NIR-T), which observe the powder bed and automated analysis of the live video stream is used to trigger layer-wise image capture. Each layer-wise image is then stored on the Savitar file storage system and the edge instance of Peregrine locally analyzes the data using the neural networks and collates the data for the entire build. After the build is complete, the operator loads the log file onto Savitar via the edge Peregrine instance. Metadata are entered into either Peregrine or the Digital before, during, and after each build.

Draft. Not approved for public release.

3.1.1.2 Meta data

Figure 4 provides an overview of the Peregrine metadata manager interface. The information listed on this page is recorded in the SQL database in multiple tables.

Figure 4: Peregrine meta data manager for the Renishaw AM 250

Most of the fields on this form are self-explanatory, however we are providing more details below for few of them:

Draft. Not approved for public release.

Table 1: meta data information for Renishaw AM 250

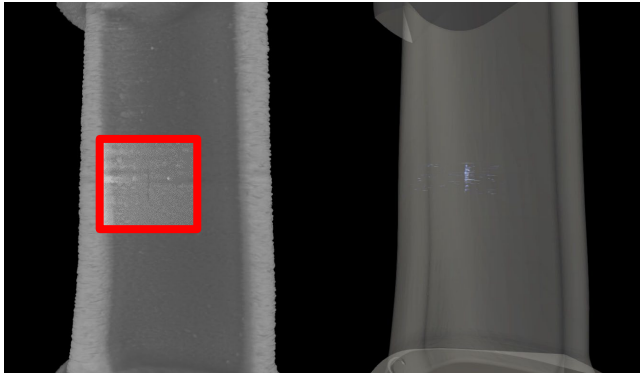
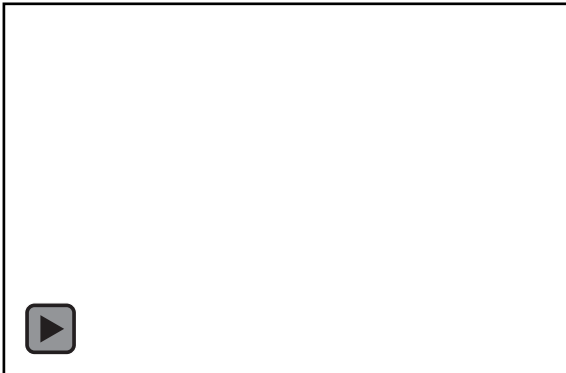
Field name	Metadata Information	DB Key	DB Table	Is list?
MDF Printer Tag	Unique name identifier for the machine, concatenating the machine type and the serial number. Can be used for keyword search using the platform API	machine_info	machine_name	No
Customers	Provide the list of the customers for any given build. More than one customer can be listed as the build chamber allows for multiple components to be manufactured simultaneously	build_info	customer_ids	Yes
Charge code	Provide the list of the charge numbers used for any given build. Multiple charge numbers can be listed if different project support a particular build	build_info	chargecode_ids	Yes
Beam calibration date	This is a foreign key to machine_info table that list of all laser calibration dates for the machine. Each build only list one date.	build_info	calib_date	Yes
Build name	Name given to the build by the operator of the machine for identification.	build_info	Build_name	No
Material type	Type of material used for this build. The name is store in a separate table specific to the type of material (in this case the table named powder, field composition). This is a foreign key to materials table	build_info	material_id	No
Powder use cycles	(In progress) provide the material cycle history for the batch of powder used for this build. This is a foreign key to materials table	build_info		
Data restrictions	Indicate the sensitivity of the data between the following options: open, EC, ITAR, and industry confidential	build_info	sensitivity_type	No
Build date -- start		build_info	start_date	No
Build date -- end		build_info	end_date	No
Feedstock batch		build_info		
Wiper uses		build_info		
Tracking ID		build_info		
Operators #1	Provides the name of the operator involved in the start-up of the build. This is a foreign key to users table	build_info	startup_tech_id	No
Operators #2	Provides the name of the operator involved in the set-up of the build. This is a foreign key to users table	build_info	setup_tech_id	No
Build volume	Provide the build volume for the build. The value will change between builds based on	build_info		

Draft. Not approved for public release.

Relevance and Impact of Additive Manufacturing

Industry Partner: Solar Turbines

- **Objective:** Fabricate near net-shaped Mercury 50 Stage 2 airfoil set with no surface breaking cracks from a high gamma prime Ni-base superalloy
- **Successfully tested on August 25th 2020**



Industry Partners: Framatome & TVA

Office of Nuclear Energy

TVA and Framatome to Load First 3D-Printed Fuel Assembly Bracket in Commercial Reactor

DECEMBER 1, 2020

Office of Nuclear Energy » TVA and Framatome to Load First 3D-Printed Fuel Assembly Bracket in Commercial Reactor

NUCLEAR MILESTONE

OAK RIDGE NATIONAL LABORATORY
Framatome

Additively manufactured channel fasteners for Framatome's boiling water reactor fuel assembly.
Oak Ridge National Laboratory

Conclusion

MDDC platform allows:

- Data tracking, processing, and exchange across AMMT facilities and collaborators
 - Indexing of instrument and equipment data
 - Access to manufacturing and materials database
 - Contribution to manufacturing and materials database
 - Simplify release of pedigree datasets
 - Access to advanced analytics and modeling and simulation capabilities
-
- Software and hardware development will be shared with the community
 - Implementation guidelines in handbooks

ORNL/TM-XXXX/XXX

Unified Software Architecture for AMMT Data Management and Processing

MDDC Platform: Multi-length Scale Data Integration



Document authored by
XXXXXXXXXXXX

September 2023

Draft. Document has not been
reviewed and approved for
public release.

 OAK RIDGE
National Laboratory

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U.S. DEPARTMENT OF
ENERGY

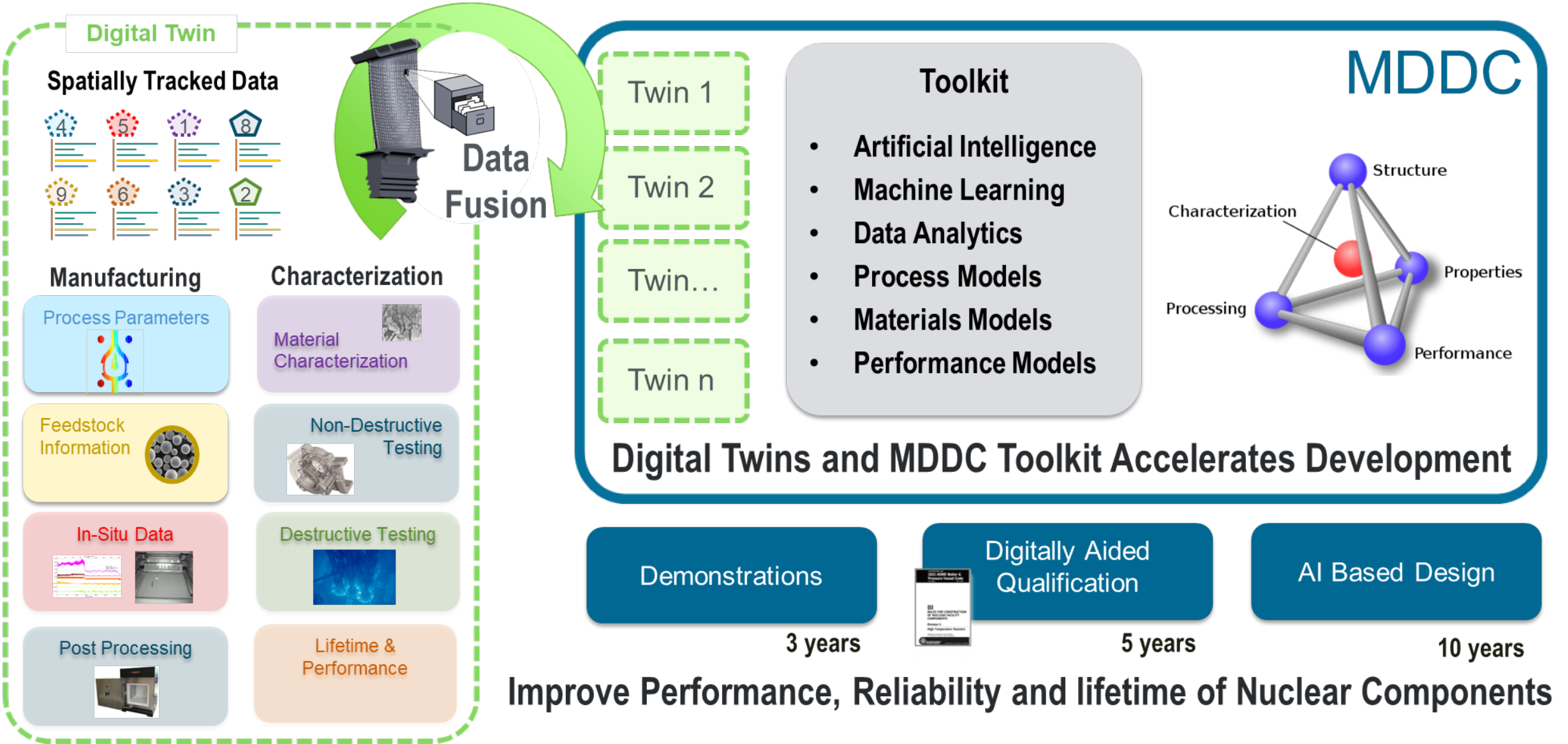
Office of
NUCLEAR ENERGY

Questions?

U.S. DEPARTMENT OF
ENERGY

Office of
NUCLEAR ENERGY

Multi-Dimensional Data Correlation (MDDC) Platform



ANL Resources

Manufacturing

Renishaw
AM 400



Beam
Modulo
250

Characterization and Test

Creep frames, hydraulic
load frames, ...



JEOL 7500 (FE) SEM



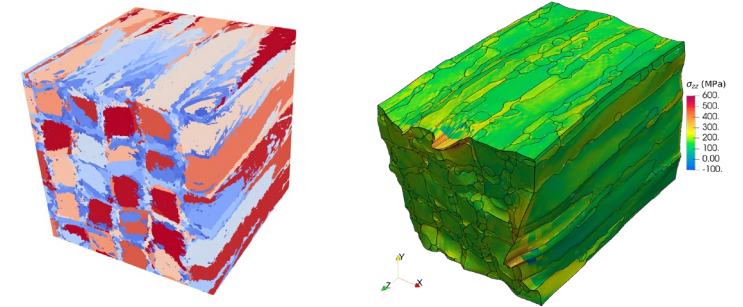
Talos F200X (S)TEM



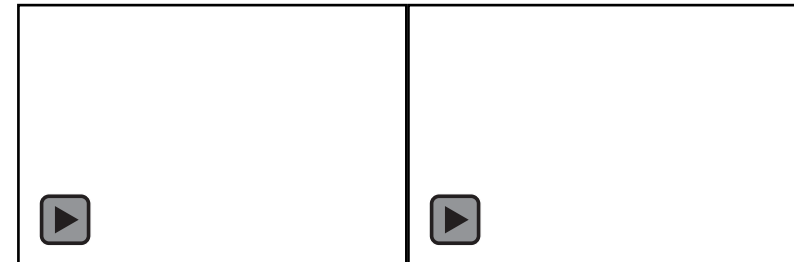
APS (back soon!)

Modeling/Simulation

MOOSE/NEML simulation providing
localized, grain scale (μm) deformation
and stress under creep conditions



Macroscale welding residual stress
simulation

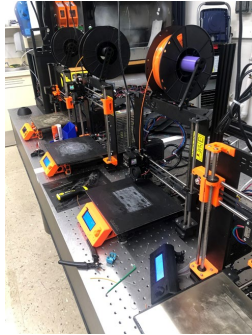


PNNL Resources

Manufacturing



Solid Phase ShAPE



Prusa Printer

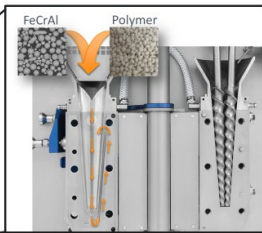


Intamsys Funmat HT Printer

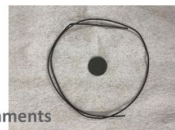
Filament making capability at 2400 Stevens ACME lab



Xplore Twin Co-rotating screw micro compounder



fabricated FeCrAl composite filaments



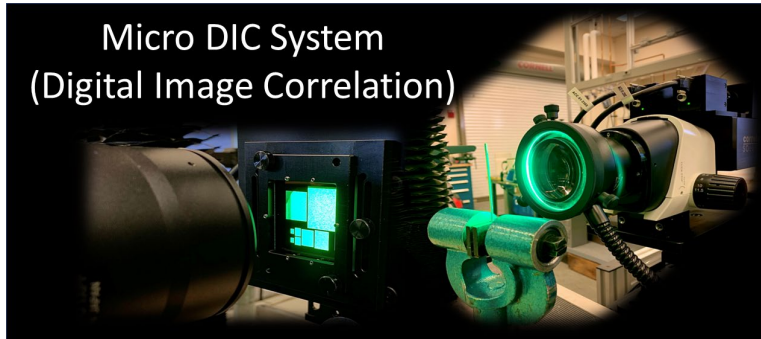
Characterization and Test



JEOL ARM200CF



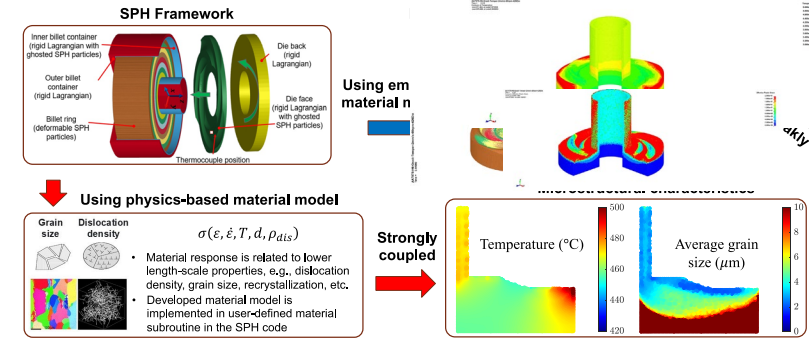
JEOL Grand ARM 300kV



Micro DIC System (Digital Image Correlation)

Modeling/Simulation

SPH simulation predicting grain size, dislocation density, temperature ... during Shear Assisted Extrusion and Processing (ShAPE)



ANL data sources: manufacturing equipment



Renishaw AM 400

Data streams:

- Build processing parameters/metadata
- Full build files
- Part STL files
- Powder chemistry/size
 - Basler - acA5472-17um
 - Pixelink - PL-D734MU-NIR-T (USB)
- In situ monitoring data on Renishaw



Beam Modulo 250

ANL data sources: characterization and test equipment



JEOL 7500 (FE) SEM



Talos
F200X
(S)TEM

Data streams (all spatially located in a build):

- Raw images (2D)
- EBSD maps (2D)
- Reconstructed/segmented tomography data (3D, structured)
- Grain morphology/orientations (3D point cloud)
- *Mechanical test data:*
 - Varies by test...
 - Often time series of stress/strain temperature
 - 1D/uniaxial



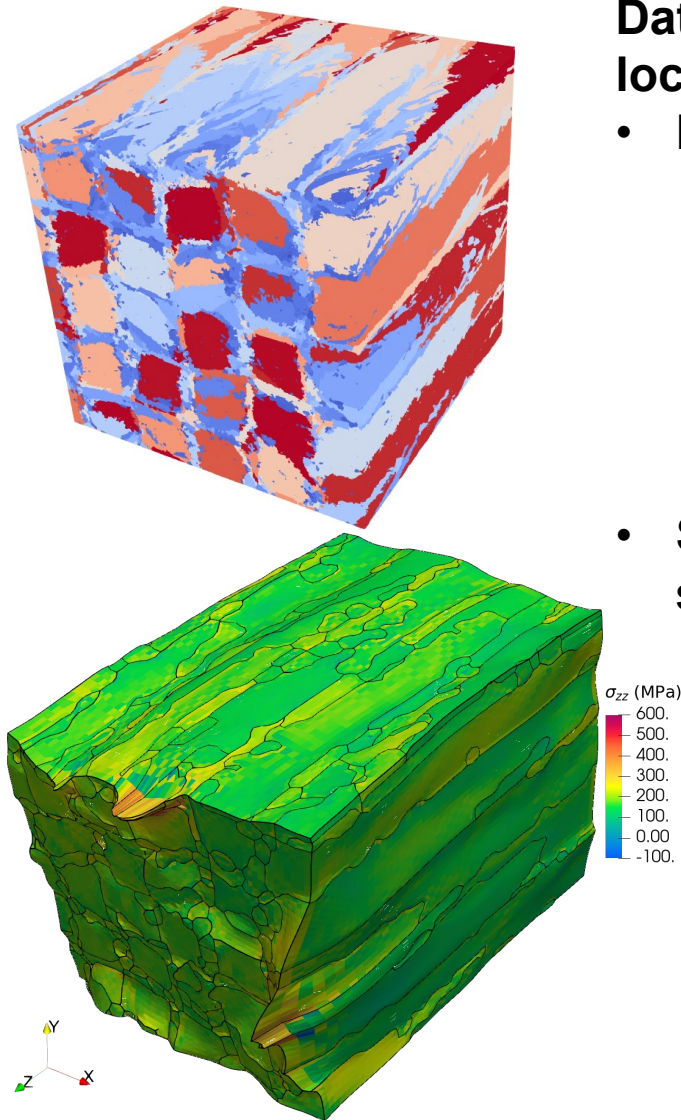
APS (back soon!)

Creep frames,
hydraulic load
frames, ...



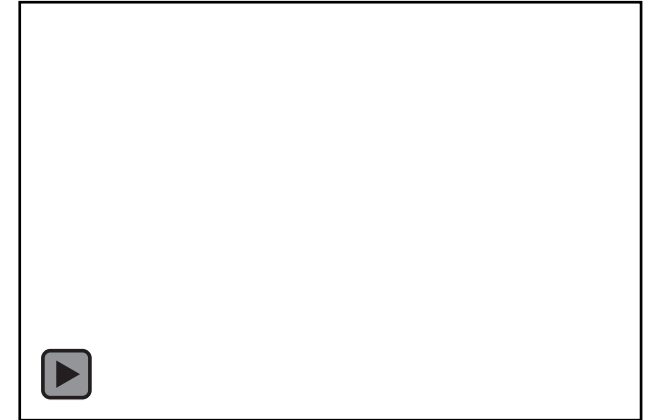
ANL data sources: modeling/simulation

MOOSE/NEML simulation providing localized, grain scale (μm) deformation and stress under creep conditions



Data streams (all spatially located in a build):

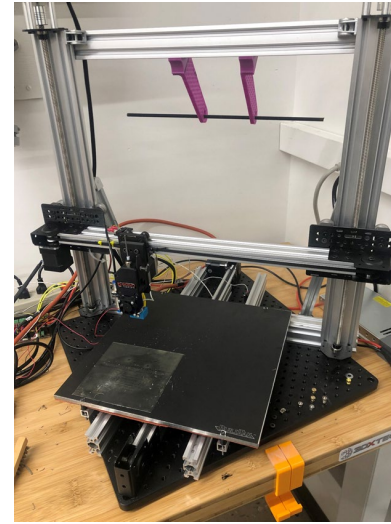
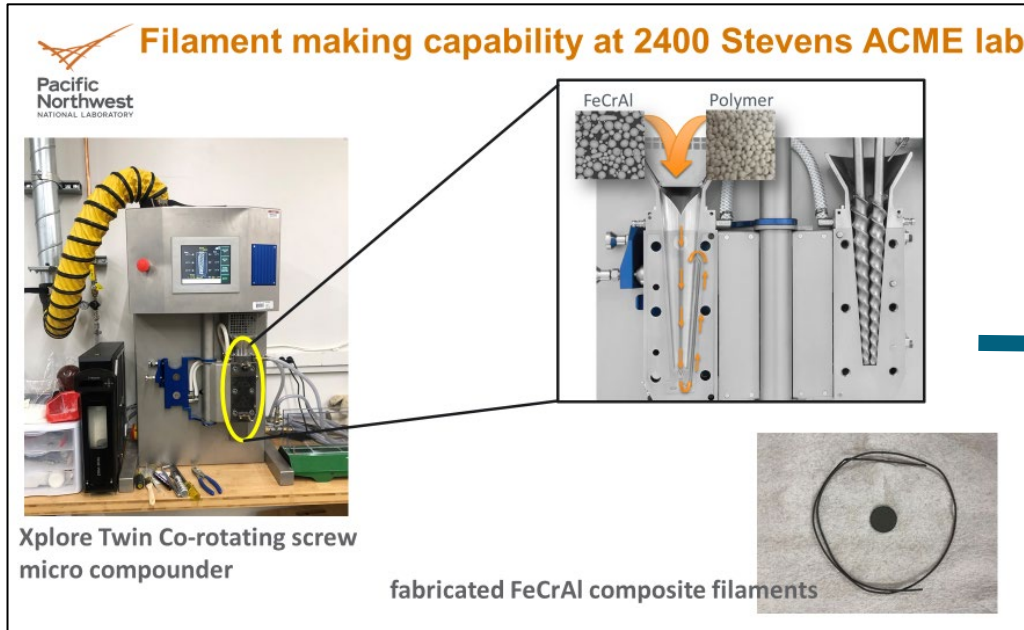
- Effective properties
 - Varies by what you're interested in
 - But we can often reduce to 1D/2D/3D time series of stress, strain, time, temperature
- Spatially resolved data (full field, structured grid):
 - Stress (including residual stress)
 - Strain
 - Temperature
 - Dislocation density
 - Precipitate size/number density/volume fraction
 - ...



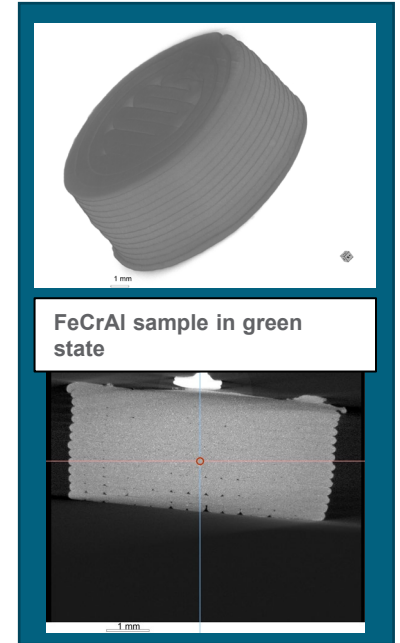
Macroscale welding residual stress simulation



Extrusion-based fused filament fabrication (FFF)



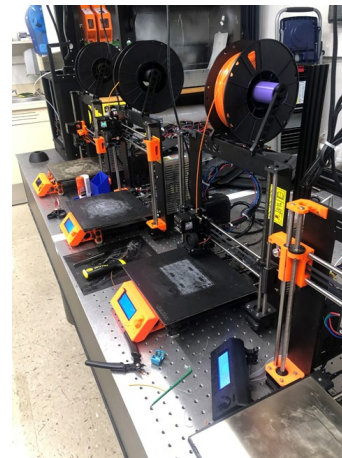
Custom built Rhombus Printer
SETO project FeCrAl samples printed



PNNL data sources:
manufacturing equipment



- Intamsys Funmat HT Printer**
- Up to 500°C extrusion temperature
 - 90°C thermal chamber
 - 145°C heated bed



Prusa printers
U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

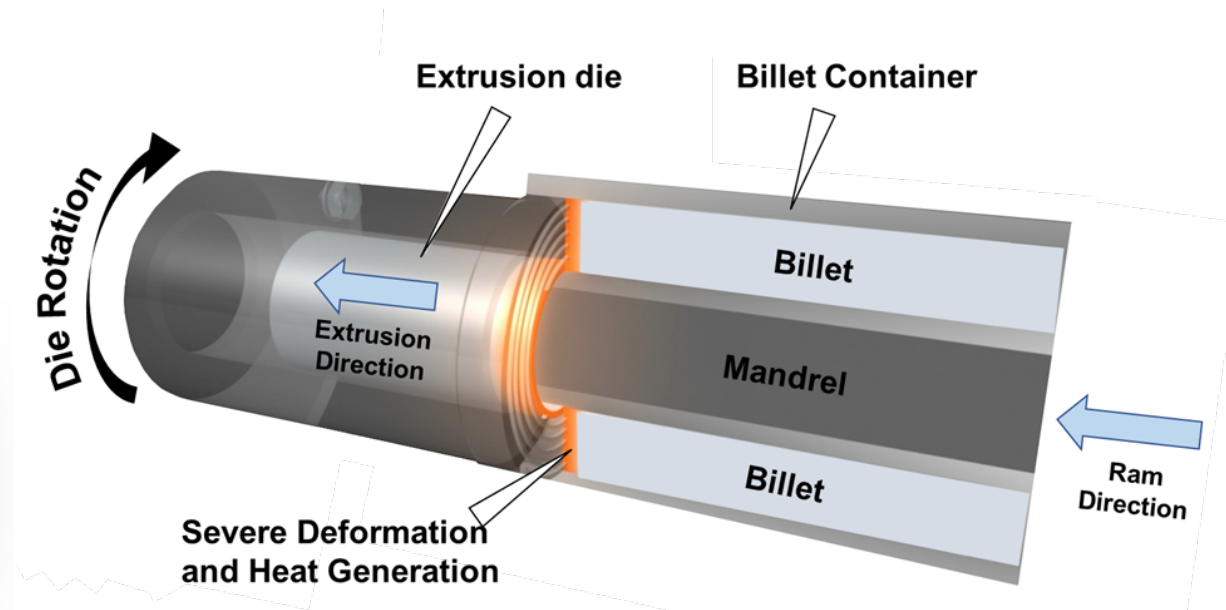
Data streams:

- Processing parameters/metadata
- Filaments geometries
- Powder chemistry/size

A picture of a first-of-its kind ShAPE machine at PNNL



A schematic explaining the extrusion process



The current ShAPE machine has 3000 Nm torque and 900 kN force and can easily fabricate ½" OD tubes with 1 mm wall thickness from high temperature materials.

Input:

Tool rotational speed
Die advance rate
Extrusion ratio

Output:

Temperature
Torque/power
Forces (X, Y, and Z)

PNNL data sources: characterization and test equipment



JEOL ARM200CF



JEOL
Grand
ARM
300kV

Data streams

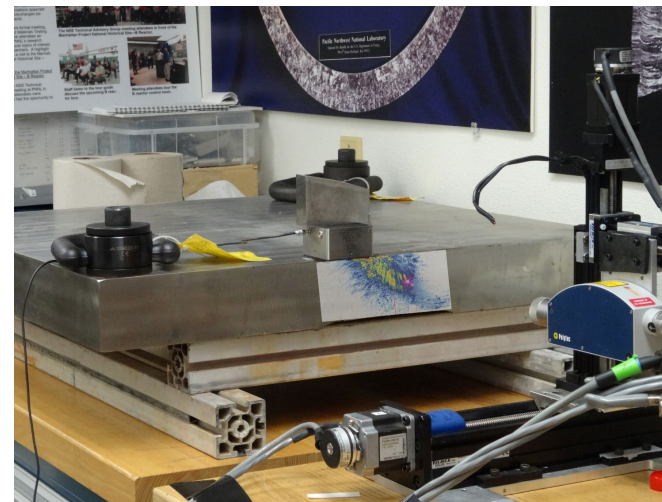
- Raw images (2D)
- Python code
- Gatan Coding Language
- Load-displacement data
- Digital imaging
- Ultrasonic waveforms
- Electrical conductivity
- Magnetic permeability

Micro DIC System (Digital Image Correlation)



3D Strain measurement at high magnifications

- Full-field measurements of
 - 3D coordinates, displacements, velocities
 - complete strain tensors
- Field of view – 0.8 mm – 7 mm
- Contour displays overlaid onto test specimen images
- Post processing statistical analysis tools
- Nodal Data can be extracted for FEA validation

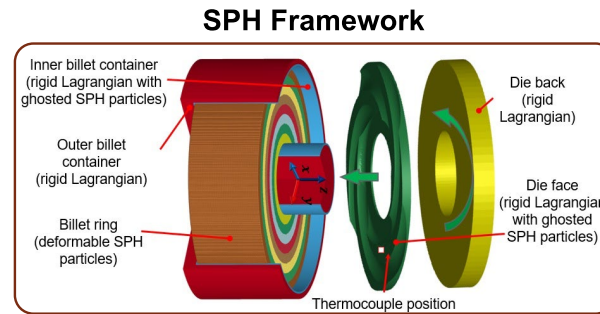


PNNL data sources: modeling/simulation

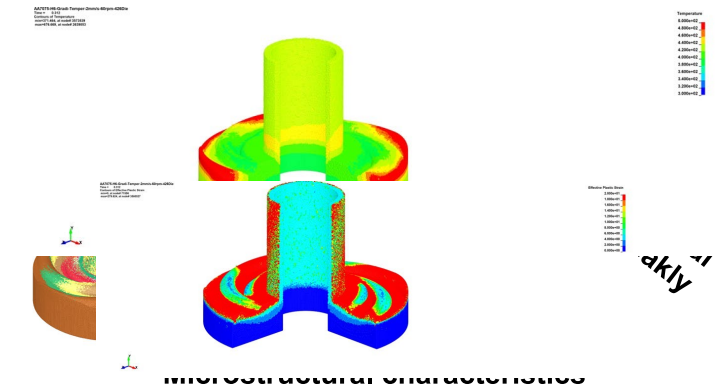
SPH simulation predicting grain size, dislocation density, temperature ... during Shear Assisted Extrusion and Processing (ShAPE)

Data streams (all spatially located in an extrudate):

- Spatially resolved data (on ~ 100 microns particle):
 - Stress
 - Strain
 - Strain rate
 - Material flow
 - Temperature
 - Dislocation densities
 - Grain size



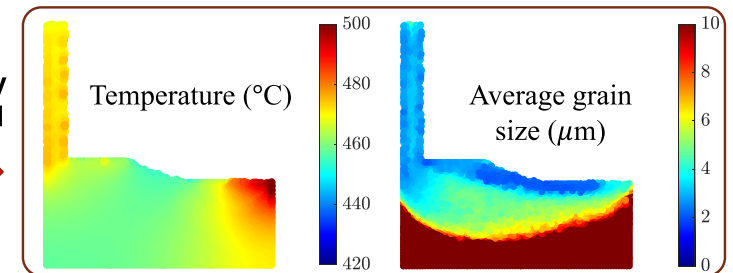
Using em material n



↓ Using physics-based material model

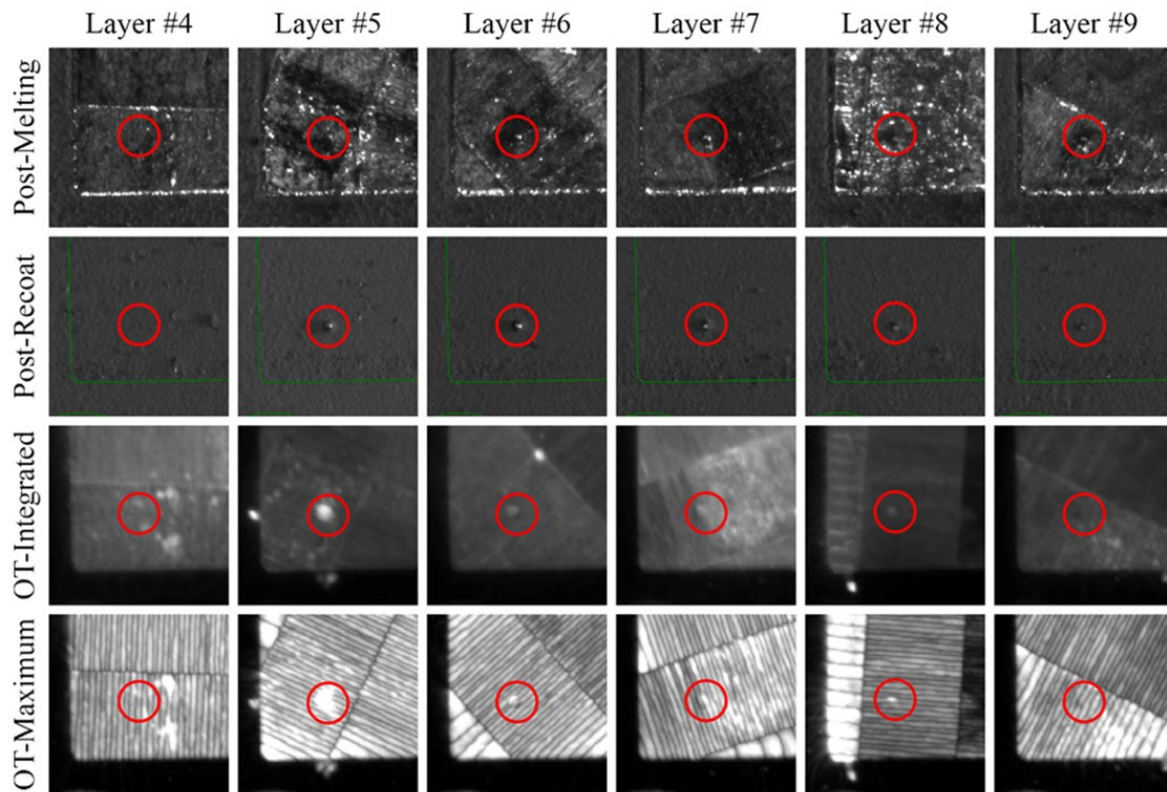
Grain size	Dislocation density	$\sigma(\epsilon, \dot{\epsilon}, T, d, \rho_{dis})$
		<ul style="list-style-type: none"> • Material response is related to lower length-scale properties, e.g., dislocation density, grain size, recrystallization, etc. • Developed material model is implemented in user-defined material subroutine in the SPH code

Strongly coupled

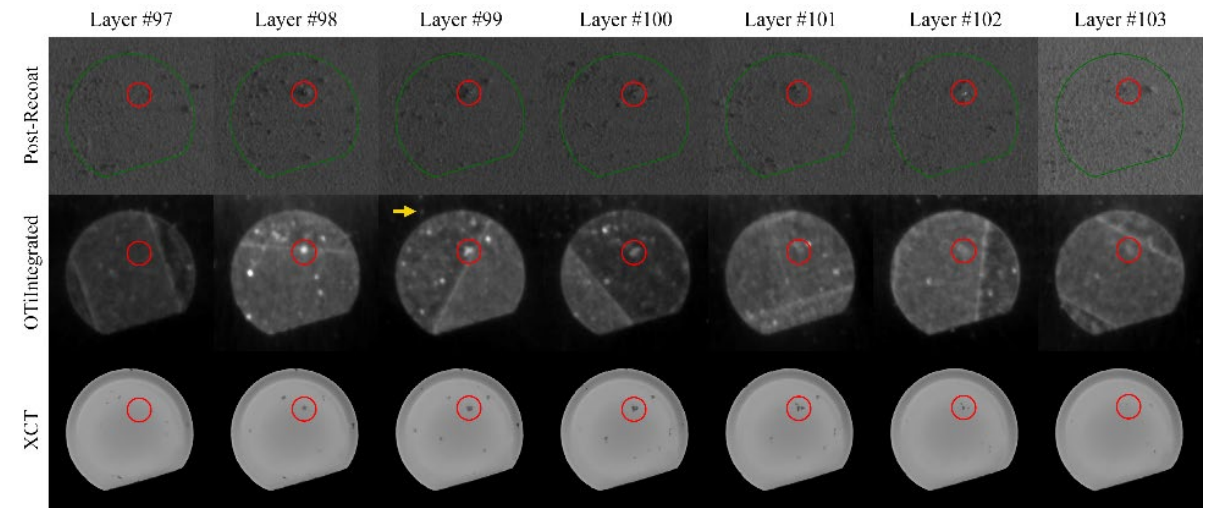


Observation of Spatter-Induced Stochastic Lack-of-Fusion in Laser Powder Bed Fusion

Detected Spatters in In-Situ Data



Detection Equivalence In-Situ / Ex-Situ



Registered post-recoating optical images and OT integrated data, and their corresponding XCT data