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

DOE-NE Advanced Materials and Manufacturing Technologies (AMMT) Program Overview

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2023 Workshop on Advanced Manufacturing Technologies (AMTs) for Nuclear Applications,
NRC HQ, Rockville, MD, October 24-26, 2023

AMMT Mission, Vision and Goals

Mission

- To develop cross-cutting technologies in support of a broad range of nuclear reactor technologies.
- To maintain U.S. leadership in materials & manufacturing technologies for nuclear energy applications.

Vision

To accelerate the development, qualification, demonstration and deployment of advanced materials and manufacturing to enable reliable and economical nuclear energy.

Goals

- Develop advanced materials & manufacturing technologies.
- Establish and demonstrate rapid qualification framework.
- Evaluate materials performance in nuclear environments.
- Accelerate commercialization through technology demonstration.

AMMT Program

Program Elements

Development, Qualification and Demonstration

- Advanced Materials & Manufacturing
- Rapid Qualification
- Materials Performance Evaluation
- Technology Demonstration

Capability Development & Transformative Research

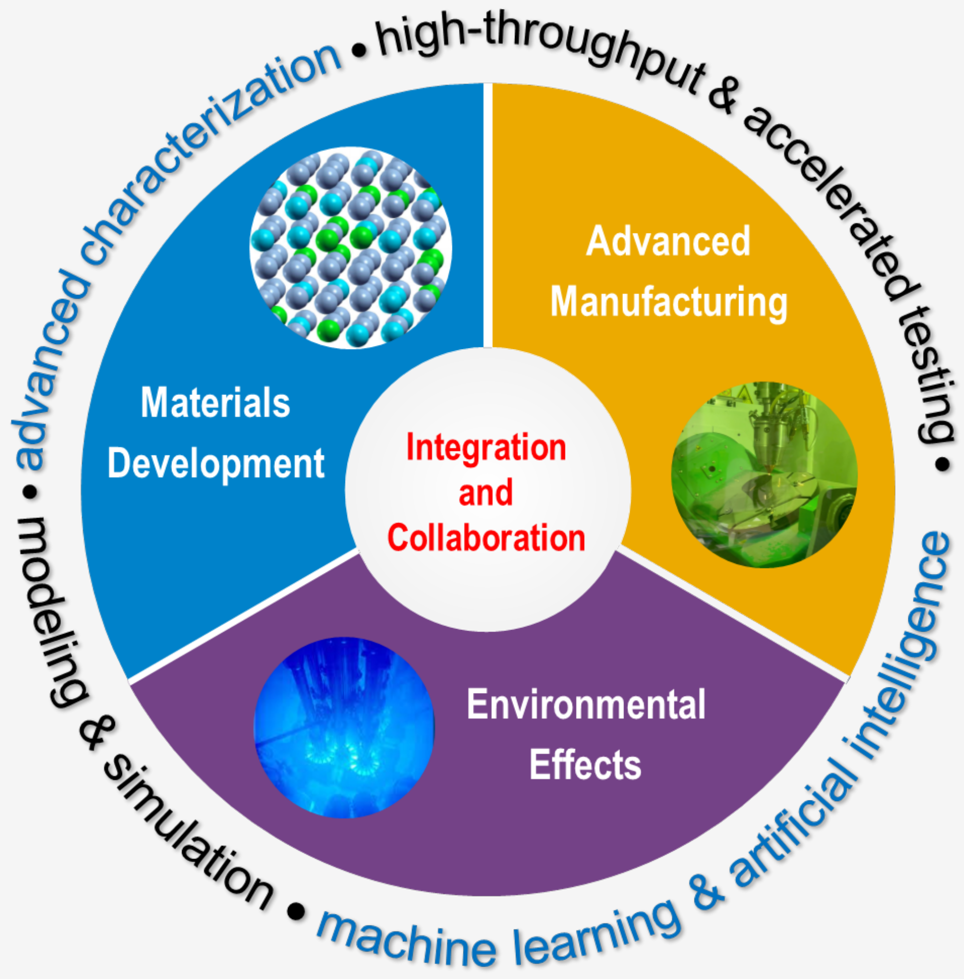
- Develop advanced experimental and computational tools
- Perform transformative research to explore new materials design & processes

Collaborative Research and Development

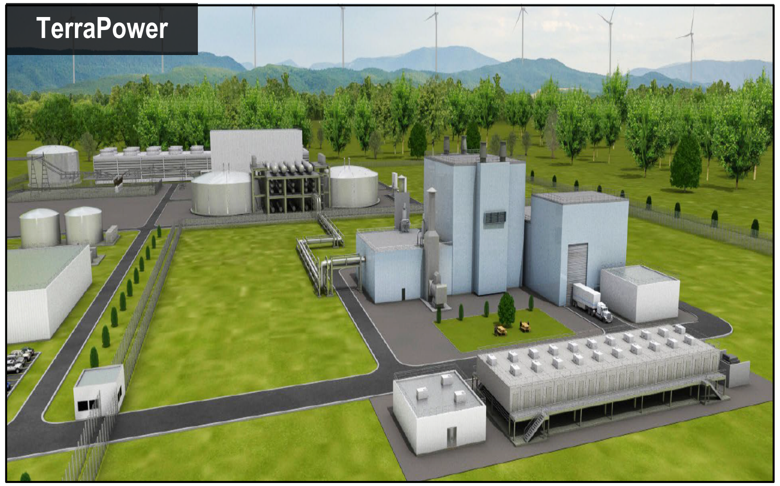
- Collaboration & partnership to address diverse needs of the nuclear community

- Investigate a broad range of technologies
- Leverage and collaborate on capability development
- Provide near-term solutions to the nuclear industry

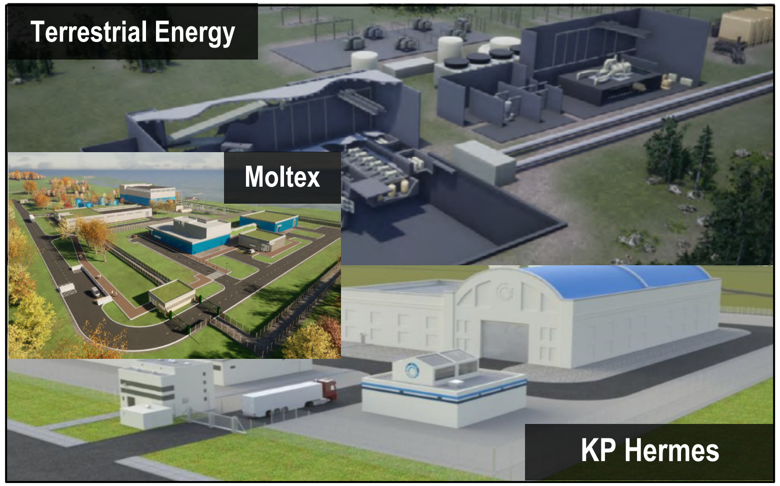
Execution Strategy



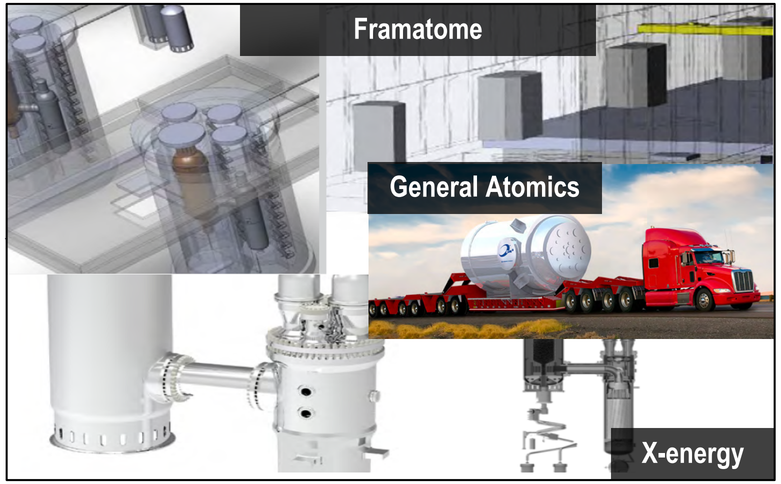
AMMT Supports a Broad Range of Reactor Technologies



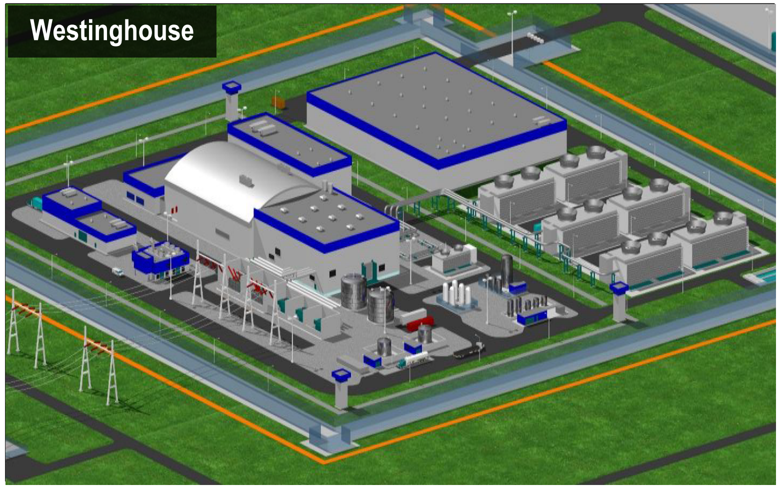
Sodium-cooled Fast Reactor (SFR)



Molten Salt Reactor (MSR)



High-temp Gas-cooled Reactor (HTGR)



Lead-cooled Fast Reactor (LFR)

Light Water Reactor (LWR)/
Small Modular Reactor (SMR)

Micro-reactor

Nuclear Innovation Alliance (2021), "Advanced Nuclear Reactor Technology: a primer."

Thematic Research Areas

Capability Development & Transformative Research

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Advanced Materials and Manufacturing

Advanced Manufacturing Technologies (AMTs) for Nuclear Applications

The NRC AMT Action Plan addressed five AMTs including:

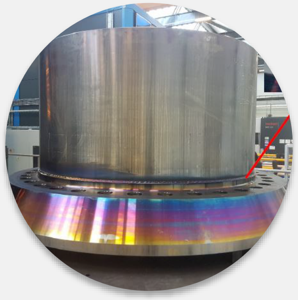
- Laser powder bed fusion (LPBF)
- Directed energy deposition (DED)
- Powder metallurgy hot isostatic pressing (PM-HIP)
- Electron beam welding (EBW)
- Cold spray

AMMT current focus:

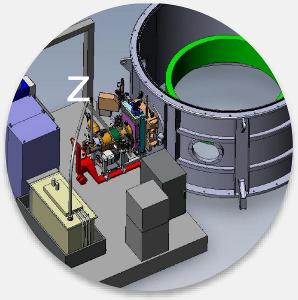
- Laser powder bed fusion (LPBF)
- Directed energy deposition (DED)

DOE-NE funded industry projects: developing and demonstrating ***PM-HIP, EBW***.

EPRI
SMR RPV
PM-HIP



EPRI
SMR RPV
EBW



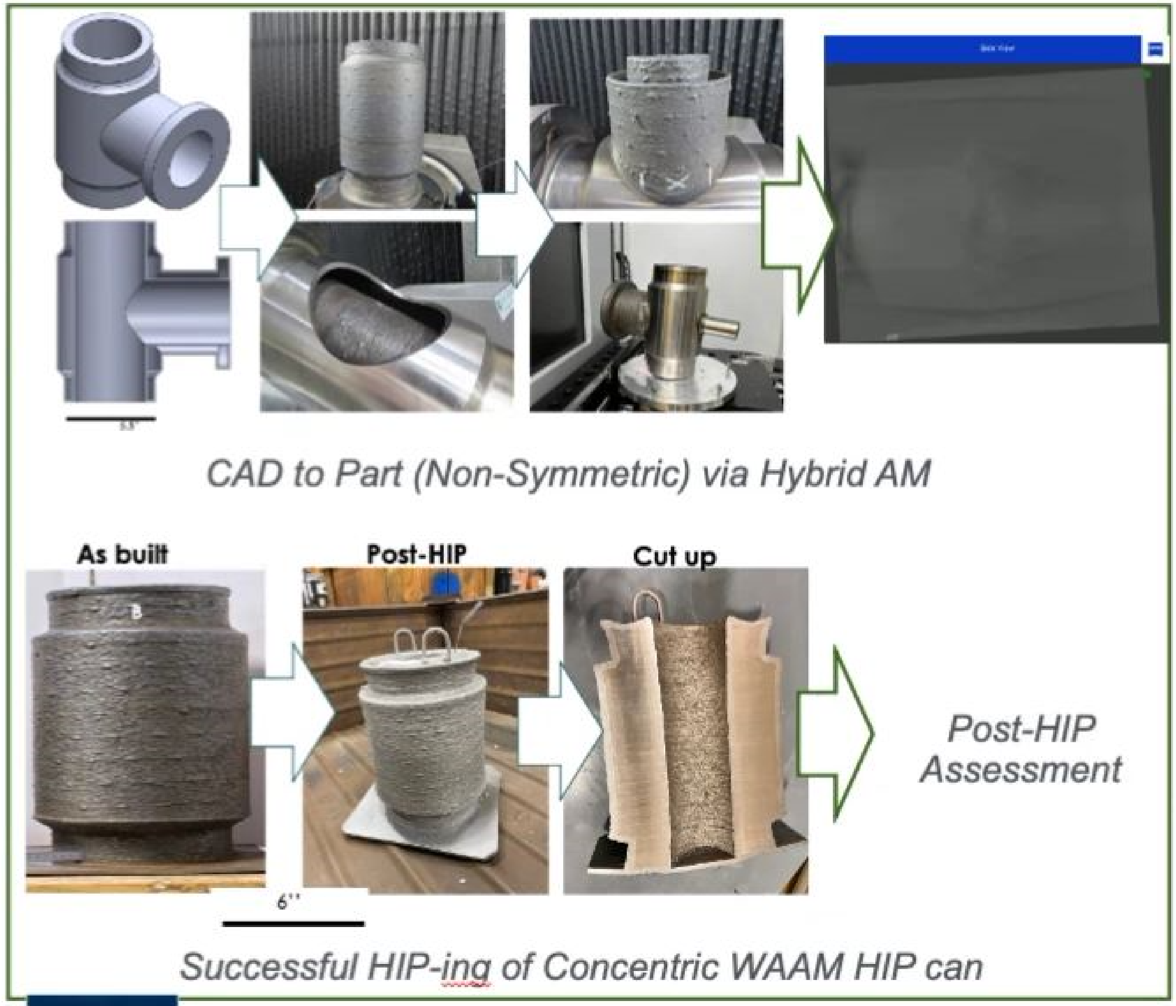
EPRI
Modular
in-chamber
EBW

Large-Scale Additive Manufacturing

In Situ Monitoring Assisted Large-Scale AM of Mild Steel and 316 SS for Nuclear Applications

Objective: Feasibility demonstration of large-scale additive manufacturing of nuclear components (e.g. pressure vessel, valves).

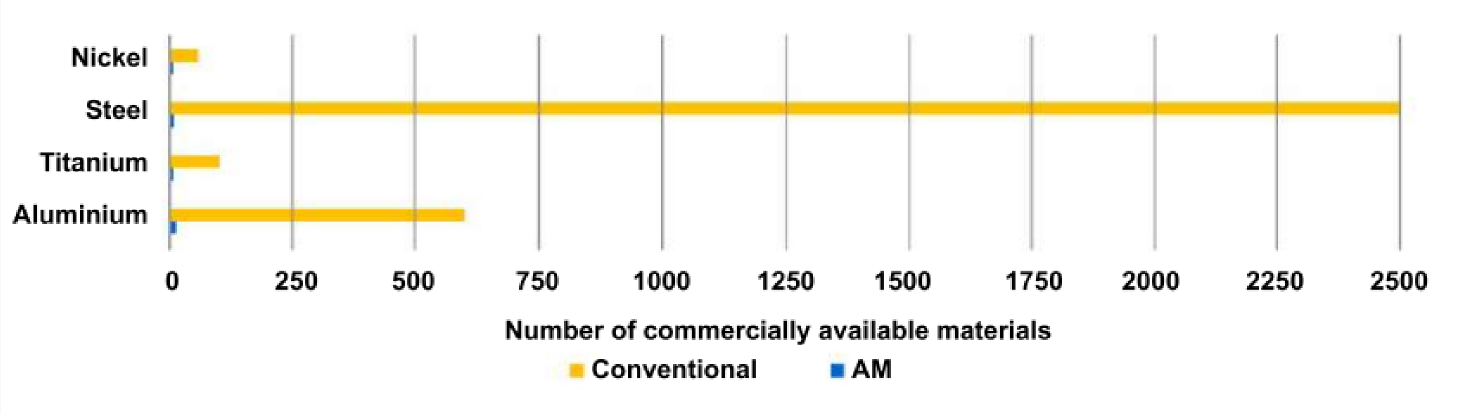
- Demonstrated initial build success with symmetric/nonsymmetric, concentric, thin-walled structures (HIP can and T-valve geometry) using three different DED AM modalities:
  - Wire arc additive manufacturing (WAAM)
  - Hybrid AM (additive and subtractive)
  - Blown powder DED
- Collected processing data using *in situ* monitoring capabilities, e.g. thermocouple-based point probes, melt pool monitoring, and IR imaging.



Acknowledge EPRI for providing CAD of t-valve

AM Material Development

- Optimize and improve existing reactor materials compatible with advanced manufacturing processes to expand their applications.
- Develop and manufacture new, high-performance materials enabled by advanced manufacturing for nuclear applications.



The number of alloys currently commercially available for metal additive manufacturing is significantly smaller than ones available for conventional manufacturing processes. (D. Beckers 2019)

- **Ferritic-martensitic steels**
- **Austenitic stainless steels**
- **Ni-based alloys**
- **ODS alloys**
- **High entropy alloys**
- **Refractory alloys**
- **Functionally graded materials**
- **Composites/coatings/claddings**

Development of Fe-based Alloys for AM

Develop Decision Criteria Matrix

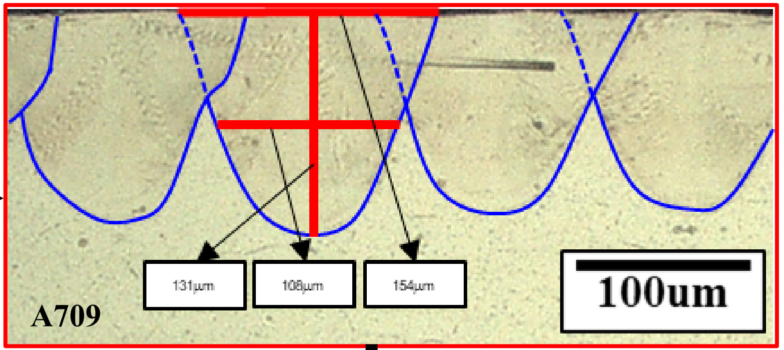
Category	Criteria					
Manufacturing/Powder	Powder Availability	Powder Properties	Powder Chemistry	Cost	Recycling	
Manufacturing/Components	Printability (LBF)	Defects	Post Treatment	Processing window	Weldability	Surface Roughness Surface Finish
History & Applications	NE Experience	Other Industries Experience	Data availability	Code Data Availability	Experience with non-LPBF AM	Scaling Up
Mechanical Properties	Creep	Fatigue	Creep-fatigue	High Temp tensile strength	Room Temp	
Environmental Effects	Radiation Resistance	Oxidation Resistance	Stress Corrosion Cracking	Molten Salt	Liquid Metal	
Physical Properties	Thermal Properties	Solidification-relevant properties	Other modeling-relevant properties	Digital Manu. relevant-properties		
Microstructure	Material Homogeneity	Microstructure Stability	LPBF Microstructure Specificity			

Using Decision Criteria Matrix to narrow down to 6 alloys

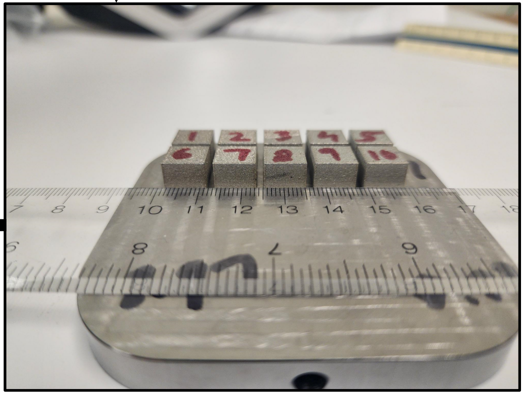
Austenitic
A-709
AFA
Ti-modified 316SS (D9)
Ferritic/Martensitic
Grade-91
Grade-92
HT-9

Single-track experiments to optimize process parameters

Single track experiments for the optimized condition

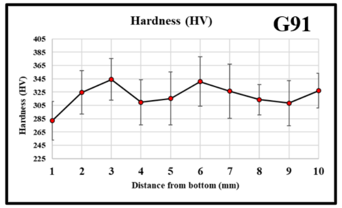


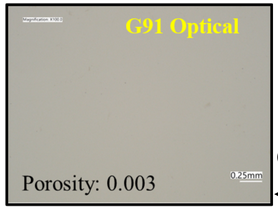
All 6 alloys printed with optimized process parameters obtained in the previous step

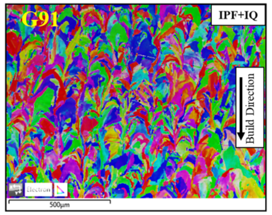


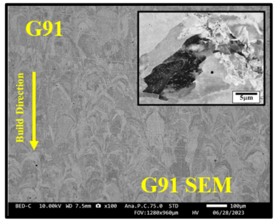
10 parts printed for each alloy

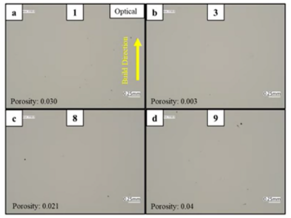
Characterization

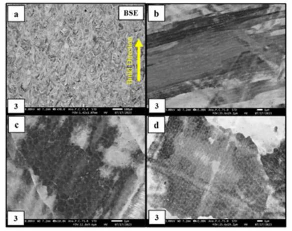


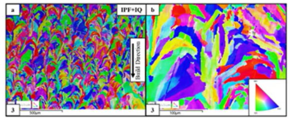












Alloy 709

Summary

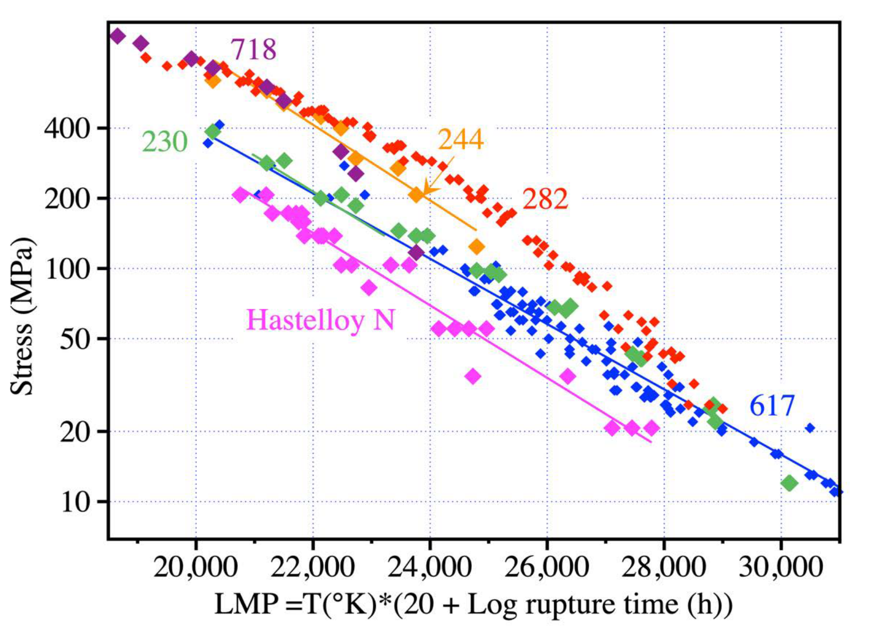
- Developed a decision criteria matrix (DCM) by 4 national labs.
- Down-selected 6 alloys using the DCM for further assessment.
- Performed single track laser experiments to optimize printing conditions.
- Printed ten samples for each alloy using the optimized process parameters.
- Performed microstructural characterization and hardness testing for initial evaluation.

Further evaluations on **A709, AFA austenitic SS and G91, G92 ferritic-martensitic steels**.

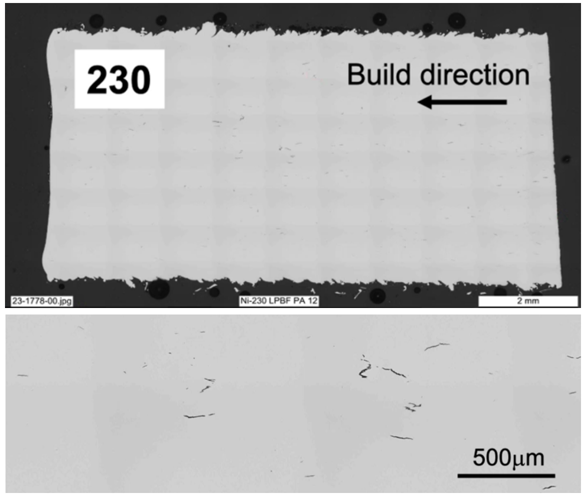
Development of Ni-based Alloys for AM

- Considered three Ni-based alloy categories based on potential applications: (1) **Low cobalt**; (2) **High temperature strength**; (3) **Low Cr, molten salt compatible**.

Low Co	High temperature strength	Molten salt (Low Cr)
718 (20Cr-5Nb-3Mo)	282 (20Cr-10Co-8.5Mo-2.1Ti-1.5Al)	Hastelloy N (7Cr-16Mo)
625 (22Cr-9Mo-3.5Nb)	230 (22Cr-14W-<5Co)	244 (8Cr-22.5Mo-6W)
800H (32Ni-21Cr-40Fe)	617 (22Cr-12.5Co-9Mo)	

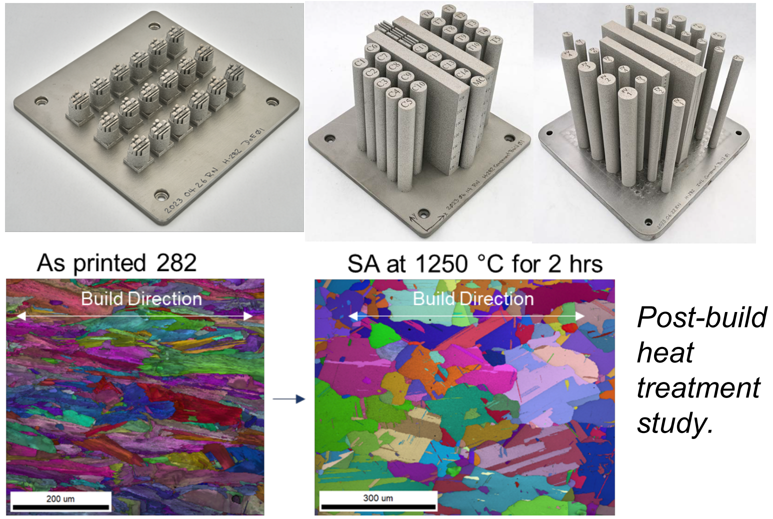


LPBF Alloy 230



Hot cracking in printed 230.

LPBF Alloy 282

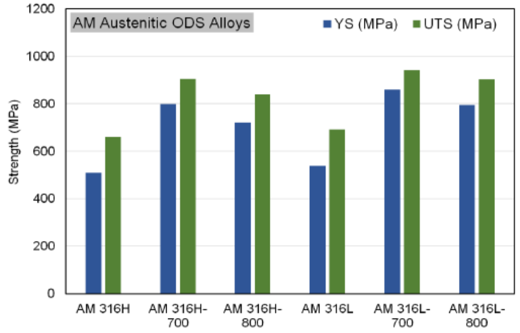


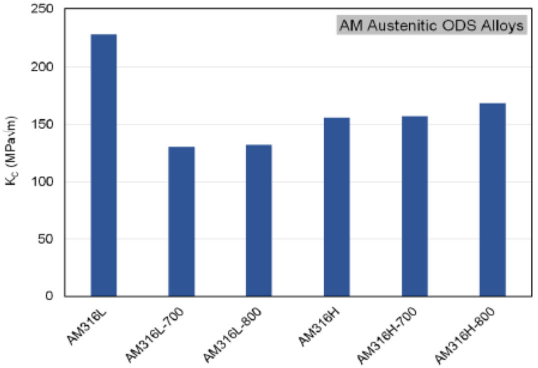
Post-build heat treatment study.

Other AM Materials Development

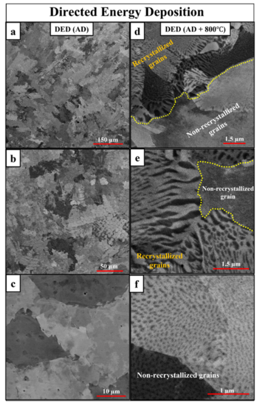
AM ODS Alloys

- Currently, the primary materials group of interest is austenitic ODS alloys.





AM High Entropy Alloys



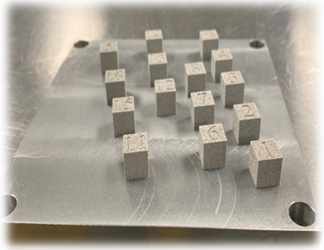
$Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$ processed via *Directed Energy Deposition* and *Selective Laser Melting*.

- Hierarchically heterogeneous microstructures (secondary $L1_2$-phase precipitates) obtained via simple one-step annealing:
  - significant better performance than the nearly homogeneous microstructures in the as-deposited state
  - Smaller than 6.6% reduction in hardness values at 500°C compared to RT, while the as-deposited conditions showed a greater than 18% reduction in the hardness
  - No microstructural instability is observed for heterogenous microstructures during nano-indentation deformation at 500°C

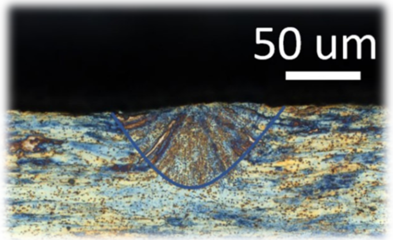
AM method	Condition	RT	250°C	500°C	% Change
DED	AD	4.157±0.287	3.763±0.212	3.197±0.233	23.13 ↓
	AD+800°C (HT)	4.710±0.123	4.663±0.183	4.387±0.153	6.5↓
SLM	AD	4.116±0.145	3.569±0.171	3.560±0.121	13.3↓
	AD+800°C (HT)	4.654±0.171	4.494±0.132	4.427±0.104	4.9↓

AM Refractor Alloys

- Consider refractory bulk for high-temperature applications and coatings for corrosion resistance.



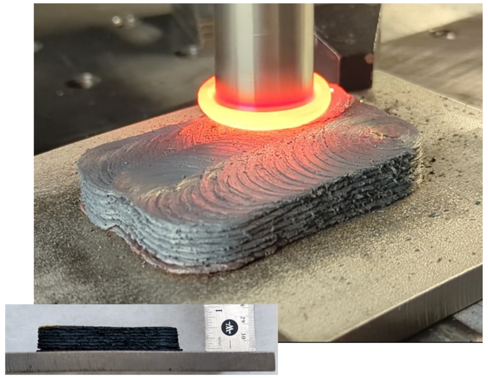
LBPF TZM Alloy



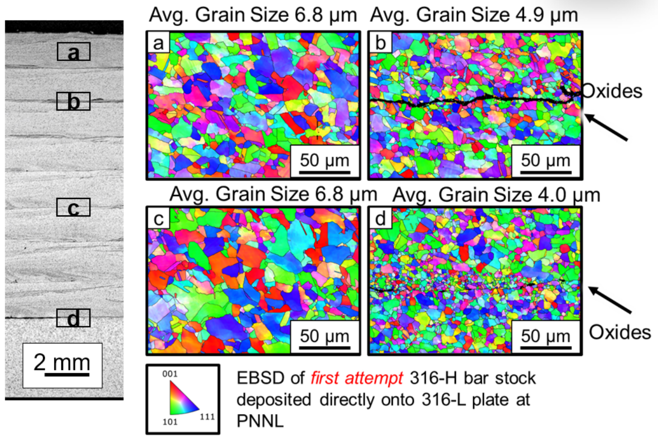
A weld pool in TZM.

Materials by Solid State Manufacturing

Nascent large scale manufacturing process with potential for improved properties, cost and lead time



Grains are significantly refined (¼ that of the extruded plate)



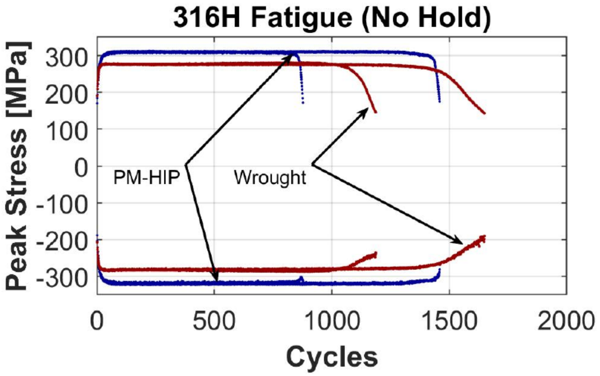
EBSD of *first attempt* 316-H bar stock deposited directly onto 316-L plate at PNNL

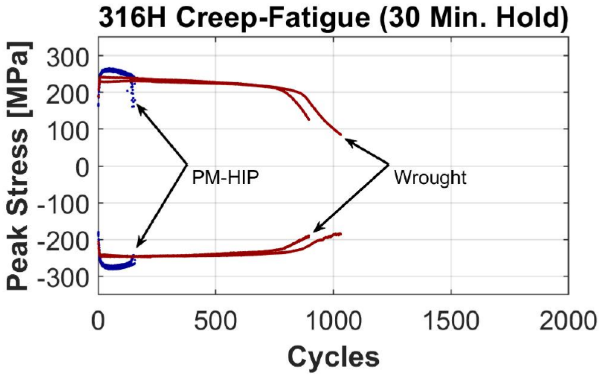
PM-HIP of 316H SS

- Assessment on creep-fatigue properties of PM-HIP 316H SS
  - Initial evaluation showed PM-HIP 316H SS has poor creep-fatigue performance compared to wrought 316H SS.
- Understand how the composition and microstructure influence PM-HIP 316H mechanical properties
  - Oxygen concentration, oxide size & distribution
  - Grain size and distribution

- **Fatigue and creep-fatigue at 650°C**

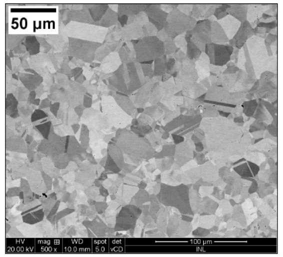
$$650°C,\ \Delta\varepsilon = 1\%,\ \ R = -1,\ \ \dot{\varepsilon} = 0.001\ s^{-1}$$



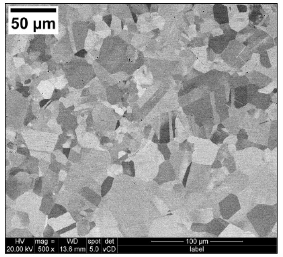


Consolidated Product Chemical Compositions (wt%)											Hardness
	Ni	Cr	Mo	C	Si	Mn	S	P	O	N	($HV_{0.3}$)
316H – MTC Heat 1	12.0	16.2	2.53	0.05	0.17	0.21	0.01	0.003	0.0190	0.141	224
316H – UK-NAMRC	11.8	17.3	2.53	0.04	0.17	0.18	<0.003	<0.005	0.015	0.069	194
316L – UK-NAMRC	11.9	17.7	2.44	0.015	0.83	1.88	0.008	0.008	0.0117	0.06	173

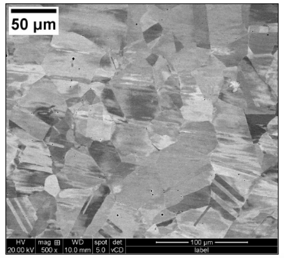
316H – MTC Heat 1



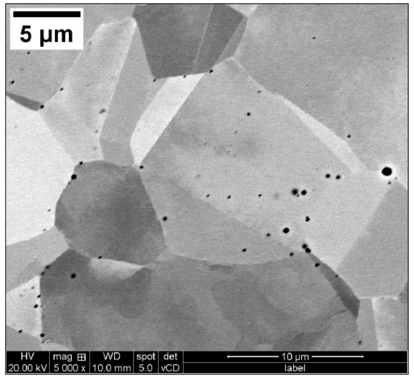
316H – UK-NAMRC



316L – UK-NAMRC

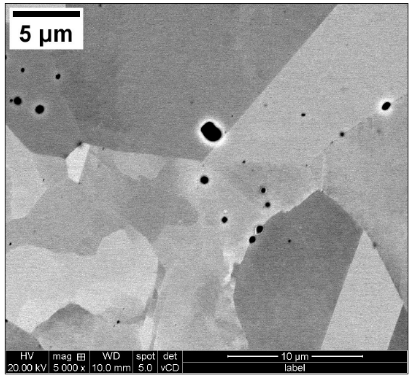


316H – MTC Heat 1



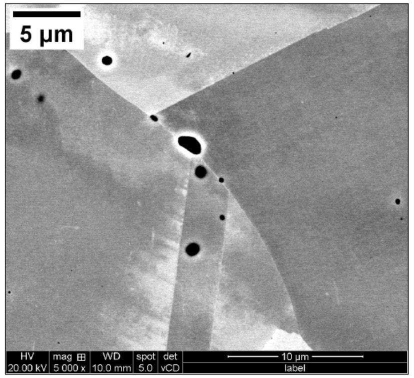
Oxide Area Fraction = 0.10%

316H – UK-NAMRC



Oxide Area Fraction = 0.18%

316L – UK-NAMRC



Oxide Area Fraction = 0.18%

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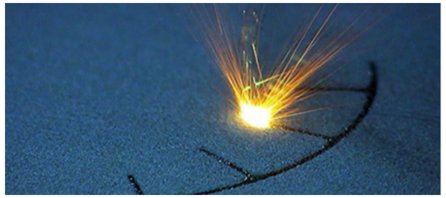
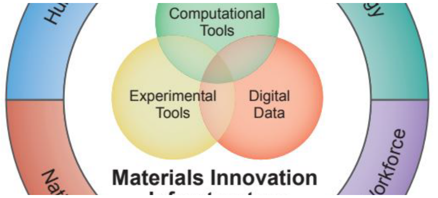
Rapid Qualification

Rapid Qualification Framework



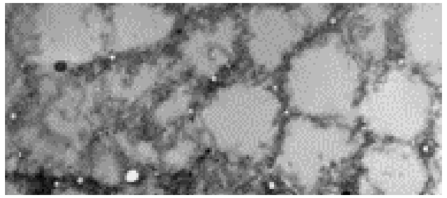
Develop Processing-Structure-Property-Performance based Qualification Framework

To address the challenges posed by advanced manufacturing that cannot be easily handled by traditional qualification approaches, we will develop a P-S-P-P based qualification framework by integrating materials development, advanced manufacturing, and environmental effects.



Use integrated experimental, modeling and data-driven tools

The new qualification framework will capitalize on the wealth of digital manufacturing data, integrated computational materials engineering (ICME) and machine learning/artificial intelligence (ML/AI) tools, and accelerated, high-throughput testing and characterization techniques.



Demonstrate new qualification framework through qualifying LPBF 316H SS

Laser powder bed fusion (LPBF) 316H stainless steel (LPBF 316H SS) will serve as a case study for the development and demonstration of a new qualification framework.

Ensure new qualification framework applicable to other materials systems

Develop an agnostic qualification approach applicable to a variety of material systems as well as a variety of advanced manufacturing techniques.

AM Qualification: Staged Approach

Consider multiple qualification pathways and take a staged approach.

Statistical/Equivalence-based Qualification

Require extensive testing and empirical modeling to demonstrate a new material or process is equivalent to a previously qualified one.

Incorporate in-situ process data into AM qualification

Use in-situ measurement data and understanding of the Processing-Structure-Property-Performance relationship.

Model-based Qualification

Demonstrate the performance in computer models with the Processing-Structure-Property-Performance relationship and verify it with minimal testing.

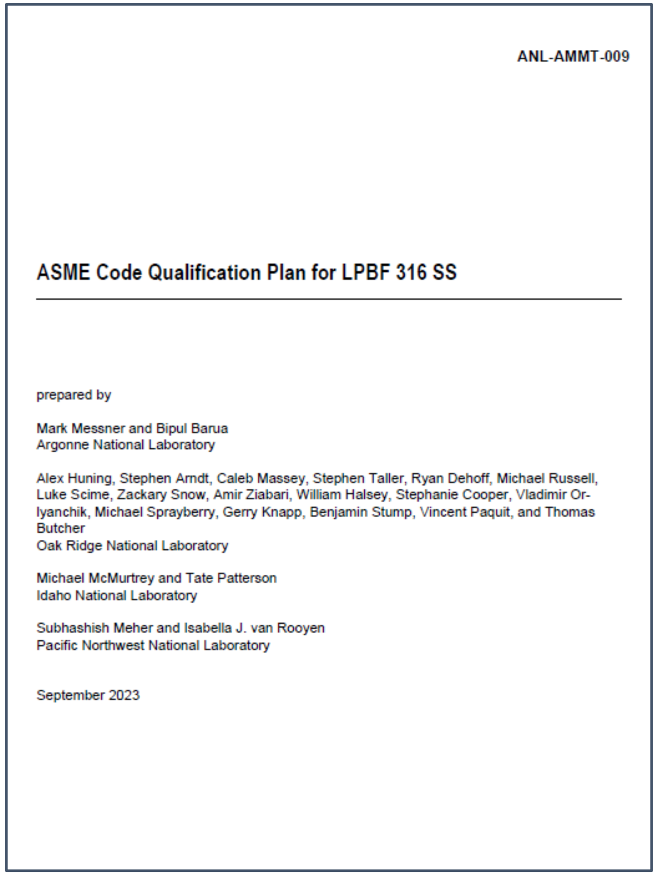
Case Study: LPBF 316H SS for High-temperature Nuclear Applications

ASME Code Case: qualify LPBF 316H SS for use with ASME Section III, Division 5, High Temperature Reactors.

- Add an AM material in ASME Division 5 is critical to the wide adoption of AM technologies in advanced reactors.
- Gain a comprehensive understanding of the AM qualification process for nuclear applications.
- Provide a testbed to demonstrate accelerated qualification methods.

Qualification differences between AM and conventional materials

TRADITIONAL WROUGHT/CAST	POWDER BED FUSION
• Centralized, repeatable manufacturing	• Decentralized, more variable manufacturing
• Established qualification process, including for high temperature applications	• Qualification approaches not yet established, particularly for high temperatures
• Basic high temperature performance often known in advance through prior testing	• Very limited extant high temperature test data
• Basic repeatability/quality control standards accepted across community	• Still considerable debate on how to establish/demonstrate repeatability
• At least notionally, negligible size/thickness effects	• Part dimensions significantly affect key material properties


ANL-AMMT-009

ASME Code Qualification Plan for LPBF 316 SS

prepared by

Mark Messner and Bipul Barua
Argonne National Laboratory

Alex Huning, Stephen Arndt, Caleb Massey, Stephen Taller, Ryan Dehoff, Michael Russell, Luke Scime, Zackary Snow, Amir Ziabari, William Halsey, Stephanie Cooper, Vladimir Orlyanchik, Michael Sprayberry, Gerry Knapp, Benjamin Stump, Vincent Paquit, and Thomas Butcher
Oak Ridge National Laboratory

Michael McMurtrey and Tate Patterson
Idaho National Laboratory

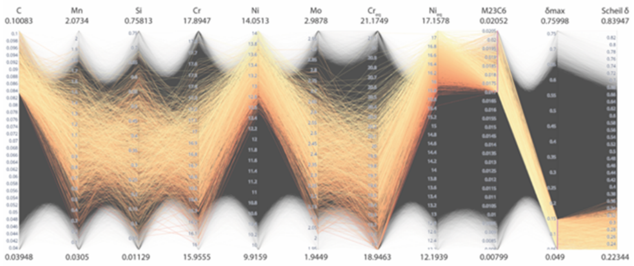
Subhashish Meher and Isabella J. van Rooyen
Pacific Northwest National Laboratory

September 2023

Experimental Understanding of Processing-Structure-Property

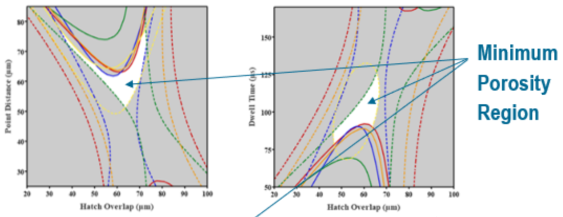
Process Understanding and Optimization

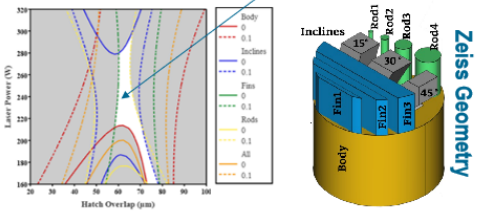
Feedstock Chemistry



Chemistry on sensitivity to energy density, and data mining highlighting 316H chemistries to maximize carbides and minimizing δ-ferrite.

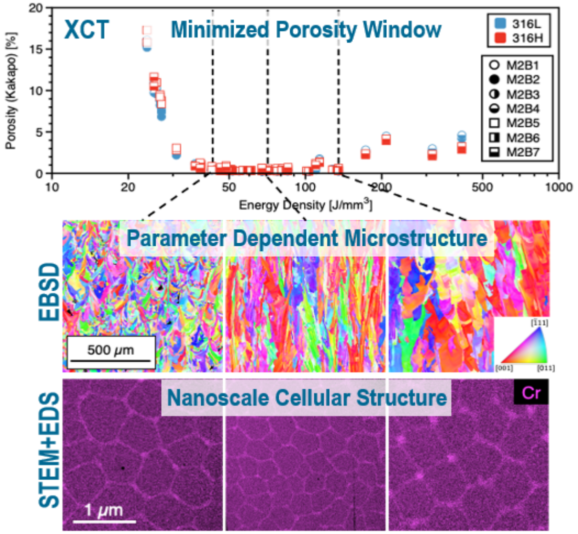
Geometry Effects





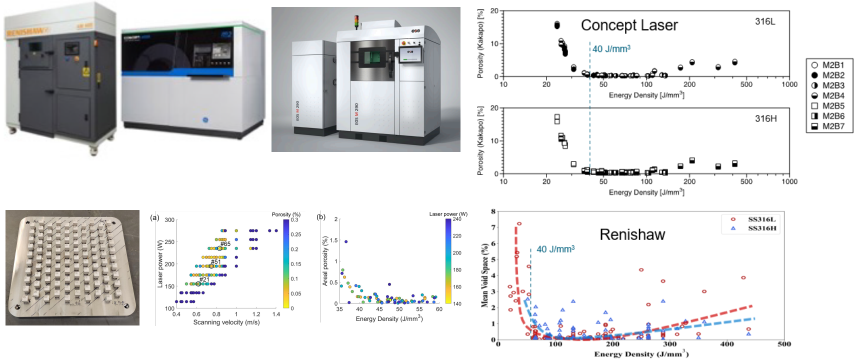
XCT used to probe geometry-specific porosity trends in AM parts.

Process Variables



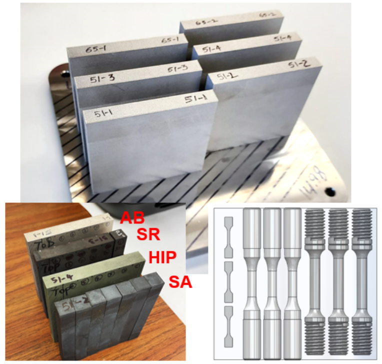
Multiscale characterization using XCT, EBSD and STEM-EDS reveals variations in porosity, grain structure, & nanoscale segregation as a function of varying processing parameters.

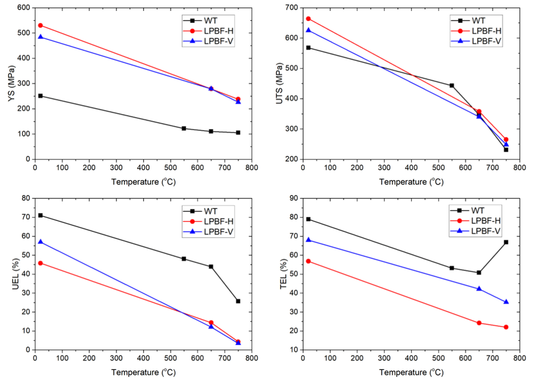
Machine Variability

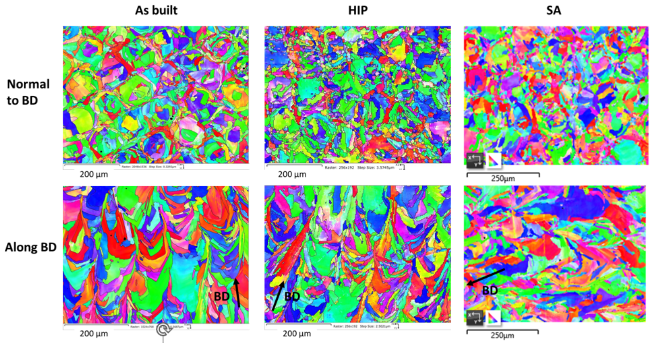


- *Volumetric energy density provides a reasonable first-pass optimization parameter for porosity minimization.*
- *Investigate the "windows" of optimal parameters between machines.*

Post-build Treatment and Property Testing

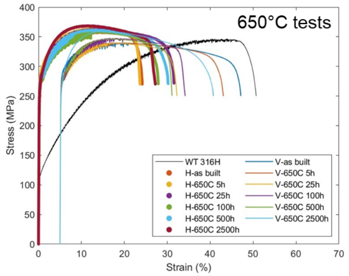


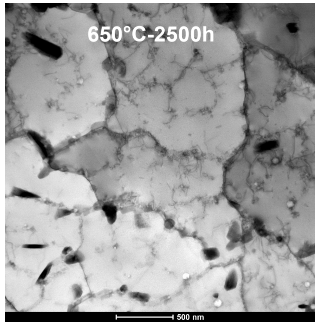




High-temperature fatigue, creep, and creep-fatigue tests of LPBF 316H SS is underway.

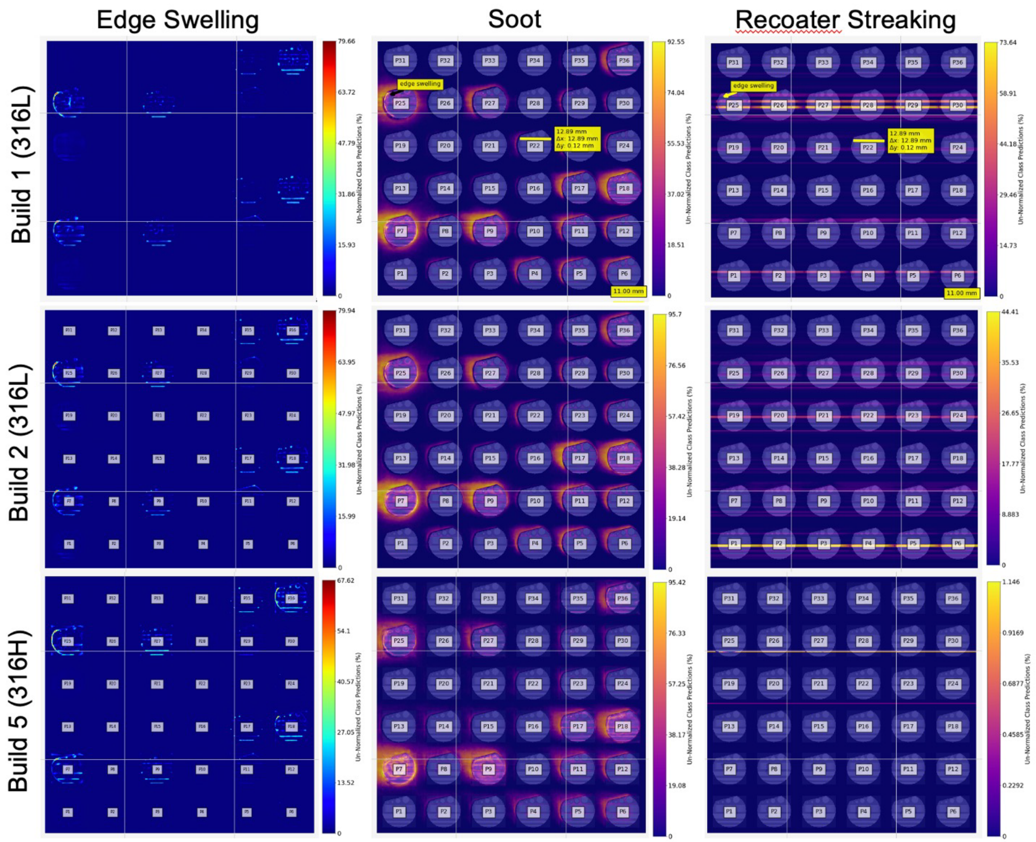
Thermal aging study of LPBF 316H SS.





In-Process Monitoring

- Use *in situ* process monitoring data to detect defects and as a QA tool to assess part quality.
- Integrate *in situ* process monitoring data into the qualification process for AM nuclear applications.
- Work with ASME to understand the pathway for utilizing *in situ* process monitoring data for AM qualification.

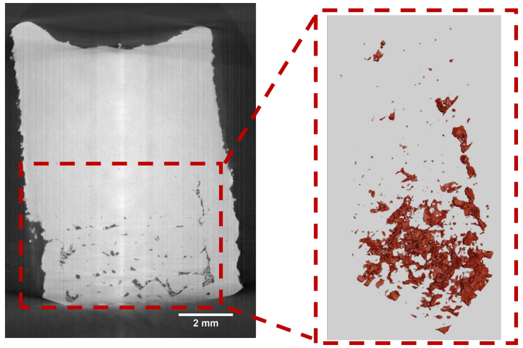


Three classes of characteristic anomalies identified through in situ data collection.

Post-Process NDE of AM Components

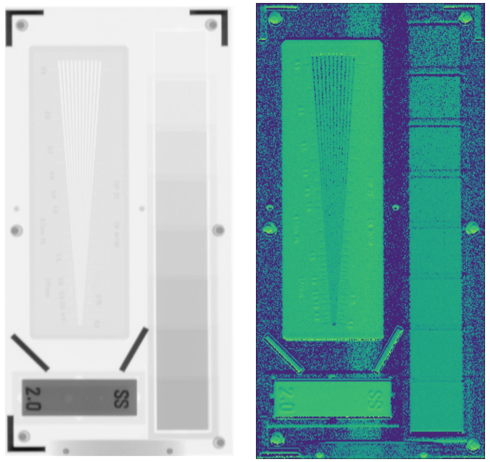
- Identify and develop advanced, reliable, and high-resolution techniques for non-destructive evaluation (NDE) of AM parts with complex geometry.
- Explore various NDE techniques for AM applications, e.g. X-ray and neutron imaging, and advanced ultrasonic methods.

X-ray Computed Tomography (XCT)



X-ray tomography result of a DED 316 SS sample for porosity measurement.

Dual Energy XCT

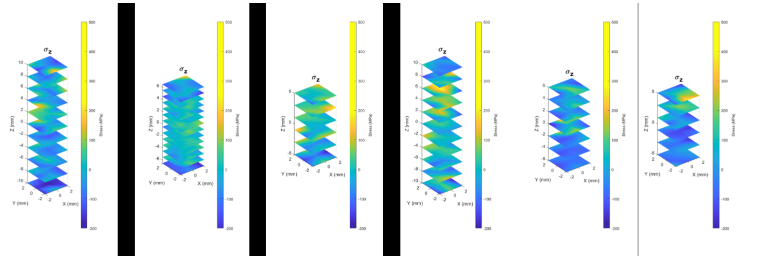


Identify material composition of the test object based on X-ray absorptiometry.

*X-Ray image of the Image Quality Indicator (IQI) phantom **(left)** and associated material identification results **(right)** displaying a map of the effective atomic number (Z_{eff}) at each point in the region of interest.*

Neutron Computed Tomography (nCT)

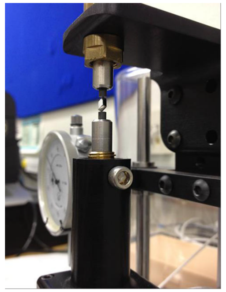
nCT can image large, dense objects because of deep penetration.

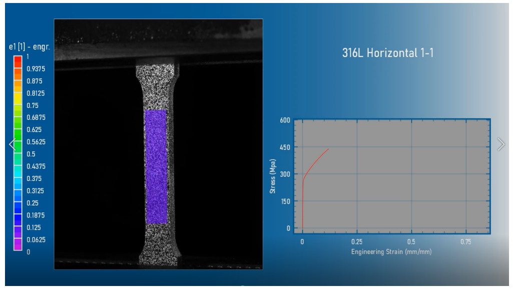


Use nCT to characterize AM 316 SS and measure the residual stress distribution along the build direction and its dependence on printing parameters.

Advanced Ultrasonic Methods

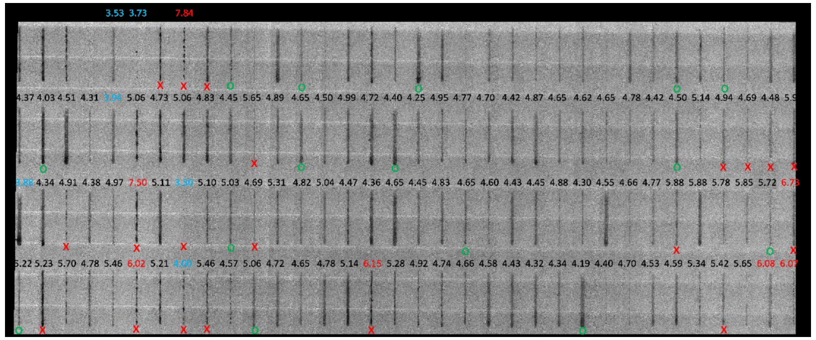
- Phased array ultrasonic testing (PAUT) to defect surface and subsurface defects.
- Resonant ultrasound spectroscopy (RUS) to evaluate elastic properties of AM materials.





Photothermal Radiometry (PTR)

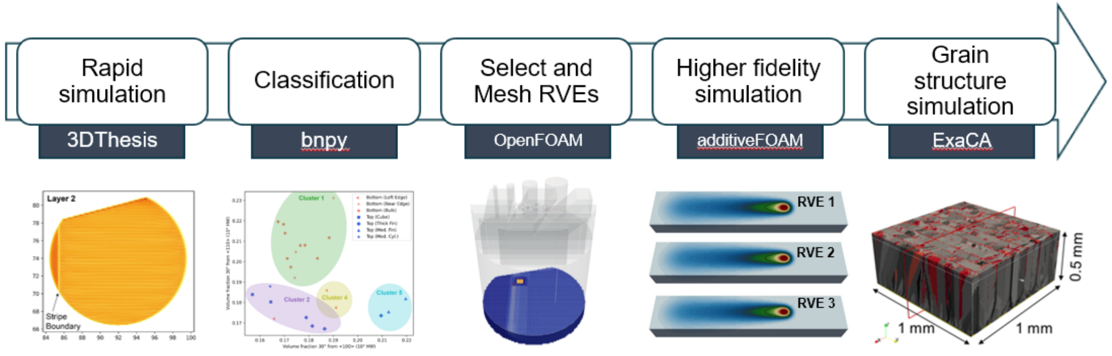
PTR measures thermal transport properties and correlates them to local porosities. The measurements are conducted through collecting blackbody radiation and thus are ideal for high-temperature environments and industrial-grade surfaces.



Thermal diffusivity measurement results on LPBF 316 tracks.

Processing-Structure-Property Modeling

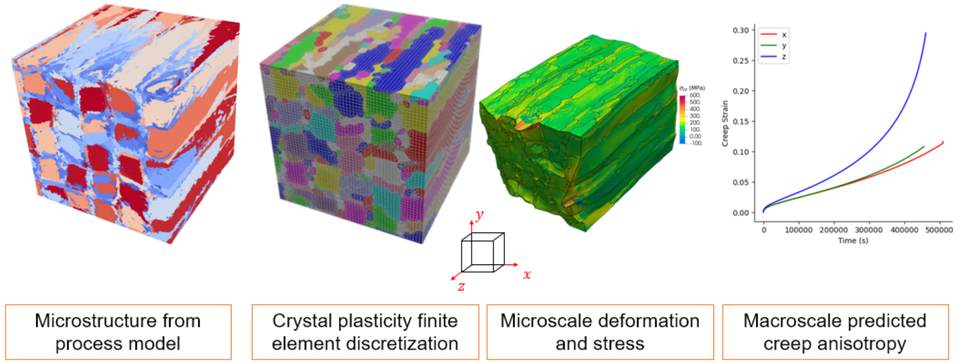
Process modeling to predict AM microstructure



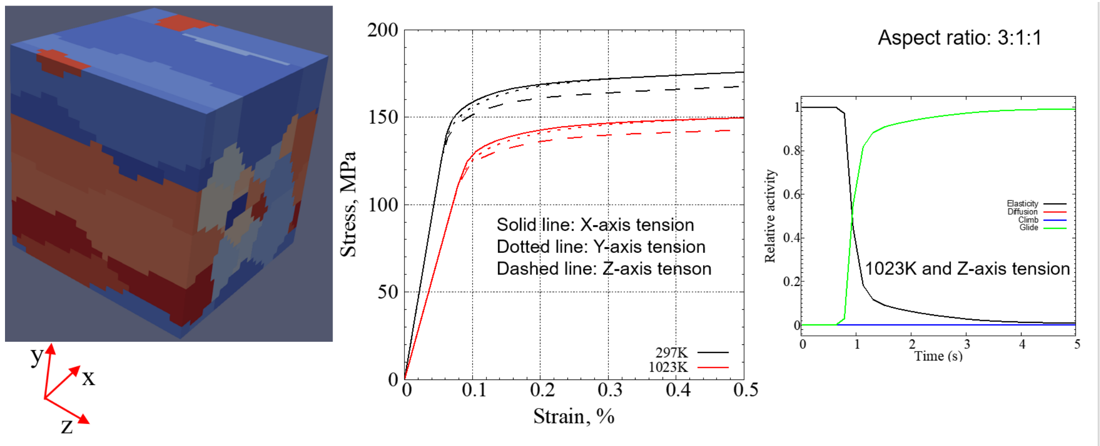
Output: *Generate representative grain structure statistics for variation found in real parts*

Connecting process modeling to property predictions

- Process model may be used to generate synthetic microstructures

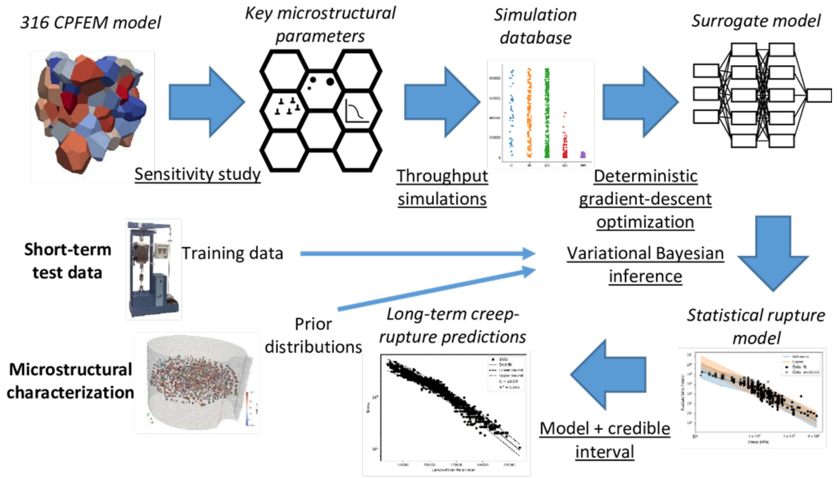


Simulate tensile behavior of AM with columnar grains

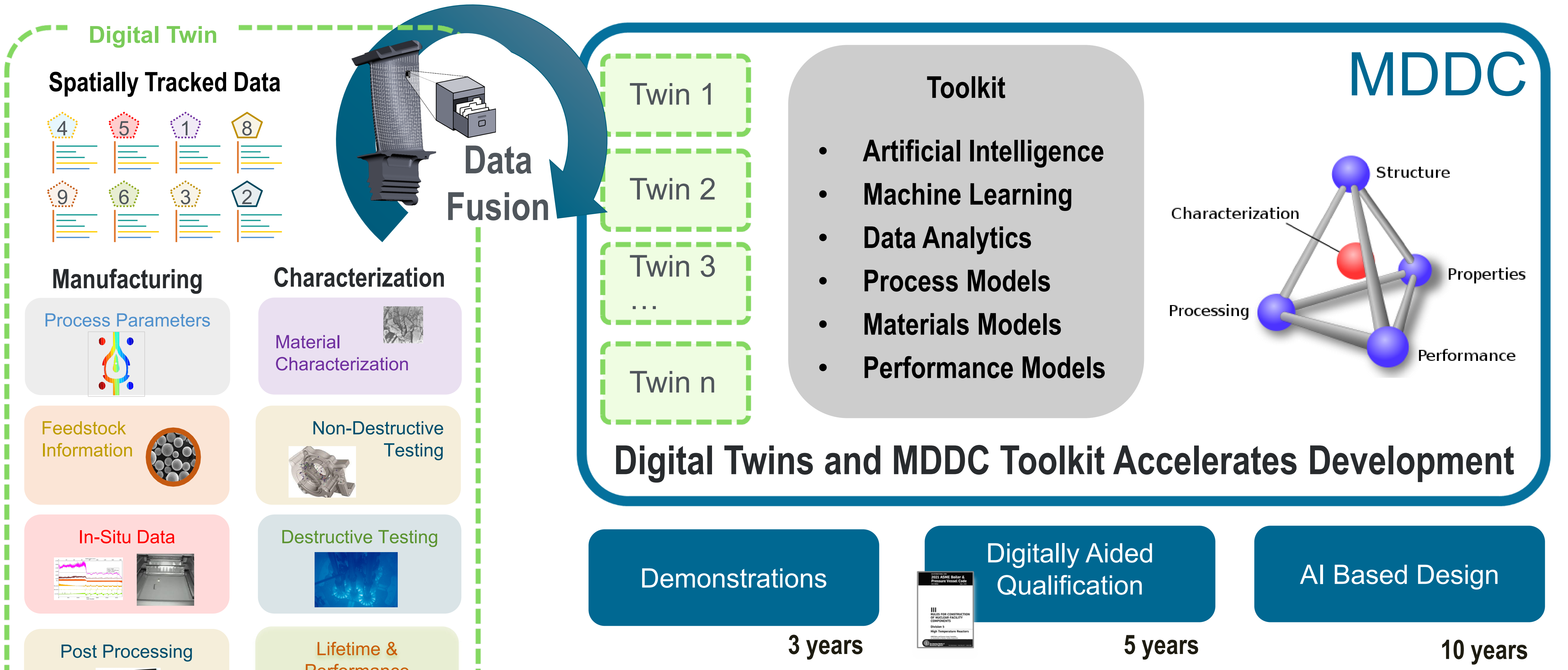


Columnar grain structure develops significant anisotropy in the mechanical responses.

Predict long-term creep rupture strength



Multi-Dimensional Data Correlation (MDDC) Platform



Improve Performance, Reliability and Lifetime of Nuclear Components

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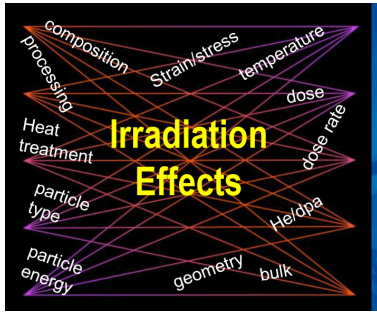
Materials Performance Evaluation

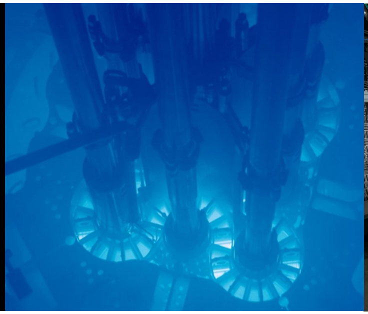
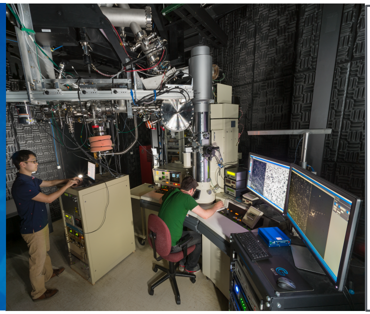
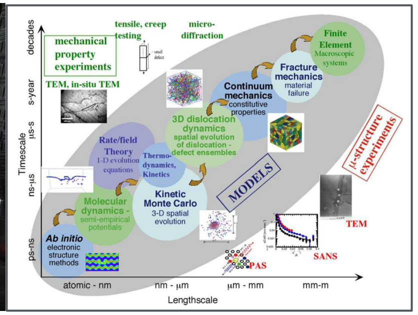
Materials Performance Evaluation

Materials Performance Evaluation investigates irradiation and corrosion effects to support material qualification in nuclear environments and address environmental degradation and aging of materials during service.

Irradiation Effects

- Qualify AM materials using combined ion & neutron irradiation data and modeling results
- Use ion irradiation for rapid screening and mechanistic understanding
- Use neutron irradiation for performance evaluation & verification



Corrosion Effects

- Understand the effects of defects and microstructural heterogeneities on AM materials corrosion behavior
- Evaluate the corrosion performance of AM materials in nuclear environments

Processing
Feedstock, printing parameters, post-processing conditions, etc.

→

Microstructure
Porosity, residual stress, surface roughness, anisotropy, chemical segregation, grain structure, dislocation structure, etc.

→

Corrosion Behavior
General corrosion, SCC, IASCC, corrosion fatigue, intergranular corrosion, mass transfer, etc.

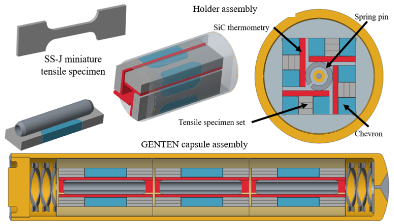
Corrosion test method standardization

Neutron Irradiation and PIE of LPBF 316 SS

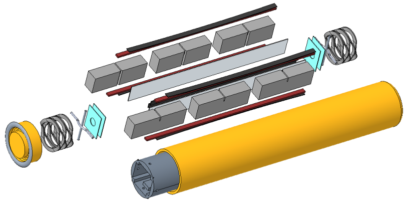
HIFR Irradiation

Flux Trap "Rabbits" Experiments

- Center cylindrical flux trap, 12.70 cm diameter
- Fast flux: 1.1 × 10^{15} n/cm^2/s
- Thermal flux: 2.0 × 10^{15} n/cm^2/s
- Small diameter: Ø9.5–11.3 mm
- 12.6 dpa/calendar year (steels)
- Single temperature (60°C–1200°C)
- Hydraulic tube (HT) for irradiation < 1 cycle

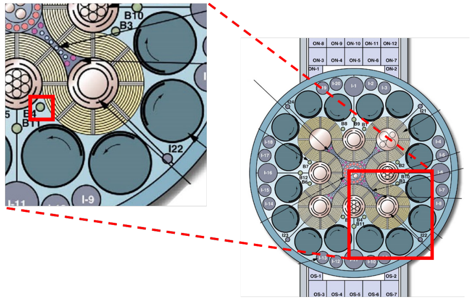


- Tensile specimens
  - SS-J2 (16 x 4 x 0.5 mm) – 36 specimens per capsule
  - SS-J3 (16 x 4 x 0.75mm) – 24 specimens per capsule
- Bend bar specimens
  - 6 bend bars per rabbit capsule
  - Specimen dimensions: 14.8 x 3 x 4.5 mm

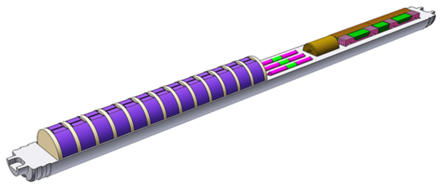


ATR Irradiation

- Spectrum is primarily thermalized
- Coolant is pressurized water at ~50 °C
- Experiment positions vary between 5/8" to 3" diameter
- Thermal Flux 2.5E+14
- Fast Flux 8.1E+13

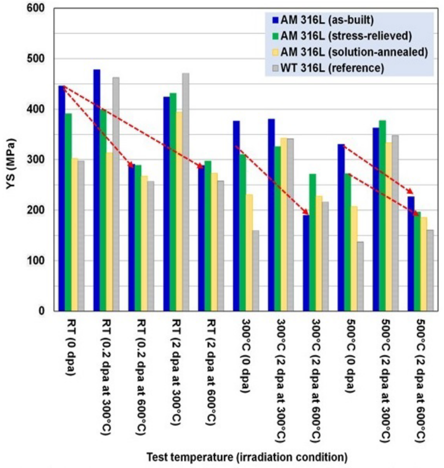


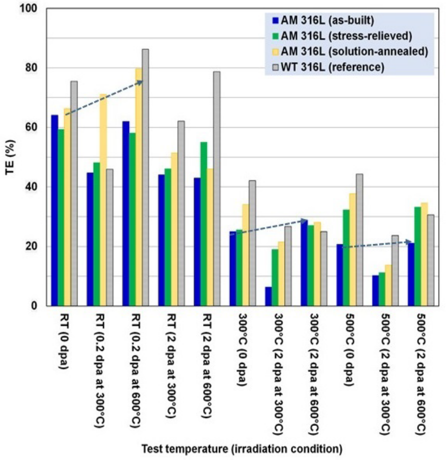
- Structural Material Testing
  - SSJ tensile bars (max 48)
  - Bend Bars (max 24)
  - Round Compact-Tension (Max 13)

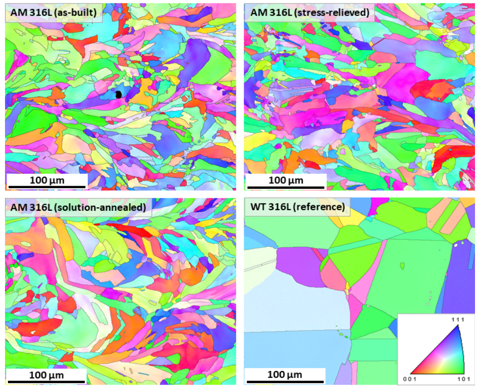


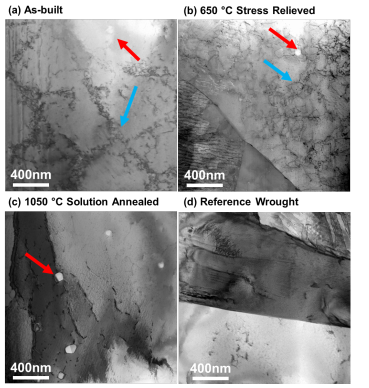
Post Irradiation Examination (PIE)

Comparison of tensile strength and ductility data for LPBF and wrought 316L SSs in various test and irradiation conditions.







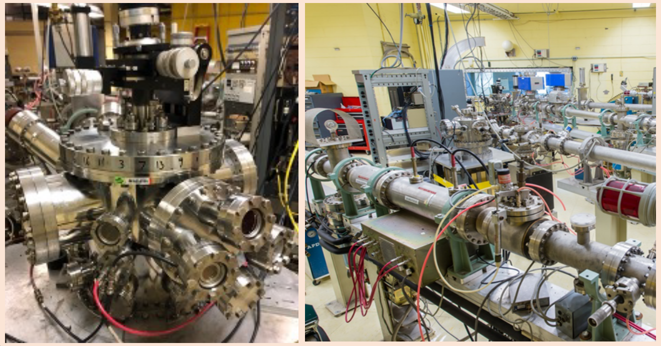


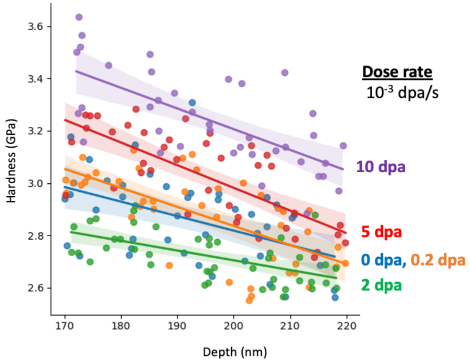
Qualify LPBF 316 SS with Combined Ion & Neutron Irradiations and Modeling

Ex situ Ion Irradiation:

A sample library of *ex situ* irradiated LPBF 316 SS to understand the composition, processing, post-build treatment, irradiation temperature, dose, dose rate dependence.

Ex situ ion irradiation

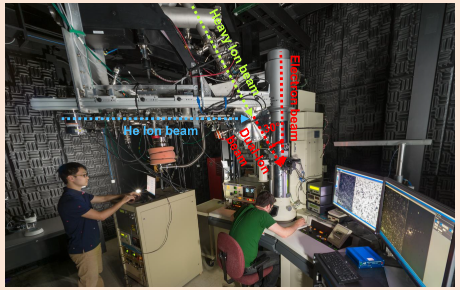


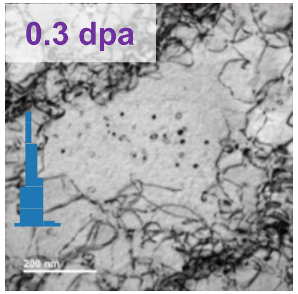


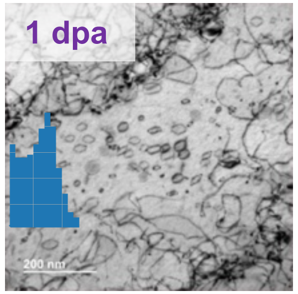
In situ Ion Irradiation:

in situ ion irradiation with TEM of LBPF 316 SS provide high-fidelity data for modeling of irradiation-induced defect evolution.

In situ ion irradiation with TEM

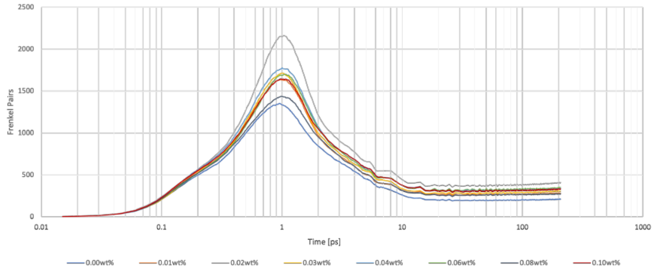




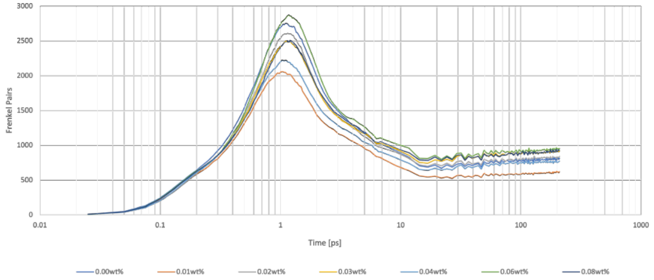


Computer Modeling

Modeling of radiation damage in LPBF 316 SS



(a) 300°C



(b) 600°C

The average time evolution of 15 keV collision cascade for a random fcc crystal with 71 wt% Fe, 18 wt% Cr, and variable carbon content.

INL/RPT-23-74577

Promoting the Regulatory Acceptance of Combined Ion and Neutron Irradiation for Material Degradation in Nuclear Reactors

September 2023

Andrea Jokisaari[1], Wei-Ying Chen[2], Yiren Chen[2], Rongjie Song[1], and Stephen Taller[3]

[1]Idaho National Laboratory
[2]Argonne National Laboratory
[3]Oak Ridge National Laboratory

INL Idaho National Laboratory

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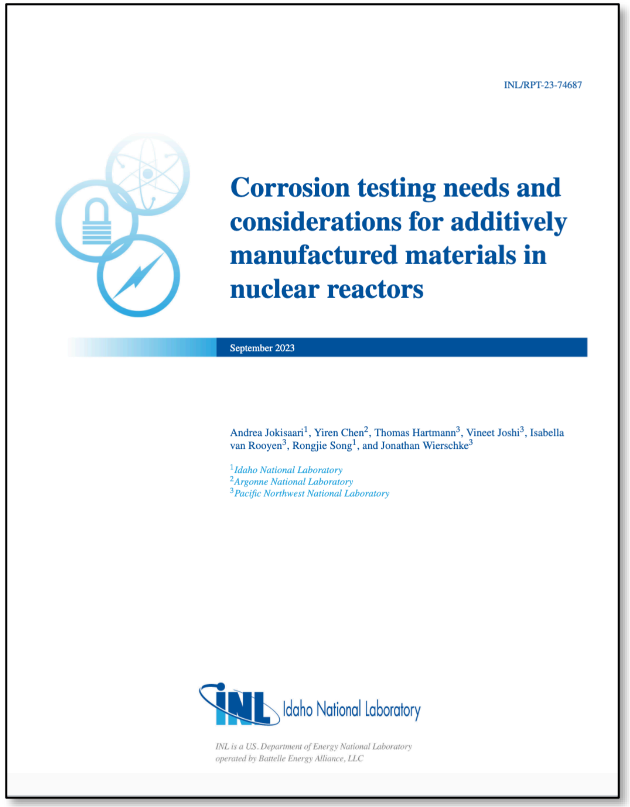
Corrosion Studies Of AM Materials

- Identified the research needs and strategies to characterize the corrosion behavior of AM materials in nuclear environments in FY 2023.
- Initiated corrosion studies of AM materials in molten salt and sodium environments in FY 2024.


INL/RPT-23-74687

Corrosion testing needs and considerations for additively manufactured materials in nuclear reactors

September 2023

Andrea Jokisaari[1], Yiren Chen[2], Thomas Hartmann[3], Vineet Joshi[3], Isabella van Rooyen[3], Rongjie Song[1], and Jonathan Wierschke[3]

[1]Idaho National Laboratory
[2]Argonne National Laboratory
[3]Pacific Northwest National Laboratory

Idaho National Laboratory

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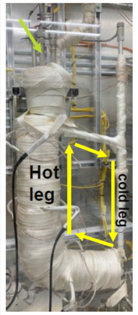
Molten Salt Experiments

Capsule and Loop Testing in FliNaK and FLiBe

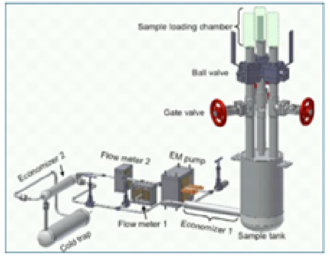


ORNL thermal convection loop, FLiBe TCL

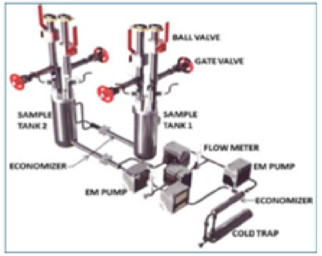
Sodium Experiments

Sodium Materials Testing Loops

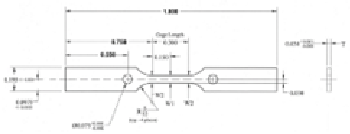
- Forced-convection sodium loops, SMT-1 and SMT-2, for sodium-exposure experiments
- SS-3 tensile samples with extended shoulder for corrosion, microstructure, and tensile properties measurements on one sample.



SMT-1, single-vessel loop, commissioned in 2011



SMT-2, dual-vessel loop, commissioned in 2013



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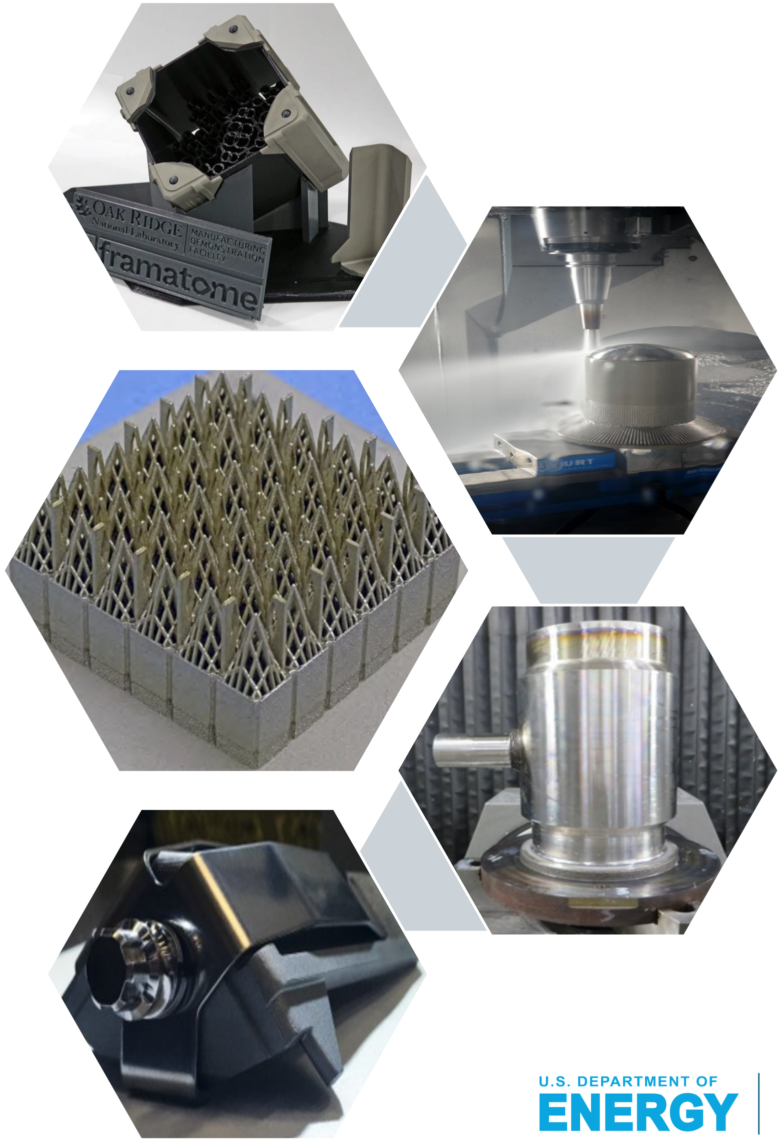
Technology Demonstration

Component Fabrication and Testing

- Engage with industry partners to identify components for potential demonstration projects.
- Manufacture selected components using AM technologies.
- Perform and benchmark demonstration analyses against modeling and simulation results.
- Include both modeling and *in situ* data in the MDDC platform.
- Apply lessons-learned from the demonstrations to complete a roadmap for demonstration of other advanced materials and manufacturing techniques.



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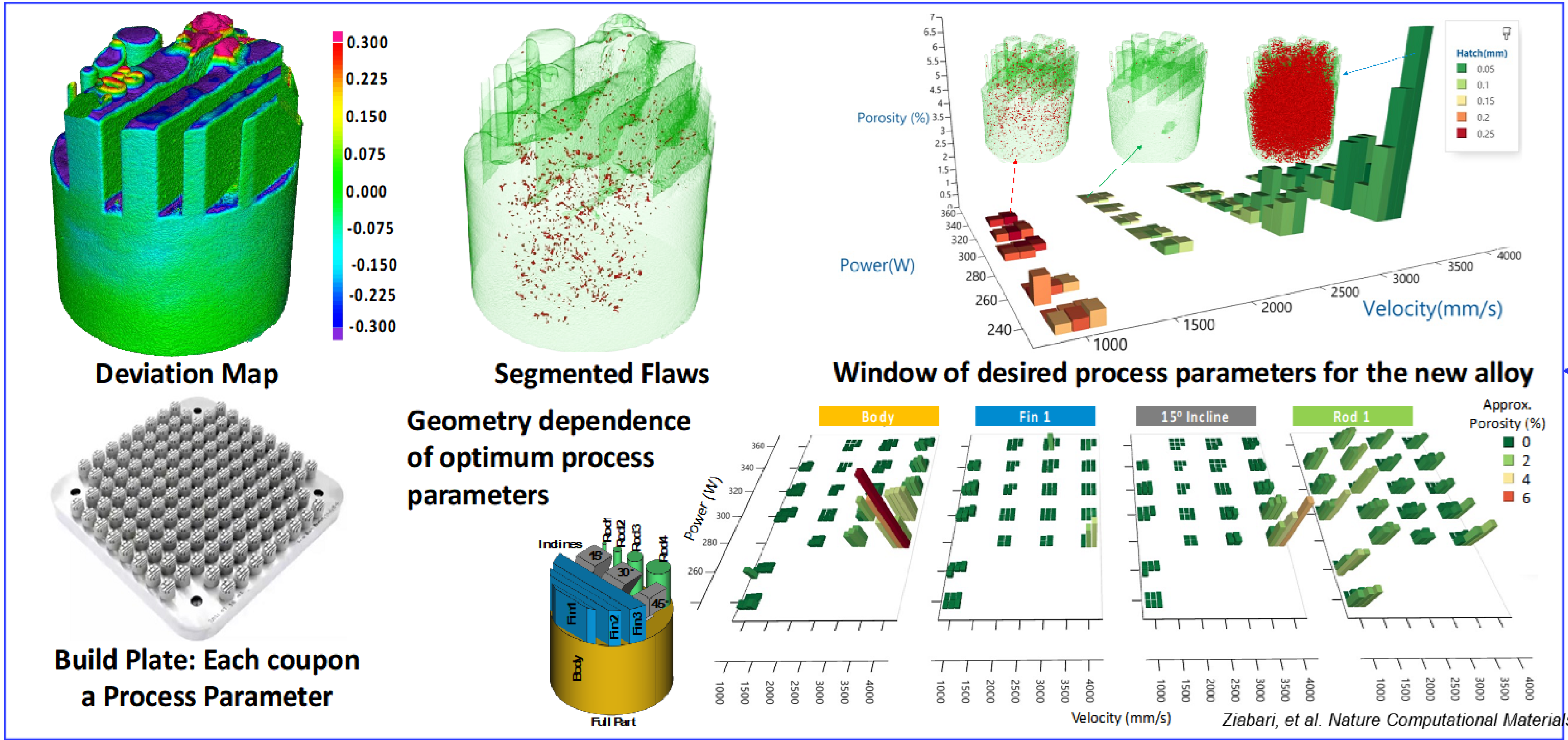
Capability Development & Transformative Research

High-throughput Automated X-ray CT NDE

1. Design of Experiment (DoE) Parameters (**A Novel Material**) → 2. Print the build plate. Remove parts from plate: (~100 parts per plate) → 3. X-ray CT **at fraction** of optimal scan time based on material → **4. Fast, consistent and accurate AI-Based X-ray CT Reconstruction** → 5. Analysis (segmentation, flaw detection, porosity & morphology, Metrology)

- Rapid automated characterization for process parameter selection
- Integrated with in-situ monitoring process

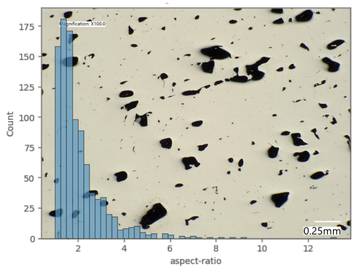


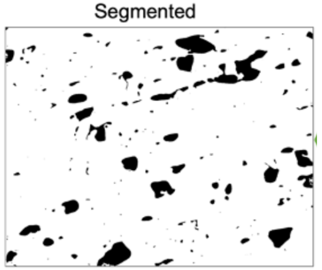
Ziabari, et al. Nature Computational Materials, 2023.

Computer Vision (CV) Automated Microstructure Quantification

Multi-scale Microstructure Quantification: CV enables rapid and consistent microscopic analysis at various length scales.

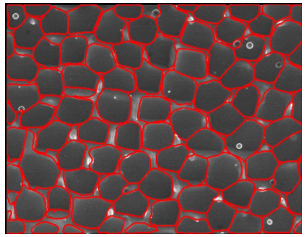
Optical Microscopy



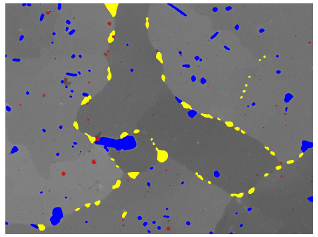


Python-based computer vision tools to analyze porosity size, density and shape in LPBF 316 SS.

Scanning Electron Microscopy (SEM)

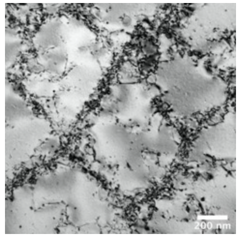


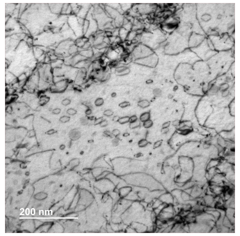
Segmentation of cell structure in LPBF 316 SS.



Annotation overlay of CrCO-rich phase, $MnSiO_3$, and MoSi rich precipitates highlighted in yellow, red and blue, respectively.

Transmission Electron Microscopy (TEM)

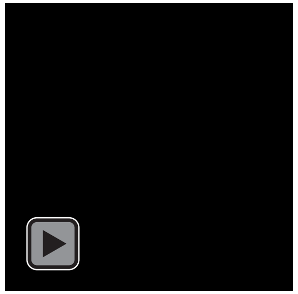


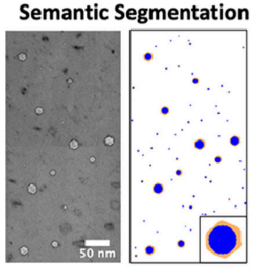


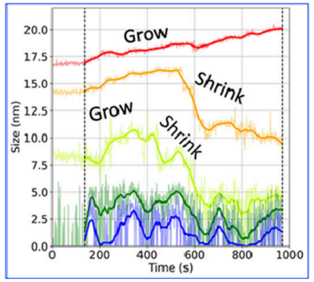
CV models to analyze TEM images to measure dislocation cells, dislocation lines and dislocation loops.

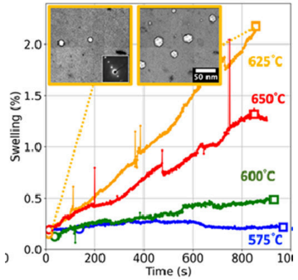
Irradiation Defect Dynamics: CV enables extracting dynamic information of irradiation-induced defects during *in situ* ion irradiation with TEM.

Track individual voids and monitor void swelling during irradiation.

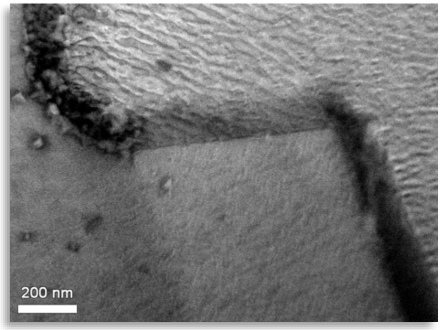




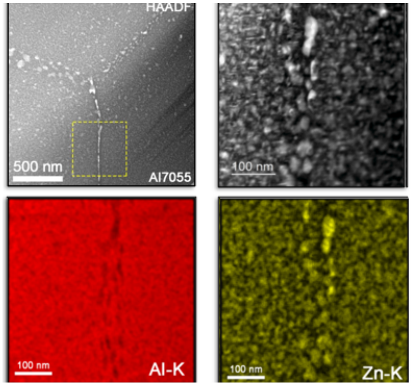




3D Characterization: automated data collection to create tilt series images and composition maps for 3D analysis.



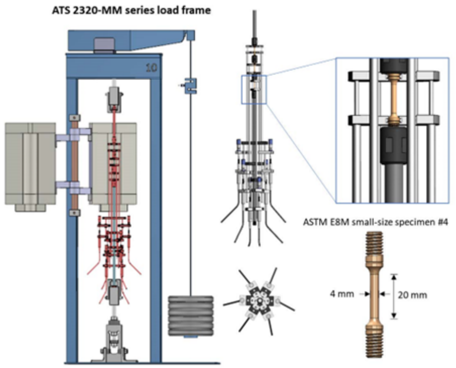
Incorporate chemical signals (EDS/EELS) to the tilt maps



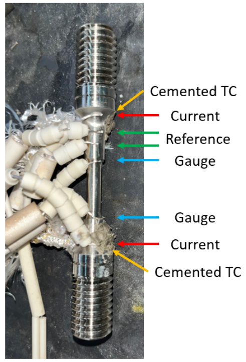
High-throughput Creep Testing Techniques

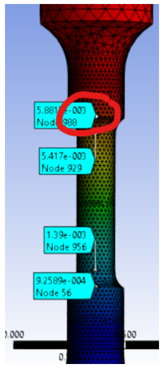
Series, multi-specimen loading

Multi-specimen creep testing with LVDT or DCPD measurements.



Creep strains measured by linear variable differential transformer (LVDT).



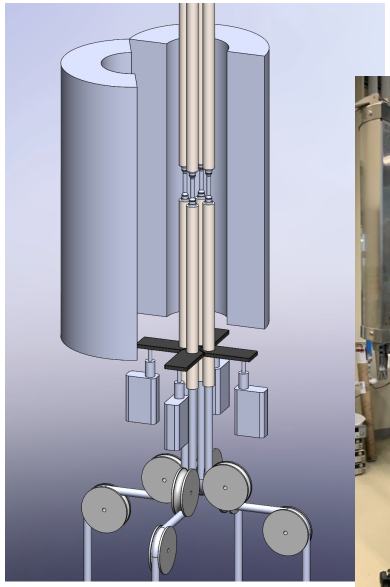


Creep strains measured by Direct current potential drop (DCPD).

Multi-specimen creep testing setup at ANL.

Parallel, multi-specimen loading

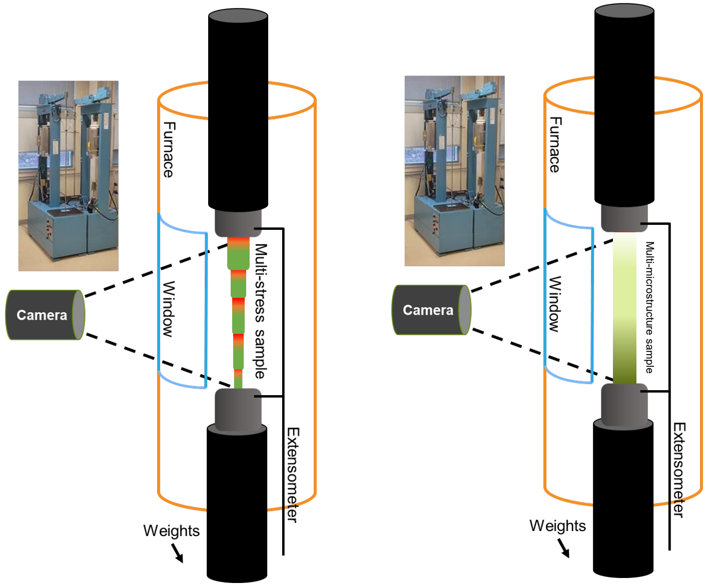
Two independent creep load trains on a modified ATS creep frame to test multiple specimens.



Multi-specimen creep testing setup at INL.

Multi-stress/microstructure specimen

Digital Image Correlation (DIC) to collect multiple parameters of interest within a creep test of a single specimen.



DIC creep testing setup at INL

Summary

Advanced Materials & Manufacturing

- Optimize/develop materials for advanced manufacturing.
- Large-scale additive manufacturing for nuclear applications.

Rapid Qualification

- Establish and demonstrate a rapid qualification framework via qualifying LPBF 316H SS.

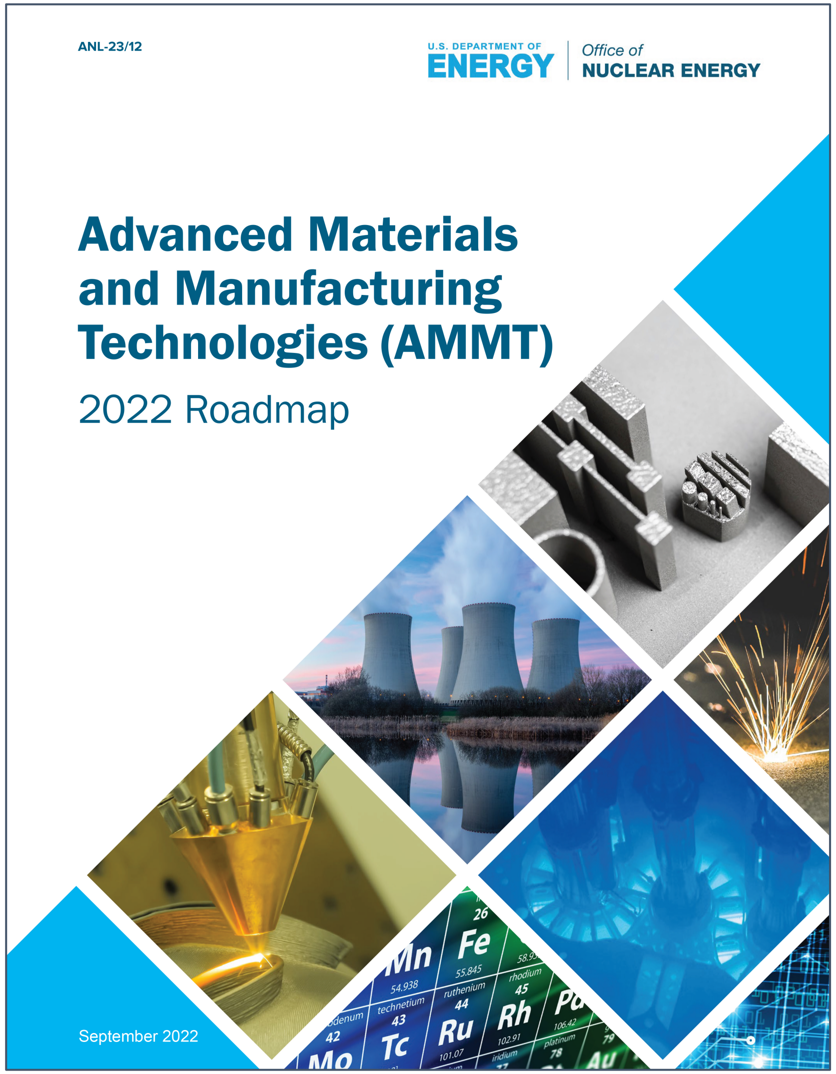
Materials Performance Evaluation

- Evaluate irradiation and corrosion behavior of advanced materials, currently focusing on LPFB 316H SS.

Technology Demonstration

- Identify, fabricate and test AM components in relevant nuclear environments.

Capability Development & Transformative Research


ANL-23/12

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

Advanced Materials and Manufacturing Technologies (AMMT)

2022 Roadmap

September 2022

AMMT Industry Workshops

AMMT Industry Workshop, MDF/ORNL, May 23-24, 2023

Goals

- Bring together subject matter experts to accelerate development, qualification, demonstration and deployment.
- Give industry an overview of the AMMT program and show capabilities and progress
- Facilitate conversation around industry needs and determine potential demonstrations with industry

Attendance

- > 80 Attendees
- >20 Companies
- NIST, NRC, ASME, NEI, EPRI
- Five National Laboratory Partners

AMMT Industry Workshop, INL, 2024

- Currently in the planning stage.
- Contacts:
  - David Andersson <andersson@lanl.gov>
  - Andrea M. Jokisaari <andrea.jokisaari@inl.gov>

Questions?