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RIL 2024-12

NRC 2023 WORKSHOP ON ADVANCED MANUFACTURING TECHNOLOGIES FOR NUCLEAR APPLICATIONS

Part II - Workshop Slides

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Research Information Letter
Office of Nuclear Regulatory Research

Disclaimer

2023 NRC WORKSHOP ON ADVANCED MANUFACTURING TECHNOLOGIES FOR NUCLEAR APPLICATIONS – WORKSHOP OVERVIEW -

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U.S. NRC
Office of Nuclear Regulatory Research
Division of Engineering – Materials Engineering Branch

OUTLINE

- Public Workshop
  - Overview and approach
  - Summary of sessions
  - Organization and logistics

WORKSHOP OVERVIEW

- Location/Dates:
  - NRC HQ in the TWFN Auditorium and online using Teams.
  - October 24-26, 2023, 8 am to ~5 pm
- Motivation – Be Ready
  - Potential interest in implementing advanced manufacturing technologies (AMTs) for nuclear applications such as replacement components in operating nuclear power plants and in initial construction of small modular and advanced reactors.
  - The efficient and effective introduction of components produced by AMTs in nuclear applications depends on a shared understanding of technical and regulatory challenges, success paths, and future opportunities.
- Objectives are to update the staff and stakeholders on:
  - Practical experience and plans for implementing AMT components/technology
  - AMT process/part qualification and certification approaches, including the incorporation of modeling and simulation, and rapid qualification
  - The latest developments in codes and standards pertaining to AMT adoption

WORKSHOP SESSIONS

- Session 1- Implementation of AMTs in Nuclear and Non-Nuclear Applications
  - Objectives: Provide information on experience using AMT components for nuclear and non-nuclear applications.
- Session 2 - Qualification and Certification (Q&C)
  - Objectives: Share approaches developed, or under consideration, to qualify AMT materials and components made using AMTs for applications involving component manufacturing and surface treatments.
- Session 3 - Performance Characteristics
  - Objectives: Provide information related to the performance of AMT materials and components including approaches to developing data for qualification
- Session 4 - Codes and Standards
  - Objectives: Provide updates on the latest codes and standards (C&S) related to the use of AMTs.

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WORKSHOP APPROACH

- Goal is to have an interactive workshop with multiple opportunities for dialogue
- Presentations:
  - See agenda for durations
  - Q&A after each presentation (~5 min)
  - Two discussion sessions each day (~20 min)
- Q&A following presentations:
  - Questions will be taken from the auditorium first, then online questions will be addressed
    - In-person attendees please use microphones to ask questions
    - Online attendees please place questions in the chat window during the presentation and we will address as many as possible in the allotted time
      - If you would like to ask your question verbally, please use the Raise Hand feature in Teams.

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NRC GUEST WI-FI

NRC Guest Wi-Fi Connection

Password: Gu3stP@ss4eV@!

OVERVIEW OF U.S. NRC AMT ACTIVITIES

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

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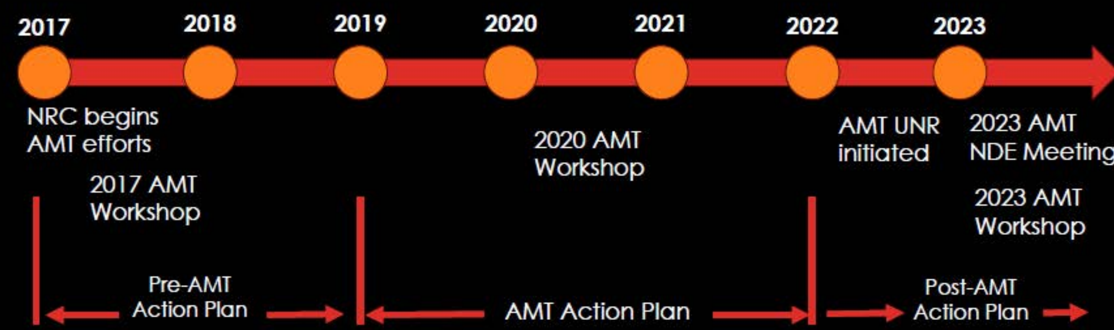
U.S. NRC
Office of Nuclear Regulatory Research
Division of Engineering – Materials Engineering Branch

DRIVERS FOR NRC ACTIVITIES

- A variety of stakeholders are working toward more widespread use in both existing and future nuclear applications:
  - Vendors and licensees/applicants
    - Identifying candidate applications
    - Developing technical bases for gaining regulatory acceptance
    - Nuclear Energy Institute – Developed advanced manufacturing methods (AMM) roadmap to understand industry needs/interests and assist with regulatory acceptance (2019)
  - Electric Power Research Institute – Developing techniques for large components in small modular reactors, developing data package for LPBF and WA-DED ASME draft Code Cases
  - US Department of Energy – Developed the AMMT 2022 Roadmap
    - Performing basic and applied research, technology development, data infrastructure, and developing a qualification framework to support AMT implementation

NRC AMT ACTIVITIES TIMELINE



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2017 NRC AMT WORKSHOP

- The objectives of the workshop were to cover topics including:
  - The state-of-the-art of AM
  - Industry activities
  - Irradiation testing and effects on AM
  - AM qualification
  - Codes & standards
  - NDE
  - Cybersecurity
  - Regulatory perspectives
- Outcomes:
  - Proceedings of the workshop published as NUREG/CP-0310 (ML19214A205)
  - Next steps included further engagement with industry.

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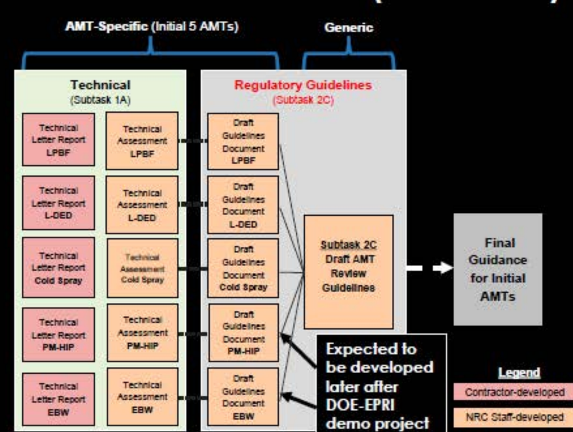
AMT ACTION PLAN (2019-2022)

- The NRC completed the AMT Action Plan which accomplished the following objectives:
  - Assessed the safety significant performance-based differences between AMTs and traditional manufacturing processes.
  - Prepared the NRC staff for potential reviews (five AMTs, modeling, and NDE).
  - Identified and addressed AMT characteristics pertinent to safety that are not managed or addressed by codes, standards, regulations, etc.
    - Risk-informed and performance-based perspective
  - Provided draft Staff guidance and tools for review consistency, communication, and knowledge management.
- Revision 1 of the AMT Action Plan was published in June 2020 (ML19333B980).

AMT ACTION PLAN (CONT.)

- NRC AMT Action Plan products:
  - Technical Letter Reports (TLRs)
    - Provide technical bases information and gap analyses
    - Prepared by NRC contractors (to date, DOE labs)
  - Technical assessments (TAs)
    - Provides the NRC staff perspective on key aspects of the AMT for safety and component performance.
  - Draft guidelines documents (DGDs)
    - Informed by the TA and TLR and generated by the NRC staff for each AMT.
  - Please visit the NRC AMT public website to download the available reports:
    - https://www.nrc.gov/reactors/power/amts.html#status



AMT ACTION PLAN PRODUCTS

Subtask	Actions/Deliverables	Status
1A AMT processes under consideration	Additive Manufacturing (AM) – Laser Powder Bed Fusion	Complete - ML20351A292
	AM – Directed Energy Deposition (DED)	Complete - ML21301A077
	Cold Spray	Complete - ML21263A105
	Powder Metallurgy (PM) – Hot Isostatic Pressing (HIP)	Complete - ML22134A437
	Electron Beam (EB) welding	Complete - ML22143A927
1B Inspection and NDE	NDE gap analysis	Complete - ML20349A012
1C Modeling and Simulation of Microstructure	M&S gap analysis to predict microstructures	Complete - ML20269A301
	ANL M&S gap analysis to predict material performance	Complete - ML20350B550

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AMT ACTION PLAN PRODUCTS

Subtask	Actions / Deliverables	Status
2A 50.59 process	Finalize document incorporating feedback from Regional staff regarding the 10 CFR 50.59 process	Complete - ML21200A222
2B Assessment of regulatory guidance	Path forward on guidance development or modification	Complete - ML20233A693
2C AMT Guidance Document	Draft AMT Review Guidelines	Complete - ML21074A037
	Draft Guidelines Documents for specific AMTs	AM-Laser Powder Bed Fusion - ML21074A040 AM-Laser-Directed Energy Deposition - ML22143A950 Cold Spray - ML22143A950
3A/3B External / Internal Interactions	Continued communication with NRC staff and external stakeholders for AMT-related activities	Ongoing as needed
3C Knowledge Management Plan	Develop Knowledge Management Plan	Complete - internal
3D Workshop	Hold public workshop	Complete - Public Meeting Summary: ML20357B071 RIL: Part 1 Part 2
3E Material Information course	Training course and course materials	First 6 seminars complete - internal

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2020 NRC AMT WORKSHOP

- The objectives of the workshop were to cover topics including:
  - nuclear industry implementation plans
  - codes and standards activities
  - research findings
  - qualification & aging management
  - regulatory approaches in other industries.
- Key Takeaways:
  - AMTs are being incorporated!
  - Use of PM-HIP with EBW for larger nuclear components looks promising, but requires larger HIP and EBW capabilities
  - AMT technologies evolve quickly, outpacing the qualification and licensing process
  - Target applications to optimize unique AM characteristics
  - SDOs need continual communication to reduce redundant standards development

2020 NRC AMT WORKSHOP: NEXT STEPS

Selected Next Steps	My Perspective
Nuclear industry / NRC: Use data from existing AMT applications to help justify and increase confidence in further applications of AMTs	This is an ongoing process as experience is gained from existing nuclear applications of AMT components (e.g., thimble plugging device, channel fastener).
Nuclear industry / NRC: Potential nuclear applications of AMTs may benefit from non-nuclear applications.	Non-nuclear applications in relevant service conditions (e.g., temperature) are helping to inform NRC assessments of AMTs
Support intelligent, performance-based qualification framework	DOE AMMT Roadmap and the America Makes Roadmap are helping greatly in this area.

2020 NRC AMT WORKSHOP: NEXT STEPS

Selected Next Steps	My Perspective
Continue developing technical basis for utilizing these technologies in nuclear applications	ASME activities to develop data packages for Code Cases are helping greatly in this area.
Gain ASME acceptance and obtain regulatory approval	ASME Code Cases have been and/or are being developed for LPBF, PM-HIP, and DED.
Continue to evaluate research needs and technology gaps	EPRI and DOE efforts are supporting this area. The NRC to continues to assess AMTs and perform gap analyses. Knowledge/data gaps may help identify research needs.

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2023 MEETING ON NDE OF AM COMPONENTS

- The meeting focused on the state-of-the-art of NDE of AM components, as well as key challenges associated with the use of these technologies. Specific topics included:
  - Ultrasonic testing (phased array, FMC/TFM)
  - Process compensated resonance testing
  - Qualification
  - Structure-property relationships
  - In-process monitoring

- Key Takeaways:
  - Integrate NDE with the design and manufacturing process of AM components.
  - Continue NRC engagement to inform staff of applicable challenges relevant to the adoption of AM components in nuclear plants.
  - The final surface condition of AM components is an important consideration for examinations.
  - Standardization of NDE calibration methods and how that applies to the different AM manufacturing processes is needed.
  - Staff gained a better understanding of AM microstructures and effects on material properties.

Meeting summary: ML23153A010

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CURRENT NRC AMT ACTIVITIES

- Continue to prepare:
  - Technical preparedness
    - AMT assessments, NDE of AMT components, data & modeling for qualification
    - Products: technical letter reports, technical assessments
  - Regulatory preparedness
    - Regulatory guidance
  - Communications and Knowledge Management
    - Internal & external interactions, KM, workshops, staff training
- Reports in review:
  - Wire-arc directed energy deposition
  - Hybrid manufacturing
  - In-process monitoring

THE END

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Rolls-Royce's Introduction of HIP Nuclear Components

US NRC Workshop on Advanced Manufacturing October 2023

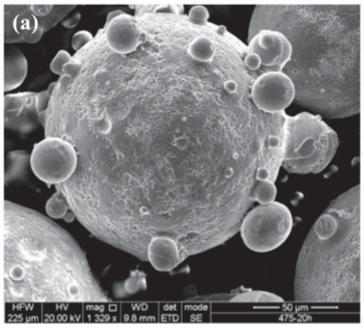
Presenter – John Sulley - Rolls-Royce Fellow

Rolls-Royce PLC

PO BOX 2000, Derby 21 7XX, United Kingdom

Agenda

HIP Process Overview



1.Inert gas atomisation to produce powder.

2.Sheet metal capsules filled with powder.

3.Capsules subjected to high isostatic pressure and high temperature to obtain full density.

4.Can pickled or machined off.

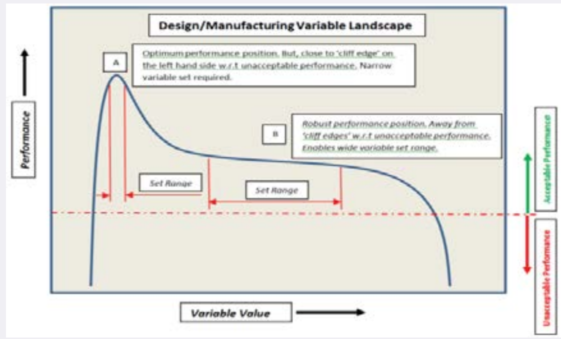
Why HIP?

- **Project:**
  - Lead-Time Reduction
    - No tooling development required, thin-can encapsulation - welding of mild steel
  - Cost Reduction
    - Scrap/re-work elimination
    - Material quantity - closer to final shape
    - Machining reduction - closer to final shape
- **Product:**
  - Material Quality Improvements
    - Cleaner material, no aligned inclusions
    - Homogeneous
    - Isotropic
    - Improved properties can be achieved due to smaller grain size
    - Smaller defect sizes (sieving size)
  - Non-Destructive Examination Improvement – Sensitivity increase due to:
    - Homogeneous material structure
    - Finer grain size

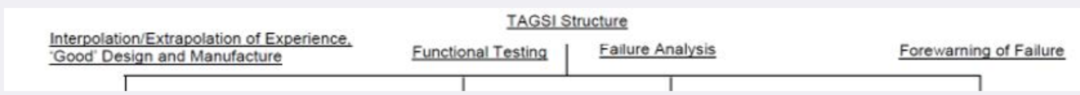
Approach

Enable a Project to adopt the technology by:

- Establishing a **robust** Method of Manufacture (MoM) – understanding of variability. Ensuring risks are appropriately mitigated.



- To provide data in order to produce a generic/base level justification – UK TAGSI four-legged structure. Additional, specific application data may still be required.



Approach

- Demonstrator units produced for each application.
- Dimensionally inspected to show geometry can be achieved.
- NDE examination and destructive examination. Units cut up for material microstructural assessment and property testing.
- Near Nett Shape? Some benefits, but design for inspectability was key consideration.

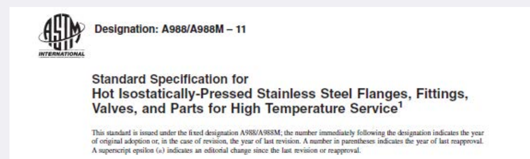
Approach

- Independent industry survey
- Incremental approach
    - Non-Pressure Boundary
    - Pressure Boundary – Leak Limited
    - Pressure Boundary – Isolable
    - Pressure Boundary - Unisolable
- Material equivalence striven for.

		Material Specification	HIP 304LE Cylinder	HIP 304LE Body	Wrought Casts
0.2% Proof Stress		207 MPa	274 MPa	300 MPa	267 MPa
Ultimate Tensile Strength		517 MPa	625 MPa	628 MPa	589 MPa
Elongation %	Longitudinal	40	73	68	65
	Transverse	30			


CASE N-834

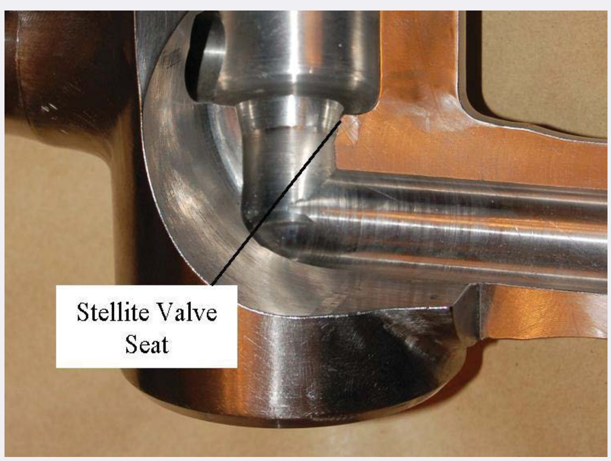
- ASME code case – N-834

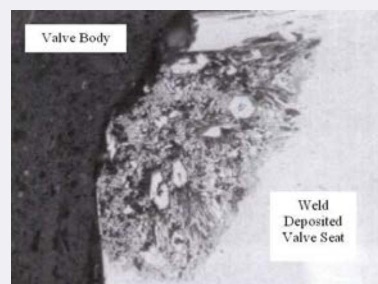

Designation: A988/A988M – 11

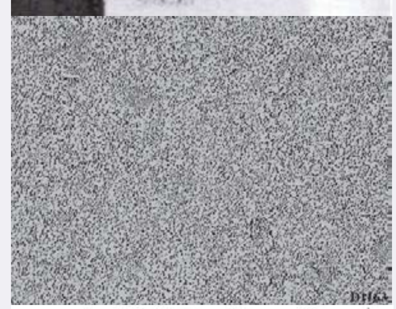
Standard Specification for
Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service[1]

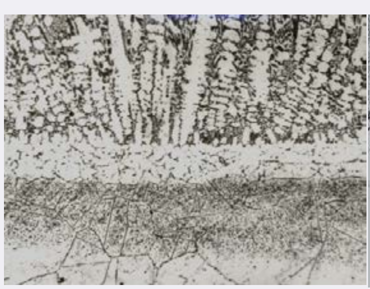
This standard is issued under the fixed designation A988/A988M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

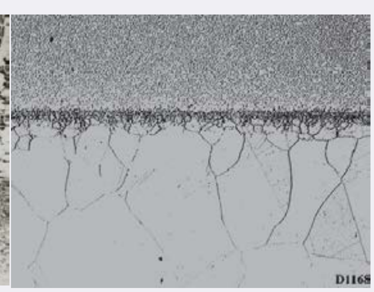
Applications - Valve Hard-Faced Seats











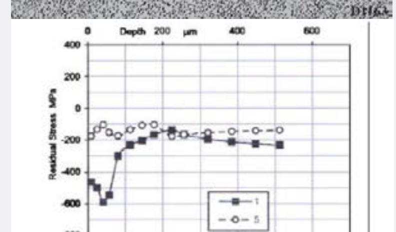


Fig. 9. Residual stress distribution for positions 1 and 5 – Radial/Axial Stresses v Depth.

References:

ICAPP 08-8110, 2008 [1]

ICONE24-61106, 2016 [2]

Applications -

Valve Hard-Faced Seats

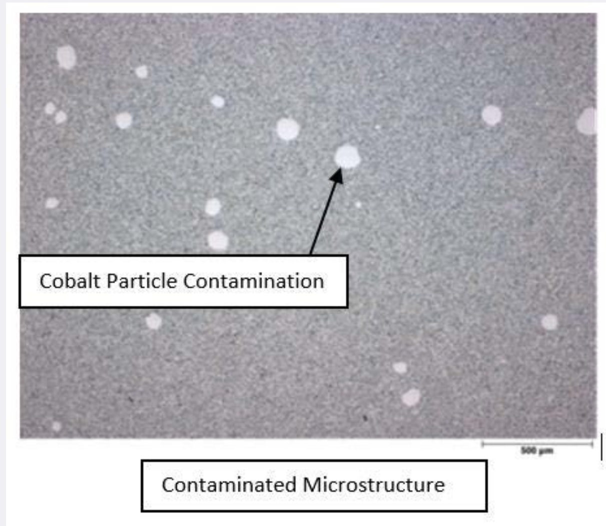

Rolls-Royce

ICONE24-61106
HIPED HARD FACINGS FOR NUCLEAR APPLICATIONS – MATERIALS, KEY POTENTIAL DEFECTS AND MITIGATING QUALITY CONTROL MEASURES

Presented by
Eur Ing J Sulley - Chief of Engineering Capability
Co-Author
Dr D Stewart – Technical Specialist

Reference:

ICONE24-61106, 2016 [2]



- **Potential Defects and Mitigating Quality Controls:**
  - **Metallic Inclusions**
  - **Non-Metallic Inclusions – Refractory Materials**
  - **Non-Metallic Inclusions – Melt Oxides**
  - **Porosity**
  - **Grain Growth**
  - **Oxide Formation**
  - **Contamination from Chemical Species**

ICONE24, Paper 61106

All Applications -

Powder Quality

Internet Search – Powder Contamination Aerospace Industry

‘The problem which the company first disclosed in July, stems from defects with powder metal used to make some popular geared turbofan engines, a flaw that can cause cracks.’

‘$3 billion charge!’

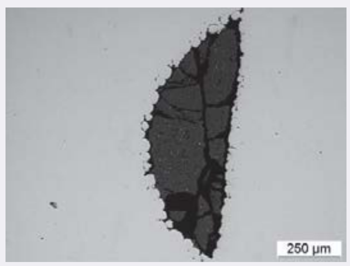
‘Discovered an issue with contaminated powder metal that could cause cracking in stage 1 and stage 2 discs in the high pressure turbine. These obviously must be inspected at certain intervals to ensure there is no actual problem.’

All Applications - Powder Quality

Ensure you have specifications covering powder quality, also other process steps, e.g. HIPing – furnace control.

Reference:

ICONE24-61106, 2016 [2]



Metallic Inclusions Cause and Mitigation

Exclude elemental cleansing 'washes', e.g. 'cobalt' wash.	If an elemental wash is conducted, any remnant powder may be drawn through in the subsequent material atomisation run.
Schedule the material production run to follow the exact same material or material family of another order.	Any remnant material from a previous production run will not be adversely different to the material run.
Sacrificial run conducted of the actual material prior to the production run proper.	Any remnant material from previous production runs/washes is most likely to be drawn through in the first quantity of material..
The whole, or specific operations (e.g. sieving), of the production process to be dedicated to a specific material family type.	Any remnant material from a previous production run will not be adversely different to the material run.
Robust clean down of all the equipment.	To remove any remnant material from previous production runs.
The design of the atomiser and sieve to be such that it eliminates/reduces areas where powder can accumulate.	To reduce the risk of remnant material from previous production runs becoming dragged through with the production material.
Examination of a HIPed specimen looking for metallic inclusions.	This is the key mitigating control measure to ensure unacceptable powder is not applied to product.

Rolls-Royce

POWDER MANUFACTURE BY GAS ATOMISATION 2.0

Rolls-Royce

CONSOLIDATION BY HOT ISOSTATIC PRESSING 4.0

Rolls-Royce	MATERIAL SPECIFICATION	RRMS Version 3.0 Date 05 AUG 2021

Acceptance Test Requirements for Metallic Powder and Powder Based Product

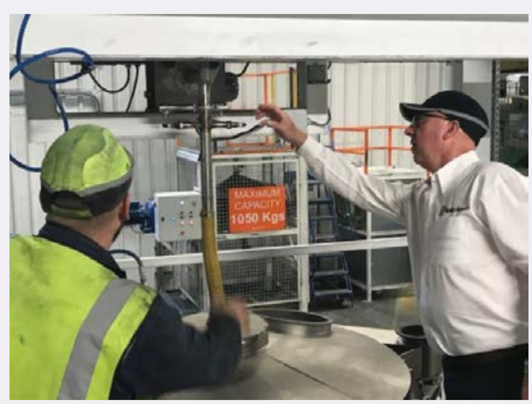
All Applications - Powder Quality

Don't be hands-off with the supply chain!

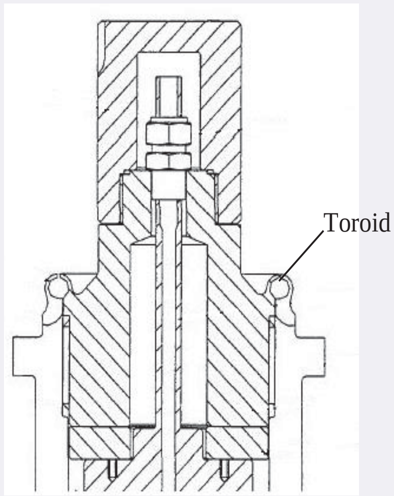
Walk the process, witness key operations, particularly clean-down.

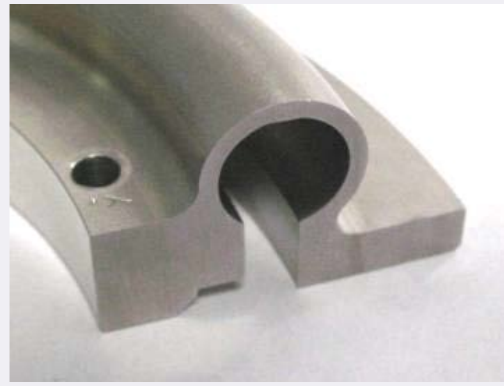
Reference:

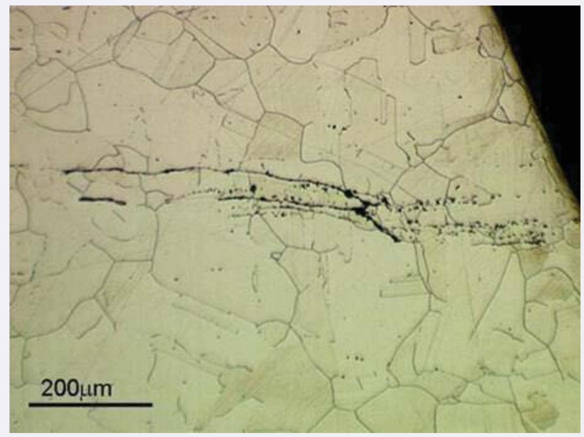
ICONE24-61106, 2016 [2]



Applications - Thin-Walled Toroidal Seals



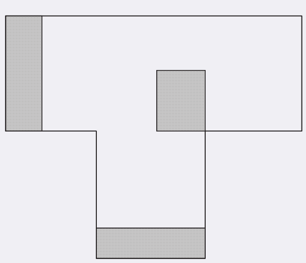


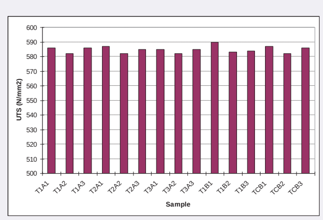


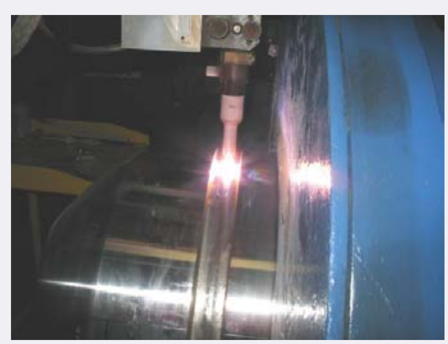
Reference:

ICAPP 08-8110, 2008 [1]

Applications - Thick-Walled Pressure Vessel Section







Locations of material used for testing

Reference:

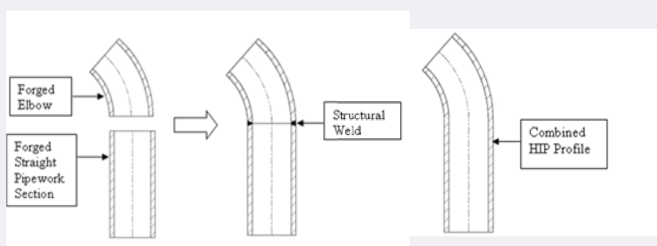
ICAPP 09-9389, 2009 [3]

Applications - Large Bore Valves

Reference:

PVP2012-78115, 2012 [4]

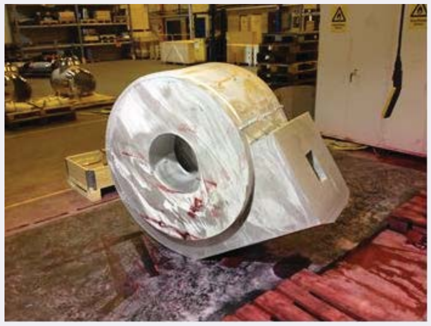
Applications - Pipework

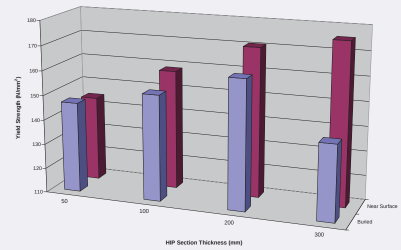


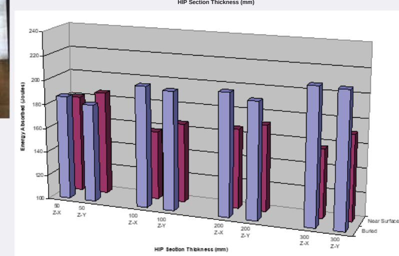
Reference:

AMEE2012, Jan18-19, 2012 [5]

Applications - Pump Bowls







Reference:

PVP2012-78115, 2012 [6]

Acknowledgments

- Our customer UK Government for funding the work conducted on Stainless Steel HIP products presented on the previous slides.

Rolls-Royce's New HIP Development Work

Future Advanced Structural Integrity (F.A.S.T)

HIPed Low Alloy Steel (LAS) Pressure Vessels with Thick-Section Electron Beam Welding (TSEBW)

Supported by:

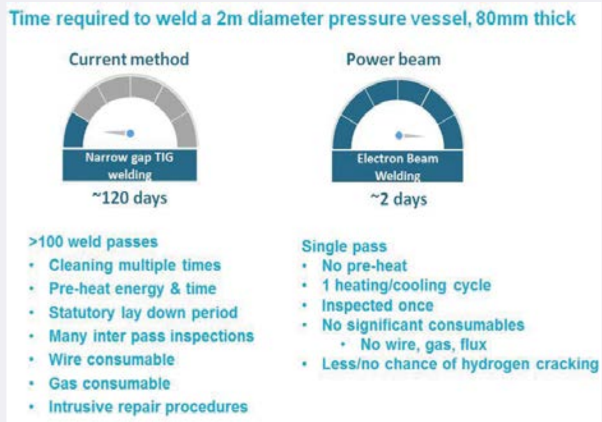
Department for Business, Energy & Industrial Strategy

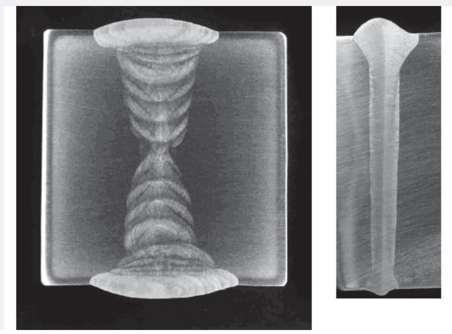
Project Objectives

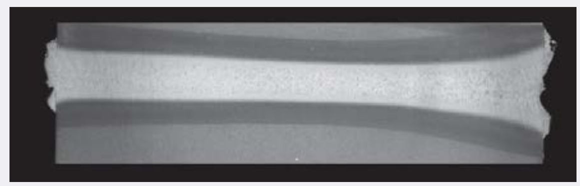
- Move to additive rather than subtractive processes for nuclear quality vessel manufacture.
- Reduce vessel manufacturing cost & lead-time
- Alternative supply chain to mitigate fragility
- Improve material quality
- Possibility to reduce in-service inspections

TSEBW

Process Overview & Structural Advantages







Reference:

ICONE28-POWER2020-16035, 2020 [7]

Previous work

- Proof of concept
- HIPed test pieces
- Powder filling process

PROJECT FAST (2019-2021)

- TSEBW for HIPed SA508
- Manufacture of a Small Vessel Demonstrator (SVD) and hydrostatic testing
- Manufacture of two Large Vessel Demonstrator (LVD) sections
- Manufacture of a Ring Section Demonstrator (RSD) and thermal cyclic testing

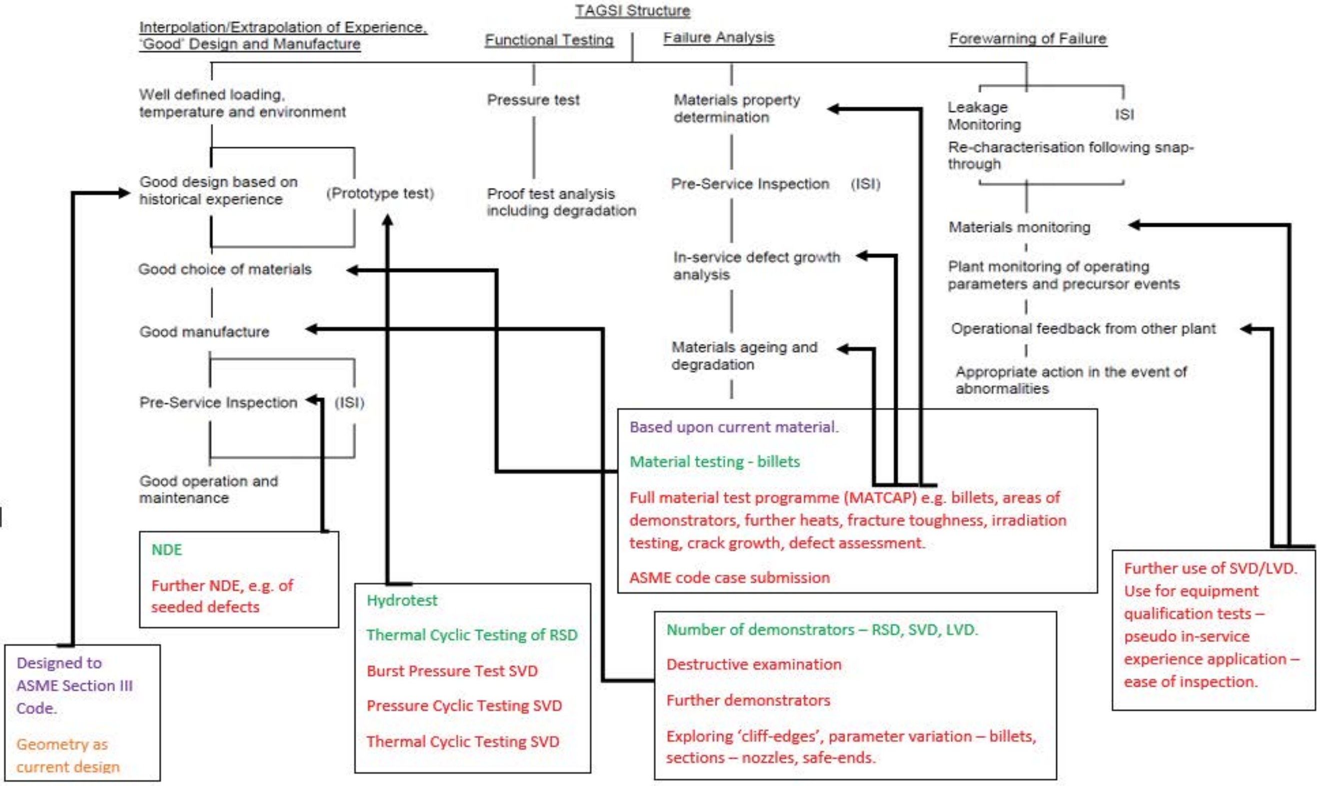
2021+

- Pressure & thermal cyclic testing
- Completed LVD for UK component qualification testing
- Full material property testing programme
- ASME code case submission

Reference:

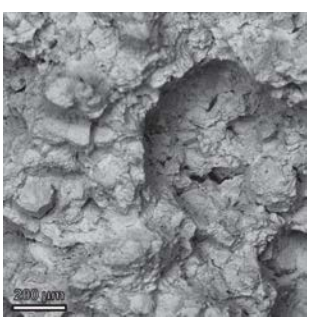
ICONE28-POWER2020-16035, 2020 [7]

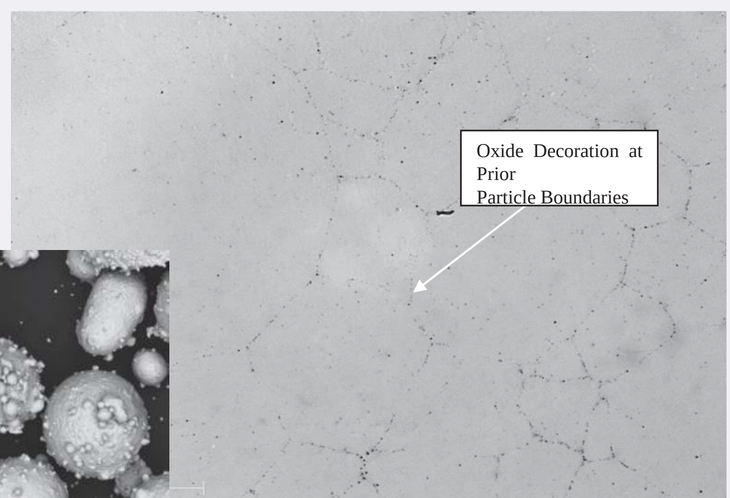
Justification Approach

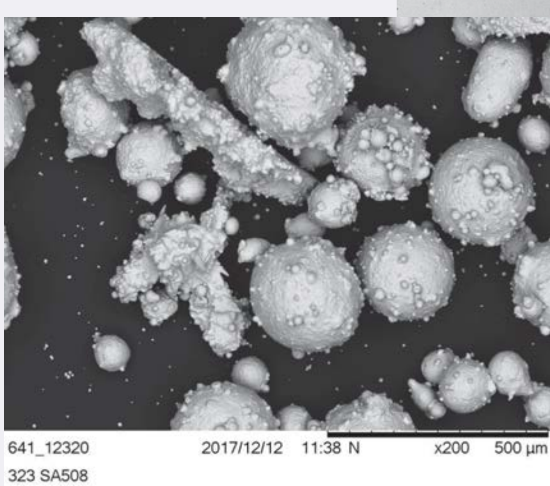


Key Technical Risks

- Poor toughness, oxidisation of powder – need low oxygen powder
- Poor quality powder – morphology – need good supplier





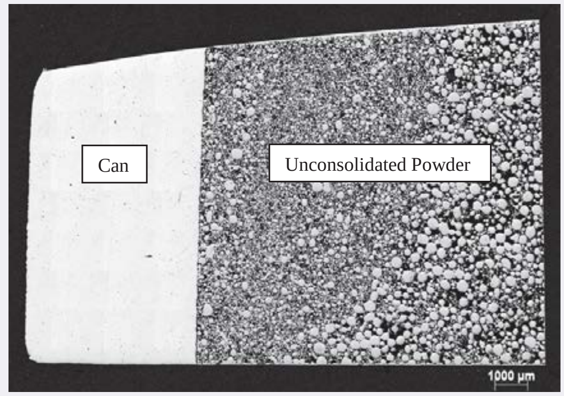


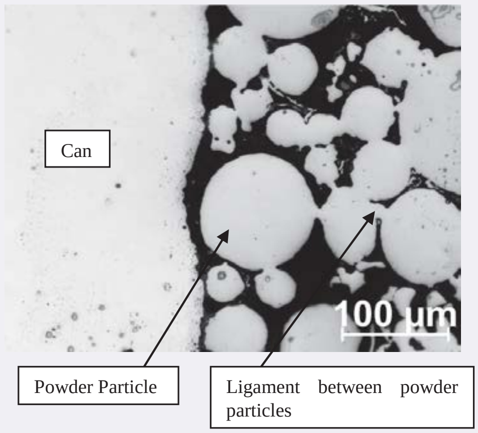
Reference:

ICONE28-POWER2020-16035, 2020 [7]

Key Technical Risks

- Can failure during HIP cycle – need high quality can manufacture – watch the welds!



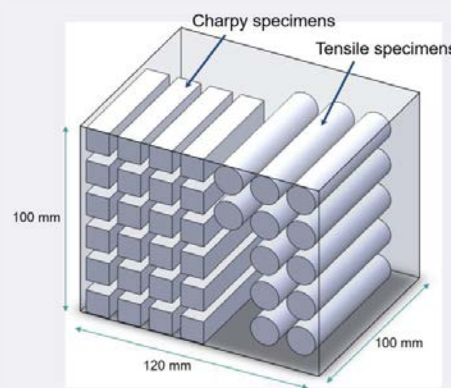


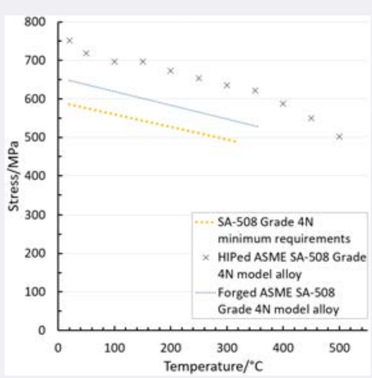
Reference:

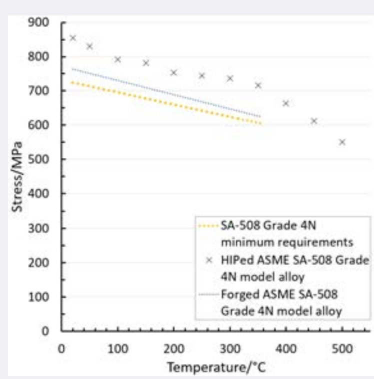
ICONE28-POWER2020-16035, 2020 [7]

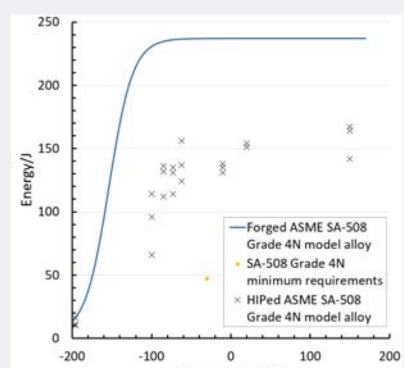
Progress

Billets & Basic Material Testing









References:

ICONE28-POWER2020-16035, 2020 [7]

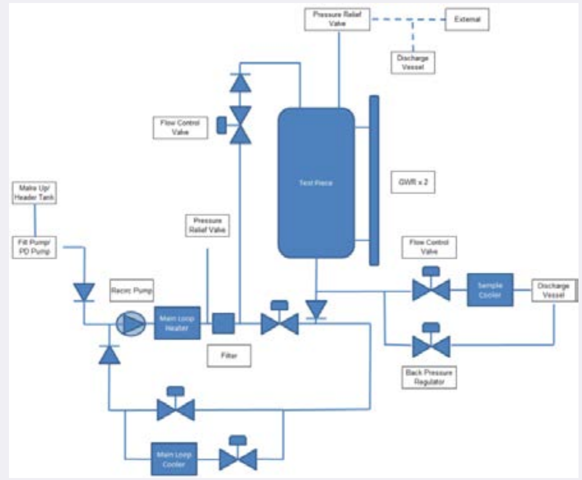
ICONE27-1021, 2019 [8]

Progress

SVD Design & Manufacture

Reference:

ICONE28-POWER2020-16035, 2020 [7]



Progress

SVD Manufacture

Upper and Lower Sections After HIPing Awaiting EBW

Progress

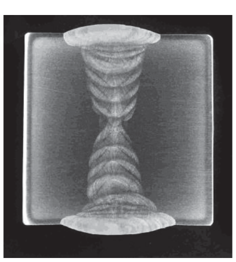
World's First Complete HIPed LAS 508 Gr 4N, EB Welded Pressure Vessel

Shape Improvements for Next Vessel – Poor Packing – Poor Vibration, Filling System Changed

Reference: Proceedings of the ASME 2022 Pressure Vessels & Piping Conference PVP2022, *July* 17-22, 2022, Las Vegas, Nevada, USA, PVP2022-79403.

Progress

Large Vessel Demonstrator



Reference: Proceedings of the ASME 2022 Pressure Vessels & Piping Conference PVP2022, July 17-22, 2022, Las Vegas, Nevada, USA, PVP2022-79403.

Achieving Toughness

Tensile Properties always exceeding forged material, max 22% increase.

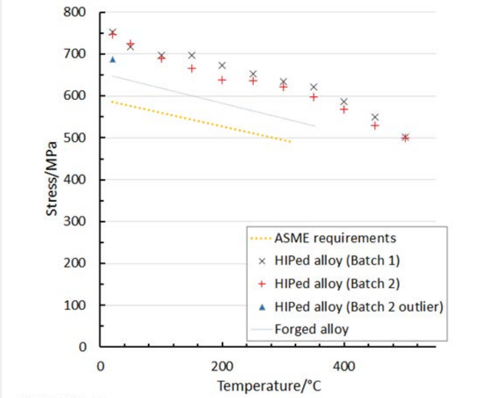


FIGURE 2: HIPED TEST SPECIMEN MEAN 0.2% PROOF STRESS VALUES VERSUS FORGED MATERIAL

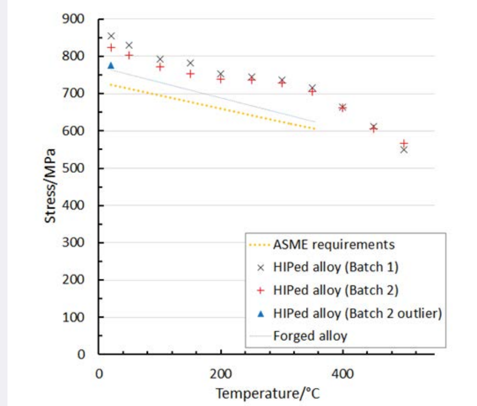


FIGURE 3: HIPED TEST SPECIMEN MEAN ULTIMATE TENSILE STRENGTH VERSUS FORGED MATERIAL

Reference: Proceedings of the ASME 2022 Pressure Vessels & Piping Conference PVP2022, July 17-22, 2022, Las Vegas, Nevada, USA, PVP2022-85077.

Achieving Toughness

Issue is toughness! Only Charpy impact testing conducted.

Equivalence to forged material finally achieved with oxide stripping process applied.

- Three batches of powder manufactured from different suppliers:
  Best toughness 66% of forged material.
  Worst toughness 21% of forged material.

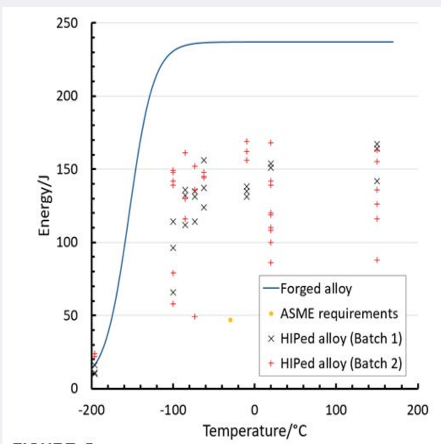


FIGURE 5: HIPED TEST SPECIMEN INDIVIDUAL CHARPY IMPACT TOUGHNESS VERSUS FORGED MATERIAL

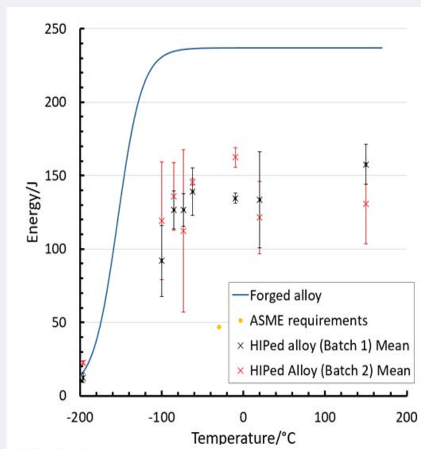


FIGURE 6: HIPED TEST SPECIMEN MEAN CHARPY IMPACT TOUGHNESS VERSUS FORGED MATERIAL

- Oxide stripping process applied – equivalent toughness to forged material achieved for first time! 250J

Reference: Proceedings of the ASME 2022 Pressure Vessels & Piping Conference PVP2022, July 17-22, 2022, Las Vegas, Nevada, USA, PVP2022-85077.

Capability Requirements for Deployment

- Large-scale HIP vessel – max dia in Europe = 1.6m – Project TITAN, circa 4m x 4M
- Large-scale EB chambers
- Improving toughness level –ideally equivalent to forged, oxygen control
- Full material test programme, e.g. fracture toughness, irradiation testing. ASME Code Case.
- Good quality powder manufacture, low oxygen level/morphology, but at a competitive price, and with reliable, short delivery time – need to ensure competitiveness to forging.

Acknowledgments

- *Project FAST was part funded by the UK Department for Business, Energy & Industrial Strategy as part of the UK £505M Energy Innovation Programme.*

Department for Business, Energy & Industrial Strategy

- TWI Limited (Cambridge, UK) for their support in manufacturing and material testing.
- The Manufacturing Technology Centre (MTC) (Coventry, UK) for their support in manufacturing and material testing.

References

[1] J L Sulley and I D Hookham, "Justification and Manufacturing Quality Assurance for the Use of Hot Isostatically Pressed, Reactor Coolant System Components in PWR Plant," Proceedings of ICAPP' 08, Anaheim, 2008, CA USA, Paper 8110, p18-20, June 8-12, 2008.

[2] J L Sulley and D Stewart, 'HIPed Hard Facings for Nuclear Applications – Materials, Key Potential Defects and Mitigating Quality Control Measures', Proceedings of the 2016 24th International Conference on Nuclear Engineering ICONE24, June 26 – 30, 2016, Charlotte, North Carolina, ICONE24-61106.

[3] I Hookham, B Burdett, K Bridger, J L Sulley, 'Hot Isostatically Pressed (HIPed) Thick Walled Component for a Pressurised Water Reactor (PWR) Application, Proceedings of ICAPP' 09, Tokyo, Japan, May 10-14, 2009, Paper 9389, p7.

[4] J L Sulley, M Bohan, 'Hot Isostatically Pressed (HIPed) Large Bore Valves for a Pressurised Water Reactor (PWR) Application', Proceedings of PVP-2012: ASME Pressure Vessels and Piping Division, ASME, Toronto, 2012, PVP 2012-78115.

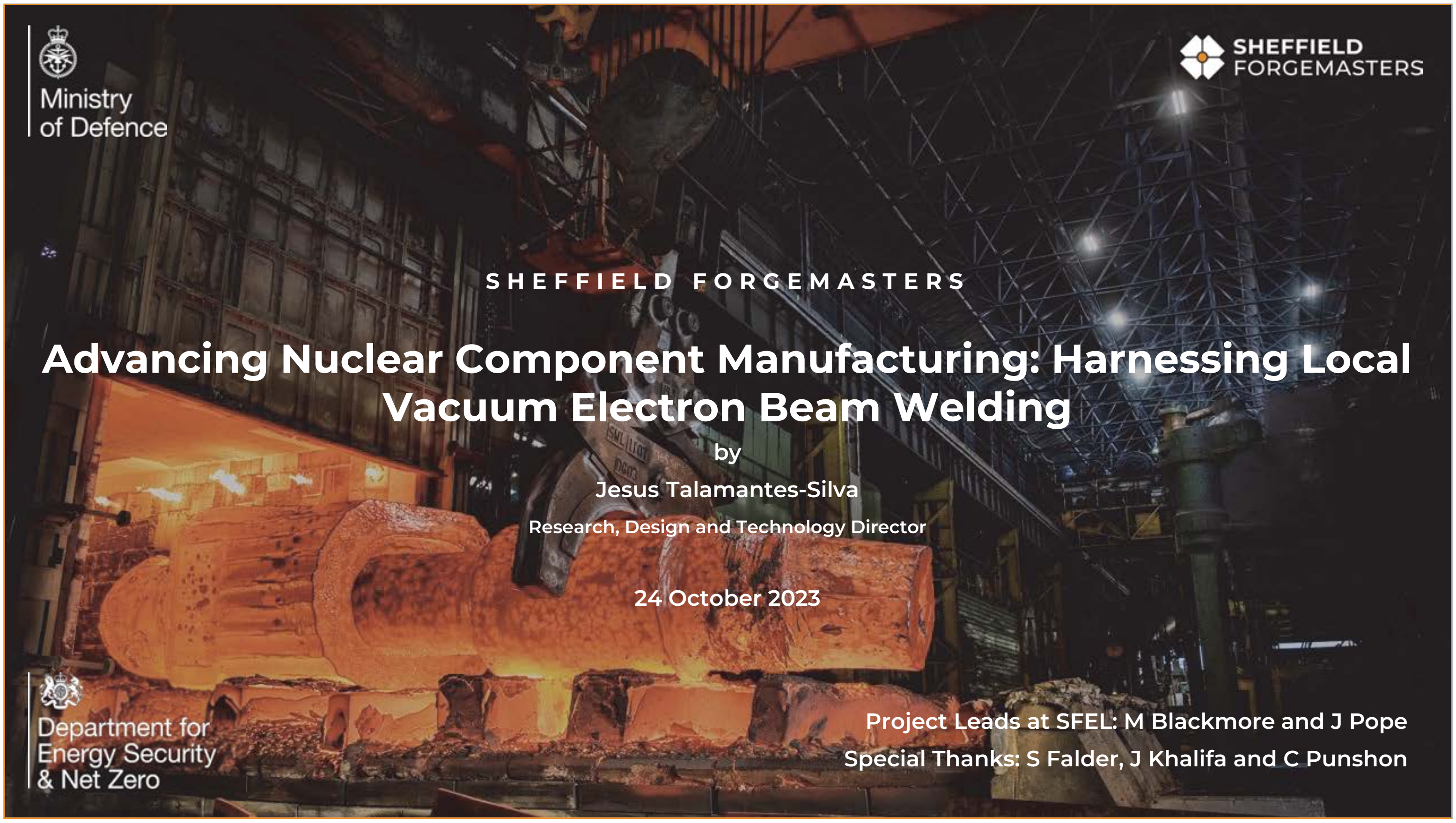
[5] J L Sulley, B Bull, A Wood, 'Hot Isostatic Pressing of Large Bore, Stainless Steel Pipework for a Safety Critical Application,' Proceedings of the International Conference on Applied Materials and Electronics Engineering, AMEE 2012, Jan 18-19, 2012, Hong Kong.

[6] J Sulley, P Mitchell, D Mills, 'Hot Isostatic Pressing of a Varying Thickness, Thick-walled Vessel (Reactor Circulating Pump Bowl) for a Pressurised Water Reactor (PWR) Application', Proceedings of PVP-2014, ASME Pressure Vessels and Piping Division, 20th- 24th July 2014, Anaheim, California, PVP 2014-28013.

[7] J Sulley, P Wallace, T Warner, G Jones, 'Nuclear Pressure Vessel Manufacture Using the Hot Isostatic Pressing (HIP) Process', Proceedings of the 28th International Conference on Nuclear Engineering Joint with the ASME 2020 Power Conference, Anaheim, USA, August 2 – 6, 2020, ICONE 28-POWER2020-16035.

[8] A Morrison, J Sulley, C Carpenter, B Borradaile, G Jones, T Warner, 'HIPed Low Alloy Steel for Nuclear Pressure Vessel Applications – Material Property and Microstructural Assessment', Proceedings of the 27th International Conference on Nuclear Engineering, ICONE 27, Ibaraki, Japan, May 19 – 24, 2019, ICONE 27-1021.

Thank you



Agenda

1. Company Background
2. Advanced Manufacturing
3. Electron Beam Welding
4. Conclusions and Future work

01 BACKGROUND

Company Background

Capabilities and Markets

Sheffield, UK

610 Staff — One-stop shop for design, manufacture, inspection and testing.

Capability — Steelmaking, forging, foundry casting, machining, offshore design & manufacture, research and development, sales.

Export

- Defence
- Nuclear
- Offshore
- Steel Processing
- Steel Plant
- Pressure Vessels

Company Background

Capabilities and Markets

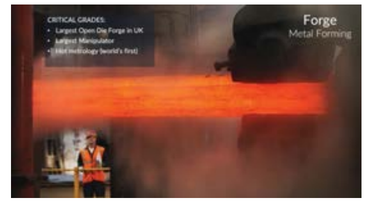
SHEFFIELD FORGEMASTERS

CASTINGS
- c650T casting weight
- Pattern and mould making
- c350T finish weight

RECAPITALISATION PROGRAM
- Investment program
- State of the art machine shop
- New forging line

FORGINGS
- 285T Ingot
- 10,000T and 4,500T Press
- c5m diameter discs/hollows
- c20m max length

KEY CHALLENGES
- Business Interruption
- Competing market sectors
- Market uncertainty
- Energy/Raw materials security
- Capacity requirements



SHEFFIELD FORGEMASTERS

02 ADVANCED MANUFACTURING

Added value activities

SHEFFIELD FORGEMASTERS

Innovation and Technology

- Advanced Manufacturing
  - **Electron Beam Welding**
  - Cladding
  - NDT
  - Cast and HIP
  - Automation and I4.0
- Design for manufacture
- Plant and process development
- ICME: Integrated Computational Materials Engineering
- Net-zero carbon technologies
- High temperature materials (RA steels)

Innovation and Technology

SHEFFIELD FORGEMASTERS

Benefits	Challenges
Developing unique products	*High financial costs*
Provides competitive advantage	*Long timescales*
Provides long term income	*Uncertain outcomes*
Identifies new opportunities	*Conditions may change*
Improves efficiency	*Reactions of rival companies*
Enhances reputation	*Possibility of failure*

03 ELECTRON BEAM WELDING

Historic Electron Beam Welding Research at Sheffield Forgemasters

Advanced Manufacturing

2015 – THE START
Innovate UK Project 102236

2017 – 200mm WELDS
- Complete Mechanical Testing on Heat treated EBW forgings
- Basic Science complete

2019 – BEIS NIP phase 2
Industrialisation of EBW

2020 – EPRI
Quality Heat treatment analysis of EBW material

2022 – LVEBW
3m diameter circ. EBW completed

2023 – DEMONSTRATOR
Full scale SMR demonstrator vessel fabrication

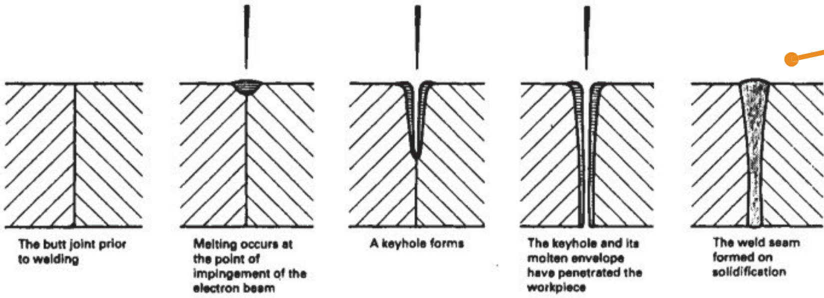
MCRL 6

Electron Beam Welding is a key advanced manufacturing capability to enable Sheffield Forgemasters to support SMR and AMR commercialisation through added value activities.

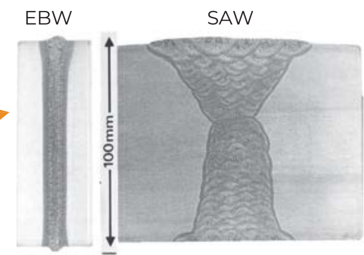
Project Background: Innovate UK Project 102236

Electron Beam Welding

SHEFFIELD FORGEMASTERS



Stages of EBW penetration taken from Electron beam welding by H Schultz, 2004



Courtesy of TWI/CVE

Courtesy of CVE

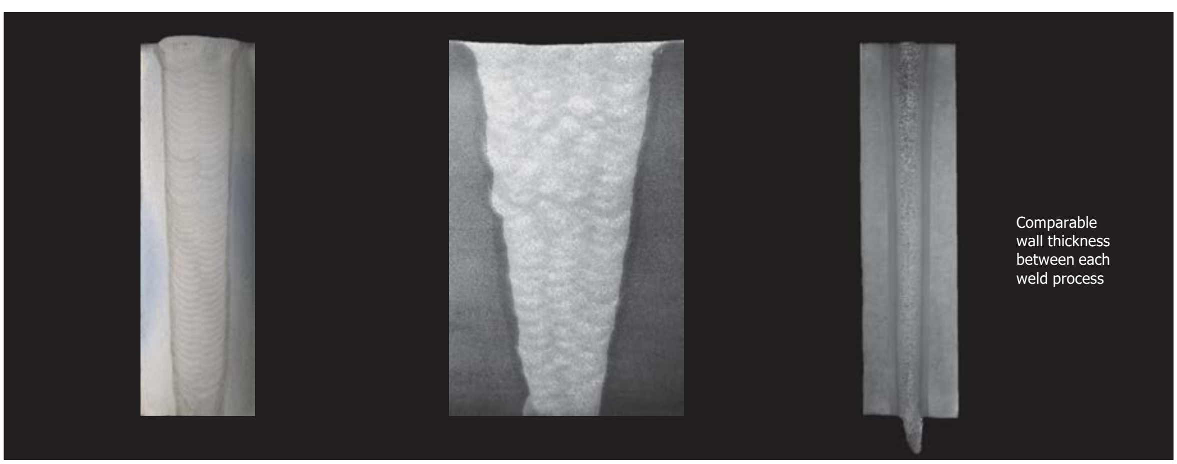
2015

2017

Project Background: Innovate UK Project 102236

Electron Beam Welding

SHEFFIELD FORGEMASTERS



A) Narrow Gap Tungsten Inert Gas **(NG-TIG)**
Circa 90 passes
MONTHS

B) Submerged Arc Welding **(SAW)**
Circa 70 passes
WEEKS

C) Electron Beam Welding **(EBW)**
Single pass
HOURS

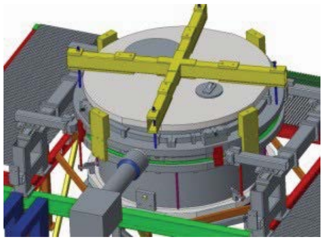
2015

2017

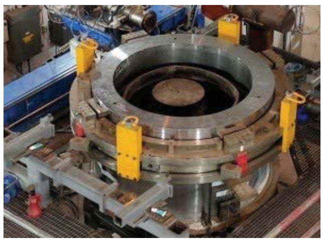
Project Background: Innovate UK Project 102236

SHEFFIELD FORGEMASTERS

Operation in reduced vacuum (Pressure 1 to 0.01mBar)



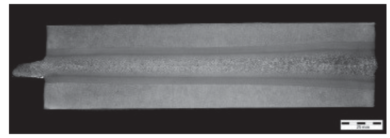
Development



Implementation

Final fabrication assembly weld.

Stable keyhole using key welding parameters for SA508



2015

2017

Project Background: Innovate UK Project 102236

SHEFFIELD FORGEMASTERS

Heat Treatment

Quality heat treatment

Mechanical testing extraction

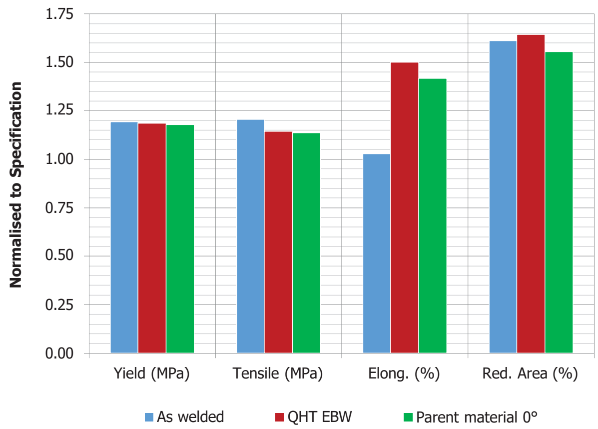
2015

2017

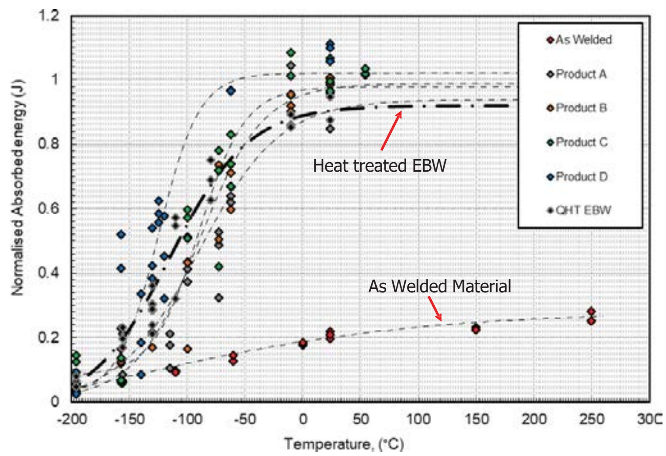
Project Background: Innovate UK Project 102236

SHEFFIELD FORGEMASTERS

Mechanical Properties



Selected Mechanical Properties



Charpy Impact FATT

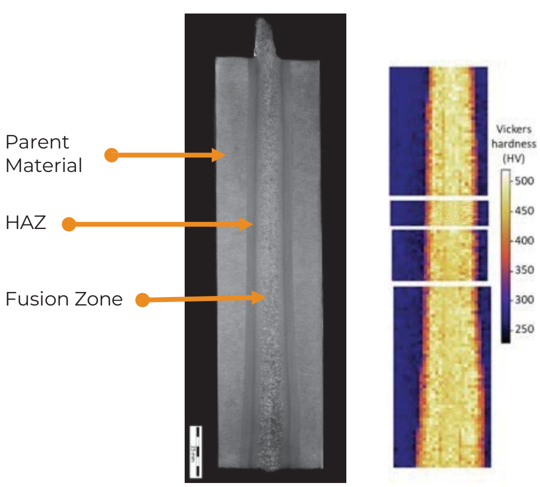
2015

2017

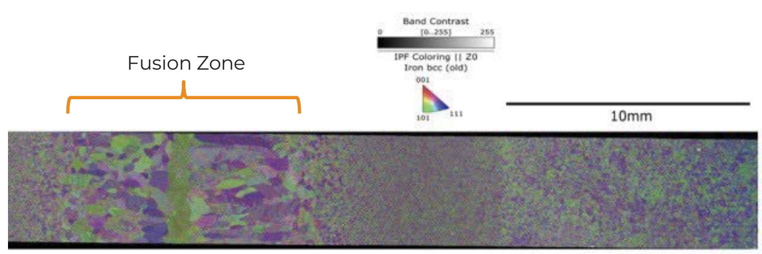
Project Background: Innovate UK Project 102236

SHEFFIELD FORGEMASTERS

Weld Characterisation



SA508 Type Material welded at SFEL



As welded EBSD map

Quality heat treatment EBSD map

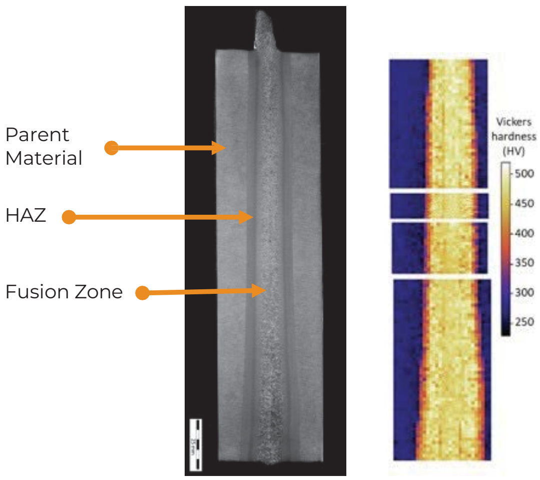
2015

2017

Weld Characterised at UoM, K Bruce and E Pickering.

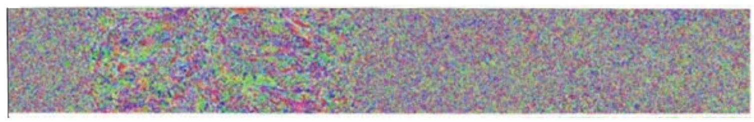
Project Background: Innovate UK Project 102236

Weld Characterisation



SA508 Type Material welded at SFEL

As welded EBSD map (reconstructed austenite grains)



Quality heat treatment EBSD map (reconstructed austenite grains)

2015

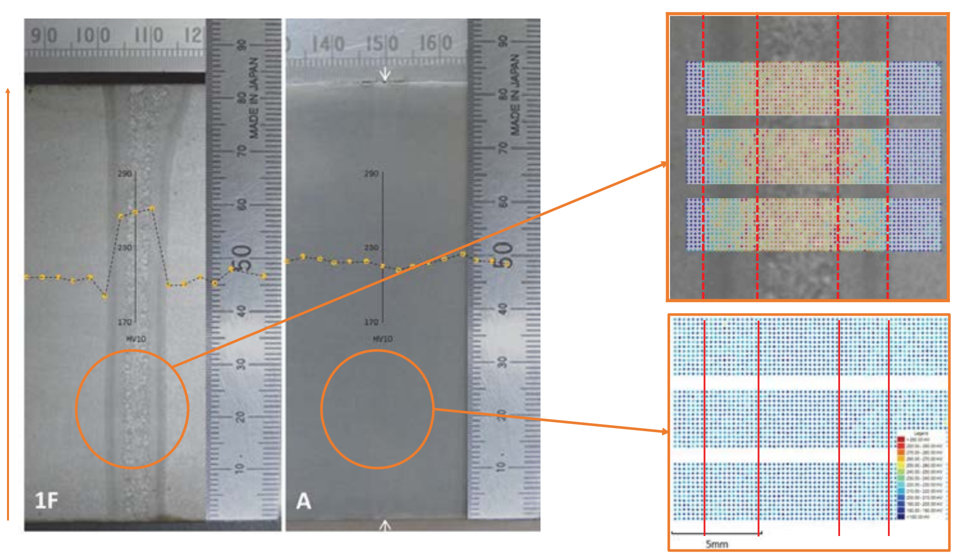
2017

Weld Characterised at UoM, K Bruce and E Pickering.

Research and Development in collaboration with EPRI

Electron Beam Welding Quality: Hardness map

Sectioned EB Weld



2020

Reference: Program on Technology Innovation: Small Modular Reactor Vessel Manufacture and Fabrication, D Gandy and M Albert, 2021

Nuclear Innovation Programme

Industrialisation

Technology Readiness Levels (TRL)		EBW Current Status
TRL 1	Bright idea	✓ Done for years
TRL 2–3	Scientific investigation	✓ Done for years
TRL 4	Laboratory scale testing	✓ TWI/AxRC environment test blocks
TRL 5	Large scale rig testing	✓ Innovate 102236 Project
TRL 6	Full scale system demonstration	× BEIS NIP Phase 2 demonstration
TRL 7	Service test	× Find vendor
TRL 8	Product development and prototyping	× Test in reactor
TRL 9	Mature product in service	× Entry into service

Manufacturing Capability Readiness Levels (MCRL)		EBW Current Status
MCRL 1 - 4	Conception and assessment of the technology.	✓ Innovate 102236 Project
MCRL 5 - 6	Pre-production phase, full-scale equipment and processes	× BEIS NIP Phase 2 demonstration
MCRL 7 - 9	Implementation on the shop floor, volume production	× SFIL Production Facility

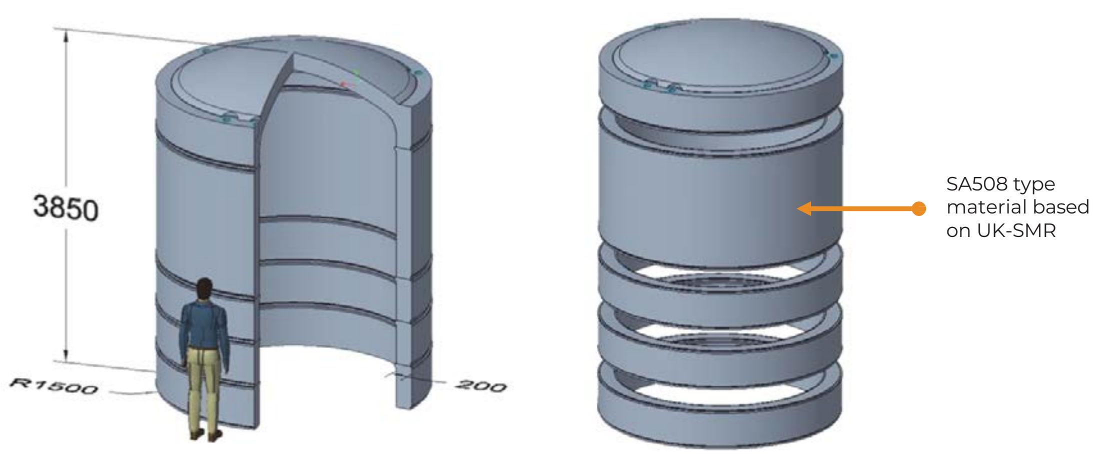
2019

2023

With support from the Department for Business, Energy & Industrial Strategy
(now the Department for Energy Security and Net Zero: DESNZ)

Nuclear Innovation Programme

Full-scale system demonstration



2019

2023

With support from the Department for Business, Energy & Industrial Strategy
(now the Department for Energy Security and Net Zero: DESNZ)

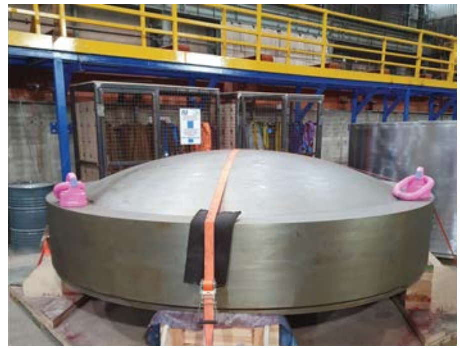
Nuclear Innovation Programme

Nuclear Component Manufacture

SHEFFIELD FORGEMASTERS

Ring Forgings

Shell Forging



Head Forging

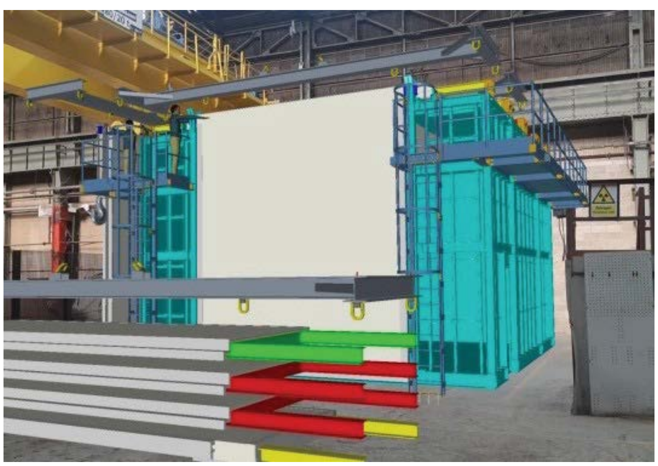
2019

2023

Nuclear Innovation Programme

Large scale EB facility

SHEFFIELD FORGEMASTERS



X-Ray enclosure using augmented reality

Completed X-Ray enclosure

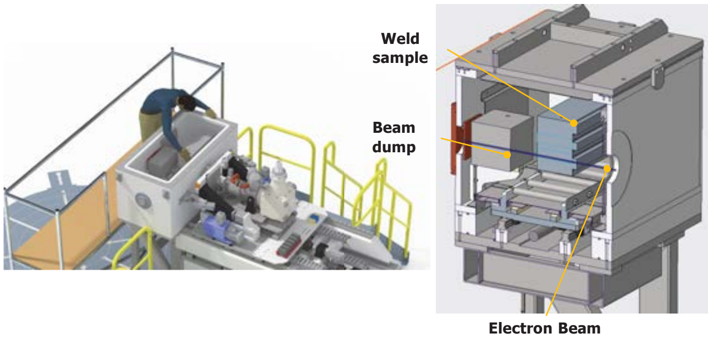
2019

2023

Nuclear Innovation Programme

SHEFFIELD FORGEMASTERS

Machine configuration No 1 of 3: Electron Beam Development



Vacuum chamber concept

Deployment

2019

Development of weld parameters for selected nuclear alloy grades. Including, rapid deployment of key process variables (KPV) control plan, beam probing and calibration methods.

2023

Nuclear Innovation Programme

SHEFFIELD FORGEMASTERS

Electron Beam Development

Vacuum chamber sample block (0.5mx0.2mx0.2m)

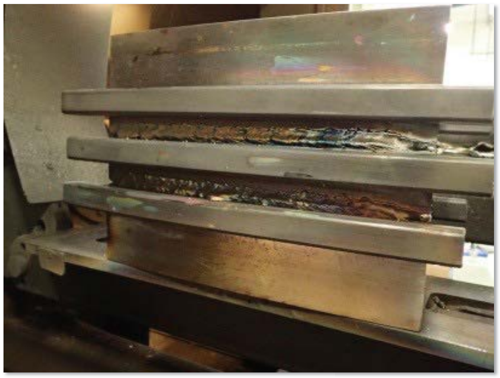
16 Ton of material used

2019

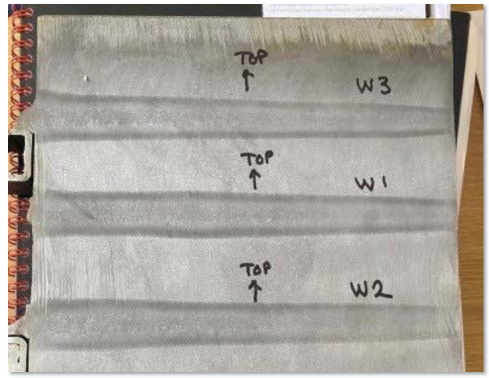
Development of weld parameters for selected nuclear alloy grades. Including, rapid deployment of key process variables (KPV) control plan, beam probing and calibration methods.

2023

Electron Beam Development



Weld Parameter Development



Macro Etched Welds

2019

Development of weld parameters for selected nuclear alloy grades. Including, rapid deployment of key process variables (KPV) control plan, beam probing and calibration methods.

2023

Nuclear Innovation Programme
SHEFFIELD FORGEMASTERS

Electron Beam Development

Weld Parameter Development

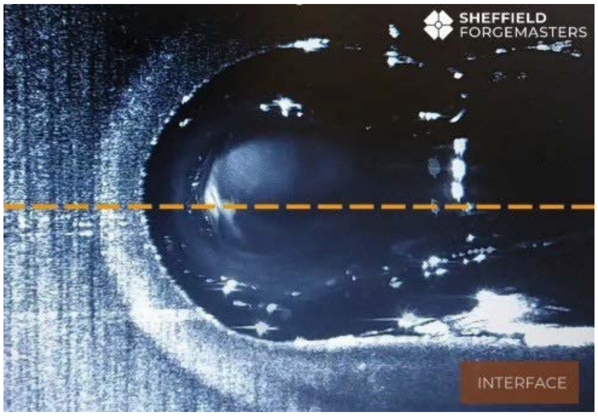
Macro Etched Welds

2019

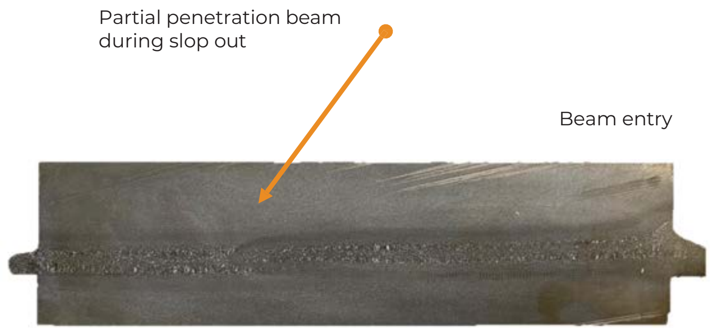
Development of weld parameters for selected nuclear alloy grades. Including, rapid deployment of key process variables (KPV) control plan, beam probing and calibration methods.

2023

Process Development – Steady State and Slope Out



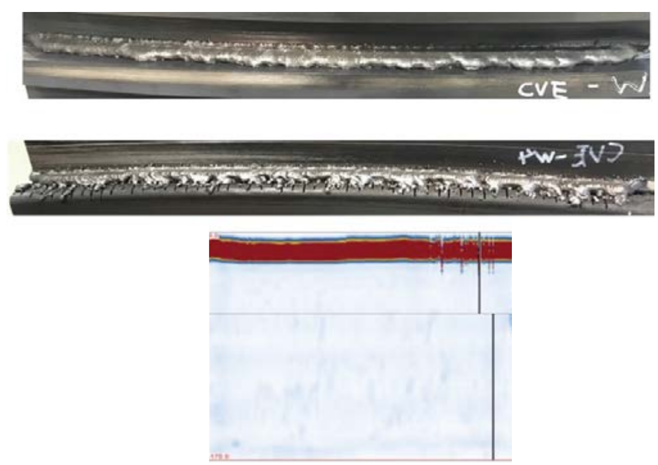
Keyhole formation during a 200mm weld



Slope out development

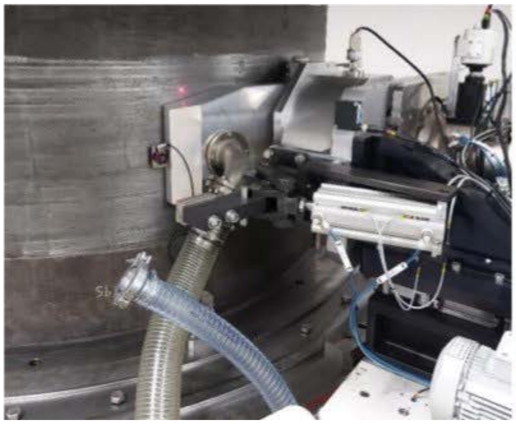
Process Development – Steady State and Slope Out

High Speed Parameters



Low Speed Parameters

Machine configuration No 2 of 3: Vacuum Head for thicknesses less than 80mm.



Sliding Head Welding

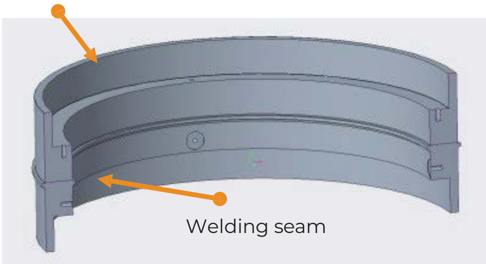
Sliding Weld on 60mm Cylinder

2019

2023

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.

Reduce thickness due
to weight constrains



Cross Section of FAT Rings

FAT Weld Crown

Welding
interface

FAT Rings Machining

2019

3m diameter, 200mm thick factory acceptance testing (FAT) rings

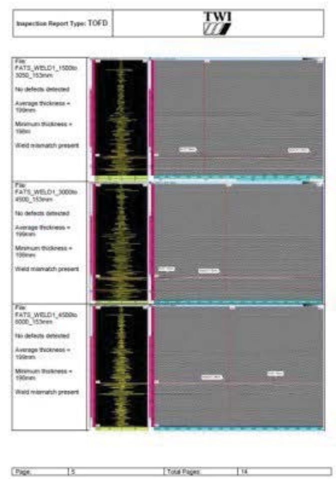
2023

Nuclear Innovation Programme

SHEFFIELD FORGEMASTERS

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.

FAT Weld Witnessed by ONR & EA



TWI Phased Array UT

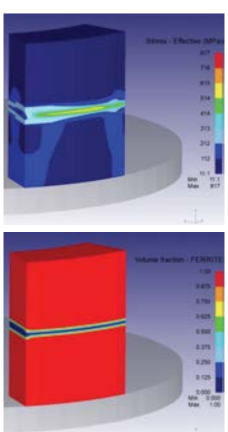
2019

2023

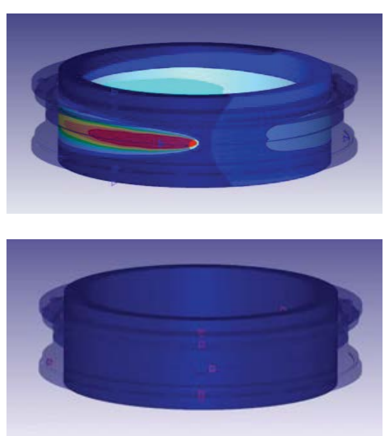
Nuclear Innovation Programme

SHEFFIELD FORGEMASTERS

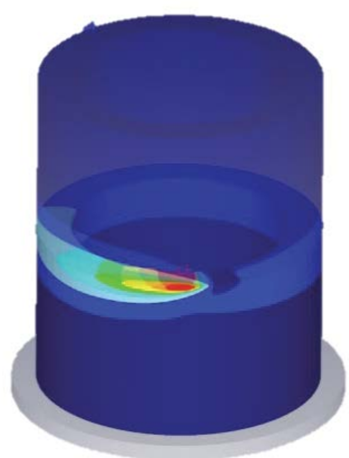
Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.



Residual Stress & Microstructure



Tooling Heat Loads



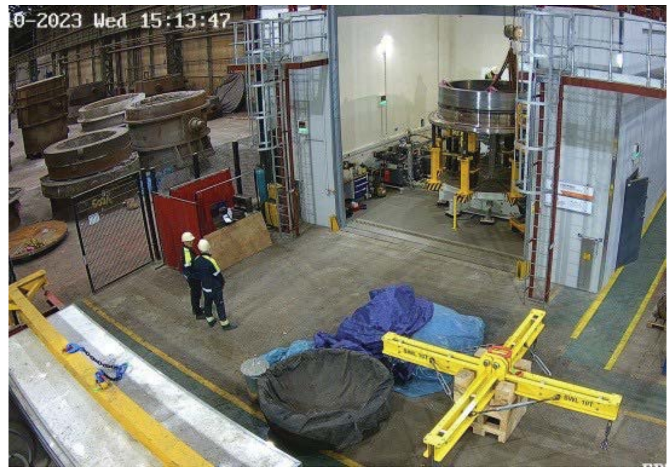
Vessel Temperature

2019

2023

Nuclear Innovation Programme

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.



2019

3m diameter, 180mm thick site acceptance testing (SAT) rings

2023

Nuclear Innovation Programme

Machine configuration No 3 of 3: Vacuum Jacket for thicknesses larger than 80mm.

2019

First set of 3m diameter, 180mm thick rings to be welded 25th October 2023

2023

Nuclear Innovation Programme

Vessel Fabrication Completed

SHEFFIELD FORGEMASTERS

2019

2023

Third parties have independently carried out NDE with no recordable indications.
All welds passed internal pressure vessel fabrications standards.

SHEFFIELD FORGEMASTERS

04 CONCLUSIONS AND FUTURE WORK

Advantages of Implementing Electron Beam Welding

Advanced Manufacturing

SHEFFIELD FORGEMASTERS

A) Full x-ray enclosure

Capable of housing 3m dia. x 4.5m, 100 Ton

B) Local vacuum approach

Reached under 10min

C) Worlds first

3m diameter (200mm thick) weld in just over 2hrs

D) Weld quality

Properties similar or better than parent material

- **Integrated into the conventional Manufacturing Process at Forgemasters**
- **Produces precise and high-quality welds with deep penetration and minimal distortion**
- **Narrow Heat-Affected Zone (HAZ) and High Joining Rate**
- **Reduced inspection campaign**
- **Supply of complete sub assemblies ready for next manufacturing steps thus reducing time and cost**
- **Eliminate the use of filler material, welding gases and pre/post heat requirements**

Advantages of Implementing Electron Beam Welding

Advanced Manufacturing

SHEFFIELD FORGEMASTERS

- ***"In order to meet the industry/customer demands we need to drive innovation"***
- ***"Innovation and technology are critical to sustain competitive advantage"***
- ***"The UK organisations need innovation to compete globally"***
- ***"Advanced manufacturing methods are critical to reduce manufacturing cost and delivery time, but challenges exist to codes and standards acceptance."***

Advantages of Implementing Electron Beam Welding

Advanced Manufacturing

SHEFFIELD FORGEMASTERS

- ✔ *“In order to meet the industry/customer demands we need to drive innovation”*
- ✔ *“Innovation and technology are critical to sustain competitive advantage”*
- ✔ *“The UK organisations need innovation to compete globally”*
- ✔ *“Advanced manufacturing methods are critical to reduce manufacturing cost and delivery time, but challenges exist to codes and standards acceptance.”*

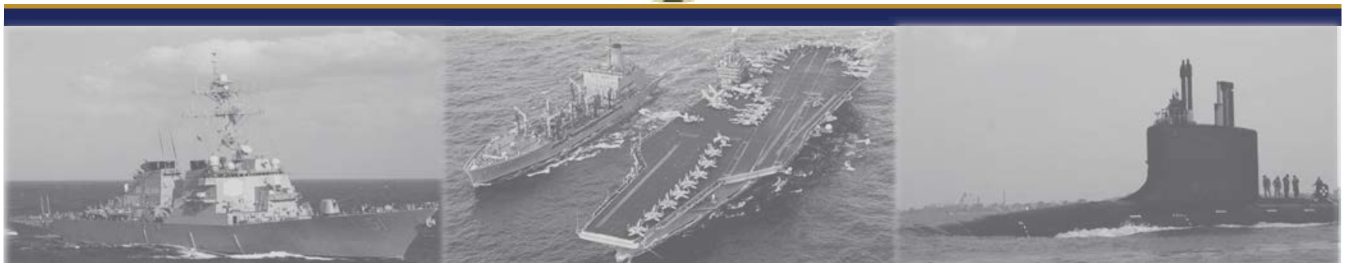
NAVSEA NAVAL SEA SYSTEMS COMMAND

NAVSEA 05T Additive Manufacturing Program

Brief to NRC

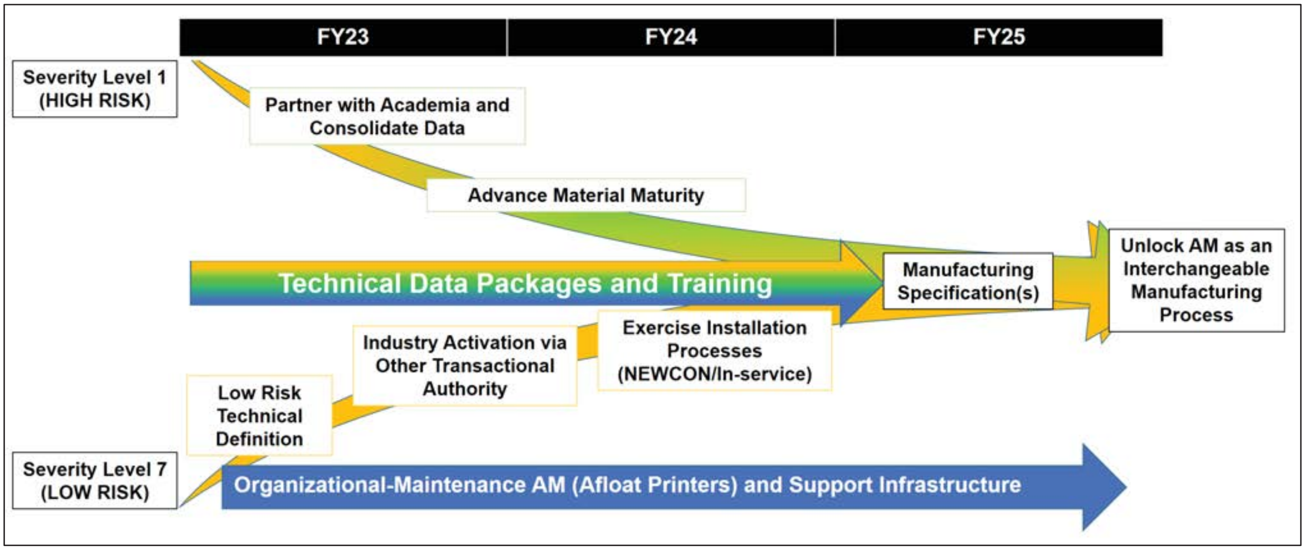
24 Oct 2023

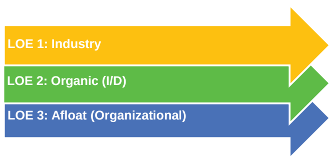
Distribution Statement A: Approved for Release. Distribution is unlimited.



Material and Process Strategy

Operationalize Additive Manufacturing as a Routine Manufacturing Process





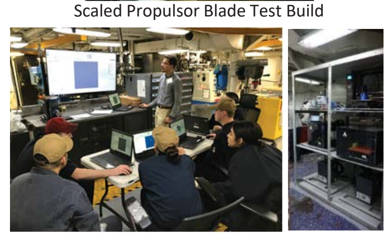
Converging material knowledge, process maturity and operational experience unlocks interchangeability

NAVSEA 05 Additive Manufacturing Overview

- **Process Qualification/Component Certification**
  - Develop Technical publications for repeatable AM processes
  - Explore in-situ monitoring
  - Collaborate closely with industrial base
    - ➢ *To Date: Tech Pubs for metal AM processes; Over 500 approved parts, 300+ polymer TDPs available to fleet*
- **Afloat/Undersea Deployment**
  - Explore how to deploy and integrate advanced / additive manufacturing equipment surface and subsurface
  - Understand environmental / motion impacts on printing process
  - Metal AM capability installed on USS BATAAN in Nov 2022
    - ➢ *Advanced manufacturing equipment installations on 9 ships; 4 submarines deployed with AM; over 4,000 parts printed afloat; 50+ Sailors trained*
- **Digital Integration**
  - Identify file securing / transiting / storage solutions, including parts repository
  - Explore topology optimization and generative design
    - ➢ *Development of digital manufacturing environment to enable networked AM equipment ashore (NNSY in 2022) and afloat (USS BATAAN in 2022)*
- **Logistics/Supply System integration**
  - Incorporate components into logistics databases to enable part provisioning, tracking and 'buy or print' decisions
    - ➢ *146 AM parts have NSNs; initial cost avoidance and lead time metrics generated for afloat components*

TOP LEFT: DSO valve installed on CVN-75. TOP MIDDLE: CAT2 CASREP for satellite IP antenna printed during deployment. TOP RIGHT: AM deck drain installed on USS LABOON. BOTTOM LEFT: Approved metal bilge strainer for SSN. BOTTOM CENTER: Approved cease fire alarm horn installed on DDG. BOTTOM RIGHT: Fuse cover to prolong fuse life, installed several LHDs.

Scaled Propulsor Blade Test Build



LEFT: AM training on-board CVN-71. RIGHT: 3D printers on CVN-69

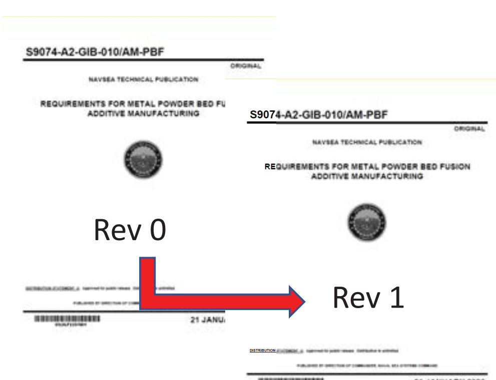
NAVSEA Guidance/Standards

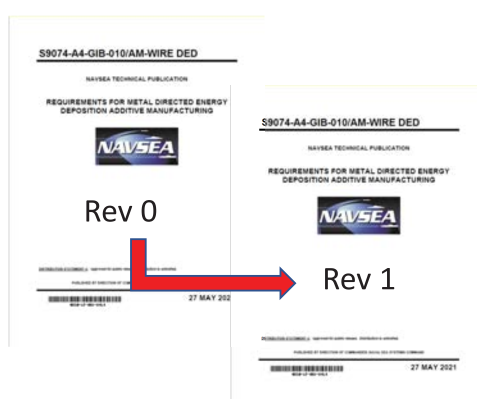
- **Guidance:**
  - Guidance on the Use of Additive Manufacturing (Issued)
  - Guidance on Identification and Installation of Low Risk Additively Manufactured Metal Components (Issued)
  - Guidance on reporting installation of AM components shipboard (under development)
  - Guidance under development for processes and technologies enabling installation of AM components shipboard:
    - Assessment and Use of In-Situ Monitoring
    - Metal Binder Jet Fusion
    - Powder Blown DED
    - Metal Material Extrusion
    - Additive Friction Stir Deposition

- **Standards:**
  - Requirements for Metal Powder Bed Fusion Additive Manufacturing (Issued)
  - Requirements for Metal Directed Energy Deposition Additive Manufacturing (Issued)
  - Requirements for Polymer/Composite Material Extrusion Additive Manufacturing (Under Development)

Process Qualification/Component Certification

- **What have we learned?**
  - Standards are difficult
  - Need for iteration/constant improvement
  - Without guidance, unable to coordinate/collaborate efforts
  - Balance systemic risk to application risk
  - Learn by doing – Need to 'snap chalk line' and start with initial applications/efforts necessary to build knowledge base





Snapping a 'Chalk Line'

- How do we balance systemic vs. component risk
  - No one-size fits all for standards requirements
  - Application specific requirements will drive adoption

- What works best for applications at hand?
  - Accept that 'chalk line' isn't applicable across all applications, but provides opportunities to build knowledge base to translate to future applications
  - Find 'safe zone' for application development that allows tolerable risk acceptance given system requirements

- **<u>As we look at application space for AM, we need to know:</u>**
  - Where we need standards
  - Where we need guidance/best practices
  - Where we identify applications to begin learning

Afloat AM Update

<u>Legacy AM Equipment Installations</u>:

- As of Aug 2022, NAVSEA R&D program installed polymer AM on 8 surface ships as R&D prototypes (3 CVNs, 4 amphibs, 1 DDG)
  - AM assets installed via nonpermanent Ship Change Document
  - Polymer AM capability deployed on three submarines (fleet funded equipment/NAVSEA supported)
- Nov 2021: Polymer printer installed via DFS on USS KEARSARGE (fleet funded equipment/NAVSEA supported)
- July 2022: Polymer printer deployed on submarine
  - Submarine deployed with a desktop 3D printer (Lulzbot Mini 2) in 2020-2021 and shared lessons learned with SEA05T
  - SEA05T, SUBLANT, submarine and PMS394 coordinated to install and evaluate improved polymer printer on FY22 NHP deployment
  - Developing updates to submarine AM guidance document to reflect addition of improved printer

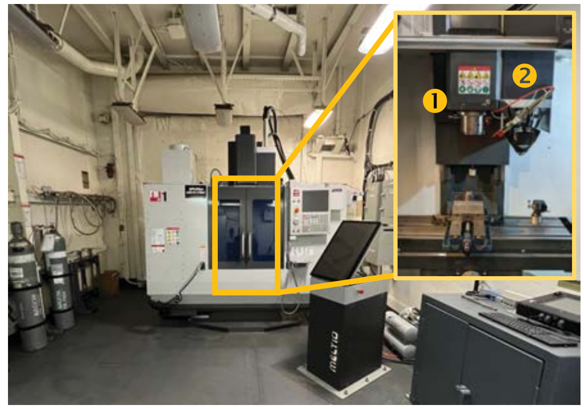
<u>Recent AM Equipment Installations</u>:

- Metal and polymer capability on USS BATAAN (LHD-5) – **<u>COMPLETED NOV 2022</u>**
  - Installation of Hybrid metal additive and CNC capability (Phillips Additive Hybrid)
  - Installation of polymer system (Markforged X7)
  - Additional planned install of Hybrid Metal and polymer AM equipment on USS WASP – Summer 2023
  - Conversion of Balloon Inflation Room to Additive Manufacturing Shop, planned as common location across WASP-Class
  - SEA05T supporting deployment by conducting shore-based R&D and providing afloat support to BATAAN

Afloat Additive Manufacturing Hybrid Metal System

- **Shipboard Metal AM**
  - Phillips Additive Hybrid Laser Metal Wire Deposition (LMWD) Hybrid AM technology
    - ❑ Wire-fed laser DED AM system (Meltio Engine)
    - ❑ CNC milling machine (Haas TM-1)
  - Combines additive and subtractive processes
- **Installed on USS BATAAN Oct-Nov 2022**
  - 5 Sailors trained (1 MR, 2 HT, 2 DC) on CNC operation, Hybrid LWMD operation, Polymer AM equipment operation (+3 KSG sailors), MasterCAM (Hybrid AM software), and SolidWorks (3D modeling) [5 weeks total]
  - MOA established between BATAAN, NAVSEA and CNSL to facilitate RDTE sample printing, data acquisition, print logging, and reach-back support

<u>R&D-Related Partners:</u>
Johns Hopkins University-Applied Physics Lab (JHU-APL), Advanced Technology & Research Corp. (ATR), Building Momentum



Phillips Additive Hybrid Aboard USS Bataan – November 2022
Laser Metal Wire Deposition System
Inset: 1) CNC Tool Spindle, 2) Deposition Head

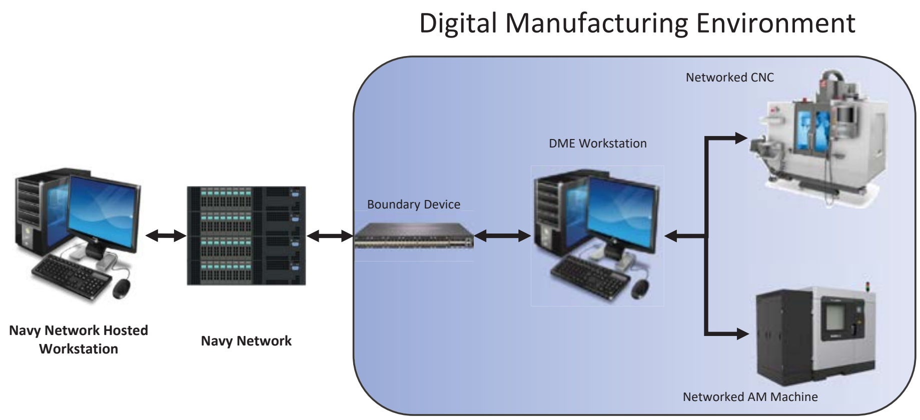
Dimensions *(L×W×H)*	168"×134"×110"
Build Envelope *(L×W×H)*	~20" × ~10" × ~12"
Machining Envelope *(L×W×H)*	~30" × ~12" × ~16"
Materials	316L Stainless Steel *(welding wire)*
Features	• 3-axis CNC milling operations • Parts designed using SolidWorks CAD software • Additive and subtractive operations controlled using MasterCAM APlus

AM Logistics Integration

- NAVSEA 05T and NAVSEALOGCEN partnered to initiate an AM Logistics Integration Team in FY19 with participation from:
  - ➢ NAVSEA 05T, 05R, 03R
  - ➢ NSWC Philadelphia
  - ➢ NUWC Keyport
  - ➢ NAVAIR
  - ➢ NSLC Mechanicsburg
  - ➢ NSLC Portsmouth
  - ➢ NAVSUP HQ & WSS
  - ➢ DLA Cataloging
- Establish toolsets to facilitate AM logistics information tracking/part identification IAW AM TWH policies and requirements
- Integrate and sustain AM parts into supply; develop vendor source approval infrastructure
- Define the process for traceability of AM parts in the supply chain
  - DRAFT guidance for leveraging the maintenance action reporting process (2K/AWN) developed
- Establish the metrics for reporting the impact of implementing AM solutions
- DLA Joint Additive Manufacturing Acceptability (JAMA) Project
- AM Acquisition procedures for logistics support/Future LOG IT Infrastructure Inclusion

Digital Infrastructure

- NAVSEA is prototyping the Digital Manufacturing Environment (DME) to address the need for advanced manufacturing cybersecurity and streamlined communication between ashore and afloat activities
- The DME provides a scalable, proof-of-concept secure network boundary that separates manufacturing equipment and workstations from the host network
- Two DME pilots to demonstrate secure connections and communication between digital manufacturing equipment and navy networks
  - Ashore DME pilot with NNSY July 2022
    - ❑ Finalized Updates 1 Sep 2022
  - Afloat DME pilot with USS BATAAN installed concurrently with AM equipment Oct-Nov 2022



Questions

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

Meimei Li (ANL), NTD; David Andersson (LANL), deputy NTD;
Ryan Dehoff (ORNL), Andrea Jokisaari (INL), Isabella van Rooyen (PNNL), TALs;
Dirk Cairns-Gallimore, DOE Federal Manager

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

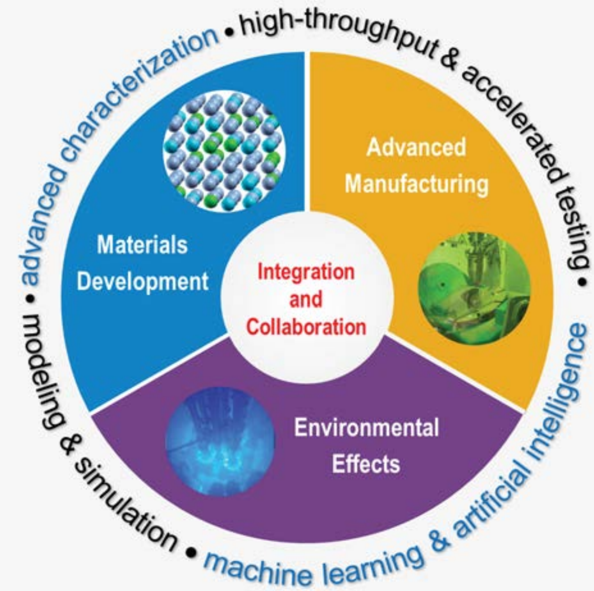
- Develop advanced experimental and computational tools
- Perform transformative research to explore new materials design & processes

Collaborative Research and Development

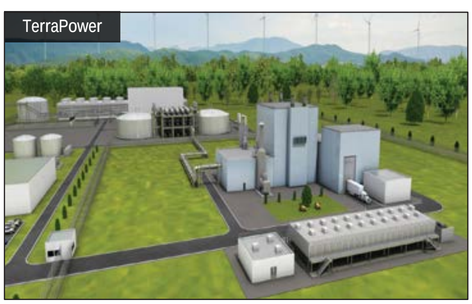
- Collaboration & partnership to address diverse needs of the nuclear community

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

Execution Strategy

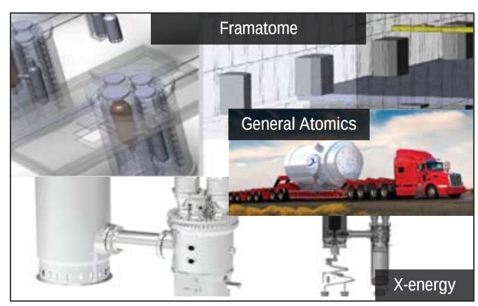


AMMT Supports a Broad Range of Reactor Technologies

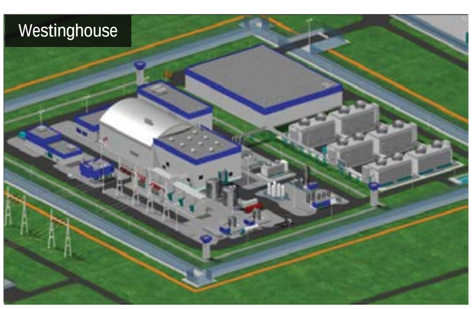


Sodium-cooled Fast Reactor (SFR)

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."

www.westinghousenuclear.com

Thematic Research Areas

Capability Development & Transformative Research

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

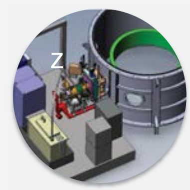
AMMT current focus:

- 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



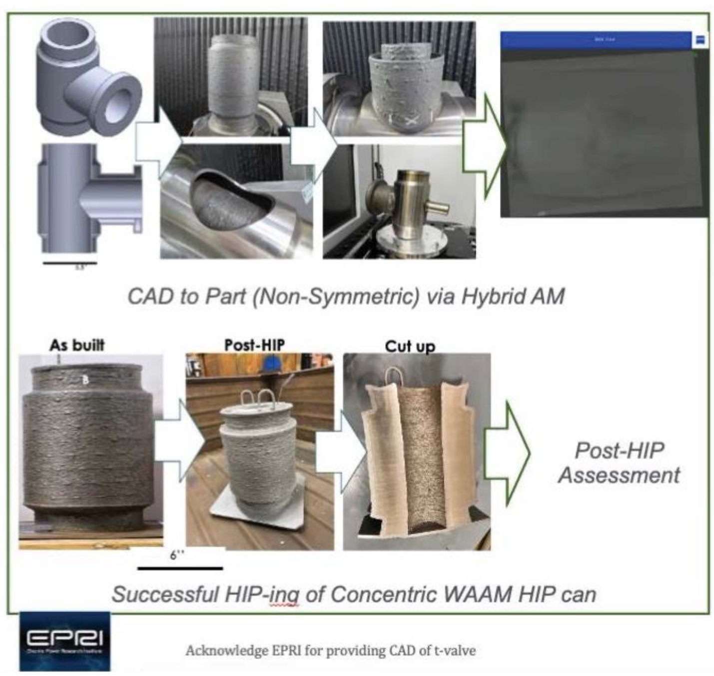
EPRI Modular in-chamber EBW

Large-Scale Additive Manufacturing

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

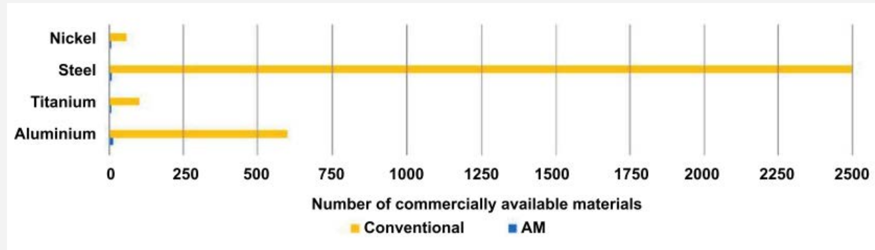
Objective: Feasibility demonstration of large-scale additive manufacturing of nuclear components (e.g. pressure vessel, valves).

- 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.



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**

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

Development of Fe-based Alloys for AM

Develop Decision Criteria Matrix

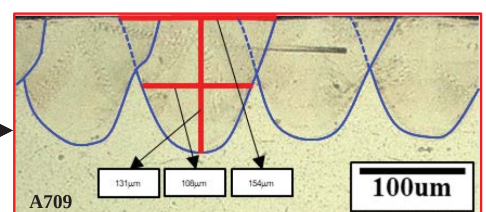
Category	Criteria					
Manufacturing/Powder	Powder Availability	Powder Properties	Powder Chemistry	Cost	Recycling	
Manufacturing/Components	Printability (LBF)	Defects	Post Treatment	Processing window	Weldability	Surface Roughness Surface Finish
History & Applications	NE Experience	Other Industries Experience	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

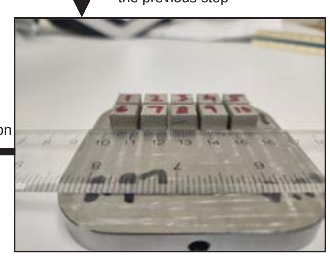
Austenitic
A-709
AFA
Ti-modified 316SS (D9)
Ferritic/Martensitic
Grade-91
Grade-92
HT-9

Single-track experiments to optimize process parameters

Single track experiments for the optimized condition

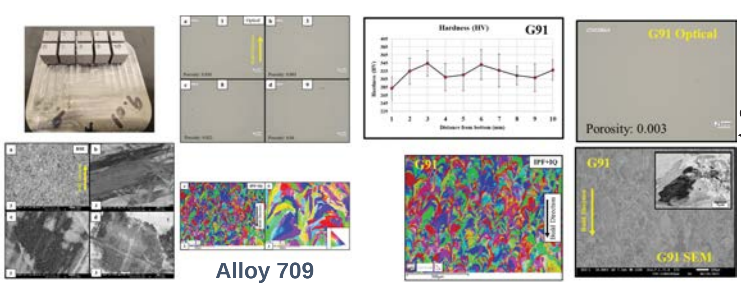


All 6 alloys printed with optimized process parameters obtained in the previous step



10 parts printed for each alloy

Characterization



Summary

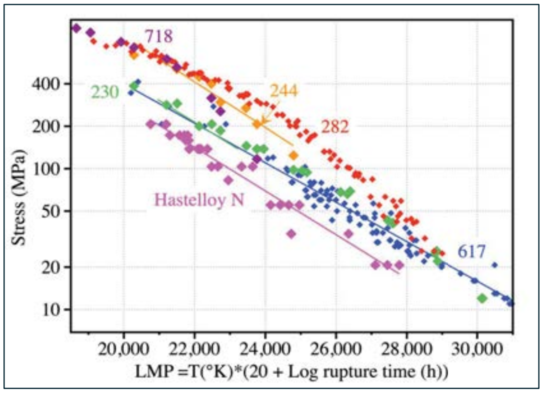
- Developed a decision criteria matrix (DCM) by 4 national labs.
- Down-selected 6 alloys using the DCM for further assessment.
- Performed single track laser experiments to optimize printing conditions.
- Printed ten samples for each alloy using the optimized process parameters.
- Performed microstructural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

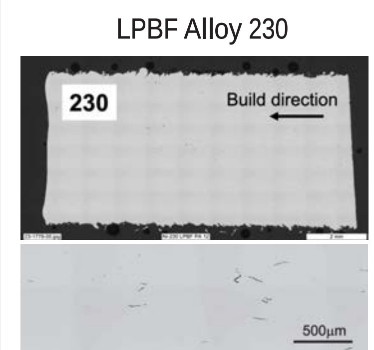
Further evaluations on **A709, AFA austenitic SS and G91, G92 ferritic-martensitic steels**.

Development of Ni-based Alloys for AM

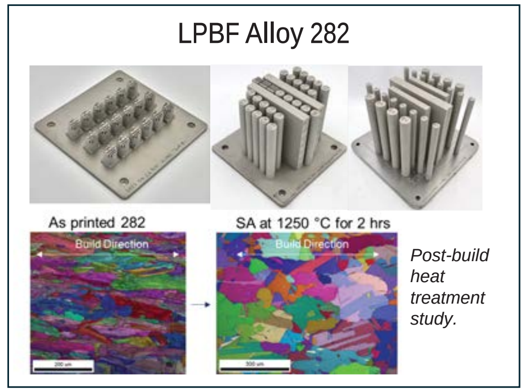
- Considered three Ni-based alloy categories based on potential applications: (1) **Low cobalt**; (2) **High temperature strength**; (3) **Low Cr, molten salt compatible**.

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)	





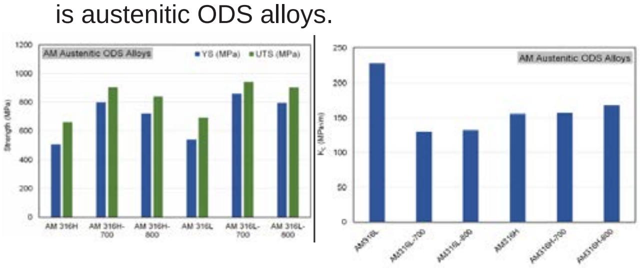
Hot cracking in printed 230.



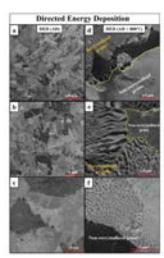
Other AM Materials Development

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*.

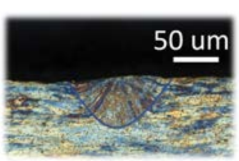
- Hierarchically heterogeneous microstructures (secondary $L1_2$-phase precipitates) obtained via simple one-step annealing:
  - significant better performance than the nearly homogeneous microstructures in the as-deposited state
  - Smaller than 6.6% reduction in hardness values at 500°C compared to 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±0.103	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

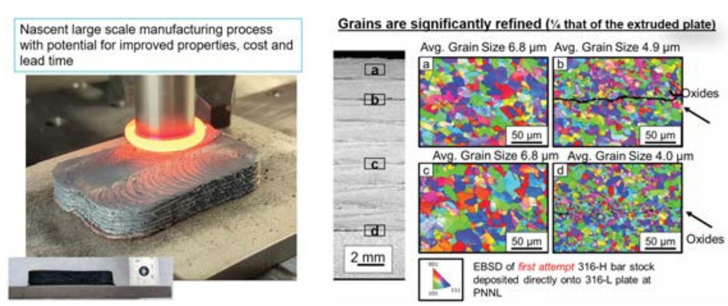
- Consider refractory bulk for high-temperature applications and coatings for corrosion resistance.


LBPF TZM Alloy



A weld pool in TZM.

Materials by Solid State Manufacturing

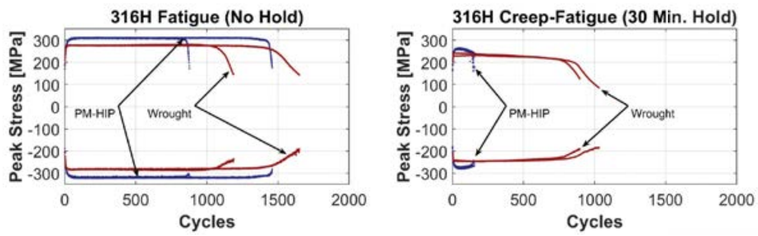


PM-HIP of 316H SS

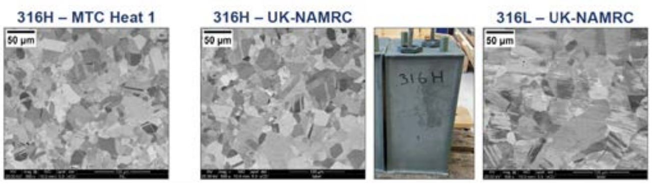
- Assessment on creep-fatigue properties of PM-HIP 316H SS
  - Initial evaluation showed PM-HIP 316H SS has poor creep-fatigue performance compared to wrought 316H SS.
- Understand how the composition and microstructure influence PM-HIP 316H mechanical properties
  - Oxygen concentration, oxide size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

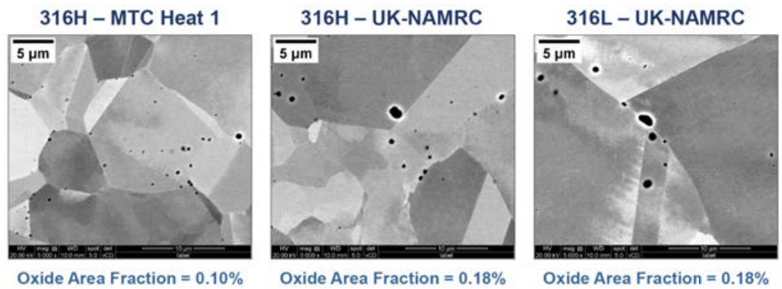
• Fatigue and creep-fatigue at 650°C

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



Consolidated Product Chemical Compositions (wt%)	Ni	Cr	Mo	C	Si	Mn	S	P	O	N	Hardness ($HV_{0.3}$)
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





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Rapid Qualification

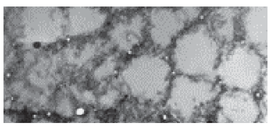
Rapid Qualification Framework

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.

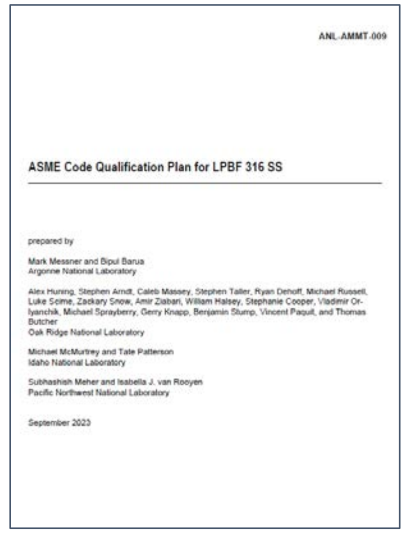
Model-based Qualification

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.


ANL-AMMT-009

ASME Code Qualification Plan for LPBF 316 SS

prepared by

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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

Qualification differences between AM and conventional materials

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

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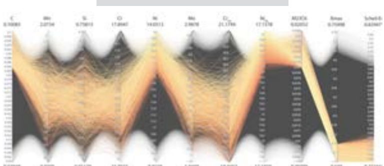
Experimental Understanding of Processing-Structure-Property

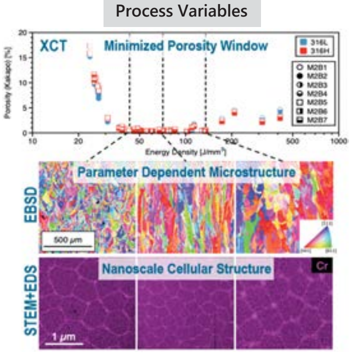
Process Understanding and Optimization

Feedstock Chemistry



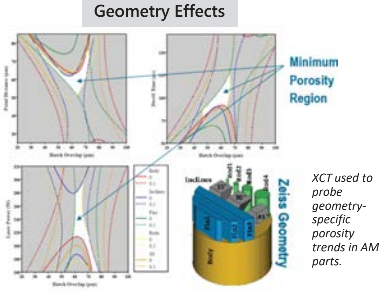
Chemistry on sensitivity to energy density, and data mining highlighting 316H chemistries to maximize carbides and minimizing δ-ferrite.

Process Variables



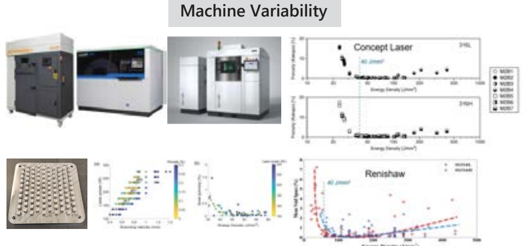
Multiscale characterization using XCT, EBSD and STEM-EDS reveals variations in porosity, grain structure, & nanoscale segregation as a function of varying processing parameters.

Geometry Effects



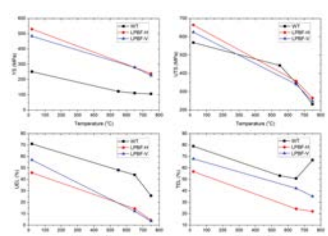
XCT used to probe geometry-specific porosity trends in AM parts.

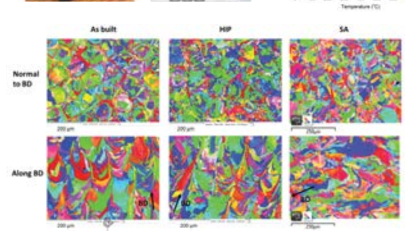
Machine Variability



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

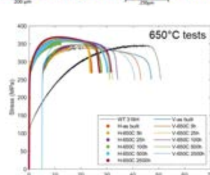
Post-build Treatment and Property Testing

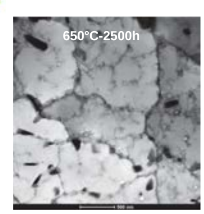




High-temperature fatigue, creep, and creep-fatigue tests of LPBF 316H SS is underway.

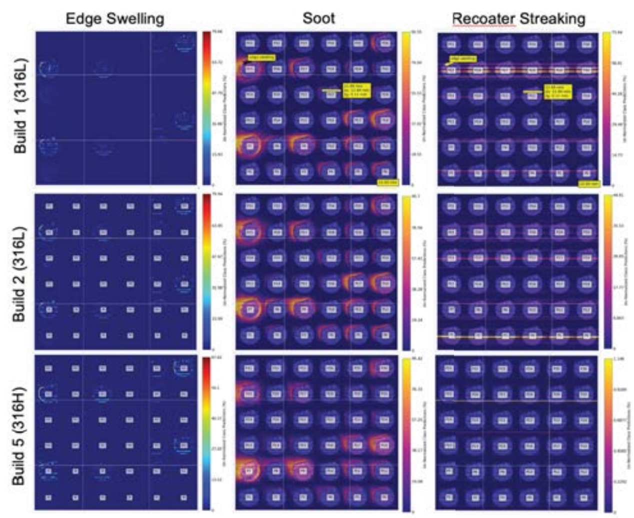
Thermal aging study of LPBF 316H SS.





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.

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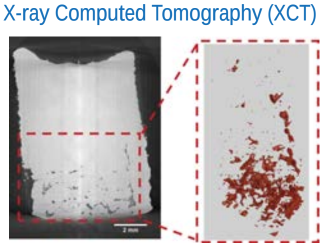
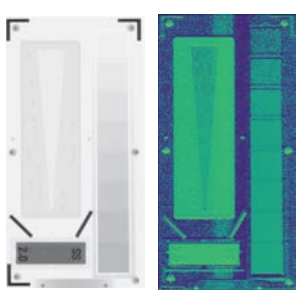
Post-Process NDE of AM Components

- 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.



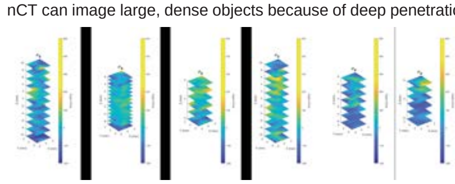
Dual Energy XCT

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)

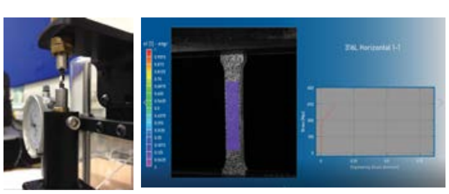
nCT can image large, dense objects because of deep penetration.



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

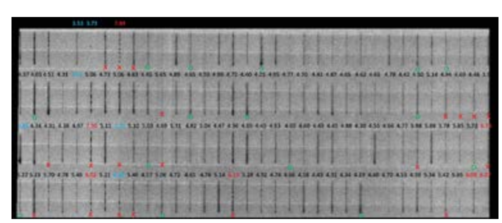
Advanced Ultrasonic Methods

- 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.



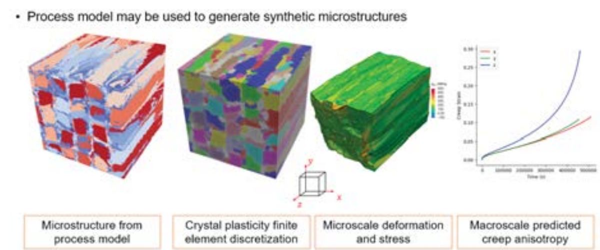
Thermal diffusivity measurement results on LPBF 316 tracks.

Processing-Structure-Property Modeling

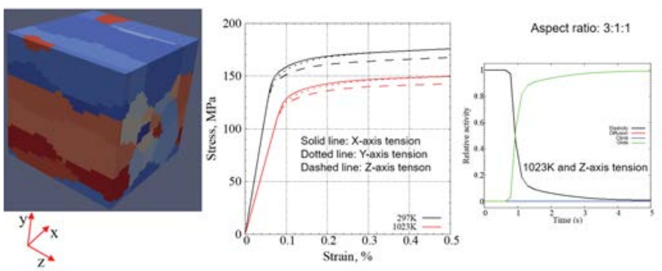
Process modeling to predict AM microstructure

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

Connecting process modeling to property predictions

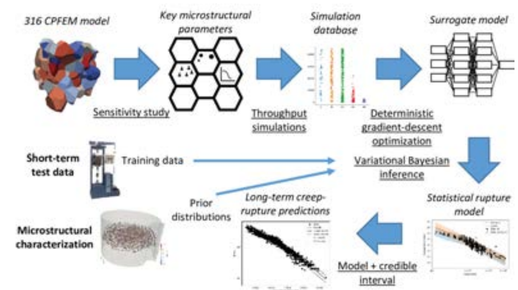


Simulate tensile behavior of AM with columnar grains

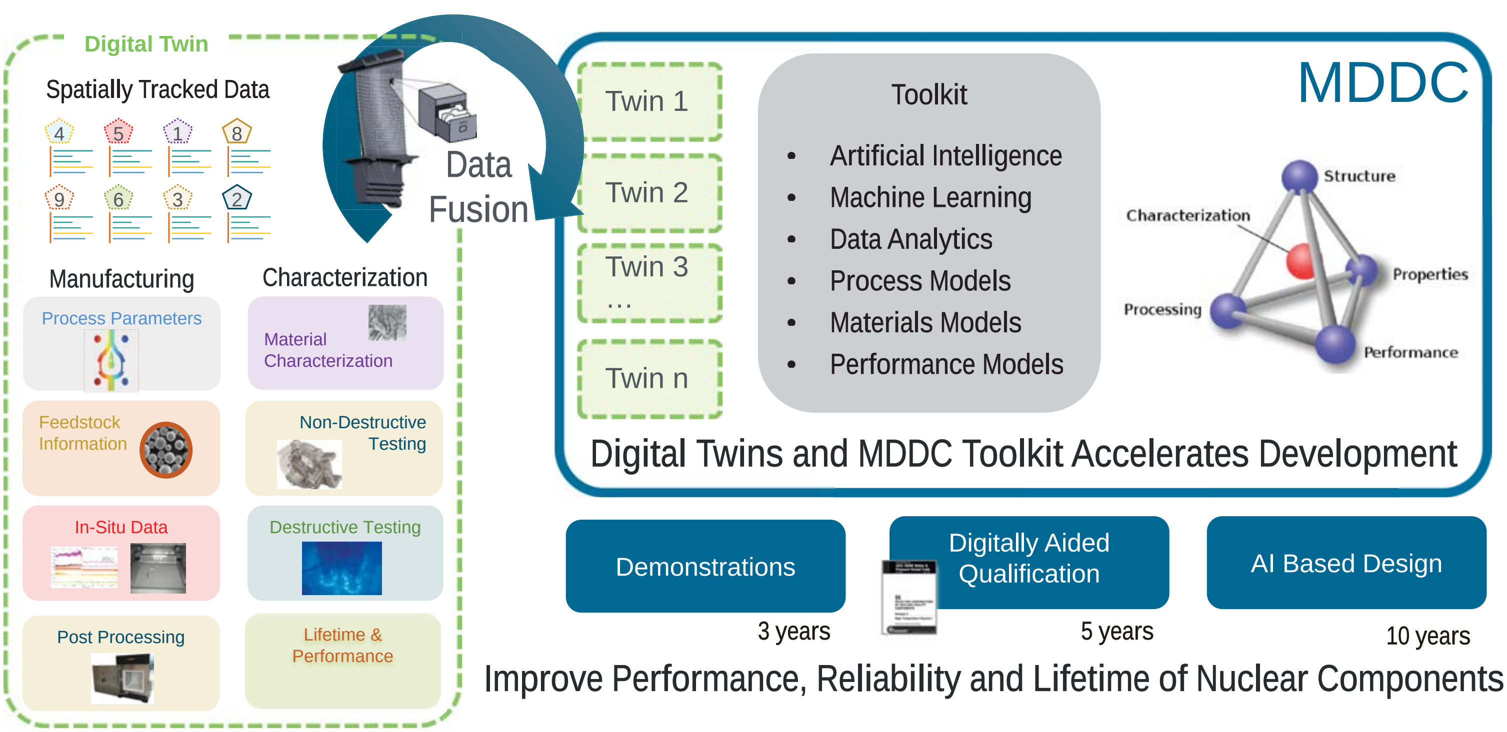


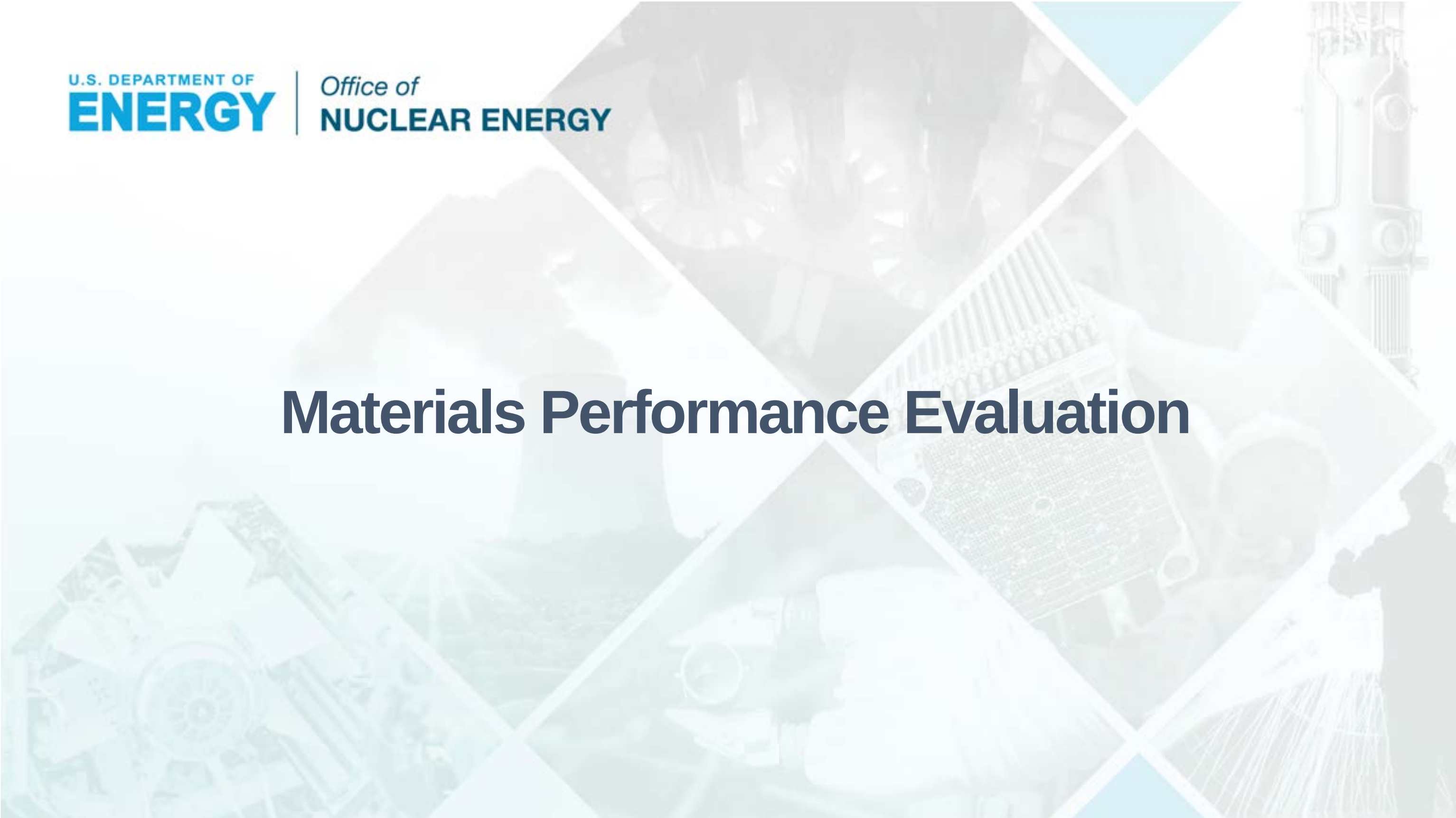
Columnar grain structure develops significant anisotropy in the mechanical responses.

Predict long-term creep rupture strength



Multi-Dimensional Data Correlation (MDDC) Platform





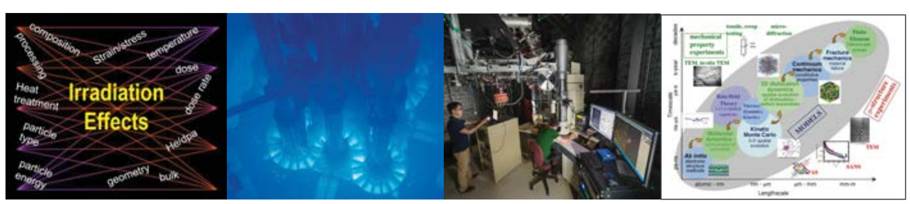
Materials Performance Evaluation

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.

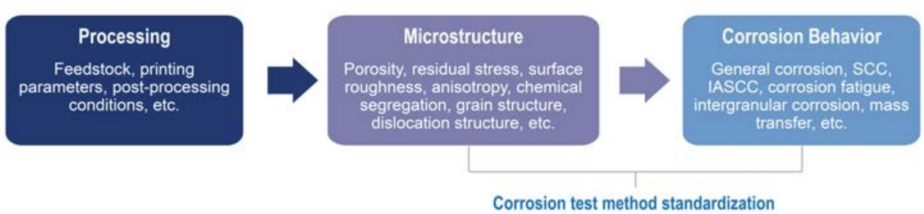
Irradiation Effects

- 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



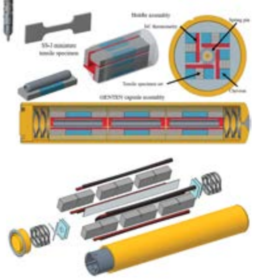
Neutron Irradiation and PIE of LPBF 316 SS

HIFR Irradiation

Flux Trap "Rabbits" Experiments

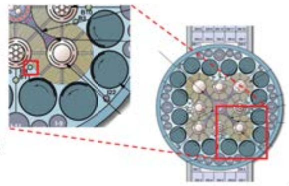
- Center cylindrical flux trap, 12.70 cm diameter
- Fast flux: 1.1 × 10^{15} n/cm²/s
- Thermal flux: 2.0 × 10^{15} n/cm²/s
- Small diameter: Ø9.5–11.3 mm
- 12.6 dpa/calendar year (steels)
- Single temperature (60°C–1200°C)
- Hydraulic tube (HT) for irradiation < 1 cycle

- 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

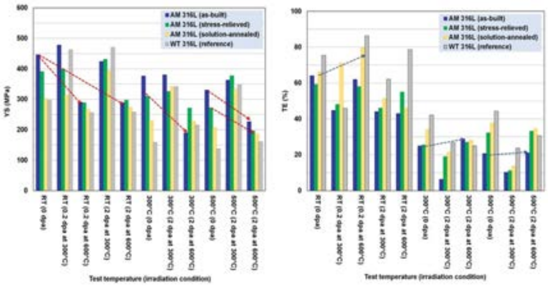
- Spectrum is primarily thermalized
- Coolant is pressurized water at ~50 °C
- Experiment positions vary between 5/8" to 3" diameter
- Thermal Flux 2.5E+14
- Fast Flux 8.1E+13

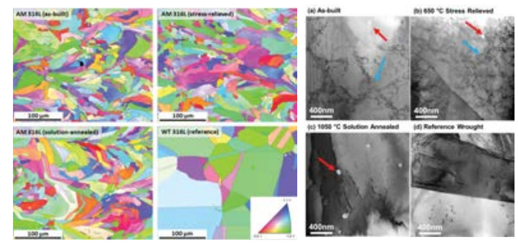


- Structural Material Testing
  - SSJ tensile bars (max 48)
  - Bend Bars (max 24)
  - Round Compact-Tension (Max 13)

Post Irradiation Examination (PIE)

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



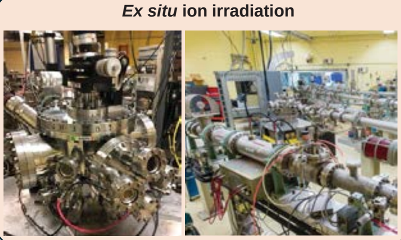


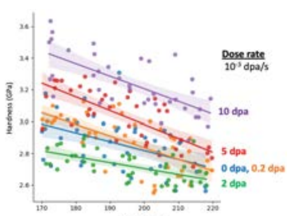
Qualify LPBF 316 SS with Combined Ion & Neutron Irradiations and Modeling

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**

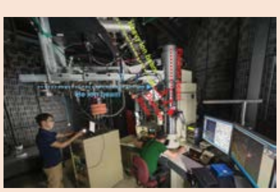


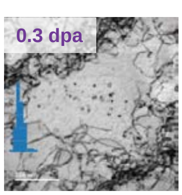


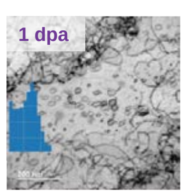
In situ Ion Irradiation:

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**

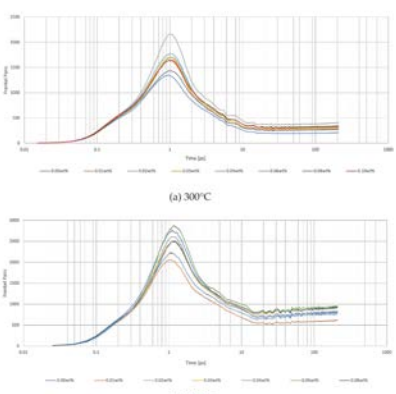






Computer Modeling

Modeling of radiation damage in LPBF 316 SS



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.

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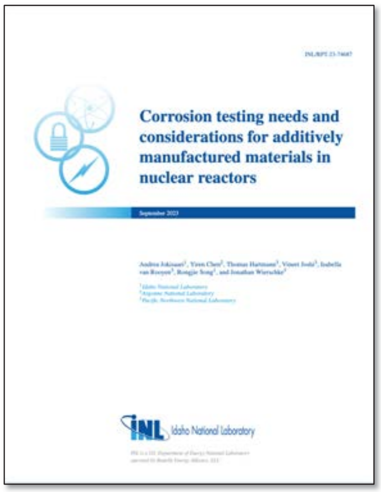
Corrosion Studies Of AM Materials

- 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.


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

September 2023

Molten Salt Experiments

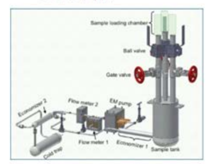
Capsule and Loop Testing in FliNaK and FLiBe

ORNL thermal convection loop, FLiBe TCL

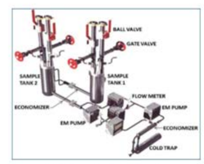
Sodium Experiments

Sodium Materials Testing Loops

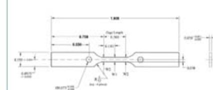
- Forced-convection sodium loops, SMT-1 and SMT-2, for sodium-exposure experiments
- SS-3 tensile samples with extended shoulder for corrosion, microstructure, and tensile properties measurements on one sample.



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



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



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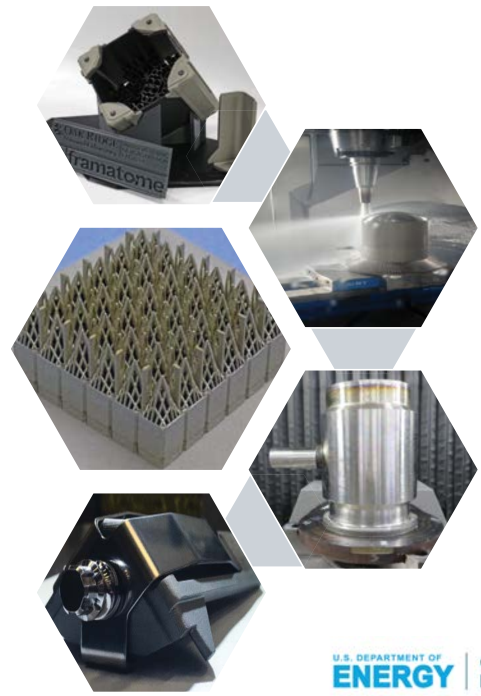
Technology Demonstration

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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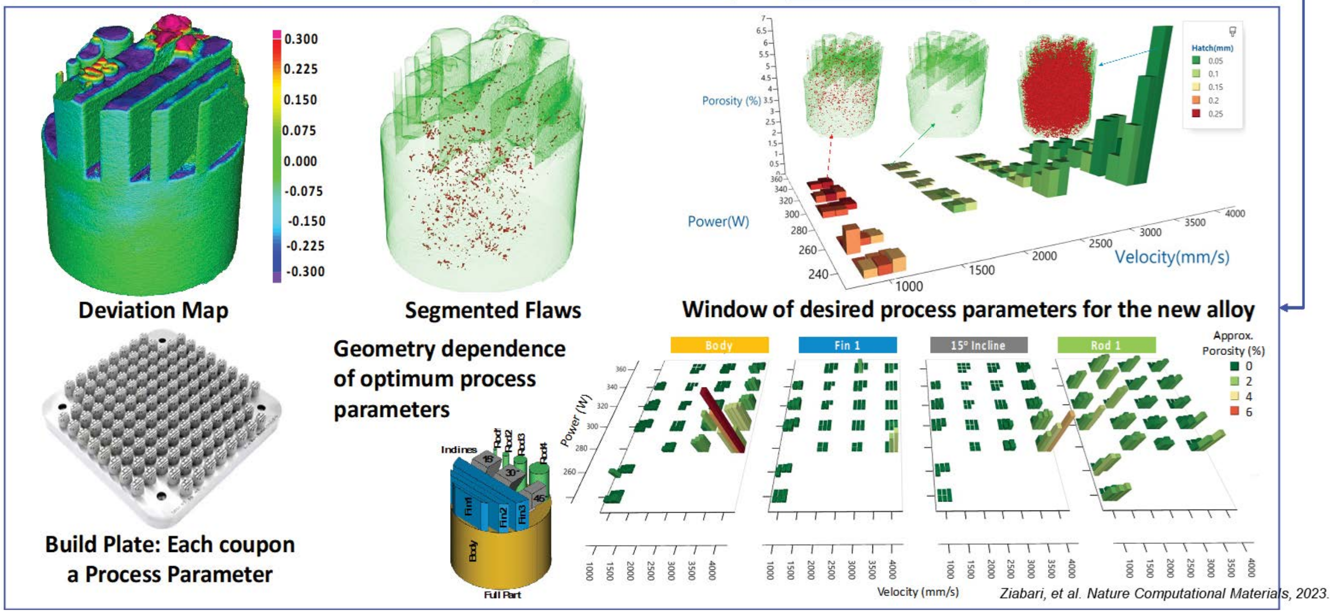
Capability Development & Transformative Research

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.

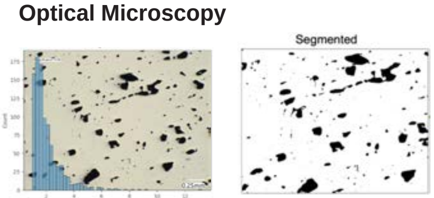
Computer Vision (CV) Automated Microstructure Quantification

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

10^{-3} m

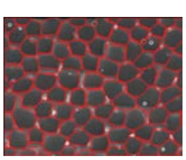
10^{-9} m

Optical Microscopy

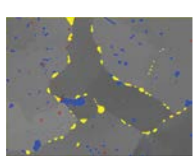


Python-based computer vision tools to analyze porosity size, density and shape in LPBF 316 SS.

Scanning Electron Microscopy (SEM)

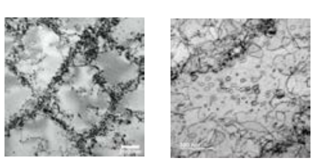


Segmentation of cell structure in LPBF 316 SS.



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

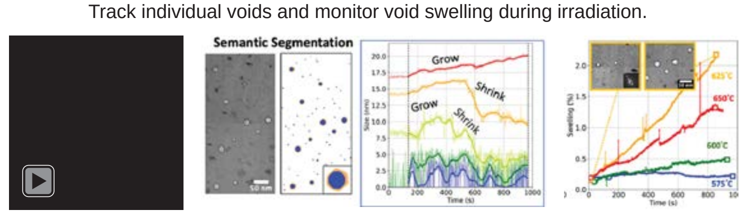
Transmission Electron Microscopy (TEM)



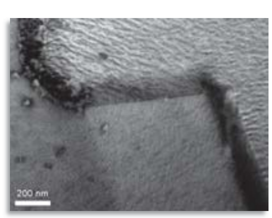
CV models to analyze TEM images to measure dislocation cells, dislocation lines and dislocation loops.

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

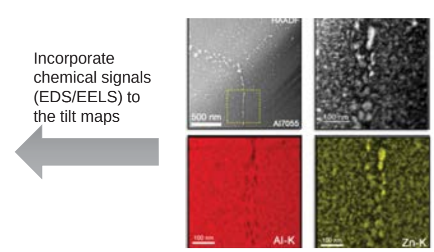
Track individual voids and monitor void swelling during irradiation.



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



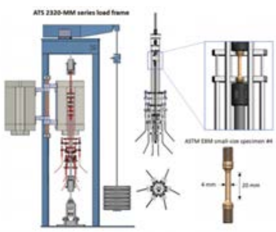
Incorporate chemical signals (EDS/EELS) to the tilt maps



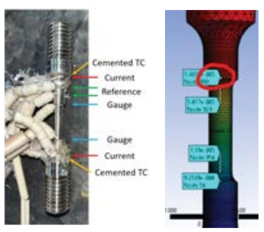
High-throughput Creep Testing Techniques

Series, multi-specimen loading

Multi-specimen creep testing with LVDT or DCPD measurements.



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

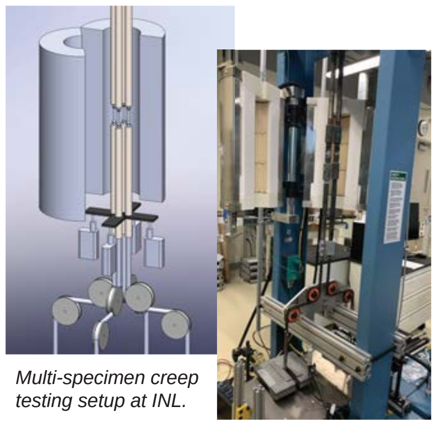


Creep strains measured by Direct current potential drop (DCPD).

Multi-specimen creep testing setup at ANL.

Parallel, multi-specimen loading

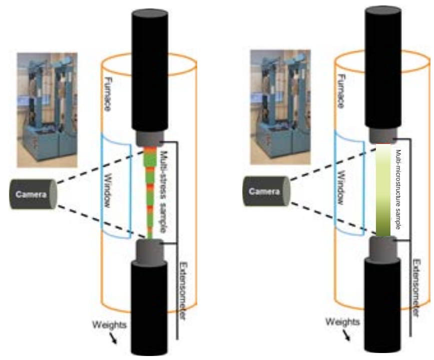
Two independent creep load trains on a modified ATS creep frame to test multiple specimens.



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.

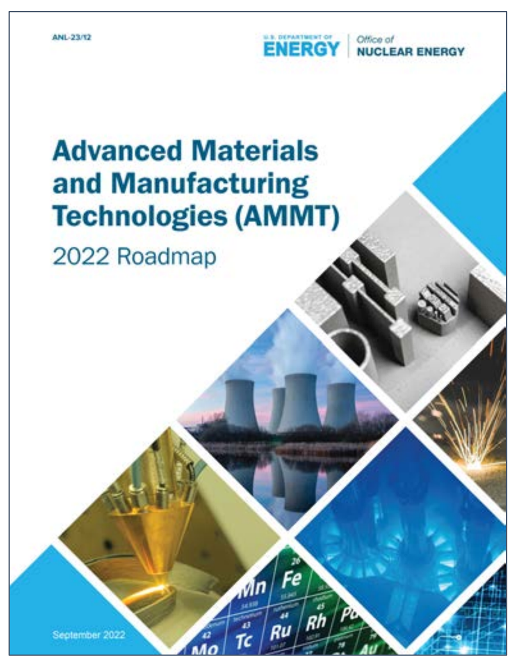
Materials Performance Evaluation

- 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



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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?

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Advanced Materials & Manufacturing Technologies (AMMT) Program on Demonstration of Advanced Manufactured Components in Nuclear Applications

Meimei Li (ANL), NTD; David Andersson (LANL), deputy NTD;
Ryan Dehoff (ORNL), Andrea Jokisaari (INL), Isabella van Rooyen (PNNL), TALs;
Dirk Cairns-Gallimore, DOE Federal Manager

2023 NRC Workshop on AMTs for Nuclear Applications
October 24-26, 2023

MDF

AMMT and ORNL has a demonstrated track record of working with industry to facilitate nuclear demonstrations

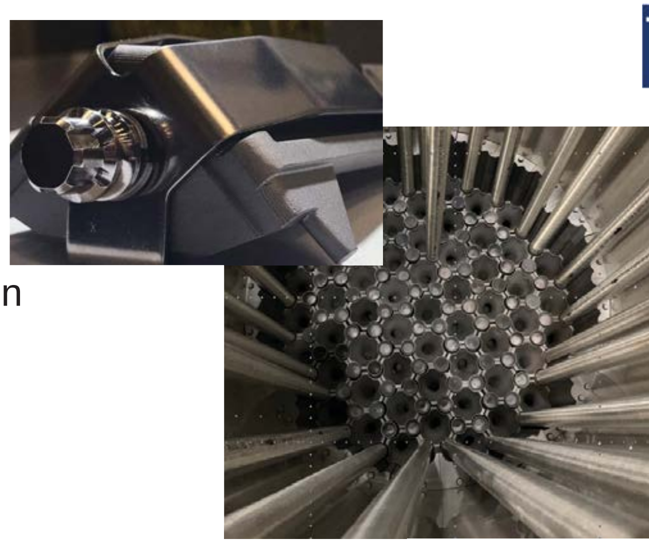
- AMMT, like its predecessor at ORNL the TCR program, has and will continue to find tangible scenarios to help and enable developers with its advanced technologies.
  - Working with advanced reactor developers to enhance the design and manufacturing of their components
  - Working with the current fleet of reactors and their vendors to adopt new cost-effective approaches to manufacturing
  - Working with the supply chain to adopt and commercialize TCR manufacturing procedures
  - Teaming to deliver a new accelerated and cost-effective approach to quality certification of additively manufacture components
  - Licensing technology to reactor developers

AMS
BWXT BWX Technologies, Inc.
CURTISS-WRIGHT
framatome
HTS IC
Kairos Power
LOCKHEED MARTIN
X energy
ULTRA SAFE NUCLEAR

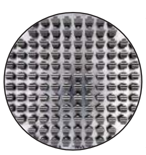
AMMT will continue the demonstration of additive manufacturing technologies for nuclear components

AMMT Nuclear Capabilities:

- Material Testing
- Component Build & Testing
- Regulatory/Standards Updates
- Qualification Program
- In-situ Monitoring & Digital Qualification
- Modeling
- Industry Partner Demonstrations
  - Framatome
  - Kairos Power
  - Westinghouse
  - Future Demonstrations?



Framatome Channel Fasteners inserted into TVA's Browns Ferry Unit 2 reactor April 26th, 2021



Powder Bed Laser Printing Expertise → MDF Process and Process Understanding from

Peregrine → In-Situ Process Monitoring of builds to determine defects

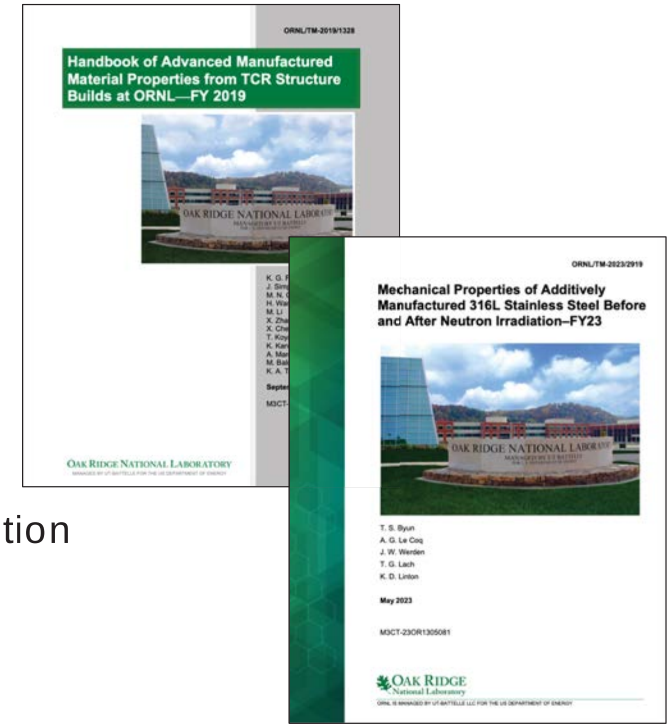
3D Characterization → Leveraged the Zeiss CRADA and ORNL Equipment for full component inspection

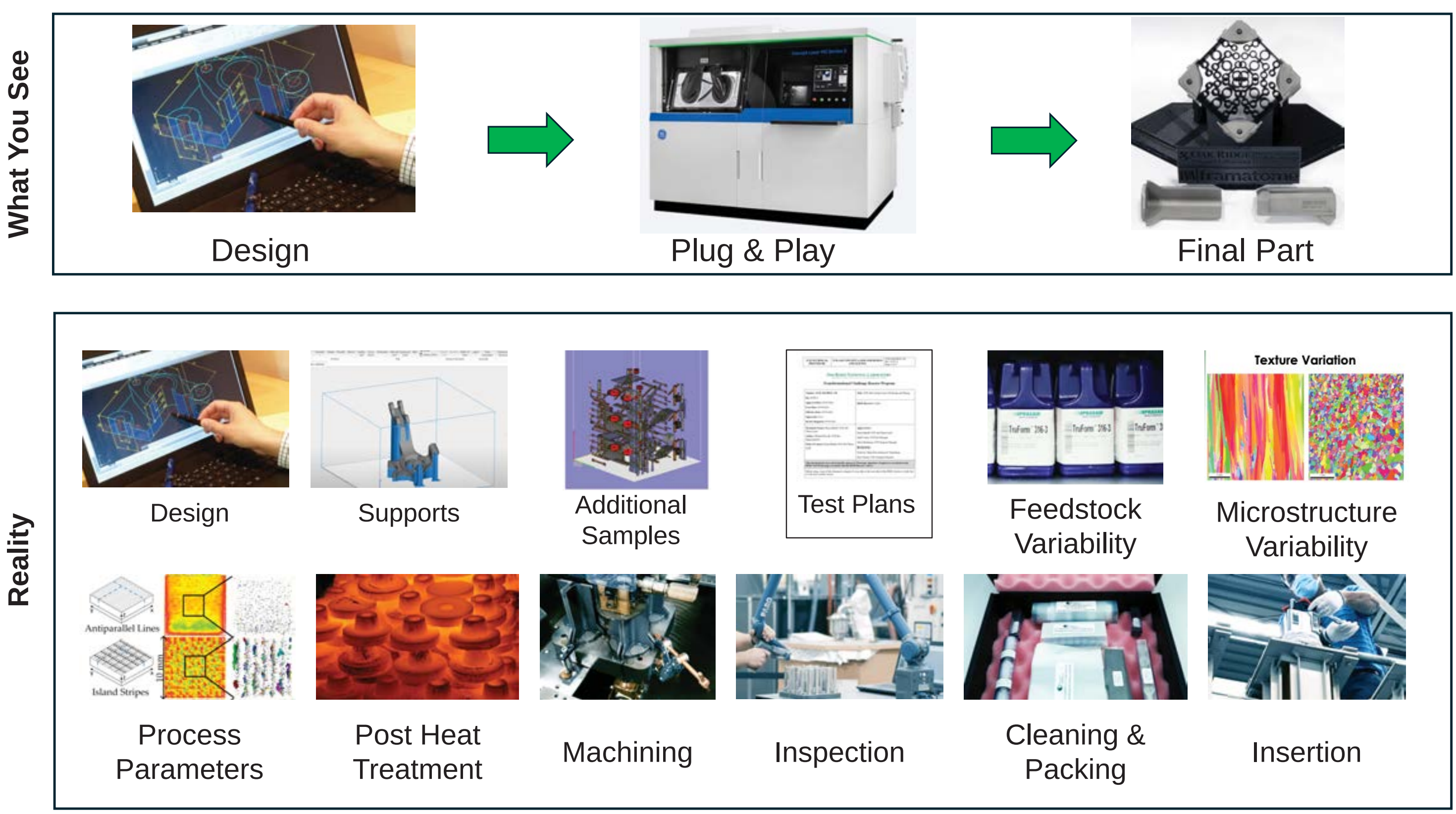
"The fuel assembly channel fasteners were printed at ORNL using additive-manufacturing techniques, also known as 3D printing, as part of the lab's Transformational Challenge Reactor Program and installed on ATRIUM 10XM fuel assemblies at Framatome's nuclear fuel manufacturing facility in Richland, Washington."

Framatome website (Dec 2020)

Challenges:

- Geometric Accuracy
  - Build layout effects accuracy
  - Surface Finish, Machining Required
  - Conversation between design and manufacturing
- Process Optimization
  - Material Testing
  - In-situ Monitoring & Digital Qualification
- Regulatory/Standards Updates
- Qualification Program





AMMT Updates to TCR AM Qualification Program:

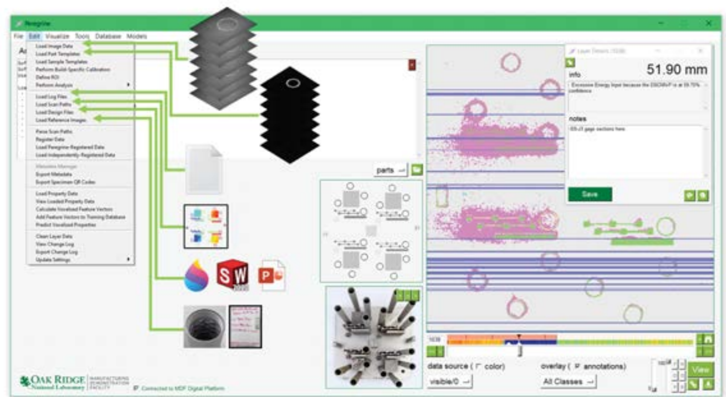
AMMT Nuclear Qualification Program:

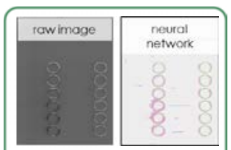
- ASME NQA-1 Quality Program
  - TCR Version used to Qualify Framatome Part
- NQA-1 Quality Assurance Plan
  - Update published in September 2023
- NQA-1 AMMT Specific – Procedure Set
  - Technical & Administrative
  - AM Machine & Process Specific
  - Powder Management
  - Post-Processing
  - Production & Test Planning
  - Conformance

MDF Digital Factory: Peregrine

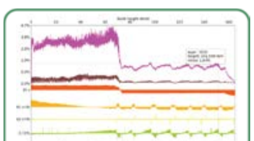
A software platform for collecting, annotating, analyzing, and visualizing AM data

- Utilizes artificial intelligence to classify process data
- Correlations with location specific testing and characterization data
- Enables simulation of AM processes



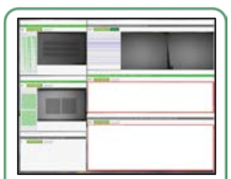


AI Image Processing

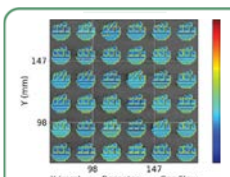


Time Series Data

Multi-modal Visualization



Real-time remote monitoring/control

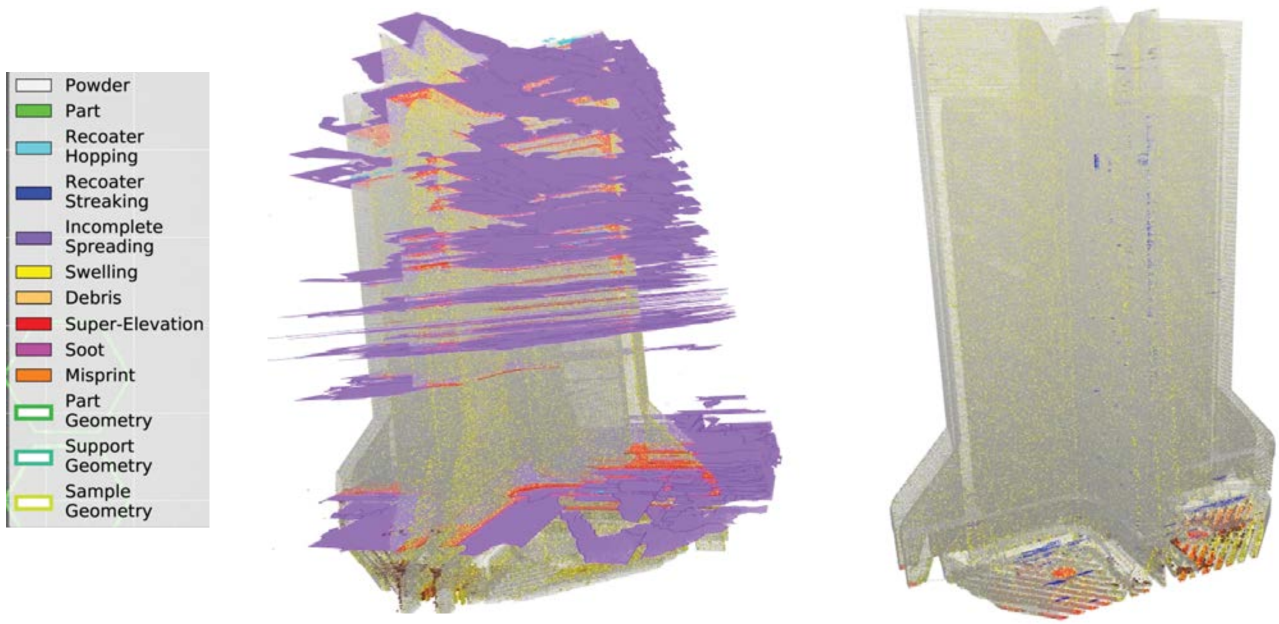


Drive simulations

Peregrine Usage Impacting the U.S.

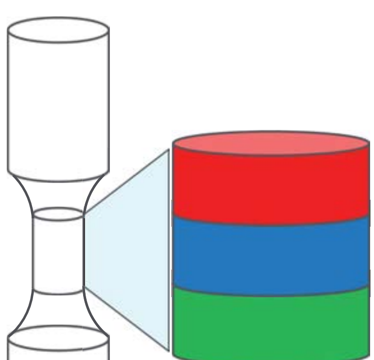
13 U.S. government labs using and developing
12 R&D licenses granted
3 CRADAs have leveraged *Peregrine*
2 universities using Peregrine for R&D
15+ organizations using **100+ GB** of in-situ data
5 journal papers and **1** U.S. patent

Peregrine used for Build/Process Optimization



AMMT Challenge Problem: Rapid Qualification

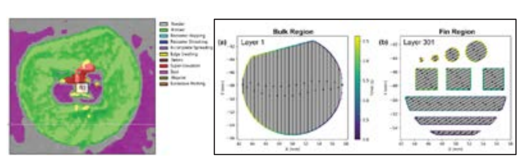
Understand our ability to predict the creep performance for a coupon with spatially varying microstructure and identify shortcomings of rapid qualification of 316H



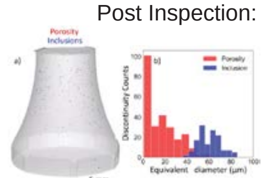
Multiple Processing Conditions in Gauge

Digital Image Correlation AM Creep Specimen

Data Captured During Build

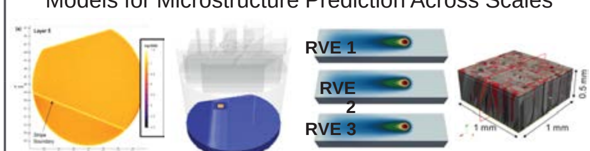


Post Inspection: Destructive & NDE



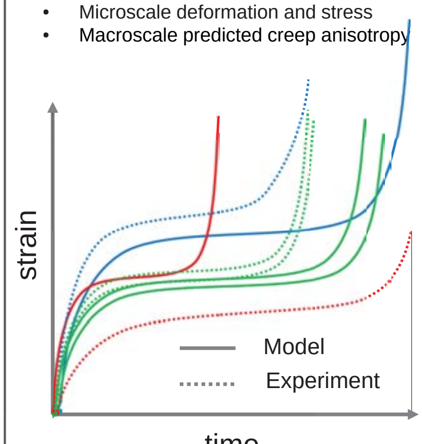
1. Computed Tomography
2. Ultrasonic Investigation
3. Microstructure Evaluation

Models for Microstructure Prediction Across Scales



Creep Performance Prediction

- Crystal plasticity finite element discretization
- Microscale deformation and stress
- Macroscale predicted creep anisotropy



How Close are We?

Powder Metallurgy via Hot Isostatic Pressing

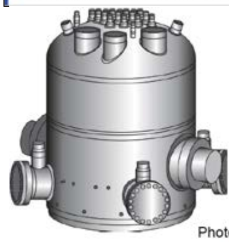

EPRI ELECTRIC POWER RESEARCH INSTITUTE

PM-HIP and Electron Beam Welding Development for Nuclear Applications

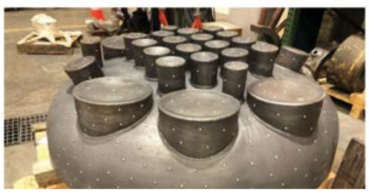
David W. Gandy
Sr. Technical Executive, Nuclear Materials

NRC Advanced Manufacturing Virtual Workshop
December 7-10, 2020

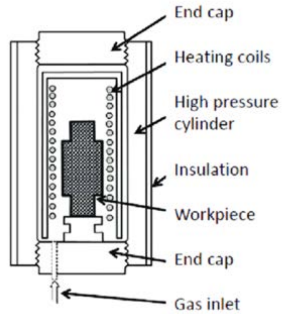
www.epri.com



Photographs courtesy of EPRI and NuScale Power

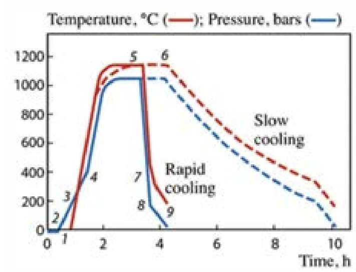


The Pressure Vessel



HIP CAN

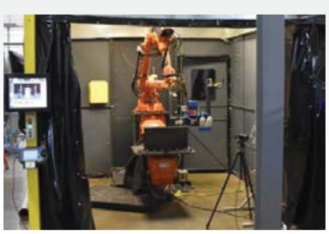
Typical Pressure-Temp-time cycle

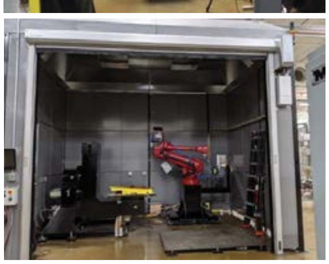


Large-scale Metal Capabilities

Lincoln Wire Arc

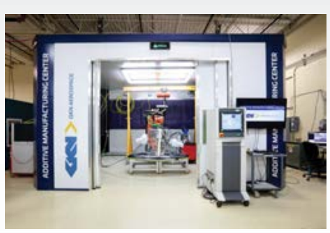
- ABB 6DOF arms and 2DOF positioners
- Lincoln Electric Welders





GKN Cells 1 and 2

- Kuka 6DOF arms and 2DOF positioner
- Laser-wire



Hybrid Systems

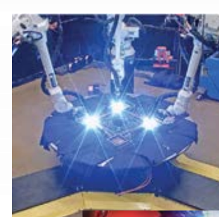
VC500A/5X AM HWD
Laser Hot-Wire
Serial #1
MU-8000V LASER EX
Blown-Powder
TRUMPF Laser

OKUMA

Mazak

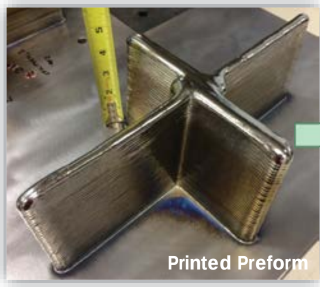
Custom Systems

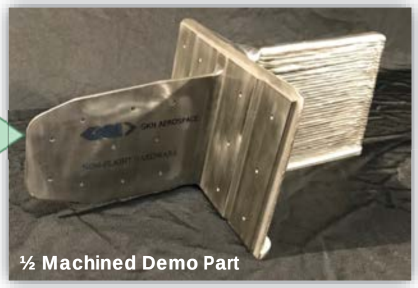
- MedUSA: Multi-agent, coordinated deposition
  - 3x ABB 6DOF arms and1DOF table
  - 3x Lincoln Electric welders
- Operando Neutron Deposition



Laser-Wire DED Background at MDF

- Replacement technology for custom forgings and billet
- **Drivers:** Lead time, cost, and buy-to-fly ratio (10:1 to 2:1)

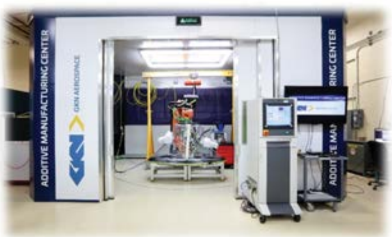

Printed Preform


½ Machined Demo Part


Notional Spar Demonstrator

Why Laser-Wire?
- Highly controllable (heat source ← → feedstock)
- Excellent surface finish for post-print machining
- Medium system cost

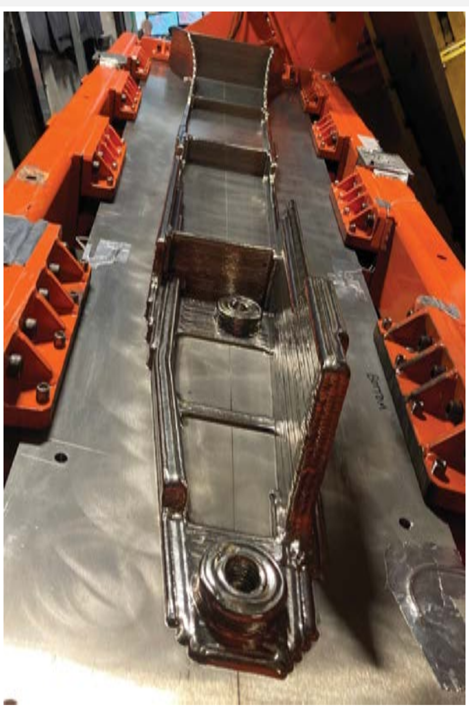
System Specs:
- 20 kW laser power
- 8 DOF motion


Cell 1: R&D

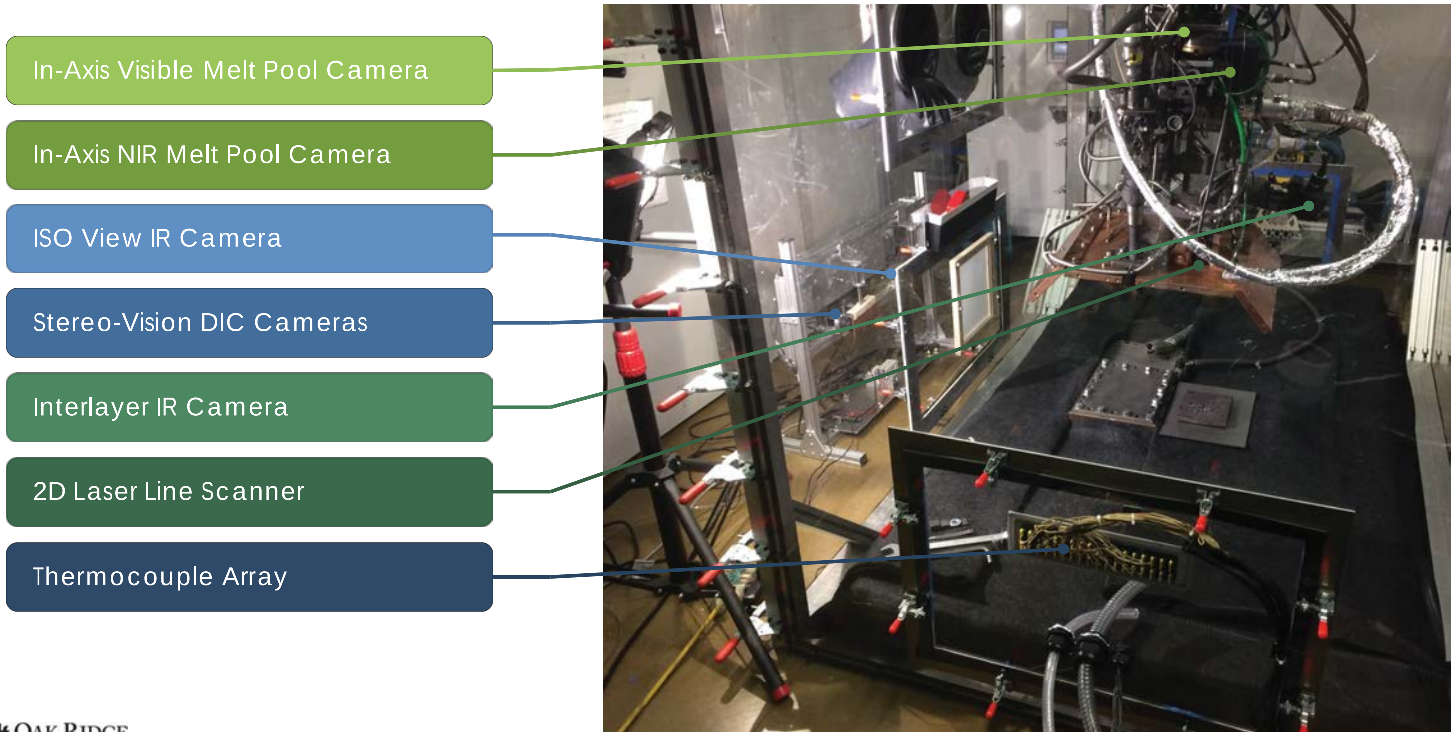

Cell 2: Pilot Production

OAK RIDGE National Laboratory

Large Scale Aerostructure Demonstrator, ~96" long, >100 lbs Ti64

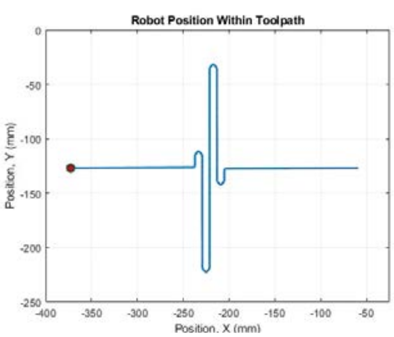


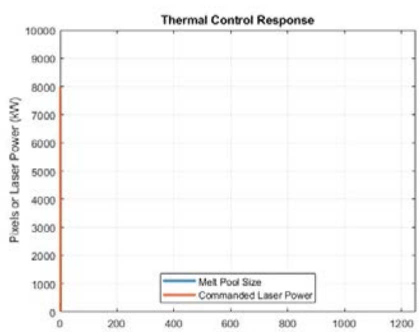
Monitoring Snapshot: Laser-Wire Cell 1



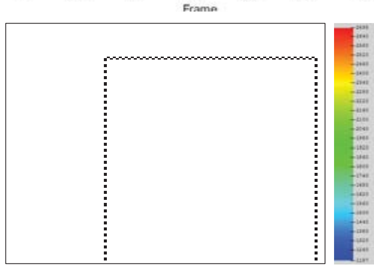
Laser-Wire Process Control

"Heartbeat" Toolpath





Process Camera



Thermal Camera

Overview Camera

Outside Melt Pool Definition
Outside Measurement Window
Melt Pool Definition

In-situ Monitoring Assisted Large-Scale AM of Mild Steel and 316L Alloys For Nuclear Application

Hybrid AM and WAAM, In-situ Monitoring and Largescale distortion modeling teams

Objective: Feasibility Demonstration and Post-HIP Assessment of AM Pressure Vessels

Scientific Achievement

- Successful Fabrication of HIP Cans via 3 unique AM modalities – Processing data collected
- Completion of full-scale HIP trial for WAAM can

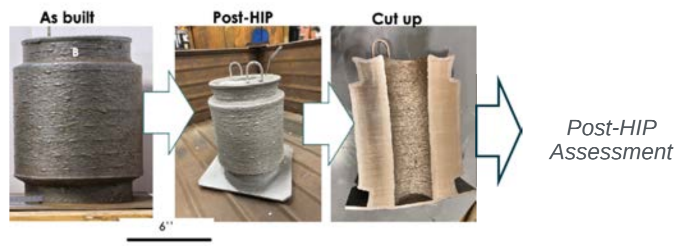
Impact & Potential Application Space

- Large Scale Nuclear Comp- SMR head, t- Valves
- Other Energy applications – Renewables, O&G

Details

- Learning as we build – Hybrid AM vs WAAM vs Blown Powder DED
- Data acquisition – melt pool, IR + visual camera, thermocouple
- Metallurgical and Mechanical assessment is key

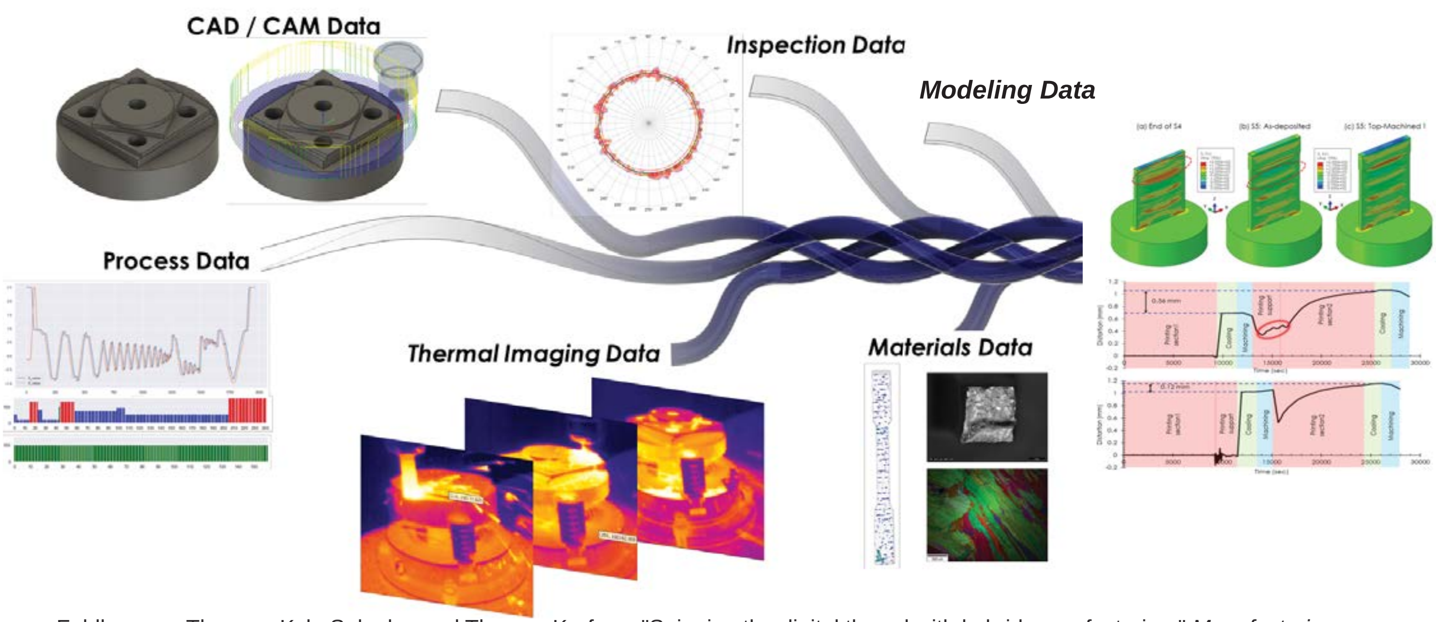
CAD to Part (Non-Symmetric) via Hybrid AM (Laser Hot Wire)



Successful HIP-ing of Concentric WAAM HIP can

Acknowledge EPRI for providing CAD of t-valve

Interdisciplinary Multi-Process Challenge

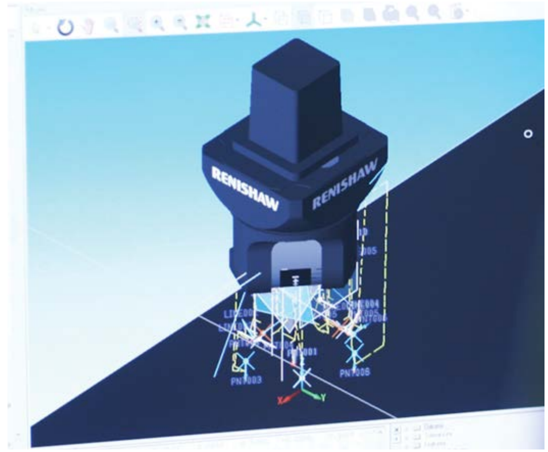


Feldhausen, Thomas, Kyle Saleeby, and Thomas Kurfess. "Spinning the digital thread with hybrid manufacturing." *Manufacturing Letters* 29 (2021): 15-18.

Nuclear Part Demonstration Process:

- Program Planning
  - Is Part Right for AM Demonstration?
  - Schedule for Development/Licensing
  - Production/Qualification Plan
- Design/Engineering
  - Design for AM Optimization
  - Fabrication Demonstration
  - Finalize Design & Specifications
- Fabrication/Qualification Plan
  - AMMT Specific
  - Customer Developed

TVA

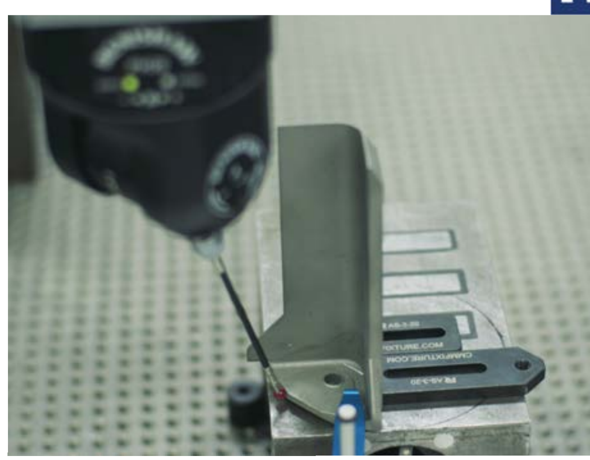


framatome

Nuclear Part Demonstration Process (cont'd):

- **AMMT Fabrication/Qualification Plan:**
  - Material Acquisition/Controls (powder/wire)
  - Part Fabrication
  - Post Processing
  - Testing (in-situ, destructive, NDE)
  - Qualification (built into every step)
    - Fabrication/Quality Traveler
    - Quality Hold-points
  - Packaging & Shipping
  - Certification of Conformance
- **Customer Licensing/Qualification Plan:**
  - Inputs to Customer Qualification Plan/Report
  - Licensing/Regulatory Support

TVA



framatome

Nuclear Part Demonstration Process (cont'd):

- **Demonstration Part Fabrication:**
  - Fabrication Team Training & Qualification
  - Pre-job Brief – Review of Fab/Qual Plan
  - Part Fabrication
  - Post-Processing (heat treat/machining)
  - Quality Checks/Inspections (integrated)
  - Testing
  - Customer Observation/Integration in process
  - Certificate of Compliance
- **Customer Licensing/Qualification Plan:**
  - Inputs to Customer Qualification Plan/Report
  - Licensing/Regulatory Support

TVA

framatome

Questions

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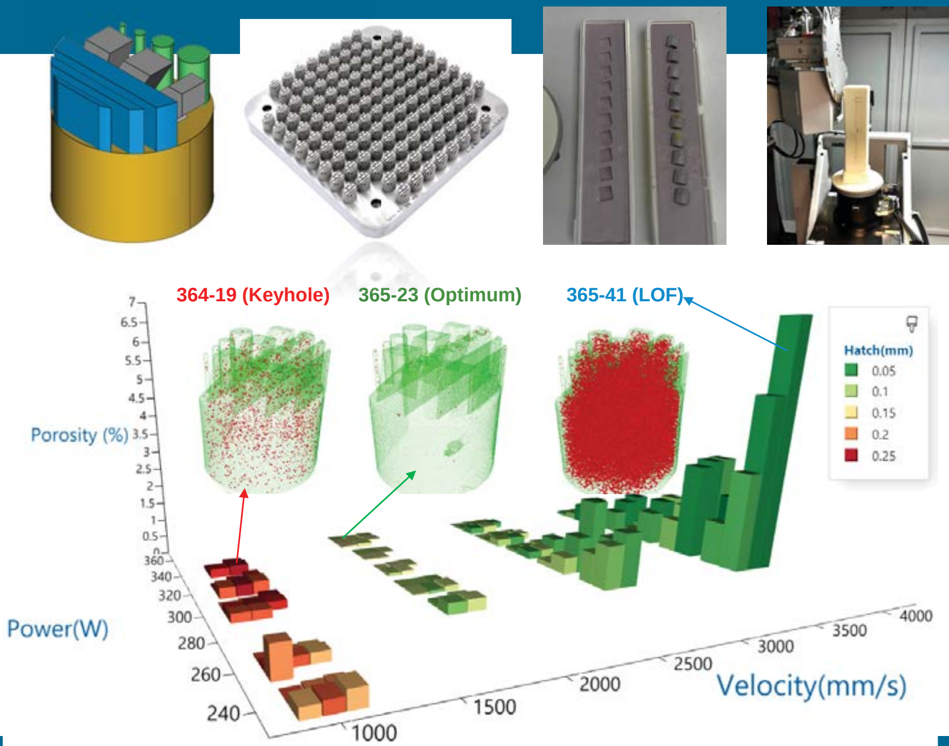
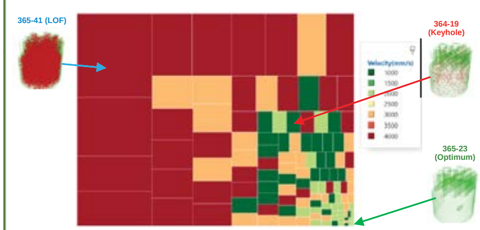
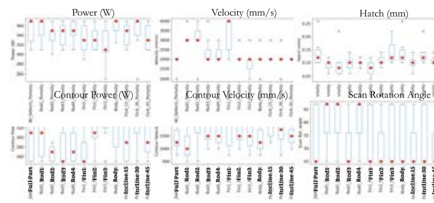
Rapid Pedigree X-ray CT Data Pipeline



Pedigree Data for Visualization, AI & ML & Validated Informatics



Visualization of Data



Preliminary Correlation

Using ML to Classify Simulated Process Data

Alex Plotkowski, Gerry Knapp, Jamie Stump, John Coleman, Matt Rolchigo

Process Modeling and Variability in AM 316 SS (CR-22OR040304)

Scientific Achievement

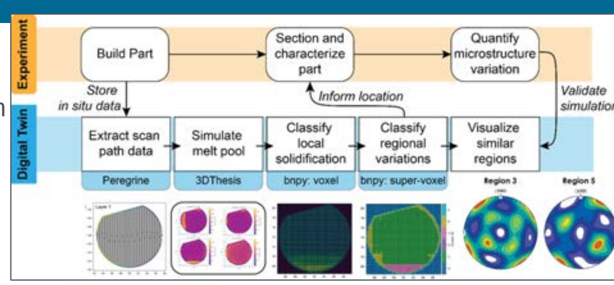
- Used unsupervised machine learning methods to classify simulation data for AM melt pools.
- Experimentally validated model and ML predictions.

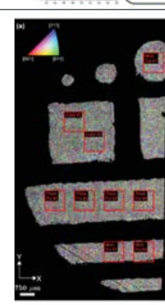
Impact & Potential Application Space

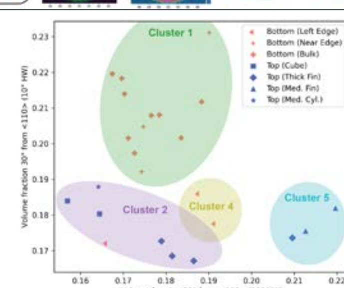
- Enables rapid determination of variability in AM components.
- Relevant for accelerated qualification of AM nuclear components.

Details

- Solidification predictions as a function of scan path made using 3DThesis.
- Multi-level classification to relate sub- and inter-melt pool behavior to anticipated solidification microstructures.
- Extensive EBSD for a representative 316 SS sample used for validation.







Workflow developed to generate and classify simulated thermal data for AM processing. Classification was experimentally validated for SS316L

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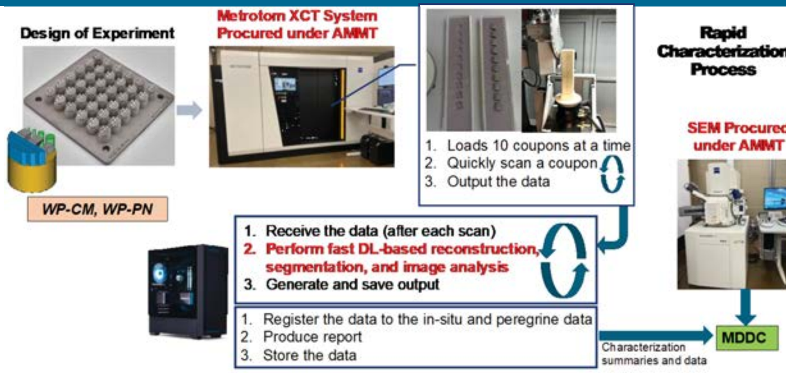
Knapp et al., "Leveraging the digital thread for physics-based prediction of microstructure heterogeneity in additively manufactured parts", Additive Manufacturing, In Review.

Using ML for Rapid Automated Characterization of 316L/H

Amir Ziabari, Andres Marquez Rossy, et al.

Automated, High Throughput Materials Characterization Techniques *(CR-22OR040601)*



DL-reconstruction allows for resolving the flaws using 6X faster scans in thick dense 316L/H

Scientific Achievement

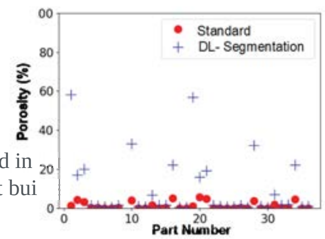
- Used ML methods for fast ex-situ characterization of dense metal components.

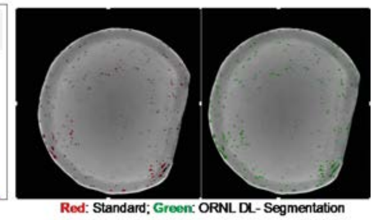
Impact & Potential Application Space

- Aid in understanding of process-structure-property-performance relationships, and in determining optimum printing process window for fully densified 316 component bui

Details

- Deep Learning based reconstruction and segmentations allowed for rapid and high-quality characterization of the parts (both verified through high resolution XCT and microscopy).
- More than 700 316L/H coupons XCT scanned and characterized allowing multiple team: to study impact of process parameters on porosity and dimensionality of different components.





DL-Segmentation demonstrates that true porosity can be underestimated by 60X! with standard algorithms

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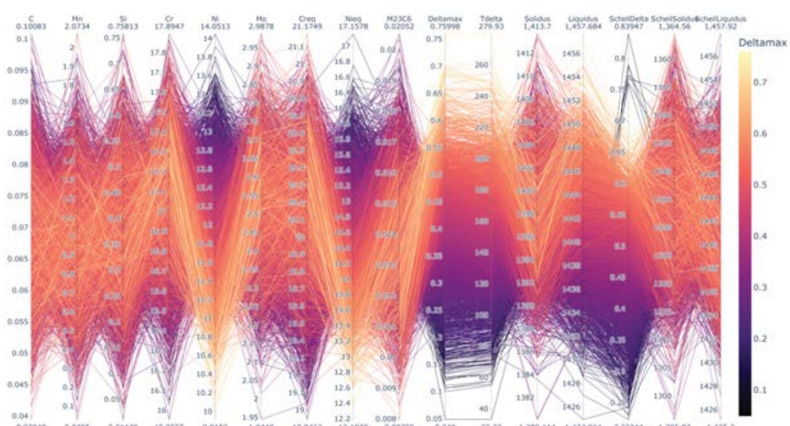
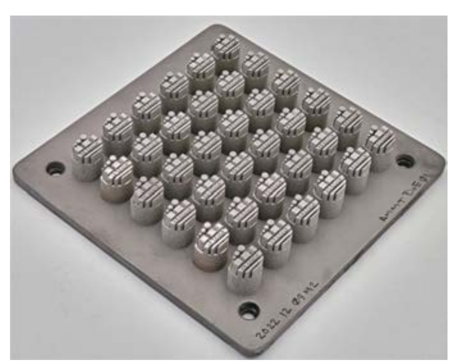
Highlights

- ➢ High throughput data mining based CALPHAD on 316L and 316H shows δ phase variation of 63% and 70% respectively, for compositions within ASTM specifications
- ➢ In 316H, the equilibrium carbide volume fraction varies from 0.8% to 2% for ASTM spec. composition
- ➢ Preliminary builds conducted using a multi-factor design of experiments to understand the impact of processing on heterogeneity





Securing the Future of the Nuclear Industry

Hilary Lane
Director, Fuel and Radiation Safety

October 24, 2023
NRC AMT Workshop

NEI NUCLEAR ENERGY INSTITUTE

THE NUCLEAR ENERGY INSTITUTE

is the **policy organization** of the nuclear technologies industry, based in Washington, D.C.

On behalf of its members, NEI is the **unified voice** of the nuclear energy industry on various **policy, technical, and regulatory issues**.

- **300+ MEMBERS IN 17+ COUNTRIES**

300+ Members

Nuclear Utilities

EPCs & Suppliers

Fuel Cycle

Decommissioning

National Labs

Investment & Financial Firms

Advanced Reactors

Universities

Law Firms

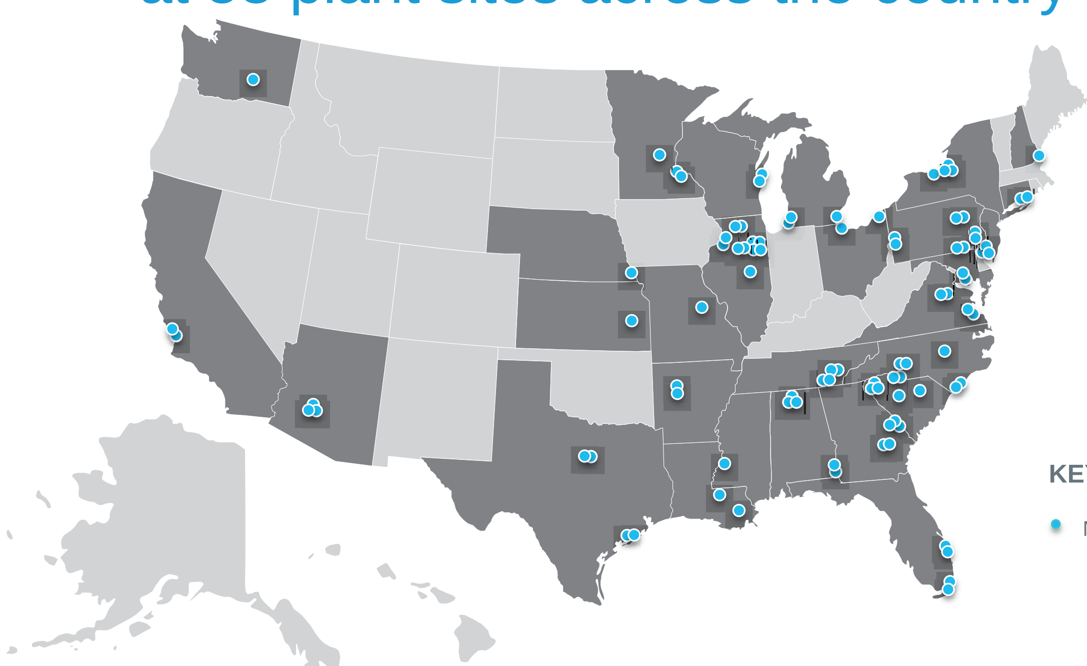
Consultants

Labor Unions

NGOs & Think Tanks

Current Fleet: **93 reactors** at 53 plant sites across the country

NEI

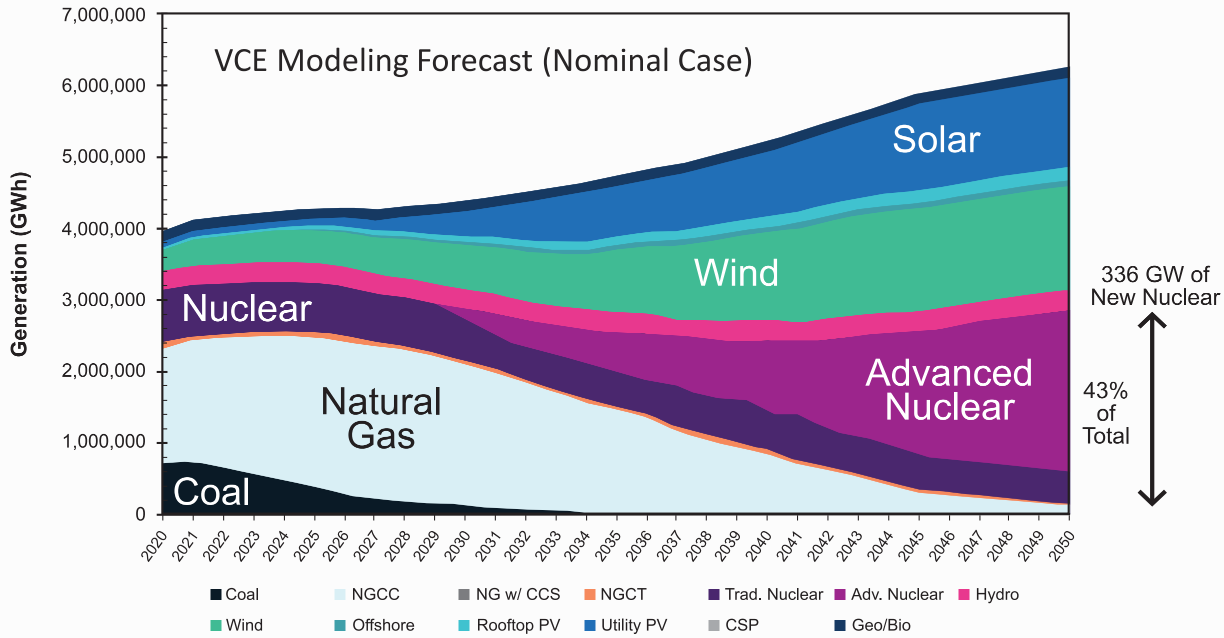


KEY

- Nuclear power reactor

Updated: May 2023

U.S. Market Opportunity for Advanced Nuclear



Source: Vibrant Clean Energy, *Role of Electricity Produced by Advanced Nuclear Technologies in Decarbonizing the U.S. Energy System* (June 2022), available at https://www.vibrantcleanenergy.com/media/reports/

Advanced Nuclear's Potentially Versatile Applications

Spectrum of Sizes and Options

Micro (Few MW)

Mini (10s of MW)

Small (100s of MW)

Large (1,000+ MW)

Variety of Outputs

Electricity

H_2 Hydrogen

Process Heat

Multitude of Uses

Homes, Vehicles, Businesses

Aviation, Rail, Shipping

Concrete, Steel, Factories

Water, Space

Watch the video: https://www.youtube.com/watch?v=7zN_YLg-roo

Nuclear Is POPULAR!

Isabelle Boemeke

Miss America 2023

Electric Utilities are Planning for New Nuclear

A recent survey of NEI's utility members confirmed nuclear power's expected role in meeting their company's decarbonization goals:

SLR

>90% of fleet expects to operate to at least **80 years**

GW

100 GW of new nuclear opportunity by **2050s**

SMRs

Translates to roughly **300 SMR-scale plants**

NEI utility member companies produce nearly half of all US electricity.

Source: NEI, *The Future of Nuclear Power: 2023 Baseline Survey* (Mar. 2023)

Advanced Reactor Developer Members

NEI

ADNA Corporation

Alpha NUR

GE HITACHI

Muons, Inc. Innovation in Research

TerraPower

Alpha Tech Research Corp

GENERAL ATOMICS

newcleo Futurable Energy

TERRESTRIAL ENERGY

USNC ULTRA•SAFE•NUCLEAR

arc CLEAN TECHNOLOGY

HOLTEC INTERNATIONAL

NuGen

NUSCALE Power for all humankind

Westinghouse

BWXT BWX Technologies, Inc.

Kairos Power

X energy

OKLO

EXODYS ENERGY

LAST ENERGY

framatome

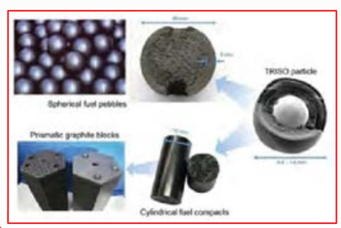
moltex clean energy

RADIANT

ZENO POWER SYSTEMS

Representative Advanced Reactor Technologies

NEI



TRISO Fuel

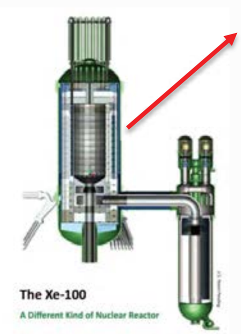
Micro Reactors (< 10MW)

Oklo (shown)
Approximately a dozen in development

LWR SMRs <300MW

NuScale (shown)
GEH BWR X-300
Holtec SMR-160

High Temp Gas Reactors



X-energy (shown)
Several in development

Liquid Metal Reactors

TerraPower Natrium (shown)
Several in development

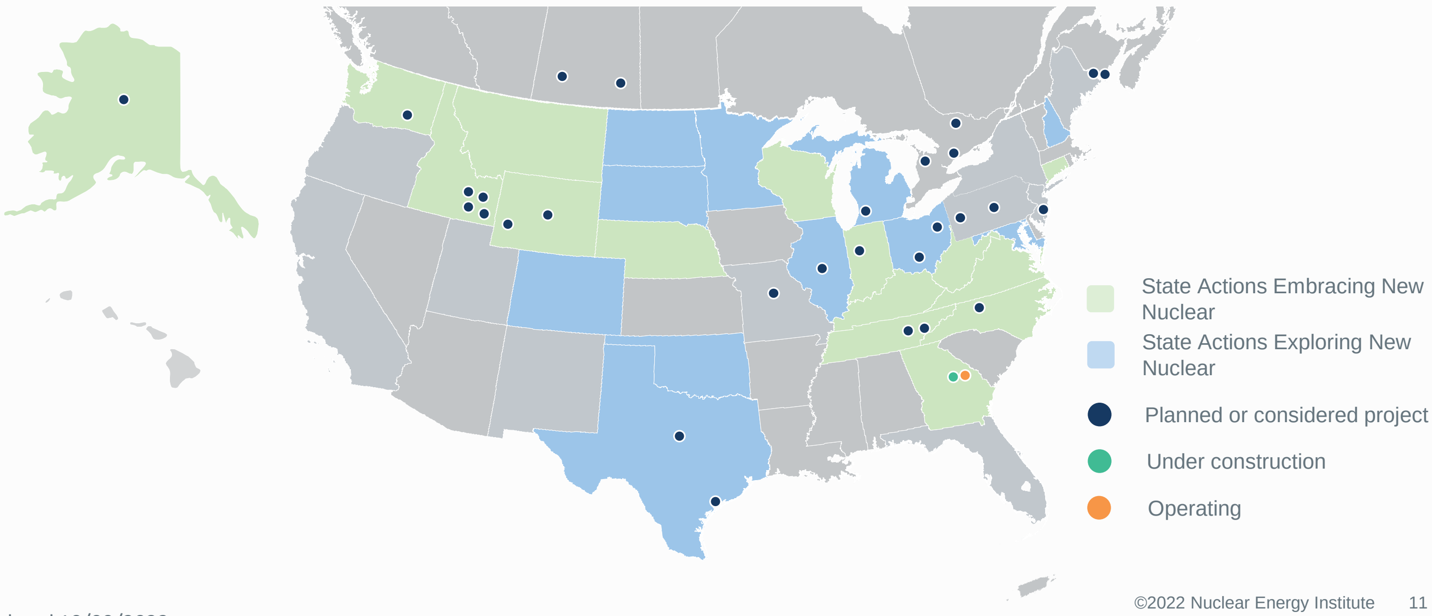
Molten Salt Reactors

Terrestrial (shown)
Several in development

Non-Water Cooled
Most <300MW, some as large as 1,000 MW

Advanced Nuclear Deployment Plans

Projects in planning or under consideration in U.S. and Canada for Operation ~2030



Updated 10/09/2023

Advanced Manufacturing Technologies (AMT)

APPLICATIONS FOR BOTH THE CURRENT FLEET AND ADVANCED REACTOR DESIGNS

Cost
- Less labor; automated
- Less material; less waste

Schedule
- Reduced lead times; some up to 90%

Quality
- Excellent inspectibility
- Excellent material properties
- Homogenous

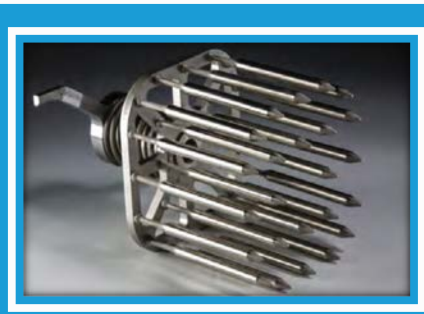
AMT Good Candidate For:

✓ Long lead time components
✓ High value components
✓ Complex geometries
✓ Obsolete parts
✓ Mitigation work
✓ High T environments
✓ Reduced weight
✓ Localizing the supply chain
✓ True “Nth-of-a-kind”
✓ And more…

First of a Kind (FOAK) Deployments – Fuel Assembly Components

2020

2021

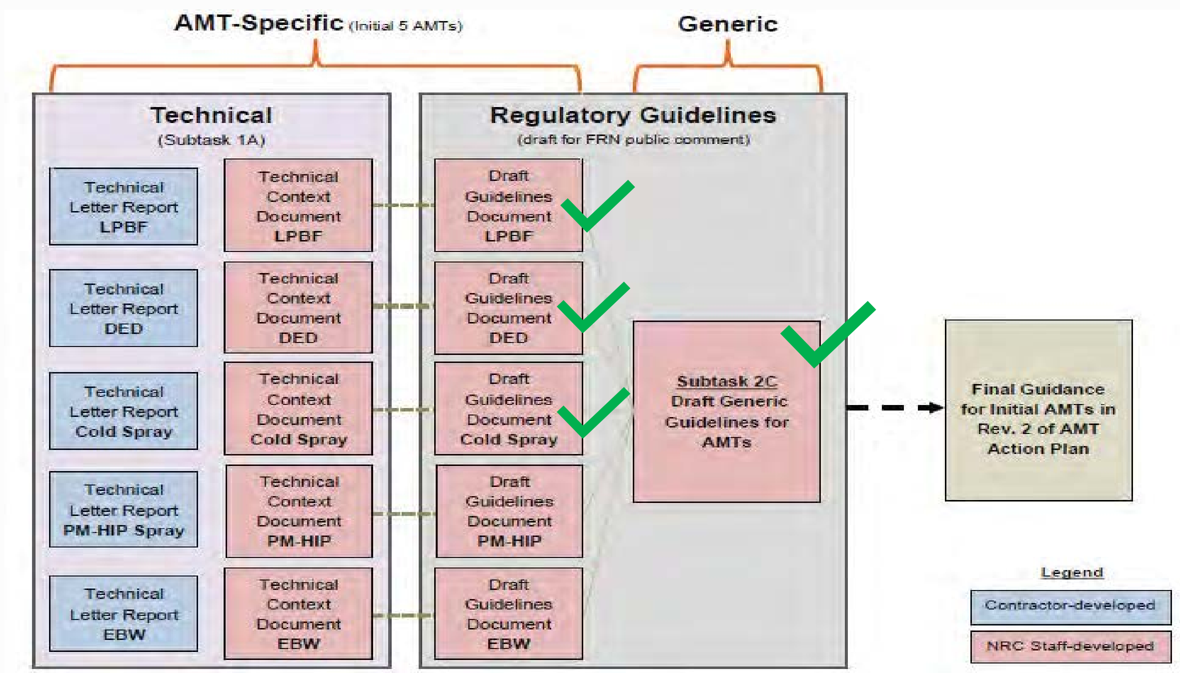


Courtesy: Westinghouse

Courtesy: Framatome

Courtesy: ORNL

NRC's AMT Action Plan (Revised June 2020)



NRC's AMT Landing Page: https://www.nrc.gov/reactors/power/amts.html

General Sentiments from NEI's Advanced Manufacturing Task Force-

Areas of Opportunity:

- *Need a more coordinated campaign (with funding) similar to Accident Tolerant Fuels (ATF) to jumpstart deployments*
- *Code acceptance is taking too long; uncertainty in qualifying new alloys of interest*
- *R&D still needed (i.e. radiation testing, etc)*
- *Interest in regulatory lessons learned and experiences*

General Sentiments from NEI's Advanced Manufacturing Task Force-

- *Strong industry management and customer support for pursuing AMT development and deployments in the near term (next 1-2 years)*
- *AMT work continues in fuel assembly component space, building upon previous successes*
- *Suppliers are ready for orders*

Thank You

hml@nei.org

Advancements in Electron Beam Welding for Heavy Section Components

David W. Gandy
Principal Technical Executive, Nuclear Materials
davgandy@epri.com

Marc Albert
Principal Technical Leader
malbert@epri.com

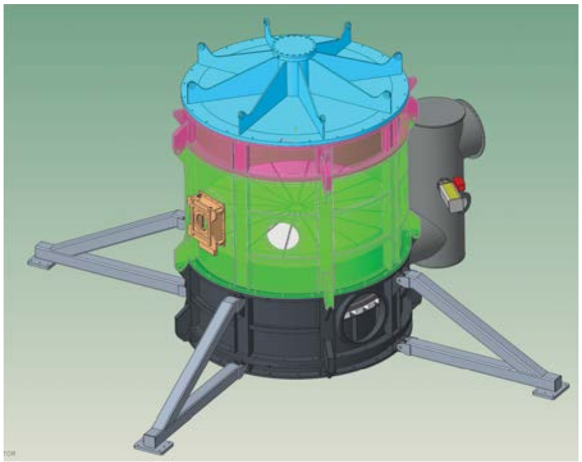
October 24-26, 2023

NRC WORKSHOP ON ADVANCED MANUFACTURING TECHNOLOGIES FOR NUCLEAR APPLICATIONS

www.epri.com

Presentation Outline

- Background & Objectives
- Modular In-Chamber EBW (MIC-EBW) Concept
- Phase 1 Equipment & Design Review
- Phase 2 Demonstrator Installation
  - Rotary Table
  - Primary Modules
  - Chimney & Platform
- What's Next?
  - Finalize Installations
  - Equipment Testing
  - Welding Demonstration
  - Benchmarking
  - Nondestructive Examination Development
- Summary

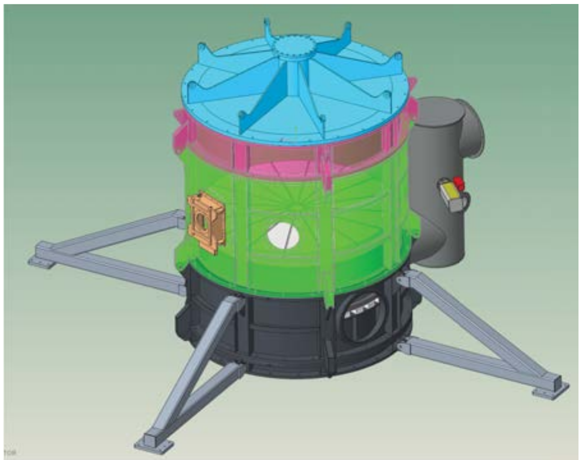


Three Different EBW Vacuum Approaches Considered

Three Options Considered

1. Build a **very long fixed chamber – 40+ ft**
   - Fixes one's options and requires higher pumping capabilities
   - Locks one in to "one size" for future
   - May prove cost prohibitive for SMRs and ARs due to vessel heights
2. Use **local vacuum** (reduced pressure?)
   - In development over 2 decades.
   - May include sliding vacuum
   - Limited use to date.
3. **Modular approach**
   - Many of the welds only require short assemblies
   - Provides options for future/alternative applications
   - Scalable

Modular In-Chamber EBW Approach
--Demonstrator and Full Height EBW System



Demonstrator

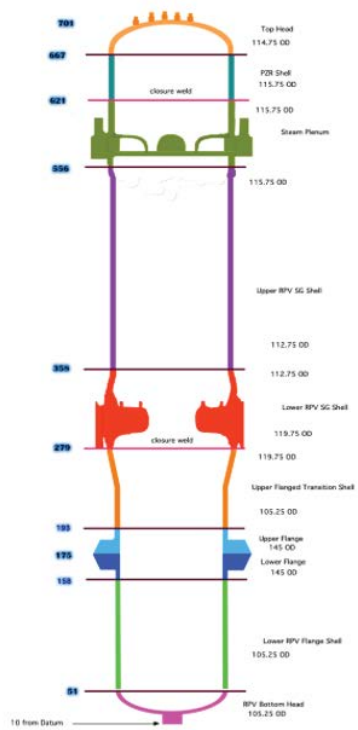
<u>Drawings for MIC-EBW System</u>

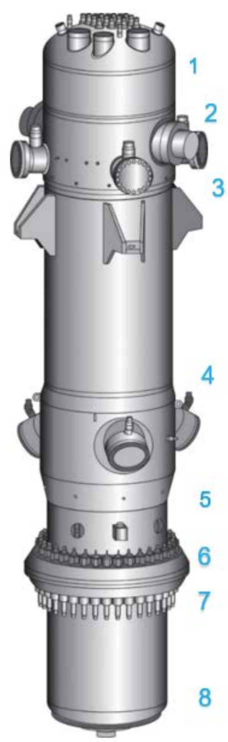
- 404371 -Base Module
- 404580 -Vessel Section Module—30-inch
- 404662 -Lid
- 406359 -Vessel Section Module—EB Gun
- 406456 -Base Arrangement – Outriggers
- 406460 -Pump Connection Section Module
- 406627 -Demonstrator Overview
- 40”, 48”, 60” modules (not produced in DOE Project)

8 Major Girth Welds Required for NuScale Power Reactor

~10 ft in diameter

Note: The MIC-EBW System is being demonstrated on NuScale Power design, but is applicable to many other systems (pressurizers, steam generators, vessels, large valves, etc.





~65 ft (19.8m) in height

Introduction/Background

- Considerable research has occurred over the past few decades in the area of "heavy section" EB welding:
  - ***TWI*** – Reduced Pressure, Local Vacuum & In-Chamber EBW
  - ***SFEL/Innovate UK*** – Local Vacuum EBW
  - ***Rolls-Royce***—Local Vacuum EBW
  - ***BEIS/SFEL/CVE/TWI/NAMRC/Arc Energy*** – Local Vacuum EBW
  - ***DOE/EPRI/NAMRC/NuScale*** – SMR Manufacturing & Repair (In-Chamber EBW)
  - ***DOE/EPRI/NuScale/Doosan/BWXT/AMRC*** – Modular In-Chamber EBW – Current Project
- Only recently has "heavy section" EBW been consistently demonstrated. Most of R&D performed in the UK.

Technologies include:
- In-chamber and local vacuum welding applications
- High kV and low kV EBW applications
- Triode and diode EB gun applications

Primary Question:
How Do We Bring This Technology/ Know-How to the USA for SMR & AR Manufacturing and Fabrication??

MIC-EBW Project Objectives

DOE Projects
DE-NE0008846
DE-NE0009039

- Develop and establish MIC-EBW capability at a major U.S. fabricator
- Reduce overall welding arc time by up to 90% compared to conventional welding technologies used for vessel production.
- Successfully demonstrate a 10-ft (3.05-m) diameter, 4.375-inch (110-mm) thick vessel EB weld in less than 90 minutes of welding time.
- Establish MIC-EBW capability to perform major RPV girth welds for the NuScale Power RPV.
- Develop manufacturing process plans based on the technology and required post-weld inspection/heat treatment.

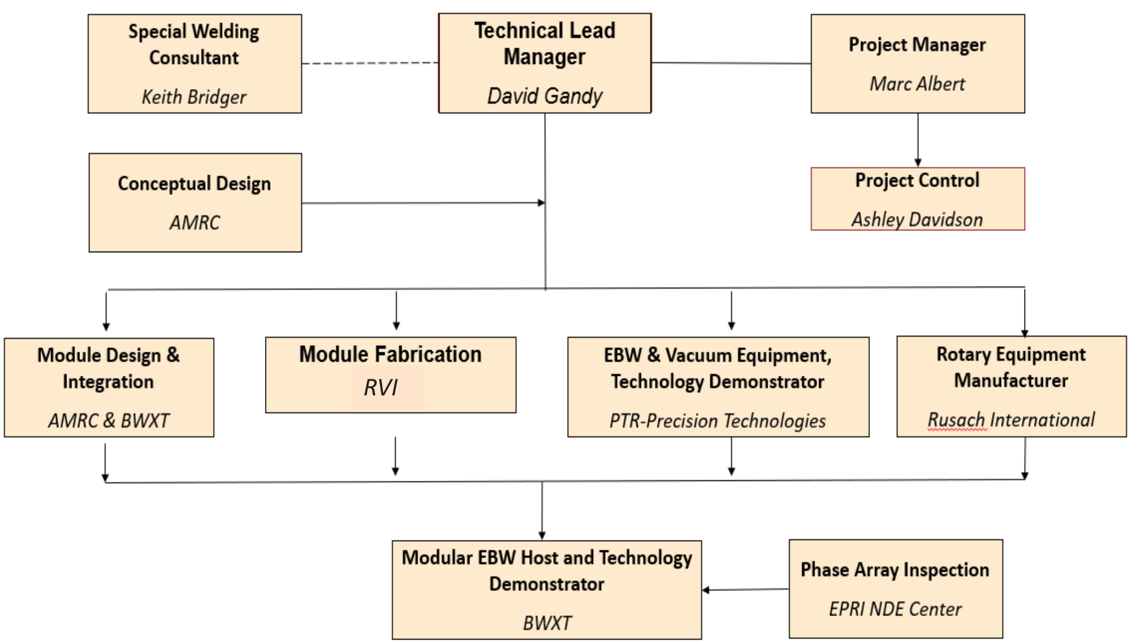
Modular In-Chamber Electron Beam Welding (MIC-EBW)—Project Overview

- Project initiated in Oct 2017 (Phase 1 – completed, **DE-NE 0008846**).
  - Assembled vacuum pumps and EB generator
  - Designed MIC-EBW system and generated all drawings
  - Performed some early-stage welds using EB generator

- Phase 2 – Initiated in August 2021 (**DE-NE 0009039**)
  - Delayed due to rotary table damage during shipment
  - Currently being installed at BWXT-Barberton OH.
  - Anticipated new completion: Q3-2024

Team Members and Responsibilities

DOE Project
DE-NE0009039



Phase 1 – Highlights
Includes: Equipment & Design Completion

Design/Manufacture Vacuum Pumping Stages of EBW System (PTR lead)

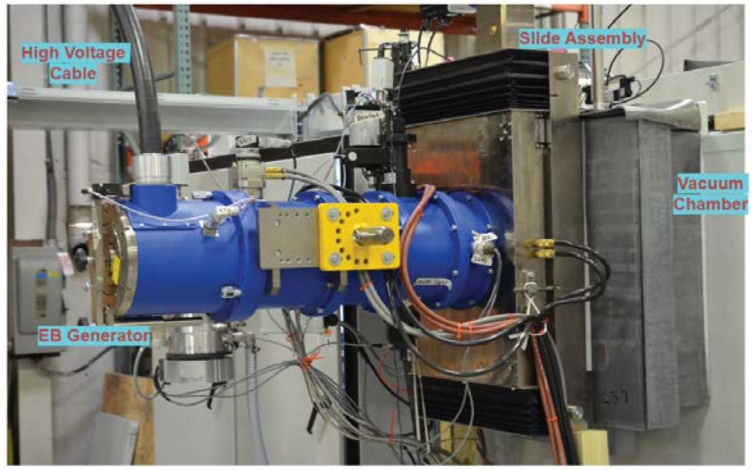
Vacuum Pumping System

- Pumps and Blowers
- Cryo-pumping System
- Vacuum Ductwork
- Chimney
- Diffusion pumps
- Note: Expected pump-down for full height system is **2-3 hours**

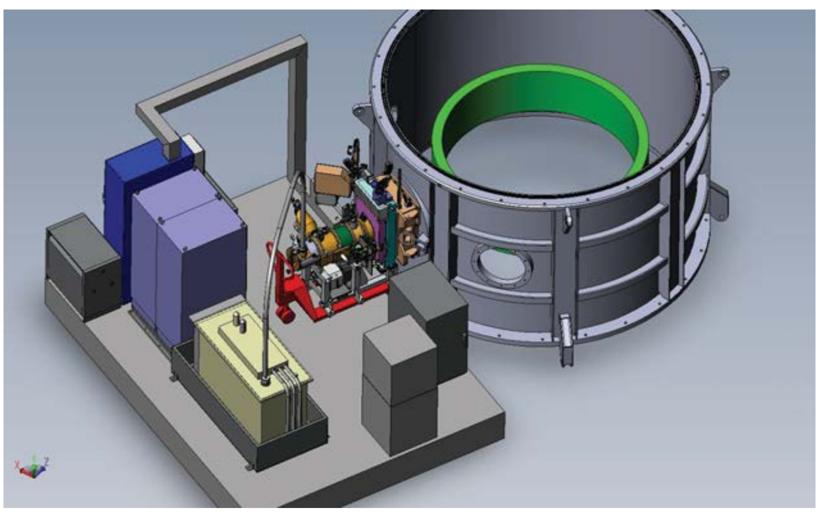
Vacuum Equipment set up at PTR

Assembly of the EB welding equipment for the MIC-EBW system

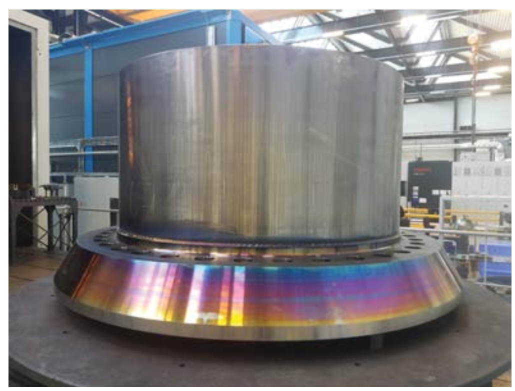
Elements of the EBW equipment set up at PTR



Electron Beam Generator (Gun) set up at PTR



MIC-EBW Platform Equipment Concept Overview



Lower Flange Shell Mockup EB Weld -- ~6 ft (1.82m) diameter (Note, mockup is upside down)

Completed in 47 minutes

Phase 2 – In-Progress

Phase 2. Full-Scale Modular In-Chamber EB Welding Demonstration

5. Design/Manufacture/Installation of the Rotary Manipulation Stage (**Rusach**) – **90% complete**
6. Produce Modular Ring Sections and Fabricate Modular Vacuum Sections for SMR Welding/Joining (**RVI**) – **100% complete**
7. Demonstrate Modular EB Welding Capabilities for Large Scale—10 feet (3.05m) Diameter Shells (**BWXT/PTR**) -- **0% complete**
8. Benchmarking & Technology Transfer (**AMRC**) – **10% complete**
9. Develop/Demonstrate NDE of Final Welds (**EPRI NDE**) -- **5% complete**
10. Facility Readiness & Support (**BWXT**) – **60% complete**

Milestone 5 – Design/Manufacture/Installation of the Rotary Manipulation Stage

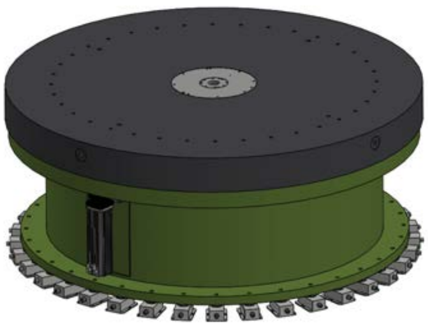
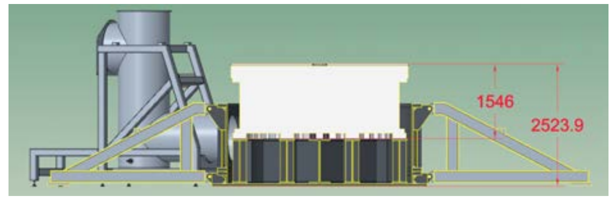


Table Platen



Rotary Table (shown in white) is 12ft in diameter and sets on the base assembly

Rotary Table Base and Table Platen Assembled

Milestone 6 – Produce Modular Ring Sections and Fabricate Modular Vacuum Sections for SMR Welding/Joining (RVI)

--Status: Completed & Set in Place at BWXT

Base Assembly & Support

- ~12ft in diameter
- Capable of supporting 150 tons
- Carbon steel
- Supports rotary table & RPV welding
- High tolerances required

Base Module -- Completed

Base Module: shown upside down after coating

Vacuum Module

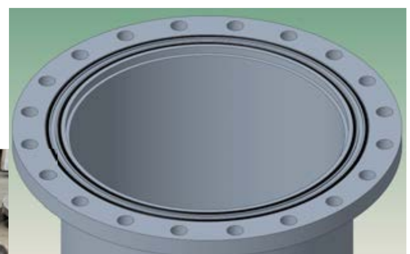
- Module fabrication is completed.
- Has been Coated and to BWXT site.

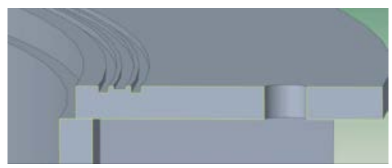
Base Module

Alignment Features

Penetrations for Electrical Wiring

Modules -- Progress





30-inch Module

- Complete
- Has been coated and delivered to site.

Upper Lid

- Complete
- Has been coated and delivered to site.

EB Module – Coated and delivered to site

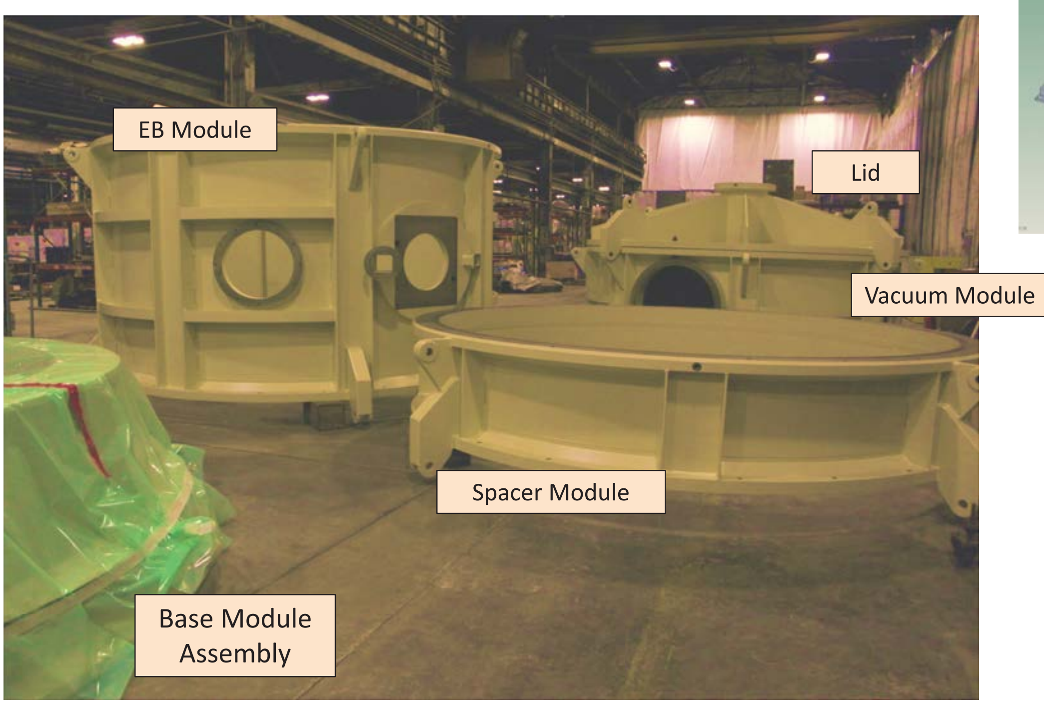
Vacuum Testing

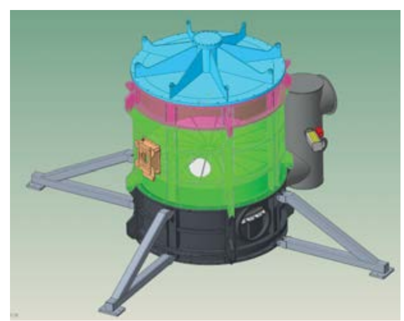
Chimney and Platform

Chimney connecting vacuum equipment to modules

Engineered platform to house EB Equipment at BWXT

Final Modules on Site at BWXT





All Modules for the Demonstrator have been completed.

Milestones 7-9 -- Next Q1-2024

7. Demonstrate Modular EB Welding Capabilities for Large Scale—10 feet (3.05m) Diameter Shells (BWXT/PTR)
   - Acquired 10ft rings for welding
   - Performed several 4ft diameter welds with system

8. Benchmarking & Technology Transfer (AMRC)
   - Limited discussions thus far

9. Develop/Demonstrate NDE of Final Welds (EPRI NDE)
   - Evaluated two 4ft diameter x 4.5inch thick welds to date

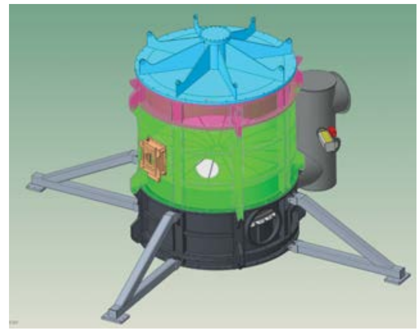
10. Facility Readiness Concrete Pad Excavation & Re-Pour

- Facility design/retrofit layout finalized in Barberton (by BWXT).
- Concrete rework completed.
- Electrical and water connections completed.

What's Next?

- Complete installation/leveling of rotary table.
- Install vacuum pumps & electrical equipment
- Install platform

Base Plate Assembly In-Place and Ready for Rotary Table



Progress

Many **hurdles addressed** to date:

- Penetration of electric cables into vacuum system
- Sensing potential vacuum leaks
- EB generator coupling and disconnection via gun slide assembly
- Impingement bar & shielding to absorb x-rays
- Parallelism of base assembly and machining
- Design of platform (removes personal from welding area)
- Viewing of electron beam via secondary viewing system
- System speed – extremely slow for welding
- Outriggers for stability
- **Rotary table delays--continuing**

Schedule Discussion—A few key dates

2022 Major Milestones

- Building Modifications & Site Prep – Oct 3
- Install Base Assembly – Nov 1 (revised to late November)
- Install/Test Rotary Table -- (revised to mid-May 2023)

- **Rotary Table Delays have moved schedule back ~24 weeks.**

2023 Milestones (Revised)

- Install Remaining Vacuum Equipment – Dec 31
- Install Power Supply & Control Panels – Q1-2024
- Install EB Gun Module – Q1-2024

2023 Testing (Revised – Q2-2024)

- Vacuum System Testing
- Radiation Testing
- EB Generator Tests
- Final MIC-EBW System Tests
- Training of BWXT Staff

Schedule Discussion—A few key dates

WELDING Demonstrations

2024 Milestones Continued

- Perform 1st and 2nd full diameter welds –
  Perform 3rd and 4th full diameter welds –

2024 Milestones (Revised)

- Perform 5th and 6th full diameter welds
- Perform 7th and 8th full diameter welds
- All Welding and Testing Complete
- **Project Complete** – ~Sept 2024

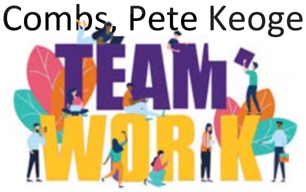
Summary

- MIC-EBW system is a "FOAK modular" vacuum chamber and electron beam welding system in USA.
- Modular design allows manufacturer to perform welds at multiple heights.
- **Provides USA with major capability for manufacturing**.
- Design is flexible
  - Can be used for RPVs, pressurizers, steam generators, or other.
- Coupled with PM-HIP (or other), the MIC-EBW system will re-establish the USA as a **major player in manufacturing of nuclear components.**

Acknowledgements – The TEAM!!!

- **DOE** -- Dirk Cairns-Gallimore
- **Advanced Manufacturing Research Centre (UK)** – Billy Redpath, James Coupe, Merv Alfred
- **Bridger Welding Engineering**—Keith Bridger
- **BWXT**—Pete Goumas, Ben Smeiles, Nick Hillard, Jason Miller
- **EPRI NDE Center**—Brett Flesner, William Ratcliff
- **EPRI**—David Gandy, Marc Albert, Greg Frederick, Randy Stark, Kurt Edsinger, Craig Stover
- **PTR-Precision Technologies** – David Tremble, Dan Fein, Derek Meyers, Al Green, Wilfried Klein, Justin Snowden
- **Rusach International**—Jeff Hatfield, Kevin McIntosh
- **RVI-Industries**—Bob Combs, Pete Keogel, James Littlewood

~30 people to date….



Joint Industry Project (JIP) – EPRI Led

Project Objective: Facilitate the deployment of EBW for joining heavy section components.

- **Why NOW?**
  - EBW can save >80% of welding time over conventional arc welding approaches when welding thick components. Also, no filler metal (no embrittlement issues).
  - Just beginning significant phase of manufacturing/construction (SMRs and ARs)
  - Significant research has shown the technology is ready for deployment, but we need to address a few remaining topics (next page) to fully realize the potential of EB welding.

Work Packages & Project Team

- WP1: ASME Submittal for EBW without Preheating (CVE/SFEL)
- WP2: Transferring Slope-out Welding Techniques (NAMRC)
- WP3: Development/Demonstration of Repair Techniques (CVE)
- WP4: NDT & Destructive Testing/Validation (SFEL)
- WP5: Magnetism, Cleaning and Surface Finish (TWI)

CVE CAMBRIDGE VACUUM ENGINEERING
NUCLEAR AMRC
TWI
SHEFFIELD FORGEMASTERS
EPRI

Project Sponsors to Date

DOOSAN

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NAVAL NUCLEAR LABORATORY

KHNP KOREA HYDRO & NUCLEAR POWER CO., LTD

IHI

Rolls-Royce

CVE CAMBRIDGE VACUUM ENGINEERING

NUCLEAR AMRC

TWI

SHEFFIELD FORGEMASTERS

EPRI

Second Technical Exchange Meeting on NDE of AMM Components for the Nuclear Industry

- EPRI will host a two-day in-person meeting at EPRI Charlotte campus on NDE of AMM Components
  - This exchange meeting will address contemporary issues to inform EPRI research directives by insight from the industry and researchers
  - We are looking for presenters who would be willing to share recent experience in NDE of AM components for the nuclear industry
- **Dates: 23-24 April 2024**
- **Location:** EPRI Charlotte, 1300 West W. T. Harris Blvd, Charlotte NC 28262
- **EPRI Contact:** George Connolly gconnolly@epri.com
- **Registration Link:** [*Coming soon*]

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Overview of Framatome's Activities Supporting Additive Manufacturing of Nuclear Fuel Components

Chris Wiltz
Contributors: D. Bardel, S. Cachat and K. Sohn

2023 Workshop on Advanced Manufacturing Technologies (ATM) for Nuclear Applications

October 24 - 26, 2023

Contains Framatome Know-How
Export Control – AL: N / ECCN: N

Framatome's Additive Manufacturing Focus for Fuel and Other Components

Objective :
- Enhancing Performance
- Reducing Manufacturing Costs
- Speeding up Market Readiness

Value Adders of Additive Manufacturing
- Design Optimization
- Functional Additions
- Enhanced Repair Scenarios
- Fast Prototyping

Engaging a Global Development Approach
- Design Skills
- Materials Characterization
- Study of Defects and Adequate Non-Destructive Examination (NDE)
- Qualification Approaches

Current Applications
- Manufacturing Tooling and Gauging
- Component Prototyping, Development and Testing
- Lead Fuel Test Components

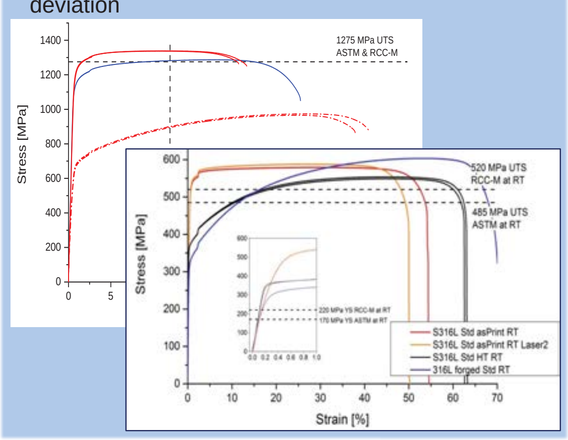
Additive Manufacturing Applied Material Evaluation – 316L SS and Inconel 718

Support of Licensing Approval for Additive Manufactured Component Applications
- In and Out of Pile Material Evaluation
- Test segments manufactured using Selective Laser Melting

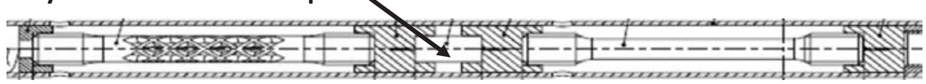
Standard Segment

Universal Segment

Out of Pile Testing - Mechanical properties at the level of forged standards and no corrosion deviation



Cylindrical Control Sample



In Pile Testing - Gösgen Nuclear Power Plant (PWR)
- In Pile irradiation accomplished using Material Test Rods (MTRs), with multiple axially arranged segments arranged in multiple MTRs
  - Initiated in 2019 and planned for up to 5 cycles of irradiation
  - Samples subjected to coolant and neutron flux
- Sample removal accomplished after 1 and 3 cycles of operation
  - Hot cell examinations progressing
- Information to be collected to evaluate:
- Evolution of material mechanical and microstructural properties due to irradiation
- Corrosion kinetics
- Additive manufacturing effects (i.e., build direction, roughness, …)

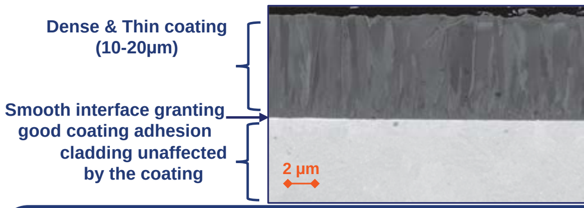
Additive Manufacturing for Fuel Rod Coating – PROtect EATF Fuel Rod Cladding

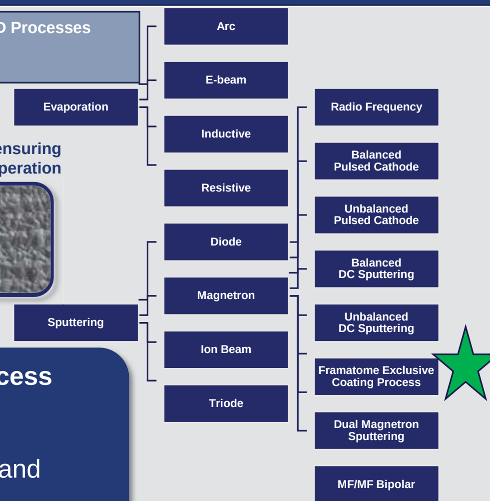
PROtect → Chromium-Coated M5$_{Framatome}$ Cladding

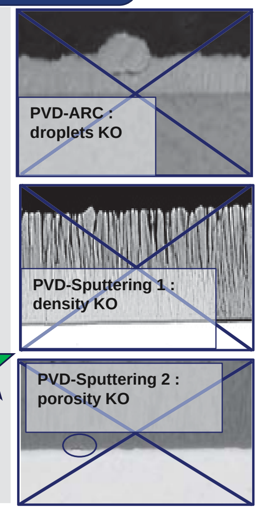
With Collaborative Support from Gösgen-Däniken AG, CEA, I3P, US DOE and BPI

Mastering the coating process, with a large variety of coating processes tested, necessary before selecting a process

- Physical Vapor Deposition
- High Performance Magnetron Sputtering Process







Over the last 10 years, **Framatome exclusive coating process performance** has been :
- **Demonstrated out of pile** in lab,
- **Confirmed in pile (Lead Fuel Rod Program since 2019)** and
- **Continuously optimized** for EATF application

Direct Nuclear Fuel Assembly Component Application – BWR Channel Fastener

Collaboration with Oak Ridge National Laboratory and TVA as Part of the Transformation Challenge Reactor (TCR) Program

Gain experience, demonstrate competency and introduce in reactor nuclear fuel assembly components produced using additive manufacturing

- Direct Metal Laser Melting Manufacturing Process – Directed Energy Deposition (ORNL)
- 316L Stainless Steel

Full Scope of Basic Product Development and Implementation Activities Accomplished

- Design modification
- Product specifications
- Additive manufacturing process/configuration control and optimization for product manufacturability
- Product qualification and quality control
- Licensing and commercial operation validation of a safety related component in reactor

Four Channel Fasteners Delivered - Browns Ferry, Unit 2 Nuclear Power Plant

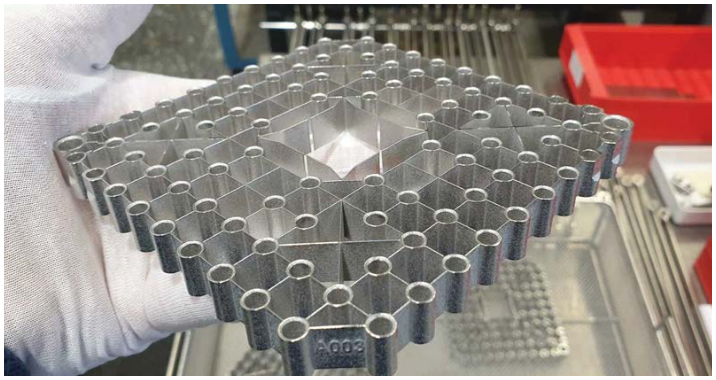
- Inserted in Spring of 2021
- Planned for up to 3 cycles of irradiation
- Post-Irradiation examinations planned in 2025 (visual) and 2027 (detailed)

Direct Nuclear Fuel Assembly Component Application – BWR Upper Tie Plate Grid

Framatome Product Design and Manufacturing Optimization and Using a Industrial/Commercial Additive Manufacturing Company (KSB)

Demonstrate Framatome's ability to bring customer value using additive manufacturing and gaining experience (Framatome and customer) with design, industrial manufacturing and irradiation behavior

- Laser Powder Bed Melting Manufacturing Process
- 316L Stainless Steel



Using Advantage of Industrial Additive Manufacturing for Product Optimization

- Innovative design for enhanced debris filtering
- Opportunity to consolidate supply chain
- Gain experience for methodology control and additive manufacturing experience

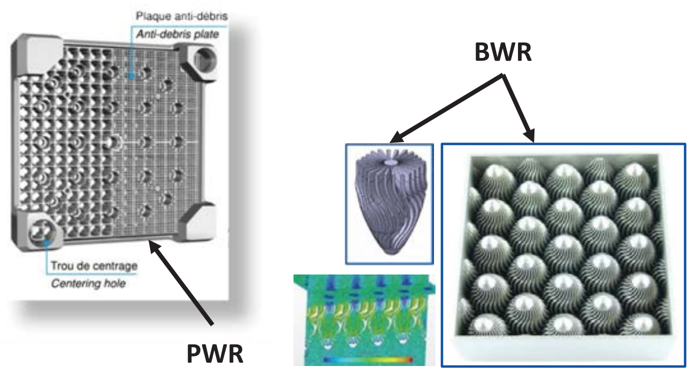
Components Delivered and Operating in Reactor - Forsmark, Unit 3 Nuclear Power Plant

- Inserted in 2022
- Planned for 4 or 5 cycles of irradiation
- Post-Irradiation examinations planned in 2027

Nuclear Fuel Assembly Component Development Activities - Examples

Debris Filters and Flow Conditioning Components

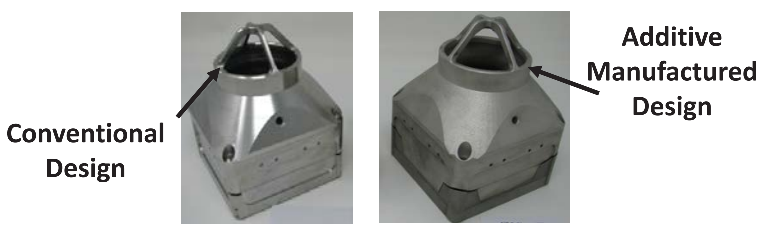
Product Performance Improvement via Available Design and Manufacturing Flexibility – Debris Filtering & Flow Conditioning



Larger Components and Assemblies (Collaboration with NovaTech)

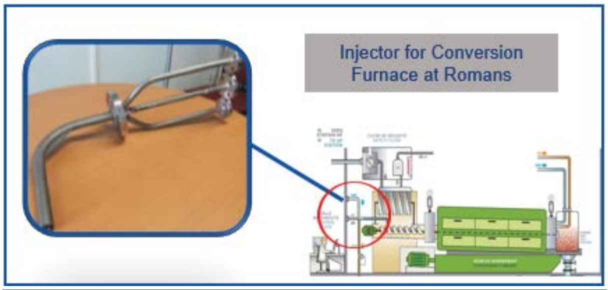
ATRIUM 11 Lower Tie Plate Assembly

- Minimized supports during additive manufacturing build process
- Reduction in number of assembly components for fewer processes and fit-ups
- Minimal geometric differences to avoid product re-qualification
- Minimized post additive manufacturing build processes
    - Heat treatment for residual stress removal
    - Wire EDM process used to remove component for build plate
    - Final machining to precise fit-up feature geometry



Non-Fuel Assembly Additive Manufacturing Applications at Framatome - Examples

Additive Manufacturing is Currently Used for "Day to Day" Applications Within Framatome



Questions, Comments and/or Observations

Acknowledgements

- The authors would especially like to thank Kernkraftwerk Gösgen-Däniken AG for their collaboration in the irradiation of E-ATF samples in the Gösgen reactor as well as their characterizations
- The authors would like to thank the CEA for contributing to the development of the full-length tubes coating process.
- The authors would like to mention also that part of the in-pile and out of pile characterizations of Cr-coated cladding is performed in the frame of the I3P collaboration (Framatome, CEA and EDF).
- This work is supported by the U.S. Department of Energy under Award Number DE-NE0009034 (and previously DE-NE0008818 and DE-NE0008220) with Framatome Inc.
- This work is supported by the BPI France under the contract DOS0151318 with Framatome

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Thank you

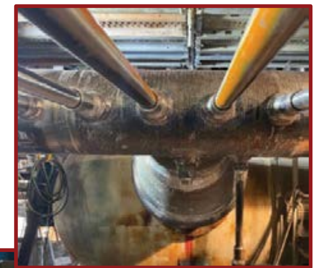
DED – Wire (*aka Welding*) Use Case Update NRC Workshop

Teresa Melfi

October 2023

Alternative to Castings and Forgings

Faster Delivery



Nuclear Reactor Door Hinges
CVN-80 *Enterprise*
100ksi steel
3D Printing < 2 weeks
HY-80 castings—several months

Gulf Coast Refinery
Nickel 617—8 parts
Qualification + 3D Printing < 30 days
Nickel 800H castings—several months

LINCOLN ELECTRIC | Additive Solutions

What's in a Name: Additive Manufacturing or Welding?

Additive Manufacturing (Drama)

- 3D printing, DED, WAAM
- Parts are "builds"
- Uses "feedstock"
- "Black Box" machine
- Non-portable procedures
- Parameters still not well known
- Often not fully dense
- NDT techniques not well established
- Properties often not well understood

Welding (Boring)

- GMAW, GTAW, EBW, LW
- Parts are "weld metal"
- Uses welding electrodes
- Welding systems
- Portable procedures
- Established "variables"
- Fully dense weld metals
- NDT techniques well known
- Material properties well known

Use Case – Weld Metal (DED-Wire) Additive
*High Temperature, Pressure Retaining Refinery Application**

* Full presentations available upon request

Robert Rettew, Chevron
Teresa Melfi, Lincoln Electric
Ben Schaeffer, Lincoln Electric
Matt Sanders, Stress Engineering

A Refinery 3D Printing Success Story

- In early 2022, a facility turnaround needed replacements for several components in hydrogen furnace service. These components were critical path to restart the facility.
- Service requirements were 1500F and 300psi, with a design lifetime of 20 years.
- Application was for a furnace header. Previous installation was Alloy 800H with Alloy 617 weldments.
- Existing components were damaged and unusable. Replacement using traditional methods estimated ~3 months.
- 3D printing was used to deliver replacements in just under 4 weeks, **avoiding a significant shutdown.**

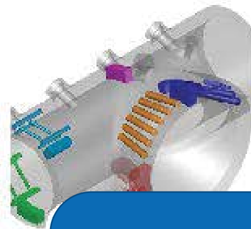
Piping components being printed at Lincoln Electric Additive Services

(left) Digital part verification, (right) Final Installation

Workflow of an Urgent WAAM Job

THE NEED
-Four tees and transitions
-Alloy 800H @ 1100 lb each
-3 month minimum lead time for forgings
-No prior work with Lincoln Electric Additive

DESIGN/ ENGINEERING REVIEW
-Alloy 617 proposed
-Some design optimization
-FEA analysis (1500°, 300 psi)
-Quality Audit
-Gather 617 electrode



MATERIAL TESTING
-ASME IX QW-600 testing
-Witness specimen tests
-API 20S sacrificial part tests
-Creep testing
-See following slides

PART TESTING & INSTALLATION
-See following slide for testing
-Machine bevels
-Install (by welding!!)

Inspection & Testing Summary

- Testing Conducted on Each Piece
  - Dimensional Checks
  - 100% Dye Penetrant surface inspection
  - Phased Array UT of Critical Locations
- Testing Conducted on Witness Coupons
  - Hardness Survey
  - Metallographical Assessment
  - Tensile Testing in multiple orientations
  - Chemistry
- Additional Testing Conducted on First Article
  - Pressure Testing at 6,000psi
  - Tensile Tests at elevated temperature, from wall thickness at various critical locations
  - Local RT Inspection
  - Creep testing using samples from sacrificial part

Printed Components Testing

- Hydrotest (photo on right)
- Acoustic Emissions
- Phased Array Ultrasonics in critical areas, require special qualification
- Radiographic Inspection of 100% Volumetric
- Dye Penetrant 100% surface

Production Images

Timeframe Recap

- Week One
  - First Inquiry
  - Meetings & Printability Assessment with Lincoln Electric
  - Determined code case and API guidance
- Week Two
  - Risk Assessment, supported by review of Lincoln and Industry Data
  - Visit to Lincoln, review QA/QC and manufacturing
  - Initial Mechanical Results, Surface Roughness, and FEA model
- Week Three
  - Hydrotest, PAUT, and RT on test piece
  - Grinding & photography of surface indications
- Week Four
  - Delivery of subsequent parts for final machining, inspection, & installation

Qualification and Testing Outline

- Qualify the deposition procedure using test pieces -- bracketing essential variables and thickness per ASME Section IX
- Compare results to a corresponding material specification
- Build the part(s), first article (if required) and witness specimens
- Destructively test the witness specimen
- Destructively test first article, if required by the referencing standard
- Non-destructively test the printed parts, as required by the referencing standard

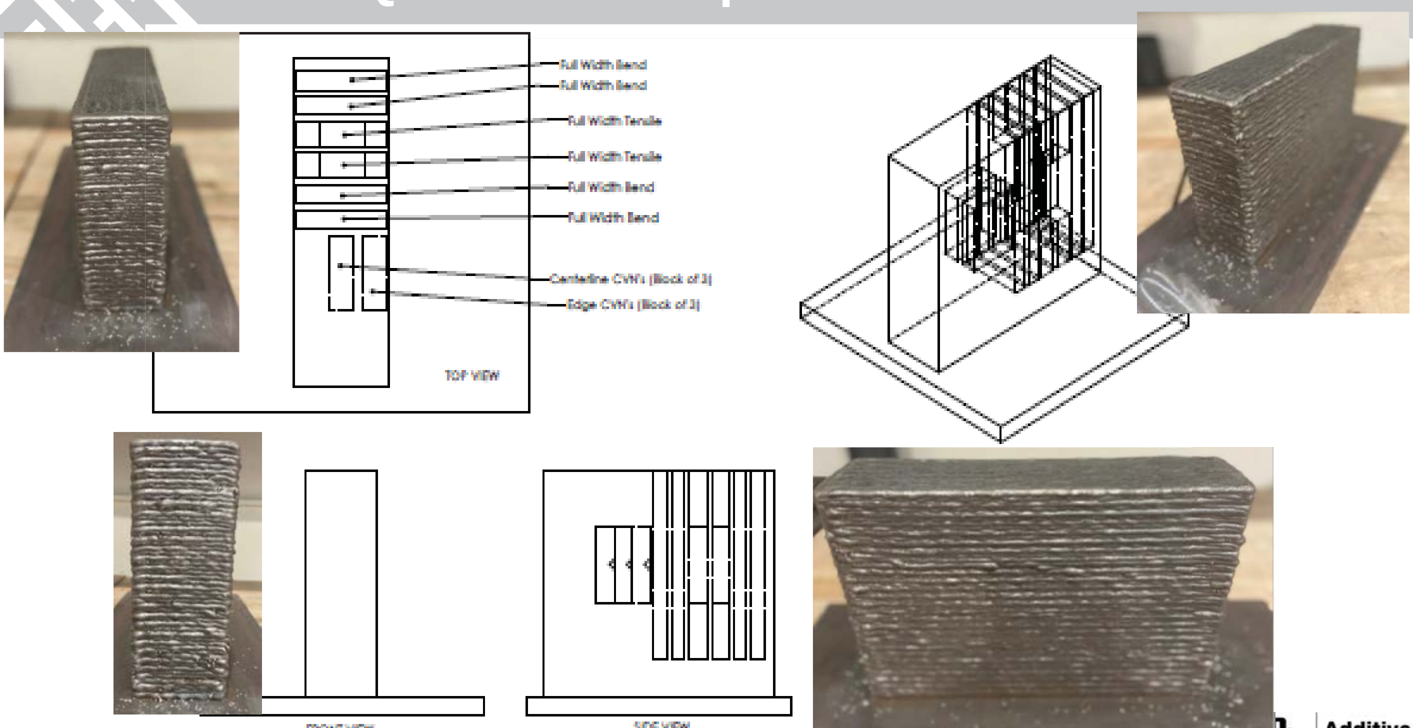
ASME IX QW-600 Bracketed Qualification

- Must test the highest cooling rate to be used in production.
- Must test the lowest cooling rate to be used in production.
- Must test the thinnest wall to be printed in production.
- Must test the thickest wall to be printed in production.

Codes require validation that all production printing stayed within these qualification bounds and also meet all other variables and rules of Section IX

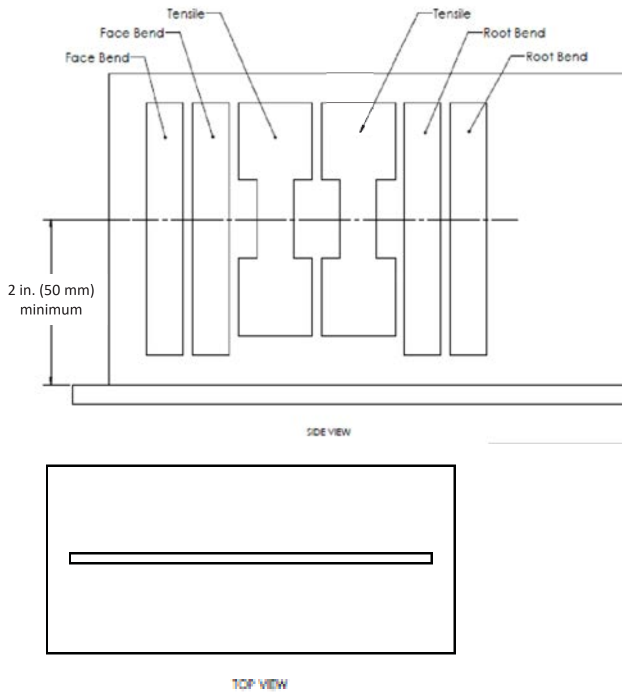
LINCOLN ELECTRIC Additive Solutions

Thick Qualification Specimen Removal



ELECTRIC Additive Solutions

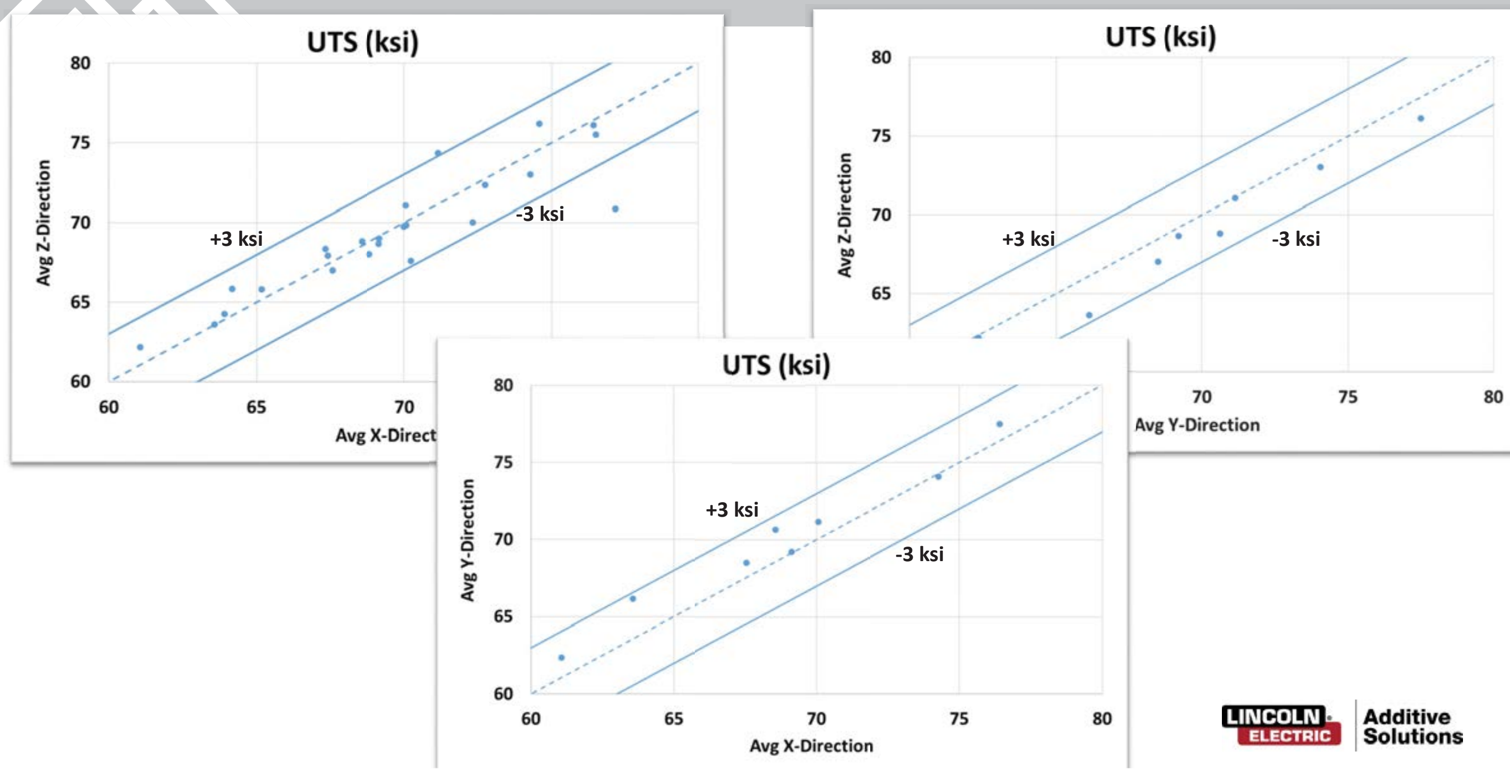
Thin Qualification Specimen Removal



ASME Research Project Execution

- Nearly **2 Tons** of weld metal deposited (**72 Walls, 15 Weeks**)
- **384 Tensile Specimens** machined and tested
- **544 CVN Specimens** machined and tested

Results: UTS vs. Sample Orientation



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Why Isotropy is Important

X-Y-Z Build Direction??

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Corresponding Material Specification

- Results must meet the requirements of a *corresponding material specification*
- A corresponding material specification is often an ASTM specification for a different product form, for example:
  - A516 gr 70 plate
  - A182 F316L forging
  - A217 WC9 casting

Sets up an "equivalence" approach for use in design and construction standards

Requires validation that all production printing stayed within the qualification bounds

LINCOLN ELECTRIC | Additive Solutions

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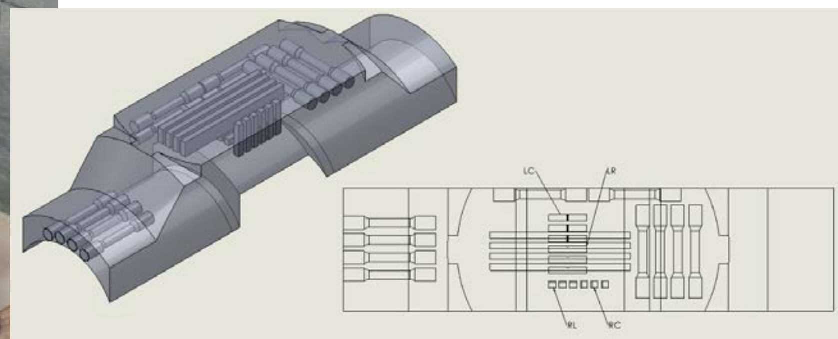
Does it work?

Replacement for 316L Valve Body

Project between Lincoln Electric & EPRI



ER316LSi Qualification

GMAAM PQR Data Summary (welding in accordance with ASME BPVC-IX & Code Case 3020)

Electrode (feedstock) classification is ER316LSi (per AWS A5.9)

Cooling Rate	Welding Transfer Mode	PWHT	# Beads	Layer Width	Wall Thickness	Yield Strength	Ultimate Strength	Elongation	ROA	Side Bends	CVN Toughness	Note
(type)	*(type)*		*(per Layer)*	*(in)*	*(type)*	*(ksi)*	*(ksi)*	*(%)*	*(%)*	*(Result)*	*(ft-lbs@-320F)*	
Slow *High Heat Input & High Interpass*	Spray	Solution Anneal (3 hrs @ 2050F)	1	0.6	Thin	30.6	70.0	68.0	74	Pass	85	
						30.3	68.0	72.0	67		79	
											92	
			9	3.1	Thick	31.9	79.0	72.0	55	Pass	79	
						32.6	79.0	57.0	42		79	
						31.6	79.0	74.0	66		115	
						33.2	79.5	72.0	54		83	
						31.5	78.0	70.0	62		84	
						30.8	78.0	72.0	62		83	
Fast *Low Heat Input & Low Interpass*	Spray	Solution Anneal (3 hrs @ 2050F)	1	< 0.3	Thin	32.8	71.5	44.0	64	Pass	12	1/4-Size CVNs
						32.5	71.0	47.0	67		14	
											11	
			21	2.1	Thick	31.4	72.0	30.0	32	Pass	63	
						31.6	80.5	56.0	33		71	
						32.0	77.0	38.0	44		78	
						31.6	80.5	61.0	44		78	
											69	
											68	

	Yield Strength	Ultimate Strength	Elongation	ROA
Min	30.3	68.0	30.0	32
Max	33.2	80.5	74.0	74
Average	31.7	75.9	59.5	55

Replacement for 316L Valve Body

ASME IX Qualification

	Yield Strength	Ultimate Strength	Elongation
	(ksi)	*(ksi)*	*(%)*
Min	30.3	68.0	30.0
Max	33.2	80.5	74.0
Average	31.7	75.9	59.5

316LSi Printed Valve Body

Table 5-8. Tensile Data at Room Temperature for K91W

Orientation	Sample ID	Temp. (°F)	Temp. (°C)	UTS (ksi)	UTS (MPa)	YS (ksi)	YS (MPa)	Elong. in 4D (%)
Build Direction, Thin Section	T16	70	21.1	80.2	553.0	31.3	215.8	67.8
	T17	70	21.1	80.2	553.0	32.3	222.7	66.8
	T18	70	21.1	80.2	553.0	31.6	217.9	67.6
	T19	70	21.1	80.1	552.3	32.1	221.3	68.1
Build Direction, Thick Section	T20	70	21.1	81	558.5	33	227.5	67.9
	T21	70	21.1	81.4	561.2	33	227.5	70
	T22	70	21.1	81.3	560.5	32.6	224.8	66.2
	T23	70	21.1	82.2	566.7	32.4	223.4	66.6
Transverse Direction	T24	70	21.1	82.2	566.7	35	241.3	60.8
	T25	70	21.1	34.9	240.6	28	193.1	7
	T26	70	21.1	78.4	540.5	32.8	226.1	38
	T27	70	21.1	82.2	566.7	33.4	230.3	63.4
Transverse, Retest	T28	70	21.1	80.2	553.0	32.9	226.8	58.4
	T29	70	21.1	80.3	553.6	32.9	226.8	56.4

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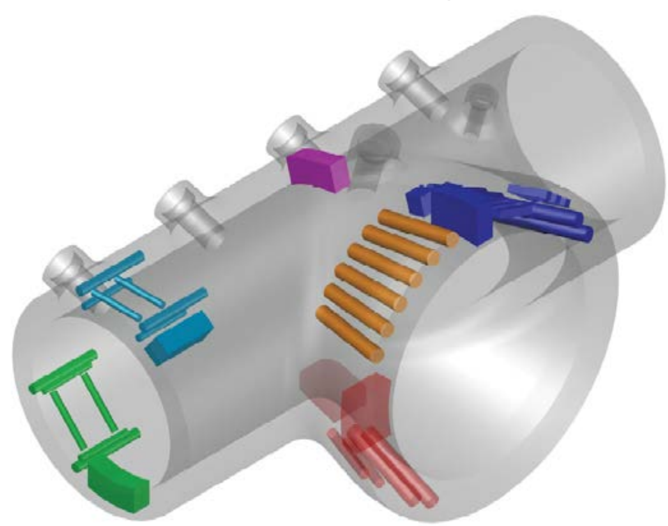
Replacement for 800HT Furnace Header

First Article Testing



LINCOLN ELECTRIC | Additive Solutions

ERNiCrCoMo-1 Qualification (Alloy 617)

GMAAM PQR Data Summary (welding in accordance with ASME BPVC-IX & Code Case 3020)

Electrode (feedstock) classification is ERNiCrCoMo-1 (per AWS A5.14)

Cooling Rate	Welding Transfer Mode	PWHT	# Beads	Layer Width	Wall Thickness	Yield Strength	Ultimate Strength	Elongation	ROA	Side Bends	CVN Toughness		Note
(type)	*(type)*		*(per Layer)*	*(in)*	*(type)*	*(ksi)*	*(ksi)*	*(%)*	*(%)*	*(Result)*	*(ft-lbs@-50F)*	*(ft-lbs@70F)*	
Slow *High Heat Input & High Interpass*	Spray	None	1	0.8	Thin	49.9	99.0	47.0	48	Pass	87		
						51.0	100.0	47.0	49		98		
											108		
			9	3.9	Thick	59.0	103.0	46.0	50	Pass		76	
						60.5	102.0	47.0	50			63	
						58.0	103.0	46.5	44			73	
						58.0	102.0	45.5	48			99	
						61.5	104.0	47.5	53			96	
						58.0	103.0	47.5	40			94	
Fast *Low Heat Input & Low Interpass*	Spray	None	1	< 0.3	Thin	57.0	96.5	50.0	55	Pass	17	17	1/4-Size CVNs
						56.0	96.5	54.0	64		20	17	
											15	22	
			9	2.2	Thick	63.5	107.0	56.0	42	Pass	94		
						63.5	98.0	33.0	35		97		
											124		
											122		
											120		
											126		

	Yield Strength	Ultimate Strength	Elongation	ROA
Min	49.9	96.5	33.0	35
Max	63.5	107.0	56.0	64
Average	58.0	101.2	47.3	48

Printed Replacement for 800HT

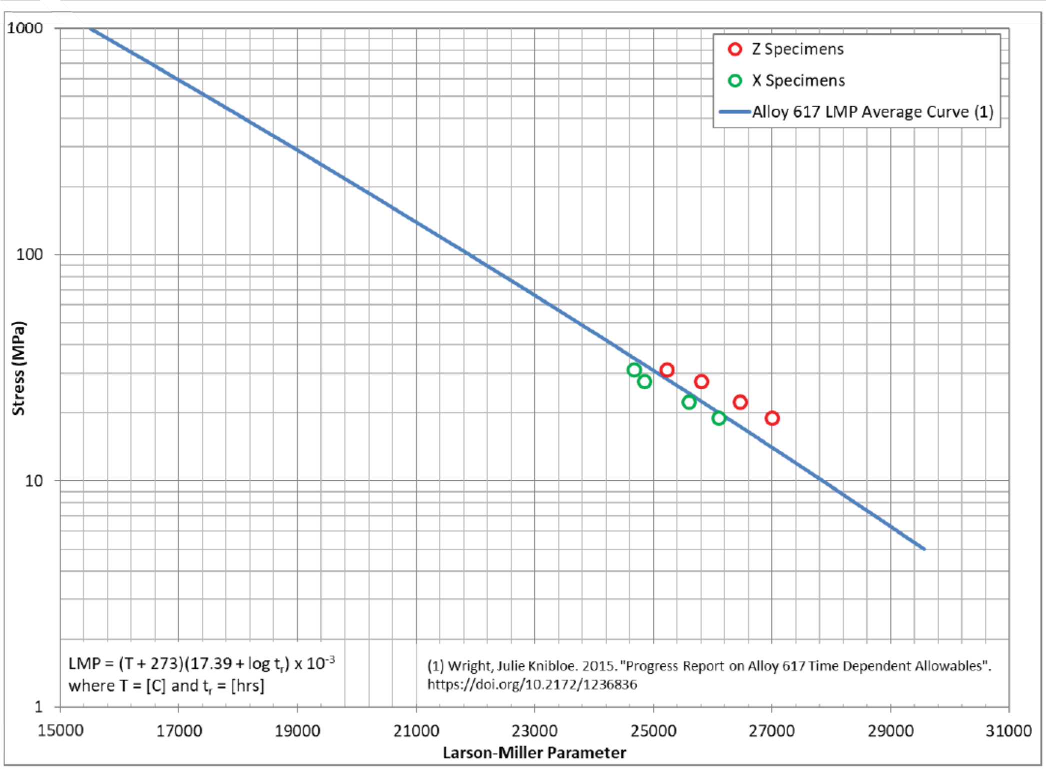
ASME IX Qualification

	Yield Strength (ksi)	Ultimate Strength (ksi)	Elongation (%)
Min	49.9	96.5	33.0
Max	63.5	107.0	56.0
Average	58.0	101.2	47.3

First Article Testing

Orientation	Location	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)
Longitudinal	ID	57.6	102.5	44.8
		55.4	99.9	40.1
Longitudinal	OD	65.5	108.7	40.4
		66.4	108.7	40.5
Transverse	Mid-wall	60.9	106.1	45.5
		59.0	102.7	34.9
Transverse	Mid-wall	63.0	107.0	39.9
		61.6	107.9	37.4
Longitudinal	ID	58.0	101.8	43.1
		58.3	102.2	44.9
	OD	64.3	109.4	42.1
		66.7	108.6	42.5
Longitudinal	Mid-wall	60.9	101.8	47.0
		60.4	102.4	48.6
Transverse		61.0	104.2	44.4
		61.5	104.7	43.7
Longitudinal	Mid-wall	60.6	101.1	46.5
		60.5	101.1	46.8
Transverse		61.4	103.5	40.3
		62.5	105.4	40.5

Creep Testing – Chevron 617 Parts

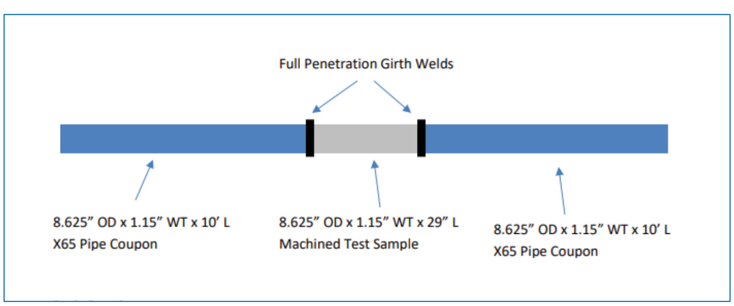


Application-based Fatigue Studies

- Georgia Tech - Ryan Sherman (USDOT FHWA)
- Printed blocks for material characterization
- Fatigue specimens printed
  - Testing as-printed and fully machined

Other Recent Fatigue Work

- U Mich – Pingsha Dong (USDOE)
- Stress Engineering – Offshore
- U of Toledo (VHCF / Eaton)
- Private industry



Is it new in pressure retaining applications?

- 1967 – Mitsubishi patented a method for construction of cylindrical and spherical pressure vessels entirely out of weld metal.
- 1976 - 64-ton pressure vessel 216 inches long, 71 inches in diameter and 8 inches thick manufactured from weld metal
- 1978 – 20 ton steel ring fabricated entirely from weld metal.
- 1980s – Shape welding in Germany
- 1980s – multiple companies produced large parts and buildups for repair of steam turbines
- 1980s – offshore oil and gas used weld metal “buildup” to increase the pressure ratings from 15,000 psi to 20,000 psi
- 1982 - 1993, approximately 450 steam turbine and 235 utility rotors were rebuilt using weld metal..Hartford has not reported a single failure of a rotor attributable to weld repair since the beginning of the program.

- For details see https://sperkoengineering.com/html/Additive.pdf

LINCOLN ELECTRIC | Additive Solutions

Is it new in nuclear applications?

- 1960 - Russians produce valve bodies using only weld metal. Used in nuclear facilities in USSR.
- 1998 -- German Nuclear Safety Standards Commission (KTA) allows use of products and components manufactured using “shape welding”.
- Shape welding used by Siemens for nozzle openings and flange surfaces
- 1970s – CB&I BWR weld metal buildup on bottom head of each reactor to avoid purchase of a forged ring with an integrally forged skirt extension.
- Westinghouse anti-rotation key lugs are produced today from weld metal, eliminating material availability issues, allowing more precision in location and are more easily they ultrasonically examined compared to the prior plates attached with groove welds.
- Inconel weld metal is used to replace bar attaching partition plate in steam generator, which simplifies fabrication and improve Ultrasonic inspection due to grain orientation in the Inconel bar stock.
- Handholds, inspection ports, flange surfaces, nozzle projections and manways produced from weld metal for pressurizers, steam generators and heater bundles
- B&W produced at least one large Inconel elbow entirely from weld metal because of the long lead times for forged high alloy elbows and safe ends. Also produced cylinders, cones, flanges elbows and dished heads by “shape melting” but unsure where or if they were put into service.

- For details see https://sperkoengineering.com/html/Additive.pdf

LINCOLN ELECTRIC | Additive Solutions

"Weld Metal Buildup" Code Cases

Accepted by the NRC in Regulatory Guide 1.147 with no added restrictions

- N-853 PWR Class 1 Primary Piping Alloy 600 Full Penetration Branch Connection Weld Metal
- Buildup for Material Susceptible to Primary Water Stress Corrosion Cracking
- N-740, Full Structural Dissimilar Metal Weld Overlay for Repair or Mitigation of Class 1, 2, and 3 Items.
- N-653, Full Structural Overlaid Wrought Austenitic Piping Welds
- N-661, Wall Thickness Restoration of Class 2 and 3 Carbon Steel Piping for Raw Water Service
- N-766, Nickel Alloy Reactor Coolant Inlay and Overlay for Mitigation of PWR Full Penetration Circumferential Nickel Alloy Dissimilar Metal Welds in Class 1 Items.

» For details see https://sperkoengineering.com/html/Additive.pdf

LINCOLN ELECTRIC | Additive Solutions

Questions / Discussion

Teresa_Melfi@LincolnElectric.com

LINCOLN ELECTRIC | Additive Solutions

Customer Focus & Innovation

Speed & Passion to Win

Teamwork & Accountability

Safety • Quality • Integrity • Trust

Westinghouse

Additive Manufacturing at Westinghouse

2023 NRC Workshop on AMTs for Nuclear Applications

David Huegel and William Cleary
Westinghouse
October 2023

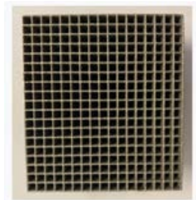
Westinghouse

Advanced Manufacturing Objectives

- **Improve industry competitiveness, through the development and implementation of advanced manufacturing (AM) technologies**
  - Drive cost reductions in manufacturing
  - Enable new products and services that provide innovative customer solutions
  - Leverage external funding sources and collaborative development

Thimble Plugging Device

Advanced AM PWR Bottom Nozzle



Advanced AM BWR Bottom Filter

Tooling - AM Laser Powder Bed Fusion

Additive Manufacturing at Westinghouse

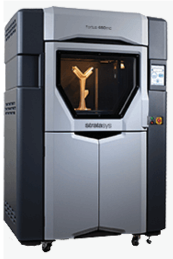
- Additive Manufacturing will have a big impact in Nuclear:
  - Cost Effect
  - Improve Performance and Reliability
  - Improve Delivery and Schedule
- Westinghouse is fully invested in the AM technology:
  - Continue to performed significant testing on 3D parts (with and without radiation effects)
  - Utilizing 3D printing for tooling for manufacturing
  - Implemented a 3D AM part in reactor to gain experience
  - Building/designing numerous parts with AM for eventual employment in a nuclear reactor (grids, nozzles, etc.)

Our Goal is for AM to Help Transform the Nuclear Industry

Additive Manufacturing – Westinghouse Equipment

- Westinghouse owns one (1) EOS M 290 machine for printing in metal with access to additional machines at the same facility
  - Currently printing in:
    - Alloy 718
    - SS Types: 316L, 304,17-4 PH and MS-1
    - Copper and Aluminum
  - Build volume 250mm x 250mm x 325mm (9.85 x 9.85 x 12.8 in)
- Additively Manufactured (3D Printed) Plastic Parts

- CFFF installed a high quality Fortus 450 polymer FDM printer.
- Build volume 406mm x 355mm x 406 mm (16 x 14 x 16in)
- Variety of ABS and Nylon materials



Westinghouse AM Equipment

First AM Nuclear Fuel Component Installed in Commercial Reactor

First AM Component (TPD) Installed at Commercial Reactor

- AM Thimble Plugging Device (TPD) first AM fuels component successfully installed in a commercial reactor (Byron 1 March 2020)
  - Low Risk Component, moderate complexity
- Westinghouse met with NRC in May 2019 at the Westinghouse Rockville offices and discussed AM TPD in detail prior to installation.
  - Implemented using the 50.59 process

AM Component (TPD) Outage 25 Inspection Summary

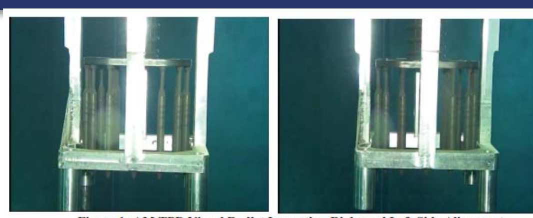


Figure 1: AM TPD Visual Rodlet Inspection Right and Left Side Alignment

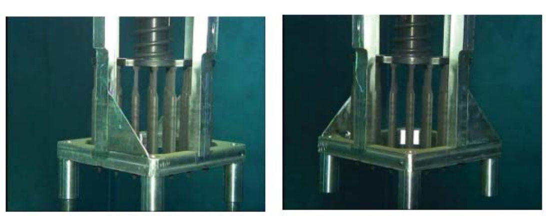
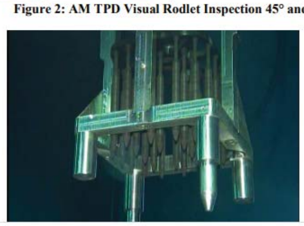


Figure 2: AM TPD Visual Rodlet Inspection 45° and 225°



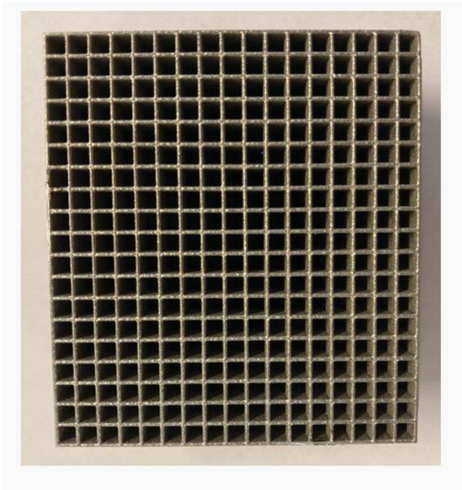
AM Component (TPD) Inspection Following Removal

- Westinghouse is currently involved with discussions with EPRI and the customer to have the AM TPD (once removed from the Byron core) shipped to a national lab for the purposes of performing detailed analyses and testing.
- Westinghouse is in the process of performing detailed dose analyses to support the shipment of the AM TPD.
- Expected removal from the Byron Unit 1 Core following Cycle 27 operation.

First AM BWR Bottom Filter Installed in Commercial Reactors

First AM BWR Bottom Filter Fuel Component Installed

- Westinghouse created the StrongHold AM filter in close cooperation with Teollisuuden Voima Oyj (TVO) and Oskarshamn (OKG)
- The StrongHold AM filter is a fully manufactured 3D printed bottom nozzle which offers enhanced capture features to prevent debris from entering the fuel assembly bundle region where it could potentially damage the fuel cladding.
- Debris testing demonstrated that the StrongHold filter performed better than the existing TripleWave+ bottom filter
- StrongHold AM filters were installed in Olkiluoto Unit 2 in Finland and Oskarshamn Unit 3 in Sweden



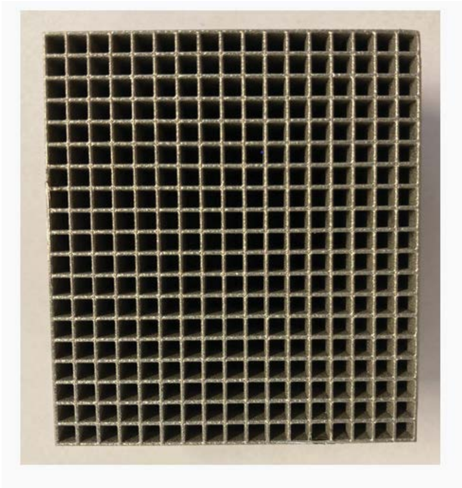
Westinghouse

Westinghouse Proprietary Class 3

First AM BWR Bottom Filter Fuel Component Installed

- Internal debris capturing features added utilizing the reduced pressure
- Design incorporates a “tortuous pathway” with unique debris capturing features
- Testing demonstrated the effectiveness of the AM filter

Filter Version	100% Efficiency Threshold
Standard TripleWave+	> 10 mm
Conventional Stronghold	~ 7mm
Additive Stronghold	5 mm
Additive Triton 11	5 mm



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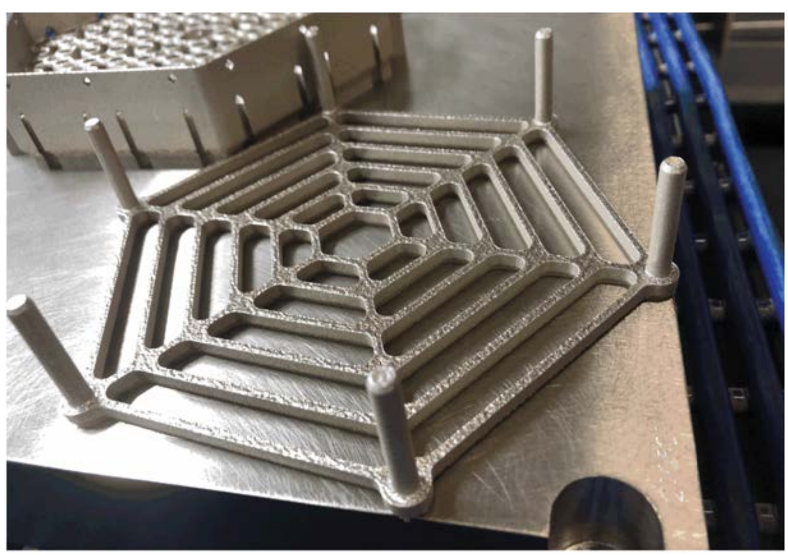
Westinghouse Developed AM Nuclear Fuel Components

Westinghouse

VVER-440 AM Top Flow Plate

- Hexagonal Russian fuel design
- Plate printed in 316L SS
- Eliminates need for welding of pins
- Combines 7 pieces into 1
- Retains fuel rods in accident scenario
- This AM top flow plate design was provided for implementation on a region basis to the Ukraine Rivne 2 plant in 2023.

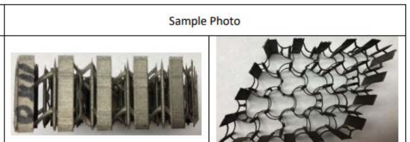
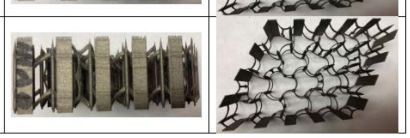


Westinghouse

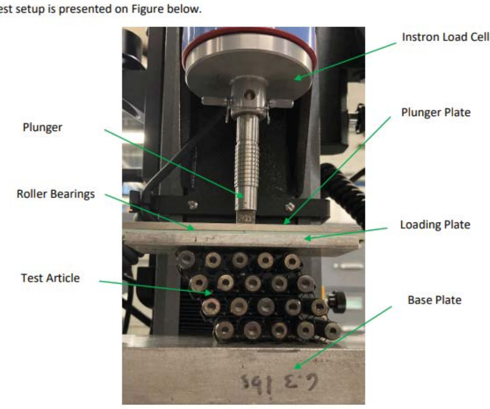
Additive Manufacturing Development Partnering with Industry/Academia

AM at Westinghouse - Partnering with Industry/Academia

- The Multiphysics Design Optimization and Additive Manufacturing of Nuclear Components project carried out under the U.S. DOE NE GAIN Voucher Program, in collaboration with Oak Ridge National Laboratory (ORNL), has established a generative design and optimization process to enable development of advanced nuclear component designs that are enabled by additive manufacturing strategies. The project is complete and a number of notable results were obtained regarding AM produced grids.

ID	Tube	Test Type	Sample Photo
OXII	Yes	Load / Unload	
OXI	No	Cycling	
OVIII	Yes	Cycling	

The test setup is presented on Figure below.



Westinghouse Developed AM PWR Bottom Nozzle

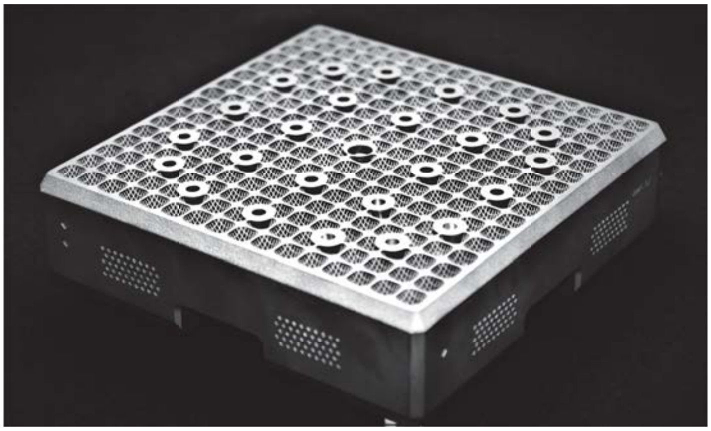
Westinghouse AM Bottom Nozzle

- AM development of the AM PWR bottom nozzle
- Debris Testing of AM PWR Bottom Nozzle
- GSI-191 Testing of AM PWR Bottom Nozzle
- Westinghouse Documentation of the AM Process (for PWR BN)
- Licensing of an AM PWR Bottom Nozzle

AM Fuel Bottom Nozzle

Full size AM produced Bottom Nozzle

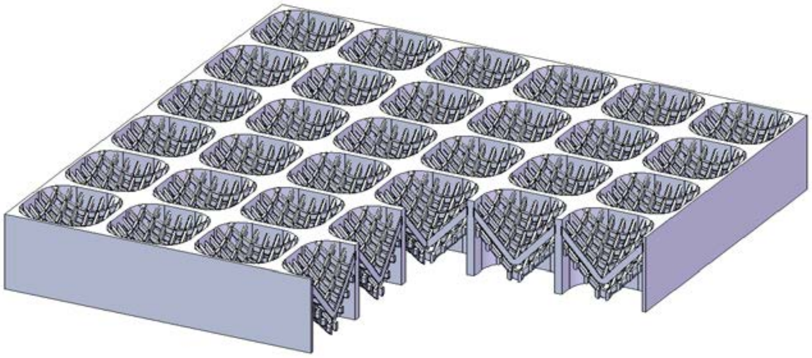
- Equivalent pressure drop to existing bottom nozzle design
- All design and safety requirements satisfied
- Improved filtering ability
- All manufacturing interfaces satisfied
- No changes to basic BN envelop nor interfacing features



Westinghouse

AM Fuel Bottom Nozzle – Debris Testing

- Debris testing of the Fine Mesh Filter (Spire) Structure Performed.
  - Double filter design (shown below) of the fine mesh filter structure achieves excellent debris capturing efficiencies exceeding the performance of existing current/advanced conventional bottom nozzle designs.



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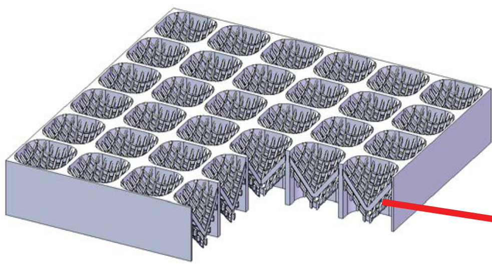
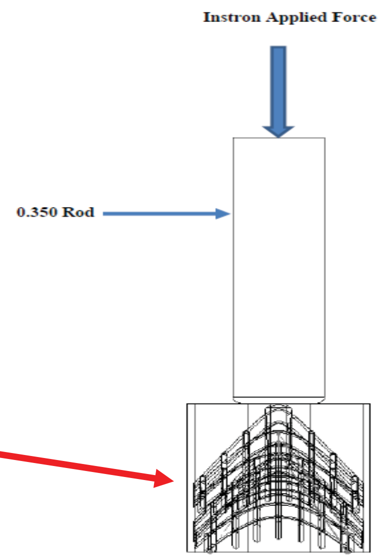
AM Fuel Bottom Nozzle - Mesh Structural Testing

- Detailed Mechanical (and T&H) Testing of Fine Mesh Filter (Spire) Structure Performed
  – Static loads applied to the fine mesh filter (spire) structure to determine strength
  – Dynamic Load testing also performed





Westinghouse Proprietary Class 3

AM Fuel Bottom Nozzle - Mesh Structural Testing

- Detailed Mechanical and T&H Testing of Fine Mesh Filter.
- Mechanical tests performed to ensure that the fine mesh filter (spire) does not fail during operation and become debris.
  – Static load testing demonstrated significant fine mesh filter (spire) strength and margin to failure.
  – Ballistic testing performed - demonstrated "spire" will not fail when debris in flow field
- T&H testing:
  – Pressure drop - matches current bottom nozzle design
  – Debris filtering - significant improvement compared to current design

AM Fuel Bottom Nozzle - GSI-191

- Subscale test loop results
  - GSI-191 testing demonstrated that the AM BN was acceptable with respect to the results presented in WCAP-17788 results (topical report for GSI-191)
  - AM bottom nozzle performed better than existing bottom nozzle

Q & A

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

Accelerated Printability Feasibility and Prioritization of Additively Manufactured Structural Materials

Isabella van Rooyen[1], Sebastien Dryepondt[2], Srinivas Aditya Mantri[3], Michael McMurtrey[4], Miles Beaux[5], T.S. Byun[2], Subhashish Meher[1], Ankit Roy[1], Mohan Sai Kiran Kumar Yadav Nartu[1], Bryant Alan Kanies[5]

[1] Pacific Northwest National Laboratory
[2] Oak Ridge National Laboratory
[3] Argonne National Laboratory
[4] Idaho National Laboratory
[5] Los Alamos National Laboratory

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

Material Identification

Decision making through Diverse Surveying

Develop materials as an integrated part of advanced manufacturing (AM)

Performance, Scalability, Reproducibility, Economics, Supply

Short Term Needs → Long Term Needs

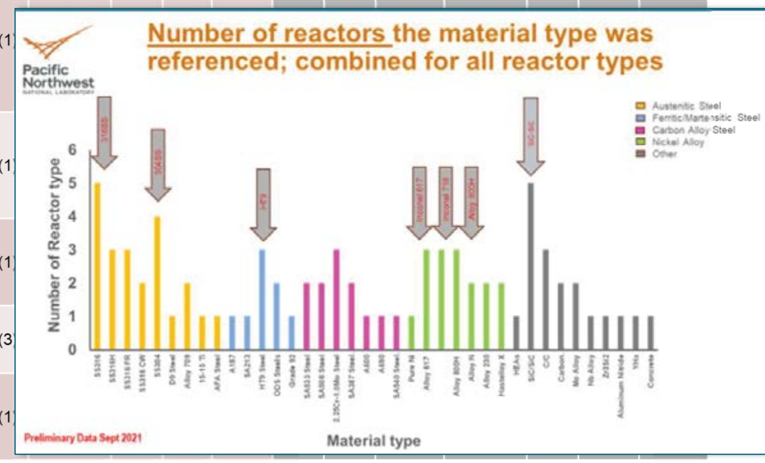
- Understanding Industry Requirements
- Upscale & Large Scale
- Next Generation Materials & Manufacturing Processes
- 316SS AM Variability
- Diverse Component & Geometry Manufacturing
- Critical minerals/materials

Multi - Laboratory and -Stakeholders effort to accelerate development and implementation

Examples of Specific Reactor Type Score Card

Material Score Cards 2020/2021

ID	Criteria	Guidance	MSR									VHTR						
			316	316H	304	Alloy 800H	Alloy N	Graphite	SiC	HT9	IN617	316	304	Alloy 800H	Graphite	SiC	IN617	IN718
1	**Code Availability**	Codes are available for all areas = 5 For two of the three areas = 3 For one area = 1	3 (3)	0 (1)	3 (3)	1 (2)	0	1 (2)	2 (2)	2	1 (2)	1 (3)	2 (3)	1 (2)	1 (2)	2 (2)	1 (2)	1 (1)
2	**Minimal Gaps in Data Availability for Performance Values and Measurements**	No or few gaps in data availability = 5 Moderate gaps in data availability = 3 Large gap in available data = 1	3 (3)	1 (1)	3 (3)	1 (2)	0 (1											
3	**Technical Maturity for End Use/Development Stage**	TRL 8-9 and/or MRL 8-10 = 5 TRL/MRL 7-8 = 4; TRL/MRL 5-6 = 3; TRL/MRL 3-4 = 2; TRL/MRL1-2 = 1	3 (3)	1 (1)	3 (3)	2 (3)	0 (1											
4	**Deployment readiness requirements**	Ready for industry deployment within 2 years = 5; In 3-5 years = 4; In 6-7 years = 3; In 8-9 years = 2; In ≥10 years = 1	3 (5)	1 (1)	3 (5)	2 (5)	0 (1											
5	**Supply Chain Availability**	No anticipated supply chain risks or impacts = 5; Moderate impacts = 3; Major impacts = 1	3 (3)	1 (1)	3 (3)	3 (3)	1 (3											
6	**Programmatic Factors**	Applications across all reactor types and/or multiple industry entities interested in a reactor type = 5	5 (5)	1 (1)	5 (5)	4 (4)	4 (1											



New Materials Decision criteria matrix and scoring criteria

Environmental Compatibility

Category	Criteria	Evaluation	Score Reference				
			5	4	3	2	1
Environmental Compatibility	Radiation Resistance	The ability of a material to maintain its shape, size, and properties after exposure to radiation	Material exhibits <1% volumetric change and limited mechanical property degradation at doses of ≥300 dpa	Material exhibits <1% volumetric change and limited mechanical property degradation at doses between 200 and 300 dpa	Material exhibits <1% volumetric change mechanical property degradation at doses between 100 and 200 dpa	Material exhibits <1% volumetric change and limited mechanical property degradation at doses between 50 and 100 dpa	Material exhibits <1% volumetric change and limited mechanical property degradation at doses ≤50 dpa
	Elemental Transmutation	Elemental stability of a material and impact of transmutation	Transmutation of elements in the material is not a concern	Transmutation of elements in the material results in at least one of the concerns or only causes concern when dose received is comparable with the reactor or material lifetime, meaning the material would be replaced before transmutation was cause for concern	Transmutation of elements in the material results in two of the concerns, or transmutation is only a concern in one neutron spectrum (either fast or thermal) but not the other	Transmutation of the elements in the material leads to premature material failure or three of the major concerns	Transmutation of constituent elements disqualifies the material from consideration or results in all of the major concerns
	High-Temperature Oxidation Resistance	The ability of a material to resist oxidation at high temperatures	Oxidation initiation occurs at temperatures ≥800°C	Oxidation initiation occurs at temperatures ≥600°C	Oxidation initiation occurs at temperatures ≥400°C	Oxidation initiation occurs at temperatures ≥200°C	Oxidation initiation occurs at temperatures <200°C
	Neutronics Compatibility	Degree of negative impact to the neutron economy of reactors	Material has a low thermal and fast neutron capture cross section and exhibits no detrimental reactions to either spectrum of neutrons	Material has moderately low thermal or fast neutron capture cross sections	Material has a low neutron capture cross section in one of either thermal or fast spectrums	Material has moderately high thermal or fast neutron capture cross sections, making it likely unsuitable for in-core applications	Material is a known neutron absorber or has a large neutron capture cross section at both fast and thermal energies
	Coolant Compatibility and Corrosion Resistance	Number of coolants, corrosion, erosion considerations The material's relative stability in a given coolant, including its resistance to corrosion, erosion, and other chemical reactions	Material is compatible with all types of coolants, showing no significant degradation	Material is compatible with 3/4 types of coolants, exhibiting good stability and inertness	Material is compatible with two types of coolants, exhibiting good stability in those coolants	Material is compatible in only one type of coolant, exhibiting significant instability in the other types of coolants	Material is not compatible with any of the coolant types, showing significant degradation in short periods of time

New Materials Decision criteria matrix and scoring criteria

Physical and mechanical properties

Category	Criteria	Evaluation	Score Reference				
			5	4	3	2	1
Physical and Mechanical Properties	Thermal Conductivity	Capability (with high thermal conductivity) to increase the thermal efficiency of an energy system and reduce transitional thermal stress in the components	Maintain >100 W/(m·K) over lifetime	Maintain 50–100 W/(m·K) over lifetime	Maintain 10–50 W/(m·K) over lifetime	Falls to <10 W/(m·K) in the end of lifetime	Begins with a low thermal conductivity < 10 W/(m·K)
	Thermal Capacity	General thermal capacity such as melting point, softening point, phase stability across temperature range	Operation temperatures in all reactor types <0.4 T_M	Operation temperatures in most reactor types in 0.4–0.6 T_M	Operation temperatures in some reactor types in 0.4–0.6 T_M	Operation temperatures in some reactor types >0.6 T_M	Operation temperatures in most reactor types >0.6 T_M
	Tensile Properties	High-temperature tensile properties including strength, ductility, and type of failure	Yield strength >200 MPa; uniform ductility >2%; no brittle failure mode over lifetime	Yield strength >150 MPa; uniform ductility >2%; no brittle failure mode over lifetime	Yield strength >100 MPa; uniform ductility >2%; no brittle failure mode over lifetime	Yield strength >100 MPa; uniform ductility >2%; possibly brittle failure mode in lifetime	Yield strength >100 MPa; uniform ductility <2%; possibly brittle failure mode in lifetime
	Creep Performance	Risk of losing dimension stability in long-term service	No creep rupture expected in lifetime. No measurable creep strain (<0.001% in lifetime) in all reactor types	No creep rupture expected in lifetime. Little creep strain <0.01% in lifetime in most reactor types.	No creep rupture expected in lifetime. No creep strain <0.1% in lifetime in most reactor types.	No creep rupture expected in lifetime. Creep strain >0.1% in lifetime in some reactor types.	Possible creep rupture in lifetime. Creep strain >1% in lifetime in some reactor types.
	Fatigue	Risk of component failure owing to crack growth by cyclic loading	Load conditions in most reactor types are more than 20% below the fatigue limit	Load conditions in some reactor types are more than 20% below the fatigue limit	Load conditions in most reactor types are close but below the fatigue limit	Load conditions in some reactor types are above the fatigue limit	Load conditions in most reactor types are above the fatigue limit
	Fracture Toughness	Capability to avoid the most probable failure mode with aging and degradation	Fracture toughness >150 MPa√m over lifetime	Fracture toughness >100 MPa√m over lifetime	Fracture toughness >50 MPa√m over lifetime	Fracture toughness >50 MPa√m over most of lifetime	Fracture toughness <50 MPa√m over most of lifetime
	Microstructural Dependency	The sensitivity of material's properties to its microstructure	Properties are not sensitive to microstructure and processing route. Microstructure is highly stable in any service environment	Properties are not sensitive to microstructure and processing route. Microstructure is reasonably stable in most of service environments.	Properties are somewhat dependent on microstructure and processing route. Microstructure is reasonably stable in most of service environments.	Properties are sensitive to microstructure and processing route. Microstructure is reasonably stable in most of service environments.	Properties are sensitive to microstructure and processing route. Microstructure is not stable in some service environments.
	Scope For Microstructural Enhancement	The possibility of enhancing material properties by microstructural engineering through feasible processing routes	Microstructure is easily controlled for desirable properties within traditional and advanced processing means. No limitation in mass production and product size.	Microstructure is easily controlled for desirable properties within traditional and advanced processing means. Some limitations in mass production and product size.	Microstructure can be controlled for desirable properties through a few limited processing methods only	Microstructure can be controlled for a few properties through a specially designed processing method only	Microstructure can be controlled for a few properties through a specially designed processing method only

New Materials Decision criteria matrix and scoring criteria

Manufacturability

Category	Criteria	Evaluation	Score Reference				
			5	4	3	2	1
Manufacturability	Reproducibility/Consistency	Degree of reproducibility and consistency in product quality for various manufacturing routes/methods of the same material (e.g., for the same material, 3D printing is not consistent, but casting is)	Number of critical parameters that need to be carefully monitored >1	Number of critical parameters that need to be carefully monitored >3	Number of critical parameters that need to be carefully monitored >5	Number of critical parameters that need to be carefully monitored >7	Number of critical parameters that need to be carefully monitored >9
	Process Complexity	Number of processing steps (when writing, provide post processing information)	If it involves: 0 preprocessing steps but a maximum of 1 postprocessing steps	If it involves: 0–1 preprocessing steps but a maximum of 2 postprocessing steps	If it involves: 0–2 preprocessing steps but a maximum of 3 postprocessing steps	If it involves: 0–3 preprocessing steps but a maximum of 4 postprocessing steps	If it involves: 0–4 preprocessing steps but a maximum of 5 postprocessing step
	Cost	Overall cost for production of components (considering the same concern as reproducibility/consistency)	If it the overall cost is 30%–50% lower than the current commercial processing method	If the overall cost is 10%–30% lower than the current commercial processing method	If the overall cost is comparable with the current commercial processing method	If the overall cost is 10%–30% higher than the current commercial processing method	If the overall cost is 30%–50% higher than the current commercial processing method
	Scalability	The ability to increase the overall # of components being produced with a certain material, and the ability to produce dimensionally larger components	Zero concerns in terms of time delay/additional required equipment/ for scaling up	1–3 concerns in terms of time delay/additional required equipment/ for scaling up	3–5 concerns in terms of time delay/additional required equipment/for scaling up	5–7 concerns in terms of time delay/additional required equipment/for scaling up	Almost impossible to scale up
	Production Method Technological Readiness Level (TRL)	The already qualified processing techniques receive a score of 5, and the ones still in the process a 3, and completely new processes receive 1	The processes with TRL between 7 and 9	The processes with TRL between 5 and 7	The processes with TRL between 3 and 5	The processes with TRL between 1 and 3	First report on the process
	Raw Material Supply	Precursor availability in the United States	If all the raw materials required for the process are manufactured and supplied in the United States. Also, the supplier/manufacturer is cheapest among the available sources internationally.	If all the raw materials required for the process are manufactured and supplied in the United States. Also, the supplier/manufacturer is not cheapest among the available sources internationally.	If all the raw materials required for the process are not manufactured in the United States but the supplier is based in the United States	If all the raw materials required for the process are not manufactured in the United States but can be shipped internationally	If all the raw materials required for the process are not manufactured in the United States but cannot be shipped internationally

New Materials Decision criteria matrix and scoring criteria

Manufacturability (continue)

Category	Criteria	Evaluation	Score Reference				
			5	4	3	2	1
Manufacturability	Flexibility Of Manufacturing	# of methods which can be used to manufacture material	If the material can be manufactured via 100% of the available processing techniques	If the material can be manufactured via 80% of the available processing techniques	If the material can be manufactured via 60% of the available processing techniques	If the material can be manufactured via 40% of the available processing techniques	If the material can be manufactured via 20% of the available processing techniques
	Conventional Machining	Need for drilling, joining, welding, riveting, etc.	A ready-to-go part can be directly manufactured without any postprocessing	A ready-to-go part can be directly manufactured with negligible postprocessing	Multiple subparts need to be manufactured with minimal postprocessing but require joining/welding/riveting	Multiple subparts need to be manufactured with significant postprocessing but require joining/welding/riveting	Parts with reasonable size scale cannot be manufactured
	Near Net Shaping (Complexity Of Shape)	How complex of a shape can the manufacturing process of a material make?	Not limited by the complexity of the design	Somewhat limited by the complexity of the design	Limited but few complex geometries can be achieved	Only simple geometries can be achieved	Only 1D/2D geometries are possible

Prioritization of current reactor materials for advanced manufacturing: Nickel Alloys

INL & ORNL

- Three Ni-based alloy categories based on potential applications: (1) **Low Co, (2) High temperature High Strength & (3) Molten Salt Compatible**
- Extensive literature review was conducted
- **Most promising alloys were further evaluated**

INL	ORNL
625	718
282	282
244	Hastelloy N
233	230
617	800H
740H	740H
GRX810	

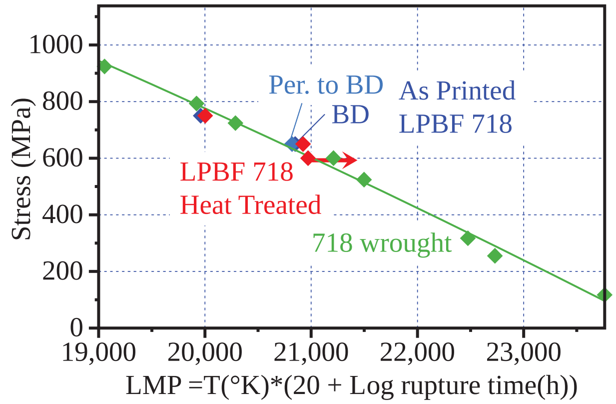
Low Co	High temperature strength	Molten salt (Low Cr)
718 (20Cr-5Nb-3Mo)	282 (20Cr-10Co-8.5Mo-2.1Ti-1.5Al)	Hastelloy N (7Cr-16Mo)
625 (22Cr-9Mo-3.5Nb)	230 (22Cr-14W-<5Co)	244 (8Cr-22.5Mo-6W)
800H (32Ni-21Cr-40Fe)	617 (22Cr-12.5Co-9Mo)	

Prioritization of current reactor materials for advanced manufacturing: Lo Co Ni-based alloys justification
INL & ORNL

718: Used in various reactors (PNNL Scorecard report), well-known & available AM alloy
- Irradiation campaign initiated under TCR
- **Creep data were generated and was consistent with wrought 718**

625: Well-known & available AM alloy
- Growing interest from industry
- Also considered for molten salt reactors

800H: Code qualified but very limited AM data & difficulty in procuring powder
- Carpenter needs an order >500kg
- Lower priority compared to 718 & 625



- Similar results between as printed and heat treated (2h@1174°C+6h@1204°C+1h@945°C+8h@718°C, 8h@621°C)
- Similar results along and perpendicular to BD

Prioritization of current reactor materials for advanced manufacturing: High temperature high strength alloys
INL & ORNL

282: Not currently used by NE industry but powder is widely available with several academic and industrial [projects on AM 282

- Defects density varies in builds fabricated for extensive characterization

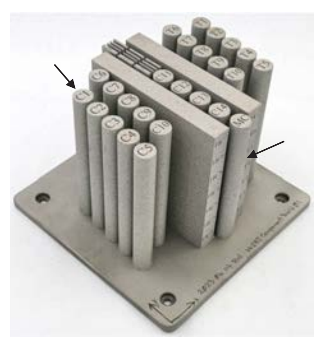
 - SA, 1h@1180°C+ aging 4h 800°C for recrystallization and grain size control

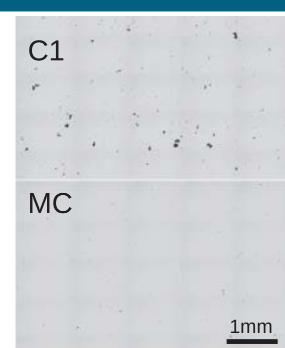
230 : Not currently used by NE industry but powders is available with limited studies

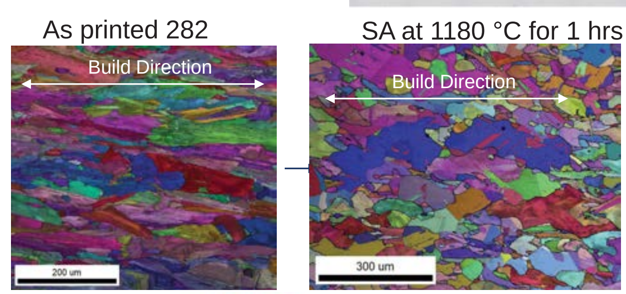
- Initial results show crack propensity

617: Code qualified alloy but limited AM work (wire-based), 90lbs was received for printing trials

Lower priority for other alloys **(233, 740H,etc.)**







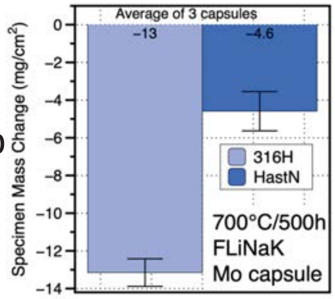
Prioritization of current reactor materials for advanced manufacturing: Low-Cr Molten Salt-Compatible Alloys
INL & ORNL

Hastelloy N.

- 2nd Ni-based alloy with score card.
- Superior performance in molten salt compared to 316H
- No powder available and limited AM data
- Interest specific to molten salt reactors

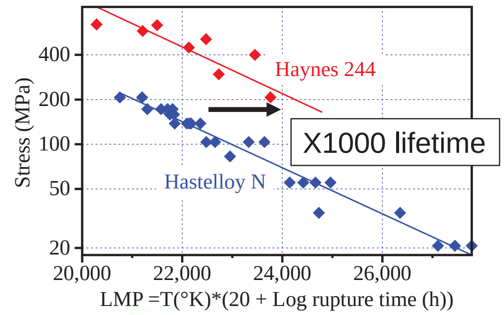
Haynes 244

- Superior strength compared to Hastelloy N
- Initial results indicate higher corrosion resistance in molten salt likely due to high W concentration
- No commercial powder and AM data. Limited data even for wrought alloy



Low mass change for Hastelloy N compared to 316H (courtesy B.A. Pint)

Superior creep strength for Haynes 244 compared to Hastelloy N



Prioritization of current reactor materials for advanced manufacturing: Further Alloy Selection
INL & ORNL

Low Co printable & available alloys.

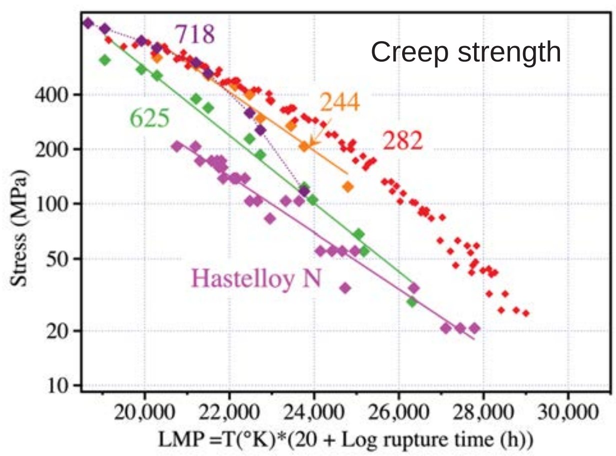
- 718: Lower cost, strength at T<700°C, AM irradiation data
- 625: Higher temperature capability & corrosion resistance

High Strength alloys: 282 selected based on current AM data & availability

- Further optimization of 282 printing parameters
- Continue comparison with LPBF 230 & 617

Molten Salt Compatible, Hast. N versus 244

- Hastelloy N: Wrought data available, superior compatibility
- 244. Very high strength, Better corrosion resistance in molten salt than high Cr alloys?



FY24 objectives

- Generate relevant database using optimized LPBF materials & collaborate with digital manufacturing team to establish processing-microstructure-properties correlation

Prioritization of current reactor materials for advanced manufacturing: Fe-based Alloys
ANL & PNNL

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

FY23

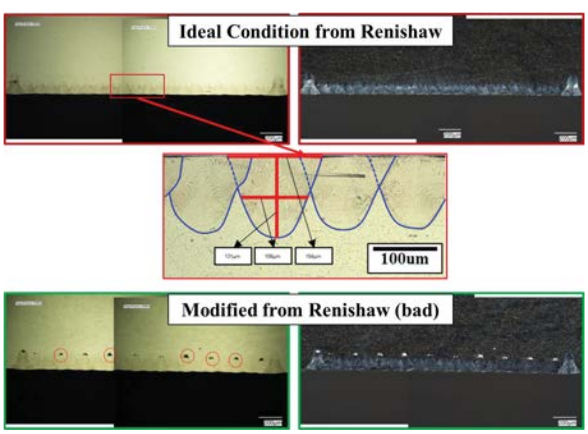
FY24

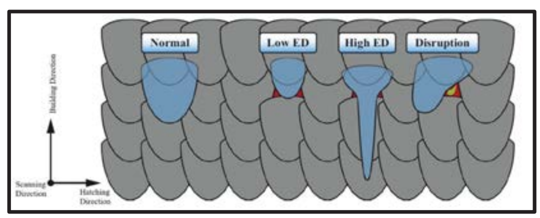
Ferritic/Martensitic Steels
- 9Cr-1Mo based alloys (Grade-91, Grade-92) code qualified, practically no AM work, powder not commercially available.
- HT9: Key alloy in PNNL score scorecards report. Has wider cross-industry appeal. Powder not commercially available, and limited AM work.

Austenitic Steels
- A-709: Close to being code qualified. No work on AM, powder not available commercially. cross-industry appeal.
- D-9: Titanium modified SS-316. Similar aspects to SS-316 can be implemented. Powder not commercially available, and no AM work.
- AFA Steel: Cross-industry appeal. Better SCC properties than SS-316. Powder is not available commercially, no AM work.
- ODS FeCrAl: High strength, corrosion resistance, collaborate with ORNL

Single Track Experiments to Optimize Process Parameters

- Single track studies are performed to determine optimal process parameters to produce a conduction/slight keyholing welds
- Weld mode produces fully dense parts
- **72** parameter sets are initially planned for Grade 91
- Laser Power, Exposure Time, and Point distance varied: Finalizing initial conditions based on literature review and inputs from Renishaw
- Variations in volumetric energy density kept within ~10% of "optimized condition" for each "set".





Volumetric Energy Density

$$E_{vol} = \frac{P}{vhd}$$

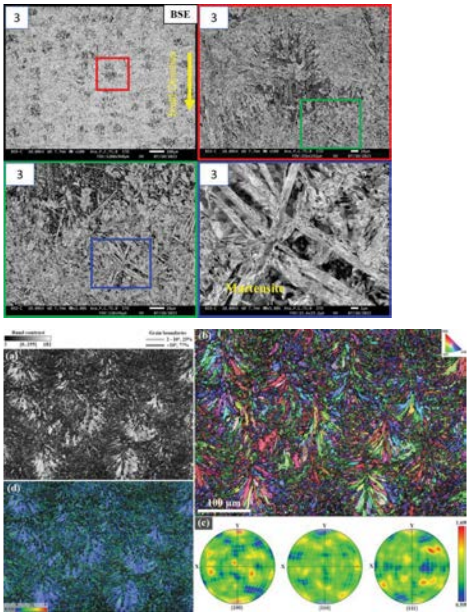
P is power (W) — h is hatch spacing

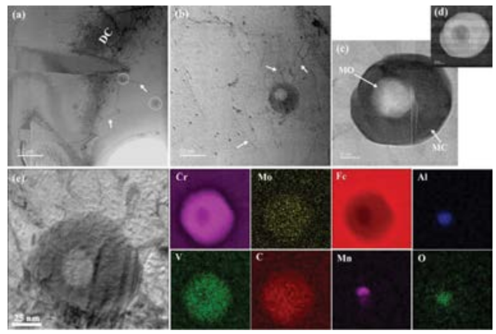
v is velocity (mm/s) — d is layer thickness

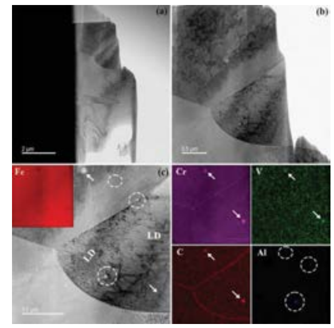
- NORMAL "Conduction mode" = adequate penetration and overlap to the previous layers and adjacent melt pools
- LOW ED = low laser power or high lasing speeds that produce a much smaller "conduction mode" shaped melt pool. Results in lack of fusion between layers and among adjacent melt pools
- HIGH ED = excessively high laser power and low lasing speeds that concentrates the heat making it penetrate through too many layers. Forms keyholing, and lack of fusion among adjacent melt pools from insufficient overlapping.
- DISRUPTED = poor process parameters, corrupt material properties, contaminants, etc.

Printability Studies HT9 Alloy (Ferritic/Martensitic)

ANL & PNNL







- Build quality good with low porosity
- SEM shows columnar grains with agglomerated smaller equiaxed grain morphology
- STEM results show presence of nanoparticles containing Cr, Mo, V, Al, Mn, O, and C
- Some grain boundary are enriched in Cr and C suggesting formation of Cr carbides
- Average hardness is 411.6 ±24.7 HV

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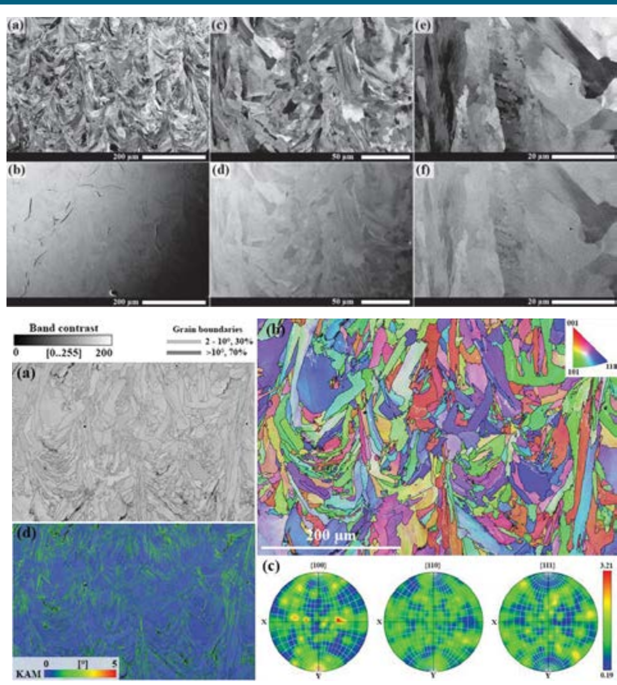
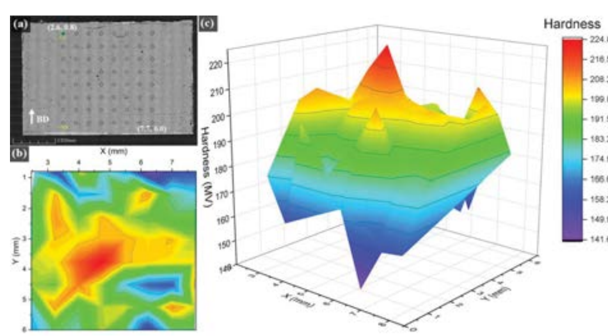
Printability Studies D-9 (Austentic steel)

ANL & PNNL





- SEM and EBSD analyses show well crystalized columnar grains
- No significant texture is observed in D-9
- Average microhardness is 189 ±16.8 HV

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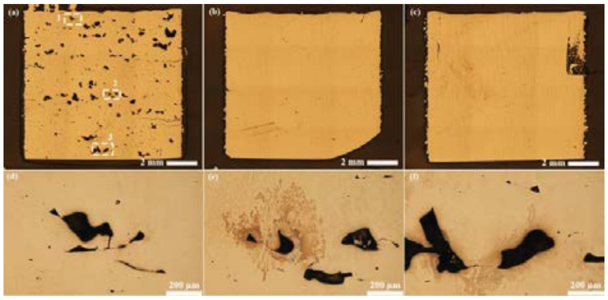
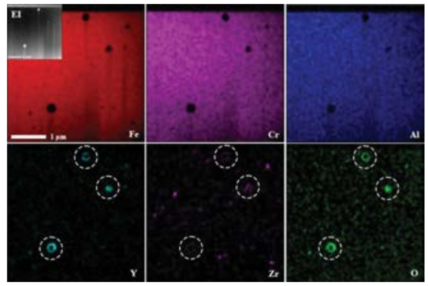
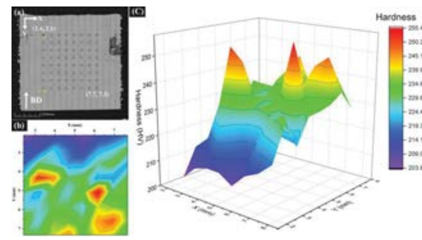
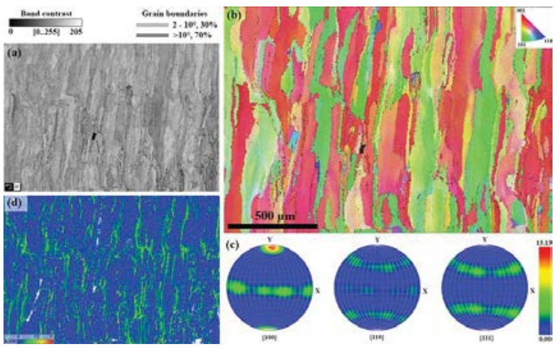
Printability Studies ODS Fe–Cr–Al
ANL & PNNL







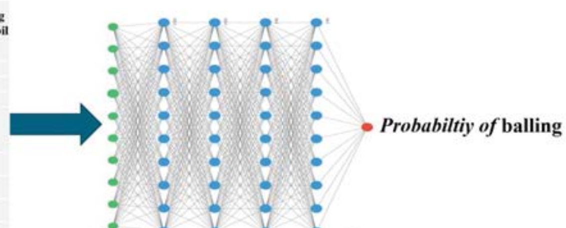


- Fabricated at ORNL
- TEM results show presence of nanoscale precipitate with Y, Zr, O.
- EBSD indicate the directional residual stress
- Variation in microhardness value, highest near substrate with value of (227.9 ±11.0 HV)

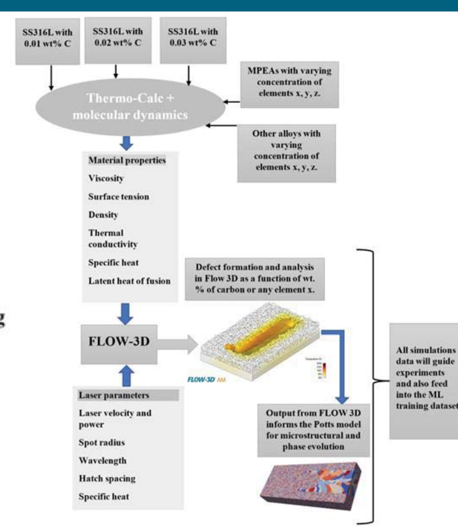
Printability Study using Machine Learning
ANL & PNNL

Printability: the ability to avoid defects like cracking, balling and lack of fusion, that are caused by thermal stresses

Alloy	Al	Fe	...	Element X	Power	Scan speed	Other process parameters	Balling probability
AlSi10Mg	0.89	0.001	0.03	0.05	130	50	xx	1
SS316	0	0.67	0.03	0.01	150	100	xx	0
Co-Cr	0	0.01	0.40	0.03	170	90	xx	0
More single principal alloys	0	0.80	0.01	0.10	140	130	xx	1
CoCrFeMnNi	0	0.20	0.25	0.20	220	170	xx	1
VNbMoTaW	0	0	0.20	0.20	190	140	xx	0
$Al_{0.5}$CoCrFeNi	0.11	0.22	0.22	0.22	110	80	xx	0
More HEAs	0.20	0.25	0.35	0.10	140	120	xx	1



Neural network model to predict balling probability in alloys shows 92 % accuracy on 240 training data and 26 testing data



- Neural network (NN) model using 240 training data and 26 testing data predicts the tendency of **balling** defect formation for a **given composition**, under a given set of processing conditions

FY24 work will demonstrate a methodology for the rapid prediction of alloy printability as a function of composition using Thermo-Calc and FLOW-3D software followed by ML prediction

ICAM 2023 presentation: Chemical composition-based machine learning model to predict deformation in additive manufacturing,. Roy A., A.R. Swope, R. Devanathan, M. Komarasamy, and I. van Rooyen

Preliminary feasibility studies of new materials for advanced manufacturing – ORNL

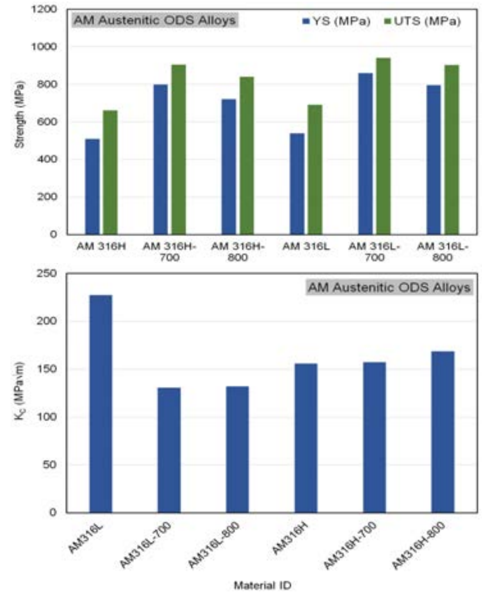
Additively Manufactured ODS Alloys

To accelerate the development, evaluation, and deployment of oxide-dispersion strengthened (ODS) alloys by employing advanced manufacturing technologies.

Scientific Achievement
- New ODS alloy processing routes employing AM processes, but not mechanical milling, were designed and applied.
- Desirable mechanical properties were achieved, depending on alloy and processing route.

Impact & Potential Application Space
- The processing route without mechanical milling might enable the economical mass production of ODS reactor components.

Details
- Seventeen ferritic and austenitic ODS variants were produced via new processing routes combining AM and TMT processes.
- The highest strength (YS > 1 GPa) was measured from a ferritic ODS alloy; the highest ductility (TE > 40%) and fracture toughness (K_C > 200 MPa√m) were from austenitic ODS alloys.
- Application of decision criteria matrix led to the downselection of austenitic ODS alloys for nearer application.



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AM oxide dispersion strengthened (ODS) steels

Experiment Details

ORNL Team

TS Byun (PI, MSTD, Process Design, Mechanical Testing)

Blane Fillingim/Thomas Feldhausen (MDF, DED Processing); Holden Hyer (NEFCD, LPBF Processing); Kevin Hanson (MSTD, TMP)

David Hoelzer/Tim Lach/Yan-Ru Lin/David Collins (MSTD, Microscopy, Mechanical Testing)

AM oxide dispersion strengthened (ODS) steels

AM 14YWT

AM ODS 316SS

14YWT-YY
- DED
- 0.3 wt.% Y_2O_3

14YWT-YYF
- DED
- 0.3 wt.% Y_2O_3+ , 0.1 wt.% Fe_2O_3

14YWT-YF
- DED
- 0.3 wt.% Y_2O_3 + 0.3 wt.% Fe_2O_3

316H-Y
- LPBF
- 0.5 wt.% Y_2O_3

316L-Y
- LPBF
- 0.5 wt.% Y_2O_3

Post-Build Thermomechanical Processing Condition

Characterization and Testing
- 700 °C and 800 °C for post-build TMP.
- Testing Temperatures: Room Temperature – 600 °C

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Application of Decision Criteria Matrix & Score Card

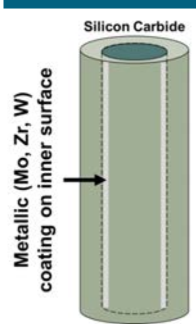
ODS Alloys

Category	Criteria	Ferritic Steels	Austenitic Steels
Application Space	Applicability to Different Reactor Types	4	3
	Other Industry Experience	1	1
	Data Availability	3	2
	Code & Standards Availability	1	1
	Component Versatility	3	3
Environmental Compatibility	Radiation Resistance	4	4
	Elemental Transmutation	4	3
	High Temperature Oxidation Resistance	3	4
	Neutronics Compatibility	4	3
	Coolant Compatibility & Corrosion Resistance	3	4

Category	Criteria	Ferritic Steels	Austenitic Steels
Physical & Mechanical Properties	Thermal Conductivity	3	3
	Thermal Capacity	4	4
	Tensile Properties	3	4
	Creep Performance	4	4
	Fatigue	4	4
	Fracture Toughness	2	4
	Microstructural Dependency	3	3
	Scope for Microstructural Enhancement	4	4
Manufacturability	Reproducibility/Consistency	3	4
	Process Complexity	3	3
	Cost	2	2
	Scalability	2	2
	Production Method TRL	3	3
	Raw Material Supply	4	4
	Flexibility of Manufacturing	4	4

- **The ODS austenitic alloys yielded slightly higher average score than the ODS ferritic alloys (3.26 vs. 3.07).**

Assessment of Advanced Manufacturing Techniques for Composite and Refractory Alloy Structures - LANL



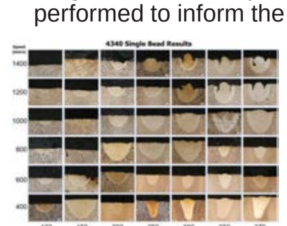
Objective: To identify, vet, and develop advanced manufacturing techniques for refractory lined composites and refractory alloys for nuclear energy applications.

Composite	C-C	W/C-C	Mo/C-C	Zr/C-C	SiC-SiC	W/SiC-SiC	Mo/SiC-SiC	Zr/SiC-SiC
Overall score	94	91	90	89	102	95	93	94

The most significant variances in scoring are linked to Data Availability, Elemental Transmutation, Thermal Capacity, and a small variance in Raw Material Supply.

Refractory Alloy	TZM	WTa	WNiFe	C-103
Overall score	106	87	97	105

Single weld studies performed on TZM, W, and Ta were performed to inform the scoring of refractory alloys.



Single weld tracks

Tungsten Density Blocks

- W/SiC-SiC will maintain its structural integrity at elevated temperatures, is thought to have satisfactory neutronics properties, and sufficient compatibility with liquid metal coolants (Pb, Li) and coolants used in MSRs and GFRs. It is seen as a candidate material for both in-core and out-of-core structural components.
- C-103 has been used in other industries, such as the aerospace industry. It is anticipated to have superior creep performance, fatigue, fracture toughness, and neutronics compatibility compared to WTa and WNiFe.

Bryant A. Kanies and Miles F. Beaux II, Michael J. Brand, Robin A. Montoya, Erofili Kardoulaki, A. David Andersson

Preliminary Feasibility Studies of New Materials for Advanced Manufacturing - LANL

Prior and Ongoing Work at LANL

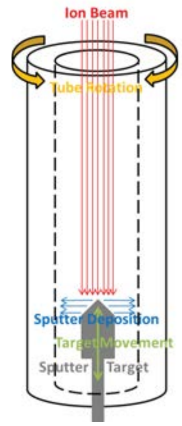
- Previous work & capabilities:
  - Inspired idea for composites
  - Informed decision criteria matrix/down-selection
  - Provided proof of concept for manufacturability
- Previous project produced free-standing molybdenum tubes via CVD
- LANL Capability: Ion Sputtering Physical Vapor Deposition (PVD) of tube interiors

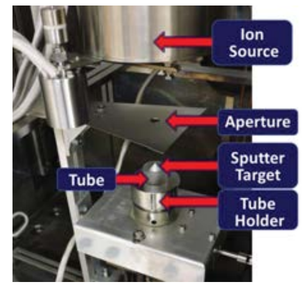
CVD of Mo Tubes

$$Mo(s) + Cl_2(g) \xrightarrow{200-400℃} MoCl_5(g)$$

$$MoCl_5(g) + \frac{5}{2}H_2(g) \xrightarrow{500-800℃} Mo(s) + 5HCl(g)$$

PVD Tube Coater





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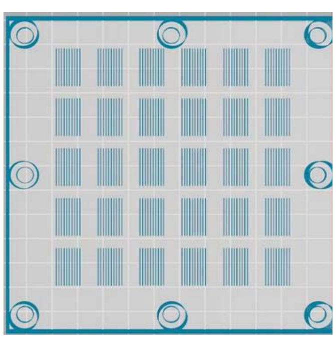
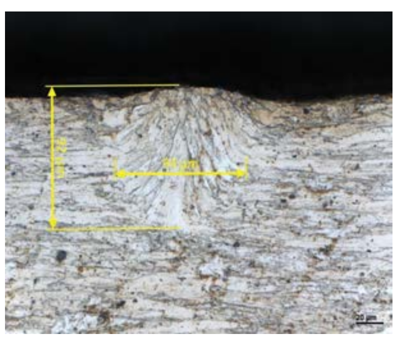
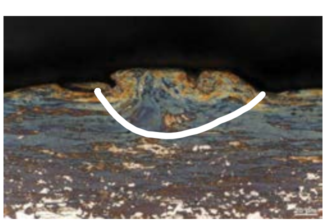
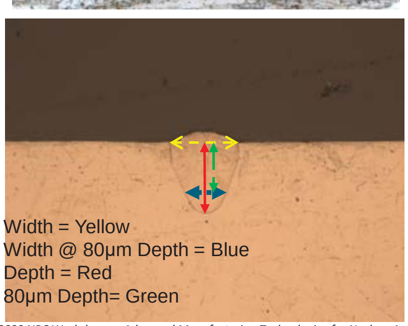
Preliminary Feasibility Studies of New Materials for Advanced Manufacturing - LANL

Prior and Ongoing Work at LANL:









Bulk Refractory Alloys Considerations:

- LANL Microreactor Program
  - Used single bead welds to elucidate relationship between scanning time and laser power
  - Demonstrated capability to produce AM TZM alloy
- Feasibility and material down select was being informed by:
  - Previous/ongoing work on stainless steels, TZM, and other refractory alloy cube production and analysis
  - Broad literature review

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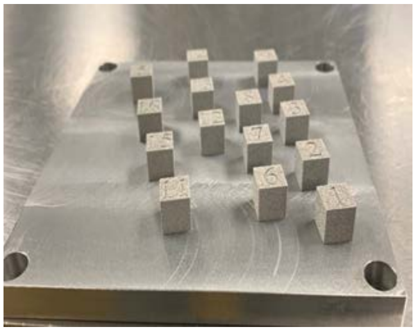
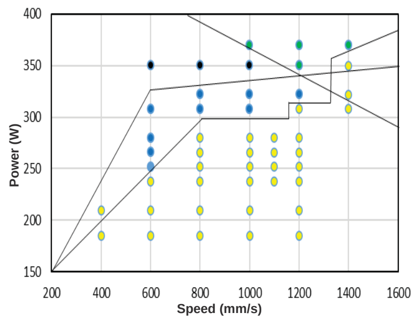
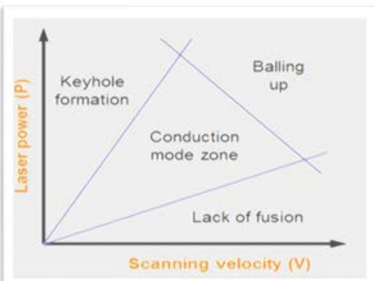
Preliminary Feasibility Studies of New Materials for Advanced Manufacturing - LANL

Prior and Ongoing Work at LANL:







Bulk Refractory Alloys Considerations:

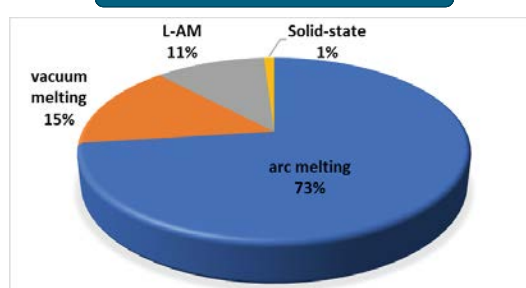
- AMMT Project :
  - Decision matrix evaluation of a broad range of bulk refractory alloys that could be produced by a Laser Powder Bed Fusion (LPBF)
  - Optimization of AM process for select alloys
  - Production and characterization of refractory lined backbones and alloys.
- Next Steps & Future Work:
  - Additional refractory alloys will be identified and evaluated and down selected in early fiscal year 2024.
  - Powders needed to investigate refractory alloys will be obtained.
  - Cubes for selected refractory alloy and tubes coated with refractory liners will be produced and characterized for feasibility in fiscal year 2024.
  - Beyond FY24: Production of a multichannel part from selected alloy or refractory lined backbone.

Preliminary Feasibility Studies of New Materials for AM: High Entropy Alloys (HEAs) - PNNL

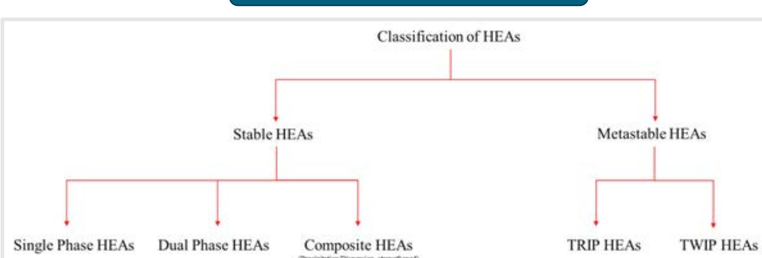
Why High Entropy Alloys?

- exhibit unusual lattice distortion and sluggish diffusion, immobilize the radiation-induced defects decreased swelling and segregation
- Tuned microstructure by exploiting their varied phase stability in different temperature regimes for enhanced sink strength.
- Multiple interfaces via secondary phase precipitation and multi-modal distribution of grain sizes enhance the sink strength

Manufacturing Process



HEA classification



This classification is based on *phase stability and mode of deformation*

- Stable HEAs deform via dislocation slip and metastable HEAs via TRIP and/or twinning induced plasticity (TWIP) upon mechanical/thermal damage.
- Stable HEAs can be further classified based on the type of phases that constitute the microstructure.

Feasibility Study of Advanced Manufacturing Techniques and Compositions of High Entropy Alloys (HEAs)

Objectives:

(1) Evaluating current ***manufacturing techniques*** addressing challenges and needs for ***upscaling***
(2) Identify & down select ***nuclear energy relevant HEAs*** using decision matrix

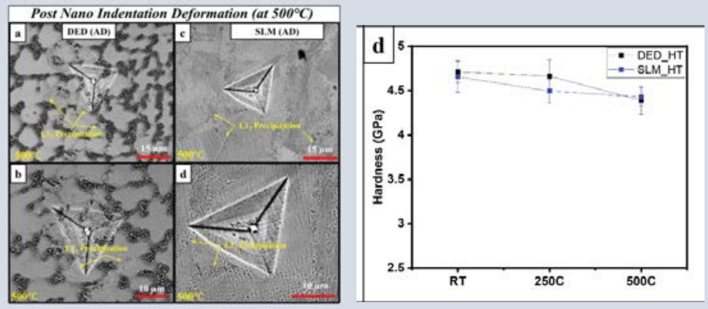
Scientific Achievement:

- Six promising HEAs identified for nuclear focusing on high temperature properties:
  - $Al_{0.3}Cu_{0.5}CrFeNi_2$, $Al_5Cr_{12}Fe_{35}Mn_{28}Ni_{20}$ and **$Al_{10}Cr_{12}Fe_{35}Mn_{23}Ni_{20}$***: NRC , RT high strength
  - $(Ni_2Co_2FeCr)_{92}Al_4Nb_4$: ppt strengthened HEA (330MPA at 870°C)
  - GRX-810 (ODS-NiCoCr with minor Al, Ti, Nb, W, and C): medium HEA
  - **$Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$** *: ppt strengthened FCC HEA ; (expected high strength up to 1100°C)
- Experiments **$Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$** :
  - Characterization of **DED** and **SLM** one-step annealed conditions, high strength @ 500°C (samples manufactured by UNT)
- Experiments for bulk & economic manufacturing
  - Characterization of DED fabricated **functionally graded** HEAs: economic INL provisional patented process demonstrated with $CoCrNiFe_{0.5}$
  - **Solid phase processing** (SPP) planned in FY 24 for bulk upscaling for alloys*

Mohan Nartu, Subhashish Meher, Isabella van Rooyen, Shalini Tripathi, Nathan Canfield

Presentation:
Nartu et al., HEAs for Nuclear Energy Applications and Potential Advanced Manufacturing Methods at International Conference on Additive Manufacturing (ICAM) 2023.

Presentation:
Meher et al., Development of High Entropy Alloy based Coatings via Directed Energy Deposition (DED) Additive Manufacturing for Nuclear Applications at 3rd World Congress on High Entropy Alloys (HEA 2023),



DED and SLM one-step annealed $Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$

Publication:
Nartu, M.S.K.K.Y., et al., Microstructure and Temperature Dependent Indentation Response of Additively Manufactured Precipitation-Strengthened $Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$ High Entropy Alloy. JOM, 2023.
Presentation:
Nartu et al., Engineering heterogeneous microstructures in Additively Manufactured $Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$ High Entropy Alloy for potential nuclear applications at Materials in Nuclear Energy Systems (MiNES 2023).

Impact & Potential Application Space:

- Preliminary decision matrix provides promising HEA compositions
- Complex high temperature components, HEA coating for high temperature application
- $(NiCoFeCrCu_{0.12}$ is researched under another DOE-NE program for extreme high irradiation dose for cladding)

Decision Criteria Matrix Applied to Diverse Material Types

Composite	W/C-C				Mo/C-C				Zr/C-C				W/SiC-SiC				Mo/SiC-SiC				Zr/SiC-SiC			
Categories	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma
Category scores	19	15	25	32	18	13	25	33	17	15	24	33	19	18	26	32	17	16	26	33	17	19	25	33
Overall score	91				89				89				95				92				94			

Refractory Alloy	TZM				WTa				WNiFe				C-103			
Categories	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma	AS	EC	PM	Ma
Category scores	23	18	32	33	18	16	26	27	22	19	29	27	23	21	34	27
Overall score	106				87				97				105			

ODS	Ferritic ODS Steels				Austenitic ODS Steels			
Categories	AS	EC	PM	Ma	AS	EC	PM	Ma
Category scores	12	18	27	26	10	18	30	30
Overall score	83				88			

HEA	$Al_{0.3}Ti_{0.2}Co_{0.7}CrFeNi_{1.7}$				$Al_{10}Cr_{12}Fe_{35}Mn_{23}Ni_{20}$			
Categories	AS	EC	PM	Ma	AS	EC	PM	Ma
Category scores	8	0	15	33.5	10	0	18	34.5
Overall score	56.5				62.5			

Material Identification

Decision making through Diverse Surveying

Develop materials as an integrated part of advanced manufacturing (AM)

Performance, Scalability, Reproducibility, Economics, Supply

Short Term Needs → Long Term Needs

- Understanding Industry Requirements
- Upscale & Large Scale
- Next Generation Materials & Manufacturing Processes
- 316SS AM Variability
- Diverse Component & Geometry Manufacturing
- Critical minerals/materials

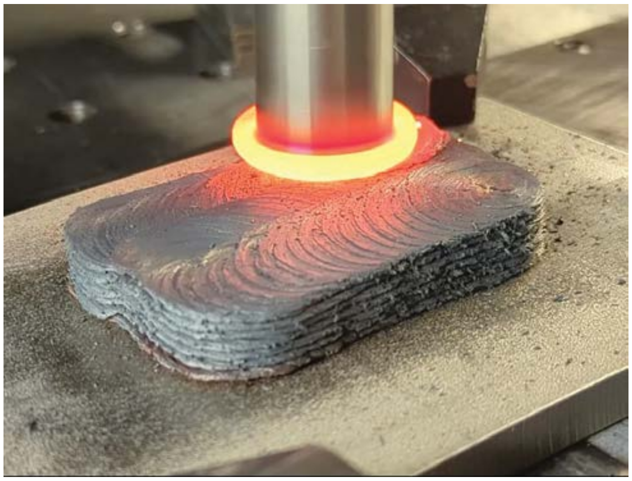
Multi - Laboratory and -Stakeholders effort to accelerate development and implementation

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

Additive Friction Surfacing (AM)

Process Description and First 316H work

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



316-H bar stock deposited directly onto 316-L plate at PNNL

PNNL team: David Garcia, Mayur Pole, Ken Ross

- Refined grain structure produces improved properties demonstrated in aluminum
- Overmatched properties possible in austenitic stainless steels
- Potentially order of magnitude cost staving on material alone compared to fusion based methods
- High deposition rate
- Application space
  - Near-net shape additive manufacturing
  - Component life extension
  - Cladding
  - Functionally graded and dissimilar materials

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Standards Considerations Towards the In-Process Quality Assurance of AM Parts

Paul Witherell, PhD

Measurement Science for Additive Manufacturing Program

National Institute of Standards and Technology

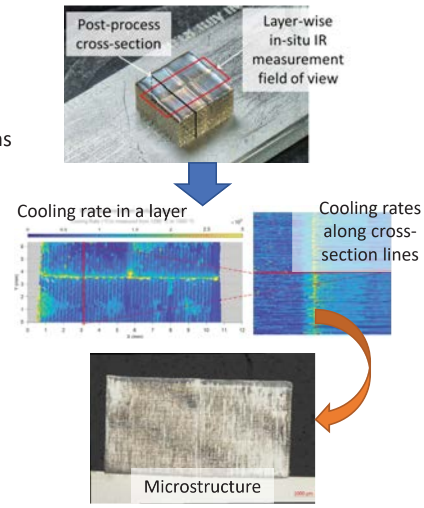
October 25, 2023

Brief Introduction to NIST AM Research

- Full spectrum of materials classes (Ceramics, Polymers, Metals, Concretes, Biological materials)
- Full spectrum of AM process categories

Focus areas:

- Unique materials and material properties
  - Comprehensive characterization of processing-structure-properties-performance (PSPP) relations
  - Determination of properties affecting printability/manufacturability
  - Provisionment of critical AM materials data to stakeholders
  - Methods to enable the insertion of new materials for additive applications
- Trustworthy in-process monitoring and control
- Verified and validated process and material models and design tools
- Rapid, inexpensive, and effective part inspection techniques
- Rapid and traditional machine and material qualification techniques
- Process and material standards and specification
- Data curation, integration, and analysis



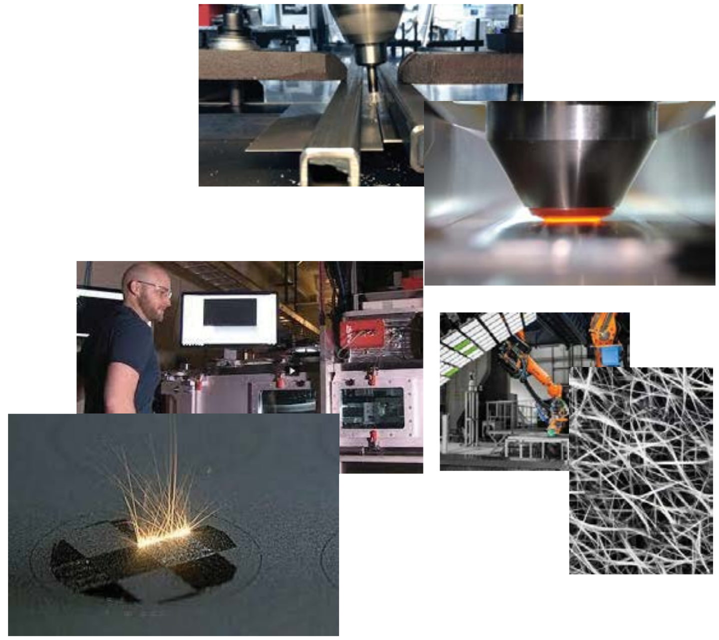
Meeting Criteria for Part Acceptance

- Whether we are referring to qualification, certification, acceptance…
- In general, the aim is to:
  - Build confidence/trust into part
  - Establish confidence that the part will perform as designed
- Traditional manufacturing processes benefit from legacy and robustness
- To build trust into the part, trust must be established for the process as well
- AMTs present many challenges

Why Are AMTs so Challenging?

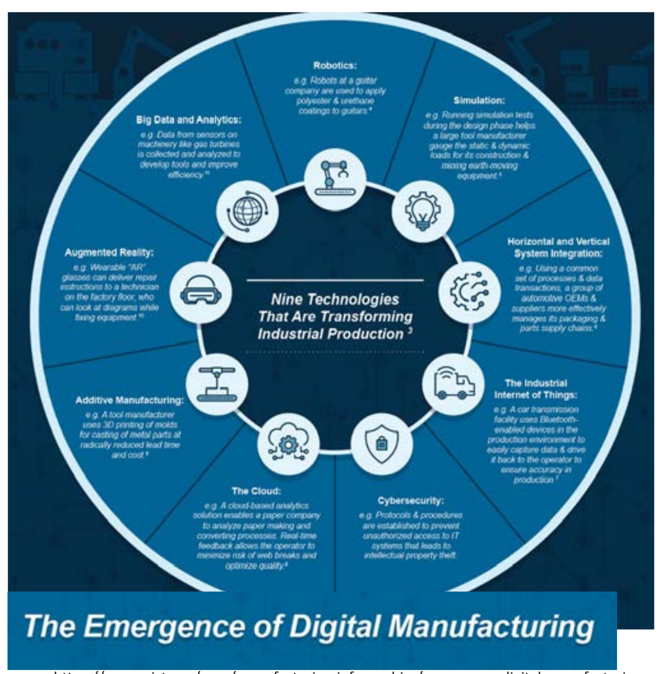
- Advanced usually implies improved, however:
  - Novelty often comes with new uncertainties
    - Creates challenges when repeatability and reliability are essential
  - Increased capabilities are accompanied by increased parameters
    - Large flexibility can lead to large variability
    - Less robust to disturbances

Traditional qualification methods have proven difficult to adopt for AMTs



Building Trust through the Digital Nature of Advanced Manufacturing Technologies

- Current "state-of-the-art" most often benefits from increased digitalization
- Advanced manufacturing processes are often driven by a strong digital component
- The digital, piecewise nature of many of these processes lend themselves well to more advanced analytics

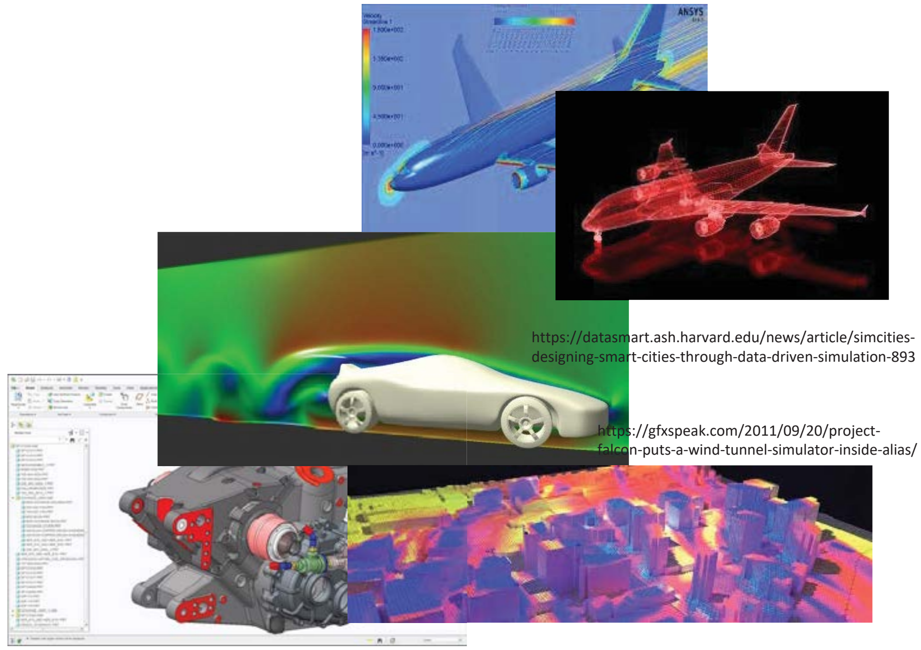


https://www.nist.gov/mep/manufacturing-infographics/emergence-digital-manufacturing

The Increasing Roles of Modeling and Simulation

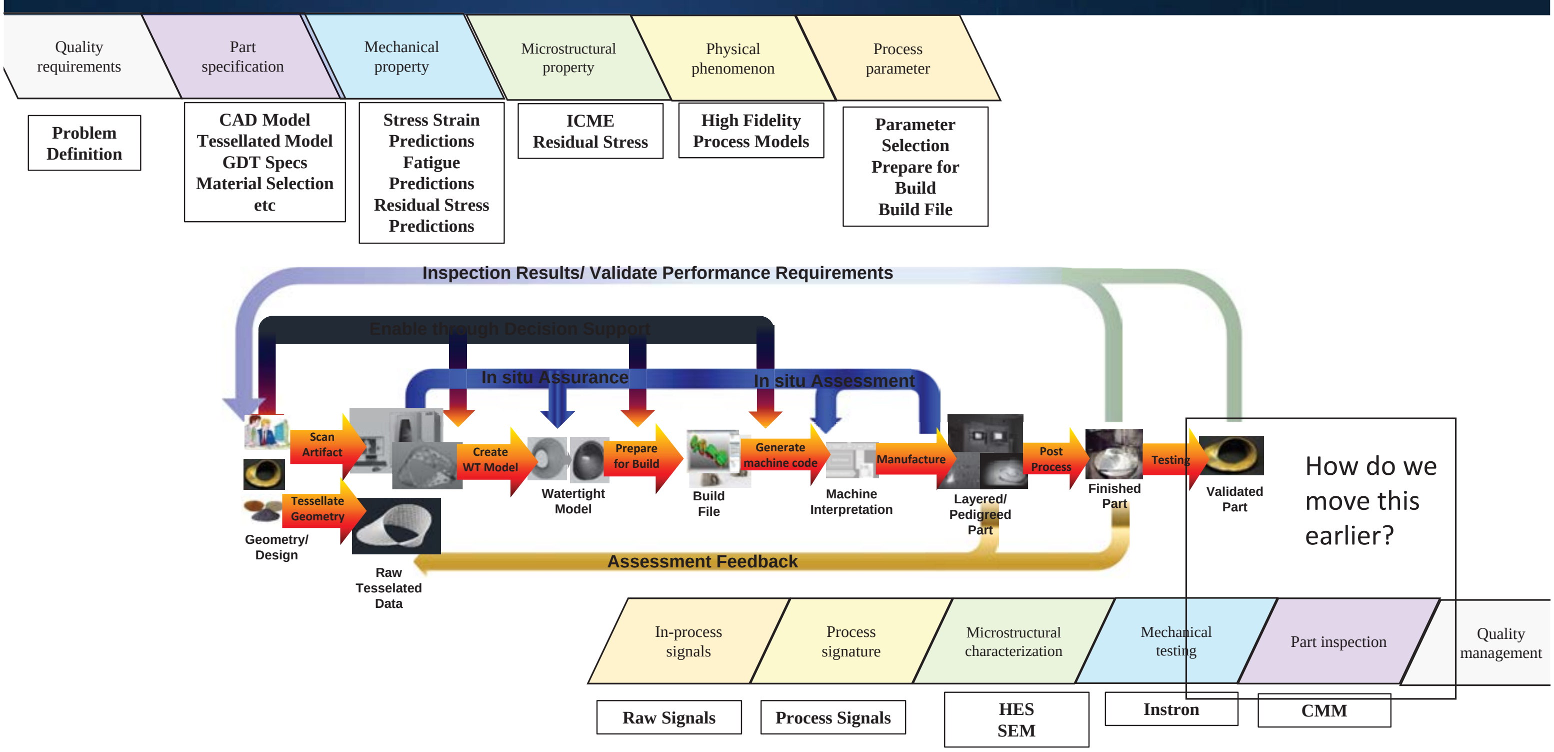
NIST

- Modeling and simulation are being used to:
  - Digitally realize a desired state of a part or process
  - Provide insight into physics interactions of parts and processes
  - Set expectations of expected performance through observed interactions
  - Provide a foundation for predictive analytics and course corrections during design, manufacture, and use phases of a part or subject



M&S Sets Expectations, but When Does the Quality Assurance Occur?

NIST



Quality Assurance through Observation and Measurements: Exploring the Digital Twin

NIST

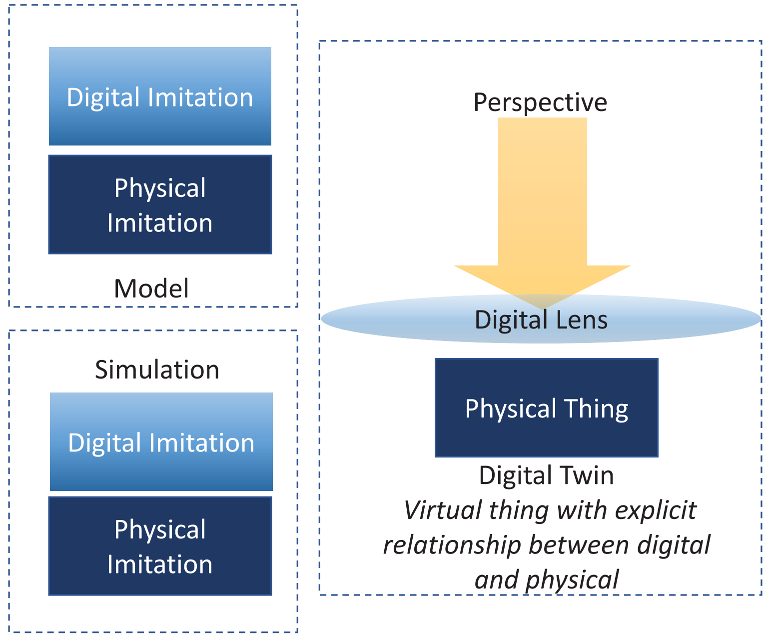
Model - Simulation- or a Digital Twin?

Modeling and Simulation

- Can exist in physical world, digital world, or both
- Represent parts, processes, behaviors…
- Context/Perspective greatly influence to what extent they are representative

Digital Twin

- Exists only in digital world– but with an explicit relationship to the physical
- Digital twin links to the physical world do **NOT** have to exist as models or simulations
- Explicit links between physical observations and digital counterparts



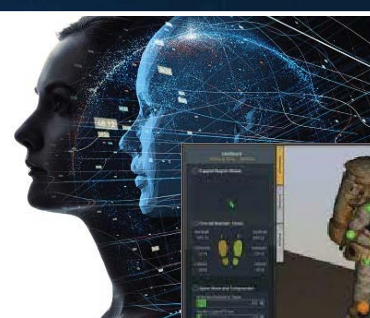
Emerging Digital Twin Opportunities

NIST

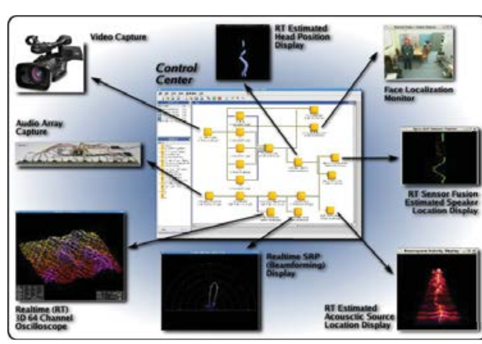
> "a digital informational construct of a physical system as an entity on its own"
> -Grieves and Vickers (2017)

Characteristics of a Digital Twin:

- A virtual representation of a thing
  - Many different definitions
- Scalable
  - A twin can exist within a twin
- Flexible
  - Simulation and emulation
- Purposeful
  - Context dependent adaptations



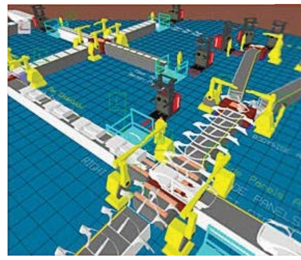
https://www.ccad.uiowa.edu/military/warfighter-simulation



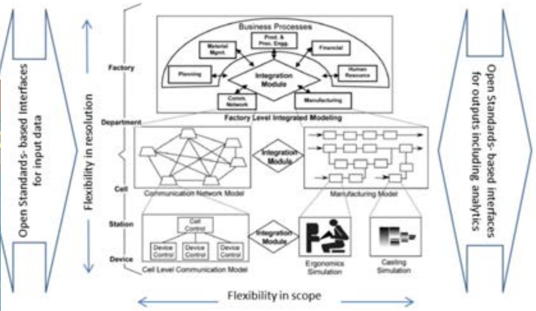
https://www.nist.gov/itl/iad/mig/nist-smart-space-project/nist-smart-space-project-data-flow/nist-data-flow-system

Leveraging the Digital Twin in Manufacturing

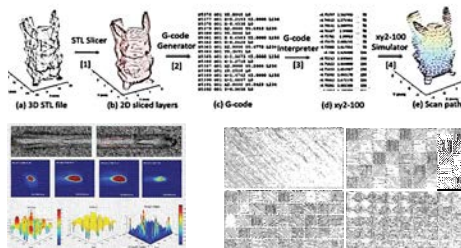
- Multi scale in manufacturing:
  - Part, machine, factory, supply chain
- Common uses in manufacturing
  - To assess behaviors of parts or processes during operation
    - M&O of machines and parts
  - To configure systems on component-system levels
    - Production system design, complex product integration
  - To establish provenance and/or control during the fabrication of a part
    - Quality control mechanism



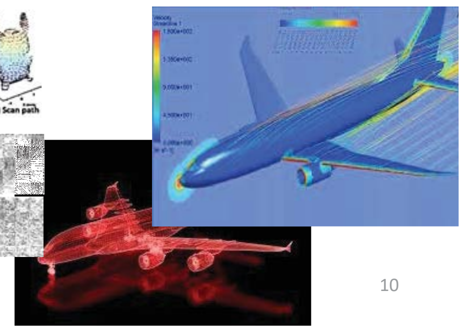
https://www.nist.gov/topics/manufacturing/nist-led-standard-enables-agility-cost-and-time-savings



Shao, Guodong, et al. "Digital twin for smart manufacturing: The simulation aspect." *2019 Winter Simulation Conference (WSC)*. IEEE, 2019.



Yeung, Ho, et al. "Continuous laser scan strategy for faster build speeds in laser powder bed fusion system." *Proceedings of the 28th Annual International Solid Freeform Fabrication Symposium*. 2017.

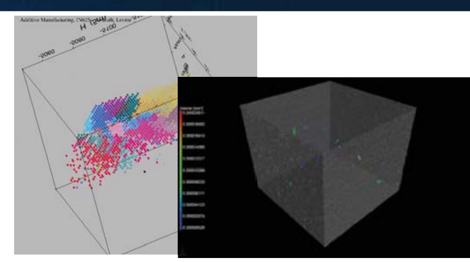


Leveraging the Digital Twin in AMTs

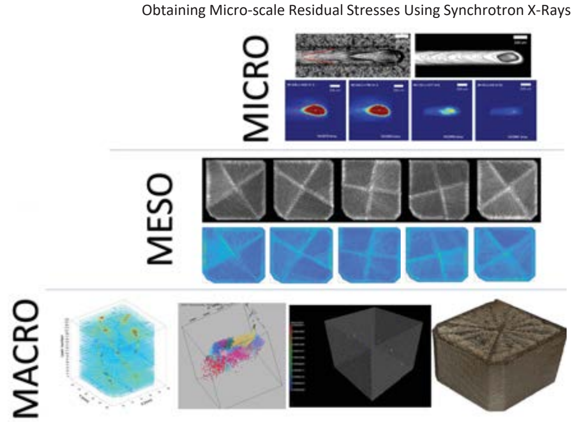
With the increasing significance of data in manufacturing, the digital twin has become an important concept:

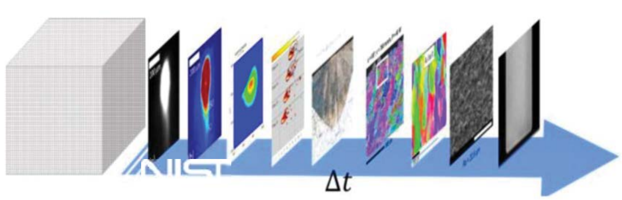
- Implications due to perspective/connotation;
- Couple to a physical counterpart;
- Often spatial and temporal components

The digital twin approach can be used to provide a basis on which detailed analyses and assessments can be performed



Obtaining Micro-scale Residual Stresses Using Synchrotron X-Rays

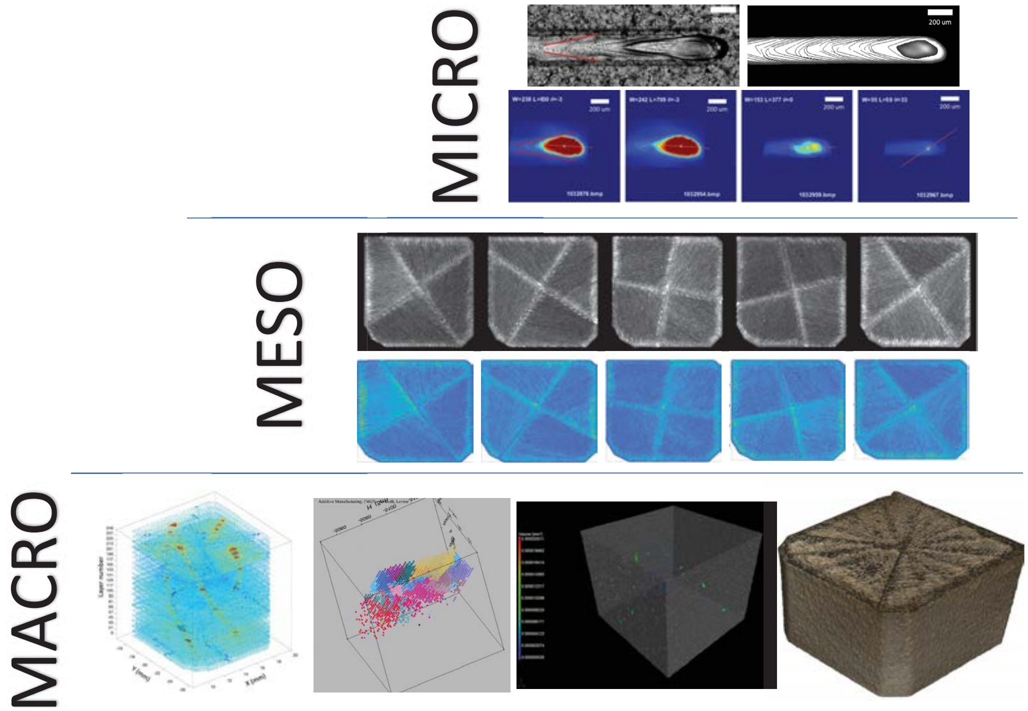




From NIST EL Measurement Science for Additive Manufacturing Program
Precursor Materials Qualification : Thien Phan

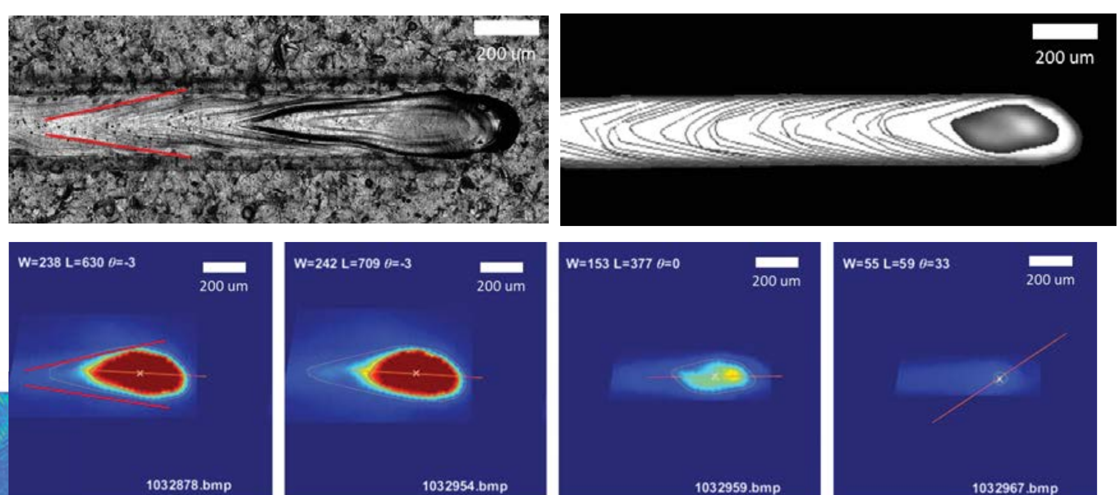
Measurements Through the Context of a Digital Twin

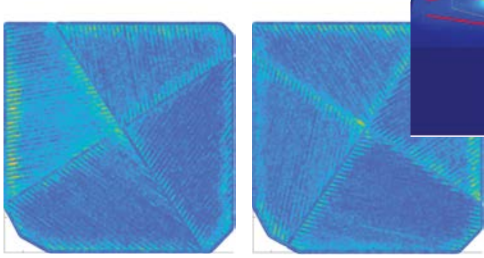
- Much of the research measurements in AM at NIST can be related through a digital twin approach



NIST Measurements in AM

- The digital twin approach can be used to map measurements taken at different times with different instruments



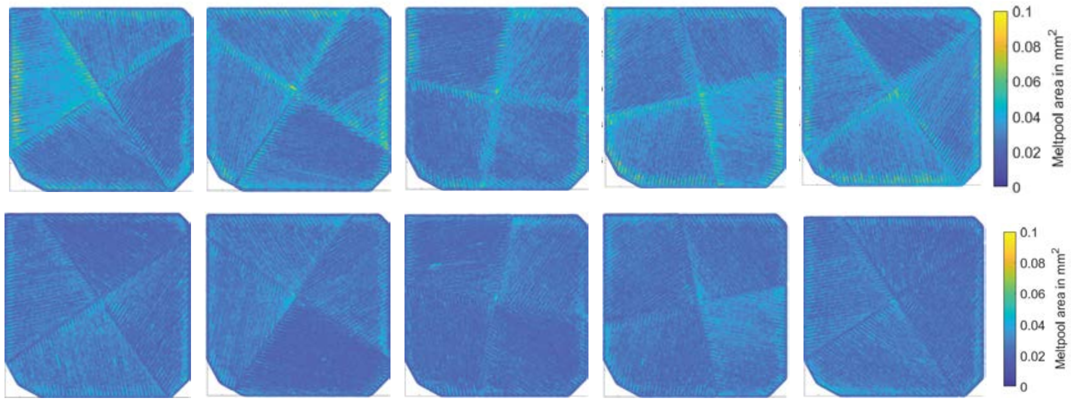


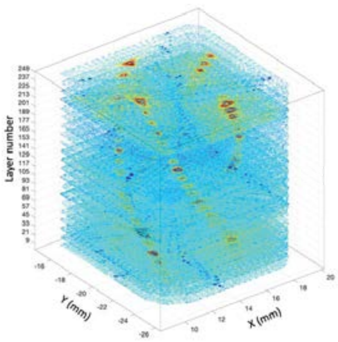
In-situ melt pool observation an analysis is mapped from tracks to layers

From NIST EL Measurement Science for Additive Manufacturing Program
AM Machine and Process Control Methods for Additive Manufacturing
Ho Yeung, Project Lead

NIST Measurements in AM

- The digital twin approach can be used to map these measurements across scales



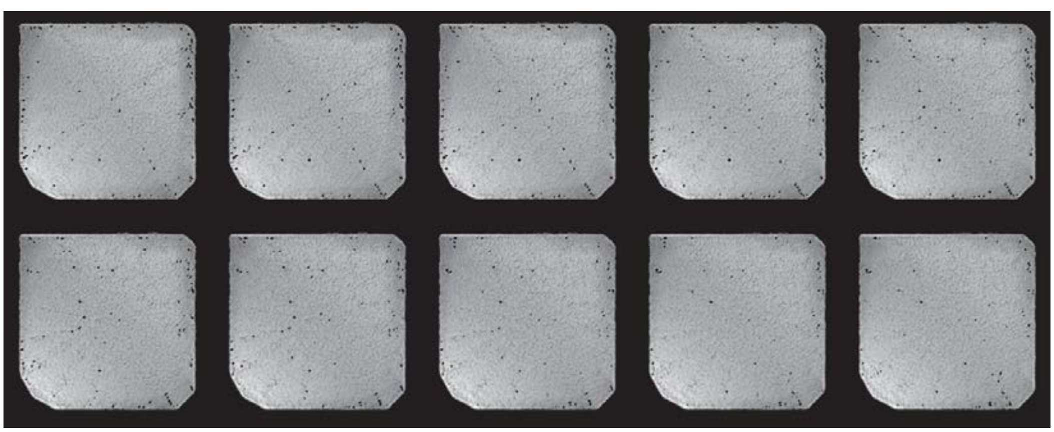


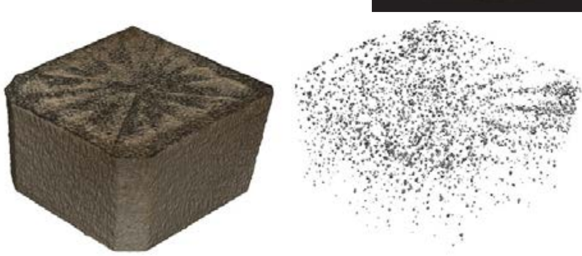
In Situ layer-wise observations can be mapped back to volumes

From NIST EL Measurement Science for Additive Manufacturing Program
AM Machine and Process Control Methods for Additive Manufacturing
Ho Yeung, Project Lead

NIST Measurements in AM

- The digital twin approach can be used to map in situ and ex situ measurements

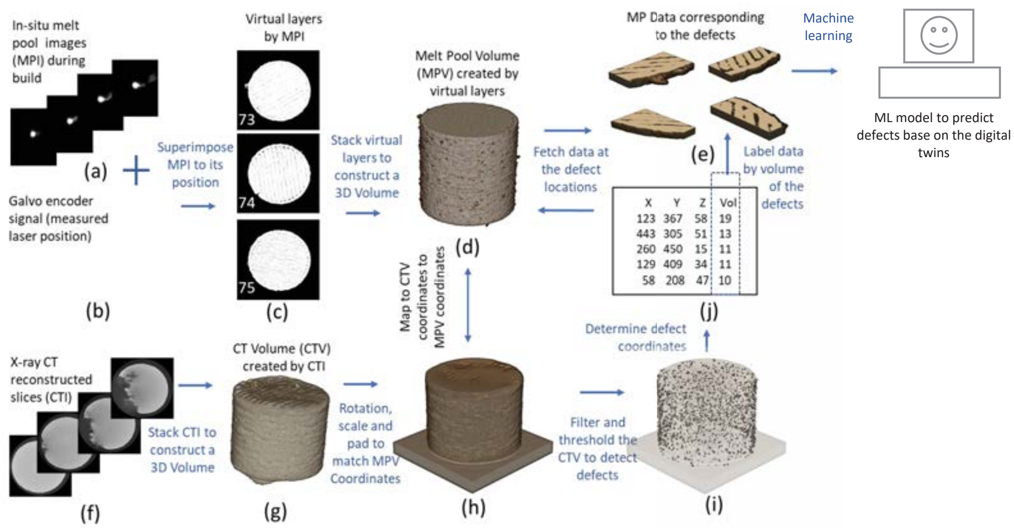




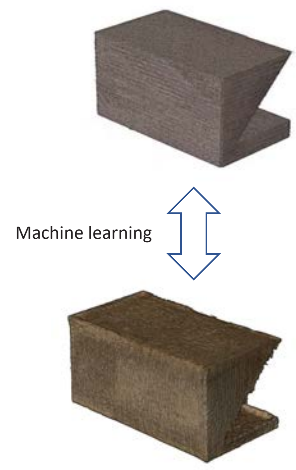
Ex Situ layer-wise observations can be mapped back to volumes

From NIST EL Measurement Science for Additive Manufacturing Program
Additive Manufacturing Part Qualification
Jason Fox, Project Lead

NIST Defect Detection with Digital Twin



Digital twin of process monitoring



XCT volume

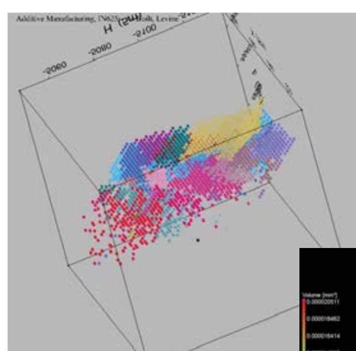
Qualify as build – defect prediction model

- Correlate the process monitoring digital twin and XCT detected defects.
- Train machine learning model to predict pores from the digital twin.

From NIST EL Measurement Science for Additive Manufacturing Program
AM Machine and Process Control Methods for Additive Manufacturing
Ho Yeung, Project Lead

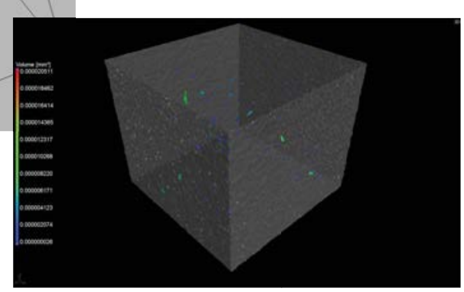
Standards Considerations to Address In-Process Assurance

- The digital twin approach can be used to provide a basis on which detailed analyses can be performed
- Acceptance requires agreement in
  - Identification of relevant data and meaning of data
  - Repeatability of data registration and fusion
  - Methods for curation and presentation for consistent analysis
  - Establishment of fundamental correlations between observations and meanings
    - E.g., design allowable and beyond



Obtaining Micro-scale Residual Stresses Using Synchrotron X-Rays

36 µm × 63 µm × 60 µm

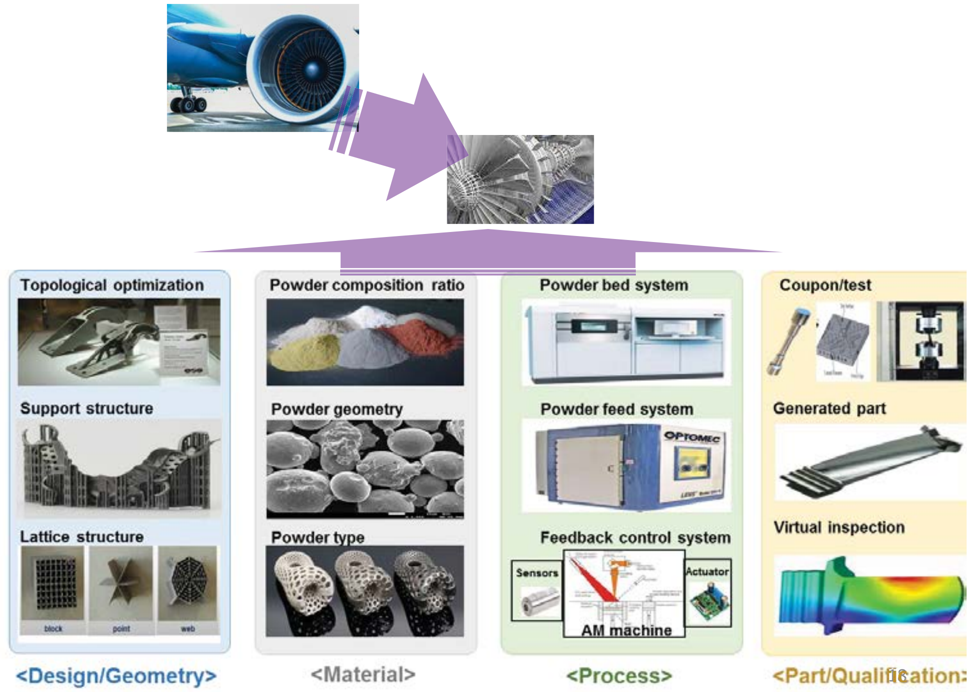


From NIST EL Measurement Science for Additive Manufacturing Program
Precursor Materials Qualification
Thien Phan, Project Lead

Thinking Back to Acceptance—Do Process Observations Reflect the Quality of the Part?

NIST

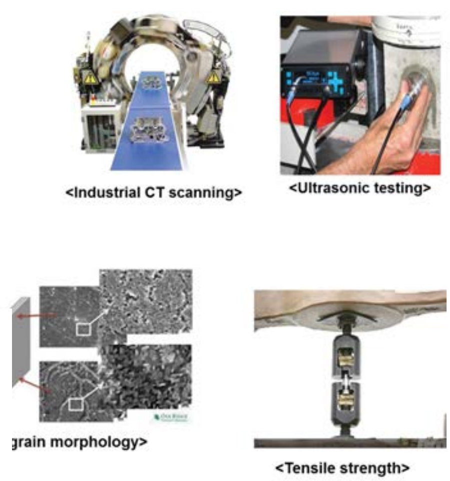
- Process assurance versus part quality assurance
- Digital twins can build confidence in processes and parts using:
    - Digital twin criteria that focuses on establishing provenance of part-process interactions
    - Digital twin criteria that focuses on establishing expectations of part within context of specific application

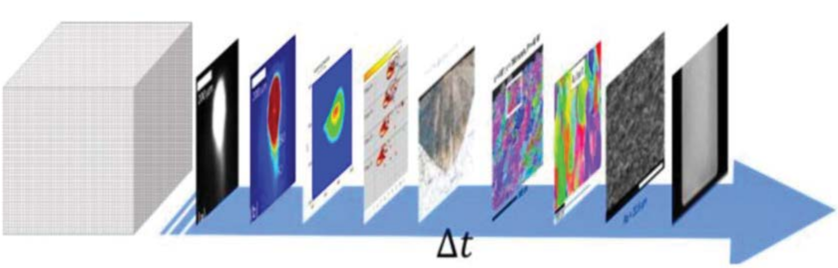


The Reconciliation Challenge: Process vs Part

NIST

- Distinguishing between process characteristics(fundamental criteria) and part characteristics (context specific criteria)
- FC and CSC measurements often established at different scales
    - Inherent differences in measurements do not always allow for one-to-one mappings
    - Integration will depend on application requirements and focusing on observable behaviors
    - Expansion of scope to system-of-system digital twins may be necessary to facilitate integration
- CSC performance criteria may not easily map to observable part characteristics
    - Process signatures and key performance indicators must be leveraged
    - VVUQ must be accounted for





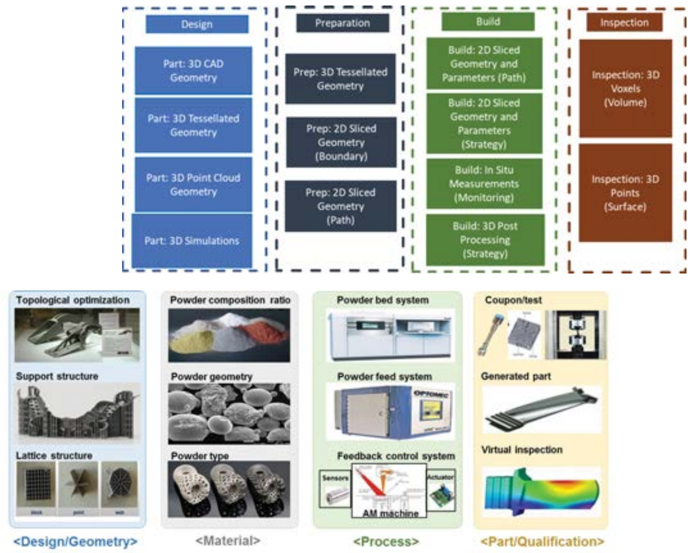
Fundamental Criteria (FC)- Process Assurance

NIST

Establish Fundamental Criteria

Five Fundamental Criteria (FC) for establishing digital twin of part:

1) Definition of successful fabrication process
   -e.g., validation against predictive model
2) Definition of what a “quality” part is
   -e.g., no crack formation
3) Established links between process characteristics and part characteristics,
   -e.g., data registration
4) Identification of process or part signatures of note
   -e.g., microstructure or surface roughness
5) Determination of acceptable metrics and measurement techniques for observation
   -e.g., grain orientation or average roughness



Context-Specific Criteria (CSC)- Part Assurance

NIST

Establish Context Specific Criteria

Five Context Specific Criteria (CSC) for establishing digital twin of part:

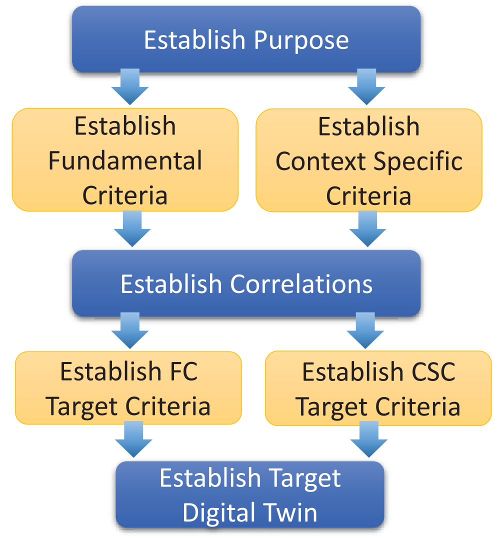
1) Identification of performance requirements
   -e.g., cyclic loading requirement
2) Identification of part characteristics that directly or indirectly will affect part performance
   -e.g., surface roughness
3) Identification of metrics to quantify noted part properties
   -e.g., average roughness
4) Establishment of baseline thresholds
   -e.g., Maximum surface roughness
5) Incorporation of uncertainty
   -e.g., safety factor

Towards a Digital Twin for the In-Process Quality Assurance of AM Parts

NIST

Establishing purpose

- Setting scope
  - Focus on appropriate lifecycle stages of development and use
- Setting context
  - Focus on Performance Requirements and Part Characteristics
- Setting target expectations
  - Focus on measurable quantities

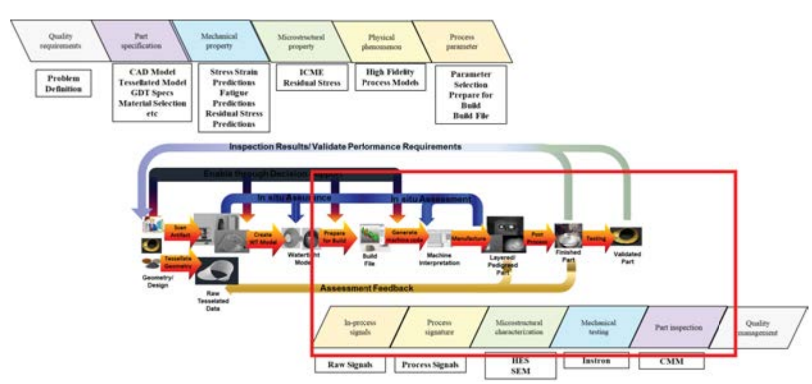


Witherell, Paul. "Digital Twins for Part Acceptance in Advanced Manufacturing Applications with Regulatory Considerations." The 46th MPA Seminar, Stuttgart, DE, 2021.
https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=933613

Standards Considerations to Address In-Process Part Quality Assurance

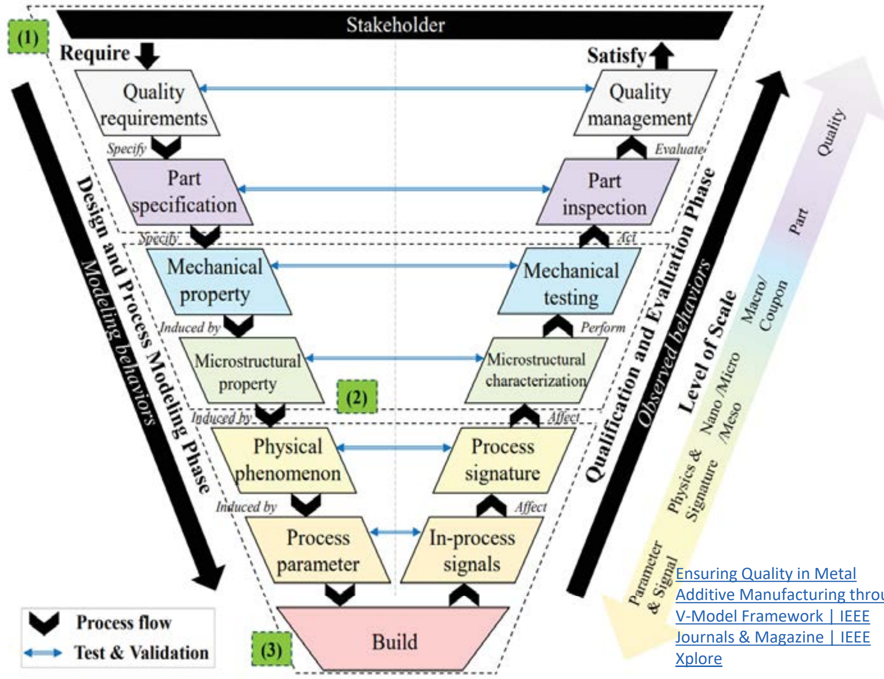
NIST

- Adopting digital twins for part quality assurance requires additional considerations in:
  - How we establish provenance at different stages
  - How we establish acceptance thresholds
  - How we test and validate for performance at earlier stages
  - How we explicitly address VVUQ at each stage
  - How we establish best practices
    - Context and application specifics
    - Case studies



Towards Establishing In-Process Acceptance

- Moving the box earlier requires
  - Accounting for specifications at all stages
  - Ability to traverse different scales
  - Ability to test and validate at all stages



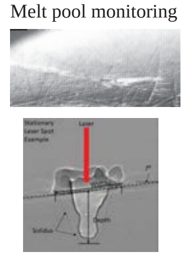
[Ensuring Quality in Metal Additive Manufacturing through a V-Model Framework | IEEE Journals & Magazine | IEEE Xplore]

One Approach: Building a Scalable Framework through Standards

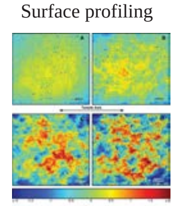
NIST Additive Manufacturing Metrology Testbed:

- Open PBF-LB/M platform,
- Metrology of process controls.

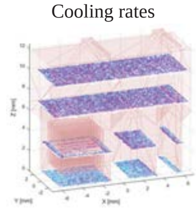
Melt pool monitoring



Surface profiling



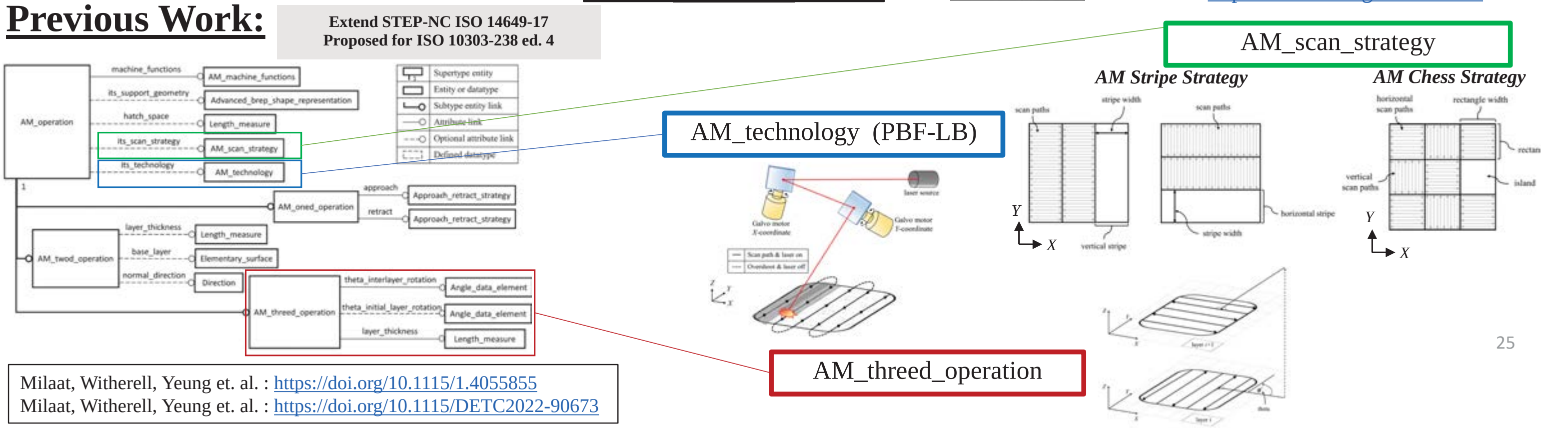
Cooling rates



Source: https://www.nist.gov/ambench

Previous Work:

Extend STEP-NC ISO 14649-17
Proposed for ISO 10303-238 ed. 4

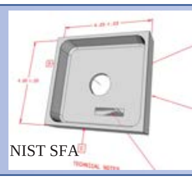
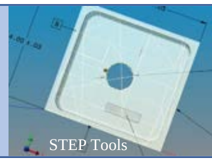
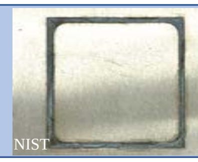


Milaat, Witherell, Yeung et. al. : https://doi.org/10.1115/1.4055855
Milaat, Witherell, Yeung et. al. : https://doi.org/10.1115/DETC2022-90673

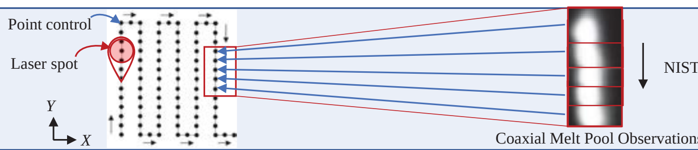
Approach: AM Discretization (PBF at Scale)

NIST ENGINEERING LABORATORY

Processing Discretization

	Specification	Observation
3D Orientation (X,Y,Z) Coordinates		
2D Sliced Layers, Scan Strategies		
1D Scan Paths, Contour		

0D Time Stepped Digital Command



Thinking Out Loud

NIST ENGINEERING LABORATORY

3D to 2D:
Layer/Slice Discretization (Layer thickness)
Anchored Orientation
Interlayer rotation

3D Geometry:
Full Part Representation
Sacrificial Geometry

2D to 3D

2D Geometry:
Layer geometry
Island Geometry

2D to 1D:
Scan Vector/Path
Infill Pattern, Interlayer rotation
Spot Size, Hatch Spacing
Pre/Post Contouring (Boundaries)
Layer to Island discretization strategy
List vs Bag- Order of Operations

1D to 2D

1D Geometry
Polyline Geometry
Island Geometry

1D to 0D
Sampling/Discretization Rate
Time Step
Start and Stop Times

0D to 1D

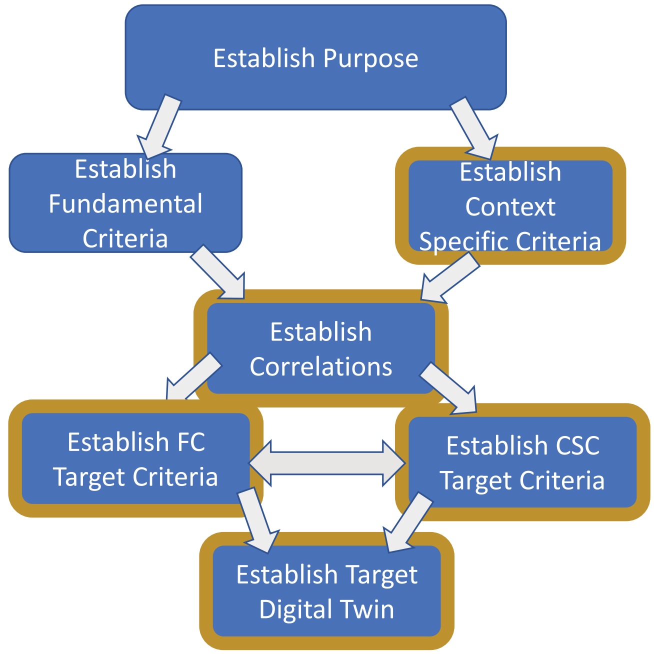
0D
Spatially Located Point

X

Final Thoughts

- Digital twins allow for assessing a part in virtual environment
  - Expected performance must be established
  - Target thresholds must be established
- Digital twins support compositionality in evaluation of parts
  - Crosslinks and reconciliation must be established
- Digital twins support analysis of reconfigured processes and designs
  - Data formats and platforms must be determined

Standards play a key role in realization



NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Thank You!

Paul Witherell, PhD

Measurement Science for Additive Manufacturing Program

National Institute of Standards and Technology

October 25, 2023

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

Qualifying Laser Powder Bed Fusion 316H for use with ASME Section III, Division 5

2023 NRC Workshop on AMTs for Nuclear Applications
October 24-26

Mark Messner
Argonne National Laboratory

Objective

- ***Develop a plan for producing an ASME Code Case to qualify powder bed fusion 316 stainless steel for high temperature nuclear applications that follows, as much as possible, past precedent in generating Code Case data and producing the final set of rules***
  - Types of test data will be the same no matter how you qualify a material
  - Provides a testbed to demonstrate accelerated qualification methods
  - Guarantees the program produces a useful product
- **Use Alloy 617 Code Case (N-898) as a precedent and example**
- **Tests with maximum durations of about 2.5 years would be required, so the draft Code Case would be about 3-4 years out + the time required to ballot for approval**

Qualification

- **Two fundamental requirements:**
  - Ensure that the process produces repeatable material properties – future components will have (nearly) the same properties as current material samples
  - Provide design material data based on experimental measurements. Typically, these design properties are statistical lower bounds on test data from several heats of material
- These two requirements are going to be the same no matter what process/method you use to qualify a material
- **A contract with designers:**

The material properties of any future components fabricated from the qualified material, using a qualified manufacturing process, will exceed the design material properties provided in the Code.

Qualification pathways

- **Hensley et al. (2021, J. Nuc. Ener.) proposed 3 qualification pathways**
  - *Deploy after post-processing*
  - In-situ data based qualification
  - Computational model based qualification: Extend ICME approach to AM process
- **Fall into two categories**
  - Demonstrate equivalence with an existing material
  - Demonstrate/provide process control and repeatability, then treat as a new material
- **Current plan sticks to a fairly conventional approach**
  - Though the data will provide a testbed and data for new methods
- **Some combination of equivalence and new material testing is the best short-term approach**

Equivalence versus new material

Equivalence

- Reduced testing required
- Provides a product with an existing “reference” to design engineers
- Postprocessing likely required

New material

- Could take advantage of improved performance of AM materials
- Could accept AM microstructure without postprocessing

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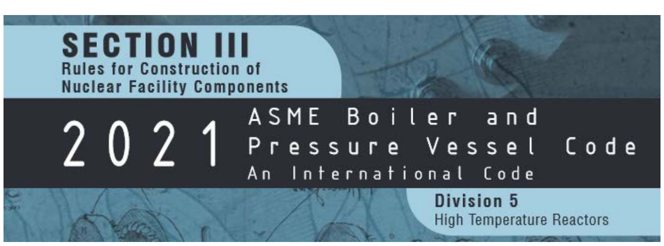
What is the Boiler and Pressure Vessel Code?



- Regulates design and construction of boilers, pressure vessels, and nuclear reactors
- Includes Section III covering nuclear reactors
  - Incorporated into NRC CFR for LWRs
  - “Endorsed” by the NRC by RG 1.87
- Any US based reactor or US reactor company is likely to design and build components to the Code
- Includes rules for design, construction, post-construction inspection, and in-service inspection

AMSE Terminology

- Two relevant sections of the ASME Boiler and Pressure Vessel Code:
  - Section III, Division 5 – high temperature design and construction rules (what we're targeting)
  - Section XI, Division 2 – in service inspection rules for high temperature nuclear components
- Could qualify a new material in two ways:
  - Modify the base Code itself
  - *Provide the new material data in a Code Case*
- Notionally, the only approval required is the Section III main committee and the Code Case can deviate from the base Code rules
  - However, most technical work shopped out to various Subgroups and Working Groups, as well as to Section II (materials)
  - Aligning with the current Code practice will help secure approval
- **Environmental effects (except thermal aging) are outside the scope of the ASME Code**
- Relevant ASME "guidelines"
  - Time extrapolation factor of 3-5 (wrought 316H would be 5)
  - Testing on at least 3 commercial (full scale) heats

Key differences: PBF versus wrought material

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

Key differences: Alloy 617 Code Case versus this effort

ALLOY 617 CODE CASE	PBF CODE CASE
• At least notionally, past procedure/precent from Grade 91 qualification • Existing test data to plan test matrices • Existing ASME/ASTM material standard • Required design properties (i.e. what tests) known in advance • No real starting point to formulate/ballot Code Case structure • ASME generally comfortable and familiar with the material type	• No direct precedent • Almost no prior high temperature testing • ASTM standard pending, but may not be enough to constrain high temperature properties • Can use Alloy 617 Code Case + balloting plan as a template • Limited expertise on relevant Code Committees

Key prerequisite decisions

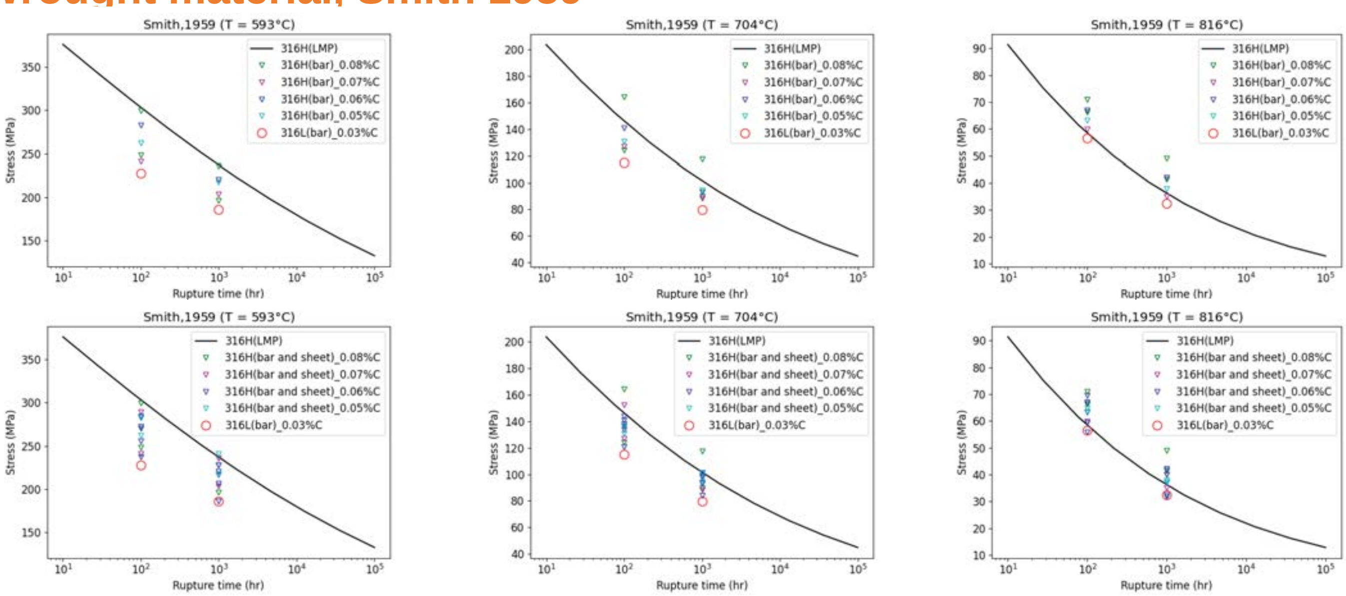
Decision	Comments
Material quality/repeatability requirements	Detailed in qualification plan, summary on next slide
Low or high temperatures?	High temperature qualification also requires low temperature qualification, we will need to provide low temperature data as well
Class A or Class B construction?	Class A is the better choice
316L, 316H, 316L(N), or 316FR?	316H – stronger creep strength, commercial wrought material
Temperature range	816° C for wrought material, but lower temperature would reduce amount of testing. Tests should go 50° C higher than upper limit
Maximum design life	Plan assumes 100,000 hours (like A617)
Surface finish	As built or not? Test data should be consistent, and requirement added to Code Case. *Data needed.*
Heat treatment	Decide (none, stress relief, full anneal, HIP) and stick with it for all test data. Preliminary testing in progress now.
Spatial variations and thickness effects	Still work in progress – one idea is bound with thin specimens.
Anisotropy	Literature review complete, some indication heat treatment could lessen effects. Alternatively, bound with testing in “worst” direction.
Welded and/or bolted construction	Weld qualification will be necessary at some point, but defer to a follow-on project
Data collection and standardization	Keep complete test records. Standardize a reporting format for all the key test types. Store data centrally, for project use. Plan on making available (eventually) to ASME

Current quality requirements

1. Meet the requirements of ASTM F3184 – Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed fusion
    1. Modified post-build heat treatment
    2. Modified chemistry requirements
2. Powder must meet UNS S31609 chemistry requirements for 316H plus additional O2 restrictions
3. Each fabricator shall demonstrate process control by one of several options. Documentation in the manufacturing plan
4. Post-build heat treatment (under development)
5. Witness testing on each build
    1. 4x room temperature tensile, 2 in z-direction, 2 in-x/y direction
    2. 1x creep-fatigue specimen in worst orientation (likely z), must meet HBB-2800 requirements
6. Surface finish per relevant ASTM test specification

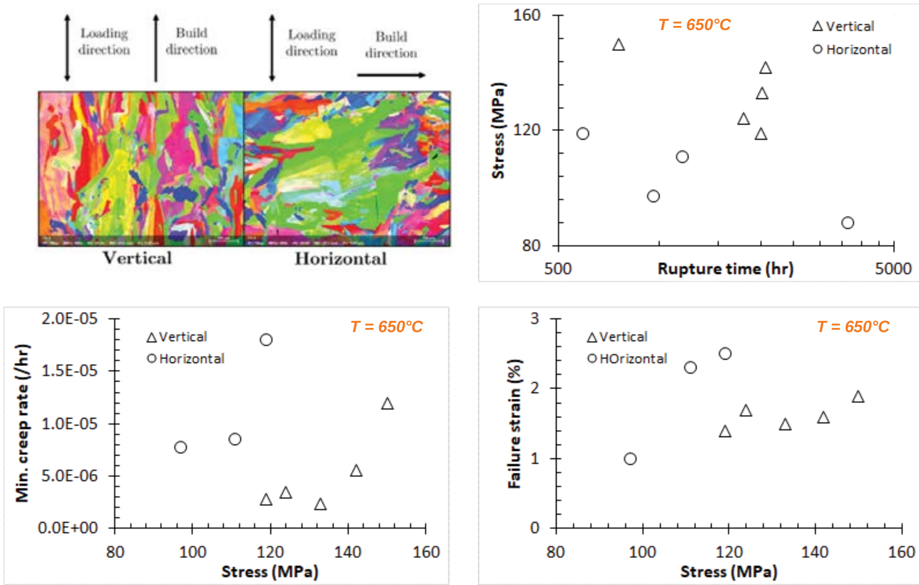
316H vs 316L creep properties

Wrought material, Smith 1959

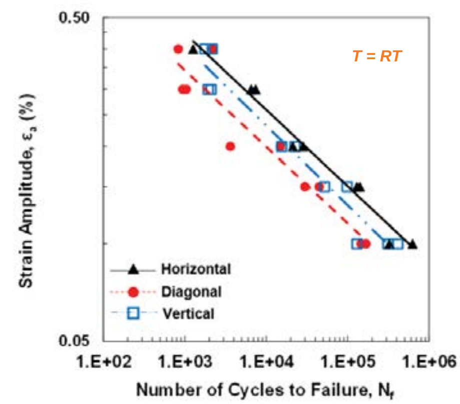


Anisotropy in high temperature properties

LPBF 316L



Williams et. al (2021), Additive Manufacturing 37, pp 101706



Shrestha et al. (2016) International Solid Freeform Fabrication Symposium. University of Texas at Austin, 2016.

Preliminary high temperature testing – heat treatment

Test type	Temp.	Other test conditions	Sample type	ASTM standard	Repeats	Total tests
Tension	20° C		Subsized	None	2	8
Tension	600° C		Subsized	None	2	8
Creep	600° C	248 MPa	Standard	E139	1	4
Creep	600° C	248 MPa	Subsized	None	2	8
Fatigue	600° C	0.5% strain range, R = -1	Standard	E606	1	4
Fatigue	600° C	1.0% strain range, R = -1	Standard	E606	1	4
Creep-fatigue	600° C	1.0% strain range, R = -1, 6 min tensile hold	Standard	E2714	1	4
					Total	40

Heat treatment	Temperature	Time	Quench	Pressure
As-printed	n/a	n/a	n/a	n/a
Stress relieved	899° C	1 hour	Air cool	n/a
Solution annealed	1093° C	1 hour	Air cool	n/a
HIP	1120° to 1163° C	4 hours	Cool in inert atmosphere	>100 MPa

Testing in progress at ANL, ORNL, and LANL

Xuan Zhang will talk about results here

Types of testing required

Draft test matrices completed

- *Thermophysical constants*
  - *Elastic constants (ultrasound)*
  - *Thermal expansion (dilatometry)*
  - *Diffusivity (laser flash heating)*
  - *Specific heat (calorimetry)*
  - *Density (displaced volume)*
- **Tension tests** (ASTM E8 and E21)
- **Creep tests** (instrumented, ASTM E139)
- **Fatigue tests** (ASTM E606 and E466)
- **Creep-fatigue tests** (ASTM E2714)
- Thermal aging tests (no standard)
- *Multiaxial creep* (no standard)
- *Strain rate jump tests* (no standard)
- *Stress relaxation tests* (ASTM E328)
- ***Cross-weldment creep tests*** (no standard)
- *Subsized testing* (tension, creep, cyclic)

Bold – subject to full 3x2 replication
Italic – could be omitted one way or another

Current test matrices

There are few firm requirements in the Code, but some guidance provided in HBB-Y based on ART program A617 experience.

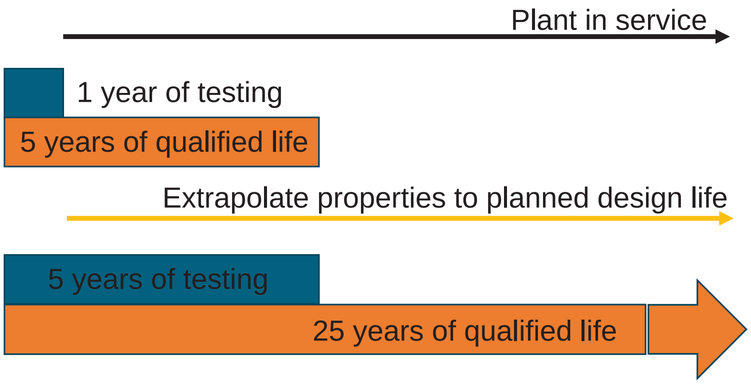
For critical data ASME expects to see data from at least 3 “heats” of material. We extend that here to 2 separate builds on 3 different machines

Full report contains detailed test matrices, included estimated durations based on wrought properties, applicable standards, etc.

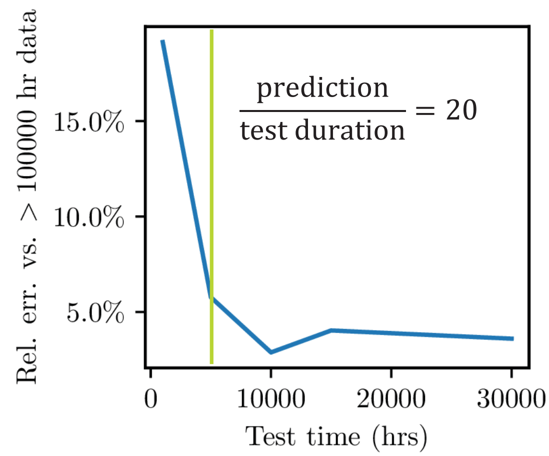
Test type	Conditions	Replicates	Total
Tension	17	6	102
Creep	36	6	216
Fatigue	34	6	204
Creep-fatigue	31	6	186
Thermal aging	6	2	12
Multiaxial creep	2	1	2
Strain rate jump	6	1	6
Stress relaxation	8	1	8
Subsized tension	9	2	18
Subsized creep	15	2	30
Subsized cyclic	5	2	10

Accelerated qualification

Staggered qualification



Mechanistic modeling



Qualification testing also supports demonstrating these and other ideas

Summary

1. **We aim to both qualify LPBF 316H for ASME III-5 Class A components, but also generate a testbed for evaluating accelerated qualification approaches**
2. **Testing underway in FY24**
3. **For more details see the report: https://www.osti.gov/biblio/1997134**

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Thanks

Office of Nuclear Energy, Advanced Materials and Manufacturing Technologies program

Bipul Barua

Ryan Dehoff et al.

Michael McMurtrey

Isabella van Rooyen and Subhashish Meher

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Computational model

- **I love this, but ASME would be skeptical**
- **And there are real problems:**
  - It's a huge amount of work to put on the designer. Now you need a microstructural model of your component accounting for the "actual" as-printed microstructure. And you need to postprocess out the microstructural features you care about from some in situ processing + characterization data.
  - Even giving people the tools to do this in the research project sense would be tough. You'd need some generic framework for going from local microstructure to local properties.
  - Formalizing the process would be difficult. The ASME Code is a legal document, you need to be quite prescriptive in how you write the Code rules.
- **There are advantages:**
  - Probably will give you the most accurate representation of your component = (hopefully) the most efficient design
  - No worries about throwing out/repair components with defects
  - A free digital twin you can use to monitor the component in service

In situ monitoring

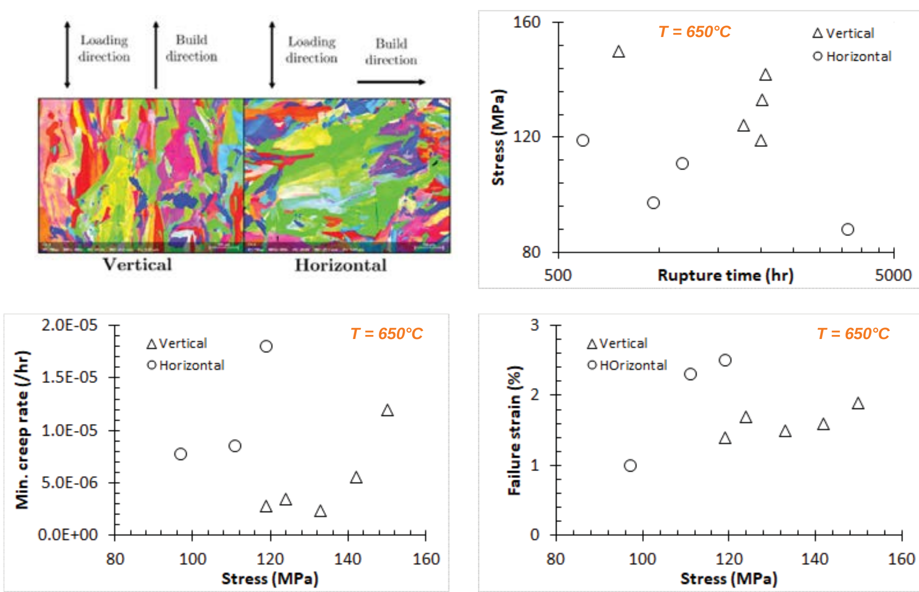
- **What defects do we care about?**
  - I don't think we know
  - Do I care about porosity? If so, how big of a pore do I need to worry about? Can we detect pores of this size?
  - Figuring out rules for "if you have a defect of size xxx you need to do something" would be challenging, but doable.
- **Can we detect the defects we need to worry about?**
  - It's possible that even if you have zero porosity or lack of fusion defects you still might have a "bad" microstructure.
  - Can we detect microstructural features based on the available camera data?
- **Commercial availability of the monitoring cameras/models**
- **Advantages:**
  - Codifying this is likely possible
  - Aims for definite criteria
  - Allows for "imperfect" components and/or repair and mitigation

Demonstrating equivalence

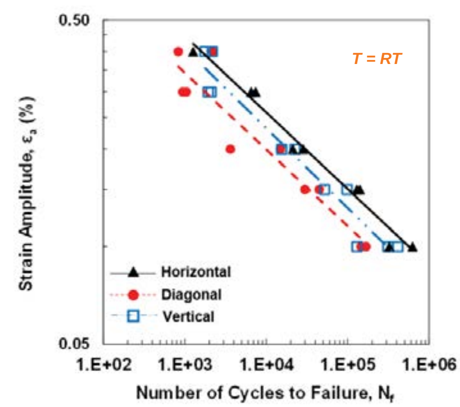
- This is in line with practices (for LWRs) that ASME seems to be comfortable with
- It's also in line with how we do things for wrought materials (i.e. equivalence with some set of minimum properties + basic microstructural characterization)
- It's probably our best bet
- **Challenges:**
  - If we care about 60 year creep strength (or creep fatigue) how would we demonstrate that directly?
  - How close to wrought (a) properties and (b) microstructures can we come?
  - What type of characterization/testing can we convince people to do on each build?
    - Tensile?
    - Creep?
    - Creep-fatigue?
    - Chemistry?
    - Grain size?
    - Grain morphology?
- You do lose some of the advantages of other methods (repairability, digital twins, etc…)
- Can't improve on wrought properties (maybe)

creep and Fatigue (RT) properties vs anisotropy

LPBF 316L

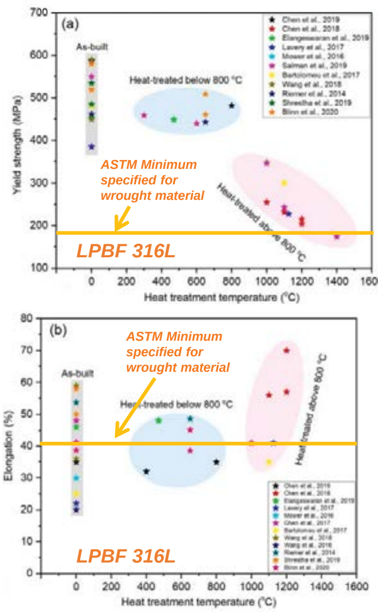


Williams et. al (2021), Additive Manufacturing 37, pp 101706

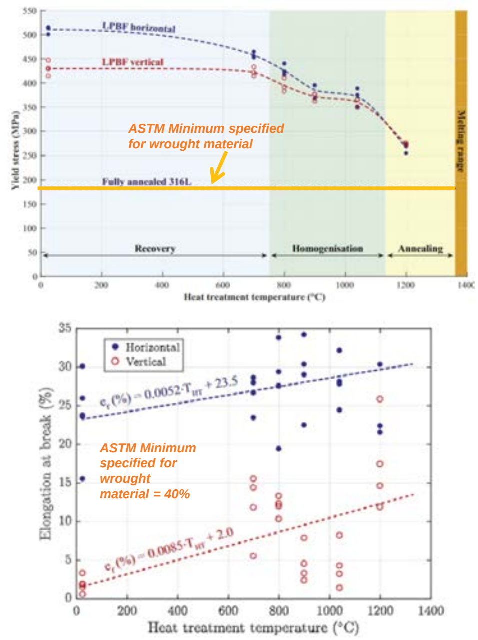


Shrestha et al. (2016) International Solid Freeform Fabrication Symposium. University of Texas at Austin, 2016.

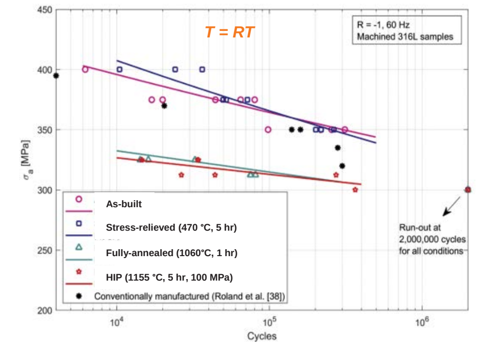
Mechanical properties vs heat treatment



Laleh et. al (2023) Progress in Materials Science, 133, pp. 101051)



Ronneberg et. al (2020) Materials and Design,189, pp. 108481)



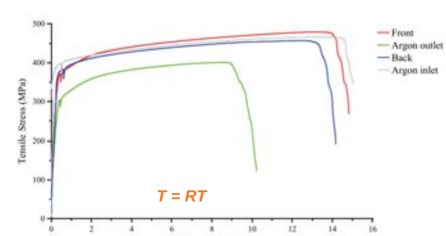
Elangeswaran et. al (2020), Materials and Design, 194, pp. 108962

Mechanical properties vs porosity and build location

- Tensile performance vs pore size/shape
  - Pore size matters but pore shape not much
  - Pores >125 μm diameter affects the most
  - Porosity affects ductility and strain at ultimate tensile strength the most
  - Ultimate tensile strength, elastic modulus, yield stress, and yield strain are not significantly affected by porosity

(Jost et al., 2021, Additive Manufacturing 2021, 39, pp. 101875)

- Mussatto et. al (Materials Today Communications 2022, 30, pp. 103209)
  - An effect of printing location on resultant part properties exists
  - Repeatability vary across locations
  - Front location prompted enhanced part densification due to a higher packing
  - Parts printed near the argon outlet are more liable to internal defects (porosity and lack of fusion defect)



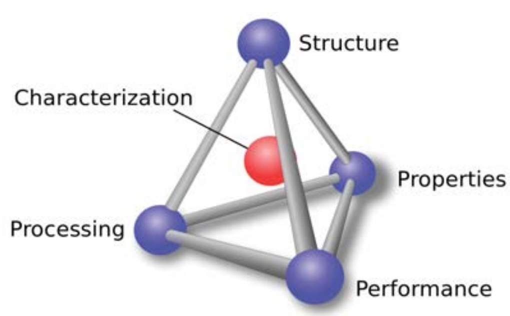
(Mussatto et. al, 2022, Materials Today Communications, 30, pp. 103209)

High Throughput, Rapid and Automated NDE for Optimizing Additive Manufacturing in Nuclear Applications

Amir Koushyar Ziabari,
Andres Marquez Rossy, Zackary Snow, Luke Scime, Selda Nayir, Holden Hyer, Joslin Chase, Caleb Massey, Peeyush Nandwana, Vincent Paquit, Ryan Dehoff

Oct 25, 2023

Characterization is critical for understanding processing, microstructure, properties, and performance



Challenges in Additive Manufacturing (AM):

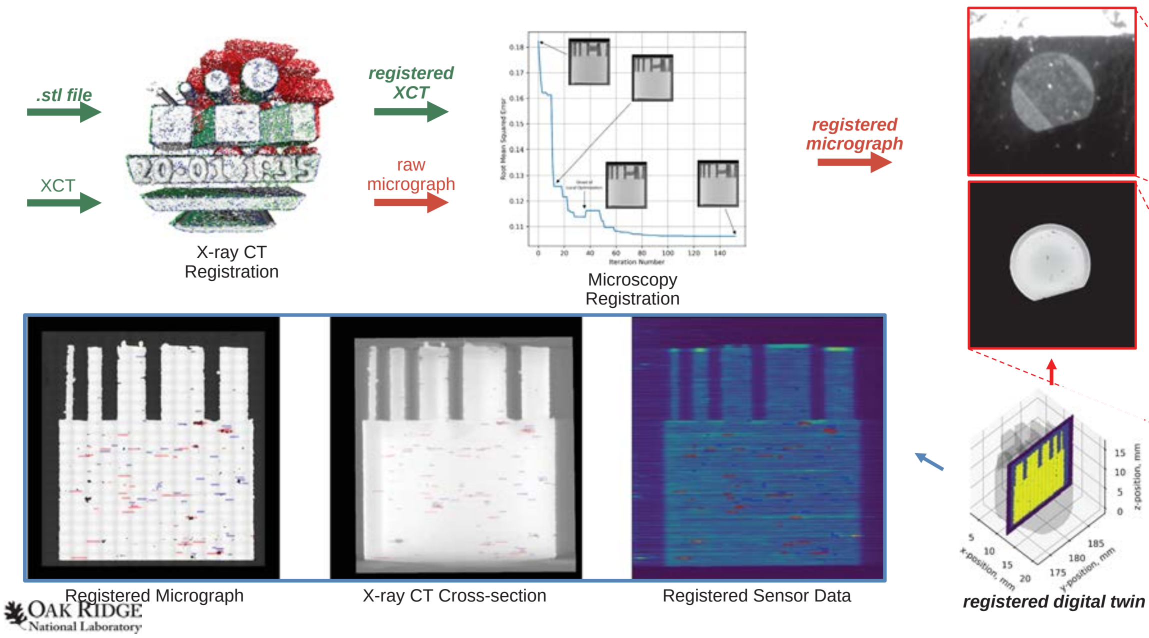
- ❑ Characterizing complex, spatially varying, multi-scale microstructures
- ❑ Characterize defect distribution
- ❑ Correlate to performance
- ❑ Learn to drive AM processes towards predictable, repeatable results

With current qualification approaches, it can take a decade to qualify a material for **nuclear applications**.

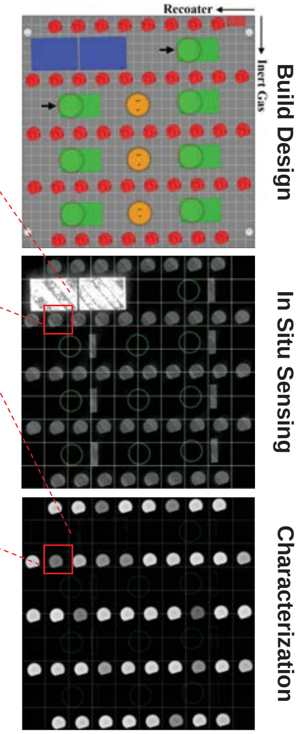
Rapid Qualification requires fast high-throughput characterization

AMMT Rapid Qualification Thrust Pathway

- ❑ Develop and leverage **automated fast characterization** to aid in understanding of **process-structure-property-performance** relationships, and in turn **finding optimum printing process window for fully dense 316 printing**.



Multi-Dimensional Data Correlation (MDDC)



High Level Connection between Thrusts

Understanding Process-Structure-Property-Performance Relationships

Process understanding for qualifying LPBF 316 SS (*Thrust-CM*)
ORNL, ANL, LANL
(Massey, Xuan, Montoya, et al.)

Improve and Optimize LPBF 316 SS to Improve Heterogeneity in AM Material (*Thrust-PN*)
ORNL (Nandwana, et al.)

This Thrust
Automated, High-Throughput Materials Characterization Techniques

Multi-Dimensional Data Correlation (MDDC) Platform
ORNL (Paquit, Scime, et al.)

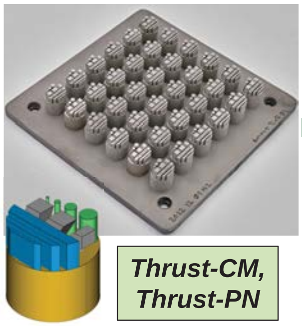
Process Modeling and Variability in AM SS316
ORNL (Plotkowski, et al.)

Improving and Optimization of Existing Reactor Materials for Advanced Manufacturing
ORNL, PNNL, ANL, INL (Dryepondt, et al.)

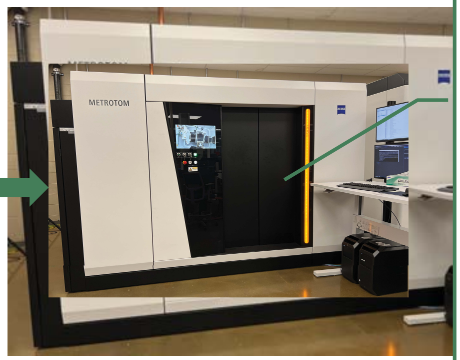
- ❑ This diagram is solely based on current collaborations.

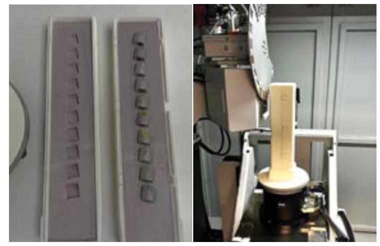
Rapid Characterization Process

Design of Experiment



Thrust-CM, Thrust-PN





1. Loads 10 coupons at a time
2. Quickly scan a coupon
3. Output the data

1. Receive the data (after each scan)
2. **Perform fast DL-based reconstruction, segmentation, and image analysis**
3. Generate and save output

1. Register the data to the in-situ and Peregrine data
2. Produce report
3. Store the data

Characterization summaries and data

MDDC

Non-Destructive Characterization (NDC) Process Using XCT

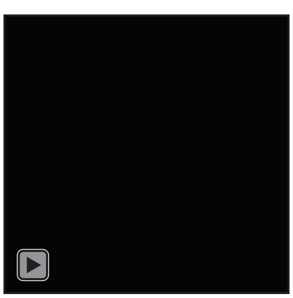
Sample

Reconstruction

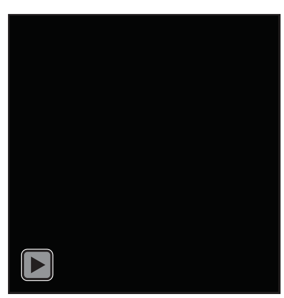
Analytics

Information
1. Flaws
2. Anomalies
3. Defects
4. Dimensions
5. Surface

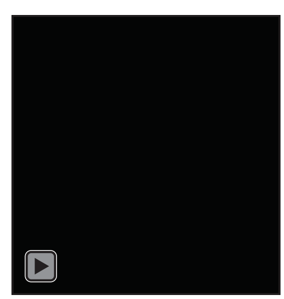
Sample



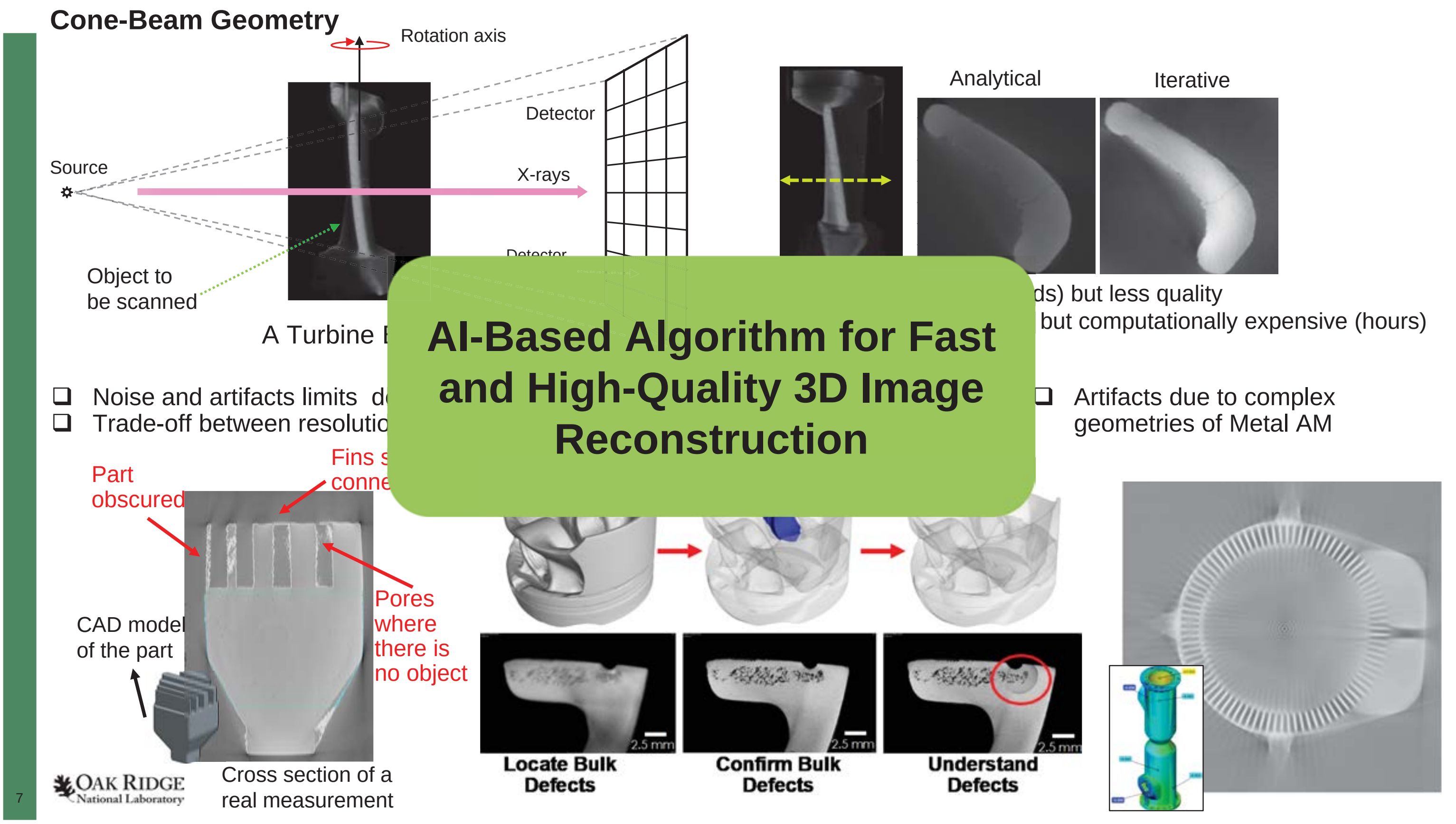
Raw Measurement



Reconstruction



Segmentation


Cone-Beam Geometry
Rotation axis
Detector
Source
X-rays
Detector
Object to be scanned
A Turbine B
Analytical
Iterative
ds) but less quality
but computationally expensive (hours)
AI-Based Algorithm for Fast and High-Quality 3D Image Reconstruction
❑ Noise and artifacts limits d
❑ Trade-off between resolutio
❑ Artifacts due to complex geometries of Metal AM
Part obscured
Fins s conne
Pores where there is no object
CAD model of the part
Cross section of a real measurement
2.5 mm
Locate Bulk Defects
Confirm Bulk Defects
Understand Defects
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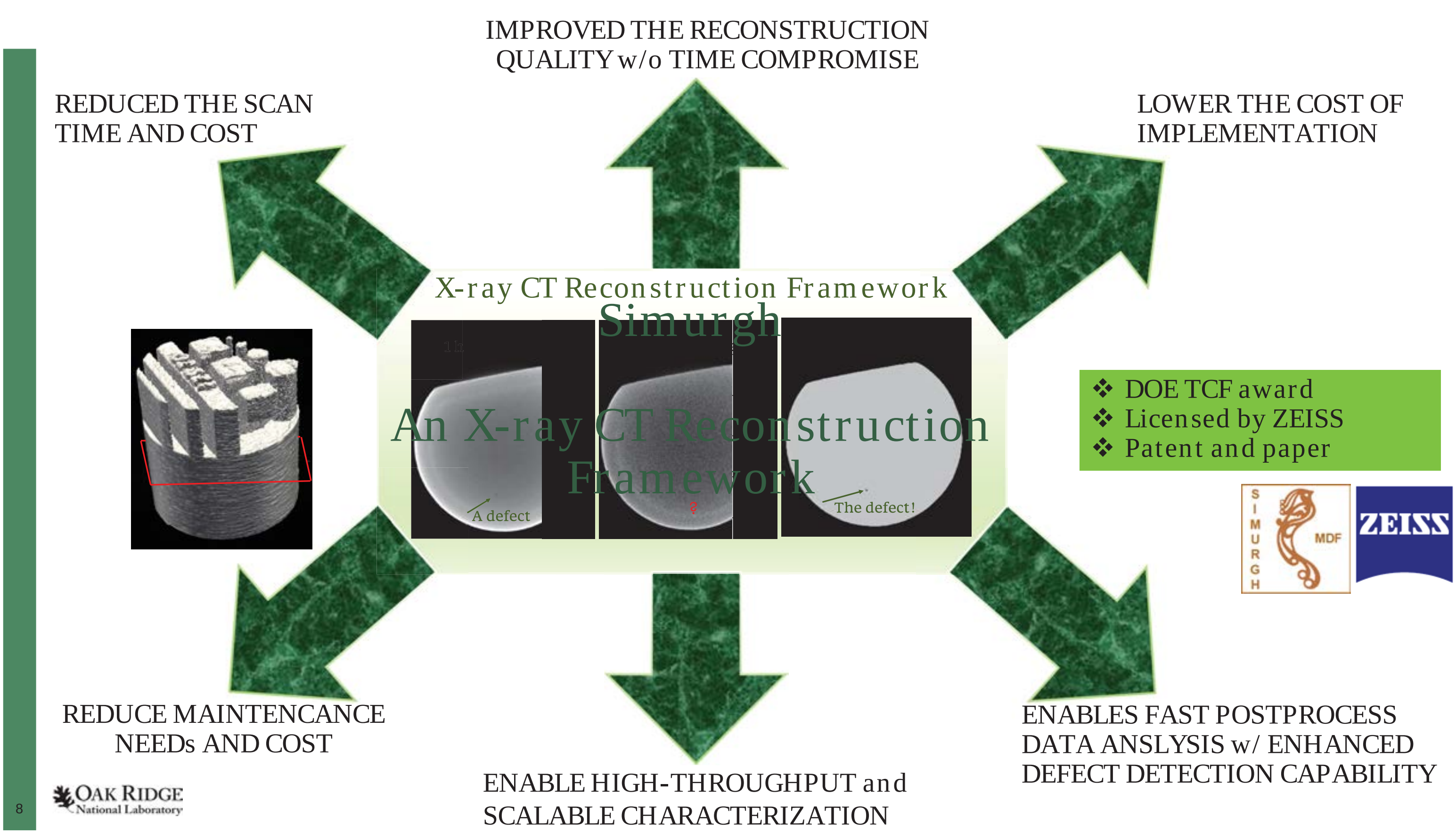
7


IMPROVED THE RECONSTRUCTION QUALITY w/o TIME COMPROMISE
REDUCED THE SCAN TIME AND COST
LOWER THE COST OF IMPLEMENTATION
X-ray CT Reconstruction Framework
Simurgh
An X-ray CT Reconstruction Framework
A defect
The defect!
❖ DOE TCF award
❖ Licensed by ZEISS
❖ Patent and paper
SIMURGH
MDF
ZEISS
REDUCE MAINTENCANCE NEEDs AND COST
ENABLE HIGH-THROUGHPUT and SCALABLE CHARACTERIZATION
ENABLES FAST POSTPROCESS DATA ANSLYSIS w/ ENHANCED DEFECT DETECTION CAPABILITY
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CAD-, Physics- and Deep Learning-Based Image Reconstructions

2.5D CAD-DLMBIR	Simurgh

1. Generate Reference Data

- ❑ CAD Models
- ❑ Physics-based Beam Hardening parameters

MBIR

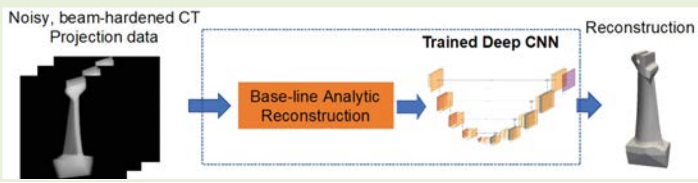
Reference High-quality Reconstruction

2. Tr… NN)

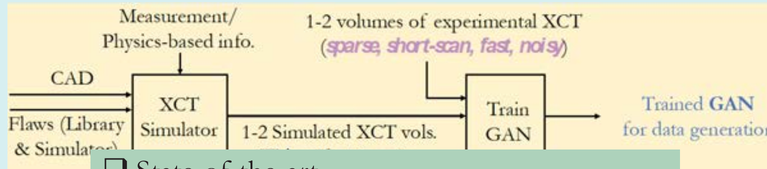
…ce …ality

- ❑ Fast, high-quality reconstructions, reducing scan-time, reducing cost and labor.
- ❑ Higher TRL research product.
- ❑ Has been integrated into the characterization framework

3. Test Deep CNN on new data!



1. Train GAN using CAD (Data Generator!)



2. Syn… N!

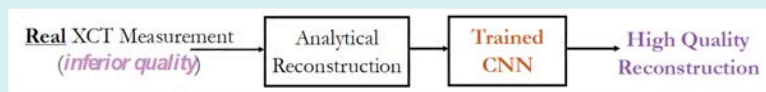
CAD

Flaws (Lib… & Simulat…

Trained CNN

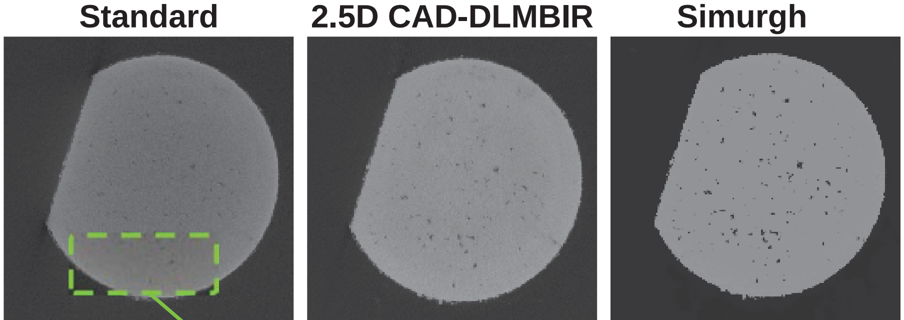
- ❑ State-of-the-art
- ❑ Addresses challenges with CAD-DLMBIR and can produce even more high-quality reconstructions
- ❑ To be integrated into the characterization framework

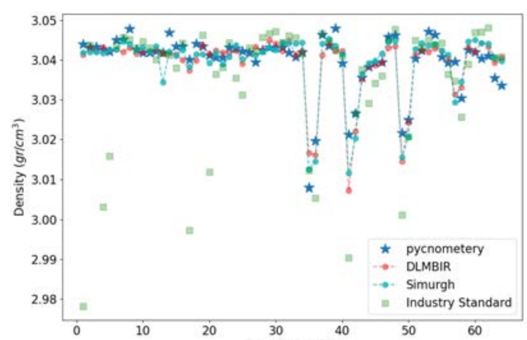
3. Test Deep CNN on new data!



Results for a Lower Density Alloy

Standard **2.5D CAD-DLMBIR** **Simurgh**





- ❑ 64 test data volumes
- ❑ Simurgh is only trained on synthetic data
- ❑ Further reduce the scan time and dealing with denser materials

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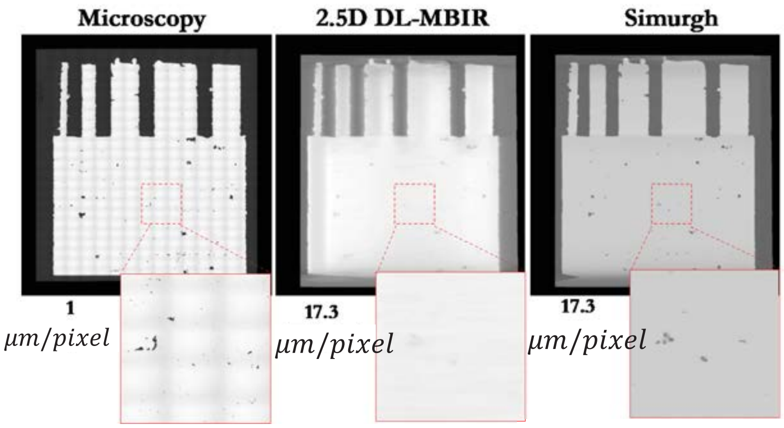
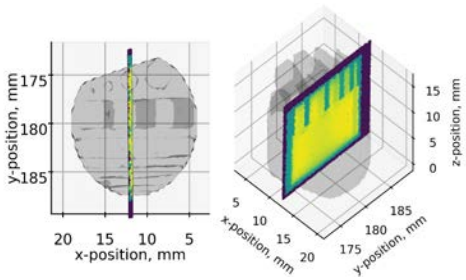
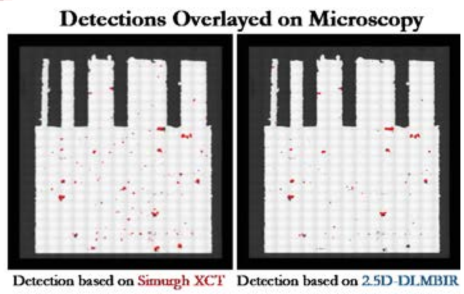
Ziabari, et al. IEEE ICIP, 2022.

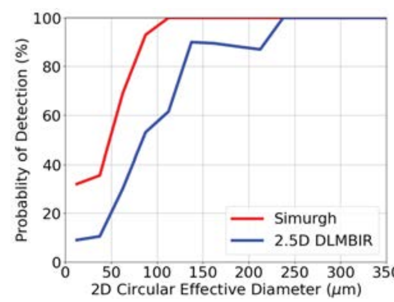
Inconel 718 Results (Highly Density Alloy)



- ❑ 1μm resolution optical microscopy as ground truth.
- ❑ 3.5X better detection capability at sub-voxel resolution.
- ❑ Allows for detection of 100% of defects >100μm effective diameter!
- ❑ 2.5D DLMBIR already outperforms standard approaches by ~4X!

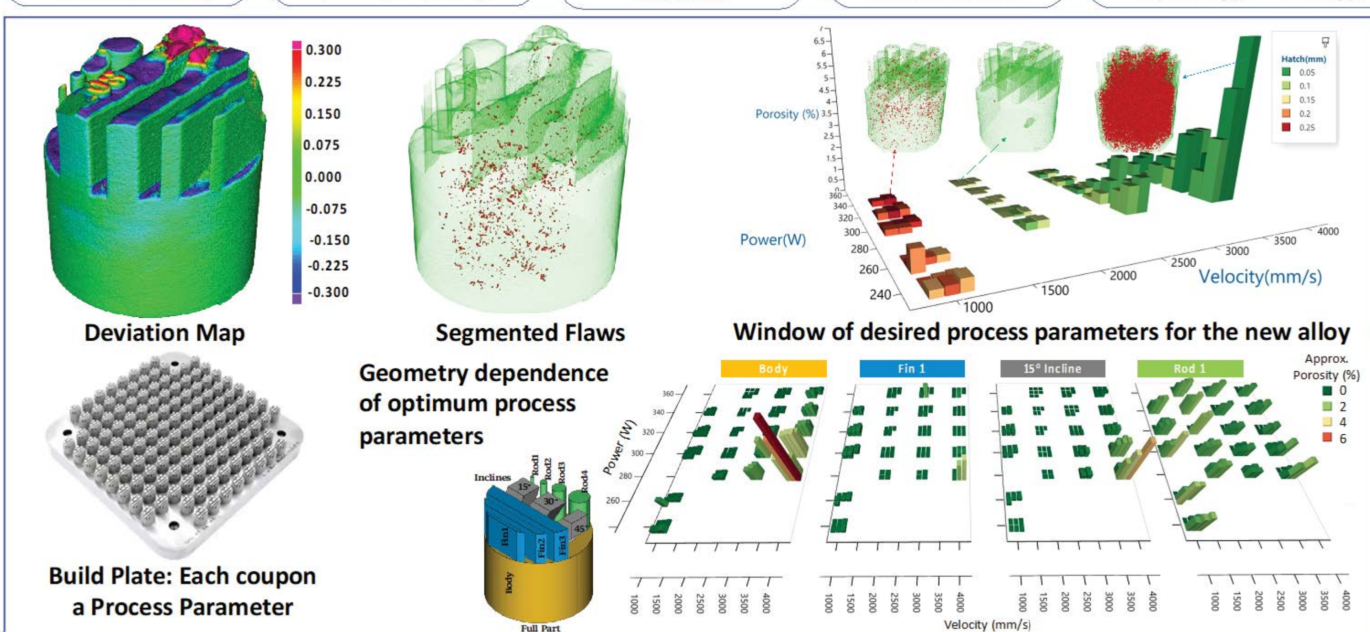






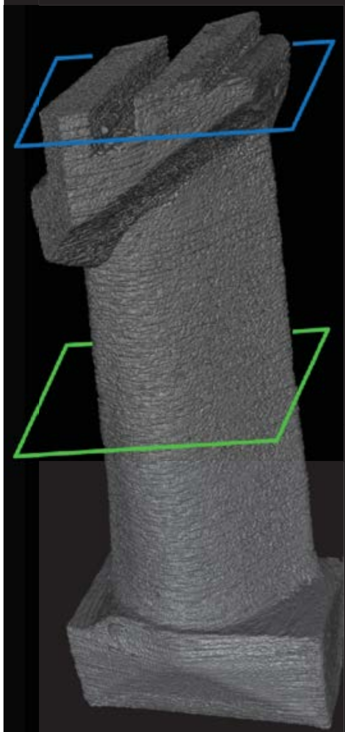
Fast Automated Characterization for Process Parameter Selection

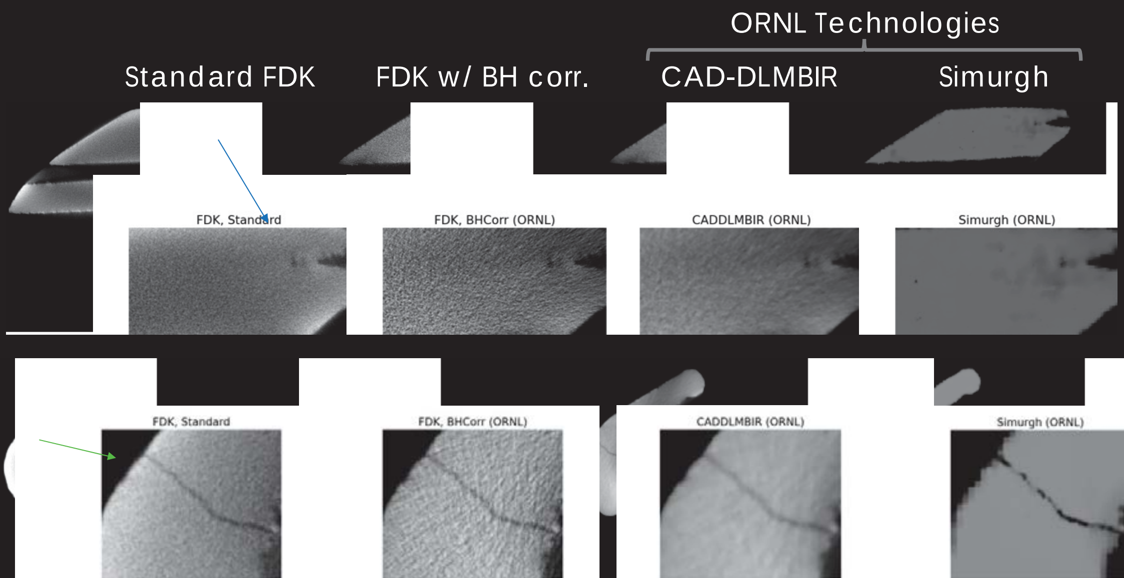
1. Design of Experiment (DoE) Parameters (**A Novel Material**) → 2. Print the build plate. Remove parts from plate: (~100 parts per plate) → 3. X-ray CT **at fraction** of optimal scan time based on material → **4. Fast, consistent and accurate AI-Based X-ray CT Reconstruction** → 5. Analysis (segmentation,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



Ziabari, et al. Nature Computational Materials, 2023.

Large Complex Geometries

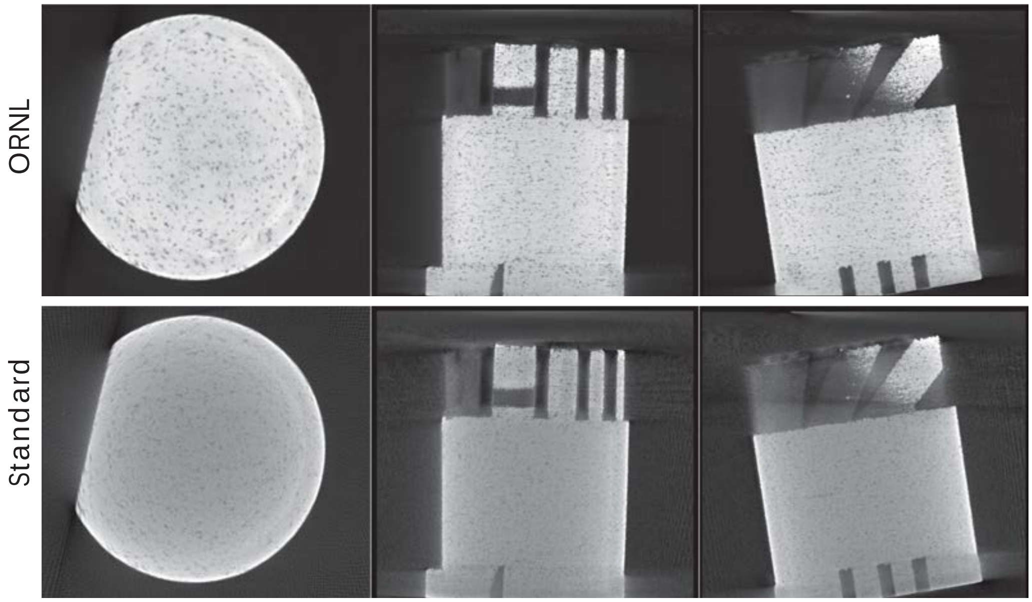




ORNL and AMMT

- 15 builds, >540 coupons
- Two systems
- Builds with various process parameters per coupon
- 316L and 316H

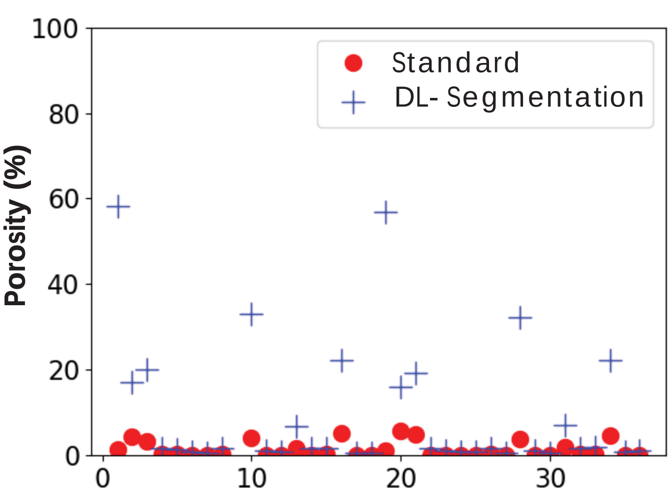
Deep Learning (DL) Based X-ray CT Reconstruction

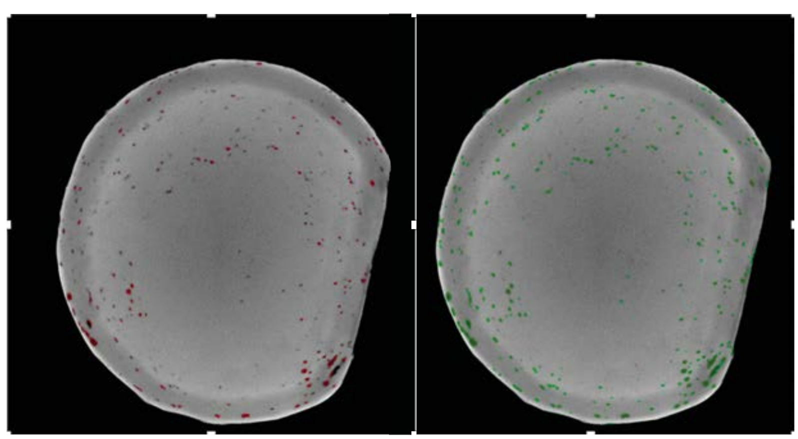


DL-reconstruction allows for resolving the flaws using 6X faster scans in thick dense 316L/H

Deep Learning (DL) Based X-Ray CT Segmentation

- *Noticed that Standard segmentation has limited accuracy (through comparison to high resolution microscopy data).*
- *Developed DL-based segmentation approach in this thrust*

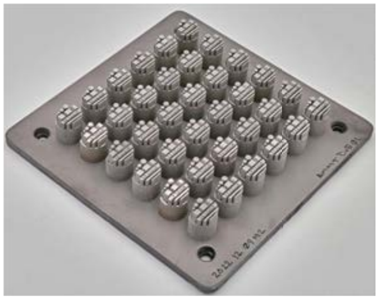




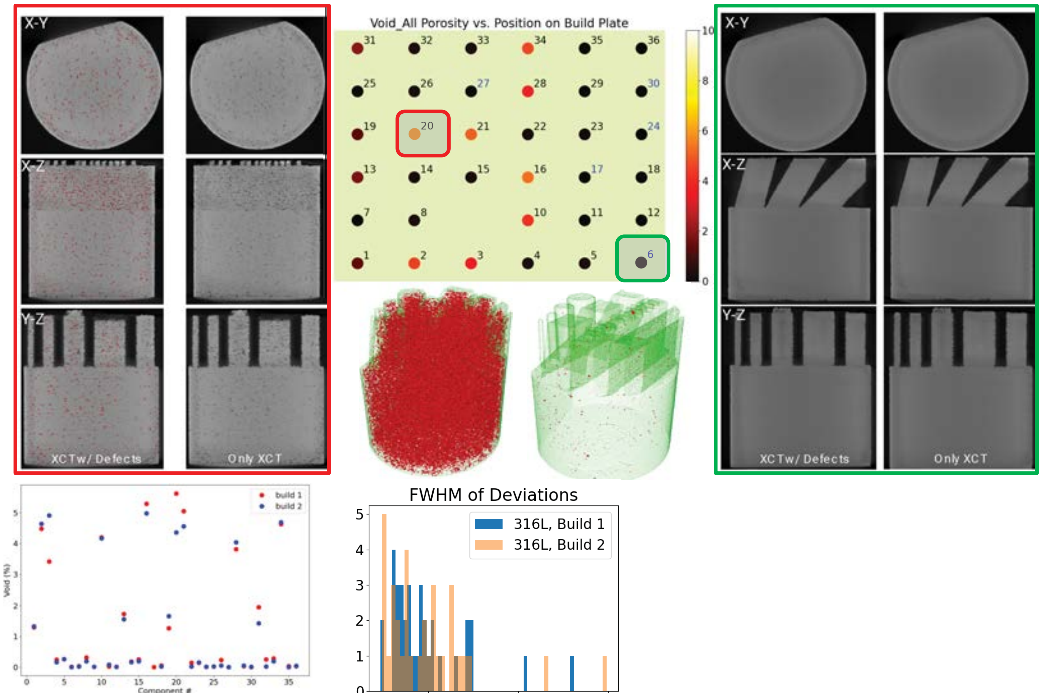
Red: Standard; **Green**: ORNL DL- Segmentation

DL-Segmentation, verified through high-res microscopy, demonstrates that true porosity can be underestimated by 60X with standard algorithms

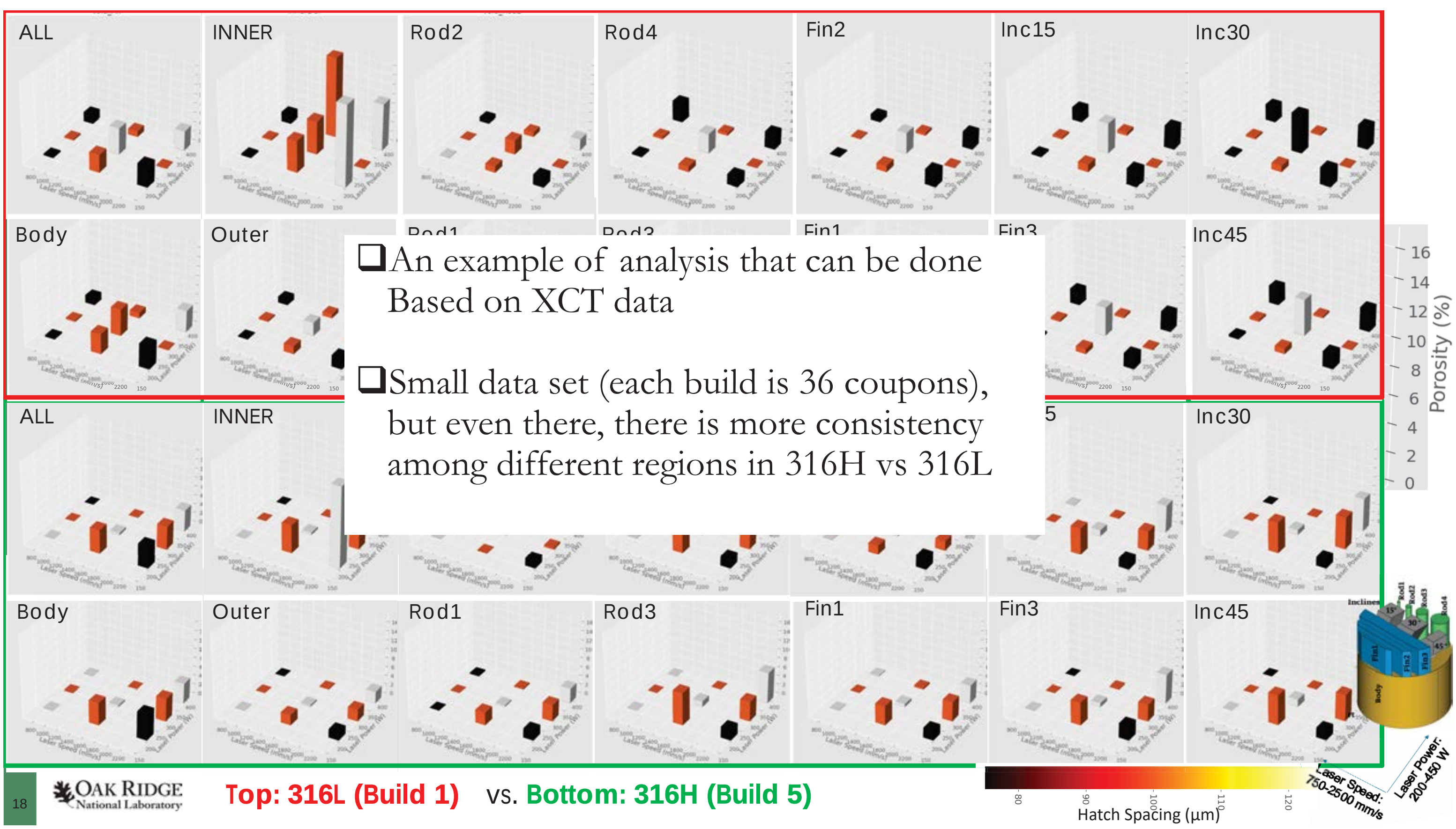
Build Consistency Analysis (B1 vs. B2)



- ❑ Parameters repeated on Parts 01-18 & 19-36
- ❑ Randomized order to avoid systematic errors
- ❑ XCT, 20min per coupon
- ❑ Two builds showed consistent behavior



Correlation = 0.98

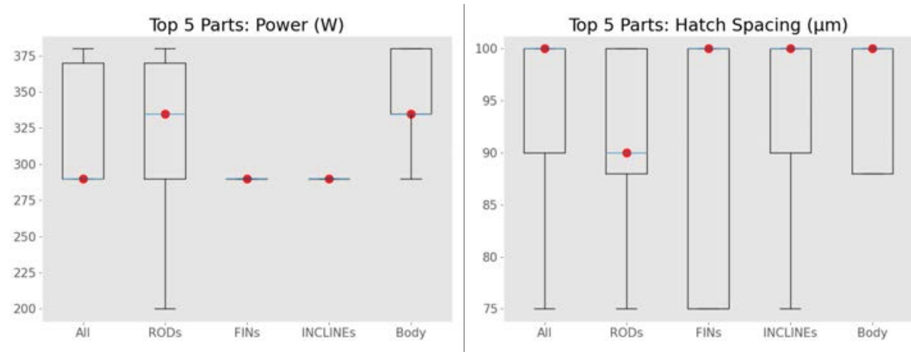


❑An example of analysis that can be done Based on XCT data

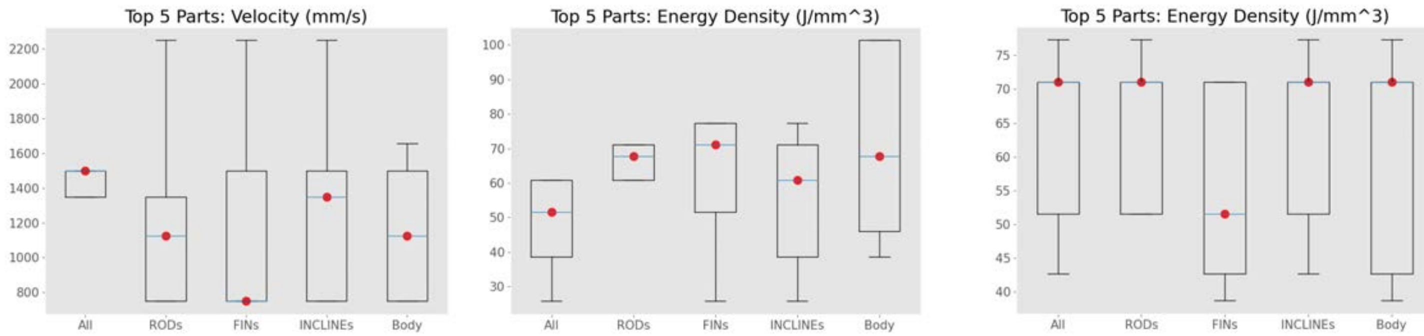
❑Small data set (each build is 36 coupons), but even there, there is more consistency among different regions in 316H vs 316L

Top: 316L (Build 1) vs. **Bottom: 316H (Build 5)**

ROI Dependence of Process Parameters of Top 5 Coupons



- ❑ 316L, 4 builds, 141 coupons
- ❑ 316H, 1 build, 36 coupons
- ❑ Single track characterization (LANL), EOS:
  316L: 54 J/mm^3
  316H: 95 J/mm^3
- ❑ Here with M2, is about 70J/MM^3 for both



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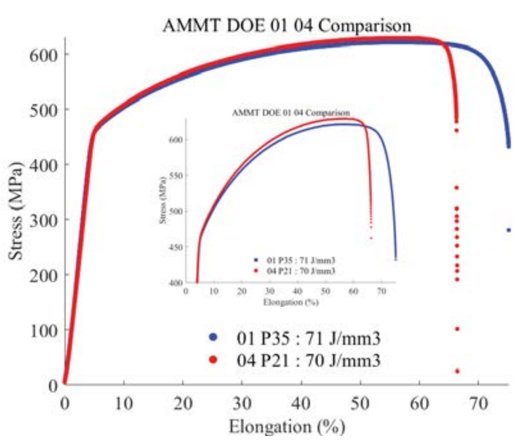
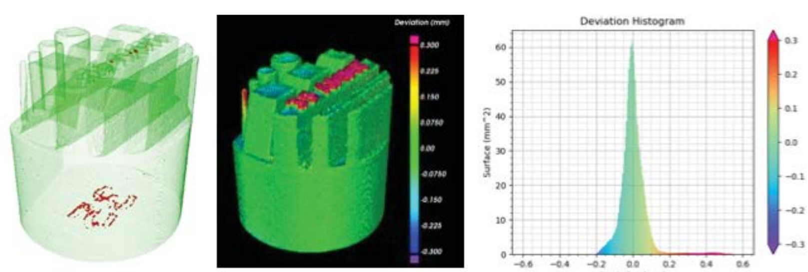
Parts With Same Energy Density (71J/mm³) And Different Process Variables



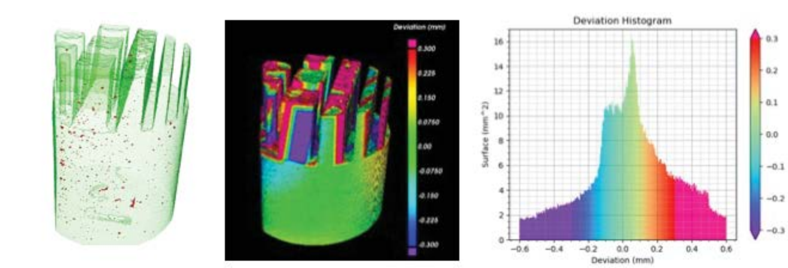
Similar energy density, despite the change in individual parameters results in **same yield strength** and insignificant differences in UTS, **BUT:**

B1-P35



- ❖ Geometric features closer to desired tolerances
- ❖ Low power (200W), low speed (750mm/s), higher hatch (75mm)

B4-P21



- ❖ Pores distributed across the whole sample
- ❖ **Larger geometric deviations**
- ❖ High power (380W), higher speed (1800mm/s), smaller hatch (60mm)

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Variations in LPBF 316H SS Microstructure Within Minimized Porosity Process Space

Scientific Achievement

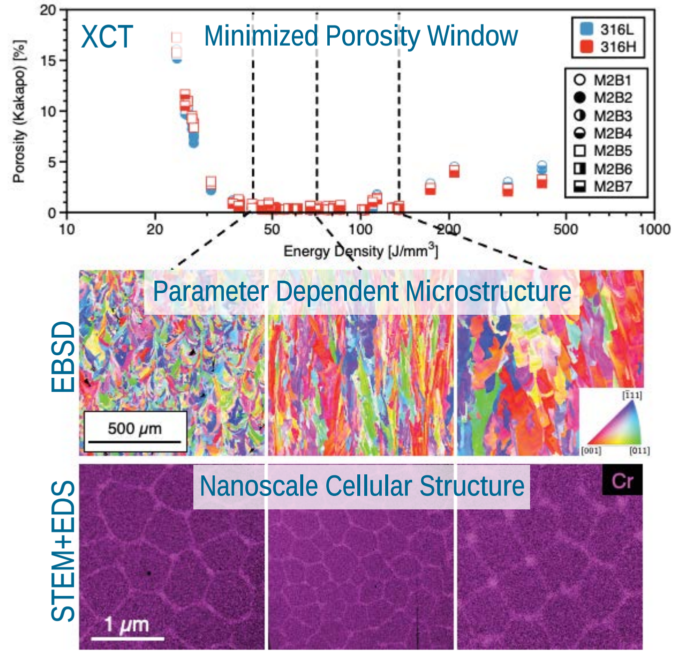
- A total of 252 SS Zeiss specimens (144 in 316L & 108 in 316H) printed as part of the concept laser experiments.
- Two characteristic microstructures identified for future campaign testing (refined chevron structure and columnar structure).

Impact & Potential Application Space

- For complex components, both of these characteristic microstructures may be present, invalidating assumptions in historical qualification frameworks.

Details

- High-throughput X-ray computed tomography (XCT) used to identify a minimum porosity process window for 316L and 316H SS, followed by targeted electron microscopy.



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

High-Throughput XCT Identified Alternative Renishaw Processing Window for 316H

Scientific Achievement

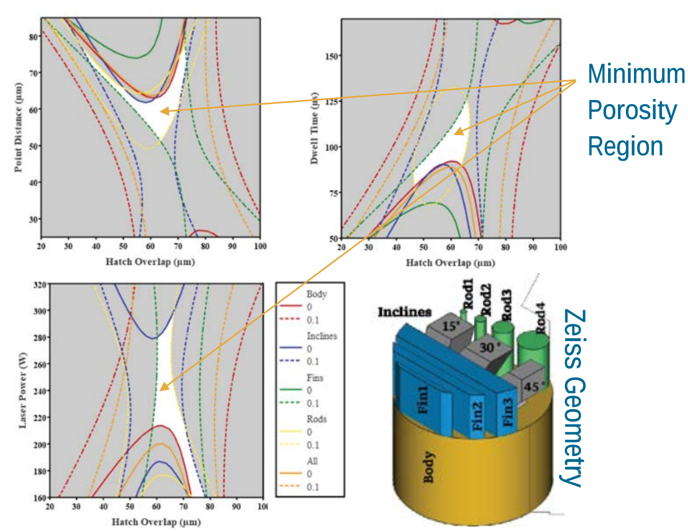
- A total of 390 SS Zeiss specimens (210 in 316L and 180 in 316H) printed as part of the Renishaw LPBF optimization efforts.
- High-throughput X-ray computed tomography (XCT) successfully used to probe geometry-specific porosity trends in AM parts.

Impact & Potential Application Space

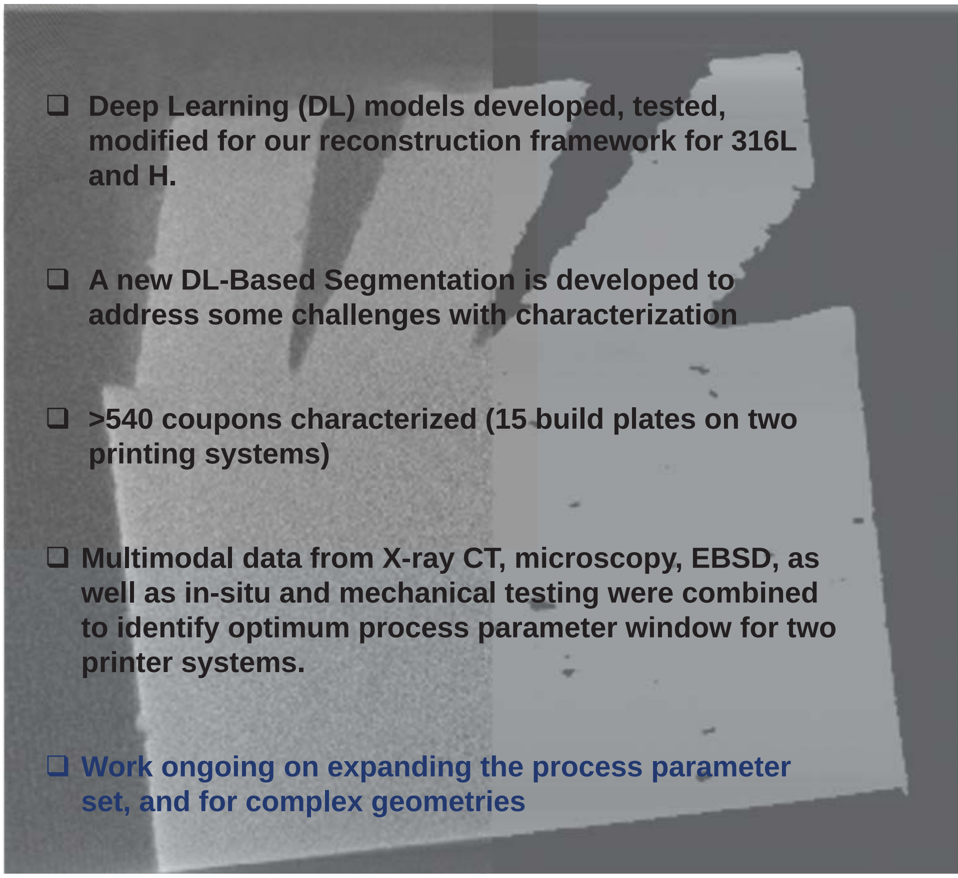
- For samples printed using 316H SS, there is only a small processing window that successfully minimizes porosity within all geometric features in the experimental Zeiss coupon, requiring additional modeling and experimentation.

Details

- High-throughput XCT used to map porosity in different regions (inclines, rods, fins, etc.) in a miniature Zeiss specimen used for LPBF print optimization at ORNL.



XCT porosity trends for one 316H build PB performed on the Renishaw varying three processing parameters. In each plot, the area between solid and dashed lines indicates porosity below 0.1%. White regions indicate processing space where porosity is minimized for all overlaid curves.



- Deep Learning (DL) models developed, tested, modified for our reconstruction framework for 316L and H.
- A new DL-Based Segmentation is developed to address some challenges with characterization
- >540 coupons characterized (15 build plates on two printing systems)
- Multimodal data from X-ray CT, microscopy, EBSD, as well as in-situ and mechanical testing were combined to identify optimum process parameter window for two printer systems.
- Work ongoing on expanding the process parameter set, and for complex geometries

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ZEISS Team
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Questions?

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

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Aerospace Framework for Certification and Qualification for Advanced Manufacturing Technologies with Examples in Additive Manufacturing Using Ti-6Al-4V EB Powder Bed Fusion

prepared for: 2023 NRC Workshop on AMTs for Nuclear Applications

prepared by: Kevin T. Slattery, D.Sc, TBGA

1-636-279-4467 / kevin@barnesglobaladvisors.com

25-October-2023

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Abstract

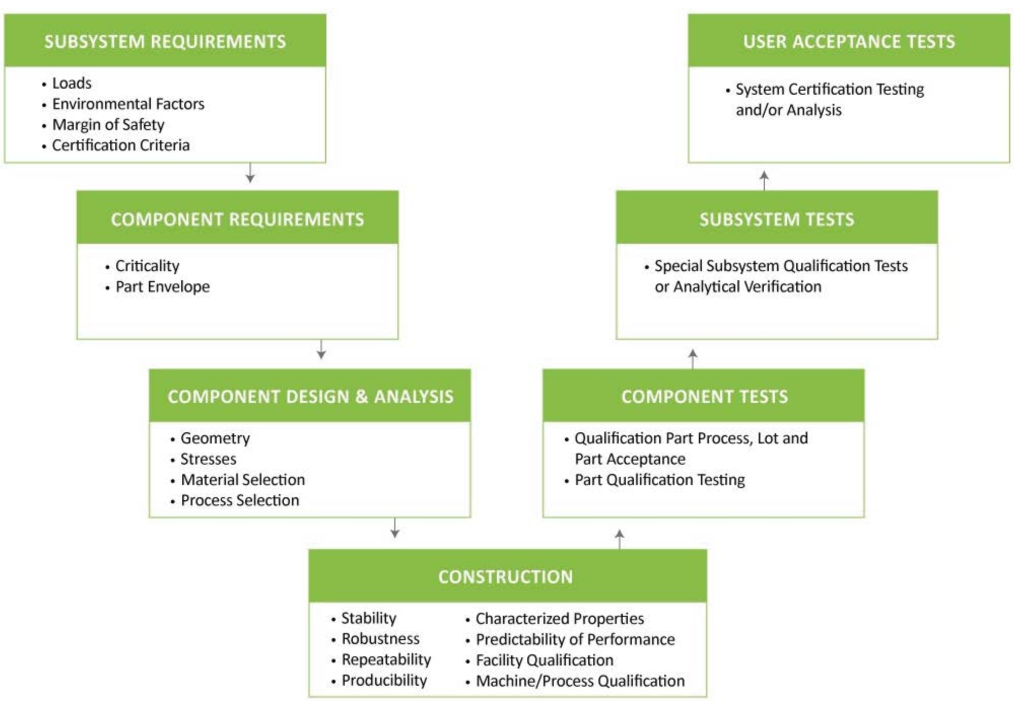
While the materials, requirements, and service environments between aerospace and nuclear applications differ, there is much commonality including part criticality, service life, and use of nondestructive testing. Additionally, as small reactors are developed, annual production rates for nuclear parts will approach those for aerospace. This presentation will discuss a common framework used for certification and qualification, with examples on how it would be applied for an alloy in common between aerospace and nuclear, 316L, replaced with Ti-6Al-4V. This framework and the example will address feedstock, process development, design values, equipment & facility qualification, part qualification, and certification.

* 316L Laser Powder Bed Fusion Data Available on America Makes CORE

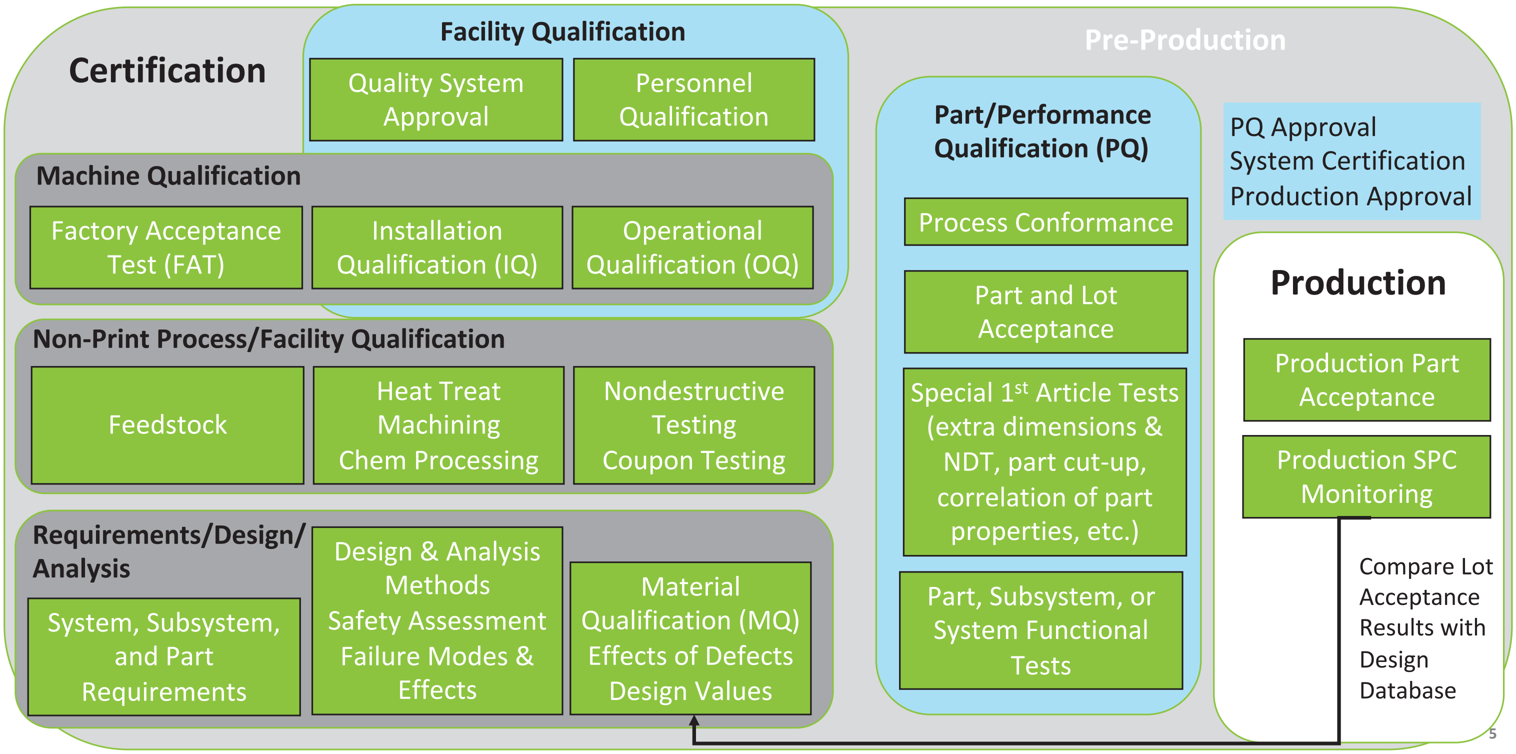
Certification & Qualification in AM

- Many Regulatory Bodies and Certifying Agencies Have Detailed Definitions
- All Engineered Products are Certified and Qualified to Some Extent
- My Basic Definitions
  - Certification – A component that meets design intent is fit for service in a system
  - Qualification – A properly manufactured component meets design intent
  - Part & Lot Acceptance – A part is equivalent to the qualified part

Related to Systems Engineering 'V'



Qualification & Certification Relationships



Certification and Qualification Taxonomy

Term	Sub-Term	Simple Multi-Industry Description
System Certification (FAA Type Certification)		Demonstration through test and analysis that the overall system will meet requirements. Often involves full-scale test of system.
Production Certification (FAA Term)		Manufacturing facilities are capable of repeatably producing product per the approved Type certificate
Subsystem Qualification		Subsystem (avionics box, actuator, etc.) meets a series of general and subsystem-specific tests
Facility Qualification		Facility that makes feedstock, parts, post-processing has quality systems in place and processes that meet qualification requirements
Personnel Qualification		Proficiency of personnel operating equipment has been demonstrated
Machine Acceptance and Qual	Factory Acceptance Test (FAT)	Equipment works properly at equipment builder's facility
	Installation Qualification (IQ)	Equipment works properly at user's facility
	Operational Qualification (OQ)	Equipment produces material/parts with expected properties
Process Validation (PV)		Overall manufacturing chain and equipment makes parts that meet requirements (good for part families)
Part Qualification	Process Performance Qualification (PQ)	Parts produced repeatably meet performance requirements
Feedstock Qualification	Specification & 1st Source (Factory vs. Warehouse)	Feedstock meets requirements and feedstock that meets specification requirements produces material that meets requirements
Part Acceptance	Lot Acceptance	Data off equipment and lot coupons (mech, chem, met) pass
	Individual Lot Acceptance	Part specific tests (NDT, dimensional, hardness)

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Certification

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Certification Pillars

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Jack Lincoln Aircraft Structural Integrity Framework

Requirements & Design Criteria

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- Geometric – Volume, Interfaces
- Service – Loads, Number of Cycles, Temperature, Corrosion
- Knock-Down Factors (Temperature, Humidity, Surface Roughness, etc.)
- Margins of Safety
- Failure Mode and Effects
- Determination of Design Values
- Certification Method (Analysis, Test, or Both)
- Test Extent – Blurs Line with Qualification
  - Full System Containing Part
  - Subcomponent (Part Only)
  - Destruct and Extract Coupons

Stability, Robustness, and Repeatability

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- Production Parts That are Accepted Meet Requirements Demonstrated by Certification Parts
- Robustness – No Dramatic Property Changes with Minor Input Parameter Changes
  - Parameters Operator can Control (e.g., Laser Power, Travel Speed)
  - Parameters Operator cannot Control (e.g., Local Variations in Power Density, Humidity, etc.)
- Stability – Minimal Creep Over Time
  - Short Term (e.g., Bed Temperature Through Build)
  - Long Term (e.g., Over Part Production Span)
- Repeatability – Combination of Robustness and Stability with Respect to Final Product – Importance of Specifications for Feedstock, Processing, Post-Processing

Producibility

- Closely Related to Stability, Robustness, and Repeatability
- Part can be produced without excessive scrappage and rework
- Accounts for geometric complexity vs simple shapes
- Well within process size capability

Characterized Properties

- Material Properties are Quantified
- Mechanical – Static (Tensile, Compression, Shear, Bearing), Dynamic, Durability – MMPDS is Excellent Guide
- Physical – CTE, Thermal Conductivity – MMPDS Contains Some
- Specialized – Wear, Friction
- Anisotropy – Look at Modulus
- Environmental Impacts (Temperature, Humidity, Surface Roughness, etc.)
- Surrogates – Hardness, Conductivity
- Ability to Nondestructively Inspect

Predictability of Performance

- Design Team confident that AM Material/Process combination will have the properties used for analysis
- Usually Not mean, median, or typical, but accounts for statistical variation
- Metallic Materials Properties Development and Standardization (MMPDS https://www.mmpds.org/) is Gold Standard
  - Static – A-Basis (99%/95% Confidence), B-Basis (90%/95% Confidence), S-Basis (99%) for More is Better
  - Typical Physical (More is Not Necessarily Better)
  - Some Durability, Damage Tolerance, Fracture
- MMPDS Standard very rigorous & challenging (Ref. Doug Hall presentation)
- Interim approach is developing part or part family specific values
- Need to account for NDT detectability limits/reliability for fatigue/fracture

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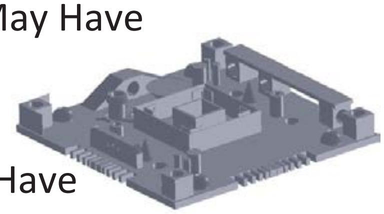
Qualification

Qualification

- Facility
  - Processes and controls in place (ISO-9000, AS-9100, etc.)
  - Not much different, If any, from other processes
- AM Machine
  - Far greater number of production machines requires different approach than wrought
  - Installation Qualification & Operational Qualification
- Material
- Performance/Part

Installation Qualification (IQ)

- Sometimes Called Site Acceptance Testing (SAT)
- Test Procedure, Program, and Pass/Fail Criteria Co-Developed by Printer Manufacturer and Printer Operator
- Performed by Printer Operator to Verify Printer Fit to Make Hardware (Reference AMS-7032, AWS D20.1)
- Surveys/Tests without Feedstock – Generally Same as FAT but May Have
  - Larger Range of Motion Unique to Intended Use
  - Energy Application Settings Unique to Intended Use
- Surveys/Tests with Feedstock - Generally Same as FAT but May Have
  - Material / Feedstock Unique to Intended Use
  - Geometries Unique to Intended Use
  - Parameter Combinations Unique to Intended Use
- May Add Heat Treatment, Along with Chemistry and Mechanical Testing



NIST Laser Powder Bed Fusion Artifact
(https://nvlpubs.nist.gov/nistpubs/jres/119/jres.119.017.pdf)

Machine Operational Qualification (OQ)

- AWS D20.1 and AMS-7032 are Existing Standards
  - Installation Qualification – Machine performs as machine builder expects
  - Operational Qualification – Machine produces material that meets material specification
- AMS-7032 Operational Qualification General Requirements
  - 3 Builds
  - 10 Tensile Tests/Direction/Build Covering Full Build Volume*DED
  - 3 Chemistry/Microstructure
  - 6 Horizontal and 6 Vertical Fatigue Recommended
  - NDT Coupons Per Material Specification
  - Coupons Meet Specification (NDT, Chem, Micro, Tensile) & T_{99} for Tensile w 1-Sample
  - Fewer Builds for Conditional and Non-Conditional Requalification

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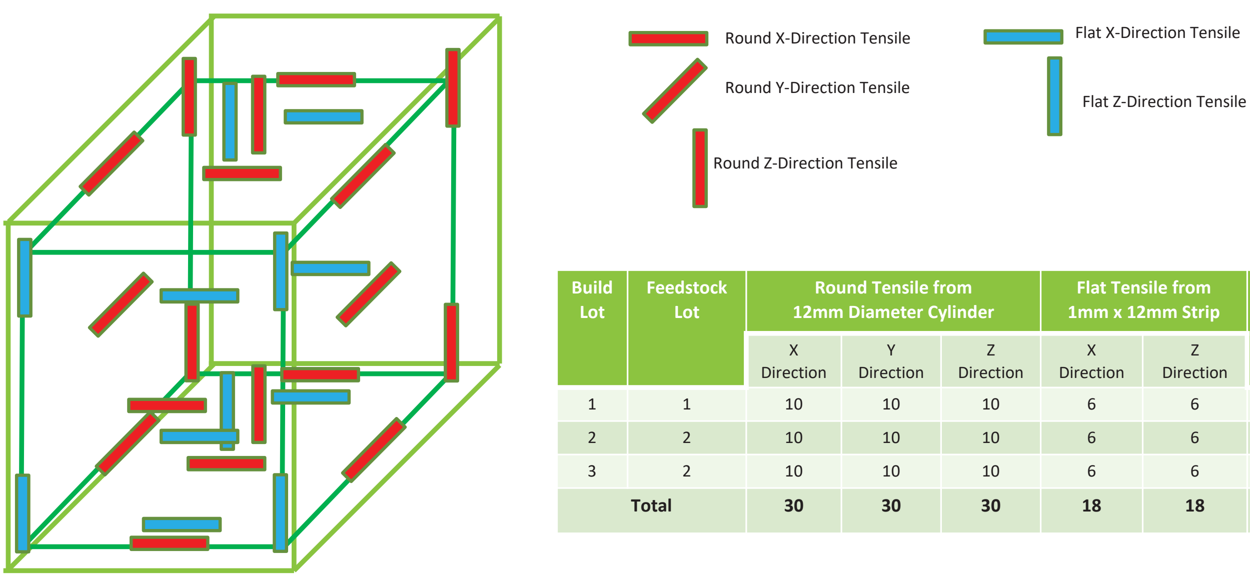
Machine Operational Qual Example Plan

- AMS7032 allows flexibility on build volume for DED processes



Build Lot	Feedstock Lot	Round Tensile from 12mm Diameter Cylinder			Flat Tensile from 1mm x 12mm Strip		Chemistry Microstructure
		X Direction	Y Direction	Z Direction	X Direction	Z Direction	
1	1	10	10	10	6	6	3
2	2	10	10	10	6	6	3
3	2	10	10	10	6	6	3
	Total	30	30	30	18	18	9

Material Qualification (MQ)

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- Lots of overlap with process development/design allowables
- Variation with part geometry and build parameters
- Other Properties
  - Physical
  - Compression, Shear, Bearing
  - Fatigue, Fracture, Creep, etc.
- Some applications may require for each machine

Performance/Part Qualification (PQ)

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- Validating that the part meets requirements
- Simple – Dimensional, NDT, Lot Acceptance (separate tensile, micro, chem coupons)
- Really complex – Full-scale test of part in service environment (landing gear component test)
- Middle
  - Additional dimensional, NDT, lot acceptance
  - Destructive sectioning of part and excising of mechanical, chemistry, and metallographic coupons

https://runwaygirlnetwork.com/2016/12/how-safran-landing-systems-tests-landing-gear-wheels-and-brakes/

Links Between Certification, Qualification, and Production

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- Tie Into Certification Pillars of Producibility and Predictability

Certification | Qualification | Production

Qualification Part:

- Manufacturing process for printer and part conform to those used to generate design values
- Geometry, tolerances, and surface finish meet those used in analysis and certification testing
- Test performance (loads, deflections, environmental exposure) meets subsystem requirements
- Microstructure and properties of excised coupons meet material specification

Production Parts:

- Manufacturing processes and plan conform to those used for the qualification part (fixed process)
- Lot acceptance coupon properties (tensile, chemistry, hardness, microstructure) meet those of material specification or part engineering
- Part acceptance inspections (volumetric NDT, surface NDT, dimensional, surface finish) meet part engineering and applicable material specifications
- Acceptable fraction of part and lot acceptance

Example – Ti-6Al-4V EB-PBF OQ

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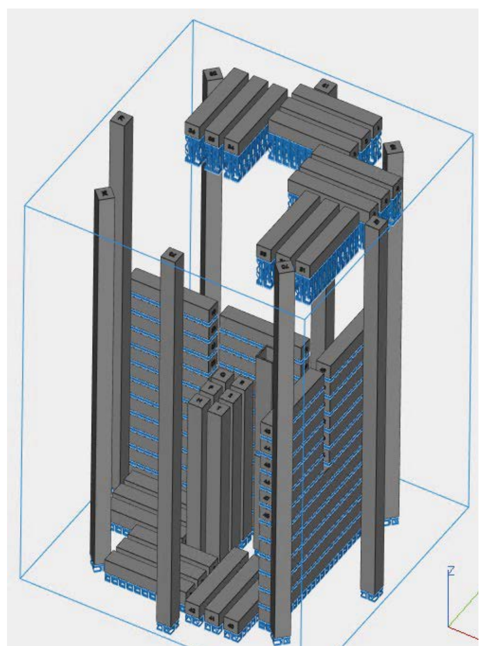
- See if a printer make and model different from that used to generate lot acceptance values for a material specification can meet AMS7032 (*Machine Qualification for Fusion-Based Metal Additive Manufacturing*) Operational Qualification (OQ) requirements
  - 1 feedstock lot, 1 thermal treatment run, 3 builds across volume
  - 30 total tensiles per lot acceptance orientation will all meeting lot acceptance minimums, and T_{99} > lot acceptance minimums
  - Composition and microstructure meet specification requirements
- Target specification
  - AMS7011 (*Electron Beam-Powder Bed Fusion (EB-PBF) Produced Preforms and Parts, Titanium Alloy, 6Al-4V, Hot Isostatically Pressed*)
  - Test data from a single printer make and model (ARCAM Q20+) meeting GAAM-18 requirements (minimum of 3 powder lots and 3 printers)

New Printer – JEOL JAM-5200EBM

- Print Volume – 250mm dia x 400mm tall
- Beam Output – 6kW
- Heating Capacity – 1100C
- Cathode Lifetime – 1500 hours
- He is Not Required
- First Printer in US Installed at Cumberland Additive in Pittsburgh
- Developing Capability of Refractory Alloys

Coupon Manufacture & NDT

- Reused TEKNA powder from a single lot that met AMS7015, with 0.16% O
- Build file encompassing entire volume of JAM-5200EBM (right)
- Coupons tested for evaluation received HIP per AMS7011, and the others retained for future use
- Radiographic inspection to notes of AMS7011, with all passing



0.5” x 0.5”

Composition Testing

- Met AMS7011 Requirements

ELEMENT	AMS7011		COUPON									
	Min	Max	214-15C	214-61C	214-75C	215-15C	215-61C	215-75C	216-15C	216-61C	216-75C	Powder
C		0.08	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.02	0.02	<0.001
H		0.015	0.005	0.004	0.004	0.003	0.007	0.008	0.002	0.004	0.003	0.003
O	0.11	0.2	0.174	0.169	0.166	0.182	0.169	0.178	0.185	0.178	0.177	0.16
N		0.05	0.014	0.012	0.013	0.014	0.013	0.014	0.013	0.015	0.014	0.016
Ti			Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder
Al	5.5	6.75	6.01	6.11	6.02	6.07	5.98	6.05	6.02	6.04	5.99	6.47
V	3.5	4.5	4.13	3.99	4.09	4.18	4.08	4.06	4.15	4.06	4.1	4.08
Fe		0.3	0.17	0.23	0.17	0.17	0.2	0.16	0.17	0.17	0.17	0.25
Others		0.4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	<0.10

Metallography

- Density below, although no minimum requirement in AMS7011
- Transformed beta microstructure
- No discontinuity larger than 20µm observed

ELEMENT	COUPON											
	214-15C	214-21M	214-61C	214-75C	215-15C	215-21M	215-61C	215-75C	216-15C	216-21M	216-61C	216-75C
Density	99.61	99.47	99.59	99.45	99.45	99.35	99.28	99.4	99.64	99.65	99.78	99.64

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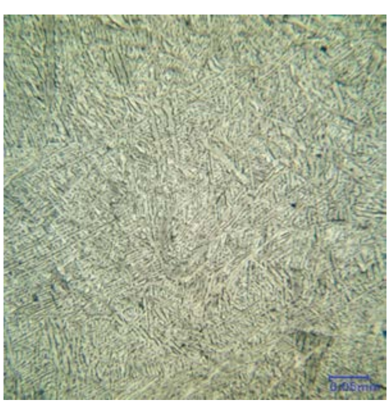

214-15

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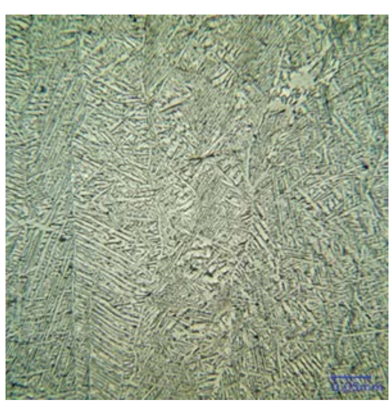

214-21

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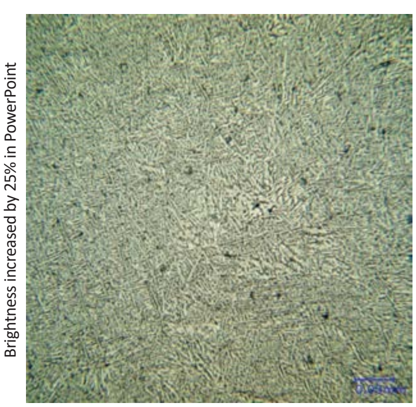

214-75

Tensile – Summaries & Statistics

- All tests met minimums, with excellent ductility
- 8 of 9 T_{99} values met minimums, with Z-Direction TYS 1ksi below, meaning it meets 1-sample acceptance test with margin requirement
- 2-3ksi of anisotropy, versus 3-8ksi in AMS7011

X-Direction

Value	TUS (ksi)	TYS (ksi)	ELG (%)	RA (%)
Max	146	133	19	47
Min	140	119	14	34
Mean	142.5	124.8	17.1	41.7
Std Dev	1.76	2.56	1.12	3.25
n	30	30	30	30
T99	137	117	11	32
AMS-7011 Accept	130	112	9	n.a.

Y-Direction

Value	TUS (ksi)	TYS (ksi)	ELG (%)	RA (%)
Max	145	128	19	51
Min	139	121	14	38
Mean	142	124.2	17	44
Std Dev	1.75	1.79	1.43	3.55
n	30	30	30	30
T99	137	119	10	33
AMS-7011 Accept	130	112	9	n.a.

Z-Direction

Value	TUS (ksi)	TYS (ksi)	ELG (%)	RA (%)
Max	143	127	21	58
Min	138	121	17	47
Mean	140.8	123.3	19	53
Std Dev	1.59	1.56	1.03	2.66
n	30	30	30	30
T99	134	119	15	45
AMS-7011 Accept	133	120	10	n.a.

Conclusions and Recommendations

Conclusions

- The ability to perform OQ on printer make and model different from that used to generate the specification minimum has been demonstrated for a given alloy & process combination.
- Ability for other alloy & process combinations needs to be demonstrated.

Recommendations

- Look at impact of adding 5200 dataset to current AMS7011 dataset on lot acceptance values
- Look at impact of additional 5200 printers/lots on 5200 T_{99} values
- Perform similar studies on other alloy & process specifications
- Since the acceptance values for several specifications are based on a single printer model, consider re-analyzing lot acceptance values at 5-year review date.
- Consider using 3 different printer models when generating initial lot acceptance values.

Presenter

Kevin T. Slattery, D.Sc is a Principal ADDvisor® at The Barnes Global Advisors. His primary expertise is in Metallic Additive and Metals Manufacturing, focusing on test program development, process and product verification, qualification, and certification. He is a 2020 Ambassador for America Makes, was part of the Materials Challenge Silver Medal team in the USAF Rapid Sustainment Office Additive Manufacturing Olympics, and a 2022 SAE Contributor of the Year Finalist. He led 7 first in the industry technology implementations, including the 1st metal additive manufacturing structural aircraft part. Prior to this, he was the Chief Scientist for AM and Metals in Boeing Research and Technology. He currently holds 40 US patents, with 13 applications pending.

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Thank you!

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MMPDS and Additive Metals

NRC Workshop on Advance Manufacturing Technologies for Nuclear Applications
October 25, 2023

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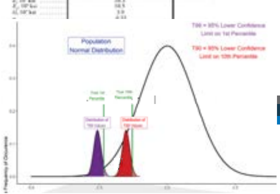
Metallic Materials Properties Development and Standardization



History

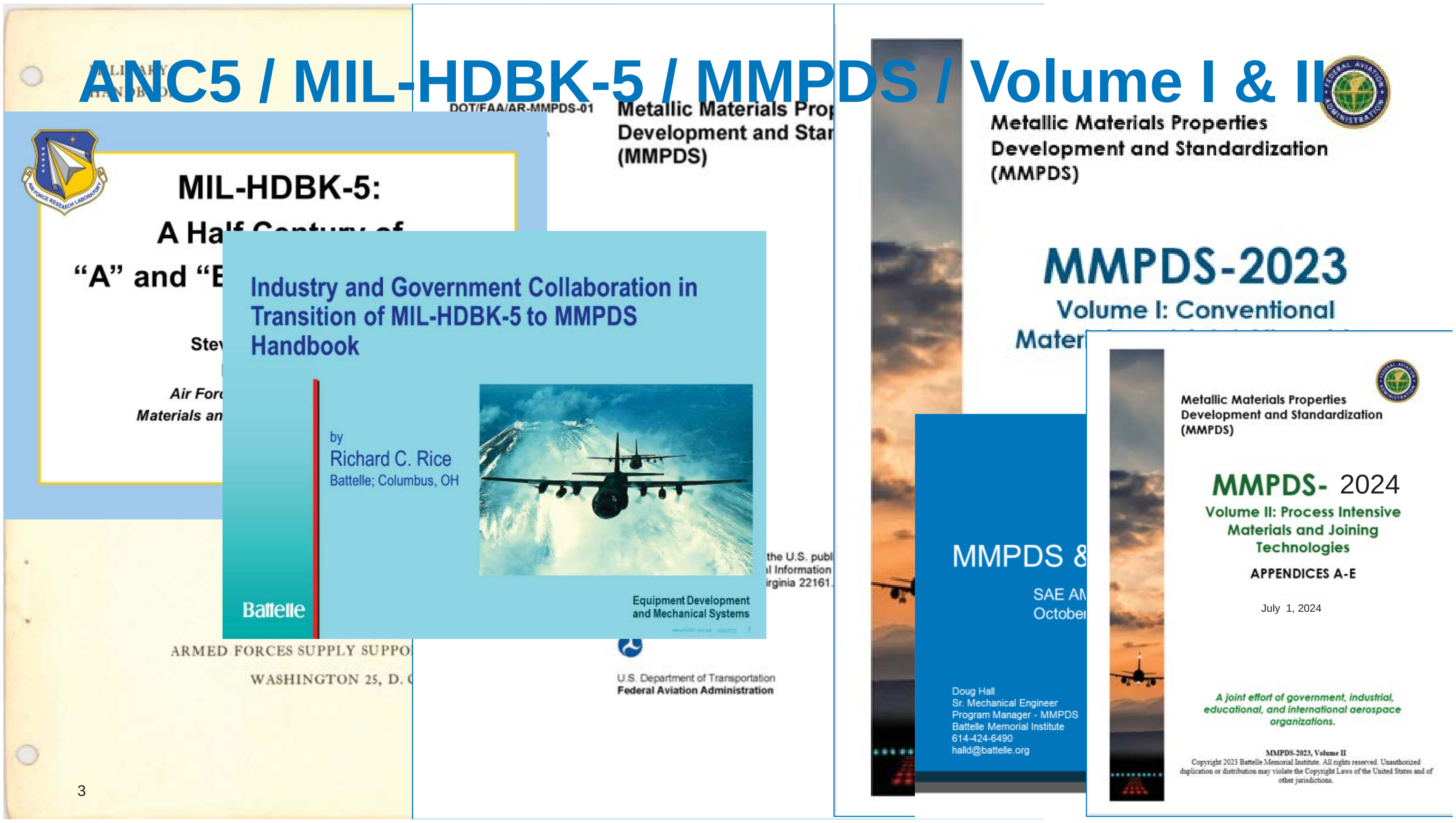
- ANC5 (1937-1954), MIL-HDBK-5 (USAF: 1954 – 2003), MMPDS (FAA: 2003-today)
- Battelle Memorial Institute - program Secretariat since 1956.
- MMPDS Handbook is the primary source of statistically-based material allowable properties for metallic materials and fasteners used in many different commercial and military weapon systems around the world.
- The MMPDS General Coordinating Committee is a collaboration between government agencies, aerospace companies, testing and data service companies, and metallic material producers.
- Biannual meetings to review and approve statistical analyses and guidelines.

Scope

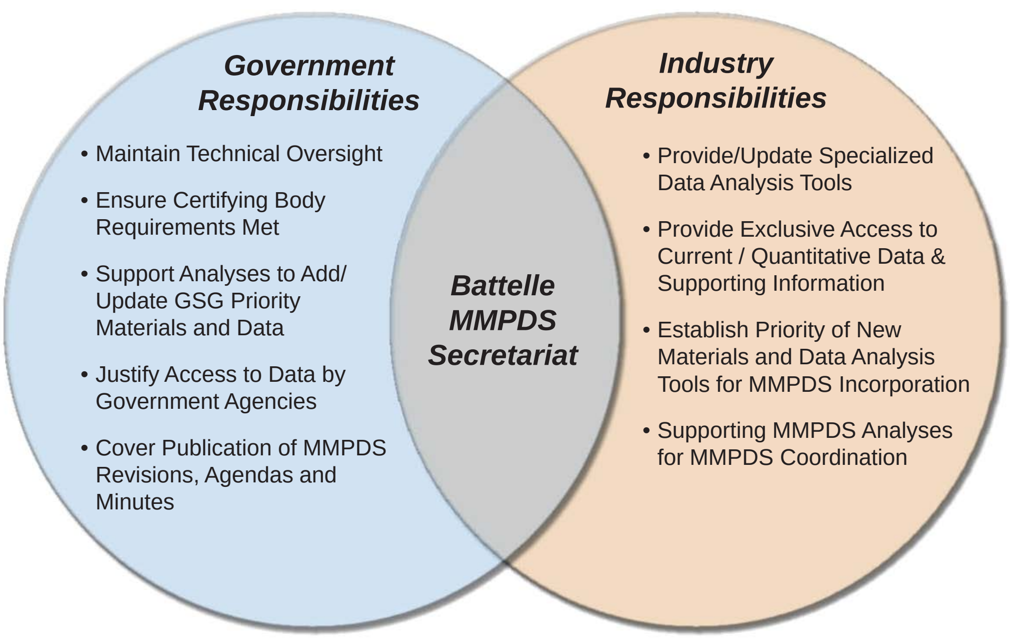
- The Handbook currently contains 600+ A/B-Basis and 1000+ S-Basis entries, 400+ unique metal specifications.
- Two to five new alloys are added each year.†
- For more information visit www.mmpds.org

† Pandemic rate has been slower.

ANC5 / MIL-HDBK-5 / MMPDS / Volume I & II



MMPDS General Coordination Committee



Task Groups:
Guidelines – approve **all** guidelines
Materials – Chapters 2-7
Fasteners – Chapter 8
Emerging Technology – Volume II

Steering Groups:
Get industry sector inputs
Airframe, Materials & Testing Services, and Propulsion

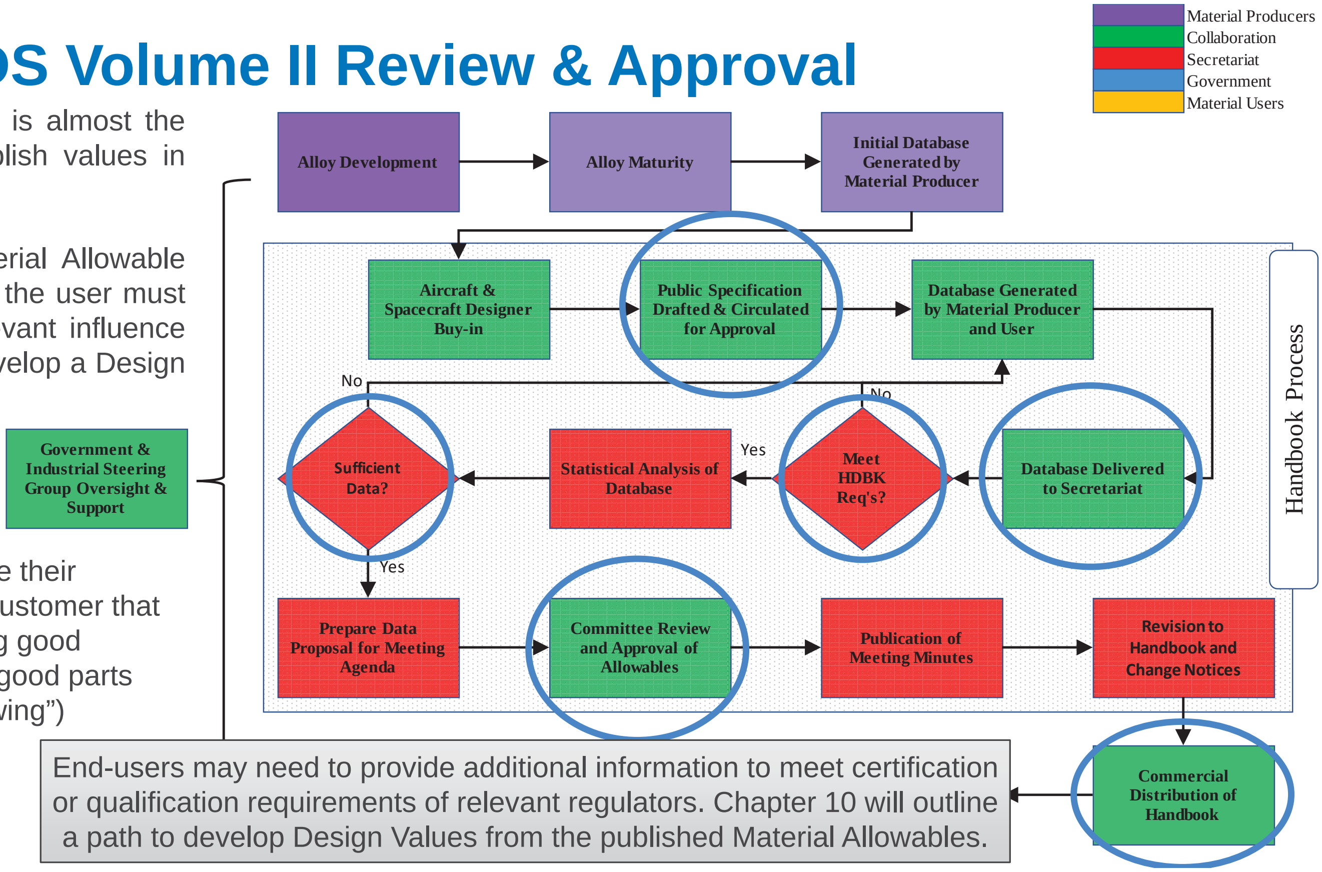
Working Groups:
Technical input from industry
Fatigue, Statistics, Welding
Volume 2

MMPDS Volume II Review & Approval

The Process is almost the same to publish values in Volume II.

Once a Material Allowable is published, the user must consider relevant influence factors to develop a Design Value.

AND convince their regulator or customer that they a making good material and good parts ("further showing")



9.2.2 Specification Requirements

- A material ". . . must be covered by a public, industry, or government specification that includes sufficient quality controls to ensure stable statistically valid mechanical properties. These controls shall include, but are not limit to, lot-release acceptance criteria for composition limits and mechanical properties, control of thermal-mechanical processing, sampling, and testing methodologies, and internal soundness/quality."
- "Test data meeting or exceeding requirements for S-Basis or better statistically based mechanical properties for properties included in the specification for lot-release shall be submitted to the MMPDS Secretariat for analysis."
- Additional requirements for Material Properties (9.2.2.1), Manufacturing and/or Processing (9.2.2.2), Feedstock (9.2.2.3), Recycling (9.2.2.4), Machine Qualification (9.2.2.5), Product Lot-Release Data (9.2.2.6)

Table 9.2.4 (1 of 3)

Table 9.2.4. Summary of Data Requirements within MMPDS Volume II

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[a]	No. of Mfg. Lots	Machines[b]	Build Cycles
Bearing Yield and Ultimate Strength[c] (Direct)	S-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Bearing Yield and Ultimate Strength[c] (Indirect)	C- and D-Basis	Strongly Recommended	Except for elevated temperature applications	20 indirect /20 reference	10	10	5	10
Coefficient of Thermal Expansion	Typical	Strongly recommended	Especially for anticipated range of usage	6	3	3	3	3
Compression Yield Strength[c] (Direct)	C- and D-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Compression Yield Strength[c] (Indirect)	C- and D-Basis	Strongly recommended	Except for elevated temperature applications	20 indirect /20 reference	10	10	5	10
Creep and Rupture	Raw Data w/ Best-Fit Curves	Recommended	Especially for elevated temperature applications	6 tests per creep strain level and temp, at least 4 temps over usage range				
Density	Typical	Mandatory		3	3	3	3	3
Effect of Temperature Curves	Same as Room Temperature Properties	Recommended	Especially for elevated temperature applications	5[d]	2[e]	5	5	5
Effect of Thermal Exposure	Same as Baseline Properties	Recommended	Especially for elevated temperature applications	5[d]	2[e]	5	5	5
Elastic Modulus - Tension Compression Dynamic Shear	Typical	Mandatory Mandatory Recommended Recommended	Dynamic modulus is strongly recommended for some engine applications	9	3	3	3	3
Elastic Modulus (T, C, D) - Elevated Temperatures	Typical	Mandatory	For anticipated usage temperature range	9	3	3	3	3

Continued on next page.

These tables are nearly identical to Table 9.2.4 in Volume I for conventional materials. Only the Machines and Build Cycle columns are new.

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Table 9.2.4 (2 of 3)

Table 9.2.4. Summary of Data Requirements within MMPDS Volume II *(continued)*

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[a]	No. of Mfg. Lots	Machines[b]	Build Cycles
Elongation	S-Basis	Mandatory	Two-inch gage length preferred	30	3	3	3	3
Fatigue-Load Control	Raw Data w/Best-Fit Curves	Recommended	Especially for high-cycle fatigue critical applications	6 test per stress ratio (R), 3 stress ratios, no minimum heat or lot requirements				
Fatigue-Strain Control	Raw Data w/Best-Fit Curves	Recommended	Especially for low-cycle fatigue critical applications	10 tests for $R\varepsilon$ = -1.0, 6 tests other strain ratios				
Fatigue Crack Growth	Raw Data w/Best-Fit Curves	Recommended	Especially for damage tolerance critical applications	Duplicate da/dN results for relevant stress ratios and stress intensity range				
Fracture Toughness - Plane Strain	Max., Avg., Min., Coef. Of Variance, S-Basis	Recommended	Mandatory for materials with spec minimum requirements for plane strain fracture toughness	30	3	10	3	10
Fracture Toughness - Plane Stress	Raw Data w/Best-Fit Curves	Recommended	Mandatory for materials with spec minimum requirements for plane stress toughness	f	2	5	3	5
Poisson's Ratio	Typical	Strongly recommended		6	3	3	3	3
Reduction In Area	Typical	Recommended		When tested, use same criteria as for elongation				
Shear Ultimate Strength[c] (Direct)	S-Basis	Mandatory	Except for elevated temperature applications	30	3	3	3	3
Shear Ultimate Strength[c] (Indirect)	C- and D-Basis	Strongly recommended	Except for elevated temperature applications	20 indirect/ 20 reference	10	10	5	10
Specific Heat	Typical	Strongly recommended	For anticipated usage temperature range	6	3	3	3	3
Stress Corrosion Cracking	Letter Rating	Recommended		Conform to replication requirements in ASTM G 47				

Continued on next page.

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Table 9.2.4 (3 of 3)

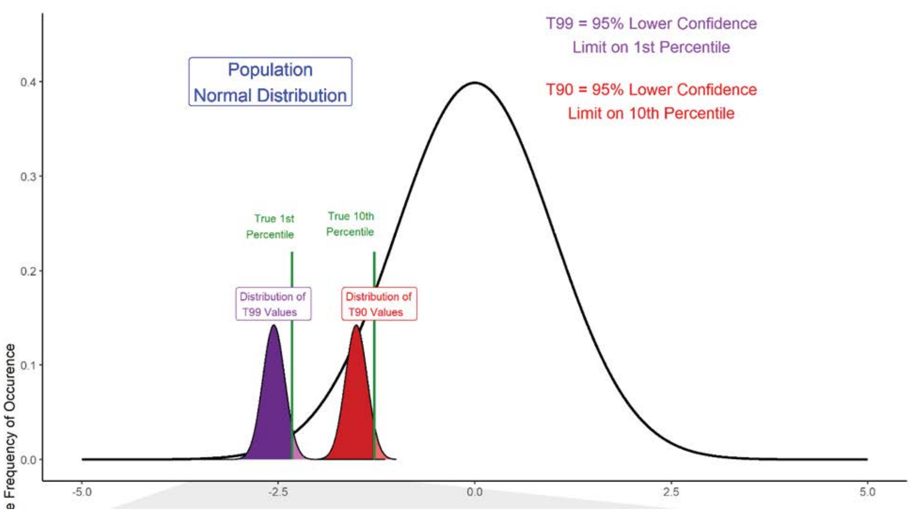
Table 9.2.4. Summary of Data Requirements within MMPDS Volume II *(continued)*

Mechanical or Physical Property	Customary Statistical Basis	Relative Importance in MMPDS Volume II	Extenuating Circumstances for Special Material Usage Requirements	Minimum Data Requirements				
				Sample Size	No. of Heats[a]	No. of Mfg. Lots	Machines[b]	Build Cycles
Stress/Strain Curves (To Yield) Tension and Compression	Typical	Mandatory	Desirable to have accurate plastic strain offsets from 10^{-6} to 3×10^{-2}	6	3	3	3	3
Stress/Strain Curves (Full Range) Tension	Typical	Mandatory	The strain rate should be constant through failure.	6	3	3	3	3
Tension Yield and Ultimate Strength (Direct)	S-Basis	Mandatory		30	3	3	3	3
Tension Yield and Ultimate Strength (Direct)	D-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is possible	100	10	10	5	10
Tension Yield and Ultimate Strength (Direct)	C-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is possible	100	10	20	5	20
Tension Yield and Ultimate Strength (Direct)	C- and D-Basis	Strongly recommended	Especially for strength critical applications; a parametric representation of data is not possible	299	10	20	5	20
Tension Yield and Ultimate Strength (Indirect)	C- and D-Basis	Recommended	For grain directions not required for lot release in specification	20 indirect/ 20 reference	10	10	5	10
Tension Yield and Ultimate Strength - Elevated Temps	Typical	Recommended	Mandatory for elevated temperature applications	g	2	5	5	5
Thermal Conductivity	Typical	Strongly recommended	For anticipated usage temperature range	6	3	3	3	3

a Heats refers to different input chemistries of the feedstock production process.
b Builds must be executed on the number of machines listed in the table or all existing machines if fewer machines exist.
c Optional direct property determination involves same minimum data requirements as tension yield and ultimate.
d Tests per temperature, at least 4 temperatures over usage range.
e 5 heats required for single form and thickness.
f Minimum sample size not specified, testing should be conducted at 6 or more panel widths to confidently represent trends over the panel widths of interest. Refer to ASTM E561 for testing details.
g Minimum sample size not specified, testing should be conducted at 6 or more temperatures to confidently represent trends over the temperature range of interest. Testing in regions where properties are expected to change rapidly with changes in temperature must be done at temperature intervals sufficiently small to clearly identify mean trends.

C-Basis (T99) – requires 20 builds. That means 20 manufacturing lots instead of 10 for A-Basis for conventional materials.
This is because there is a perception that build-to-build is a significant source of variations.

Volume II C-Basis, D-Basis, S-Basis: Material Allowables



T_{99} and T_{90} are one-sided lower tolerance bounds. Both are calculated from data.

C-Basis = the lower of the specification minimum or T_{99} value.

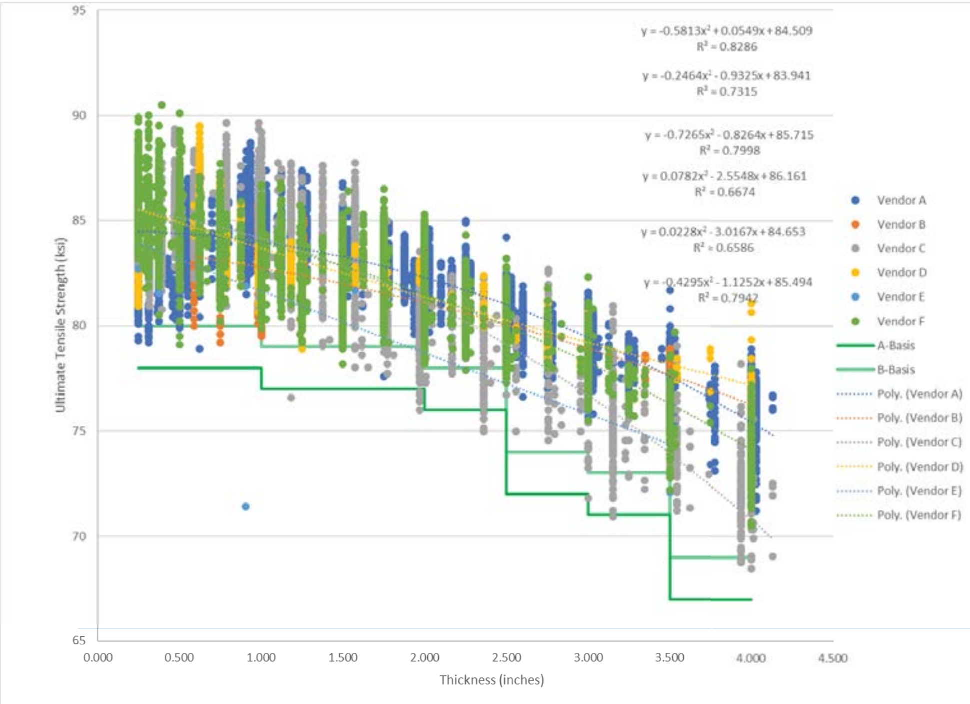
D-Basis = is the T_{90}. It is not related to the spec minimum.

S-Basis = is a T_{99} that does not meet C-Basis requirements for sample size or distribution fit.

Metallic C-/D-/S-Basis published in MMPDS Volume II require "further showing." A large sample is required.

MMPDS is the primary gov't approved source for A/B/C/D/S-Basis metallic material allowables. Proprietary values require extra effort by the CEO.

Conventional Material Legacy Alloy Review



- Four major aluminum producers, making plate & sheet in six separate factories
- All producers of 7075-T6 per AMS4045 are not making identical material
- The published A/B-Basis allowables are safe, at least for these producers.

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Next Steps

- At the request of the Government Steering Group, material allowables will not be published in Volume II before GCC approval of these Agenda Items
  - 21-20: Microstructural Submittal Requirements
    - Micrographs are required.
    - Details are being ironed out with input from government and industry.
  - 21-46: MMPDS Vol 2, Certification & Qualification “Further Showing”
    - OEMs and their customers requested introductory information about this process.
    - This will not be a checklist guaranteeing approval.
    - Material producer quality requirements are imposed on the owner of the machine.
  - 22-13: V2, 10.8 Considerations for Development of Design Values
    - MMPDS publishes bulk material allowables.
    - The user is responsible for applying influence factors for their application.
    - Many existing rules of thumb may no longer apply.

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Phase 2 – Populate Volume II & Expand Guidelines

- Expand & Revise Guidelines†
  - 21-02: Section 9.5 & 9.6 for Volume II – data analysis methods
  - **21-20: Microstructural Submittal Requirements** ††
  - **21-46: MMPDS Vol. 2, Certification & Qualification "Further Showing"** ††
  - 23-04: V2, 10.3 Overview of Qualification
  - 23-11: Section 10.6 Consensus Standards
  - **22-13: V2, 10.8 Considerations for the Development of Design Values** ††
  - 23-19: Review of 9.7 for Volume II – fastening technologies
  - 23-20: Section 9.8 & 9.9 for Volume II – example problems
  - 21-46: MMPDS Vol 2, Certification & Qualification "Further Showing"
- Populate Volume II
  - 21-53: Analysis of 718 Laser Powder Bed Fusion per AMS 7038 – test plan approved at 40th
  - 23-22: 6061-RAM2 per AMS 7054 – test plan approved at 41st
  - 23-48: Ti-6Al-4V per AMS 7004/7005 – test plan approved at 42nd

† - a summary of significant open items covering Volume II.
†† - **Bold items** required to publish entries

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Coordination with SDOs & Other Organizations

- America Makes
  - AMSC WG5 Finished Material Properties - Co-Chair w/Rachael Andrulonis
  - Team member for JMADD, GAMAT, & Delta Qual projects
- ASTM International
  - F42 membership
- FAA-EASA AM Workshops
  - WG1 - Discussing S-Basis as an acceptable material allowable for low criticality parts.
- NIAR
  - JMADD - Air Force/FAA funded project to develop a specification and allowables for PBF Ti 6-4.
- NIST
  - NIST team defining data management standards. FAIR guiding database modernization project.
- SAE AMS
  - Advisory Group & Metals Committee
  - Additive Manufacturing Data Consortium – Battelle is a Liaison member
  - SAE AMS AM Metals Committee
    - Update to the AM Data Submission Guideline – Andrew Steevens (Boeing) sponsor
    - Multiple specs being developed. Battelle analyzes data to establish lot-release values.
      - Currently analyzing data for AMS 7024, 7030, 7036, 7038, 7039.
    - AMS 7032 (Machine Qualification) – reporting requirement to send data to Battelle to support MMPDS

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SAE AMS-AM Material Properties for Spec Mins and Design Values

- Additive Integrated Specification Ecosystem (AISE™)*

➢ AM Standards Generation	➢ SAE AMS-AM
➢ AM Data Generation	➢ SAE AMDC
➢ AM Data Storage	➢ MMPDS, NIAR
➢ Audit/Oversite	➢ Nadcap
➢ AM Testing/Inspection	➢ ASTM
➢ Operator/Process Qualification	➢ AWS/SAE
➢ Supplier Pre-Qual Registry	➢ PRI/ITC p-QML*
➢ Supplier/Part Registry	➢ PRI/ITC QSL/QPL*

*PROPOSED – UNDER DEVELOPMENT

BATTELLE

It can be done

800.201.2011 | solutions@battelle.org | www.battelle.org

Biography

Doug Hall

Doug Hall joined Battelle Memorial Institute in 2017 as the MMPDS Program Manager. Before that, he spent 30 years at Honeywell Aerospace as a stress and material allowables data analyst supporting safety and mission critical engine and airframe components for military and commercial programs. Doug began using MIL-HDBK-5D in 1987 and CMH-17, Rev G in 2011 to develop material allowables and design values both metals and composites used in critical applications. From 2011 to 2017, he supported approximately 150 stress analysts and 350 materials engineers at Honeywell offices around the world.

His current role at Battelle includes technical management of the MMPDS program and supporting material characterization, stress analysis, and life prediction on a variety of projects.

Doug has a bachelor’s degree in Mathematics and a master’s degree in Engineering Mechanics from Ohio State University.

Qualification and Certification for Additive Manufacturing Supported by Model-based Approach

Dongchun (Mary) Qiao | October 25, 2023

ABS

Acknowledgements

- This project is funded by Grant 70NANB21H038 from the U.S. Department of Commerce, National Institute of Standards and Technology (NIST).

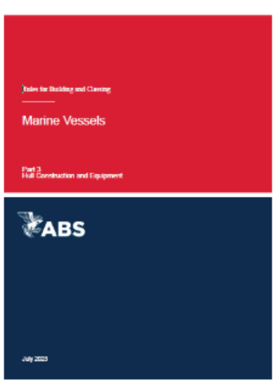
American Bureau of Shipping

Establish Design Rules and Standards

Review Designs against Rules and Standards

Confirm Vessels/Equipment Built in accordance with Approved Plans

Verify Vessels/Equipment Maintained to Accepted Standards

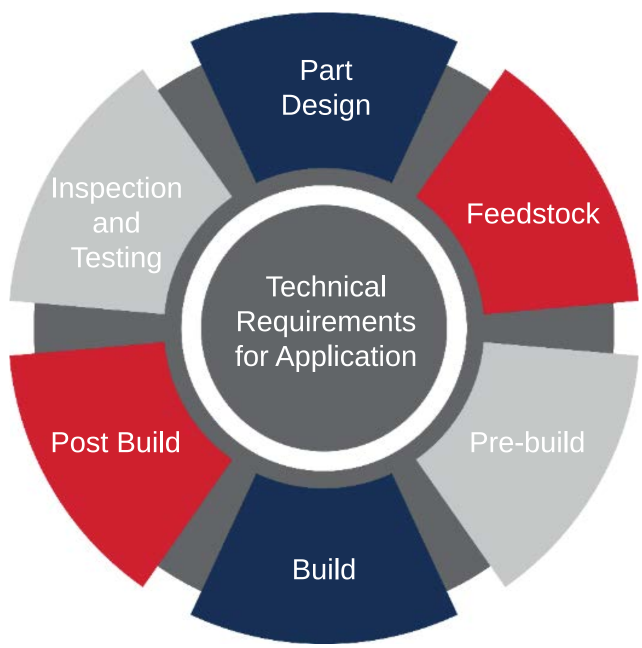


Outline

- Standard Qualification Approach
- Risk Assessment
- Rapid Qualification by Model-Based Approaches
- Summary

Standard Qualification Approach

- Documentation
  - Part Design Package with Revision
  - Manufacturing Procedure/Process Plan
  - Inspection and Testing Plan
  - Applicable Rules, Industry Standards
- Qualification
  - Procedure Qualification
  - Material Qualification – AM Facility
  - Prototype Part Qualification – AM Part for Each Specific Part
- Production
  - Qualified AM Process
  - Agreed Inspection and Test Plan
  - Quality Control



Part Design

Part Design Package

- **Technical Specification**
  - ABS Rules or Industry Standards
  - Specifications by Designers
- **Engineering Design**
  - Part Solid Model/Drawing
  - Specific Digital Design for AM
  - Engineering Calculation/Simulation for Alternative Design
- **Materials Specification**
  - Requirements for Mechanical Properties
  - Requirements for Other Properties such as Fatigue, Corrosion etc
  - Non-destructive Testing
  - Approval for Alternative Material
- **System/Equipment to be Installed for Function Requirement**
  - Load Tests
  - Pressure Tests
  - Balance Tests etc.

Design Requirements

Design Criteria

- Strength, ASME BPVC II D

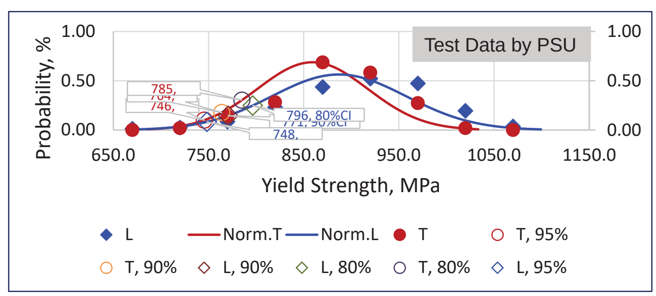
$$\sigma_{max} = \frac{\sigma}{f}$$

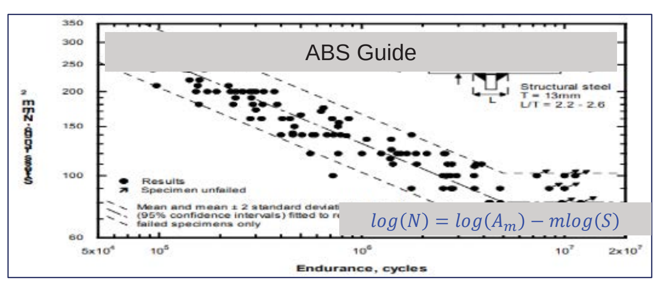
- Fatigue

$$Fatigue\ Design\ Factor\ (FDF) \geq 1$$

- Fracture

$$K = \sigma\sqrt{\pi a} \leq K_{Ic}$$





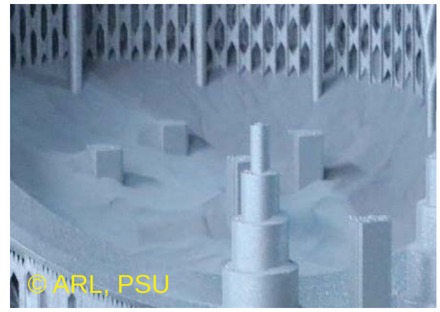
Feedstock

Powder Specification

- Material grade
- Chemical composition
- Powder manufacturing process
- Post-atomization classification Powder size & distribution
- Powder morphology and internal microstructure
- Flowability
- Applicable AM process
- Documentation

Wire Specification

- Material grade
- Chemical composition
- Wire size
- The applicable additive manufacturing process
- Documentation



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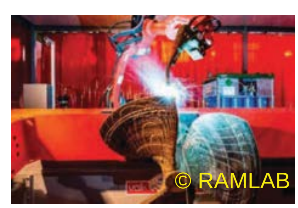
Build Procedure Specification

Industry Standards

- AWS D20.1 for Specification for Fabrication of Metal Components using AM
- ASME PTB-13 for Criteria for Pressure Retaining Metallic Components using AM
- ASTM F3303 for PBF Process
- ASTM F3187 for DED Process

PBF and DED Procedure Specification

- Heat Source
- Deposition
- Build Environment and Other Parameters
- Procedure Qualification Record (PQR) – Pre-build, Build and Post-Build



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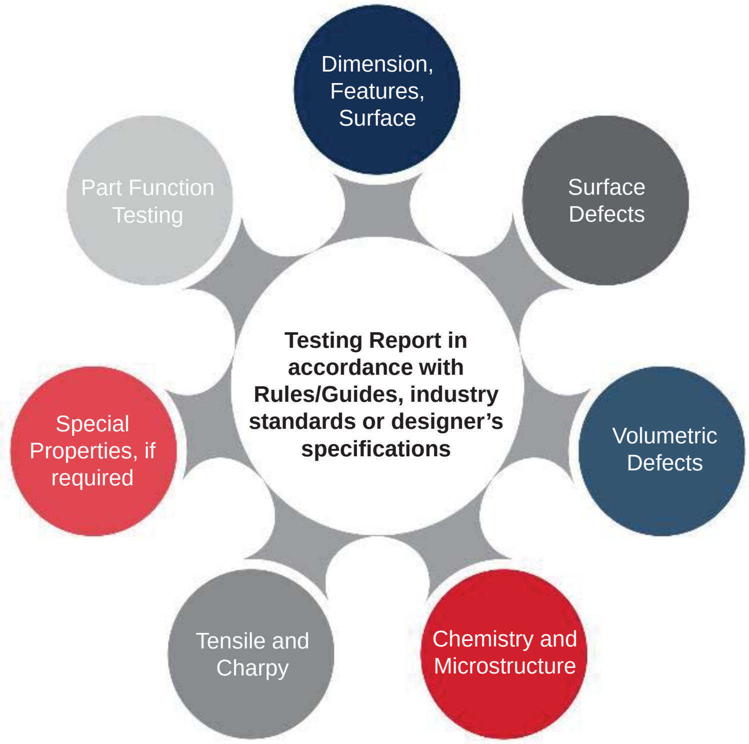
Inspection and Testing

- ABS Rules for Materials and Welding and the applicable sections enclosed in other ABS Rules for application
- ASTM A751 for Chemical Analysis
- ASTM A370 for Mechanical Testing
- ASTM E8 for Tensile Testing
- ASTM E23 for Notched Bar Impact Testing
- ASTM E10 for Hardness
- ABS Guide for Non-Destructive Inspection or ISO 5817, ISO 10675-1
- Other recognized standards, such as ISO, ASTM, API, ASME

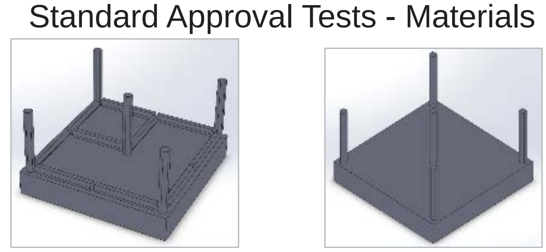


Standard Qualification Approach

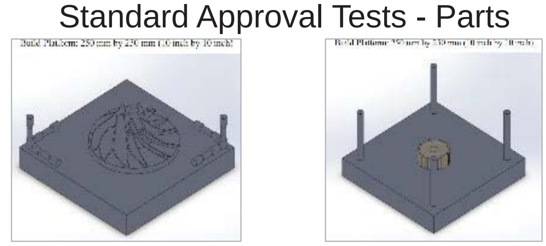
Challenges

- Qualification is linked to each part design, material grade and AM machine.
- Qualification/approval cost is high.
- Standard qualification approach is not suitable for AM benefits in spare parts, obsolete parts, small batch production.
- High approval test scope is big hurdle for expanded adoption.

Standard Approval Tests - Materials



Standard Approval Tests - Parts



Risk Assessment

- AM Test Level 1, 2, 3
  - Critical application (Test Level 3, High)
  - Semi-critical application (Test Level 3, Medium)
  - Non-critical application (Test Level 3, Low)

Likelihood	(<20%, >10%)	3 High	**3**	**6**	**9**
	(<10%, >5%)	2 Medium	**2**	**4**	**6**
	(<5%)	1 Low	**1**	**2**	**3**
Risk Assessment = Likelihood × Consequences **AM Level 1, 2, 3**			1 Low	2 Medium	3 High
			ISO 5817 Class D	ISO 5817 Class C	ISO 5817 Class B
			Consequences (Increasing Severity >>)		

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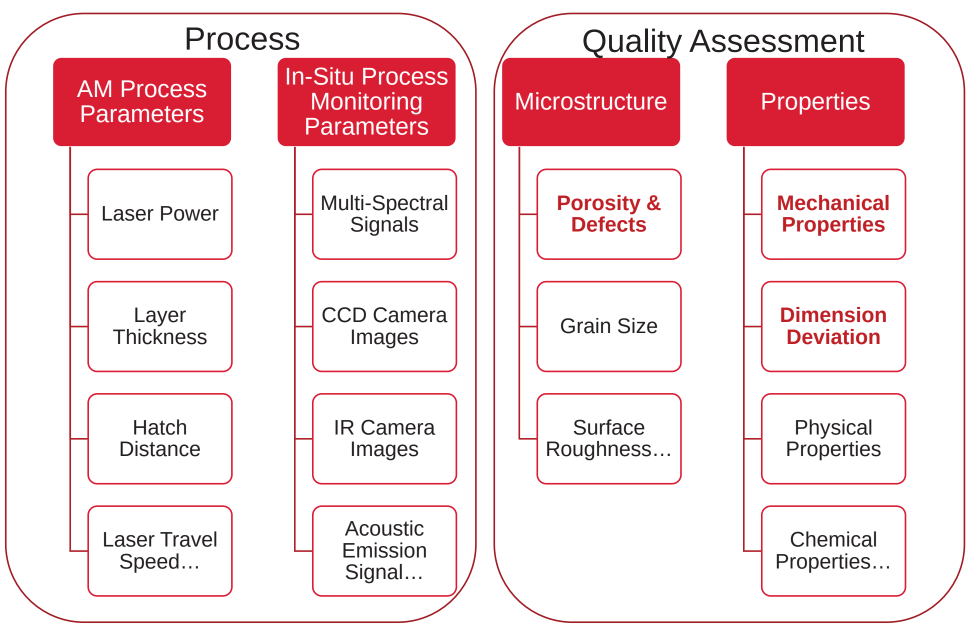
Rapid Qualification by Model-Based Approaches

- Expert System/knowledge-Based Approach
- In-Situ Process Monitoring Approach
- Physics Model Approach
- Guidance for AM Industry – Rapid Qualification with Verified and Validated Model Based Approaches



https://link.springer.com/article/10.1007/s11837-020-04155-y

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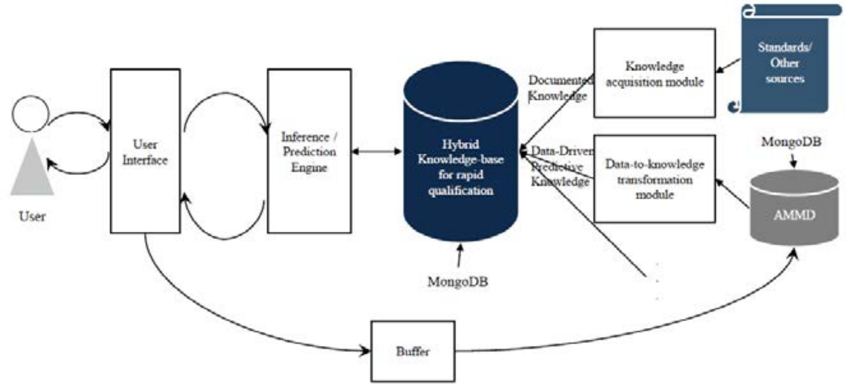
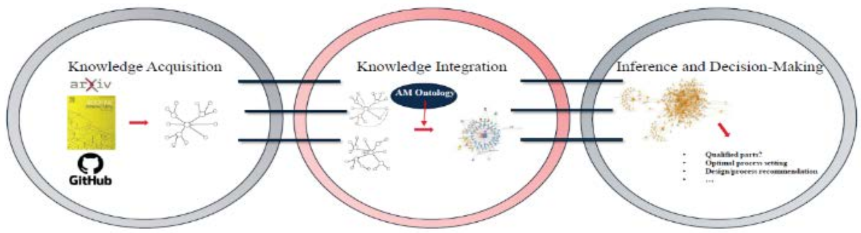
Expert/Knowledge-Based Model

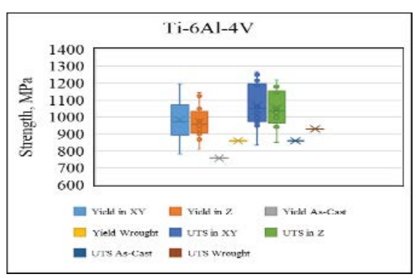
- User's Request
  - Knowledge Acquisition
  - Data to Knowledge Transformation
  - Hybrid Knowledge for Prediction
- Inference and Decision-Making

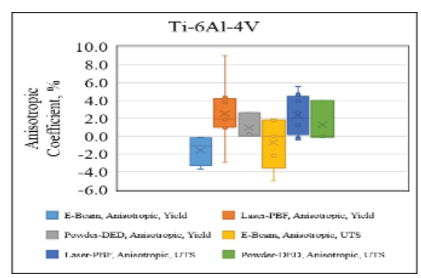




Reduction of Test Scope Supported by Expert/Knowledge-Based Model

- Expert-System or Statistics Model
  - $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{X-\mu}{\sigma}\right)^2}$, for test data from literature or manufacturer
  - Design required yield and UTS
  - Anisotropic coefficient
- Reduce Test Scope for Approval Tests





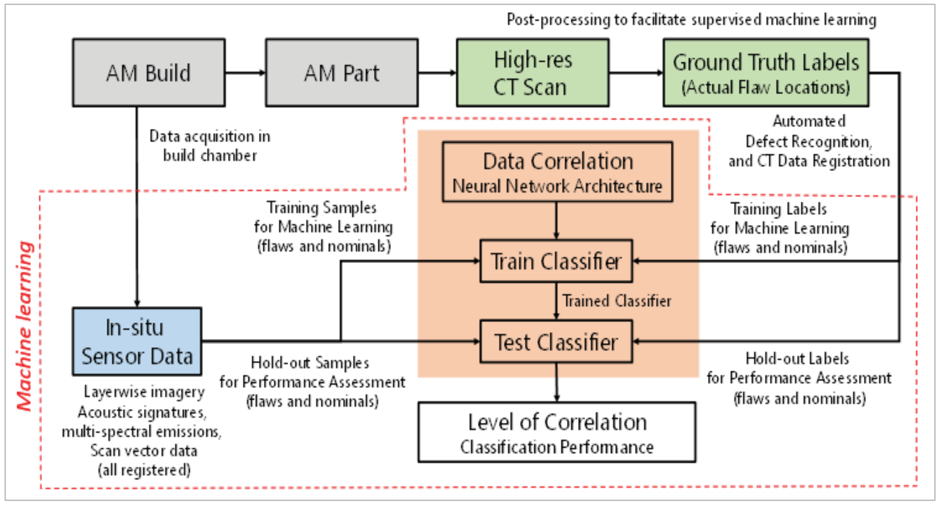
Yield, UTS and Anisotropic Coefficient in X/Y and Z direction for E-Beam-PBF, Laser-PBF and Laser-Powder-DED Ti-6Al-4V

Kok, Y. Anisotropy and Heterogeneity of Microstructure and Mechanical Properties in Metal Additive Manufacturing: A Critical Review, Materials and Design, 2018, 139: 565-586

Direction	Yield, ksi		Charpy, ft-lbs at 0 °C	
	Avg.	Std. Dev.	Avg.	Std. Dev.
X	86.2	0.78	95.5	2.89
Y	86.0	1.38	-	-
Z	76.2	1.17	79.3	1.53
ASTM F3184 for PBF 316L: Min. Yield 30.0 ksi				

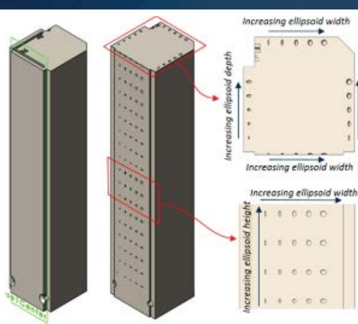
In-situ Monitoring and Machine Learning Model

- In-Situ Monitoring Flaw Detection
  - $P_2 = 1 - \sum_{x=S}^{N} \binom{N}{x} (P_1)^x (1 - P_1)^{N-x}$, for sufficient seeded defects and defined accuracy
  - Train and Test Classifier
  - Ground Truth Labels by CT Scan
  - Partial/full replacement of NDT

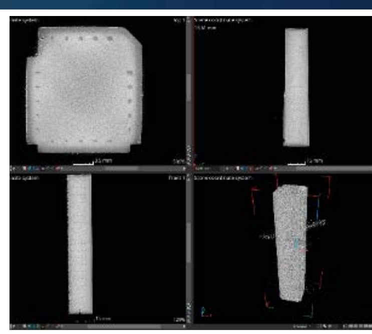


PennState Applied Research Laboratory ABS

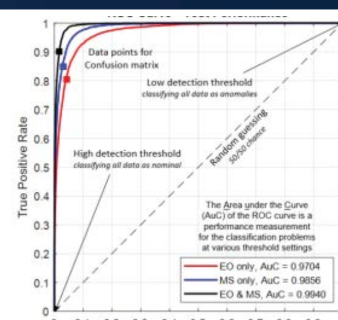
Flaw Detection by In-situ Monitoring and Machine Learning Model



Surrogate Flaw © ARL, PSU

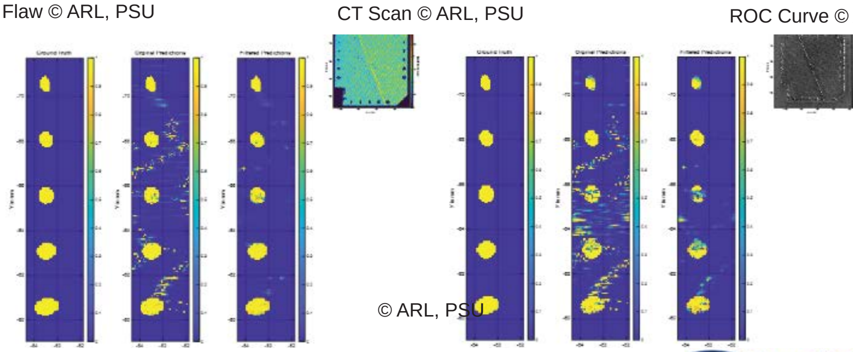


CT Scan © ARL, PSU



ROC Curve © ARL, PSU

- Ground Truth
- Original Predictions
- Filtered Prediction for Multi-Spectral (Left)



© ARL, PSU

- Ground Truth
- Original Predictions
- Filtered Prediction for Layerwise (Right)

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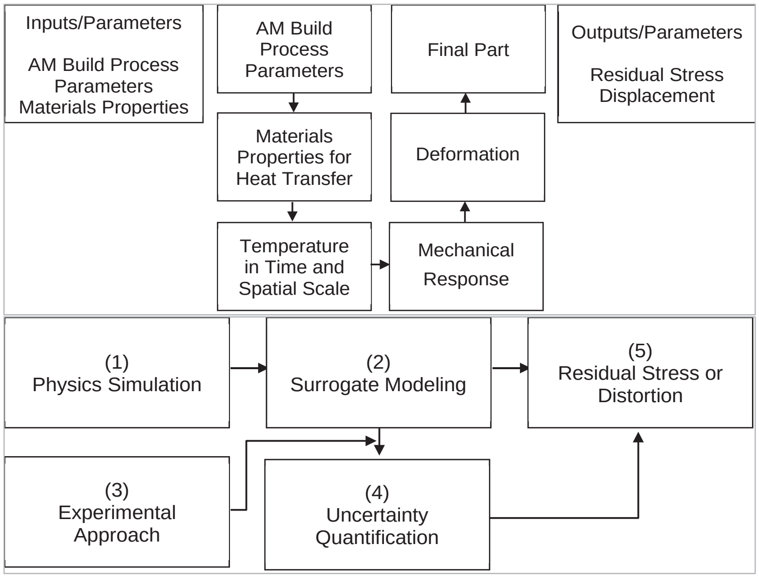
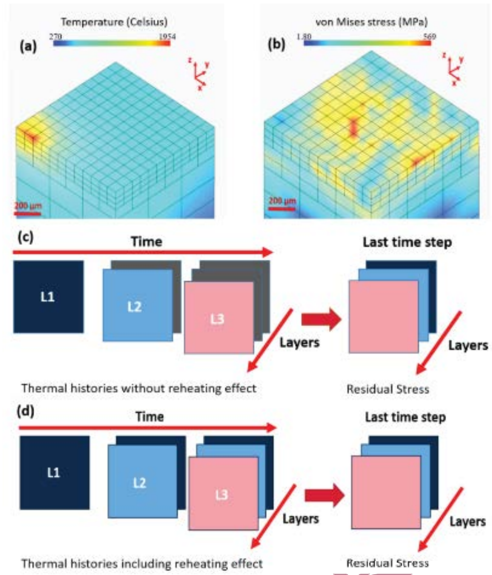
Physics Simulation Model

- Physics Simulation

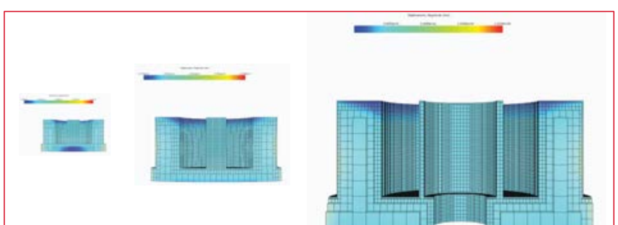


Fine Scale Model

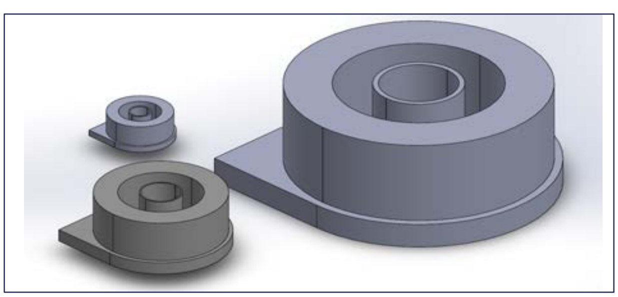


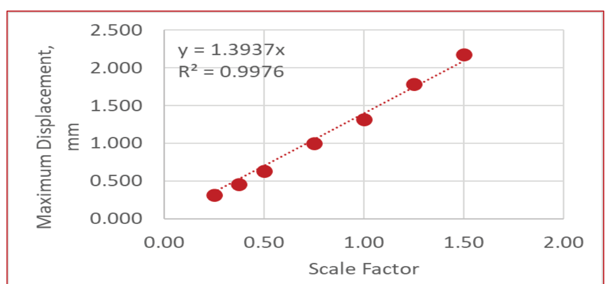
Distortion and Residual Stress Prediction by Physics Simulation Model

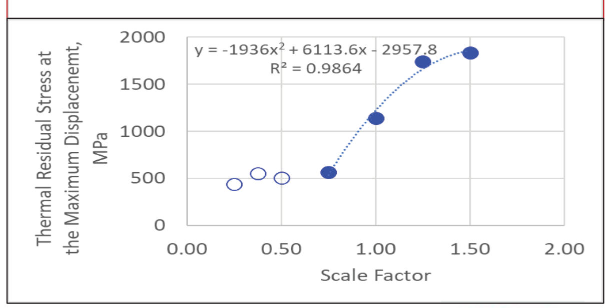
- Cylinder Test Artifact Results – Part Scale Model



Φ=25 mm Φ=50 mm Φ=100 mm

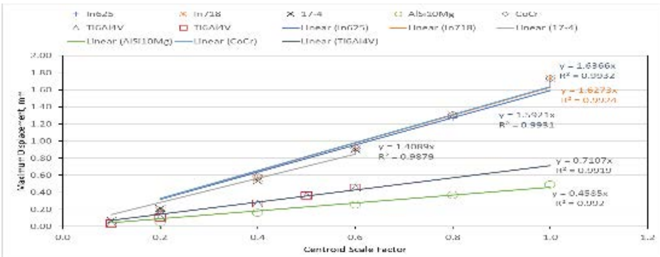


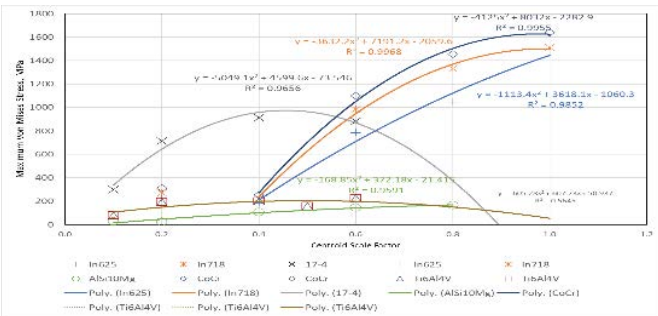




Distortion and Residual Stress Prediction by Physics Simulation Model

- Nozzle Ring Results





Scale Factor	Dimension, mm	Scale Factor	Dimension, mm
0.1	22.277×22.277×4.76	0.7	155.94×155.94×33.32
0.2	44.554×44.554×9.52	0.8	178.22×178.22×38.08
0.4	89.108×89.108×19.4	1.0	222.77×222.77×47.6
0.6	133.66×133.66×28.56	-	-

VIRGINIA TECH ABS

Summary

Purchase Specification

- Part Design Package – Solid Model and AM Final Material Specification
- Test Level – AM Level 1, 2, 3
- Any Additional Requirements for Intended Application

Manufacturing Procedure

- Manufacturing Procedure and Specification
- Inspection and Testing Plan
- Procedure Qualification
- Material Qualification
- Part Qualification

Rapid Qualification

- Reduced Essential Parameters for Range of Approval
- AM Level 3, 2, 1 – Qualification for Specific Part, by Part Family or by Design Feature Family
- Partial/Full Replacement NDT using In-situ Monitoring Tool
- Reduced Test Scope by Recognized Test Data from Literature or Manufacturer
- Potential Qualification by Material Group

ABS

Thank You

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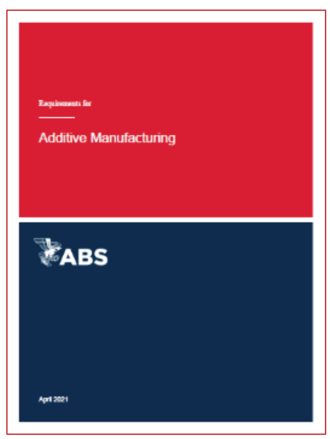
Recent ABS Projects on Additive Manufacturing

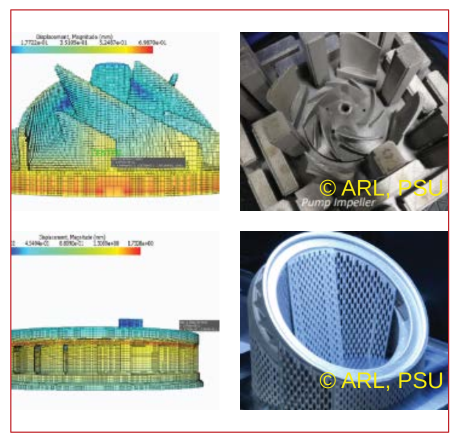
- ABS Requirements for Additive Manufacturing
- Robotic Arc Directed Energy Deposition (DED) – Marine Component or Repair
- Rapid Qualification of Metal-based AM Supported by Models
- Shore-Based Additive Manufacturing in Support of MSC (Military Sealift Command)
- Scaling Up 3D Printed Steel Castings
- Crane Hook with Design Load 80 Metric Tonnes using Wire Arc Additive Manufacturing
- Implementation of AM Spare Parts Onboard

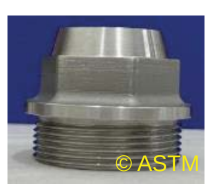

Requirements for

Additive Manufacturing

ABS

April 2021





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

Accelerating the qualification of AM materials through modeling and simulation

2023 NRC Workshop on AMTs for Nuclear Applications
October 24-26

Mark Messner

Argonne National Laboratory

Why is qualification so slow?

Empirical extrapolation isn't all that powerful

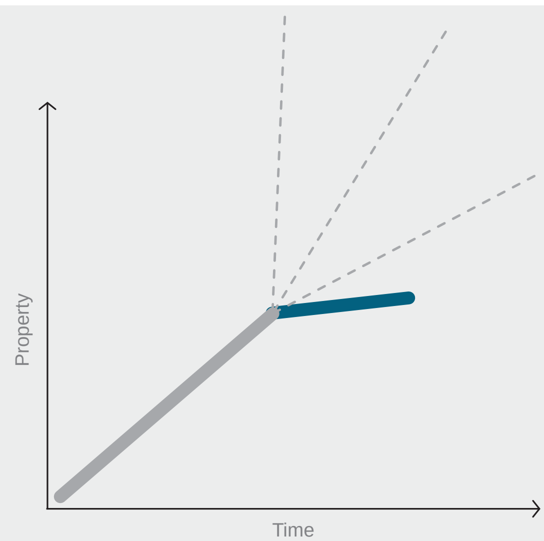
KEY FACT

Nothing is really static – particularly at high temperatures

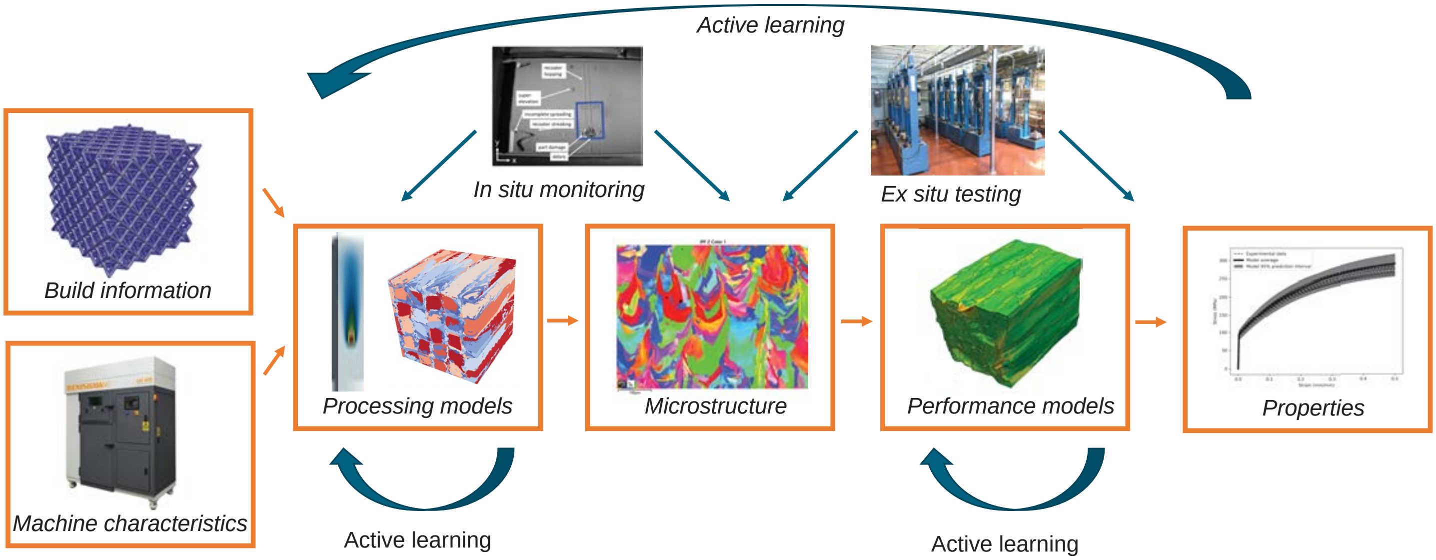
RULE OF THUMB

30-year life equals 6–10 years of testing

Creep test lab at NIMS, Japan



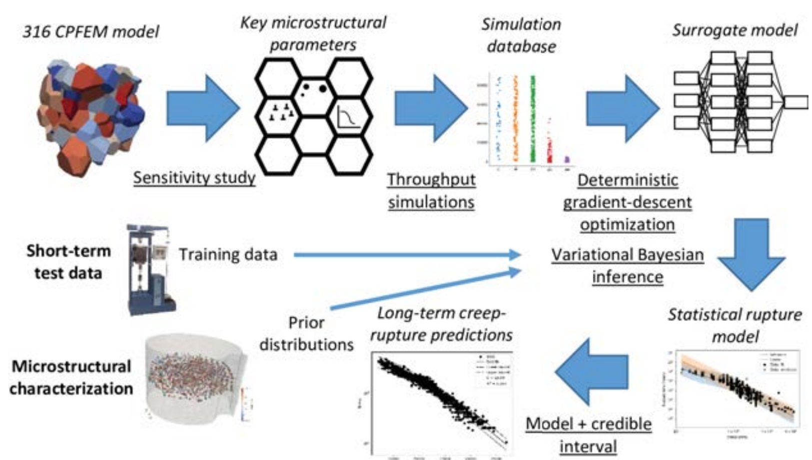
A digital twin for advanced manufacturing



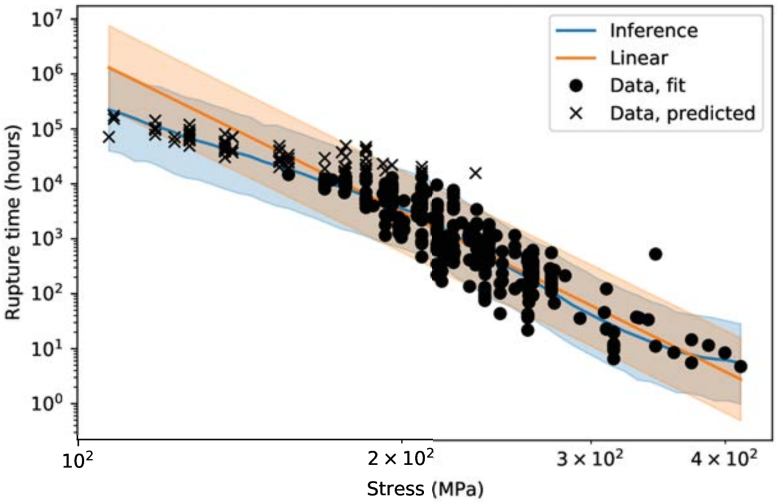
Minimize the *time* and *cost* it takes to qualify a new material

Example: Predicting long-term creep rupture strength

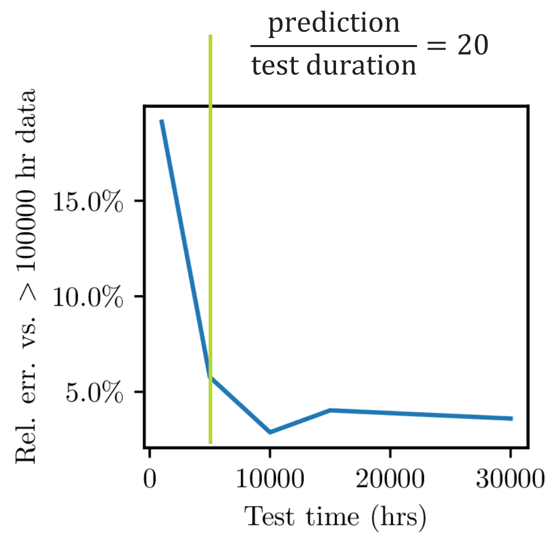
- Can a physics-based CPFEM model better extrapolate short-term creep rupture tests to long creep rupture times compared to conventional, empirical models?
- **Framework – what if analysis of 316H**
  - Pretend like we have only the 316H tests with times less than X hours
  - Extrapolate life with Larson-Miller
  - Extrapolate life with a CPFEM model + Bayesian inference to find parameters (using only the "available" data)



Key result: increase time extrapolation factor from 3 to 20

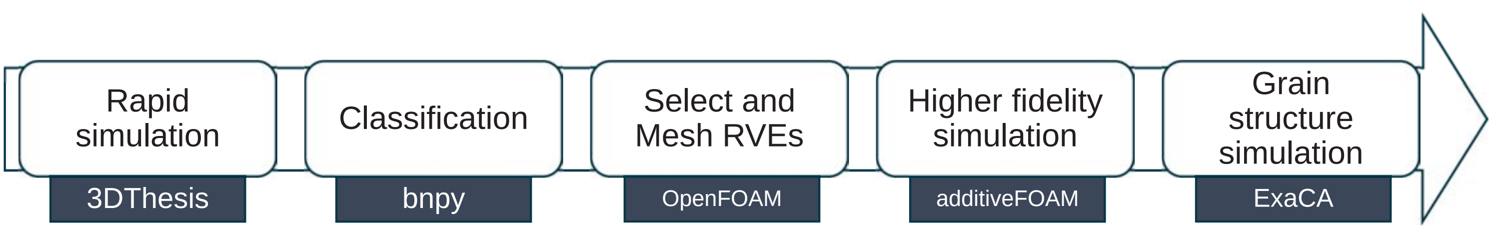


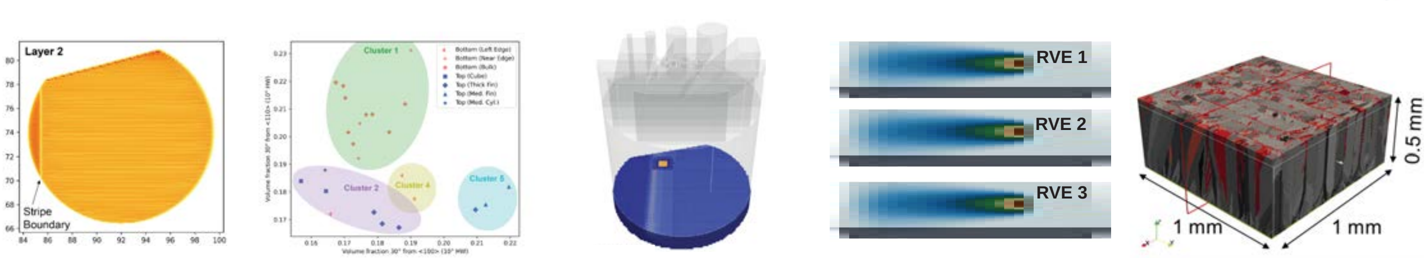
Predictions with < 5000 hour data



Accuracy against long-term data as a function of available test length

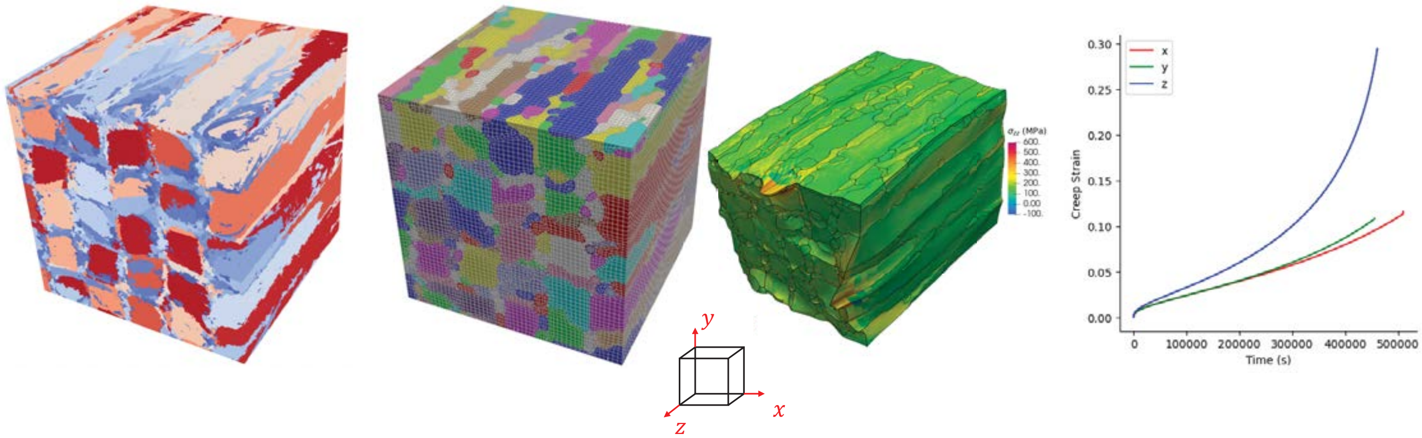
Towards an Automated Workflow for Quantifying Microstructure Variability





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

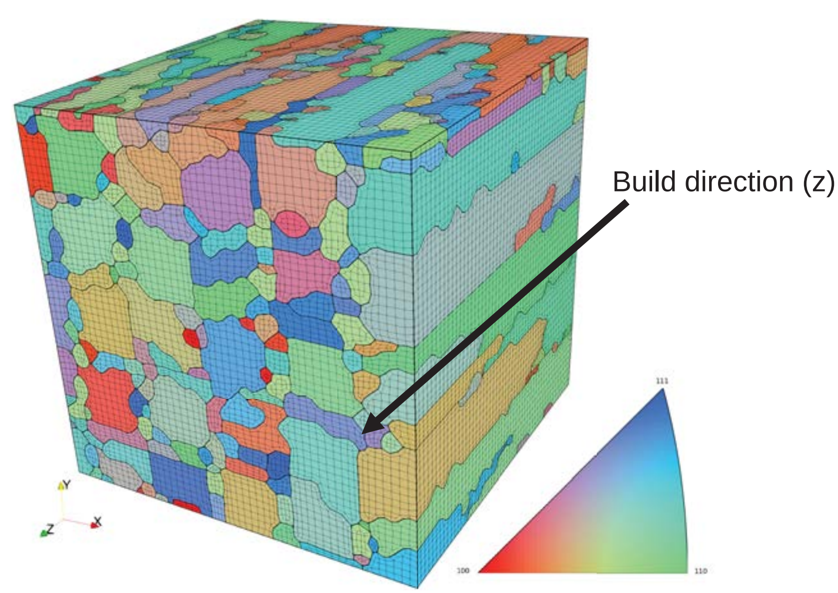
Connecting process modeling to property predictions



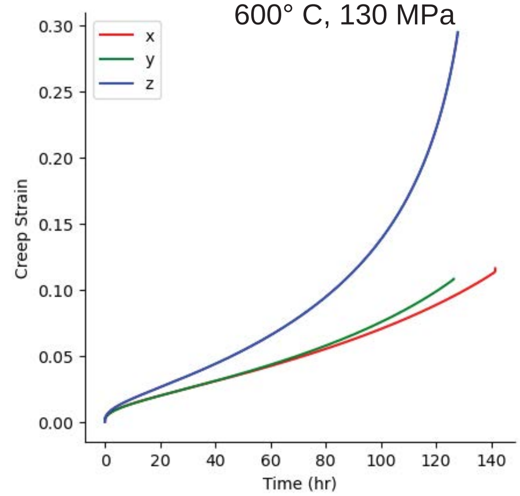
Microstructure from process model	Crystal plasticity finite element discretization	Microscale deformation and stress	Macroscale predicted creep anisotropy

Simulating creep anisotropy

Very preliminary modeling using ORNL AM (but not 316H) microstructures

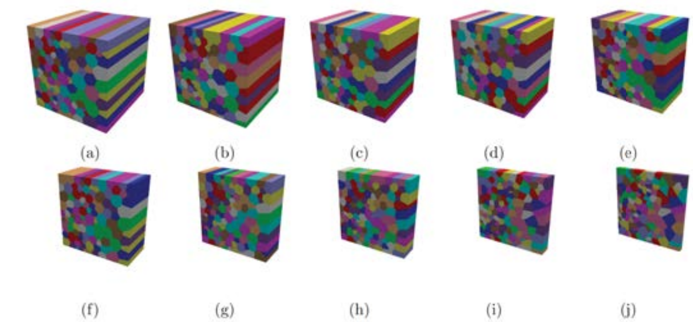


Wrought 316H single crystal model
600° C, 130 MPa

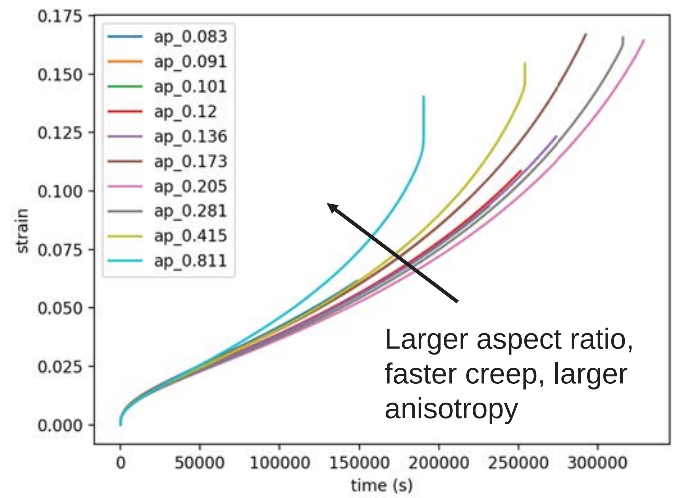


Matches experimental observations on 316L!

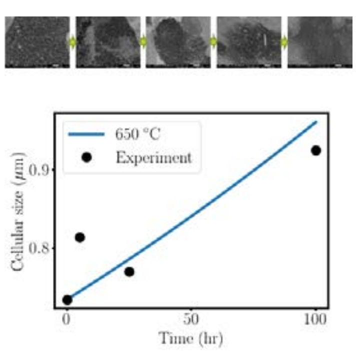
What is causing this anisotropy?



Induced by the columnar grain structure

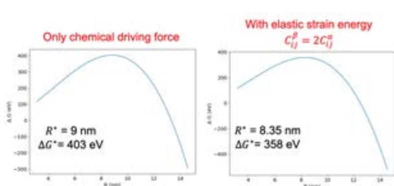


Progress modeling degradation mechanisms unique to AM materials



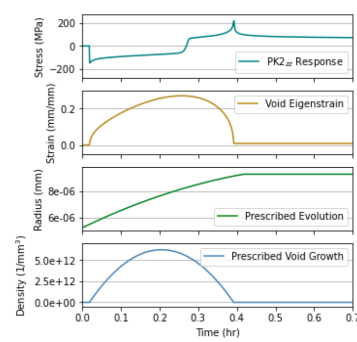
Thermal recovery of dislocation structure

Dislocation structure



Stress effect on precipitation kinetics

Precipitation kinetics



Radiation-induced deformation and damage

Radiation effects

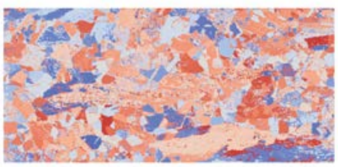
Better integration: experiments, physics models, and surrogate models

Current approach is mostly sequential

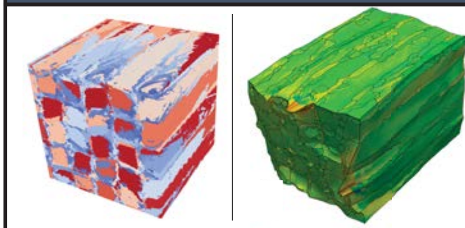
Fixed inputs

Processing parameters

Characterization data (in situ or ex situ)



Physics-based modeling

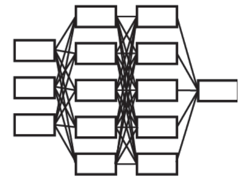


Fixed output

Key material properties (creep, fatigue, radiation…)

Mechanical test data

Surrogate model



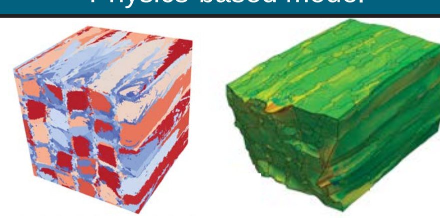
If it doesn't work we iterate, ***manually***…

Better integration: experiments, physics models, and surrogate models

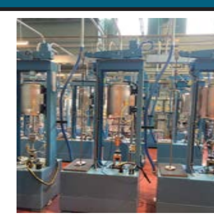
Better approach: active learning

Characterization data

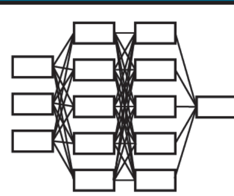
Physics-based model



Mechanical test data



Surrogate model



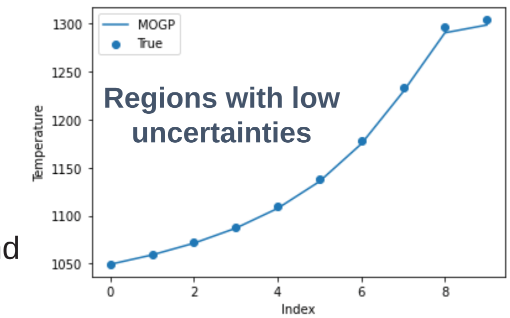
Characterization, mechanical testing, and physics-based simulations are all expensive.

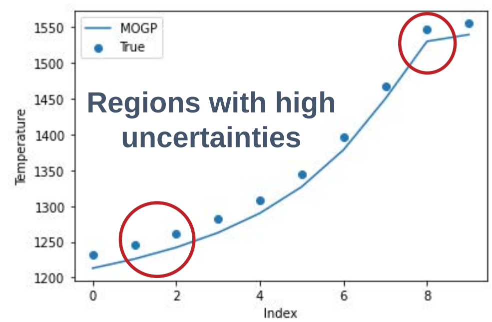
All we care about is how accurate these predictions are!

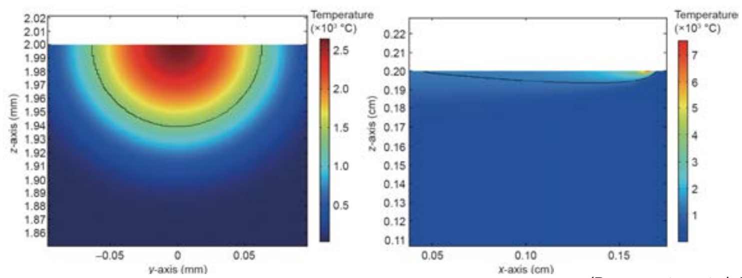
Let the property model uncertainties determine which tests and simulations to run

Active learning demonstration: melt-pool temperature

- Gaussian process-based surrogate model predicts the temperature field around melt-pool given by an analytical model
- Inputs are 5 process params: ambient temp, absorptivity, power, conductivity, and velocity
- Model compares predicted temperatures with the testing data and captures associated uncertainties
- Additional data is needed to improve predictions in the regions with higher uncertainties







(Promoppatum et al. 2017)

Temperature Distribution

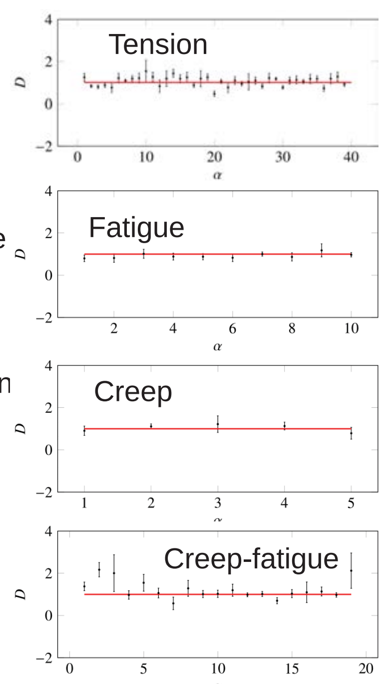
Neural constitutive models

ML for material behavior

- Physics-based models rely on two pieces:
  - Field equations – often general balance laws derived from basic thermodynamics
  - Constitutive models – often very specific and heavily reliant on expert judgement
- Can we get some help from machine learning?

Experts are great here

We slow things down a lot here



ART Alloy 617 data

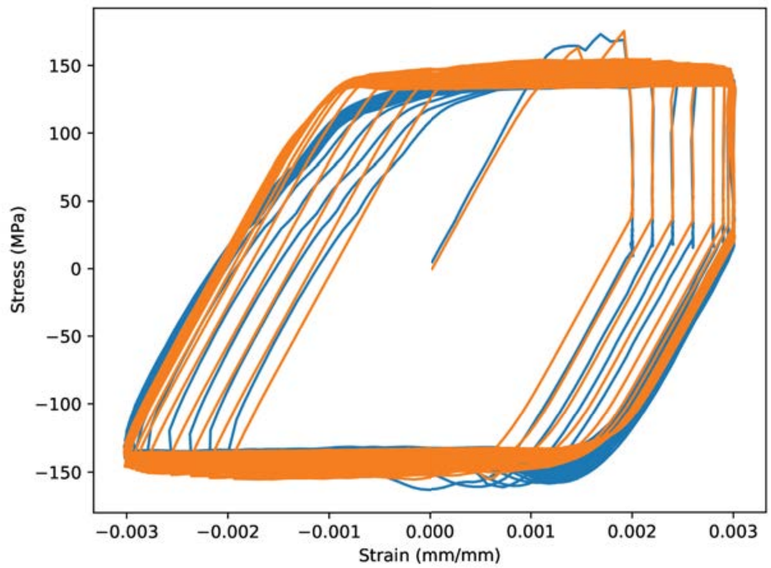
- Lots of tests
- Full datasets all the way to failure

Neural constitutive model

- Continuum damage mechanics: $\dot{D} = f\left(D, \sigma, \dot{\varepsilon}, \dot{\varepsilon}_p, T, \ldots\right)$
- Neural damage model: same thing except
  - We don't choose a functional form (deep neural network)
  - We let the ML algorithm pick the most important quantities to use

Works pretty well (INL A617)

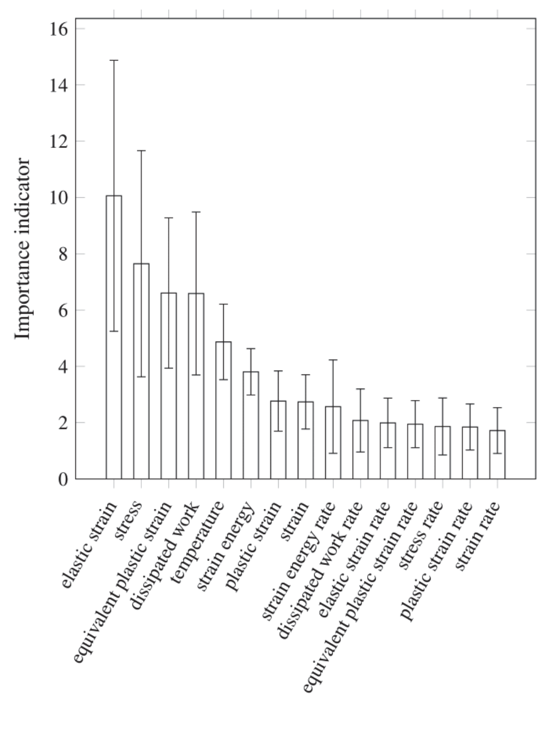
Mean response only here



Example of mean prediction vs INL data for an arbitrary creep-fatigue test (0.6% strain range, 10 minute hold, 950 C)

Let AI determine important model features

- The importance scores here are the average weights in the first layer in the entry corresponding to that feature
- Feature importance: surprisingly unsurprising
  - stress
  - equiv. plastic strain
  - dissipated work
  - temperature
  - strain energy



Take away thoughts

- An integrated approach linking, maybe even automatically, testing and advanced modeling/simulation has the most “bang for the buck” – the fastest qualification for the least cost
- Machine learning techniques are getting to be robust enough to guide the qualification process – both the simulations and the experiments
- ***A key challenge might be logistics***: how to practically fuse data from multiple sources in a database that is easy to access – both for machine learning and for end users

Thanks

Sagar Bhatt, Tianju Chen, Hao Deng, and Gary Hu

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Stephanie Pitts and Sudipta Biswas

INL Idaho National Laboratory

Alex Plotkowski

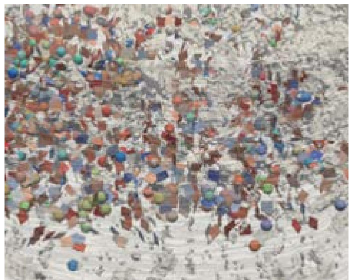
OAK RIDGE National Laboratory

Laurent Capolungo

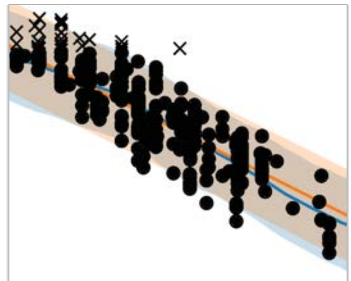
Los Alamos NATIONAL LABORATORY

A digital twin for advanced manufacturing

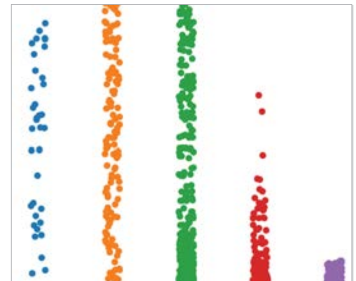
High throughput testing



Advanced characterization and in-situ monitoring



Automated physics-based model development



Calibration against large data sets

Input: particular build file (composition for conventional material)

Output: property variation in the part

Accelerate tests with models

Select tests/simulations with active learning – minimize cost and time

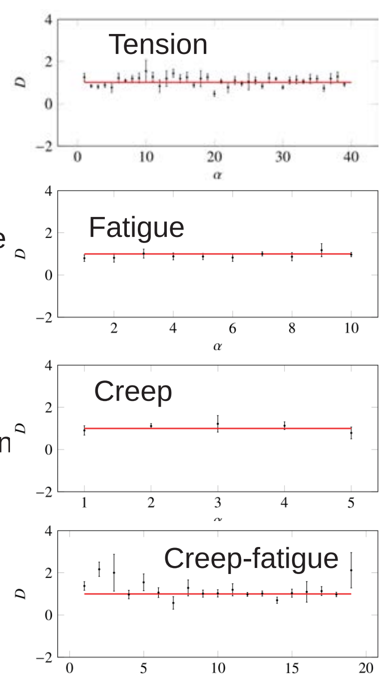
Neural constitutive models

Let's remove me from the loop…

- Physics-based models rely on two pieces:
  - Field equations – often general balance laws derived from basic thermodynamics
  - Constitutive models – often very specific and heavily reliant on expert judgement
- Can we get some help from machine learning?

Experts are great here

We slow things down a lot here



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Neural constitutive model

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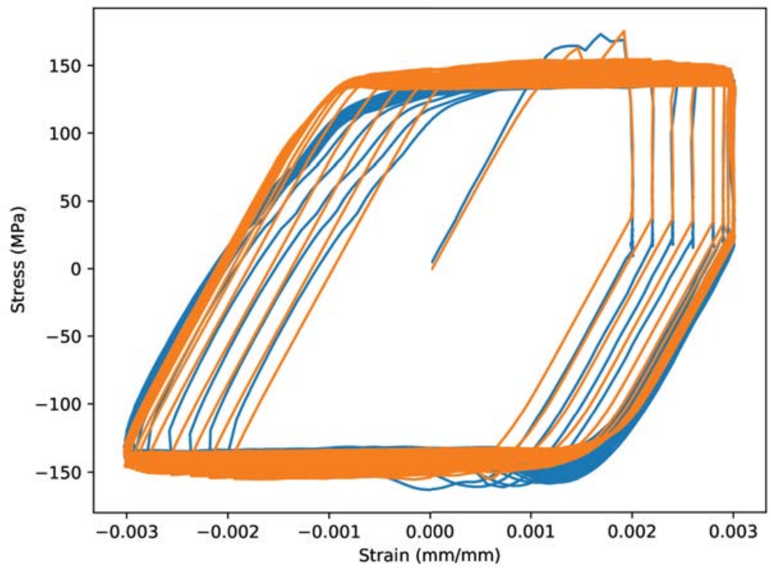
  - We don't choose a functional form (deep neural network)
  - We let the ML algorithm pick the most important quantities to use

Works pretty well for real data as well (INL A617)

I'm trying to figure out a way to visualize the variance in these plots…

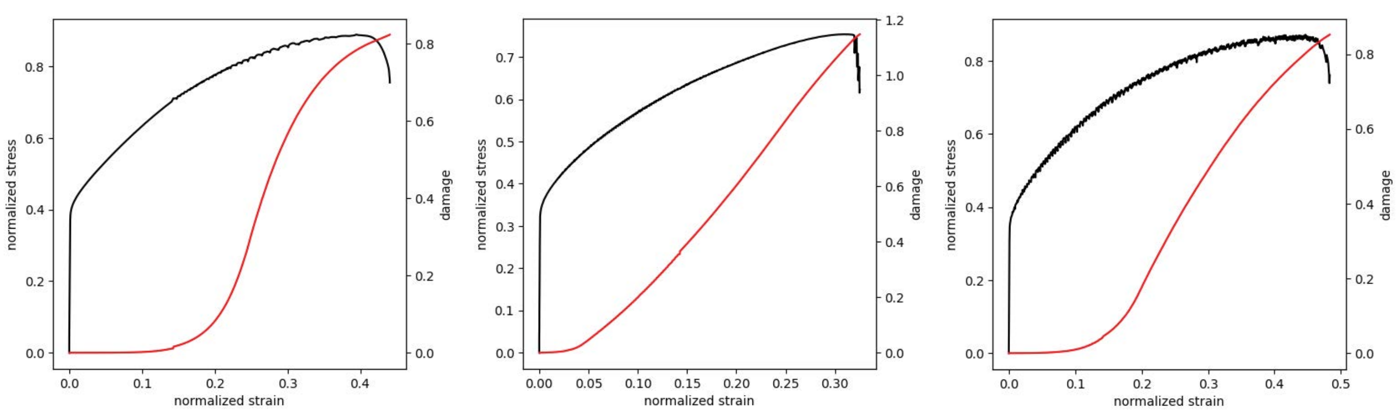


Example of mean prediction vs INL data for an arbitrary creep-fatigue test (0.6% strain range, 10 minute hold, 950 C)

Results

Models seem reasonable

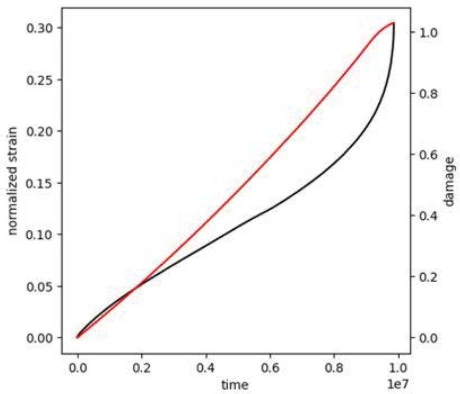
Elastic deformation produces little damage

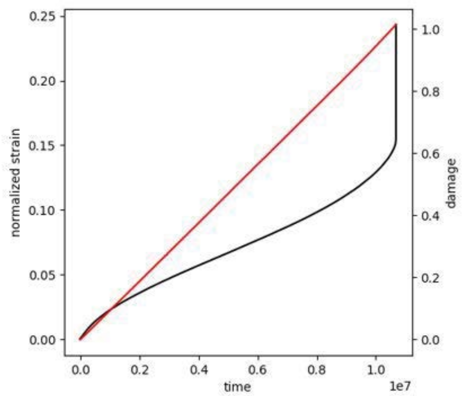


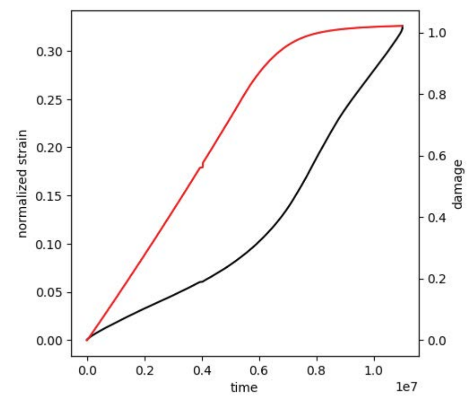
Results

Models seem reasonable

Secondary creep features a constant damage rate.
Damage saturates at tertiary creep.



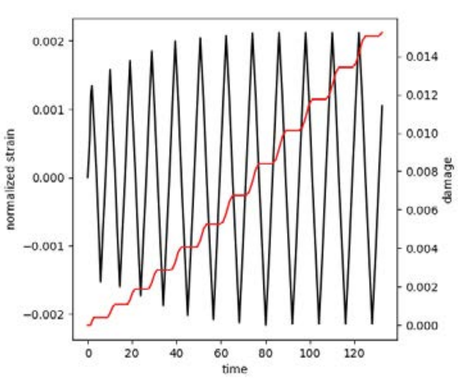


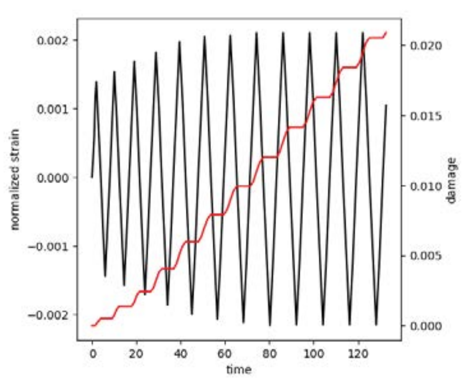


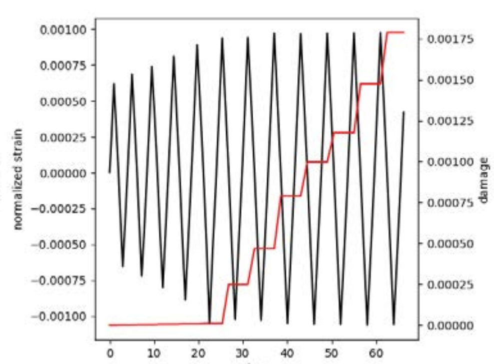
Results

Models seem reasonable

Damage rate is in sync with cyclic loading.







Feature selection

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  - stress
  - equiv. plastic strain
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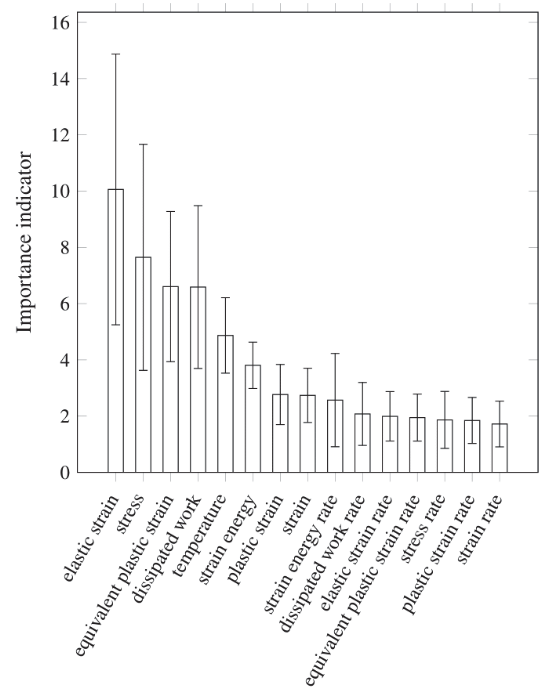
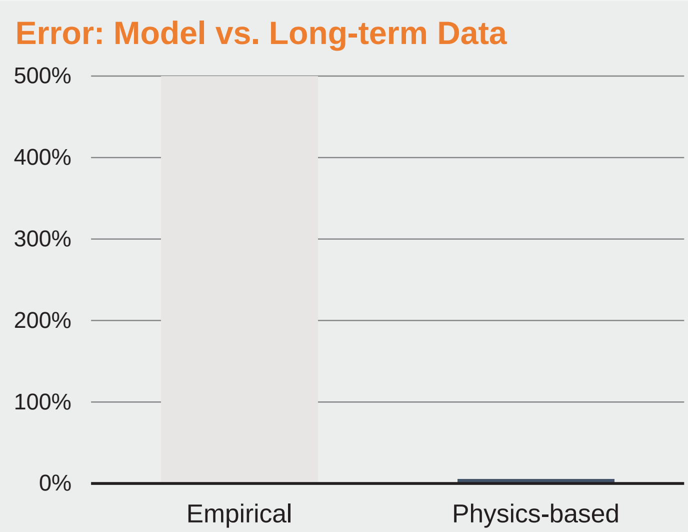
  - temperature
  - strain energy



Predicting long-term creep rupture strength

Early Result

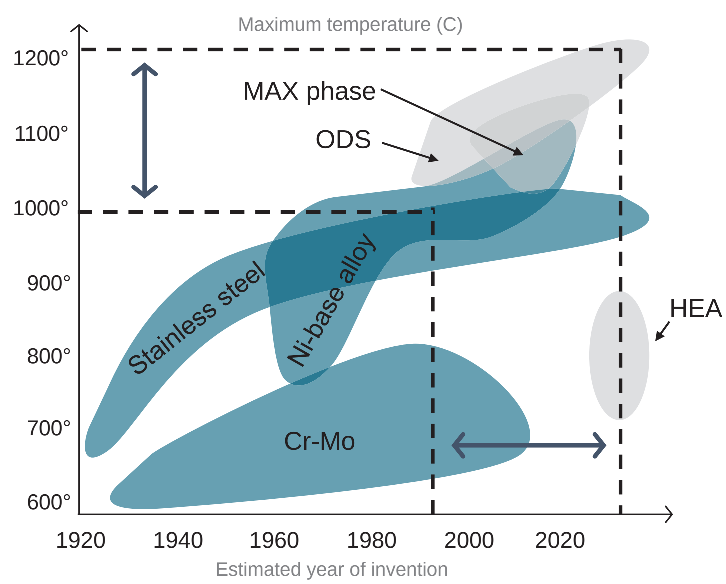
Can a physics-based CPFEM model better extrapolate short-term creep rupture tests to long creep rupture times compared to conventional, empirical models?



Qualifying new high temperature materials takes decades

	1950	1960	1970	1980	1990	2000	2010	2020	Beyond 2021
Nuclear Reactors			1972 **Alloy 617 Invented** 1975 **Grade 91 Invented**		1992 **Grade 91 Qualified**			2020 **Alloy 617 Qualified**	
Fossil Plants						2002 **Alloy 282 and Alloy 740H Invented**	2011 **740H ASME Code Case**		Beyond 2021 **282 ASME Code Case**
Jet Engines *Combustor*	1952 **Hastelloy X**	1960 **Alloy 188**	1972 **Alloy 617, Nimonic 263**	1982 **Alloy 230**					

We are working with material systems that are 30 years out of date



Better materials would have a broad impact

- Energy production efficiency
- Decarbonization of process heat
- Thermal energy storage
- Combustion efficiency

The Trouble with Physics-based models

GO BEYOND

Model-Assisted Validation and Certification of AM Components

David Furrer
Pratt & Whitney

Sergei Burlatsky
Raytheon Technologies Research Center

October 25, 2023

Outline

- Materials definitions in the Information Age (Industry 4.0)
- Product and process design approaches
- Approaches for component material requirements
- Testing and qualification planning

Traditional Engineering Materials Development and Definitions

- Design Curves – Empirical; Data Driven
- Specifications
- Prints Notes
- Fixed Process Requirements

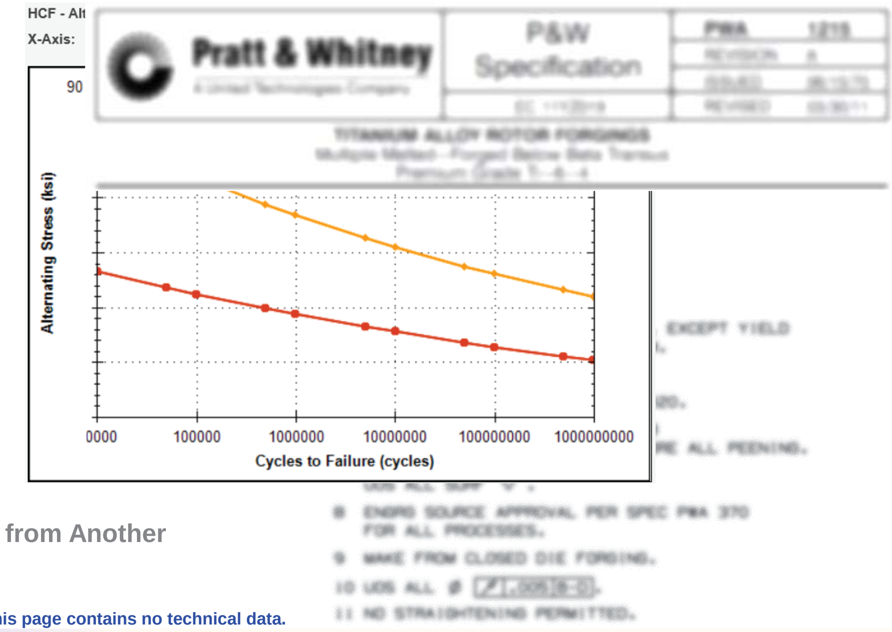
Material Equivalency - Material Pedigree - Application Space

Materials Definitions

Compilation of tools to define materials and establish equivalency

Traditionally:

- Specification Documents
- Design Curves
- Drawing Notes
- Quality Standards
- Component Testing and Qualification Approaches



Defining of Material Equivalency and Methods to Differentiate Material of One Controlled Pedigree from Another

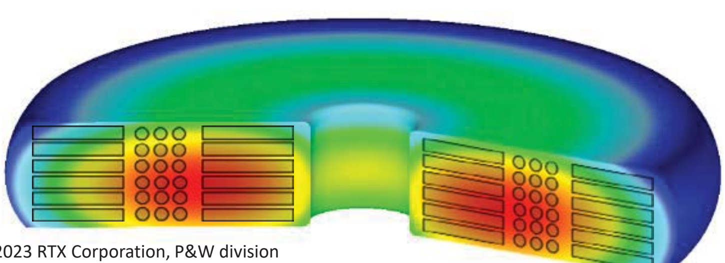
Specifications Defined Based on Statistical Minima*

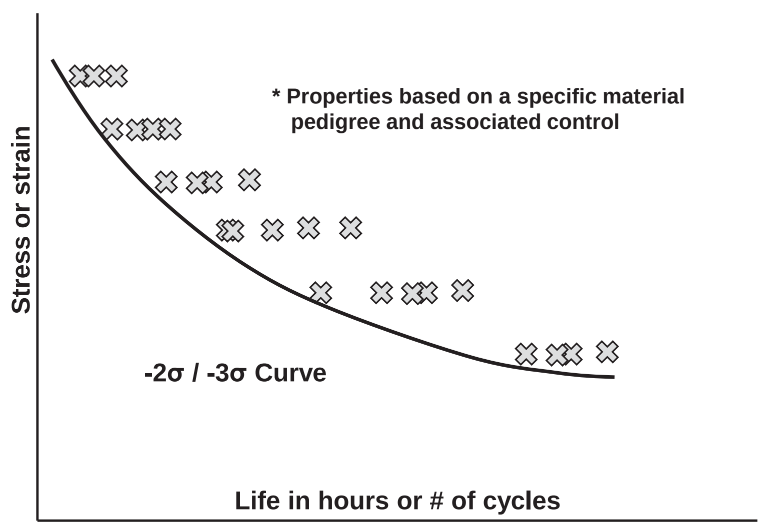
Material properties depend on processing path (manufacture and application)

Multiple components produced on manufacturing equipment

Test samples extracted from components using randomized locations, orientation, test conditions, etc.

Manufacturing path for components (pancakes, etc.) define range of pedigree space

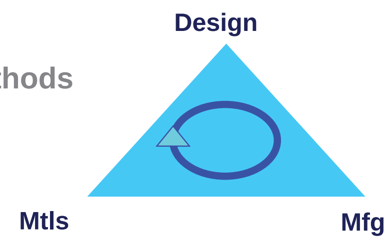




Materials & Product Engineering

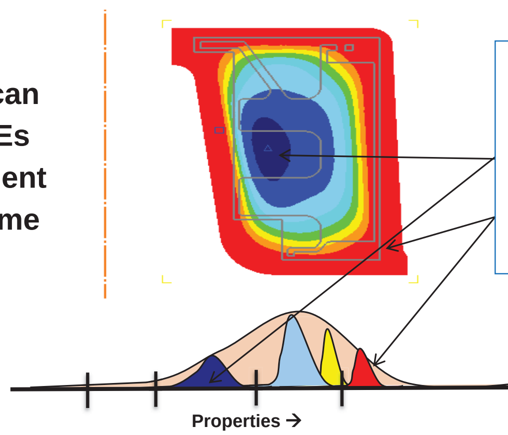
- Mechanical Properties → fn (chemistry and structure)
- Structure → fn (chemistry and processing)
- Processing → fn (component geometry)

Materials, Manufacturing Methods and Component Design are Strongly Coupled



Materials Definitions

Volumetric regions can be defined by SERVEs (Statistically Equivalent Representative Volume Elements)



True material capability and property distributions are controllable and reproducible; not "random variability".

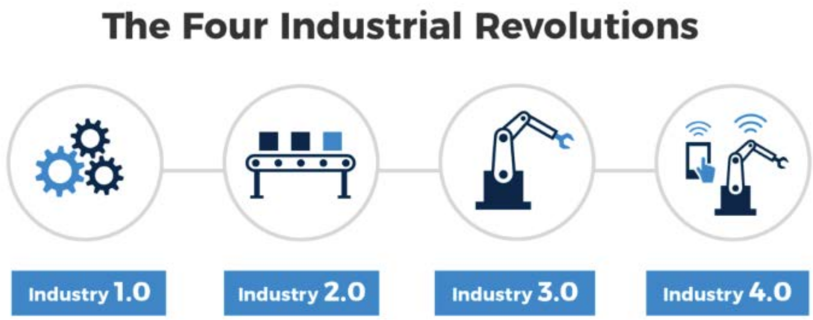
Properties are a fn (chemistry, microstructure, stain, cooling rate, etc.); i.e. pedigree.

Materials properties are path dependent and are often "location-specific". Engineering specifications often treat entire material volume as single, homogeneous property capabilities.

Modeling and simulation can help enhance material, process and component definitions

Industry 4.0

Industry 4.0 is a true technology revolution and not a buzz-word term



Framework for digital engineering, manufacturing, simulation, communication and optimization …. Including validation and certification

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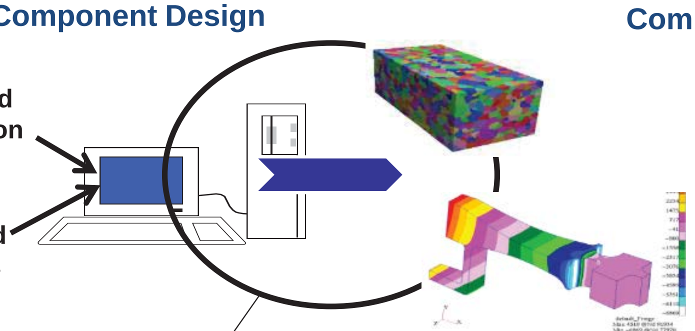
Integrated Materials & Process Modeling

Use of models to link design, producibility & component performance

Component Design

Model-based Mt'l definition

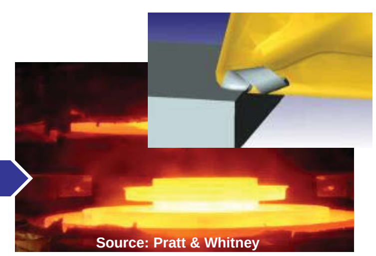
Model-based Mfg process definition

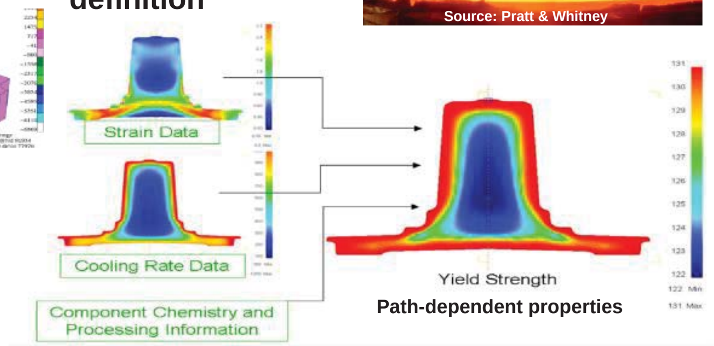


Parametric model includes local structure and properties

Component Manufacture

Model-based component definition





Path-dependent properties

Utilization of Modeling to Predict Component Capabilities and Proactively Mitigate Producibility Risks

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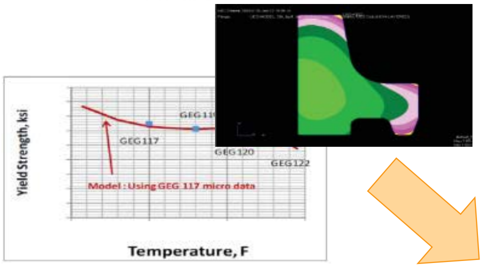
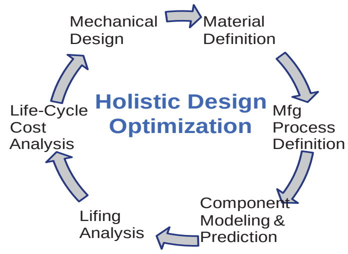
Probabilistic Property & Performance Predictions

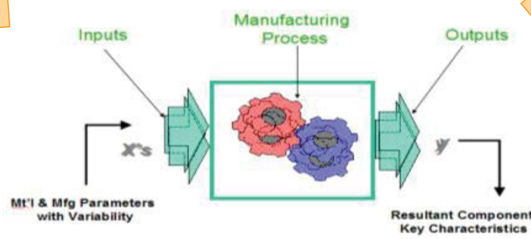
Material and manufacturing process modeling enables design for variation

Materials Modeling



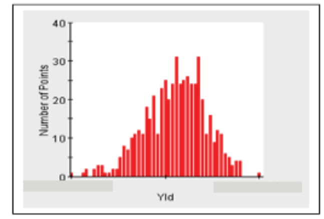
Development and Application of Physics-Based Models





Identification and Assessment of Material and Process Variability

Design for Variation



Predicted Material and Component Properties

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Model-Informed Process Controls and Product Testing

Engineered process controls and test location selection provides for efficient processes

- **Modeling methods are guiding process control requirements**
- **Prediction of component location-specific attributes provide insight relative to test locations that are most sensitive to processing**
  - **Smart testing to minimize tests and maximize value**

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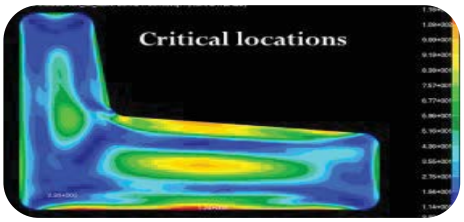
Smart Testing

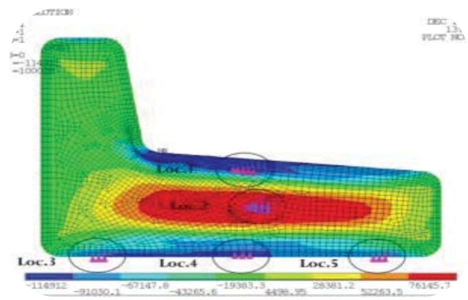
Engineered process controls and test location selection provides for efficient processes

Critical measurement locations
from UQ perspective



Measurement requirements :

Locations (XYZ)
Components (xx, yy, zz)
Applied method and specifications
Report data format

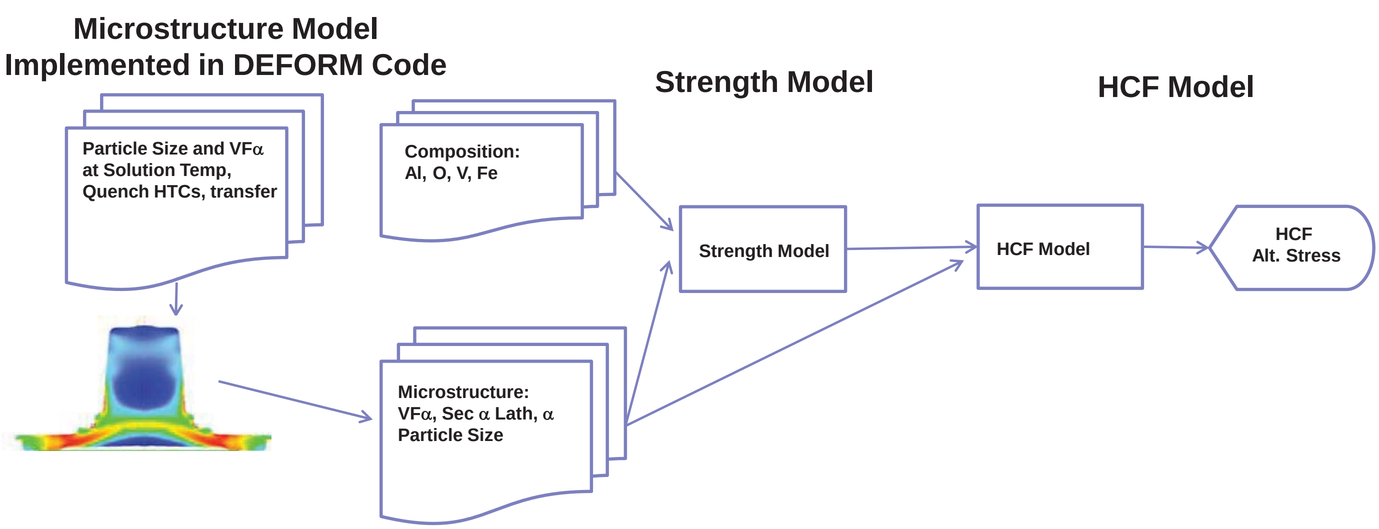


Test to confirm component capabilities versus model prediction

Continuous learning about material and process with Bayesian updating approach

Model-Based Material Definition

MATERIAL – MICROSTRUCTURE – PROPERTY MODELS



Model-Based Material Definition Enabled Design and Lifing Optimization

Application of Additive Manufacturing

Mature

- Polymer tooling
- Demonstration hardware
- Visual Aids

Expand & Leverage

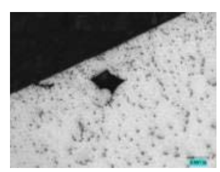
- Demonstration hardware
- Rig & test hardware
- Production hardware
- Tooling
- Certification

Develop

- Design system
- Material and process modeling data
- Process control capabilities

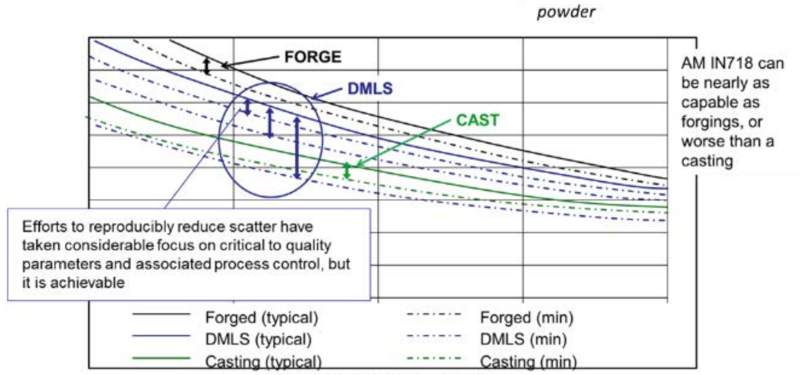
AM Certification and Qualification

- Process defects
- Microstructure control
- Chemistry control
- Resultant property scatter
- Part-to-part/Batch-to-batch/ Machine-to-machine variability
- Powder handling and re-use
- Geometry control
- Surface finish



Lack of fusion

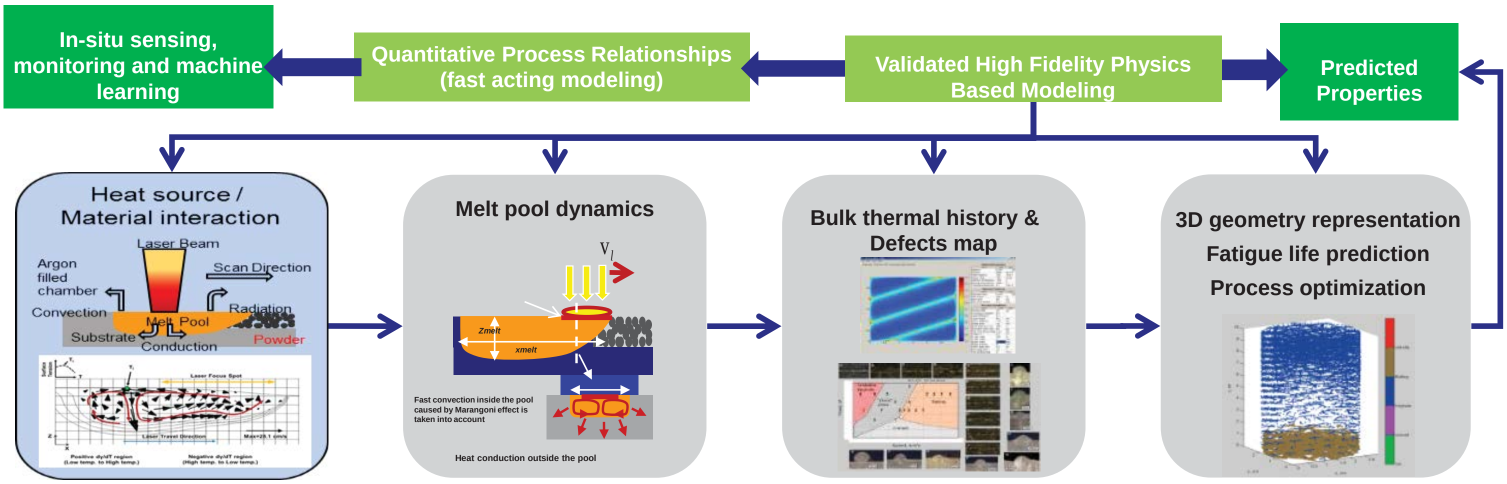
Partially sintered powder



No Technical Data Per the EAR or ITAR

Laser Powder Bed Fusion Modeling Framework

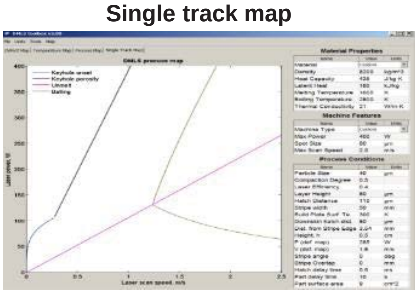
Integrated physics-based simulation of AM processes to predict part level distortion defects, microstructure and establish correlation to performance (fatigue)



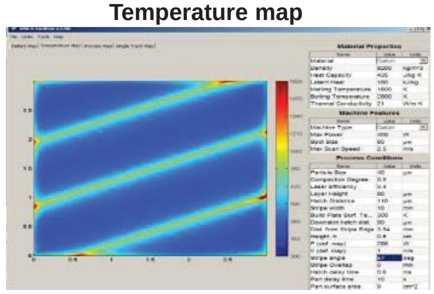
Model Input / Output

Model includes part geometry and location-specific processing path

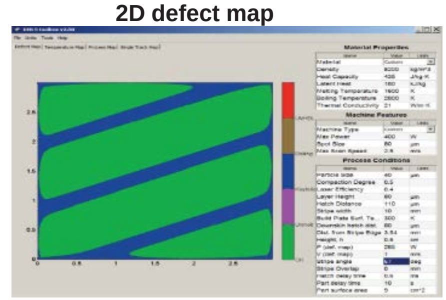
Single track map



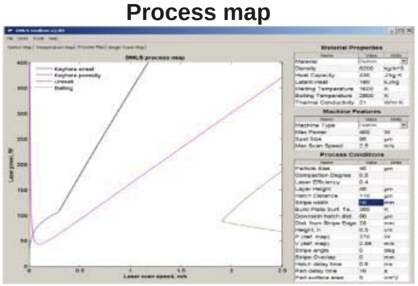
Temperature map



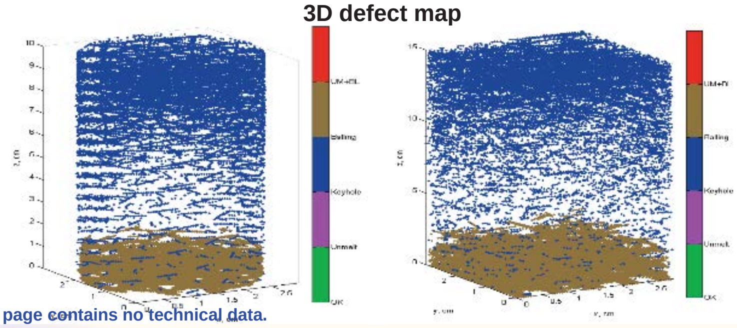
2D defect map



Process map



3D defect map

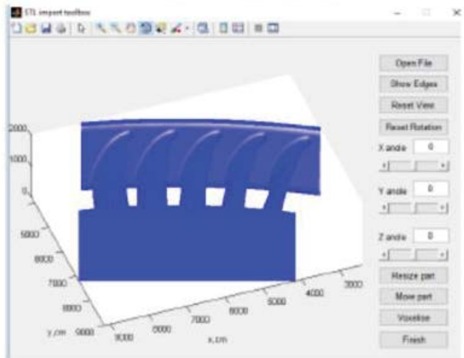


Modeling Applied to Component Configurations

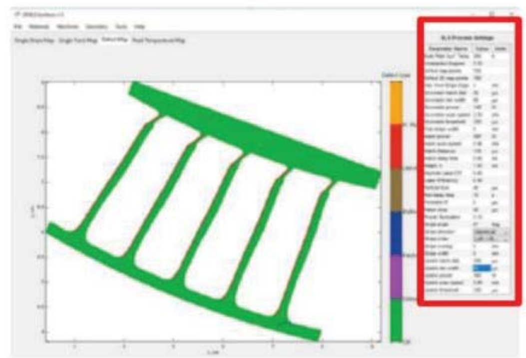
Models provide optimal build paths (process operation conditions) for arbitrary geometries, build direction and bed loading density

Part geometry

Import STL file with part geometry



Operational conditions

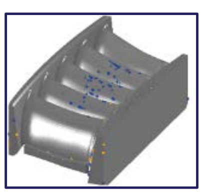


Additive Manufacturing Model Application

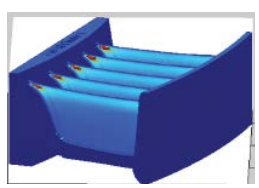
Component Model and Build Validation

STL part geometry

3D defect map



Surface roughness map



Final optimized built component

AM defect prediction model successfully applied to complex component build and final process design and control requirements

Physics-based fast acting tool for defects prediction

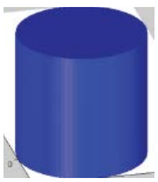
Analytical model-based approach does not require time-consuming simulations and extensive experimental calibration

Model capabilities and features

Calculation of process map. Visualization of defect free/rich areas in P(laser power) – V (scanning rate) cross-section of multi-parameter space

Calculation of 2D and 3D defect maps from first-principles with minimal and universal (is not part, material and shape) calibration

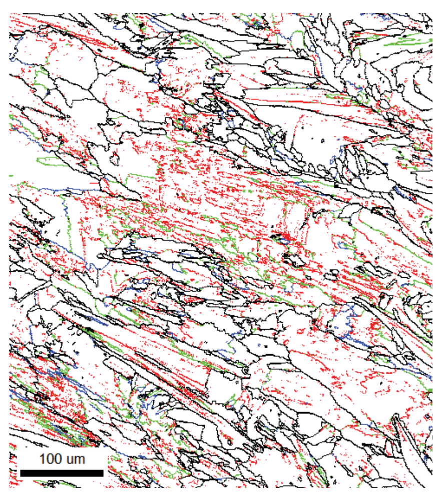
Calculation of 3D defect map for simple geometry takes ~ 7 s, for complicated geometry takes ~ 100 seconds on 4-core desktop



6 s

75 s

AM Material Microstructure Analysis and Control

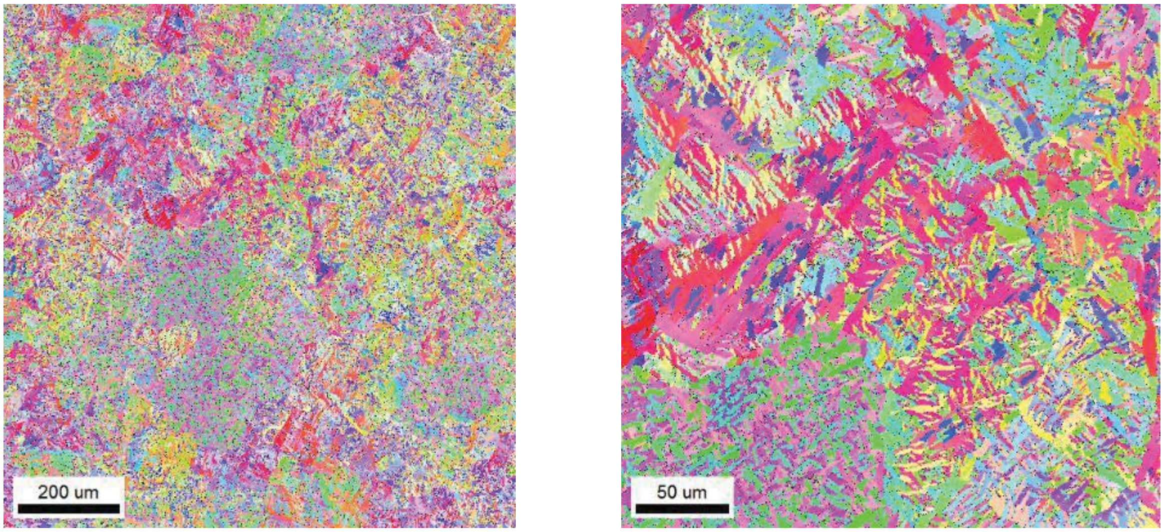


AM IN718 component microstructure

Boundaries: Rotation Angle

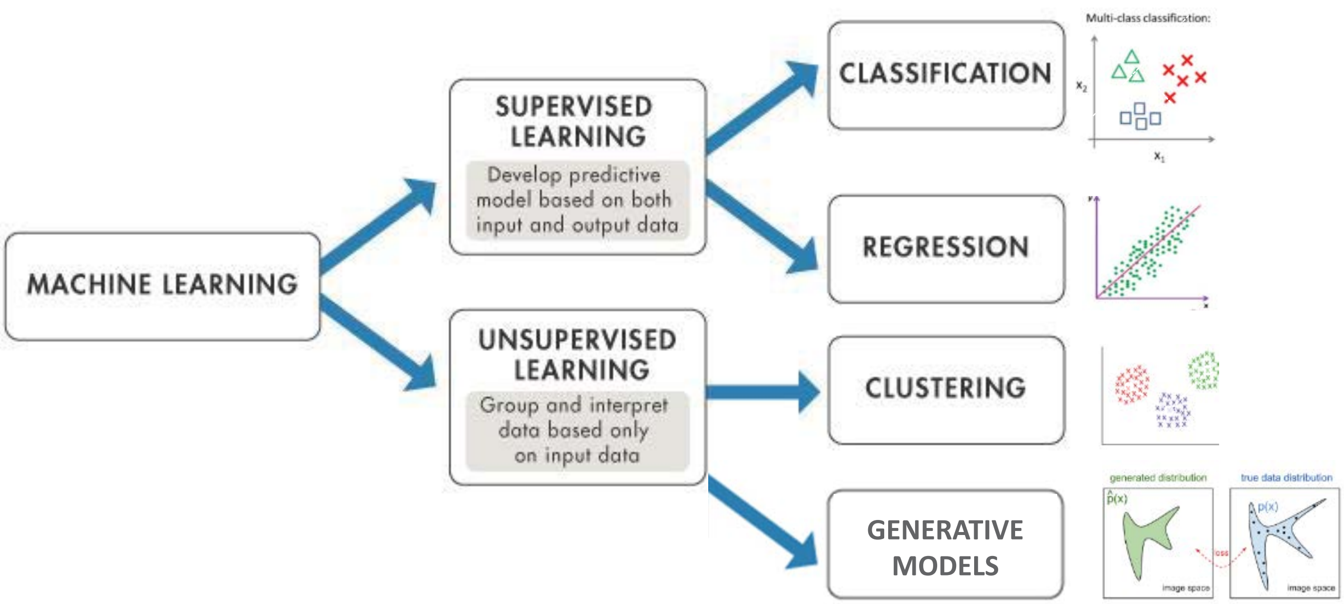
	Min	Max	Fraction	Number	Length
red	2°	5°	0.338	41325	2.39 cm
green	5°	10°	0.141	17204	9.93 mm
blue	10°	15°	0.060	7300	4.21 mm
black	15°	65°	0.462	56475	3.26 cm

AM Material Microstructure Analysis and Control



EBM Ti 6-4 IPF Maps

Machine Learning Methods: Enhanced Material Definitions



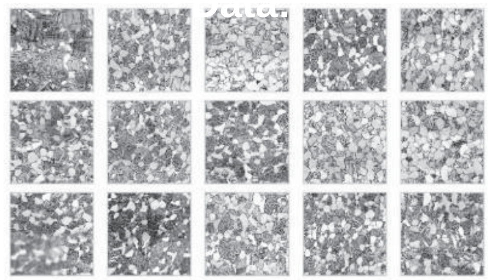
Machine Learning Providing New Understanding

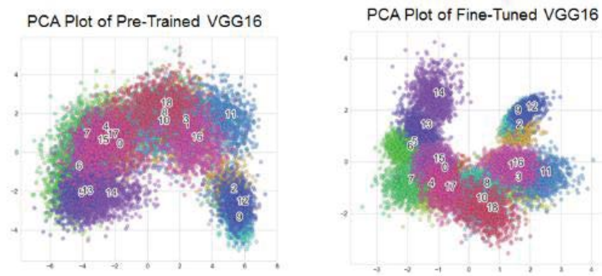
GO BEYOND

Microstructure data can be used to predict properties and classify materials

CLASSIFICATION

REGRESSION





Microstructure dataset can be collected with variation in manufacturing pedigree

Machine Learning models can be used to provide principal component analysis (PCA)

Predictive models can also be developed to guide testing and process control understanding

Immediate applications for:

- Visual similarity assessment / lookup
- Outlier detection
- Quality control
- Process development

Models are fast -- analyze 100's of images / second

ML Tools and Methods can be applied directly to manufacturing data as well as component properties.

Automated Data Capture and Analytics

GO BEYOND

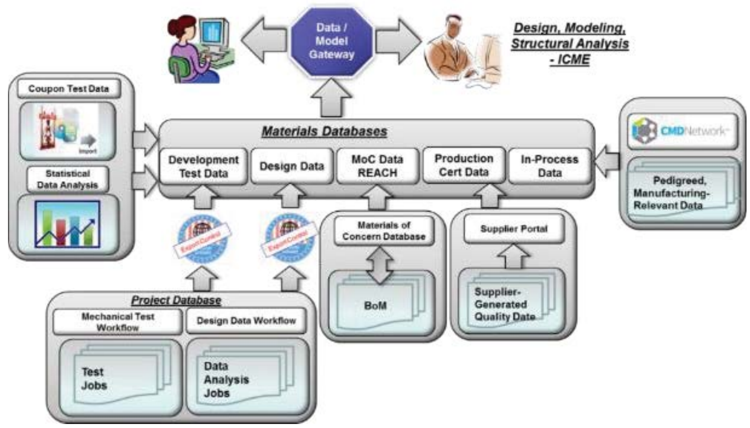
Industrial processes generate large amounts to data that produce digital thread elements

- Industry 3.0 provided manufacturing automation and computerization
- Industry 4.0 provides simulation, automated capture of sensor data which enables real-time automated process monitoring and controls
  - Linkage of process data capture, data analysis and modeling

Digital Data Management

Industry 4.0 requires a robust digital data infrastructure

- Material and process pedigree capture
- Performance correlation to processing
- Model-based data capture and visualization activities

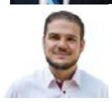


Zero Cost for Data Capture • Zero Data Loss • Data Availability for Analytics

Conclusions and Take-Away

- Integration of modeling, sensors and data analytics are providing significant benefits
- Model-based material and process definitions are becoming the new standard in holistic design, manufacturing and part/process validation and certification

Uncertainty Quantification of the Metal Laser Powder Bed Fusion Additive Manufacturing via the Hypercomplex-based Finite Element Method



Arturo Montoya, Prof.
Matthew Balcer, PhD Candidate
Mauricio Aristizabal, Post Doc.
Juan Rincon-Tabares, PhD Candidate
David Restrepo, Assist. Prof.
Harry Millwater, Prof.

Margie and Bill Klesse College of Engineering and Integrated Design

UTSA
The University of Texas at San Antonio™

Overview

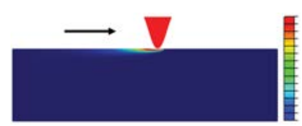
Long-term objective:

Develop, implement, verify, and validate a new computational methodology to provide sensitivities and uncertainty quantification metrics for metal-based additively manufactured components

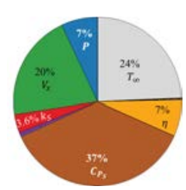
What is new with our approach?

Uses hypercomplex algebra combined with traditional finite element methods to compute arbitrary-order high-accuracy derivatives.

- → Arbitrary order, shape, material, and loading parameters available.
- → Linear, nonlinear, or time dependent
- → Step size independent method ensures high accuracy.
- → The traditional real-valued results are still obtained and can be reused.
- → Non-Intrusive – a **postprocessing** code is programmed using hypercomplex algebra
  - → Traditional functions still used, e.g., same shape functions, etc.



Methodology is programmed **based on** a user element (UEL) for the **Abaqus** commercial software.



Partial Derivative Calculation

Finite Differentiation Method (FDM)

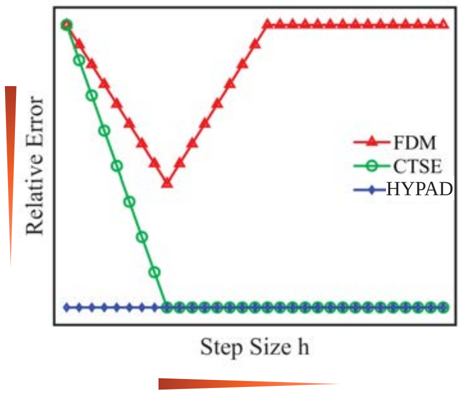
$$\frac{d\mathbf{u}(a_o)}{da} \approx \frac{\mathbf{u}(a_o+h) - \mathbf{u}(a_o)}{h}$$

- Determining h is problematic
- No code modifications

Complex Taylor Series Expansion (CTSE)

$$\frac{d\mathbf{u}(a_o)}{da} \approx \frac{Im\left(\mathbf{u}(a_o+ih)\right)}{h}$$

- h can be "very" small $\sim 10^{-30}$
- Built-in in languages



Set of Hypercomplex Numbers

Complex

$$a^* = a^{Re} + i a^{Im}$$
$$i^2 = -1$$

Dual - OTI

$$a^* = a^{Re} + \epsilon a^{\epsilon}$$
$$\epsilon^2 = 0$$

HYPAD:
HYPercomplex Automatic Differentiation

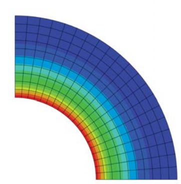
$$\frac{d\mathbf{u}(a_o)}{da} = \frac{Im_\epsilon\left(\mathbf{u}(a_o+\epsilon h)\right)}{h}$$

If a is perturbed along multiple imaginary directions high order sensitivities (interactions) are obtained

- h can be unitary
- Exact derivative
- Requires specific algebra packages
- Algebra accounts for composition and chain rule

HYPercomplex Automatic Differentiation (HYPAD)

Mathematical model, $f(\boldsymbol{x})$



Nodal derivatives using HYPAD

$$\frac{\partial f(\boldsymbol{x})}{\partial x_1}, \frac{\partial f(\boldsymbol{x})}{\partial x_2}, \frac{\partial^2 f(\boldsymbol{x})}{\partial x_1^2}, \frac{\partial^2 f(\boldsymbol{x})}{\partial x_1 \partial x_2}, \frac{\partial^3 f(\boldsymbol{x})}{\partial x_1^3}, \dots$$

Taylor series expansion of nodal outputs

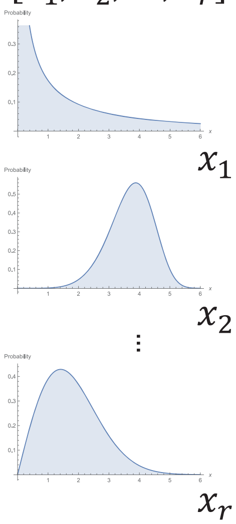
$$f(\boldsymbol{x}) \approx f(\boldsymbol{\mu}_x) + \sum_{i=1}^{m} \frac{\partial f(\boldsymbol{x})}{\partial x_i}(x_i - \mu_{x_i}) + \cdots$$

Uncertainty Quantification

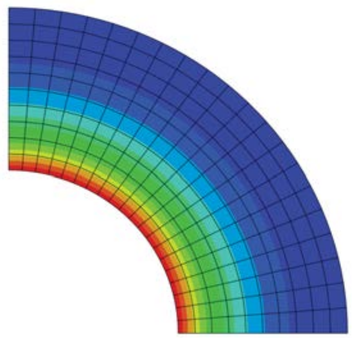
Quantifying Uncertainty in Finite Element Outputs with the Taylor Series

Random Variables

$\boldsymbol{x} = [x_1, x_2, \ldots, x_r]$



Mathematical Model, $f(\boldsymbol{x})$

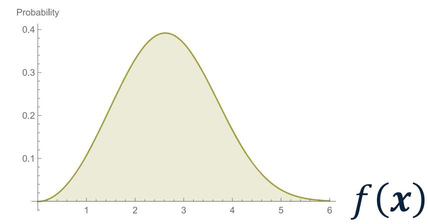


Surrogate Model

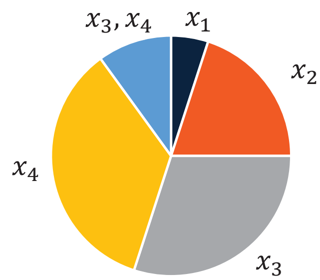
$f(\boldsymbol{x}) \approx Y_n$

(n^{th}-order Taylor series expansion)

Output



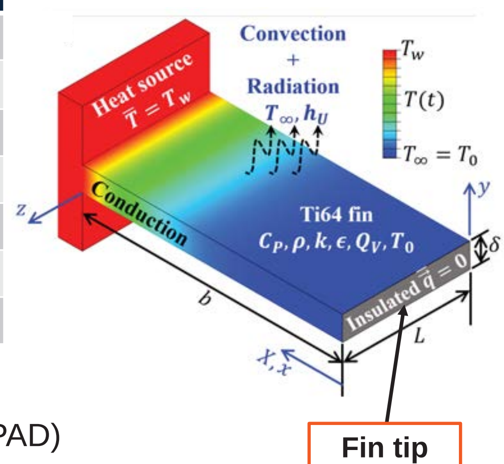
Sobol' Indices



Heated Fin: Verification Problem [1]

Goal: Quantify uncertainty of temperature at tip of fin through time

Variable	Distribution	Mean, μ_x	COV= σ_x/μ_x
Thermal conductivity, k	Log-Normal	$7.1\ \mathrm{W/(m \cdot K)}$	0.20
Specific heat, c_p	Log-Normal	$580\ \mathrm{J/(kg \cdot K)}$	0.20
Density, ρ	Log-Normal	$4430\ \mathrm{kg/m^3}$	0.20
Heat transfer coefficient, h_U	Log-Normal	$114\ \mathrm{W/(m^2 \cdot K)}$	0.20
Ambient temperature, T_∞	Triangular	$283\ \mathrm{K}$	0.01
Heat source temperature, T_w	Uniform	$389\ \mathrm{K}$	0.20
Length of fin, b	Uniform	$51\ \mathrm{mm}$	0.20



- Analytical solution was used for verification [2]
- HYPAD-UQ conducted with a 2D FEM model (using OTI-based HYPAD)
- Compared computational performance against linear regression-based stochastic perturbation finite element method

[1] Balcer, M., Aristizibal, M., Rincon-Tabares, J.-S., Montoya, A., Restrepo, D., & Millwater, H. (2023). HYPAD-UQ: A Derivative-based Uncertainty Quantification Method Using a Hypercomplex Finite Element Method. doi: 10.1115/1.4062459.
[2] Rincon-Tabares, J.-S., Velasquez-Gonzalez, J. C., Ramirez-Tamayo, D., Montoya, A., Millwater, H., & Restrepo, D. (2022). Sensitivity Analysis for Transient Thermal Problems Using the Complex-Variable Finite Element Method. Appl. Sci., 12(5), 2738. doi: 10.3390/app12052738

Hypercomplex-based Taylor Series vs Linear Regression-based Taylor Series

Computational performance of HYPAD-UQ was compared to linear regression

HYPAD-UQ

- Taylor series expansion of $f(\boldsymbol{x})$ about the mean values of $\boldsymbol{x}$

$$f(\boldsymbol{x}) \approx f(\boldsymbol{\mu_x}) + \sum_{i=1}^{m} \frac{\partial f}{\partial x_i}(x_i - \mu_{x_i}) + \frac{1}{2}\sum_{i,j=1}^{m} \frac{\partial^2 f}{\partial x_i \partial x_j}(x_i - \mu_{x_i})(x_j - \mu_{x_j}) + \cdots$$

- Derivatives calculated with HYPAD

Linear Regression-based Stochastic Perturbation Finite Element Method [1]

- Taylor series expansion of $f(\boldsymbol{x})$ (same polynomial basis)

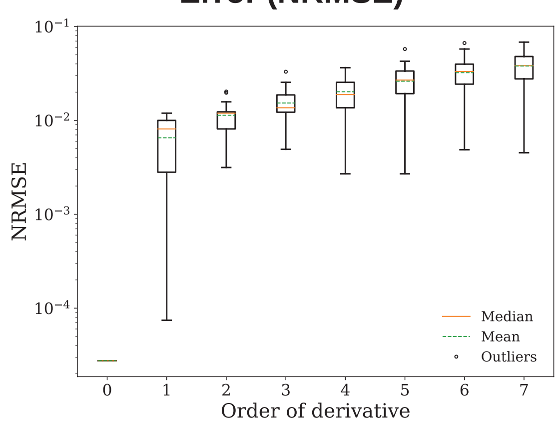
$$f(\boldsymbol{x}) \approx b_0 + \sum_{i=1}^{m} b_i x_i + \sum_{i,j=1}^{m} b_{ij} x_i x_i + \cdots$$

- Samples drawn from $f(\boldsymbol{x})$
- Unknown coefficients, b_i, approximated by Ordinary Least Squares (OLS)

[1] Kaminski, M., 2022, Uncertainty analysis in solid mechanics with uniform and triangular distributions using stochastic perturbation-based finite element method, Finite Elements in Analysis and Design, 200, 3.

HYPAD Derivative Accuracy and CPU Time

Normalized Root Mean Square Error (NRMSE)



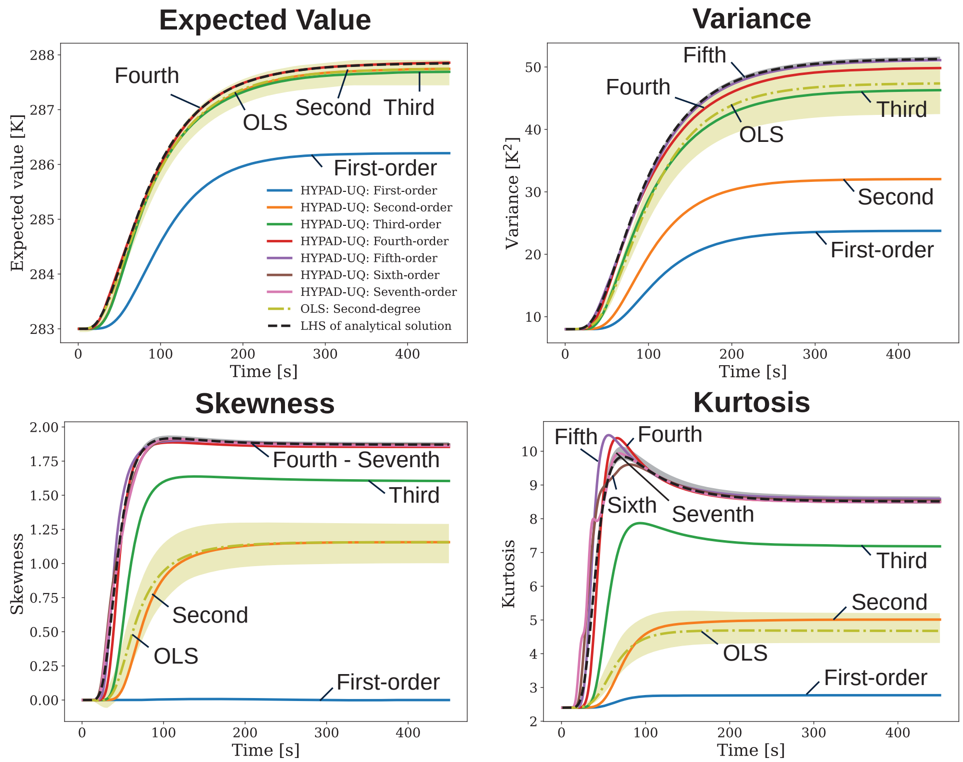
- Derivatives calculated using OTI Algebra [1]
- Each run computes all 1^{st}- through n^{th}-order partial derivatives
- **NRMSE** measured using derivatives of the analytic solution
- Error increases with order of derivative

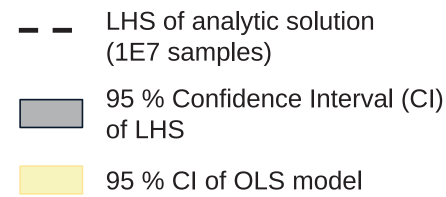
$$\mathrm{NRMSE} = \frac{\sqrt{\frac{\sum_{i=1}^{N}\left(\phi_{\text{approx}}^{(i)} - \phi_{\text{analytic}}^{(i)}\right)^2}{N}}}{\max\left(\phi_{\text{analytic}}\right)}$$

Derivative order, n	First	Second	Third	Fourth	Fifth	Sixth	Seventh
Total computed derivatives	7	35	119	329	791	1715	3431
CPU time relative to a single real analysis	2.60	5.00	10.4	22.1	64.7	133.5	205.5

[1] Aristizabal Cano, M., (2020). Order truncated imaginary algebra for computation of multivariable high-order derivatives in finite element analysis, PhD thesis, Universidad EAFIT.
[2] Balcer, M., Aristizibal, M., Rincon-Tabares, J.-S., Montoya, A., Restrepo, D., & Millwater, H. (2023). HYPAD-UQ: A Derivative-based Uncertainty Quantification Method Using a Hypercomplex Finite Element Method. doi: 10.1115/1.4062459.

Central Moments

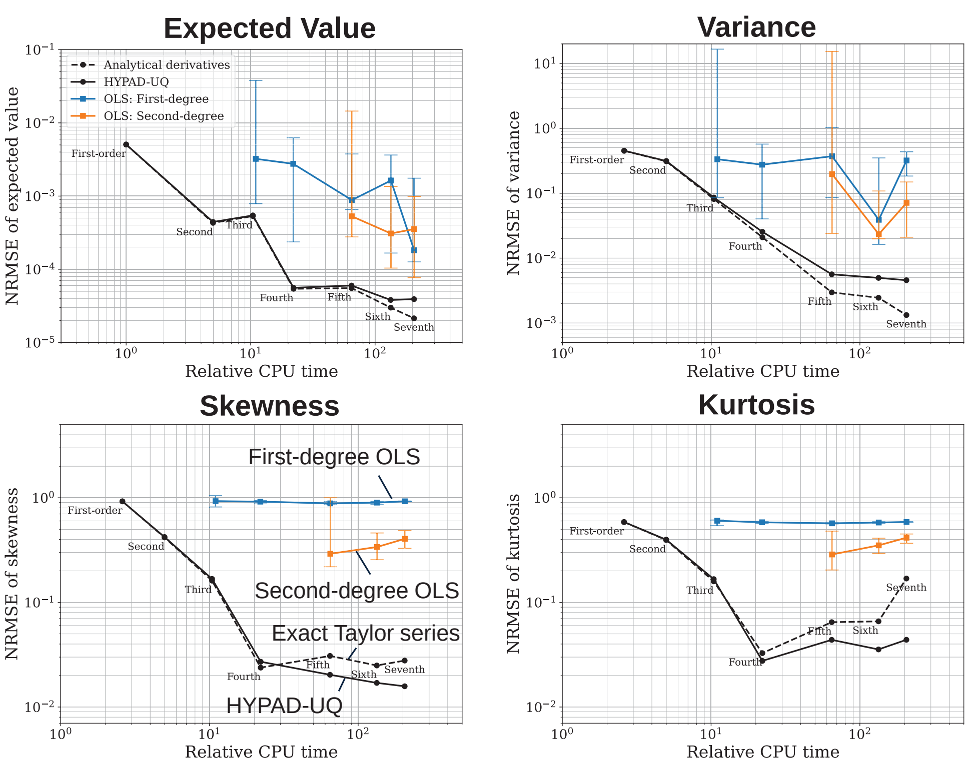




HYPAD-UQ is compared to:

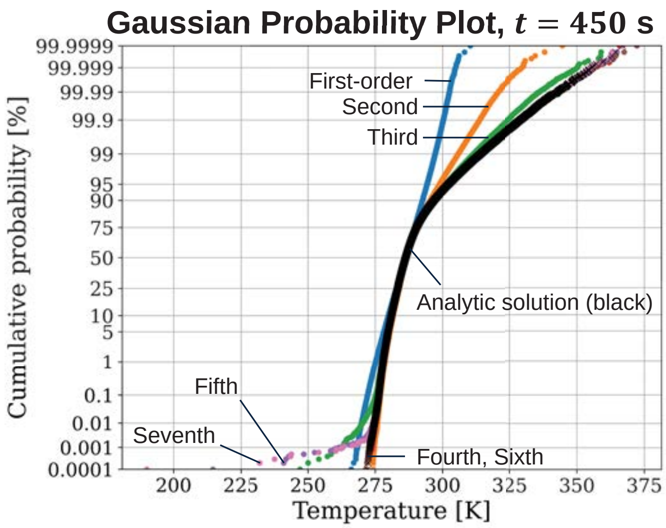
- LHS of analytical solution (1E7 samples)
- 2^{nd}-degree OLS regression, trained with 206 samples

Error of Central Moments



- HYPAD-UQ moments converge to lower errors than OLS within the same CPU time
- Higher-order expansions can increase accuracy
  - Higher-order expansions do not guarantee monotonic convergence

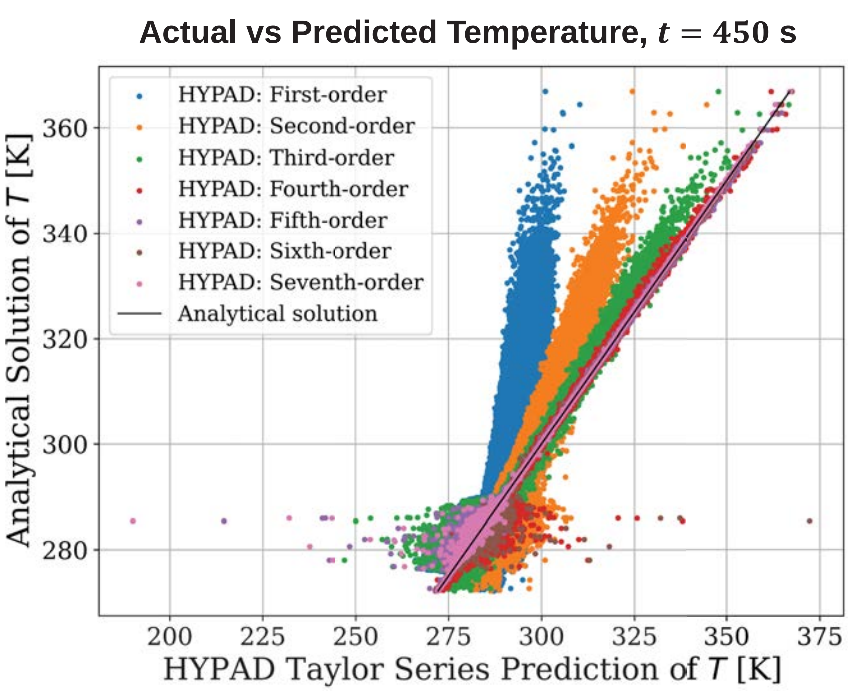
Cumulative Distribution at Steady-State



- HYPAD-UQ accurate near mean of temperature
- Higher-order HYPAD-UQ Taylor series expansions can *diverge* near the *tails* of distribution
  - Odd-ordered Taylor series diverge near low probabilities

[1] Balcer, M., Aristizibal, M., Rincon-Tabares, J.-S., Montoya, A., Restrepo, D., & Millwater, H. (2023). HYPAD-UQ: A Derivative-based Uncertainty Quantification Method Using a Hypercomplex Finite Element Method. doi: 10.1115/1.4062459.

HYPAD-based Taylor Series Prediction vs Actual Temperature

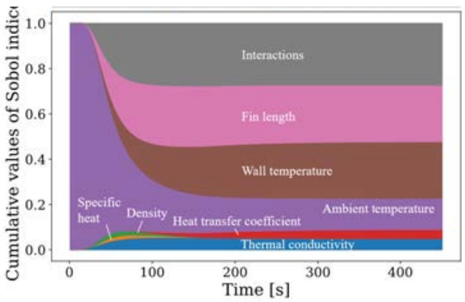


- 1E6 evaluations
- Taylor series converges to analytical solution for most of the random variable domain
- Certain combinations of random variables lead to large error in *higher-order* Taylor series expansions

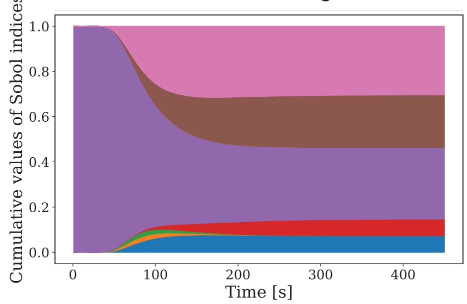
[1] Balcer, M., Aristizibal, M., Rincon-Tabares, J.-S., Montoya, A., Restrepo, D., & Millwater, H. (2023). HYPAD-UQ: A Derivative-based Uncertainty Quantification Method Using a Hypercomplex Finite Element Method. doi: 10.1115/1.4062459.

Sobol' Indices

LHS of Analytic Solution (7×10^7 samples)

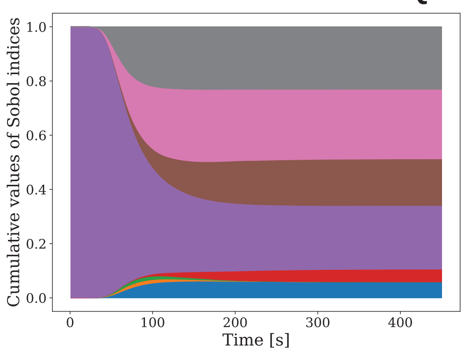


First-order HYPAD-UQ

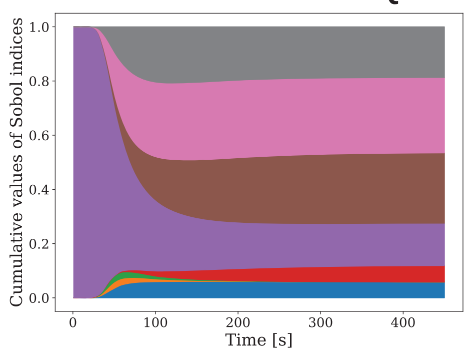


- Max of 28% of the total variance is due to *interactions*
- First-order HYPAD-UQ correctly identifies important variables
- Second-order HYPAD-UQ captures most of the interaction effect

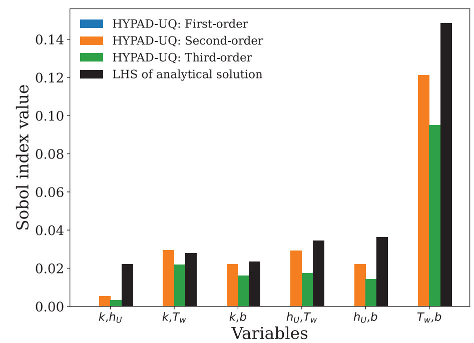
Second-order HYPAD-UQ



Third-order HYPAD-UQ



Interaction Effects at Steady-State



AM Application: Physics Involved

Thermal Profile

Transient heat transfer:

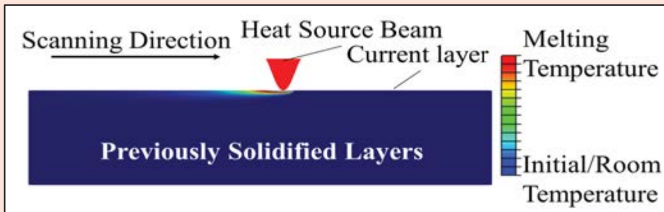
- **Fourier equation**
- **Convection/Radiation boundary conditions**
- **Moving heat source boundary condition**
- **Temperature-dependent properties**

Thermal history

Thermomechanical

- T-dependent properties
- Residual thermal strain
- Thermoelasticity
- Thermoplasticity

3D Sequential Model

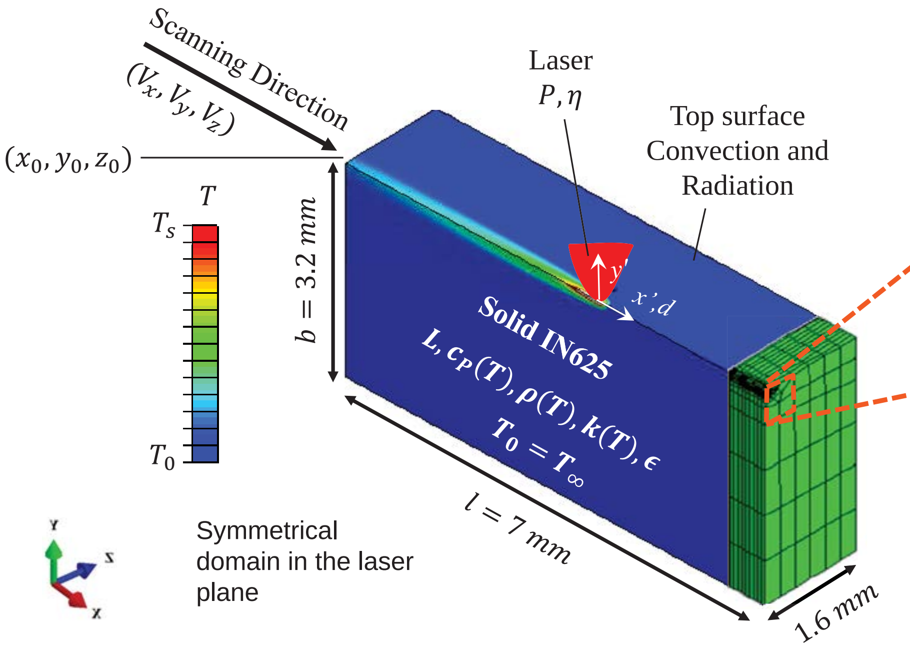


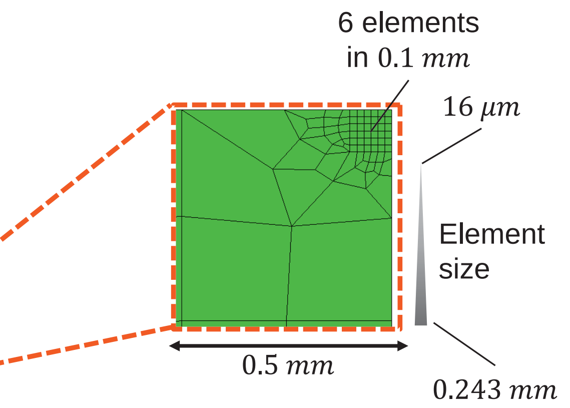
Outputs

Thermal Residual Stresses, Final Track Shape, **Thermal History**

AM Application: Bare Plate Single Track 3D Model

Goal: Quantify uncertainty in mean surface temperature





Assumptions: solid conduction, radiation, convection, moving laser, variable properties, linear solid-liquid-solid phase change, latent heat
Physics disregarded: internal convection, vaporization, chemical reactions, calibration parameters

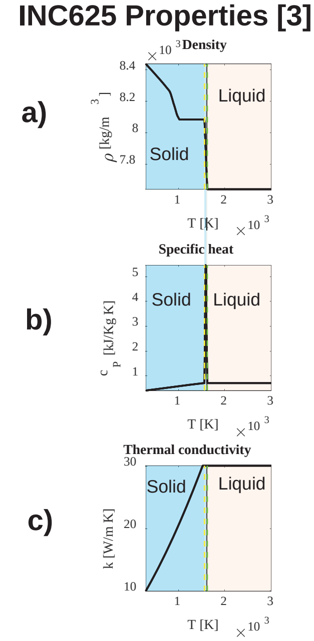
AM Application: Random Variable Distribution Parameters

All variables are normally distributed

Type	Physics	Parameter	Mean, μ_x [1]	COV= σ_x/μ_x (%)
Constant	Laser	Radius, r_x	$0.1\ mm$	5.0
		Depth, r_y	$0.1\ mm$	5.0
		Absorption, η	0.43	2.5
		Power, P	$195\ W$	2.5 [2]
		Initial location, x_0	$-2\ mm$	1.5
		Initial location, y_0	$0\ mm$	$Std = 1.5e-4$
		Scanning speed, V_x	$800\ mm/s$	1.5 [2]
	Build Chamber Conditions	Chamber temperature, T_∞	$303K$	1.5
		Convection, h_{conv}	$18\ W/mK$	5.0
		Emissivity, ϵ	0.4	3.0
	Initial Condition	Temperature, T_0	$303\ K$	1.5
	Phase Change	Energy, ΔH_{LS}	$290\ kJ/kg\ K$	3.0
		Solidus temperature, T_S	$1563\ K$	0.5
		Liquidus temperature, T_L	$1623\ K$	0.5
Temperature -dependent	Material Properties	Density, ρ_s	Figure (a)	3.0
		Specific heat, c_{P_s}	Figure (b)	3.0 [2]
		Thermal conductivity, k_s	Figure (c)	3.0 [2]
Mesh Dependent	Geometry	Solid layers length, l	$14\ mm$	0.5 [2]
		Solid layers thickness, b	$3.2\ mm$	0.5 [2]

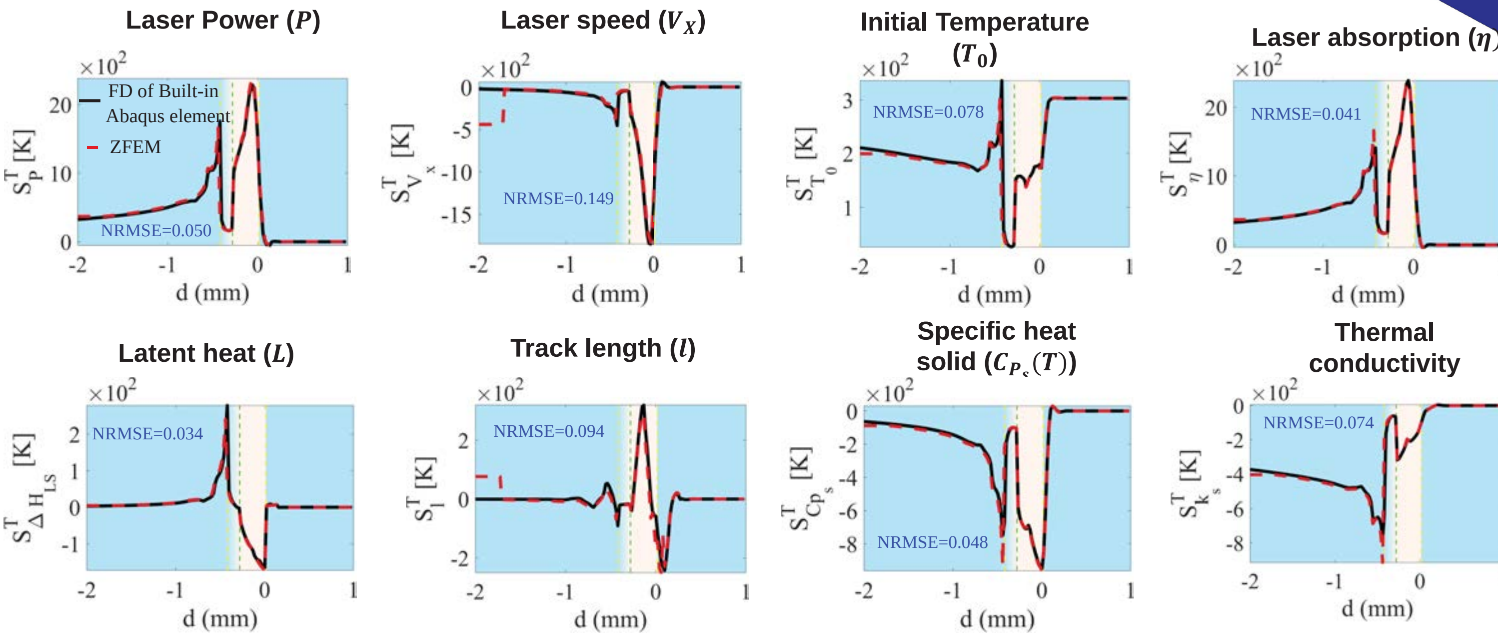
* Values were assumed

INC625 Properties [3]



[1] Heigel, J.C.; Lane, B.M.; Levine, L.E. In Situ Measurements of Melt-Pool Length and Cooling Rate During 3D Builds of the Metal AM-Bench Artifacts. *Integr. Mater. Manuf. Innov.* **2020**, *9*, 31–53, doi:10.1007/s40192-020-00170-8.
[2] Moges, T.; Witherell, P.; Ameta, G. On characterizing uncertainty sources in laser powder bed fusion additive manufacturing models. In Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE); American Society of Mechanical Engineers (ASME): Salt Lake City, UT, USA IMECE2019-11727, 2019; Vol. 2A-2019.
[3] AFRL Additive Manufacturing (AM) Modeling Challenge Series; 2019;

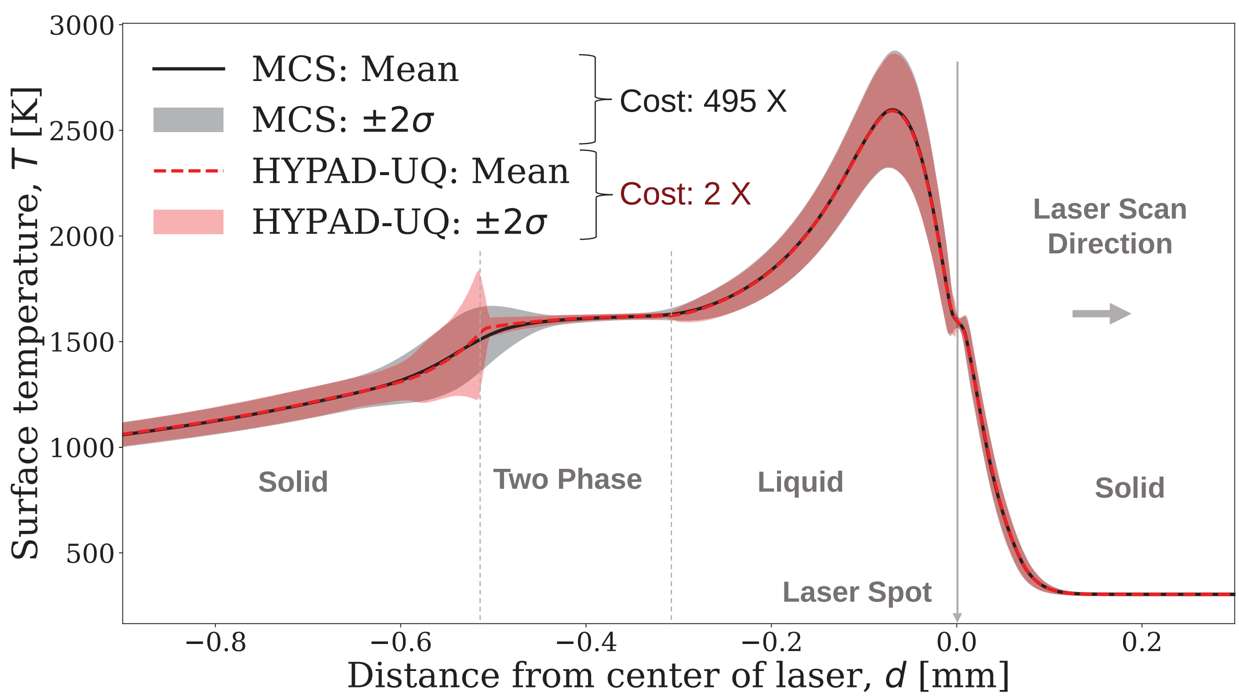
AM Application: First-order Sensitivities of Temperature, $S_\theta^T = \frac{\partial T}{\partial \theta}$



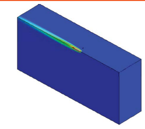
Liquid phase Solid phase

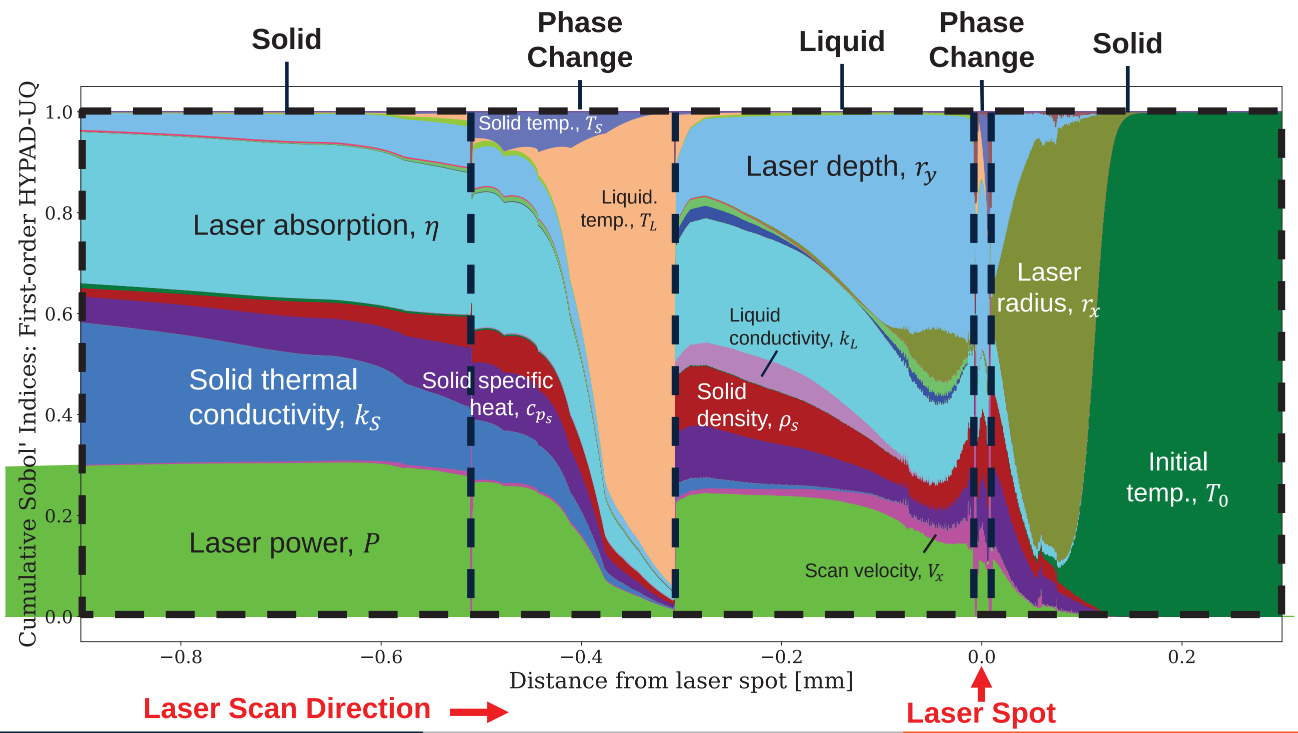
First-order HYPAD CPU Time = ~2x a single real analysis

AM Application: Uncertainty in Mean Surface Temperature



Sobol' Indices: First-order HYPAD-UQ

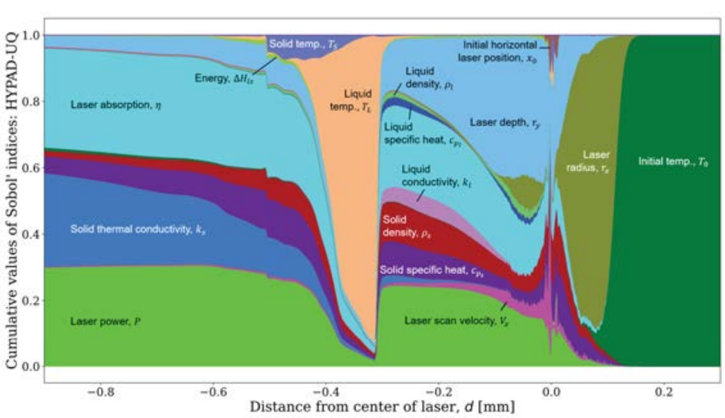


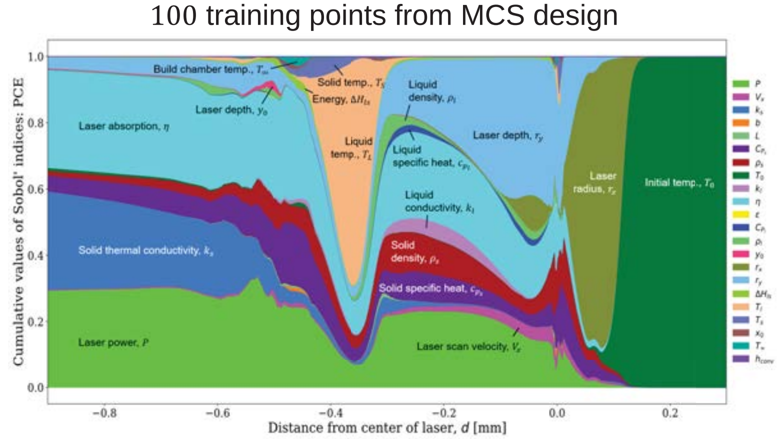


Sobol' Indices: First-order HYPAD-UQ vs First-degree PCE

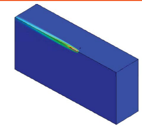
First-order HYPAD-UQ (CPU Time = 3 X)

First-degree Polynomial Chaos Expansion (PCE),
100 training points from MCS design

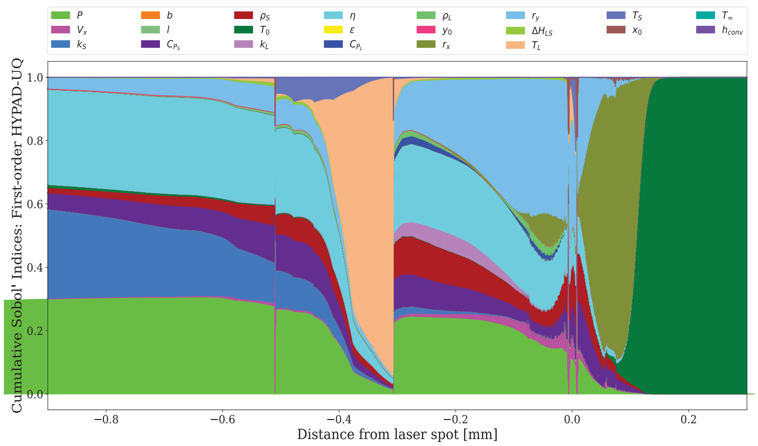




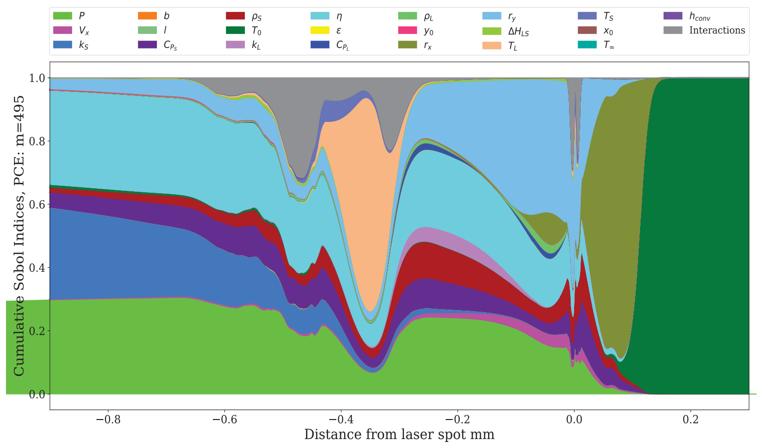
Sobol’ Indices: First-order HYPAD-UQ vs Second-degree PCE



First-order HYPAD-UQ (CPU time = 3 X)



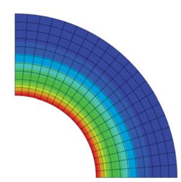
Second-degree Polynomial Chaos Expansion (PCE), 495 training points from MCS design



Summary

- Higher-order partial derivatives were calculated with HYPAD in finite elements
  - Significantly faster than finite difference with no step size issues
- HYPAD sensitivities were used to construct Taylor series expansions for UQ (HYPAD-UQ)
- HYPAD-UQ was conducted on:
  - Transient linear thermal analysis of a fin
  - Non-linear thermal analysis of an AM PBF process

Mathematical model, $f(\boldsymbol{x})$



Nodal derivatives with HYPAD

$$\frac{\partial f(\boldsymbol{x})}{\partial x_1}, \frac{\partial f(\boldsymbol{x})}{\partial x_2}, \frac{\partial^2 f(\boldsymbol{x})}{\partial x_1^2}, \frac{\partial^2 f(\boldsymbol{x})}{\partial x_1 \partial x_2}, \frac{\partial^3 f(\boldsymbol{x})}{\partial x_1^3}, \ldots$$

Taylor series expansion of nodal outputs

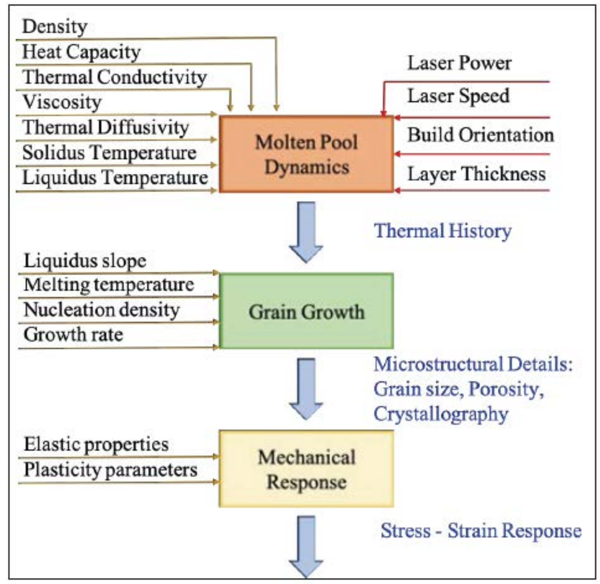
$$f(\boldsymbol{x}) \approx f(\boldsymbol{\mu}_x) + \sum_{i=1}^{m} \frac{\partial f(\boldsymbol{x})}{\partial x_i}(x_i - \mu_{x_i}) + \cdots$$

Uncertainty Quantification

Future Work

- The current development will allow the investigation of the uncertainty propagation starting from the process parameters, to the material microstructure and the bulk mechanical properties of the fabricated parts.

- Acknowledgements:
  - **Department of Energy CONNECT Consortium**
  - **Army Research Office under grant W911NF2010315. Dr. Michael Bakas Program Manager.**
  - **National Nuclear Security Administration under grant DE-NA0003948. Dr. David Canty Program Manager.**



Questions ?

Learn how to compute derivatives with HYPAD!

Backup

HYPAD Libraries

MultiZ [1]

- Multicomplex and multidual algebra support
  - Type declarations
  - Operation overloading $(+, -, \times, \div)$
  - Mathematical operation support (sine, cosine, exponential, log, sqrt, and power)
  - Arbitrary-order of hypercomplex numbers available
- Can be used with FEA simulation and other codes for sensitivity analysis
- Fortran and Python languages supported

OTI Library [2]

- Order Truncated Imaginary (OTI) algebra support
- Can be used with FEA simulation and other codes for sensitivity analysis
- Python, C, and Fortran versions developed

[1] Aguirre-Mesa, A. M., Garcia, M. J., and Millwater, H. (2020). Multiz: A library for computation of high-order derivatives using multicomplex or multidual numbers. *ACM Trans. Math. Softw.*, 46(3).
[2] Aristizabal Cano, M., (2020). Order truncated imaginary algebra for computation of multivariable high-order derivatives in finite element analysis, PhD thesis, Universidad EAFIT.

HYPAD-UQ Method Overview

Advantages

- HYPAD computes accurate Taylor series expansions
- Higher-order expansions can yield accurate results for large variation in random variables
- Works with any distribution of random variables
- Change in standard deviation or distribution is trivial to recalculate (mean stays the same)
- Computationally efficient compared to finite difference, stochastic perturbation finite element method, and random sampling

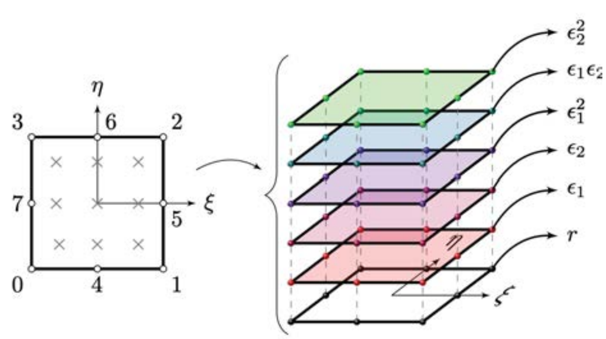
Limitations

- Potentially many terms in the Taylor series expansion
- Increase in order of expansion does not guarantee monotonic increase in accuracy
- HYPAD is intrusive – requires source code alterations
  - Once implemented, the code can be reused to compute sensitivities evaluated at any parameter

Hypercomplex Finite Element Method

- Real-valued variables are “uplifted” to hypercomplex variables
- External library used to “overload” elemental algebraic operations with hypercomplex algebra
  - Hypercomplex numbers can be expressed in matrix form to allow real-only linear algebra operations (avoids use of external library, but inefficient)
- Additional degrees of freedom to nodes for each imaginary direction

Degrees of freedom in an OTI element for truncation order of $n = 2$ and $r = 2$ variables



[*] Aristizabal Cano, M., (2020). Order truncated imaginary algebra for computation of multivariable high-order derivatives in finite element analysis, PhD thesis, Universidad EAFIT.

Block Forward Substitution to Solve Hypercomplex System of Equations

Full OTI system of equations for $n = 2$ and $r = 2$ variables

$$\mathbf{K}^*\mathbf{u}^* = \mathbf{f}^* \rightarrow \begin{bmatrix} \mathbf{K}_R & 0 & 0 & 0 & 0 & 0 \\ \mathbf{K}_{\epsilon_1} & \mathbf{K}_R & 0 & 0 & 0 & 0 \\ \mathbf{K}_{\epsilon_2} & 0 & \mathbf{K}_R & 0 & 0 & 0 \\ \mathbf{K}_{\epsilon_1^2} & \mathbf{K}_{\epsilon_1} & 0 & \mathbf{K}_R & 0 & 0 \\ \mathbf{K}_{\epsilon_1\epsilon_2} & \mathbf{K}_{\epsilon_2} & \mathbf{K}_{\epsilon_1} & 0 & \mathbf{K}_R & 0 \\ \mathbf{K}_{\epsilon_2^2} & 0 & \mathbf{K}_{\epsilon_2} & 0 & 0 & \mathbf{K}_R \end{bmatrix} \begin{Bmatrix} \mathbf{u}_R \\ \mathbf{u}_{\epsilon_1} \\ \mathbf{u}_{\epsilon_2} \\ \mathbf{u}_{\epsilon_1^2} \\ \mathbf{u}_{\epsilon_1\epsilon_2} \\ \mathbf{u}_{\epsilon_2^2} \end{Bmatrix} = \begin{Bmatrix} \mathbf{f}_R \\ \mathbf{f}_{\epsilon_1} \\ \mathbf{f}_{\epsilon_2} \\ \mathbf{f}_{\epsilon_1^2} \\ \mathbf{f}_{\epsilon_1\epsilon_2} \\ \mathbf{f}_{\epsilon_2^2} \end{Bmatrix}$$

Solve real-only system

$$\mathbf{K}_R\mathbf{u}_R = \mathbf{f}_R$$

Solve first-order system

$$\mathbf{K}_R\mathbf{u}_{\epsilon_1} = \mathbf{f}_{\epsilon_1} - \mathbf{K}_{\epsilon_1}\mathbf{u}_R$$
$$\mathbf{K}_R\mathbf{u}_{\epsilon_2} = \mathbf{f}_{\epsilon_2} - \mathbf{K}_{\epsilon_2}\mathbf{u}_R$$

Solve second-order system

$$\mathbf{K}_R\mathbf{u}_{\epsilon_1^2} = \mathbf{f}_{\epsilon_1^2} - \mathbf{K}_{\epsilon_1}\mathbf{u}_{\epsilon_1} - \mathbf{K}_{\epsilon_1^2}\mathbf{u}_R$$
$$\mathbf{K}_R\mathbf{u}_{\epsilon_1\epsilon_2} = \mathbf{f}_{\epsilon_1\epsilon_2} - \mathbf{K}_{\epsilon_1}\mathbf{u}_{\epsilon_2} - \mathbf{K}_{\epsilon_2}\mathbf{u}_{\epsilon_1} - \mathbf{K}_{\epsilon_2^2}\mathbf{u}_R$$
$$\mathbf{K}_R\mathbf{u}_{\epsilon_2^2} = \mathbf{f}_{\epsilon_2^2} - \mathbf{K}_{\epsilon_2}\mathbf{u}_{\epsilon_2} - \mathbf{K}_{\epsilon_2^2}\mathbf{u}_R$$

Summary of HYPAD

Advantages

- Simplicity – No new formulation of equations; same shape functions, integration schemes, time-integration algorithms, etc.
- Robust - No step size considerations (use very small step size or dual variables).
- Comprehensive - Once "hypercomplexified", derivatives with respect to ANY parameter available. Selection made from the input file.
- Scalable – Mixed and higher order derivatives available.
- Intrinsic support (1st order only) - No additional libraries required for first order derivatives using complex variables.

Disadvantages

- Intrusive – requires source code modification.
- Library support (mixed and higher order) - libraries required to support hypercomplex operations for mixed and higher order derivatives.
- Efficiency - Increased run time.

Taylor Series Expansions of Central Moments

Taylor series expansion of the r^{th} central moment

$$\mu_r\left(f\left(\boldsymbol{x}\right)\right) \approx \mu_r\left(Y_n\right) = E\left[\left(Y_n - E\left[Y_n\right]\right)^r\right]$$

can be computed with algebraically for any distribution of random variables, $\boldsymbol{x}$

Expected Value

$$E[Y_0] = Y(\mu_{\boldsymbol{x}})$$
$$E[Y_1] = E[Y_0]$$
$$E[Y_2] = E[Y_1] + \sum_{i=1}^{m} \frac{1}{2} \mathcal{D}_{ii}^{(2)} \mu_{2i}$$

where, $\mathcal{D}_{ij\ldots}^{(n)} = \dfrac{\partial^n f\left(\boldsymbol{x}\right)}{\partial x_i \partial x_j \ldots}$

$$\mu_{ri} = \mu_r(x_i)$$

Variance

$$\mu_2\left(Y_1\right) = \sum_{i=1}^{m} \left(\mathcal{D}_i^{(1)}\right)^2 \mu_{2i}$$
$$\mu_2\left(Y_2\right) = \mu_2\left(Y_1\right) + \sum_{i=1}^{m} \left\{\frac{1}{4}\left(\mathcal{D}_{ii}^{(2)}\right)^2 \mu_{4i} - \frac{1}{4}\left(\mathcal{D}_{ii}^{(2)}\right)^2 \mu_{2i}^2 + \mathcal{D}_i^{(1)} \mathcal{D}_{ii}^{(2)} \mu_{3i}\right\} + \sum_{i<j} \left(\mathcal{D}_{ij}^{(2)}\right)^2 \mu_{2i}\mu_{2j}$$

Sobol' Indices (Global Sensitivity Analysis)

1. Decompose function into High Dimensional Model Representation (HDMR)

$$f\left(\boldsymbol{x}\right) = f_0 + \sum_i f_i\left(x_i\right) + \sum_{i<j} f_{ij}\left(x_i, x_j\right) + \ldots + f_{12\ldots m}\left(x_1, x_2, \ldots, x_m\right)$$

$\boldsymbol{x}$ are independent random variables

$$f_0 = E\left[f\left(\boldsymbol{x}\right)\right]$$
$$f_i = E\left[f\left(\boldsymbol{x}\right)|x_i\right] - f_0$$
$$f_{ij} = E\left[f\left(\boldsymbol{x}\right)|x_i, x_j\right] - f_i - f_j - f_0$$

2. Take variance of HDMR function

$$V = \sum_i V_i + \sum_{i<j} V_{ij} + \ldots + V_{12\ldots m}$$

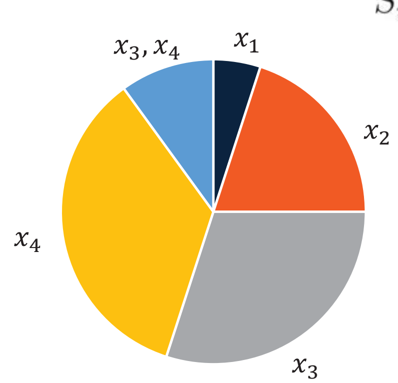
3. Divide by total variance

$$1 = \sum_i S_i + \sum_{i<j} S_{ij} + \ldots + S_{12\ldots m}$$

Main Effects $S_i = V_i/V$

Interaction Effects $S_{ij} = V_{ij}/V$

$S_{ij\ldots m} = V_{ij\ldots m}/V$



Sobol' indices sum to 100% of the total variance

Taylor Series Expansions of Sobol' Indices

Substitute $f(\boldsymbol{x}) = Y_n(\boldsymbol{x})$ (n'th-order Taylor series expansion)

Main Effects $$S_i = \frac{V_i}{V}$$

First-order $$V_i\left[Y_1\right] = \left(\mathcal{D}_i^{(1)}\right)^2 \mu_{2i}$$

Second-order $$V_i\left[Y_2\right] = V_i\left[Y_1\right] + \frac{1}{4}\left(\mathcal{D}_{ii}^{(2)}\right)^2 \mu_{4i} - \frac{1}{4}\left(\mathcal{D}_{ii}^{(2)}\right)^2 \mu_{2i}^2 + \mathcal{D}_i^{(1)}\mathcal{D}_{ii}^{(2)}\mu_{3i}$$

Interaction Effects $$S_{ij} = \frac{V_{ij}}{V}$$

Second-order $$V_{ij}\left[Y_2\right] = \left(\mathcal{D}_{ij}^{(2)}\right)^2 \mu_{2i}\mu_{2j}$$

Iterative Construction of a Sparse Taylor Series Expansion

An increase in:
- Number of random variables, r
- Order of expansion, n

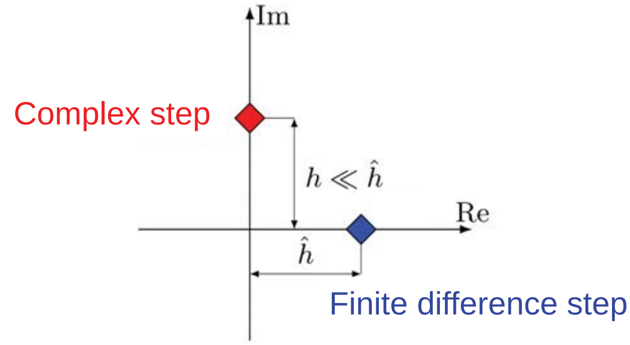
Leads to an increase in:
- Number of partial derivatives, d
- Computational time to compute the complete n'th-order Taylor series
- Unnecessary derivative computations
  - Some terms in the expansion will not significantly contribute to increasing the accuracy in the Taylor series estimation of the output variance

Sparse Taylor series expansion
1. Compute first-order Taylor series expansion
   - Sobol' indices to identify unimportant variables (screening)
2. Compute second-order derivatives of important variables

Partial Derivative Calculation using Hypercomplex Algebra

Complex-step Method for First-order Derivatives

- Perturb variable of interest along the imaginary axis
- Imaginary axis can be represented by a:
  - Complex number, $i^2 = 1$
  - Dual number, $\epsilon^2 = 0$
- The step size can be made arbitrarily small to neglect truncation error



HYPercomplex Automatic Differentiation (HYPAD) for Higher-order Derivatives

1. Variables are perturbed along multiple imaginary directions using hypercomplex numbers
   - Multicomplex numbers generalizes imaginary numbers to any number of directions
   - Multidual numbers generalizes dual numbers to any number of directions
   - Order Truncated Imaginary (OTI) numbers efficiently compute all derivatives in Taylor series expansion in a single analysis
2. The function is evaluated using hypercomplex algebra
3. Derivatives are extracted from the imaginary parts of the output

Hypercomplex Differentiation Implementation in Source Code

Setup

- Initialize hypercomplex library (for algebraic operation overloading)
- Define variables of interest as hypercomplex
- Define functions that use these variables as hypercomplex
- If variable/function is an array, change syntax to match hypercomplex library
- Write code to extract real and non-real parts (derivatives) of output

Running the code

- Add a non-real step to variable(s) of interest
- Run code
- Real part of output = output evaluation
- First non-real part = first derivative
- Second non-real part = second derivative, etc.

Multidual Code Conversion Example

Example

$$f(\boldsymbol{x}) = e^{x_2}\sin(x_1 x_2)$$

$$\boldsymbol{x} = [x_1, x_2] = [2, 3]$$

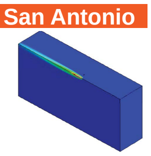
Real Code

```
program main
  implicit none
  ! declare variables
  real*8 x(2) ! input: real vector
  real*8 f    ! output: real number
  ! assign input
  x(1) = 2.0d0
  x(2) = 3.0d0
  ! calculate output
  f = exp(x(2))*sin(x(1)*x(2))
end program
```

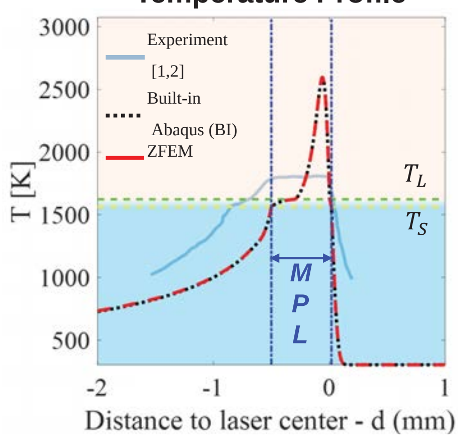
Multidual Code

```
program main
  use multiz          ! use MultiZ library
  implicit none
  ! declare variables
  type(mduvec) x      ! input: multidual vector
  type(mdual) f       ! output: multidual number
  integer n           ! size of multidual numbers for allocation
  ! derivatives
  real*8 d1, d2, d11, d12, d22, d111, d112, d122, d222
  n = 6               ! for 6 non-real steps
  ! allocate multidual vector
  call mallocate(x, n, 2)
  ! assign input with non-real steps
  call mset(x, 1, 2.0d0 + eps(1) + eps(2) + eps(3))
  call mset(x, 2, 3.0d0 + eps(4) + eps(5) + eps(6))
  ! calculate output
  f = exp(mget(x,2))*sin(mget(x,1)*mget(x,2))
  ! extract sensitivities
  d1   = aimag(f,1)          ! ∂f(x)/∂x1
  d2   = aimag(f,4)          ! ∂f(x)/∂x2
  d11  = aimag(f,[1,2])      ! ∂²f(x)/∂x1²
  d12  = aimag(f,[1,4])      ! ∂²f(x)/∂x1∂x2
  d22  = aimag(f,[4,5])      ! ∂²f(x)/∂x2²
  d111 = aimag(f,[1,2,3])    ! ∂³f(x)/∂x1³
  d112 = aimag(f,[1,2,4])    ! ∂³f(x)/∂x1²∂x2
  d122 = aimag(f,[1,4,5])    ! ∂³f(x)/∂x1∂x2²
  d222 = aimag(f,[4,5,6])    ! ∂³f(x)/∂x2³
end program
```


AM Application: Real Value of Mean Surface Temperature



Mean Surface Temperature Profile



Mean surface temperature profile

$NRMSE(BI, ZFEM) = 1.92e-3$

Melt Pool Length (MPL)

$MPL_{exp} = 0.782\ mm$

$e_{ZFEM}(MPL) = 33.7\%$

Melt Pool Depth (MPD)

$MPD_{exp} = 0.091\ mm$

$e_{ZFEM}(MPD) = 38.6\%$

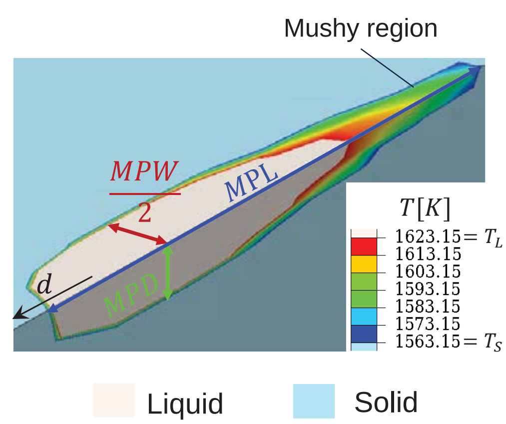
Melt Pool Width (MPW)

$MPW_{exp} = 0.133\ mm$

$e_{ZFEM}(MPW) = 16.8\%$

Model underpredicts dimensions

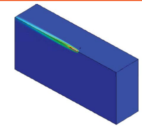
Melt Pool Section

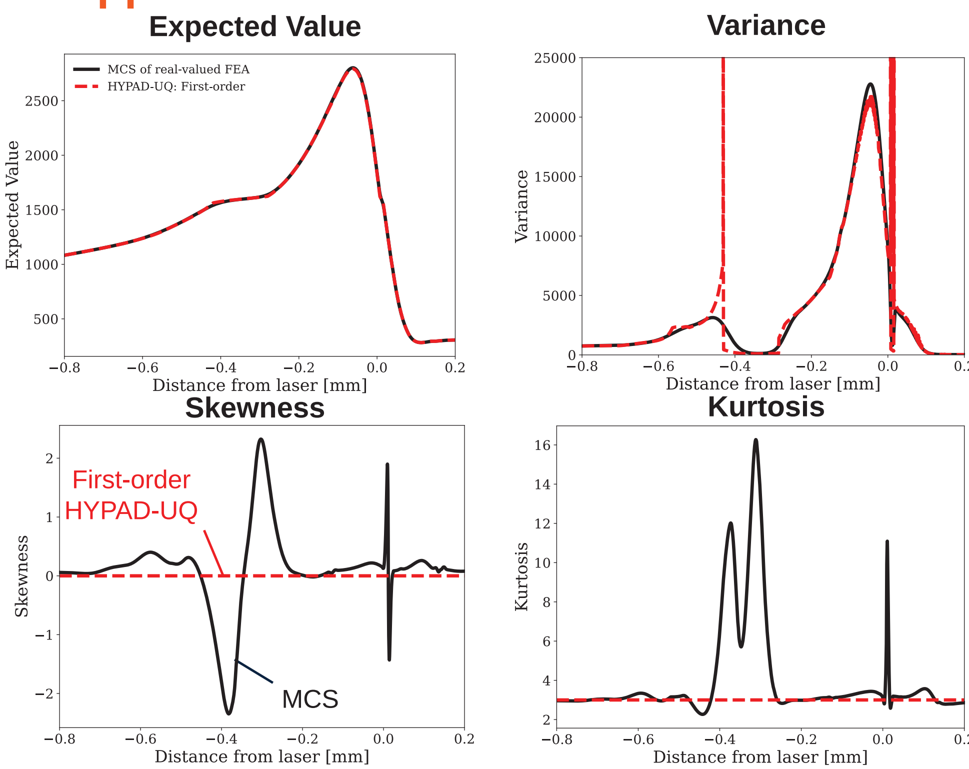


Simplifications of this model limit the precision compared to the experiments. However, the trend is in agreement.

1. Kollmannsberger, S., Carraturo, M., Reali, A., & Auricchio, F. (2019). Accurate Prediction of Melt Pool Shapes in Laser Powder Bed Fusion by the Non-Linear Temperature Equation Including Phase Changes. *Integrating Materials and Manufacturing Innovation*, *8*(2), 167–177. https://doi.org/10.1007/s40192-019-00132-9
2. Heigel, J. C., Lane, B. M., & Levine, L. E. (2020). In Situ Measurements of Melt-Pool Length and Cooling Rate During 3D Builds of the Metal AM-Bench Artifacts. Integrating Materials and Manufacturing Innovation, 9(1), 31–53. https://doi.org/10.1007/s40192-020-00170-8
3. K.-M. Hong, C. M. Grohol, and Y. C. Shin, "Comparative Assessment of Physics-Based Computational Models on the NIST Benchmark Study of Molten Pool Dimensions and Microstructure for Selective Laser Melting of Inconel 625," *Integr Mater Manuf Innov*, vol. 10, no. 1, pp. 58–71, Mar. 2021, doi: 10.1007/s40192-021-00201-y.

AM Application: Central Moments of Mean Surface Temperature



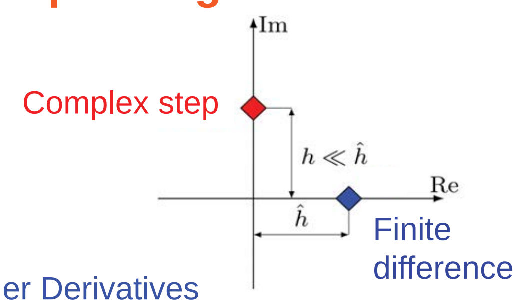


MCS of ABAQUS built-in simulation (356 samples)

1st-order HYPAD-UQ

- Higher-order Taylor series expansion needed to capture non-Gaussian skewness and kurtosis

Partial Derivative Calculation using Hypercomplex Algebra



Complex-Step Differentiation Method

- Perturb variable of interest along the imaginary axis
- Imaginary axis can be represented by a complex number, $i^2 = 1$
- Machine precision derivatives

HYPercomplex Automatic Differentiation (HYPAD) for Higher-order Derivatives

1. Variables are perturbed along multiple imaginary directions using hypercomplex numbers
   - Multicomplex numbers generalizes imaginary numbers to any number of directions
   - Multidual numbers generalizes dual numbers to any number of directions
   - Order Truncated Imaginary (OTI) numbers efficiently compute all derivatives in Taylor series expansion in a single analysis
2. The function is evaluated using hypercomplex algebra
3. Derivatives are extracted from the imaginary parts of the output

Postprocess to Compute HYPAD Derivatives

- n'th-order derivatives computed from the residual of the converged finite element solution

HYPAD-UQ Overview

HYPercomplex Automatic Differentiation (HYPAD)

- Accurate *arbitrary*-order partial derivatives
- Straight-forward implementation for any order of derivative
- Implemented in Finite Element Method (FEM)

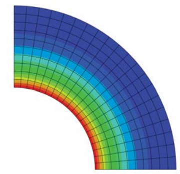
Taylor series expansion of finite element outputs

- Taylor series constructed from HYPAD sensitivities

Uncertainty Quantification (UQ) with Taylor series

- Taylor series is a surrogate model used to approximate:
  - Probability distributions
  - Central moments
  - Sobol' indices (global sensitivity analysis)

Mathematical model, $f(\boldsymbol{x})$



Nodal derivatives with HYPAD

$$\frac{\partial f(\boldsymbol{x})}{\partial x_1}, \frac{\partial f(\boldsymbol{x})}{\partial x_2}, \frac{\partial^2 f(\boldsymbol{x})}{\partial x_1^2}, \frac{\partial^2 f(\boldsymbol{x})}{\partial x_1 \partial x_2}, \frac{\partial^3 f(\boldsymbol{x})}{\partial x_1^3}, \ldots$$

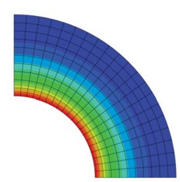
Taylor series expansions of nodal outputs

$$f(\boldsymbol{x}) \approx f(\boldsymbol{\mu}_x) + \sum_{i=1}^{m} \frac{\partial f}{\partial x_i}(x_i - \mu_{x_i}) + \cdots$$

Uncertainty Quantification

Uncertainty Quantification using HYPAD (HYPAD-UQ)

Mathematical model, $f(\boldsymbol{x})$



Nodal derivatives using HYPAD

$$\frac{\partial f(\boldsymbol{x})}{\partial x_1}, \frac{\partial f(\boldsymbol{x})}{\partial x_2}, \frac{\partial^2 f(\boldsymbol{x})}{\partial x_1^2}, \frac{\partial^2 f(\boldsymbol{x})}{\partial x_1 \partial x_2}, \frac{\partial^3 f(\boldsymbol{x})}{\partial x_1^3}, \ldots$$

Taylor series expansion of nodal outputs

$$f(\boldsymbol{x}) \approx f(\boldsymbol{\mu}_x) + \sum_{i=1}^{m} \frac{\partial f(\boldsymbol{x})}{\partial x_i}(x_i - \mu_{x_i}) + \cdots$$

Uncertainty Quantification

Testing Approach and Initial Results on PM-HIP Ni-Based Alloys

Presenter: Kevin B. Fisher
Contributors: Paul N. Pica, Rachel E. Turfitt

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Outline

- History and timeline
- Approach
  - Materials
  - Test types and methods
  - Additional considerations
- Examples of Initial Results

History and Timeline of ‘Modern’ PM-HIP Materials Program

2009
- Interest in PM-HIP 600
- Testing plan formed
- Procurements for 2 billets initiated (gen 0)

2012
- Interim report on measured properties
- Interest waned, primarily due to cost
- Testing continued at a low level

2020
- Whitepaper on cost/benefit analysis
- Started procuring contemporary material (1st gen)
- Plan for 600/625/690/316 testing issued

2021
- Machining and testing contracts initiated
- Environmental testing contracts initiated
- 2nd gen billet procurements
- Original specifications issued

2022
- Feb: 1st gen Alloy 600 results (Air)
- Aug: 1st gen 625/690 results (Air)

2023
- 3rd gen billet procurements
- June: 2nd gen 625/690 results (air)
- Oct: 1st gen 600/625/690 env. results

2024
- 316L results (air)

2025
- 3rd gen follow up results
- Final environmental results
- Specification revision
- Program wrap-up

“Finished”

Parallel efforts on:
- UT inspectability
- Weldability
- NNS design

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Approach: Scope of Materials

- 4 Alloys: 600, 625, 690, 316L SS*
  - Each alloy tested in 2 conditions
    - “Reference” per the specification and modeled after wrought processing
    - “Alternate” seeking to improve properties/economy by altering HIP parameters and post-HIP heat treatment
- 4 Vendors (2 considered minimum): A, B, C, and D
  - 2 Vendors considered “Generation 1” material
  - 2 Vendors considered “Generation 2” material
  - Generation 3 material utilized the same vendors but modified processing requirements as necessary
- In-spec material is:
  - Vacuum induction melted
  - N_2 gas atomized
  - 250 µm maximum particle size
  - 150 ppm oxygen max
  - 2000 ppm nitrogen max

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Approach: Scope of Materials

Rectangular Billets:
4 x 8 x 24 inches or
5 x 10 x 30 inches

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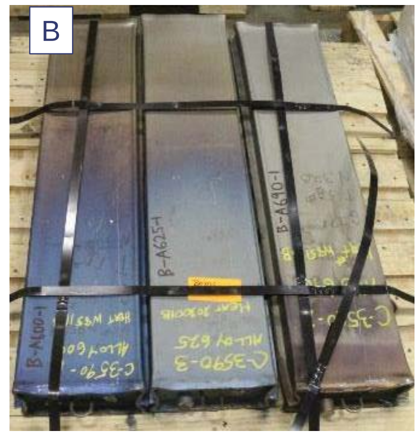
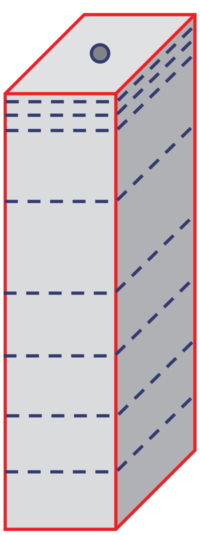


Approach: Billet Sectioning



A, 0.5, Scrap
B, 0.5 Retainer Slice
C, 0.5, Metallography/Microcleanliness/Hardness

D, 5.5, Mechanical Properties
Orientation effects

E, 6.25, Weld Mock Up

F, 3.5, Mechanical Properties
Position Effects

G, 3.0, Thermo-
physical Properties

H, 3.5,
Environmental
Testing

I, Excess

Heat Treat,
per spec

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Approach: (Air) Material Properties Tested

- Metallography: Grain size (ASTM E112), Microcleanliness (ASTM E45)
- Mechanical:
  - Tensile (ASTM E8, E21)
  - Fatigue Crack Growth Rate (ASTM E647)
  - Fatigue Initiation (ASTM E606)
  - Fracture Toughness (ASTM E1820)
  - Charpy Impact (ASTM E23)
- Thermo-physical
  - Young's Modulus (ASTM E111)
  - Poisson's Ratio (ASTM E132)
  - Thermal Expansion (ASTM E228)
  - Thermal Conductivity (ASTM E2584)
  - Density (ASTM B311)

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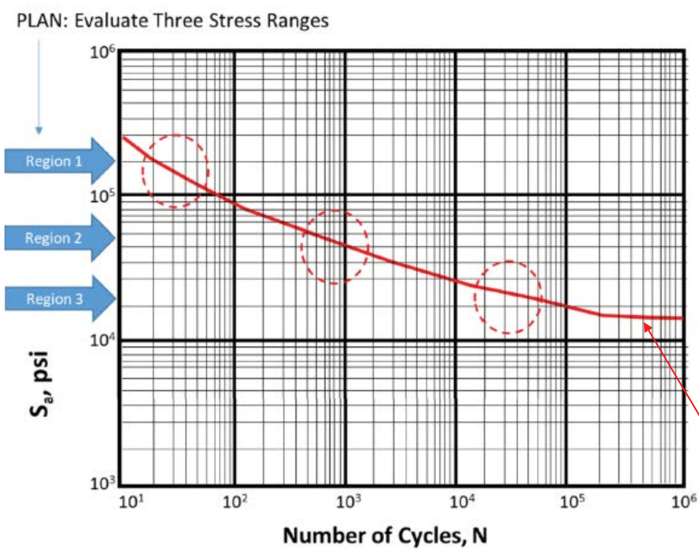
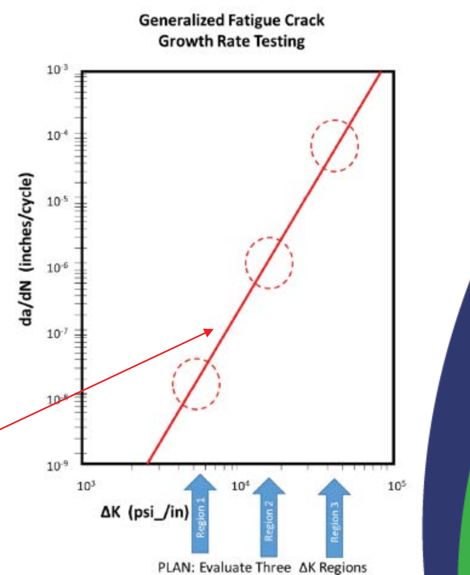
Approach: Scope of testing

Generalized Fatigue Initiation



Example wrought best estimate curve

Generalized Fatigue Crack Growth Rate



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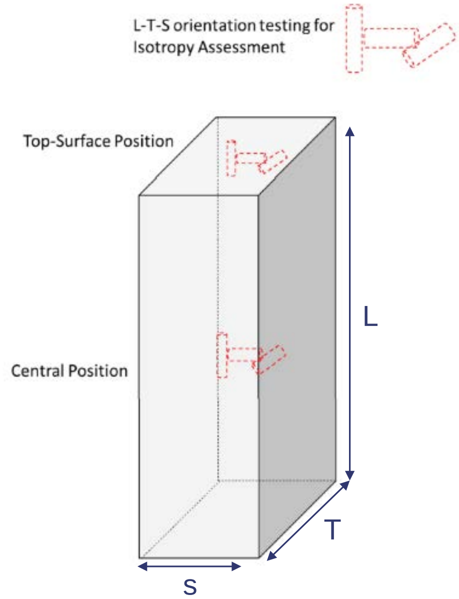
Approach: Additional Considerations

- Orientation effects
  - Tensile: L, S, and T
  - FCGR: SL and LT
  - Metallography: L, S, and T
- Position Effects
  - Tensile: Top and Middle
  - FCGR: Top and Middle
  - Metallography: Top and Middle, Center and Near Can



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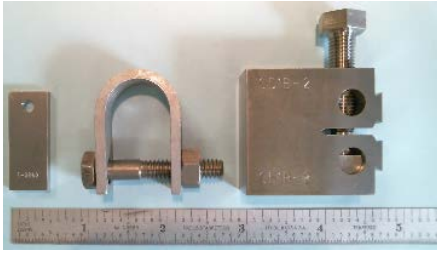
Approach: Environmental Testing



- General Corrosion
  - Aerated and deaerated high temperature water
- Stress Corrosion Cracking
  - Aerated and deaerated high temperature water
  - Active load (compact tension) CGR measurements
  - Passive load (single U bends, bolt loads, and ring loads) at multiple Kmax levels
- Corrosion Fatigue Crack Growth Rate
  - Deaerated high temperature water
  - Active load (compact tension) CGR measurements at multiple R, ΔK)
  - Reduced test scope compared to air. Rely on Air testing to prove equivalence
- Also testing HAZ Specimens

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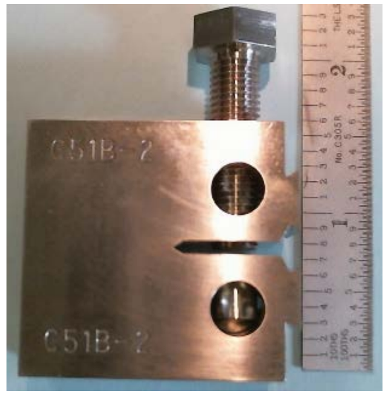
Approach: Environmental Testing

Single U-Bends



Bolt Loaded Compact Tension Specimens

Corrosion Coupons

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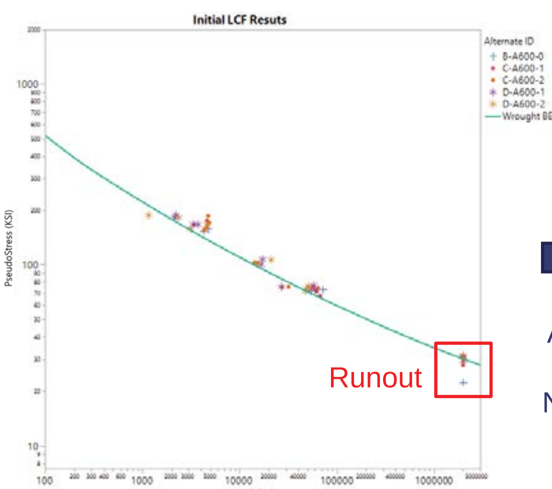
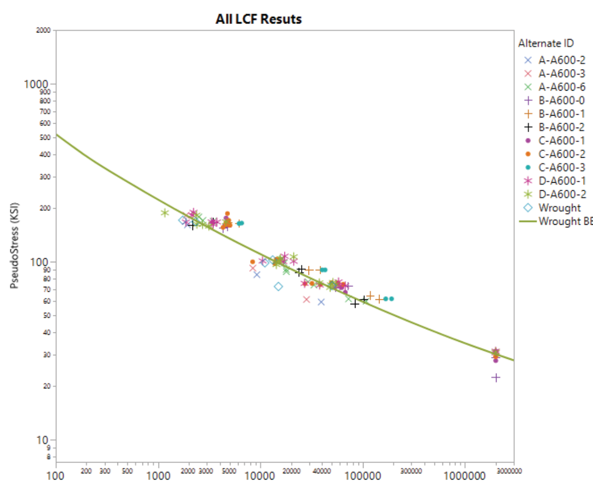
Example Results: Fatigue Initiation in Alloy 600



Additional Testing Necessary



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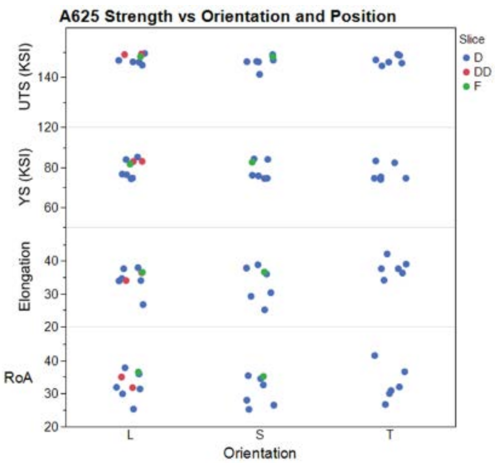
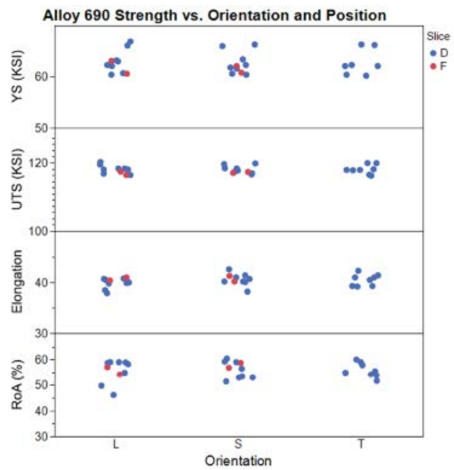
Example Results: Position and Orientation Effects





- No position or orientation effects observed.
- Gen 1 materials (especially 625) had some ductility (% Elongation and RoA) concerns.

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Example Results: Specification Compliance – A690

A690 Material Specification Compliance Matrix

Billet	A-A690-1	A-A690-2	A-A690-3	A-A690-6	B-A690-1	B-A690-2	C-A690-3	C-A690-4
Particle Size Max (µm)	250	250	250	*500*	250	250	250	250
Powder Oxygen (wt%)	0.0141	0.0141	0.0141	0.0141	0.0147	0.0147	0.0143	0.0143
Powder Nitrogen (wt%)	*0.209*	*0.209*	*0.209*	*0.2138*	0.109	0.109	0.114	0.114
Consolidated Chemistry Violations	*N, O*	*Fe, N*	*N, O*	*N, O*	*B*	*O*	*B, C, Fe*	*B, C, Fe*
HIP T (°F)	Ref	*Alt*	*Alt*	*Alt*	Ref	*Alt*	*Alt*	*Alt*
Post HIP HT	None	*Alt*	None	None	None	None	None	None
Room T YS (ksi)	*High*	*High*	*High*	*High*	*High*	*High*	*High*	Pass
Room T UTS (ksi)	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Room T Elong. (%)	Pass	*Low*	*Low*	*Low*	Pass	Pass	Pass	Pass
Room T RoA (%)	Pass	*Low*	Pass	*Low*	Pass	Pass	Pass	Pass
600°F YS (ksi)	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
600°F UTS (ksi)	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Grain Size	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
Microcleanliness	Pass	*Fail*	*Fail*	*Fail*	Pass	Pass	Pass	Pass
Density[1] (lb/in^3)	Pass	Pass	Pass	Pass	DNM	Pass	DNM	DNM

DNM = Did not measure

Tested one billet with higher PSD

Minor chemistry violations. O and N most undesirable

Tested various HIP T

High strength and low ductility commonly observed, improved through HIP T modifications and in Spec nitrogen

Some failing microcleanliness measurements, but additional examination showed no major concern

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Summary of PM-HIP Testing Approach

- Goal: 4 materials in 5 years
  - Rely on existing wrought properties and prove equivalence
  - Generate material specifications up front, and work to them
  - Test to ASTM standards whenever possible
  - Standardize approach and perform testing all in parallel
- PM-HIP material is generally proving to be homogenous and equivalent to wrought
  - Perform targeted “extra” testing and characterization as required to feel comfortable with properties
  - Perform simultaneous parallel testing aimed at proving material properties and/or process economy → revise specification later to take advantage

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Laser Powder Bed Fusion of 316H Stainless Steel for High-Temperature Nuclear Applications

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Content

- Background
- Process parameter study
- Variations in powder feedstock
- Thermal aging effect
- Mechanical testing

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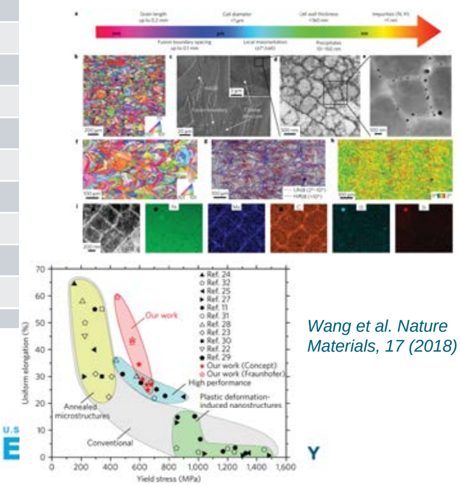
Why qualifying LPBF 316H SS

- **Opportunities for additive manufacturing in nuclear energy:**
  - Innovative component design
  - New materials development
  - Embedding sensors for real-time monitoring
  - Repair/replace obsolete parts
- **Program interest:** DOE-NE's Advanced Materials and Manufacturing Technologies (AMMT) program has an overarching vision of accelerating the development, qualification, demonstration and deployment of advanced materials and manufacturing technologies to enable reliable and economical nuclear energy*.
- **Industry interest and code availability:** The wrought form of 316H SS is one of the six qualified materials in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section III, Division 5 for high temperature reactor construction.
- **Research readiness:** Extensive research has been performed on LPBF 316L SS (L for low carbon) as a reference for LPBF 316H SS. Data show that the LPBF material has a potential for improved performance due to the unique microstructure.
- **LPBF 316H SS** has been chosen by AMMT program* based on the recent material scorecard** work as **the first target material** for design improvements, materials optimization and rapid qualification. It also serves as a test case for qualifying other materials produced by advanced manufacturing.

The laser powder bed fusion (LPBF) process with a Renishaw AM400 machine.

Composition (wt.%)	Type 316H UNS S31609	Type 316L UNS S31603
Fe	Bal.	Bal.
Cr	16.0-18.0	16.0-18.0
Ni	11.0-14.0	10.0-14.0
Mo	2.00-3.00	2.00-3.00
Mn	2.0	2.0
Si	1.00	1.00
C	**0.04-0.10**	**0.035**
O	- -	- -
N	- -	- -
P	0.045	0.045
S	0.030	0.030



Wang et al. Nature Materials, 17 (2018)

**M. Li, et. al., "Advanced Materials and Manufacturing Technologies (AMMT) 2022 Roadmap", ANL-23/12, 2022*
***T. Hartmann, et. al., "Materials scorecards, Phase 2," PNNL-32744, PNNL, March 2022.*

Challenges and approaches in qualifying a LPBF part

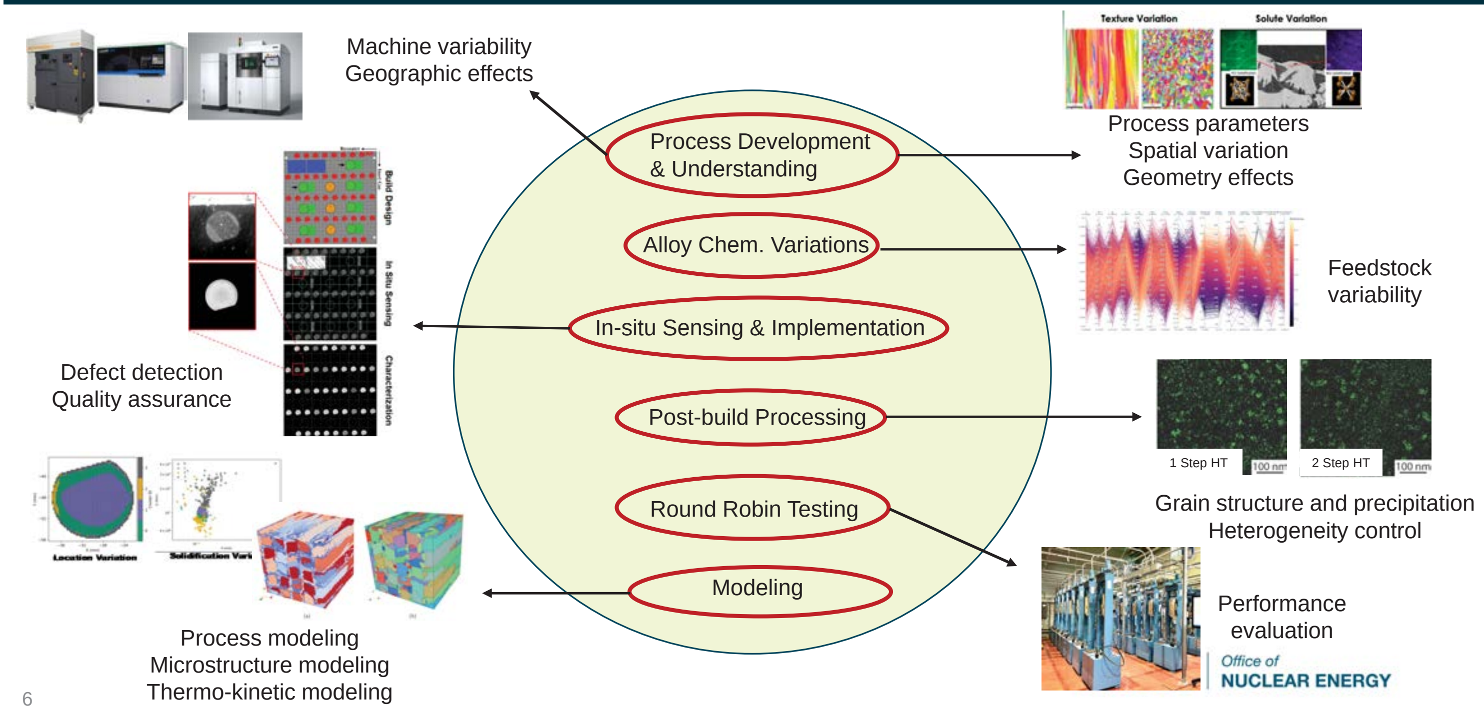
Challenges

- Decentralized manufacturing
- Variability
- Repeatability
- Heterogeneity
- Very limited high temperature test data
- Uncertain qualification pathway
- Accelerated qualification

Approaches

- Leverage multiple PBF units across multiple national labs and print with powders from different batches
- Extensive characterization combined with modeling
- Combine standard and subsized part geometries to capture spatially varying properties
- Leverage comprehensive testing capabilities across multiple national labs
- High-throughput testing
- Integrate in-situ process monitoring as an additional QA tool to detect build-specific defects.
- Combine testing data with physics-based modeling

Approach to qualification: a multi-lab effort (ANL, INL, LANL, ORNL, PNNL)



Laboratory Specific Contributions: Powder and Machine Variation

	ANL	ORNL	LANL
Renishaw	✓	✓	
Concept Laser		✓	
EOS		✓	✓

	ANL	ORNL	LANL
0.08 wt% Praxair	R ✓	R ✓ CL	E ✓
0.06 wt% Praxiair	R ✓	✓ CL	
0.05 wt% Praxiar	R ✓		
0.04 wt% PAC		R ✓ CL	E ✓

Data generated as of 10/19/23

✓ Available to print
✓ Builds complete
R = Renishaw AM400
CL = Concept Laser
E = EOS 290

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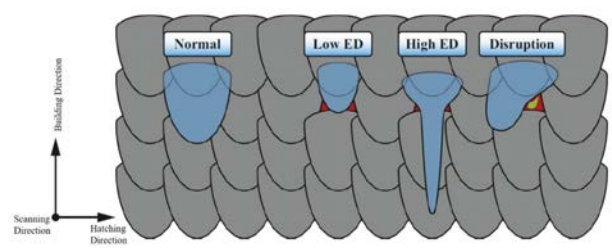
Importance of Processing Parameters

Volumetric Energy Density

$$ED_{vol} = \frac{P}{vhd}$$

P is power (W)
v is velocity (mm/s)
h is hatch spacing
d is layer thickness



- NORMAL "Conduction mode" = adequate penetration and overlap to the previous layers and adjacent melt pools
- LOW ED = low laser power or high lasing speeds that produce a much smaller "convection mode" shaped melt pool. Results in lack of fusion between layers and among adjacent melt pools
- HIGH ED = excessively high laser power and low lasing speeds that concentrates the heat making it penetrate through too many layers. Forms keyholing, and lack of fusion among adjacent melt pools from insufficient overlapping.
- DISRUPTED = poor process parameters, corrupt material properties, contaminants, etc.

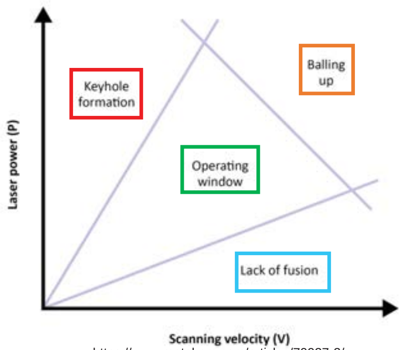
LANL: a single-bead study

Process understanding for qualifying LPBF 316H SS, LA-UR-23-30967, 2023

Objective: Develop process-structure-property data sets linked to in situ monitoring data and detailed feedstock characterization to strengthen process - structure and process -property relationships.

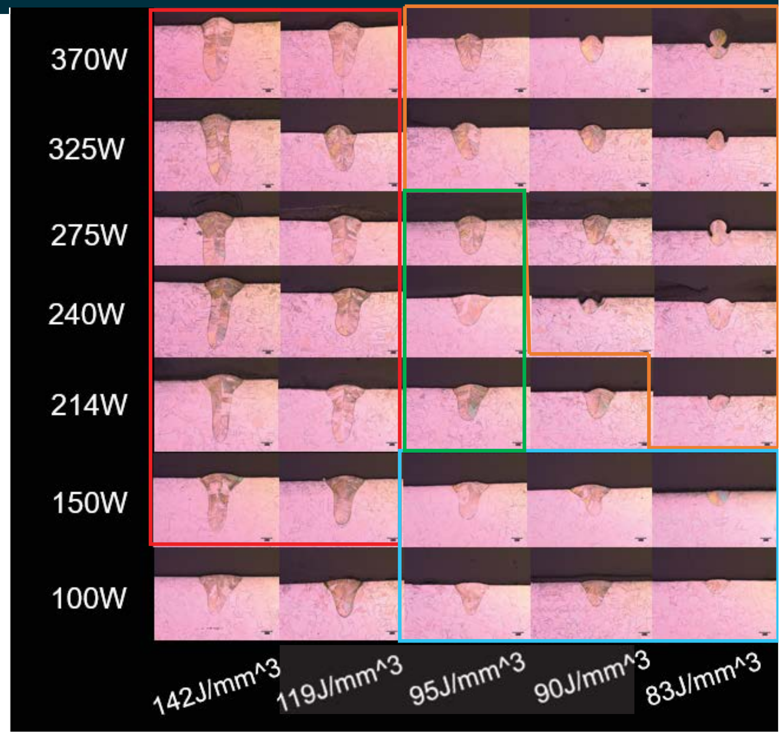
Initial Development

- Optimizing process parameters using single bead welds to find the acceptable operating window (OW) that provides full density parts.
- With layer thickness held constant, the P vs. V chart indicates the behavior for single bead trials and LPBF parameters
- Parameter used for 316H builds were based on 3 sets from the OW and three variation sets



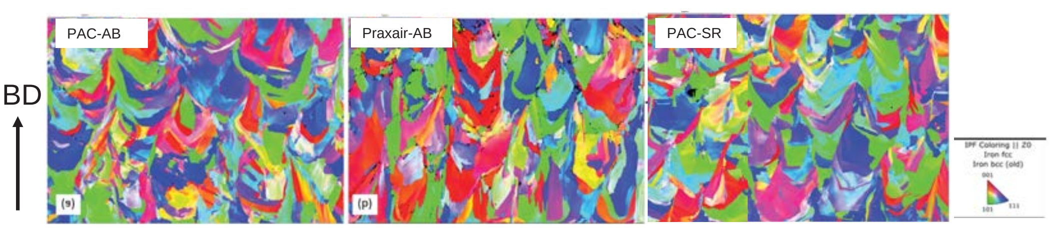
https://www.metal-am.com/articles/70927-2/

Set	Power (W)	Speed (mm/s)	ED (J/mm^3)
13 OW	275	688	95
18 OW	240	600	95
23 OW	214	525	95
Var. 1	257	644	95
Var. 2	227	567	95
Var. 3	200	521	95



LANL: 316H Characterization

EBSD



All as-built and stress-relieved materials showed grain morphology typical to the laser printing process. Additionally, the microstructures are non-equilibrium and are weakly textured.

Surface Roughness of As Built Parts

Set	Surface Roughness				
	Area1				
	Sa	Sz	Str	Spc	Sdr
	μm	μm		1/mm	
13 - OW	8.073	106.257	0.745	120.235	0.1696
18 – OW	8.540	133.659	0.628	201.005	0.2078
23 – OW	7.980	116.047	0.566	136.678	0.2067
Variation #1	8.311	125.209	0.480	165.832	0.1753
Variation #2	7.181	111.503	0.634	111.176	0.1360
Variation #3	7.061	106.431	0.597	161.975	0.1558

Porosity

Set	As-Built		Stress-relieved
	Praxair Porosity %	PAC Porosity %	PAC Porosity %
13 – OW	0.049	0.069	0.046
18 – OW	0.054	0.051	0.057
23 – OW	0.176	0.236	0.159
Variation #1	0.069	0.139	0.017
Variation #2	0.107	0.257	0.02
Variation #3	0.085	0.058	0.029

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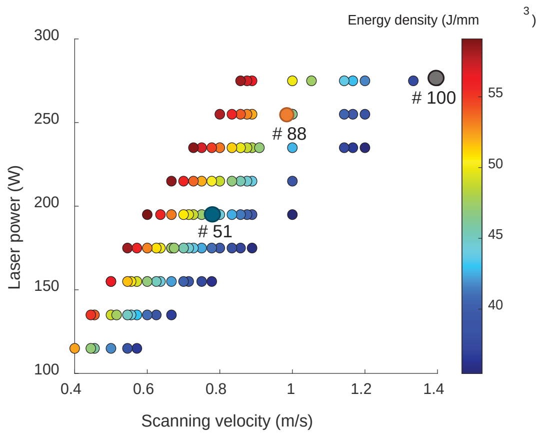
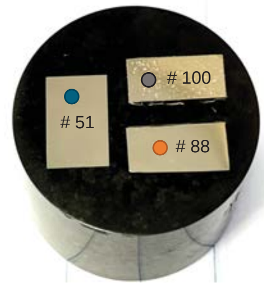
ANL: Building upon LANL single track experiments, exploring high-throughput printing

Development of process parameters and post-build conditions for qualification of LPBF 316 SS, ANL-AMMT-004, 2023

- Build 20230303 has 100 sets of laser parameters for 100 cubes
  - 0.06% carbon, 0.03% oxygen in powder
  - Varying **laser power, point exposure time, point distance**





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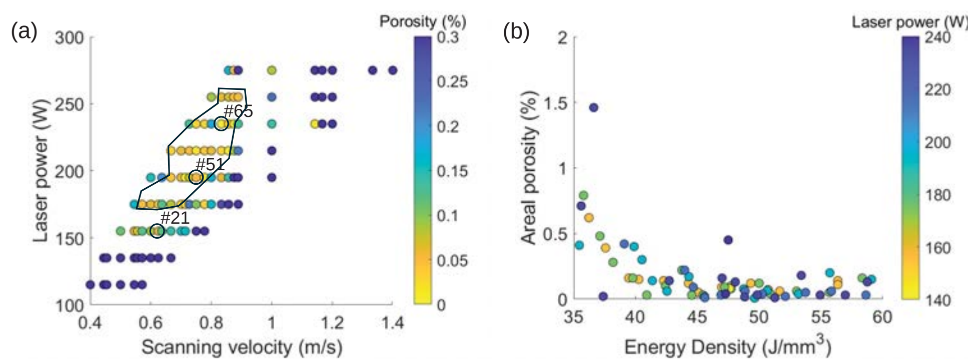
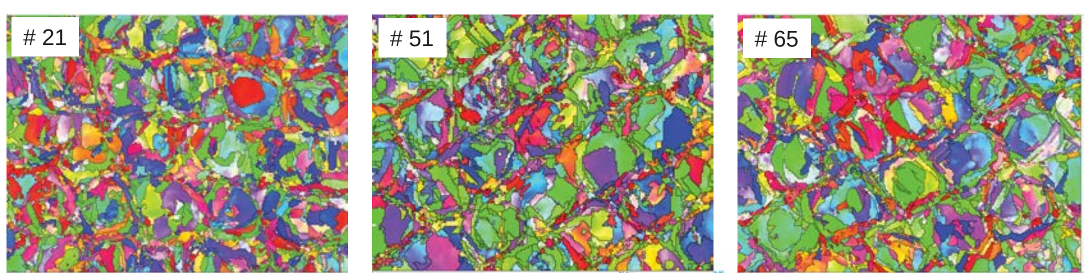
ANL: An optimum process window identified

Development of process parameters and post-build conditions for qualification of LPBF 316 SS, ANL-AMMT-004, 2023

Observations:

- Through optical examination of interior surfaces of the cubes, an optimum operating window is identified.
- This window corresponds to an optimum energy density range with ~ 40 J/mm^3 as the minimum.
- Grain structures of materials printed with similar energy density (47 J/mm^3) are similar, displaying random textures.
- The grain structures reflects the rapid solidification process.





Images taken in normal to build directions

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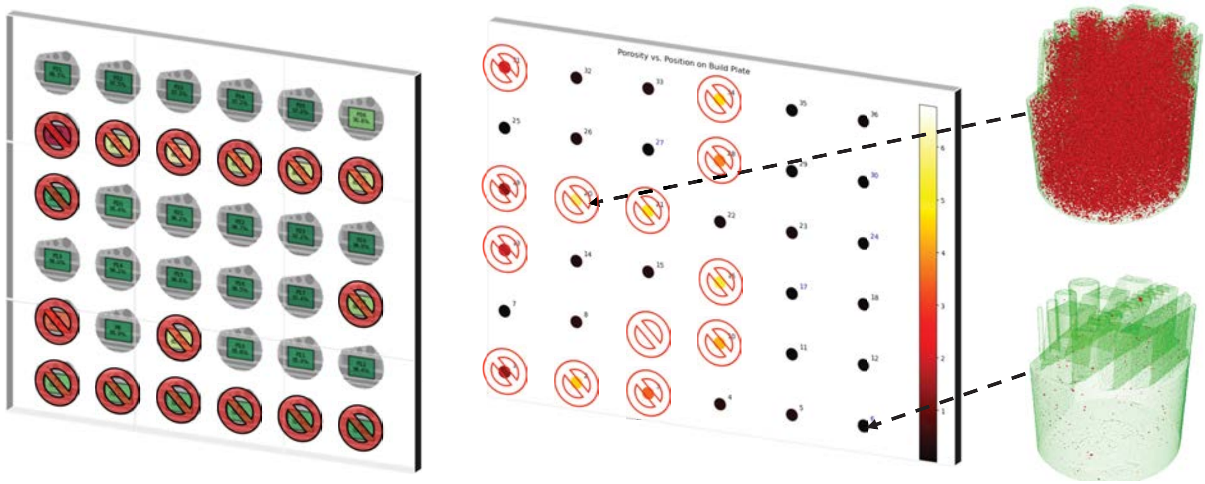
ORNL: Combining Process Monitoring and X-ray Tomography for high-fidelity screening

Use in-situ data as a QA tool to assess general part quality (Filter 1) → Use high-throughput XCT data to identify specimens of desired heterogeneity (Filter 2) → Extract specimens to evaluate microstructure variation in high-density parts (Filter 3)



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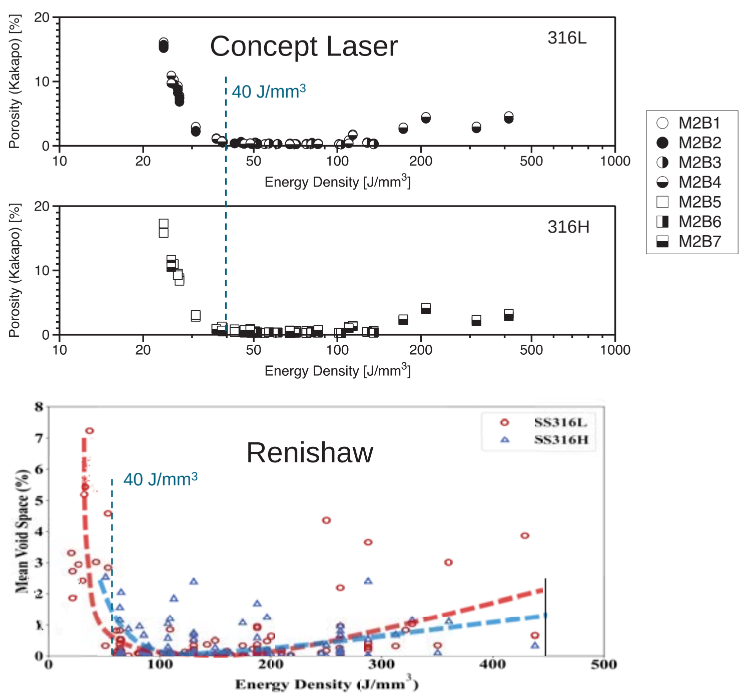
ORNL: High-Throughput Porosity Measurements (XCT + Pycnometry)

Data-Driven Optimization of the Processing Window for 316H Components Fabricated Using Laser Powder Bed Fusion, ORNL/TM-2023/3115, 2023



To Date, 288 printed samples from the Concept Laser and 390 printed samples from the Renishaw have been analyzed using high-throughput XCT.

Both Renishaw and Concept Laser builds have identified energy density windows of minimal porosity.

The existence of potentially different ”windows” of optimal parameters between machines is being investigated, using similar agnostic down-selection criteria depending on available data.

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Content

- Background
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- Variations in powder feedstock
- Thermal aging effect
- Mechanical testing

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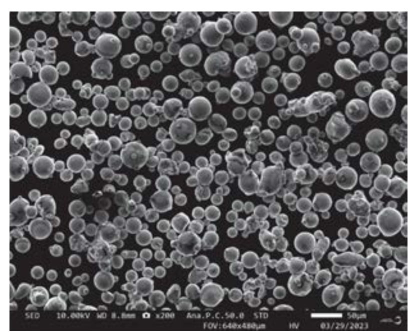
Variability in powder feedstocks

The ASTM specifications for 316H SS and the measured feedstock powder chemistry

		ASTM UNS S31609	316H powder	316H powder	316H powder	316H powder
Manufacturer			Praxair	Praxair	Praxair	PAC
Designation		--	Prax-**AM316H-1**	Prax-**AM316H-2**	Prax-**AM316H-3**	PAC-**AM316H-4**
Order quantity (kg)		- -	50	200	500	200
Composition (wt.%)	Fe	Bal.	Bal.	Bal.	Bal.	Bal.
	Cr	16.0-18.0	17.6	16.8	17.0	16.94
	Ni	11.0-14.0	12.3	12.1	12.3	10.88
	Mo	2.00-3.00	2.6	2.5	2.3	2.23
	Mn	2.0*	1.03	1.13	1.05	1.02
	Si	**1.00***	**0.41**	**0.48**	**0.07**	**0.37**
	C	**0.04-0.10**	**0.05**	**0.06**	**0.08**	**0.043**
	O	**- -**	**0.05**	**0.03**	**0.03**	**0.048**
	N	- -	0.01	0.01	0.01	**0.05**
	P	0.045*	<0.005	<0.005	<0.005	0.031
	S	0.030*	0.00	0.00	0.00	0.001

* Maximum.



SEM image of the powders from the Prax-AM316H-1 batch

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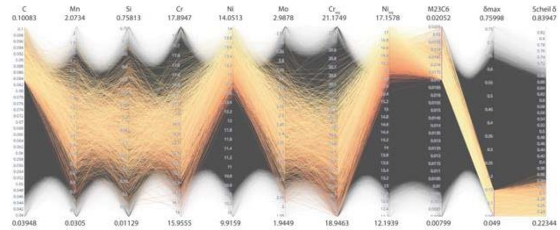
ORNL: informed printing with synthetic data simulations

Preliminary Report on Compositional Specifications for Printed 316SS, ORNL/TM-2023/3031, 2023

1 million synthetic compositions of 316H (within spec) were analyzed to determine what expected variations in carbide and delta-ferrite content would occur based on powder variability



Comparison of the ASTM specifications with the proposed compositions for 316SS-H. Compositions in wt. %

	Fe	C	Mn	Si	Cr	Ni	Mo
ASTM	Bal.	0.04-0.1	2.0	1.00	16-18	11-14	2-3
Proposed	Bal.	0.08-0.1	2.0	0.75	16-18	12-14	2-3

Approach based on Kannan & Nandwana, Scripta Mat. 2023

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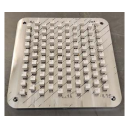
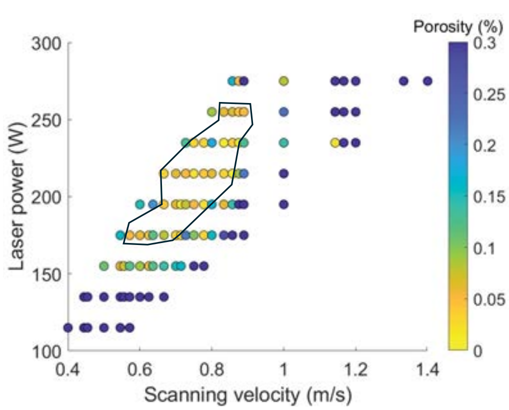
ANL: exploring compositional effect on printability

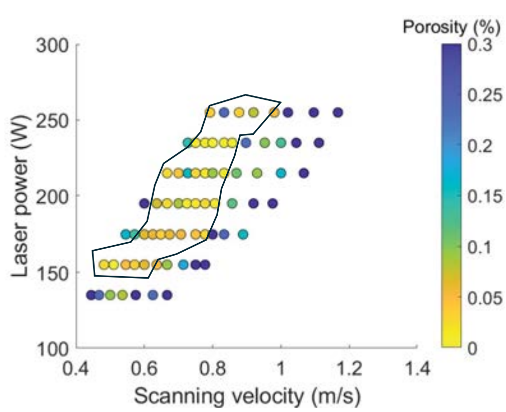
Unpublished data



Build 20230303
(Powder: Prax-AM316H-2, 0.06% C, 0.48% Si)



Build 20230811
(Powder: Prax-AM316H-3, 0.08% C, 0.07% Si)



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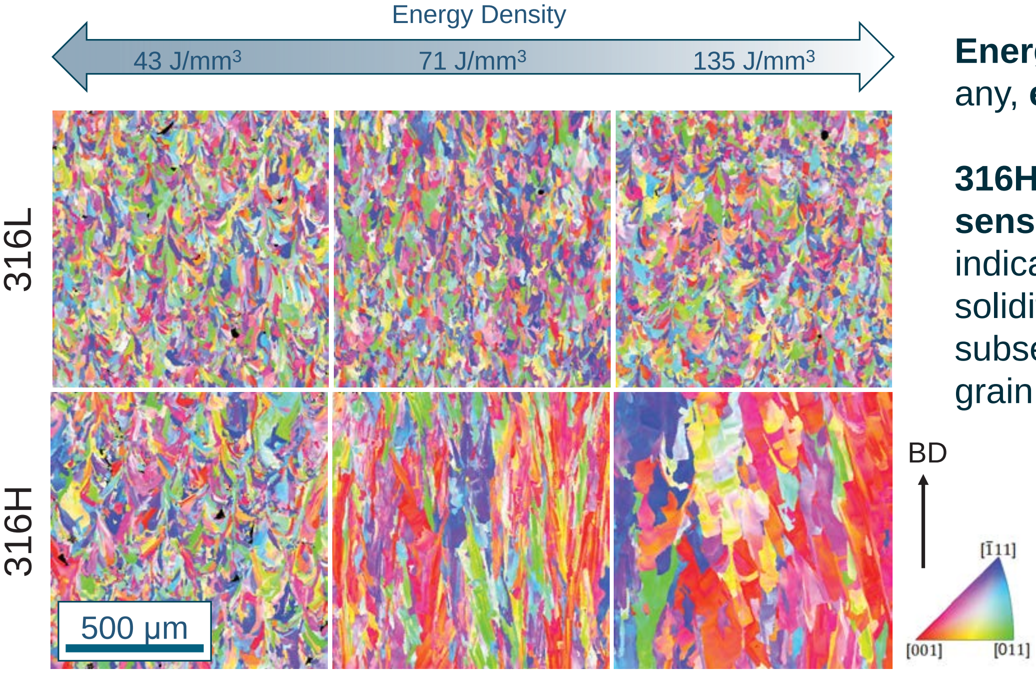
ORNL: 316L vs. 316H exhibit differences in grain structures within the same low-porosity region

Data-Driven Optimization of the Processing Window for 316H Components Fabricated Using Laser Powder Bed Fusion, ORNL/TM-2023/3115, 2023



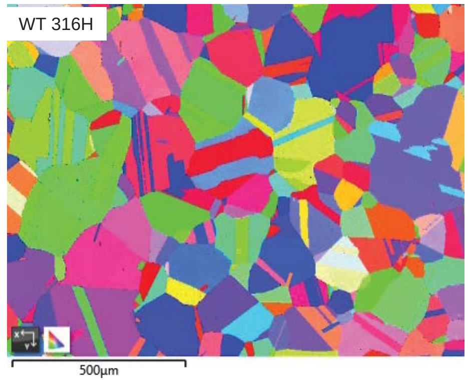
Energy density has a weak, if any, **effect on SS316L**

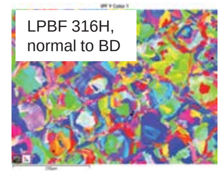
316H, on the other hand is **more sensitive to the heat input**, indicating a difference in solidification behavior and subsequent texture evolution and grain morphology.

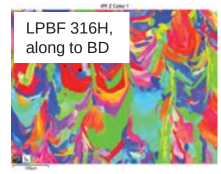
Content

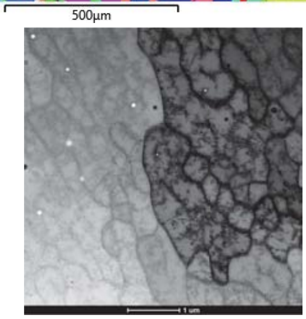
Long term behavior of LPBF 316H under advanced reactor service conditions needs to be addressed

- LPBF 316H has very different microstructure from the wrought.
  - Far from thermal equilibrium
  - Fine grain structure
  - High density dislocations and dislocation networks ➔ internal stresses
  - Chemical heterogeneity
  - Porosity
- Thermal aging is an important factor in assessing materials in-service performance.
- Experimental data is also needed for developing physics-based mechanistic models to predict long-term creep behavior.









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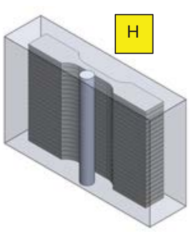
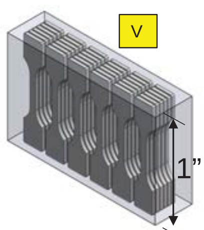
ANL: Thermal aging experiment

Development of process parameters and post-build conditions for qualification of LPBF 316 SS, ANL-AMMT-004, 2023

- **LPBF 316H aging experiment is on going.**





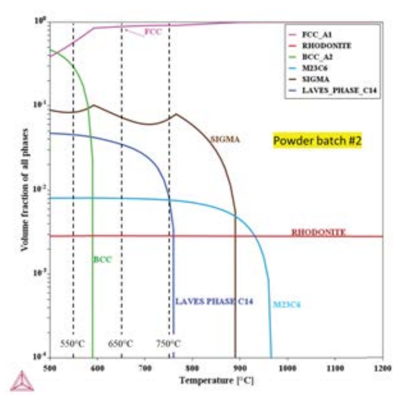
- **Encapsulated specimens are placed in furnaces.**

- **Three temperatures are picked to expedite kinetics (trade temperature for time)**

T (°C)	t0	t1 (h)	t2 (h)	t3 (h)	t4 (h)	t5 (h)	t6 (h)
550	AR	5	25	100	500	2500	10000
650	AR	5	25	100	500	2500	10000
750	AR	5	25	100	500	2500	

Black conditions are done.
Red conditions are on-going.

- **ThermoCalc simulation predicts equilibrium phases.**

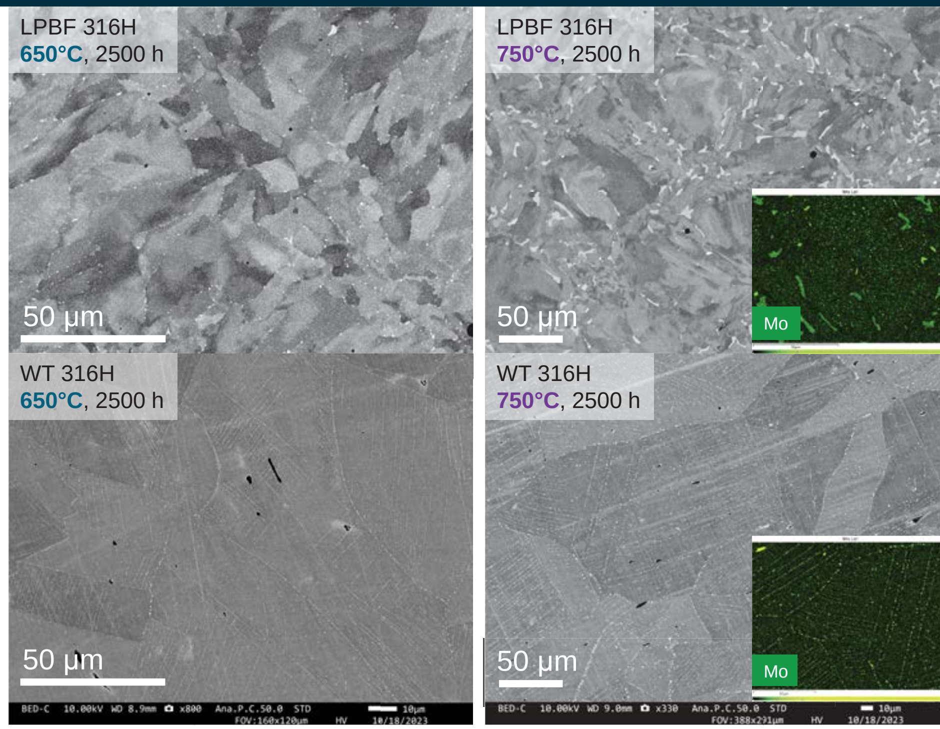


Distinct precipitation behavior compared to wrought material

Compared to WT 316H SS, LPBF 316H SS has:

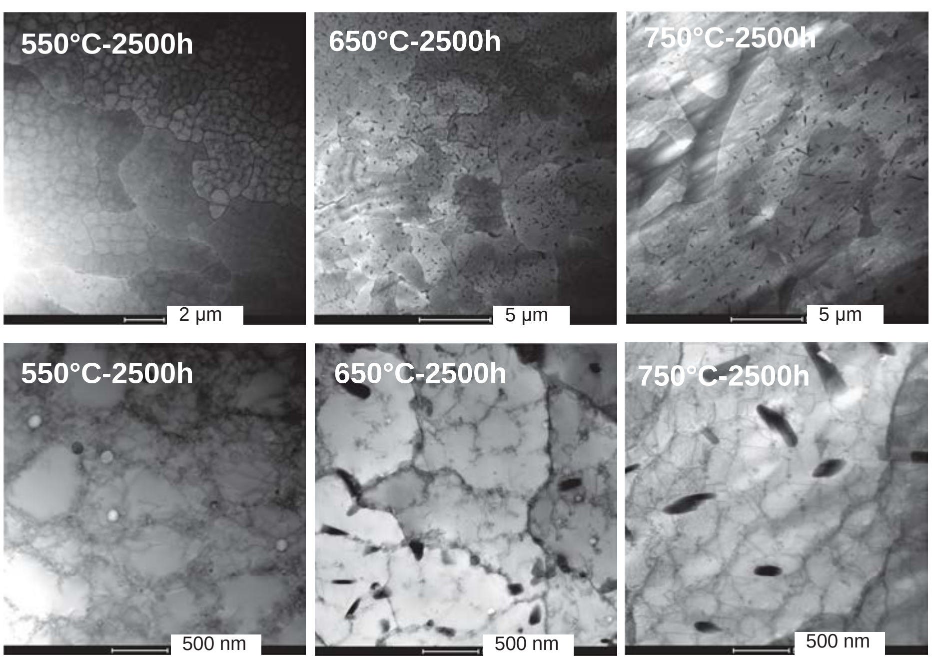
- Smaller grain size and higher dislocation density → fast diffusion channels for heterogenous precipitation
- Chemical segregation at grain boundaries and dislocation cell walls → low nucleation barriers

The result is very different precipitation behaviors.



Complicated precipitation in LPBF 316H SS

Development of process parameters and post-build conditions for qualification of LPBF 316 SS, ANL-AMMT-004, 2023

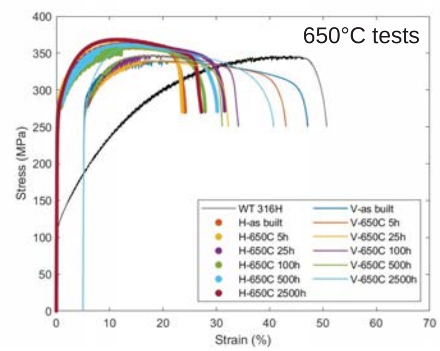


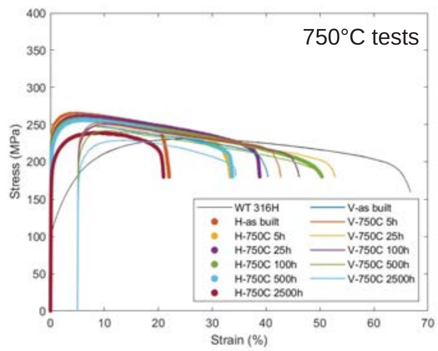
Material condition	Secondary phase description	Location	Shape	Size
As built	Dislocation cells: thick dislocation tangle walls, Cr and Mo segregation	Entire material	Cellular	Average 531 nm [14]
	$MnSiO_3$ Rhodonite	Cell walls	Round	Average 110 nm
550°C-2500h	Dislocation cells: thick dislocation tangle walls	Entire material	Cellular	Average 530 nm
	$MnSiO_3$ Rhodonite	Cell walls	Round	Average 110 nm
	Cr-C-O enriched	Cell walls and junctions	Cuboidal	5-20 nm
	Mo-Si enriched	On cell walls and junctions	Elongated	50 nm
650°C-2500h	Dislocation cells: dislocation tangle walls	Entire material	Cellular	Average 310 nm
	$MnSiO_3$ Rhodonite	Cell walls	Round	Average 50 nm
	Cr-C-O enriched	Grain boundaries, cell walls and junctions	Cuboidal	Average 20 nm
	Mo-Si enriched	Cell walls and junctions	Elongated	Hundreds of nm to 1 µm in length
750°C-2500h	Dislocation cells: thin walls	Entire material	Cellular	Average 320 nm
	$MnSiO_3$ Rhodonite	Cell walls	Round	Average 55 nm
	Cr-C-O enriched	Cell walls and junctions	Cuboidal	Average 30 nm
	Mo-Si enriched	Cell walls and junctions	Elongated	Hundreds of nm to 1 µm in length
	Mo-Cr-O enriched	Grain boundaries	Irregular	5-20 µm

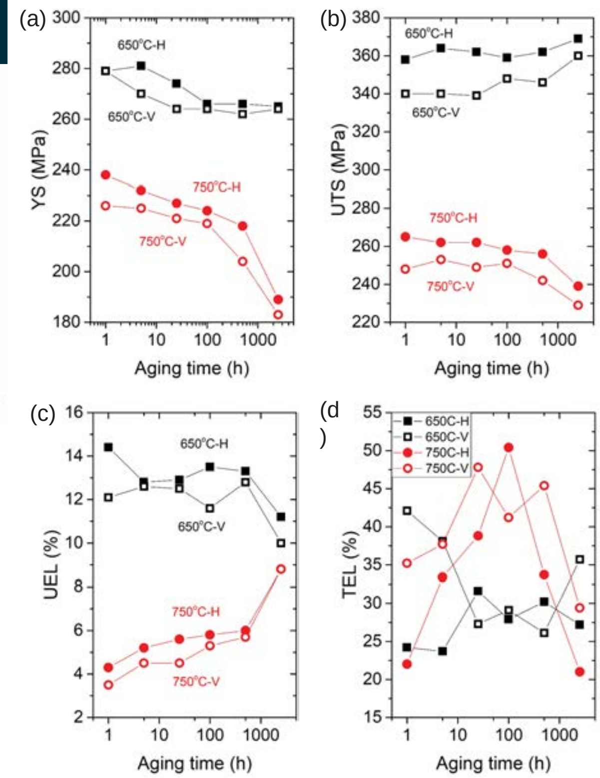
Baseline tensile property evaluation

Development of process parameters and post-build conditions for qualification of LPBF 316 SS, ANL-AMMT-004, 2023

- Compared to WT 316H SS, the LPBF material exhibited much higher yield stresses (YS) and comparable or higher ultimate tensile stress (UTS), but much lower uniform elongation (UEL). The total elongation (TEL) of the LPBF material has a relatively large scatter.
- During the 650° C aging, the YS decreases, the UTS increases and the UEL decreases with aging time. Specimens exhibit dynamic strain aging except the two 2500-h aged specimens.
- During the 750° C aging, the YS decreases, the UTS decreases and the UEL increases with aging time.







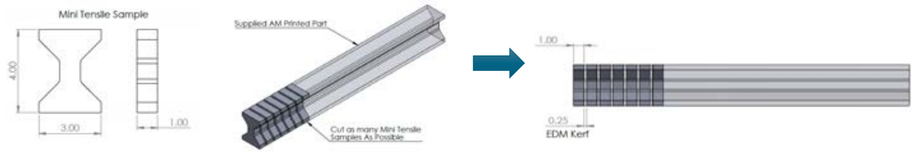
Content

- Background
- Process parameter study
- Variations in powder feedstock
- Thermal aging effect
- **Mechanical testing**

LANL: tension tests with miniature specimens addressing data scatter

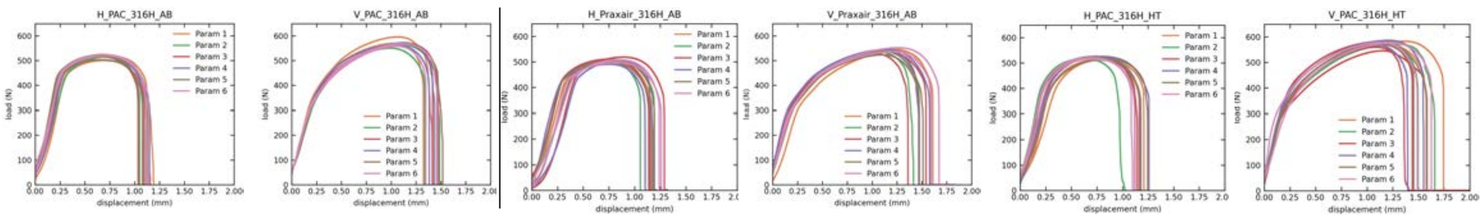
Unpublished data

Micro-Tension Geometry

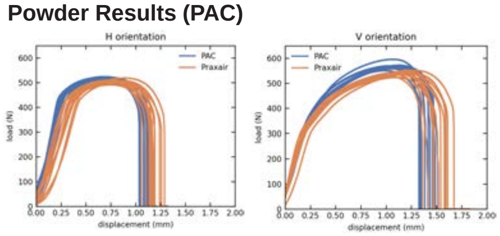


To be compared to full size tensiles in FY24

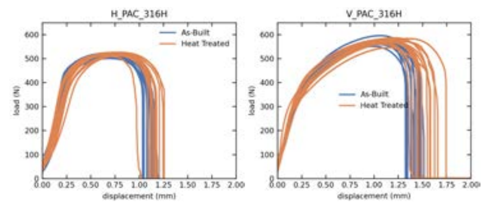
Build Parameters Results (AB and HT)

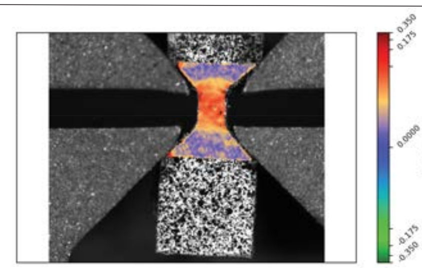


Powder Results (PAC)



Stress-relief Results (PAC)





ORNL: tension tests with miniature specimens addressing anisotropy

Data-Driven Optimization of the Processing Window for 316H Components Fabricated Using Laser Powder Bed Fusion, ORNL/TM-2023/3115, 2023

Micro-Tension Geometry:

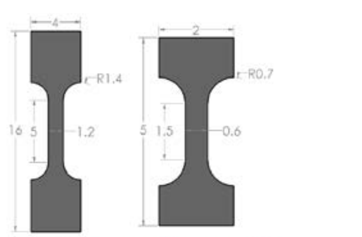
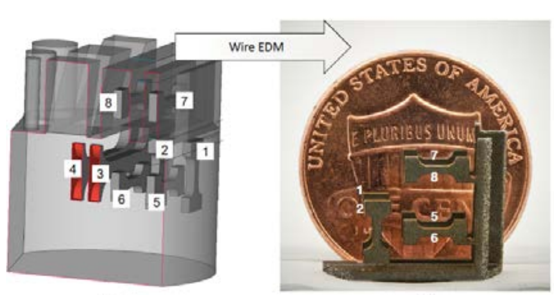
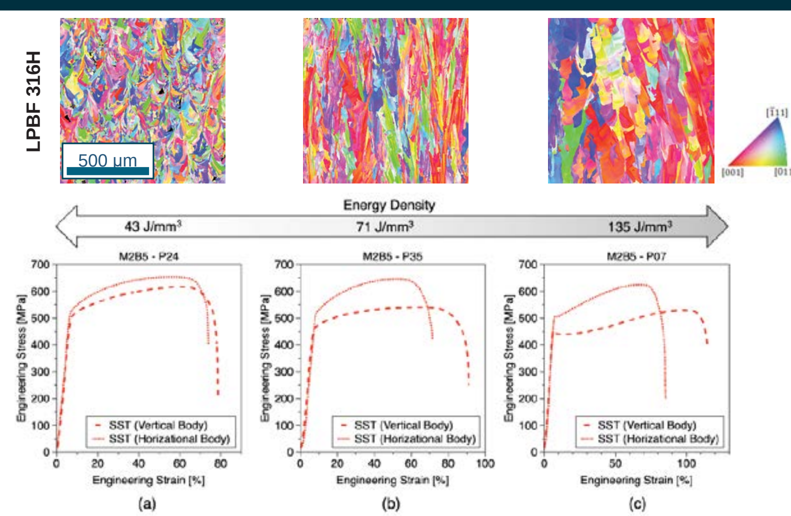


Figure 11. SSJ3 (left) and SST (right) nominal geometries; both are flat dog bone–type specimens. The nominal sample thicknesses are 0.75 mm and 0.6 mm, respectively.

Tensile specimen harvesting strategy for SSJ3 and SST specimens:



(a) (b)



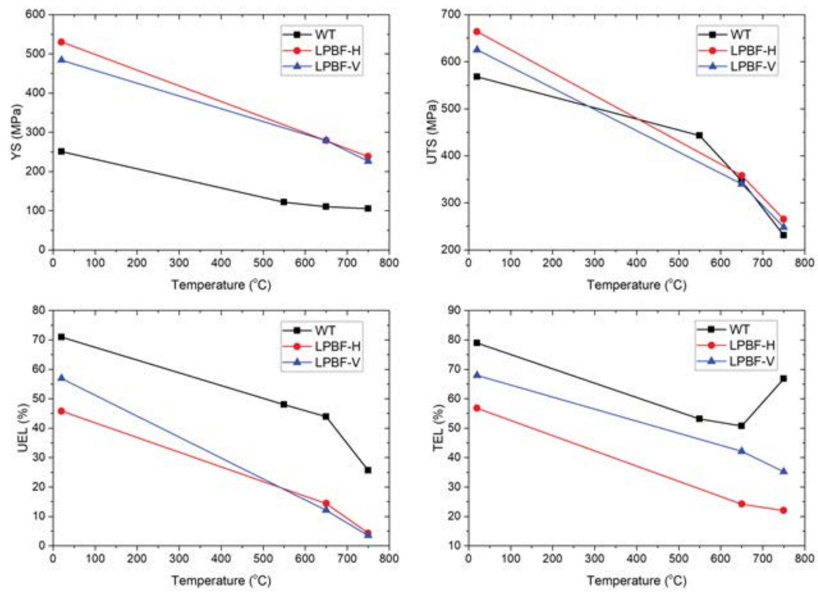
- This comparative analysis reveals the degree of anisotropy in each microstructure at RT.
- The larger the microstructural anisotropy, the larger the differences in yield stresses and work hardening rates at RT.

ANL: Baseline tensile property evaluation at elevated temperatures

Development of process parameters and post-build conditions for qualification of LPBF 316 SS, ANL-AMMT-004, 2023

Observations:

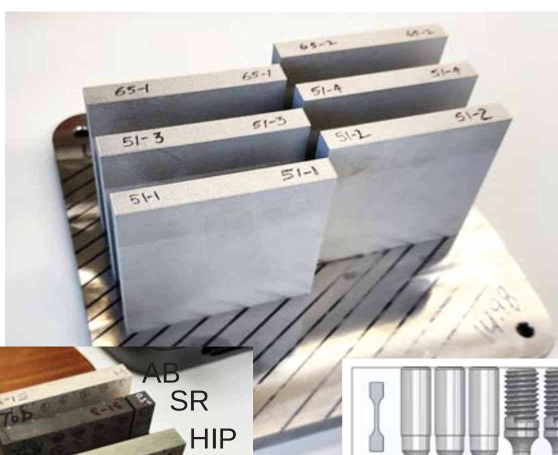
- At all temperatures, the as-built LPBF material has higher yield stress (YS), comparable ultimate tensile stress (UTS), lower uniform elongation (UEL) and lower total elongation (TEL) compared to the WT material.
- All materials show decreasing YS, UTS, UEL and TEL as the test temperature increases, except for the WT material that has an increase in TEL from 650ºC to 750ºC.



ANL: Larger builds for heat-treatment down-selection

Development of process parameters and post-build conditions for qualification of LPBF 316 SS, ANL-AMMT-004, 2023

- Build 20230410 was completed with 0.06%-C powder.

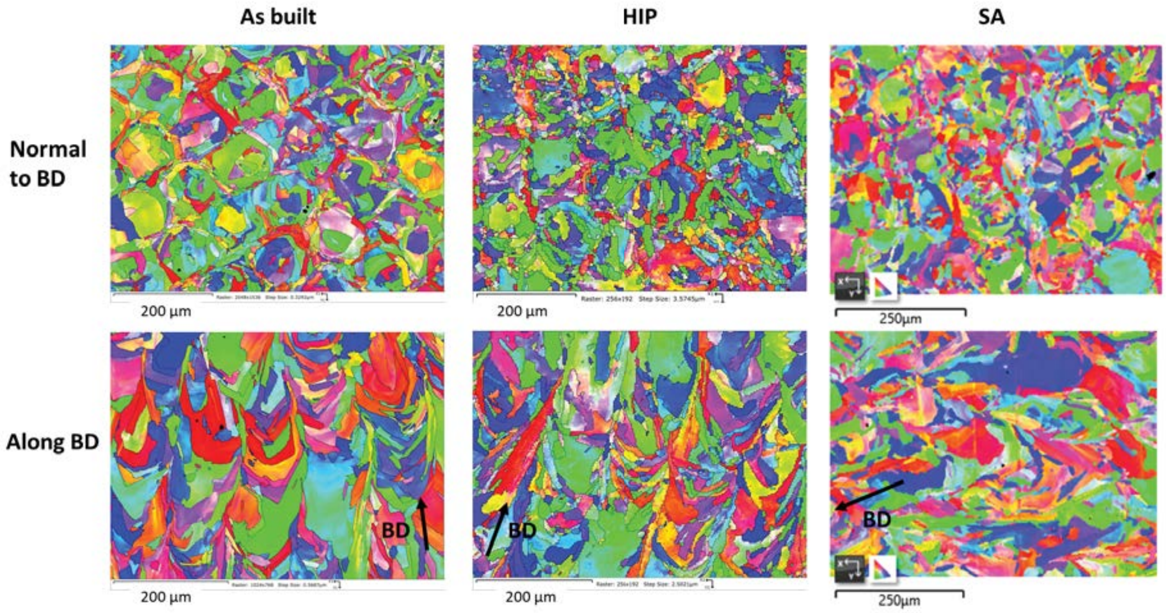


Heat treatment	Temperature	Time	Quench	Pressure
As-built	n/a	n/a	n/a	n/a
Stress relieved	650° C	24 hour	Furnace	n/a
Solution annealed	1100° C	1 hour	Water	n/a
HIP	1120° to 1163° C	4 hours	Cool in inert atmosphere	>100 MPa

Test type	Temp.	Other test conditions	Sample type	ASTM standard	Repeats	Total tests
Tension	20° C		Subsized	None	2	8
Tension	600° C		Subsized	None	2	8
Creep	600° C	248 MPa	Standard	E139	1	4
Creep	600° C	248 MPa	Subsized	None	2	8
Fatigue	550° C	0.3% strain range, R = -1	Standard	E606	1	4
Fatigue	550° C	0.5% strain range, R = -1	Standard	E606	1	4
Creep-fatigue	550° C	0.5% strain range, R = -1 6 min tensile hold	Standard	E2714	1	4
					Total	40

Post-treatment grain structures

Development of process parameters and post-build conditions for qualification of LPBF 316 SS, ANL-AMMT-004, 2023



High-temperature fatigue, creep and creep-fatigue tests are initiated at ANL and INL in FY24.

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Summary

- Qualification of LPBF 316H SS will require comprehensive phenomena identification/ranking, enhanced QA tools, extensive testing and close collaboration between experimental and modeling teams.
- ORNL, LANL, and ANL teams are leveraging resources to provide a process understanding of LPBF 316H SS and provide recommendations on materials optimization.
- Initial builds have been completed on three different laser powder bed systems using three different 316H powder compositions.
- Microstructural variation (porosity and grain structure) has been captured as a function of process variables, enabling future studies on post-build anisotropy.
- Initial thermal ageing has identified unique second phase particles requiring additional consideration on compositional specifications and long-term performance.
- Larger-scale builds are underway to provide performance metrics (tensile, creep, fatigue, creep-fatigue) as a function of microstructure and post-process heat treatment.

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References

- Zhang, X., *et. al.*, **Development of process parameters and post-build conditions for qualification of LPBF 316 SS,** ANL-AMMT-004, 2023
- Massey, C., *et. al.*, **Data-Driven Optimization of the Processing Window for 316H Components Fabricated Using Laser Powder Bed Fusion,** ORNL/TM-2023/3115, 2023
- Montoya, R., *et. al.*, **Process understanding for qualifying LPBF 316H SS,** LA-UR-23-30967, 2023
- Nandwana, P., *et. al.*, **Preliminary Report on Compositional Specifications for Printed 316SS,** ORNL/TM-2023/3031, 2023

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Programm NANU: "Funding of junior research groups in nuclear safety research at German universities"

funded by:

Federal Ministry
for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection

Critical assessment of the safety of innovative, future-proof manufacturing processes for internationally relevant SMR concepts

Kritische Bewertung der Sicherheit von innovativen, zukunftsfähigen Fertigungsverfahren für international relevante SMR-Konzepte

acronym: SiFeKo

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Materialprüfungsanstalt Universität Stuttgart
Pfaffenwaldring 32
70569 Stuttgart

SiFeKo

Project Overview

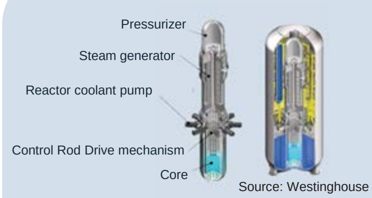
Global Motivation: demand for more low-CO_2 / carbon-free forms of energy generation promotes the development of new reactor concepts, like small modular reactors (SMR).

Current PWR

Construction: 3 … 15 years
Core diameter: ~ 4 m
Refueling: 1 year
Power: 1.400 MW(e)

1985 - today

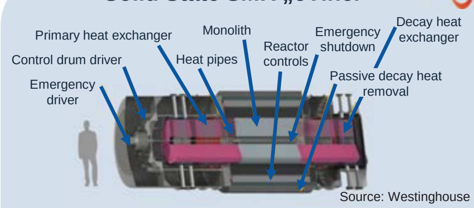
SMR



Construction: 1 year
Core diameter: ~ 2 m
Refueling: 2 years
Power: 250 MW(e)

2025

Solid State SMR „eVinci"



Construction: 30 days
Core diameter: ~ 0.5 - 1 m
Refueling: 7 years
Power: 5 MW(e)

2030

Our goals: - sustain competence in nuclear safety and develop safety relevant knowledge
- keep track of international trends and technologies regarding safety
-> development of new reactors and manufacturing technologies is not part of funding!

SiFeKo

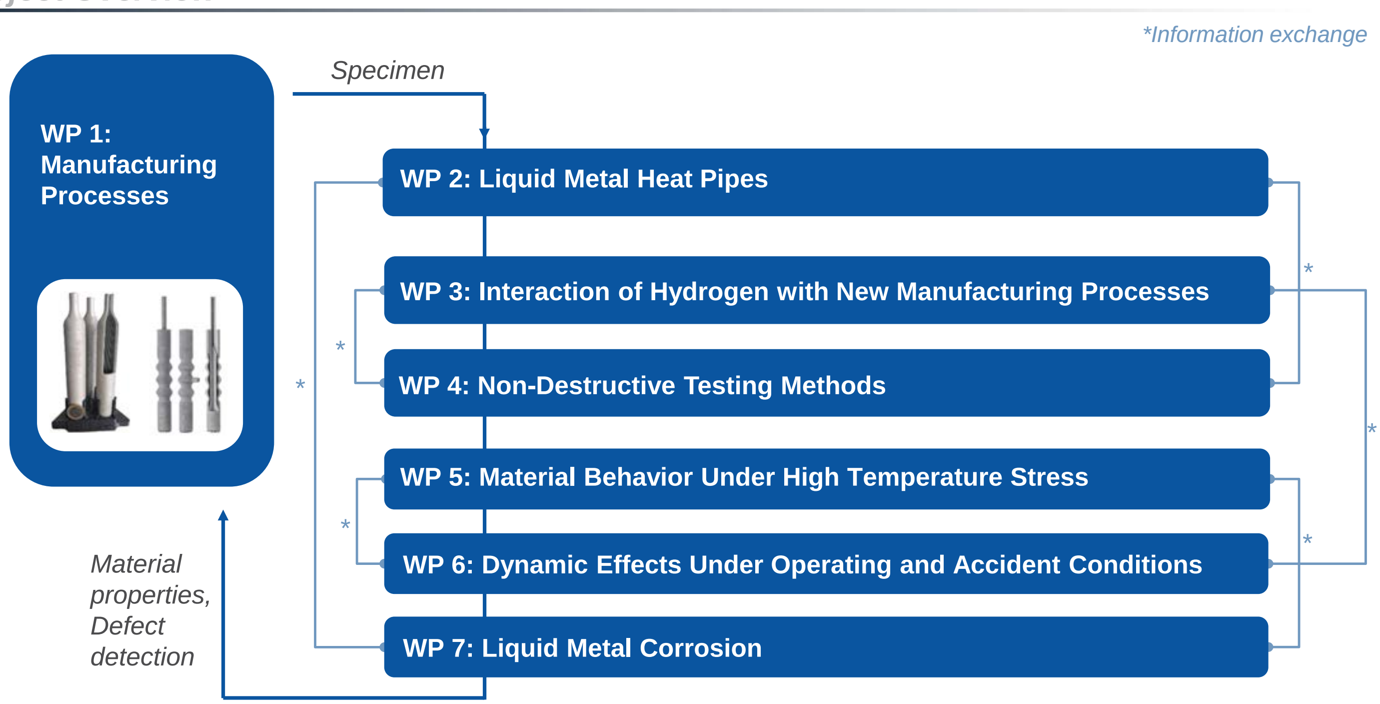
Project Overview

Traditional Manufacturing Processes

Advanced Manufacturing Processes

SiFeKo

Project Overview



WP 1: Manufacturing Processes

WP1.1: Literature review on manufacturing parameters and expected process inaccuracies and failures and their impact on safety

WP1.2: Definition of test specimens and their manufacturing parameters for safety evaluation

WP1.3: Manufacturing of the specimens and a preparation for subsequent investigations

WP1.4: Basic mechanical characterization of the test specimens

WP1.5: Comparative assessment of the impact on safety

Examined manufacturing processes

- Laser Powder Bed Fusion (LPBF)
- Wire Arc Additive Manufaturing (WAAM)
- Hot Isostatic Pressing (HIP)
- Electron Beam Welding (EBW)
- Cold Gas Spraying (CS)

WP 1: Manufacturing Processes

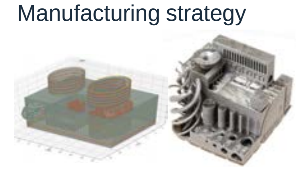
Contents of work

- Active tracking of international developments
- Determination of representative geometries and manufacturing strategies for the materials 316L, IN718 and 22NiMoCr3-7
- Acquisition and generation of test specimens from candidate materials
- Specimen analysis
- Estimation of process capability and robustness
  - LPBF
  - WAAM
  - EBW
  - HIP
  - CS

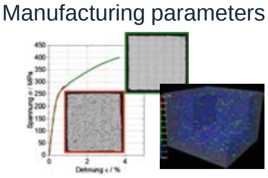
➡ Provision of representative material and test specimens for subsequent subprojects 2-7

Manufacturing process

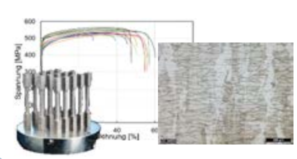
Manufacturing strategy



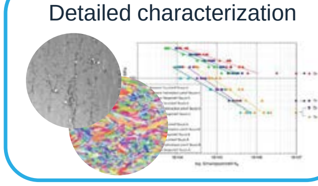
Manufacturing parameters



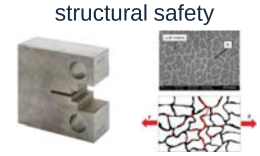
Basic characterization



Detailed characterization

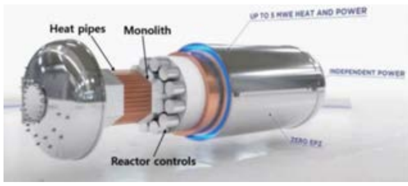


estimation of structural safety



WP 2: Liquid-Metal Heat Pipes

Motivation:
- Passive heat transport using innovative liquid metal heat pipes (LM-HP) in vSMRs
- Heat pipes are an integral part of the safety and functional concept of vSMRs



Objective:
- Design and additive manufacturing of innovative LM-HP taking into account conceptual application requirements for vSMRs
- Determine functional aspects and limits
- Experimental investigation of the heat transfer characteristics of AM-manufactured LM-HP for relevant thermal vSMR operating conditions including postulated accident scenarios

WP 2.1: Selection of LM-HP Design Variants

Consideration of AM processes
Constructive design of prototype
LM-HP variants for WP 2 and WP 3

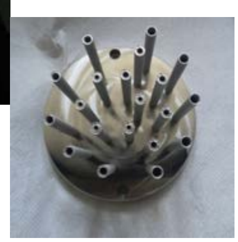
WP 2.2: AM Manufacturing

Production of test pieces and prototype LM-HP variants
Construction of a test bench
Provision of LM-HP filled with heat transfer fluid potassium

WP 2.3: Experimental Test Program

Qualification on AM-manufactured samples
Variation of thermal boundary conditions (550 - 750 °C) Start-up behavior, unsteady/stationary heat transport

WP 2: Liquid-Metal Heat Pipes

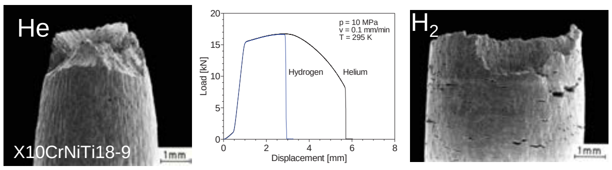


Design → Manufacturing → Testing

WP3: Interaction of Hydrogen with New Manufacturing Processes

Materials can become brittle under the direct influence of hydrogen

- Hydrogen embrittlement can lead to a reduction in ductility, fracture toughness and fatigue life.
- What is the influence of hydrogen on additively manufactured parts?



WP 3.1: Literature review

Collection of data referring to the mechanical-technological behavior under hydrogen atmosphere
Basis for modelling the service life under the influence of hydrogen

WP 3.2: Influence of hydrogen on material properties

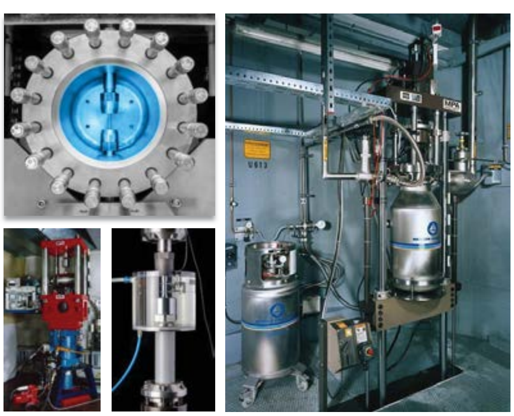
Analysis of diffusion processes (numerical), quasi-static & dynamic testing in pressurized hydrogen atmosphere, comparison with conventionally manufactured material

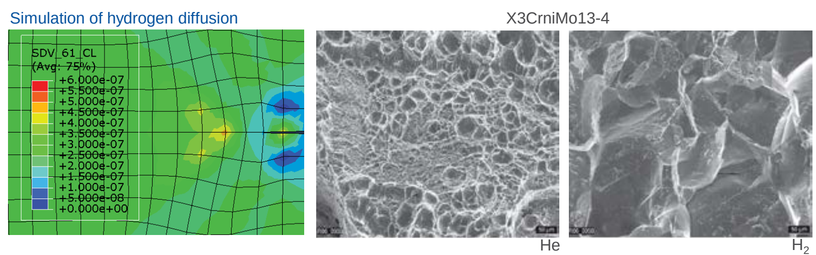
WP 3.3: Evaluation and safety assessment

Comparison of experimental data with literature, development of methods to assess the safety in hydrogen atmosphere, analyses of the influence of material imperfection, optimization of the hydrogen suitability of the additively manufactured materials (with regard to life time)

Objective of this work package

Gain insight into the hydrogen suitability of different additively manufactured materials





Testing → Modelling → Safety assesment

WP 4: Non-Destructive Testing

First-time and repetitive non-destructive detection of defects is necessary for the safe operation of machinery!

Established methods not applicable to SMRs:

- New manufacturing processes = differently oriented defects
- New reactor concepts = different damage patterns (location, size)
- Novel material composites ≠ established processes
- Very small geometries = limited accessibility

Objective:

Testing of adapted test solutions for special SMR solutions, taking into account manufacturing defects and stresses under operating and fault conditions.

WP 4.1: Identification of relevant defects

Determination of relevant flaws (production and operation) and definition of permissible/ inadmissible flaws

WP 4.2: Test methods for relevant defects

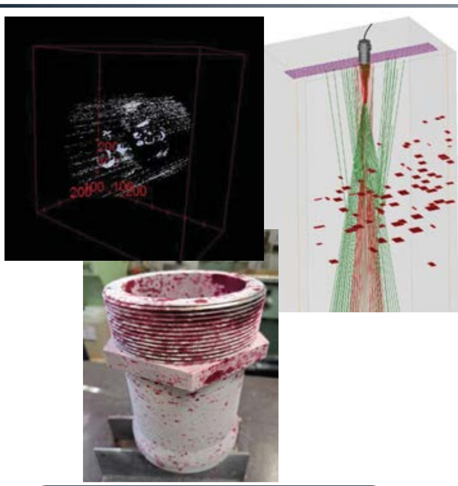
Definition and further development of NDT methods for flaws defined in WP1
Development of test solutions for safety-critical components and testing on mock-ups

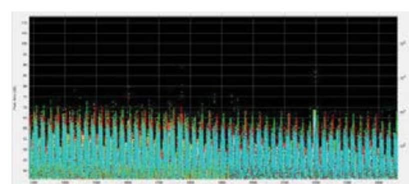
*

WP 4.3: Automated testing on a real scale

Raise testing solutions to a higher TRL
Adaptation of mechanized testing, e.g. via robotic systems to real-scale components

WP 4: Non-Destructive Testing





Use of different NDT methods → Inspectability of complex geometries → Additional use of in-situ monitoring

Motivation:

- Additive manufacturing allows to create parts with complex geometries
- But: properties are not comparable with conventionally manufactured parts

Objective:

- Qualification of additive manufacturing material for parts in high temperature SMRs
- Development of understanding for degradation mechanisms
- Evaluation of material behaviour and adaption of existing design- and assessment-concepts

WP5.1: **Experimental investigations for determination of material behaviour under relevant loading scenarios**

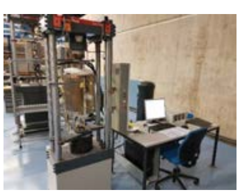
WP5.2: Description of degradation mechanisms

WP5.3: **Simulations, approaches for assement of damaging behaviour, life-time consideration**

WP 5.1

- Selection of two candidate materials with already known data from conventional manufacturing (examples: Alloy800 H, P93)
- Qualification under relevant loading scenarios: Tensile tests, LCF-tests, TFMF-tests, creep and creep-fatigue tests, crack initiation and propagation

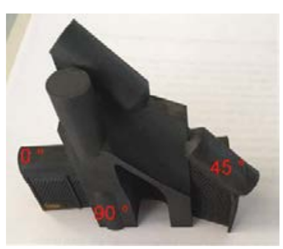
Creep test stands



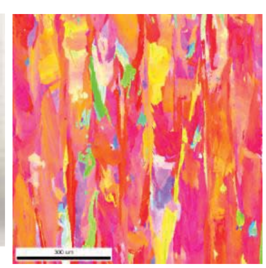
LCF-test stand

WP 5.2

- Microstructural examination for characterisation of damage mechanisms
- Examination of error behaviour and sensibility towards imperfections due to manufacturing



Generic part AM718



EBSD-image of AM718

WP 5.3

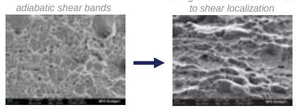
- Derivation and adaption of material laws for simulations
- Draft of assessment criteria under consideration of structural properties of material states
- Comparison with known and modified regulations
- Adaption of design and assessment concepts

WP 6: Dynamic effects under operating and loading condition

Dynamic loads in Small Modular Reactors

- Occur primarily under beyond-design-basis events and design basis accidents
- Material behavior changes due to high velocities and temperature developments
- Failure limits of additively manufactured specimen unknown

Fracture surface without adiabatic shear bands — *Melting of a fracture surface due to shear localization*



Objective:

Expand knowledge

Influence of additive manufacturing processes (WAAM, PBF-LB/M) on material behaviour under dynamic loading

WP 6.1: Identification and analysis of dynamic effects under operational and accident conditions

WP 6.2: Material requirements and material properties

WP 6.3: Safety-critical evaluation of the components by numerical investigations

WP 6: Dynamic effects under operating and loading condition

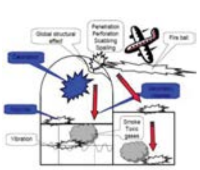
WP 6.1

Possible dynamic load scenarios

- Crash and fall during assembly and transport

U.S. Government Accountability Office (GAO): GAO-20-380SP, 2020

- External impacts due to e.g. pressure waves or the crash of missiles

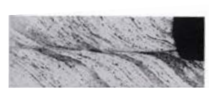


Lo Frano, R.; Forassi, G.: „Influence on aircraft impact on seismic isolated SMR reactor", 2011

- Internal hazards (explosion) due to an accumulation of flammable gases

WP 6.2

- Modelling of the strain hardening and softening process of additively manufactured components



Adiabatic shear bands (2014-T6 Al) Source: „The Physics and Mathematics of Adiabatic Shear Bands", T.W. Wrigth, 2002

- Characterisation of the material properties

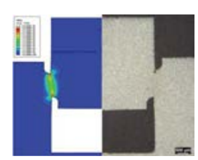
Split-Hopkinson pressure bar

Drop-weight systems

High-speed ripping machine with high-speed camera

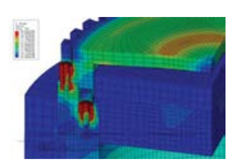
WP 6.3

- Validation of damage models



Shear failure under dynamic loading

- Simulation of components under accident conditions



Numerical simulation of the crash of a nuclear cask for the evaluation of the lid tightness

Offermanns et al. Proc. PATRAM-15 2007

WP7: Liquid metal corrosion

Heat pipe
- Passive safety concept
- Removal of fission heat from reactor core

-> Application example for LPBF-parts

- additive manufactured heat pipes with scaled dimensions for production and testing
- LPBF-material in contact with liquid potassium

assessment of Liquid metal embrittlement behaviour
- Development test stand
- Short and long term behaviour
- Determine failure mechanisms
- …

WP7.1: Corrosion behaviour and embrittlement in liquid potassium at ~700°C

WP7.2: Eperiments under liquid potassium and microstructural characterisation

WP7: Liquid metal corrosion

WP 7.1	WP 7.2

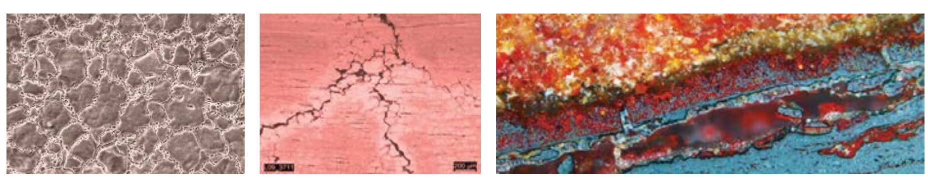
Materials:
- Stainless steels (AISI 316, AISI 437, …)
- Nickel-base alloys (Alloy 617, Inconel 718)

Influencing factors:
- Porosity and Impurities
- Presence of mechanical loads
- Temperature gradients

Experiments:
- Ageing experiments with and without mechanical load
- Electrochemical experiments at high temperatures

Metallographic and electron microscopical investigations of following phenomena:

- Grain coarsening, precipitations, diffusion
- Liquid metal embrittlement
- Crack forming and growth
- Oxide layer formation and their chemical composition
- Porosity



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GOAL: Estabilishing a correlation between microstructural changes and corrosion mechanisms with prevention measures

Thank you for your attention!

Dr. Ing. Martin Werz

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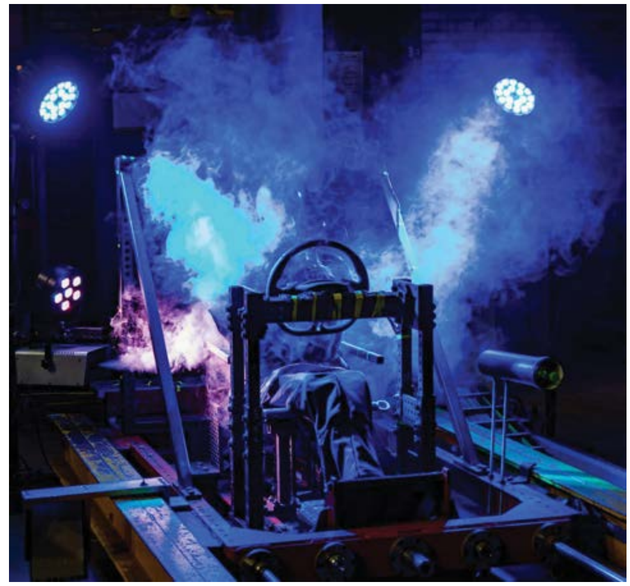
Impressions



INL/CON-23-75183

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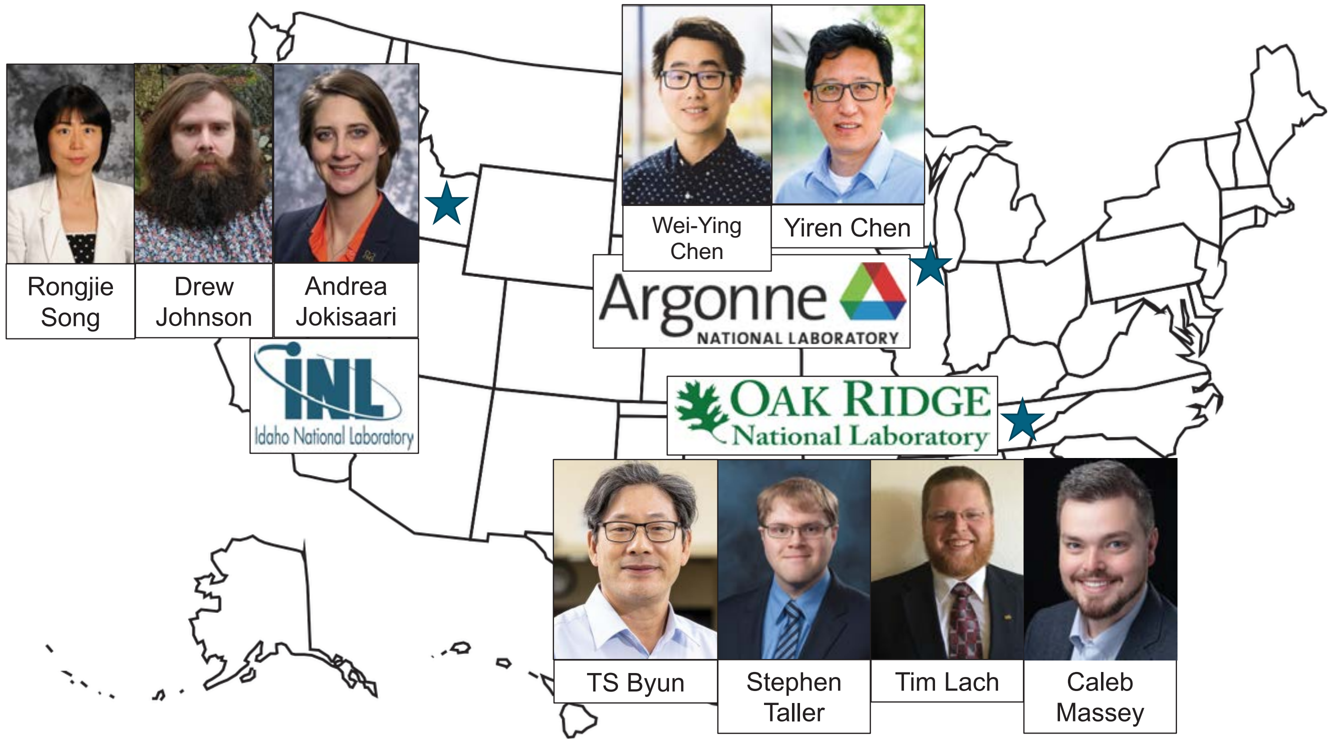
Irradiation and corrosion testing of laser powder bed fusion-manufactured materials in the AMMT program

Andrea Jokisaari

NRC Workshop on AMTs for Nuclear Applications, October 24-26, 2023, Rockville, MD

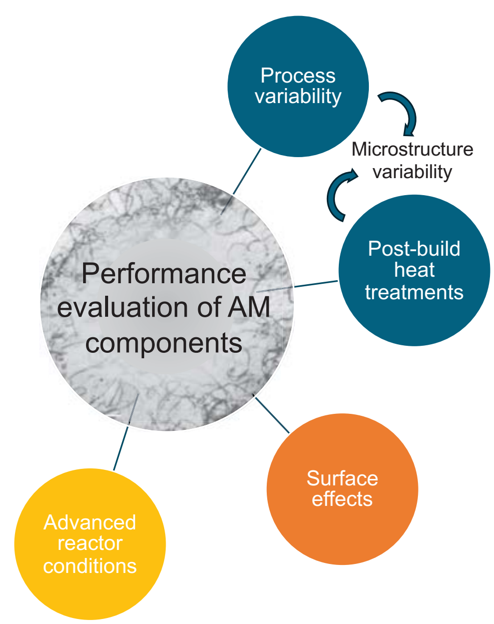
We are an interlaboratory collaborative research team



2

What's the big deal for environmental effects testing of additively manufactured materials?

- **Material evolution and lifetime in harsh advanced reactor environments must be part of a reactor material development and qualification program**
  - Irradiation, corrosion, and high-temperature loading conditions
  - Complex damage processes that are often coupled phenomena
  - Experiments can be time-consuming and costly
- **Evaluating irradiation performance of new materials is one of the most critical technical hurdles for their rapid adoption in nuclear energy systems**
- **AM materials have challenge of process variability: how much does that matter?**
  - Existing qualification regime will be prohibitive
- **Goal: Rapid and effective qualification of the effect of process variability on performance and degradation of AM materials in reactor environments**



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3

The AMMT solution: an integrated environmental effects testing strategy for AM 316H

Build

Ions

Neutrons

Corrosion

500 μm

Corrosion Testing of AM Materials

Corrosion is a natural process of removing useful material thickness

- Uniform
- Localized
- Erosion
- Dealloying
- Environment-assisted cracking

Corrosion costs nuclear industry ~$4B/yr

- Each reactor type has its own corrosion issues
- Elevated temperature + intense irradiation are common conditions for all advanced reactor types

Unique features of AM materials may impact corrosion behavior

- Influence of surface roughness, porosity, residual stresses
- Influence of melt pool boundaries
- Influence of microstructural anisotropy

Some types of corrosion are difficult to detect but have severe consequences of critical importance

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[1]

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

Idaho National Laboratory

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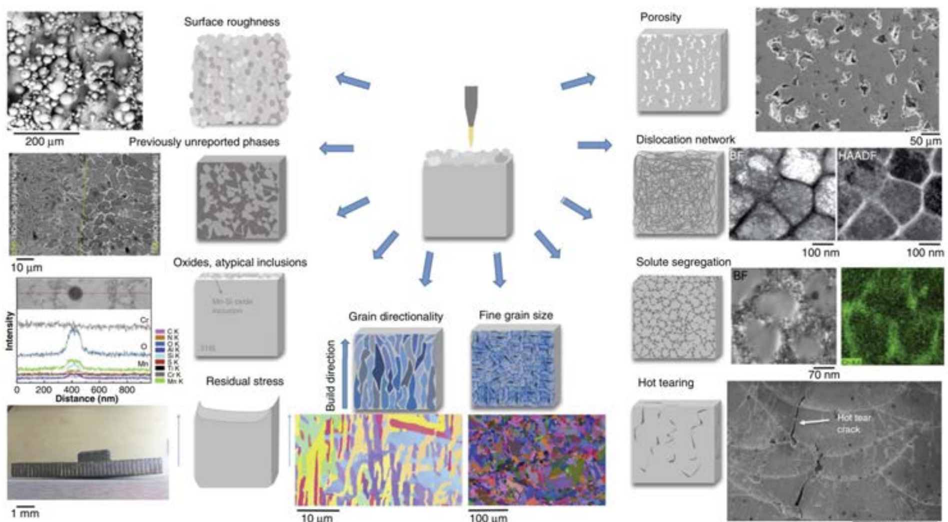
AMMT program corrosion testing strategy on AM 316 prioritizes advanced reactor concerns



G. Sander, et al. Corrosion 74(2018)1318. //D. Kong, et al. npj Materials Degradation 24(2019)1.

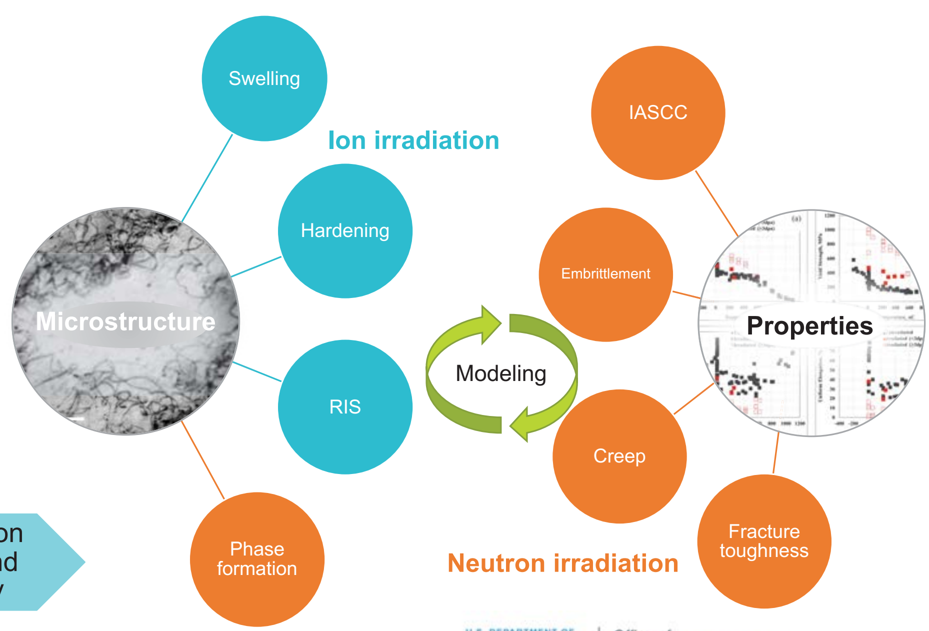
- **Corrosion systems:**
  - Liquid sodium
  - Molten chloride salts
- **Two-surface tests:**
  - As-built surfaces
  - Machined smooth surfaces
- **Macroscopic behavior:**
  - Weight gain/loss
- **Microscopic behavior:**
  - Localized effects (leaching, phase changes…)
- **Staged approach:**
  - Unirradiated material
  - PIE corrosion of irradiated material
  - Prototypical testing *in situ*

Corrosion resistance of stainless steel comes from its passive film

AMMT selects the right tool for the job in evaluating irradiation effects on material performance

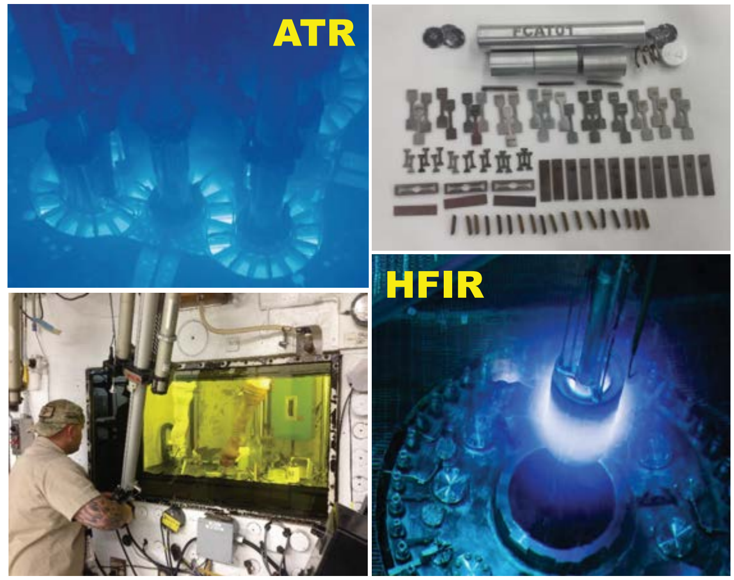
- **AMMT uses its expertise to select the right tool for the job**
  - High level conceptualization of radiation testing for design achievement
  - Timelines to obtain data (accelerated vs prototypical)

Data needs → PIE needs → Radiation type and facility



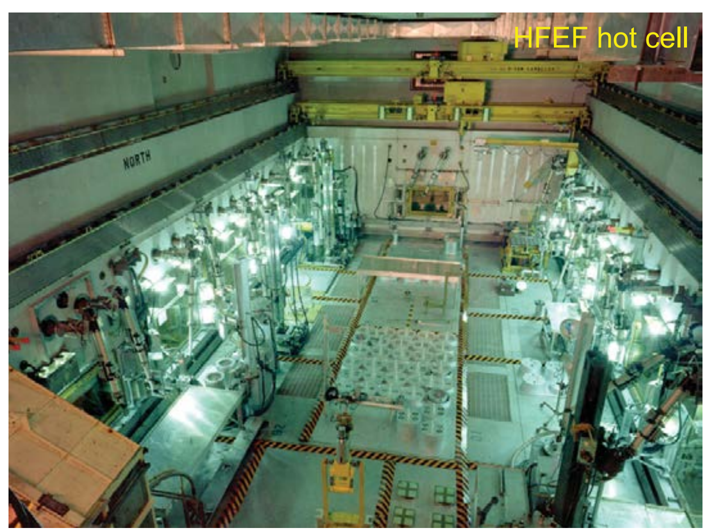
Neutron irradiation campaigns are integrated to provide rapid insight into AM processing impacts on 316H

- **Neutron irradiations are designed to:**
  - Provide rapid screening of AM processing effects (microstructure variability) on radiation response behavior (microstructure and mechanical properties)
  - Provide targeted neutron irradiation information for promoting the regulatory acceptance of the combined use of ion and neutron irradiation data
- **Integrated campaign catering to the strengths of both High Flux Isotope Reactor (ORNL) and Advanced Test Reactor (INL) and post-irradiation examination facilities**
  - Link irradiation data of the selected materials to AM builds with high-pedigree digital signatures and well-characterized local microstructures
  - Leveraging standard capsule designs to make neutron irradiations faster and cheaper



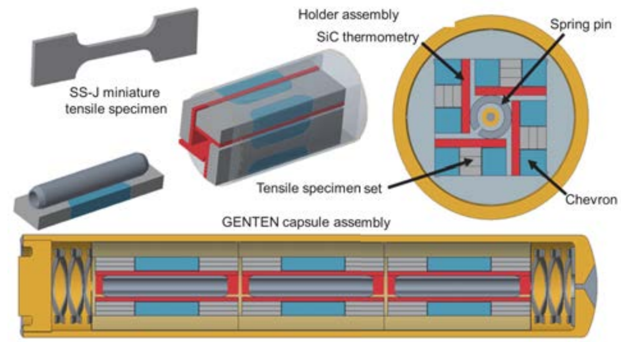
AM 316H irradiation campaign provides useful information to industry quickly

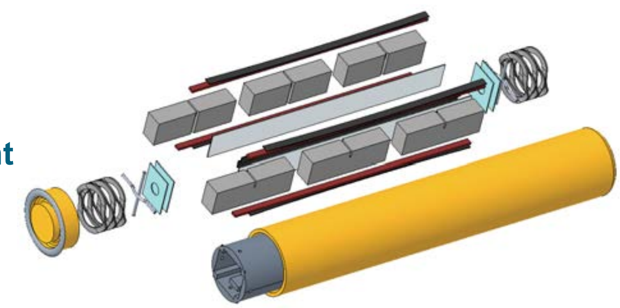
- **Focusing primarily on neutron irradiation conditions in the range of interest for deployment of AM 316H in advanced reactors**
  - 400 °C – 600 °C
  - 1 to 10 dpa
  - LPBF, wire-DED, and wrought material
- **Producing data of interest for advanced reactors and multiple specimens in each condition for data replication and statistical variation**
  - Uniaxial tensile tests (SSJ specimens) performed at irradiation temperature and room temperature
  - Fracture toughness tests (bend bars)
  - Creep tests (SSJ specimens) of irradiated material in hot cell
  - Creep crack growth and fatigue (compact tension specimens) of irradiated material in hot cell
  - Microstructure characterization using TEM disks, FIB lift-outs, atom probe and hardness testing of material from grip areas of other specimens



Near-term HFIR irradiations evaluate post-irradiation strength, ductility, and fracture toughness

- **Evaluate impact of material (build), orientation, and thermomechanical treatment**
- **Tensile testing and fracture toughness testing evaluates:**
  - T_{irr} = 400 °C and 600 °C
  - 2 dpa and 10 dpa
  - Stress-relieved, solution annealed
  - Chevron and columnar microstructures
  - Loading in the build and transverse orientations
  - Wrought material
- **Two specimens for each unique AM combination**
- **Additional tests at 650 °C will investigate susceptibility to high-temperature He embrittlement**
- **Additional tests at 475 °C from 2 dpa – 30 dpa to test cavity swelling**

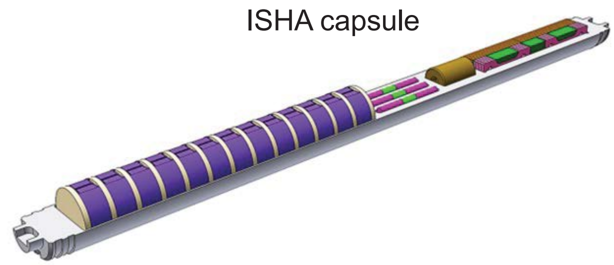




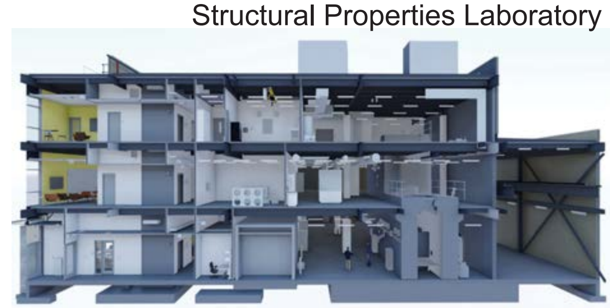
ATR irradiations provide information specific to advanced reactor concerns

- **Evaluate impact of material (build), orientation, thermomechanical treatment, and neutron spectrum by comparison to HFIR data**
- **Tensile, creep, creep-fatigue, creep crack growth testing evaluates:**
  - T_{irr} = 400 °C and 600 °C
  - 1 dpa and 2 dpa
  - Subset of material tested at HFIR
- **Duplicate specimens for each unique AM combination**
- **Novel PIE leveraging the upcoming SPL**
- **Tensile testing at 2 dpa provides overlap with HFIR**

ISHA capsule



Structural Properties Laboratory



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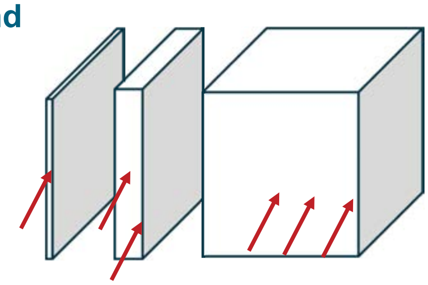
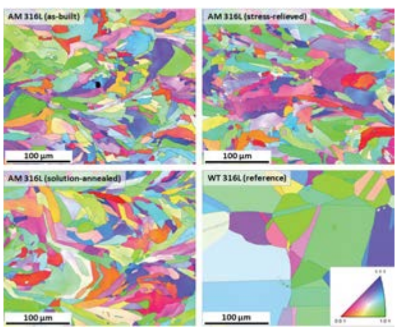
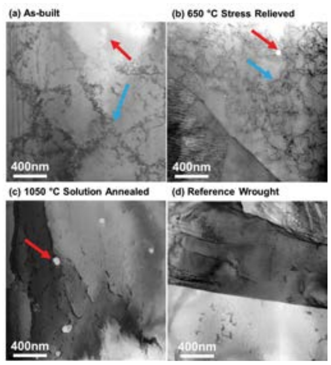
HFIR irradiation results on AM 316L reveal hardening and ductility behaviors

- **Evaluate impact of material (build), orientation, and thermomechanical treatment**
- **Tensile testing and PIE evaluates:**
  - T_{irr} = 300 °C and 600 °C (targeted)
  - 0.2, 2, and 10 dpa
  - As-built, stress-relieved, and solution annealed material and wrought conventional
  - Sampling from different locations with the AM build (stress-relieved)



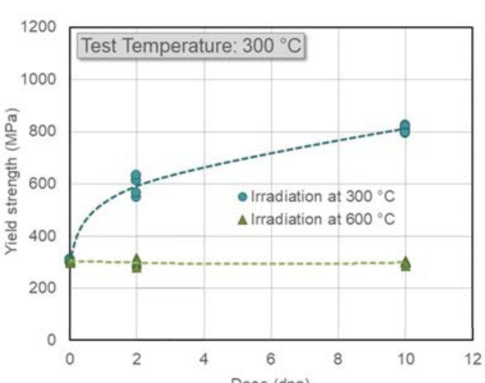
Sampling Location
1.5mm plate layer
5mm block center layer 5 mm block surface layer
40mm cube 10mm from surface
40mm cube center layer
40mm cube surface layer

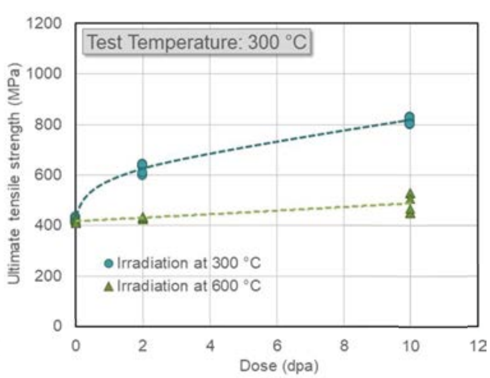


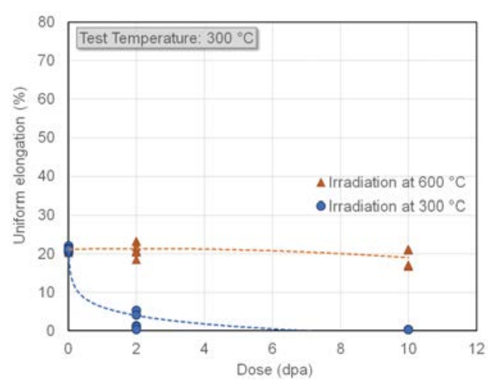


Testing after neutron irradiation reveals degree of effect of process variability on tensile behavior

- **Variations in UTS and uniform elongation are similar after 600 °C and 300 °C irradiation**
  - Different defect mobilities: vacancies and interstitials at 600 °C, interstitials only at 300 °C
  - No consistent dependency on sampling location
  - As-built material exhibited softening, stress-relieved appeared to provide the best combination of properties
- **Complete loss of uniform elongation at 300 °C**

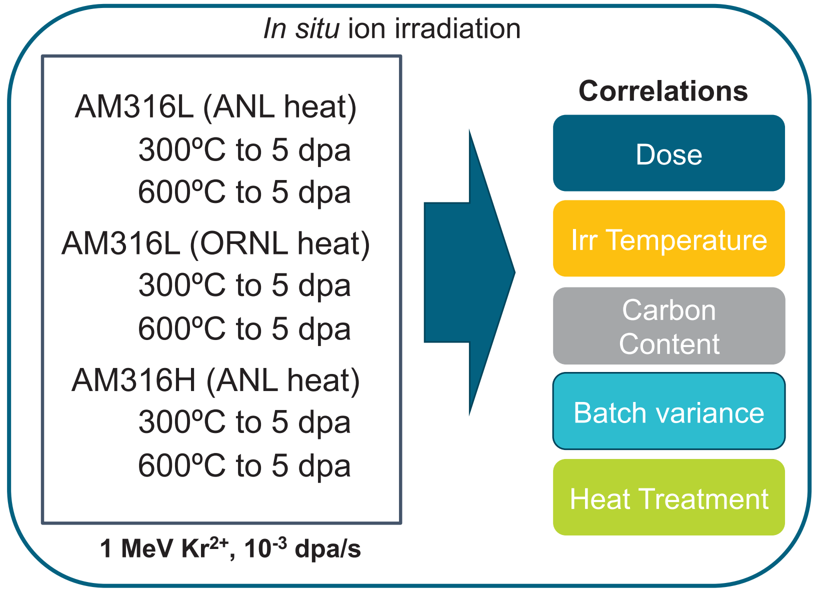






Ion irradiation provides initial insights into microstructure evolution under irradiation for AM 316L and AM 316H

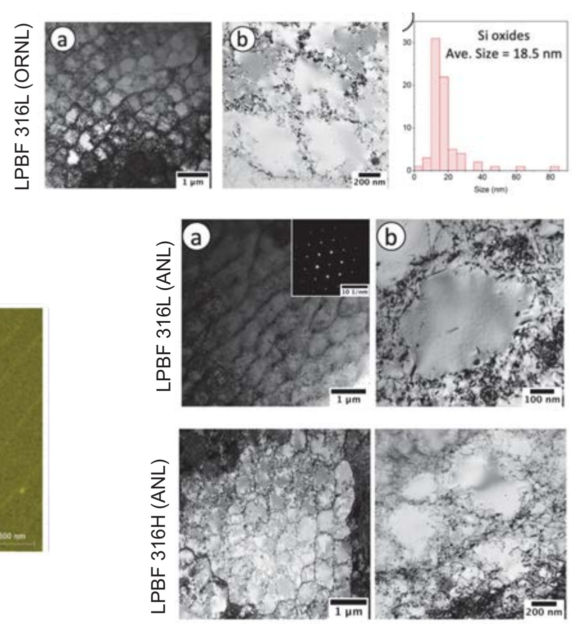
- **Ion irradiations can:**
  - Provide rapid screening of materials evolution under a wide parameter array
  - Create cascade damage that can be linked to prototypical neutron irradiation conditions via microstructure
  - Help calibrate microstructure evolution models used to predict neutron-irradiated microstructures
- ***In situ* ion irradiations allow real-time imaging of radiation damage and mechanistic insight**
- ***Ex situ* ion irradiations provide a larger damage volume and fine-tuning data for models to predict behavior in neutron environments**

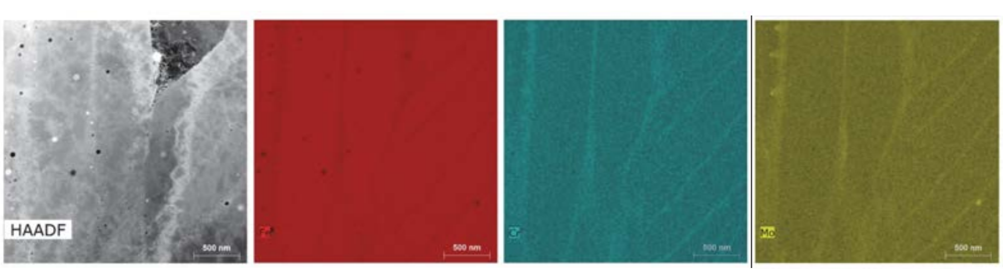


Ion irradiation provides initial insights into microstructure evolution under irradiation for AM 316L and AM 316H

- **Compared three LPBF builds**
  - Similar starting microstructure (as-built)
  - Dislocation cell size approximately 500 nm, walls approximately 50 – 100 nm wide
  - Nanoscale oxide particles present
  - Microsegregation of Cr, Si, Ni at at dislocation cell walls and HAGBs

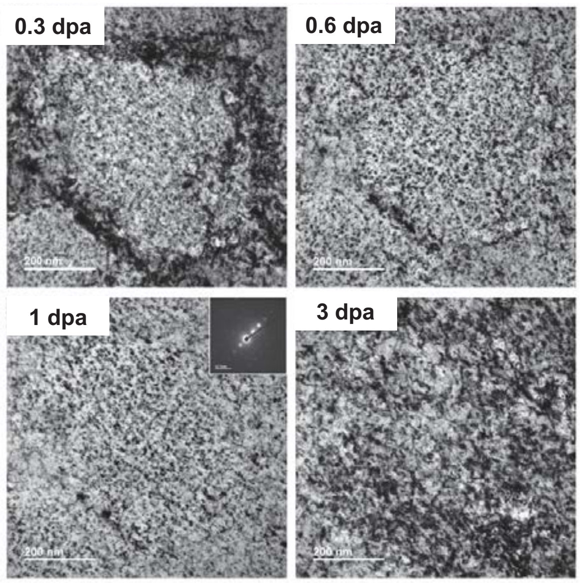
Pre-irradiation characterization of as-printed material





LPBF 316H (ANL)

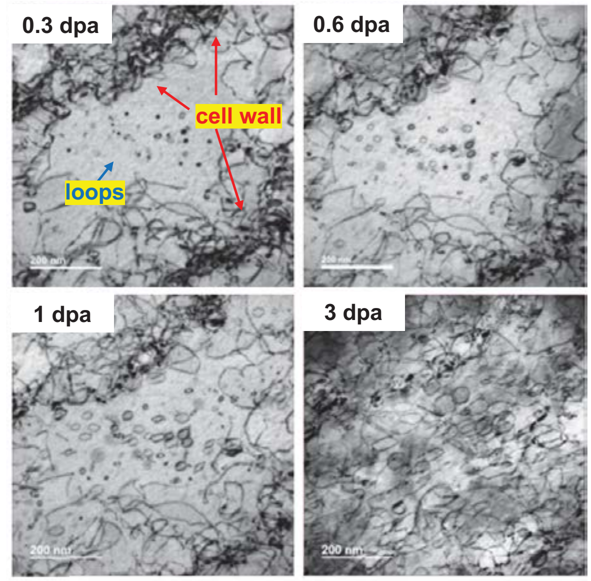
Irradiation temperature qualitatively impacts irradiation-driven microstructure evolution



LPBF 316H irradiated at 300 °C

Loops: small, plentiful and uniform

10^{-3} dpa/s
1 MeV Kr^{+}
In situ irradiation



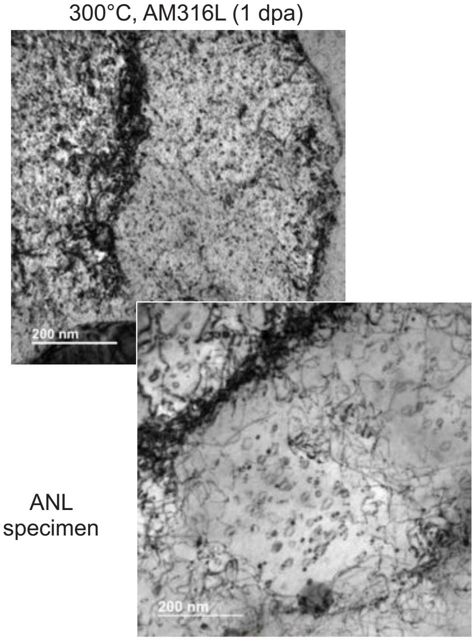
LPBF 316H irradiated at 600 °C

Loops: larger, fewer, nonuniform

No voids observed in any in-situ irradiation

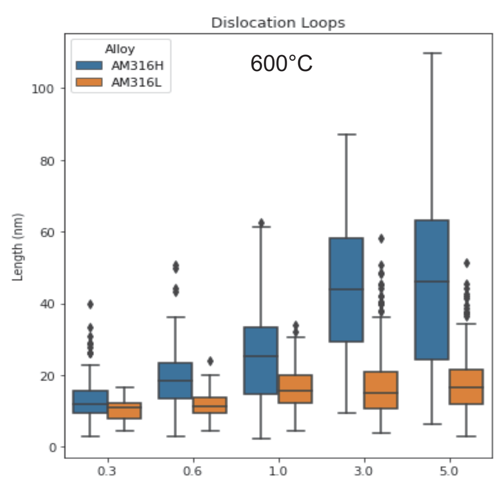
Carbon content appears to affect dislocation loop population evolution and stability

300°C, AM316L (1 dpa)



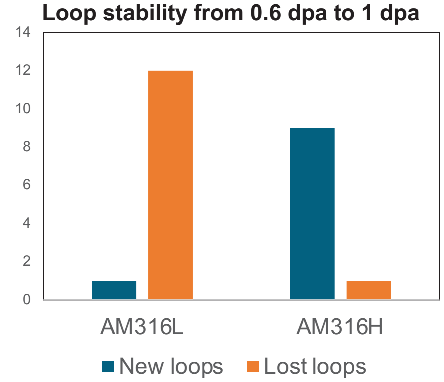
ANL specimen

600°C, LPBF 316L (1 dpa)

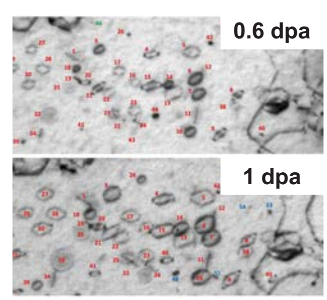


Qualitatively similar results at 300 °C and 600 °C for 316H and 316L, quantitative differences

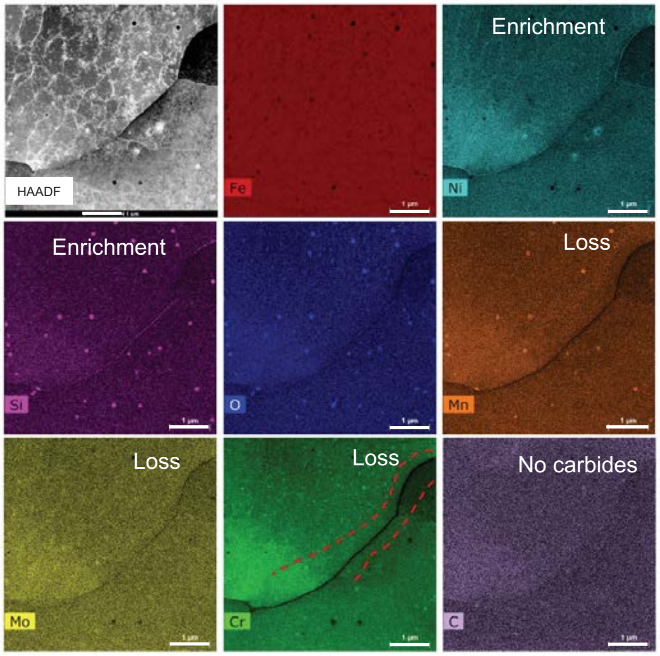
Loop stability from 0.6 dpa to 1 dpa



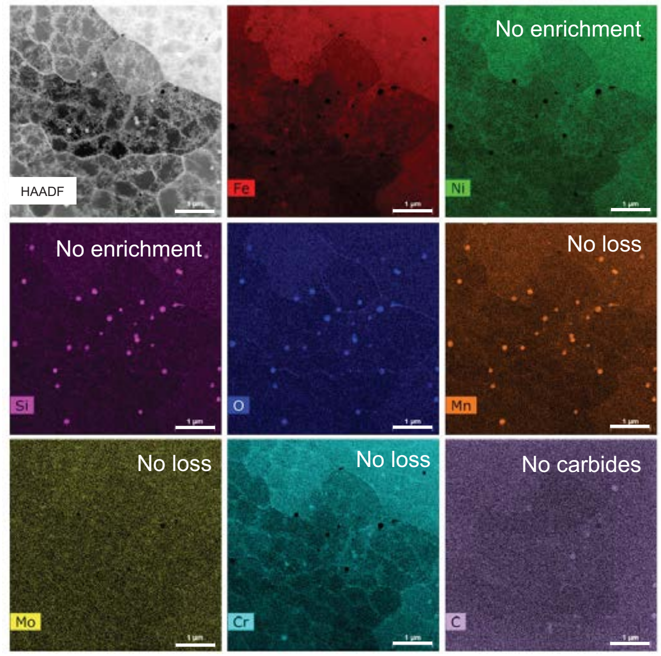
AM 316H, 600°C



Radiation-induced segregation occurs at high-angle grain boundaries and dislocation cell walls



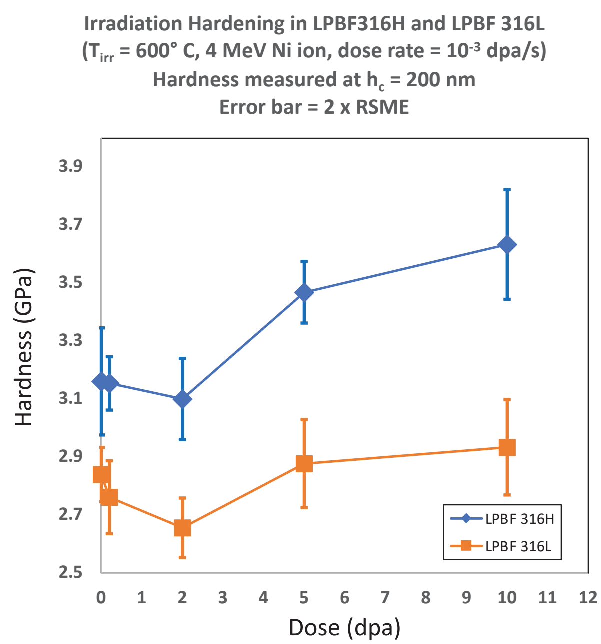
600°C, AM316H (5 dpa)



600°C, AM316H (thermally aged 90 minutes)

Ex-situ ion irradiation and nanohardness testing reveals initial irradiation softening at 600 °C

- **Ion irradiation of LPBF 316H at 600 °C and tested at room temperature**
- **Nanohardness testing reveals softening at 2 dpa and subsequent hardening through 10 dpa**
- **Hypothesize the softening is due to the recovery of the dislocation cell structure, formation of dislocation loops and and subsequent development of the uniform dislocation network**



Microstructure evolution comparison from neutron irradiation in HFIR

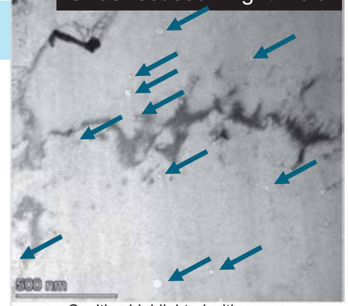
- **Actual neutron irradiation conditions:**
  - 250 °C, 277 °C , 376 °C, 600 °C, 673 °C (targets: 300 °C and 600 °C)
  - 0.2, 2, and 10 dpa
  - As-printed, heat treated, and wrought
- **Dislocation cell structure generally gone (need to determine if driven by thermal, radiation, or mixed effects)**
- **Features observed in all cases (population statistics vary depending on temperature and dose)**
  - Further characterization needed to determine if features are cavities or (Mn, Si) oxides

Summary of cavity(?) observations

	0.2 dpa	2 dpa	10 dpa
250 °C (AP)	Low density of a wide range of cavity sizes (AP)		
277 °C (AP, SA, WT)	High density of small cavities (SA)		High density of <5 nm cavities, some larger (AP, SA, WT)
376 °C (AP, SR, SA, WT)		Wide variety of cavity sizes (AP) / mostly large (SR) / Few cavities (WT)	
600 °C (AP, SR, SA)		Bimodal cavity size distribution (AP)	
673 °C (AP)	Only large cavities (AP)		

AP: As-printed SR: Stress-relieved
SA: Solution-annealed WT: Wrought

Underfocused Bright Field



As-printed, 600 °C irradiation to 2 dpa

Cavities highlighted with arrows

Microstructure evolution comparison from neutron irradiation in HFIR

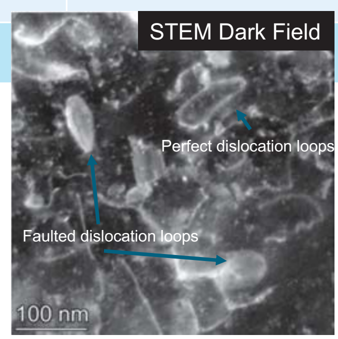
- **Actual neutron irradiation conditions:**
  - 250 °C, 277 °C , 376 °C, 600 °C, 673 °C (targets: 300 °C and 600 °C)
  - 0.2, 2, and 10 dpa
  - As-printed, heat treated, and wrought
- **Dislocation cell structure generally gone (need to determine if driven by thermal, radiation, or mixed effects)**
- **Varied dislocation structure depending on dose and temperature, qualitatively more similar than by material condition**

Summary of dislocation observations

	0.2 dpa	2 dpa	10 dpa
250 °C (AP)	High density of black spots (AP)		
277 °C (AP, SA, WT)			Large density of dislocation loops (AP, SA, WT)
376 °C (AP, SR, SA, WT)		Black spots and loops up to 100 nm (AP) / High density of loops up to 50 nm (SR, WT)	
600 °C (AP, SR, SA)		Black spots and network dislocations (AP) / few loops (SR)	
673 °C (AP)	Very little dislocation structure (AP)		

AP: As-printed SR: Stress-relieved
SA: Solution-annealed WT: Wrought

STEM Dark Field



As-printed, 376 °C irradiation to 2 dpa

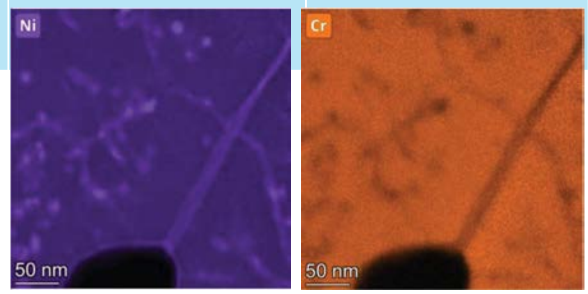
Microstructure evolution comparison from neutron irradiation in HFIR

- **Actual neutron irradiation conditions:**
  - 250 °C, 277 °C , 376 °C, 600 °C, 673 °C (targets: 300 °C and 600 °C)
  - 0.2, 2, and 10 dpa
  - As-printed, heat treated, and wrought
- **Radiation-induced segregation is observed**
- **(Si, Mn)-oxide particles generally observed**
- **Cr-oxide and carbide particles not evident**
- **RIS may be more severe at lower temperatures**

Summary of segregation observations

	0.2 dpa	2 dpa	10 dpa
250 °C (AP)	Slight Si enhancement at HAGB (AP)		
277 °C (AP, SA, WT)			Ni, Si enhancement at GB and dislocations, Cr, Mo, Fe depletion (AP, SA)
376 °C (AP, SR, SA, WT)		Ni, Si enhancement at GB and dislocations, Cr, Mo, Fe depletion (AP, WT)	
600 °C (AP, SR, SA)		Ni, Si enhancement at GB and dislocations, Cr, Mo, Fe depletion (AP, SR)	
673 °C (AP)	Slight Ni enhancement/Gr depletion at HAGB (AP)		

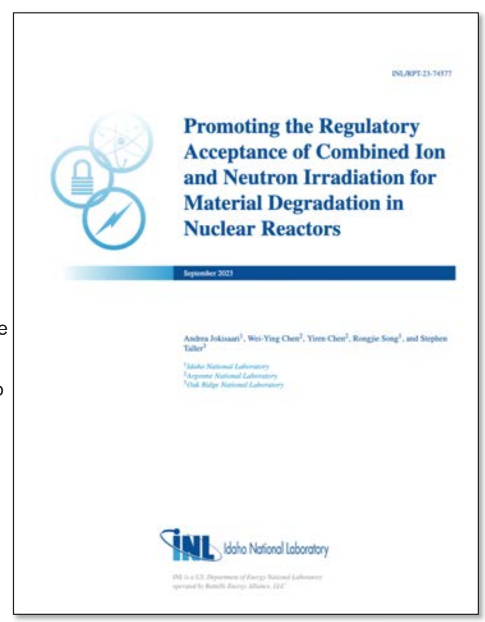
AP: As-printed SR: Stress-relieved
SA: Solution-annealed WT: Wrought



As-printed, 376 °C irradiation to 2 dpa

Qualitative similarities between neutron and ion irradiated results provides strong basis for relating the two

- ***In situ* ion irradiation and neutron irradiation both observe:**
  - Similar development of dislocation loops → network dislocations
  - RIS to HAGB
  - (Si, Mn) oxide particles are stable
  - Carbide formation not observed
  - Softening at higher temperatures and low dpa
- **Differences in *in situ* ion irradiation vs neutron irradiation may be due to the characterization of 316L (neutron) vs 316H (ion)**
  - No cavities under ion irradiation; dual-beam irradiation is necessary and more work needed to determine nature of "cavity-like" features of neutron-irradiated material
  - Does not observe strong RIS to network dislocations or loops (weakly observed), but this may be due to the differences carbon content (316L vs 316H)
  - Observes Cr-oxide formation (may be due to differences in composition)
  - Observes dislocation cell walls remaining at higher dpa (may be due to better thermal stability in 316H)
- **Modeling and simulation effort will link results of the two irradiation campaigns**
- **White paper developed on the path forward for promoting the regulatory acceptance of combined ion and neutron irradiation data**


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[3], and Stephen Taller[3]

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

Idaho National Laboratory

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Summary

- AMMT program corrosion testing strategy on AM 316 prioritizes advanced reactor concerns
- Neutron irradiation campaigns are integrated at multiple DOE facilities to provide rapid insight into AM processing impacts on 316H
- Ion irradiation provides initial insights into microstructure evolution under irradiation for AM 316L and AM 316H and provide high quality data for model development
- AMMT is combining neutron irradiation, ion irradiation and modeling to progress a comprehensive framework for rapid qualification

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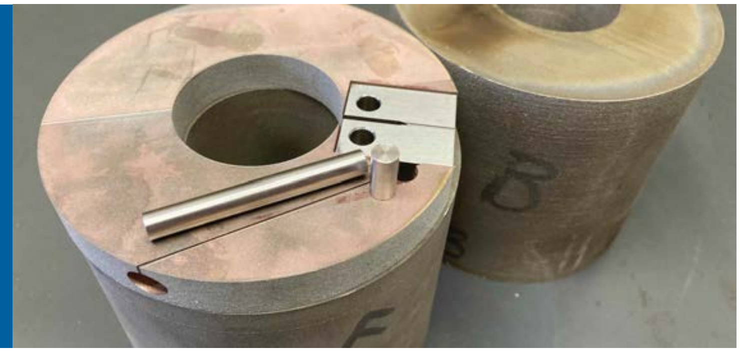
PERFORMANCE OF LASER ADDITIVELY MANUFACTURED SS316L IN LWR-RELEVANT ENVIRONMENTS



BOGDAN ALEXANDREANU, YIREN CHEN, XUAN ZHANG, AND SRINIVAS MANTRI
NUCLEAR SCIENCE AND ENGINEERING DIVISION
ARGONNE NATIONAL LABORATORY

2023 NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications
Oct. 24-26, 2023, NRC Headquarters, Rockville MD

PRESENTATION TOPICS

- Introduce new US DOE LWRS program at ANL “Performance Evaluation of Additive Manufacturing Materials for Light Water Reactor Sustainability”

- Present preliminary results
  - Preliminary Stress Corrosion Cracking (SCC) Crack Growth Rate (CGR) Evaluations
  - Preliminary Fatigue Evaluations

- Embedded watermarks in AM components

PERFORMANCE EVALUATION OF ADDITIVE MANUFACTURING MATERIALS FOR LIGHT WATER REACTOR SUSTAINABILITY

Objective:

Facilitate the adoption of Additively Manufactured (AM) technologies by the nuclear industry to fabricate replacement parts faster and cheaper, thus, facilitating the extended operation of the existing LWR fleet

Tasks:

Task 1: Support the regulatory acceptance of EPRI-led ASME code case (Record # 20-254) by conducting the additional stress corrosion cracking (SCC) and environmentally-assisted fatigue (EAF) testing

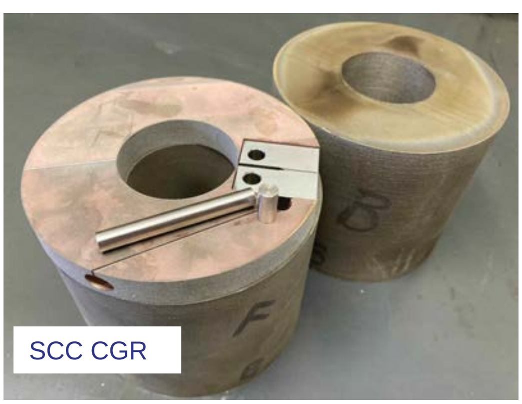
Task 2: Understand and quantify the effect of AM surface on fatigue and SCC crack initiation (CI) in LWR environment

Task 3: Evaluate the applicability of ANL-proposed F_{en} model to AM-produced alloys as well as long term operation

PERFORMANCE EVALUATION OF ADDITIVE MANUFACTURING MATERIALS FOR LIGHT WATER REACTOR SUSTAINABILITY

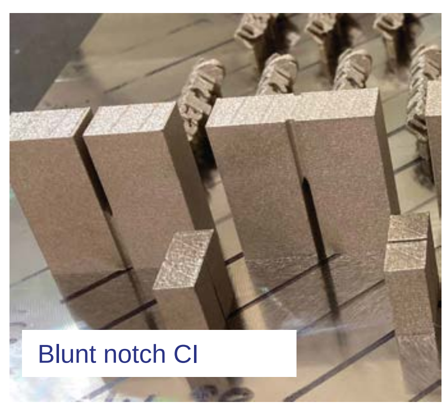
FY24 Key activities to be initiated

- EAF and SCC testing of AM materials to support the regulatory acceptance of EPRI-led ASME code case (Record # 20-254) submitted in Section III, Division 1 – Subsection NB/NC/ND, Class 1, 2 and 3 Components.
- Testing to understand and quantify the effects of porosity and AM surface finishing on the fatigue and SCC crack initiation in LWR environment.
- Evaluation of the applicability of ANL-proposed Fen model to AM-produced alloys as well as long term operation.



SCC CGR

Fatigue, EAF



Blunt notch CI

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Argonne NATIONAL LABORATORY

PRELIMINARY RESULTS

- Preliminary Stress Corrosion Cracking (SCC) Crack Growth Rate (CGR) Evaluations
- Preliminary Fatigue Evaluations

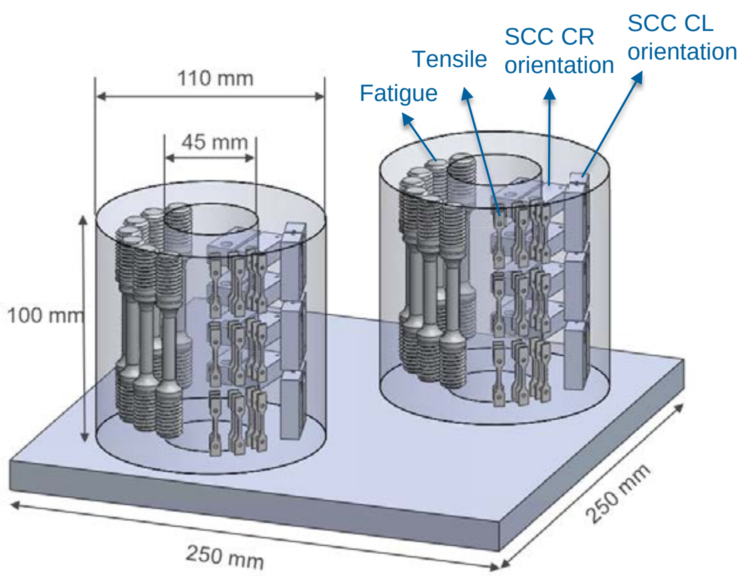
Objective

- Evaluate the "performance" of AM 316L SS in a light water reactor (LWR) – relevant environments, and compare with the response of the conventionally-produced alloy

Approach

- Build a component-like part using laser powder bed fusion (LPBF)
- Conduct microstructural investigation (with a focus on porosity)
- Conduct mechanical testing on the as-printed alloy with a focus on "performance testing" – SCC CGR and fatigue, and compare with the behavior of the conventionally-produced alloys

AM 316L TUBES



- AM 316L SS tubes – surrogates for component-like structures - were produced at Argonne with the Renishaw AM400 LPBF system

BUILD PARAMETERS

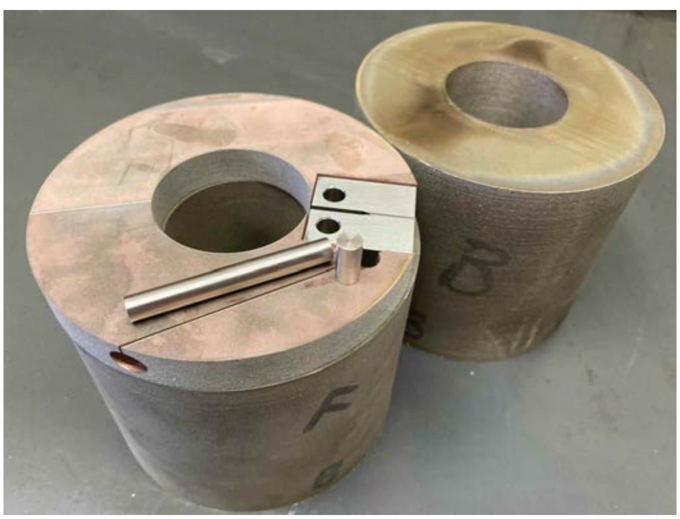
Parameter	Value
Laser Power	195 W
Layer Thickness	50 μm
Melting Method	Stripe (5mm)
Rotation	67 degrees
Exposure Time	80 μs
Point Distance	60 μm
Effective Velocity	0.75 m/s
Hatch Spacing	110 μm
Energy Density	53.33 J/mm^3
Recoater Blade	Rubber
Atomization Gas	Argon
Build Chamber Atmosphere	Argon
Equipment Type	Renishaw AM400

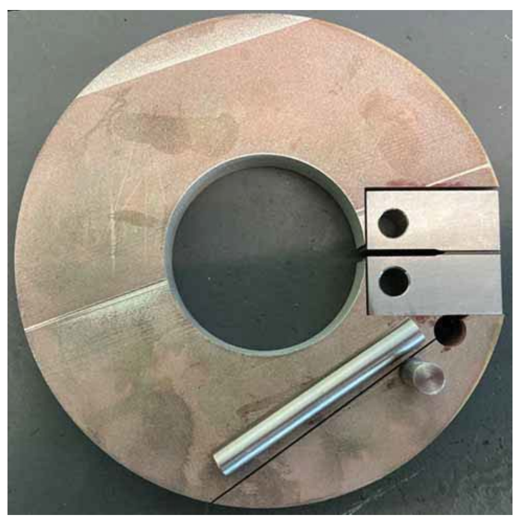
- AM 316L SS tubes were produced at Argonne with a Renishaw AM400 LPBF system

Composition of powder

Element	Mass (%)
Iron	Balance
Chromium	16.00 to 18.00
Nickel	10.00 to 14.00
Molybdenum	2.00 to 3.00
Manganese	≤ 2.00
Silicon	≤ 1.00
Nitrogen	≤ 0.10
Oxygen	≤ 0.10
Phosphorus	≤ 0.045
Carbon	≤ 0.03
Sulphur	≤ 0.03

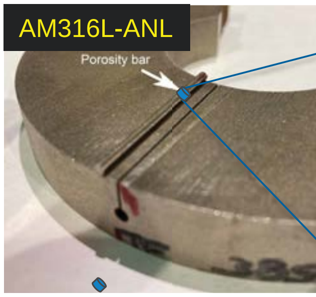
AM 316L SS TUBES



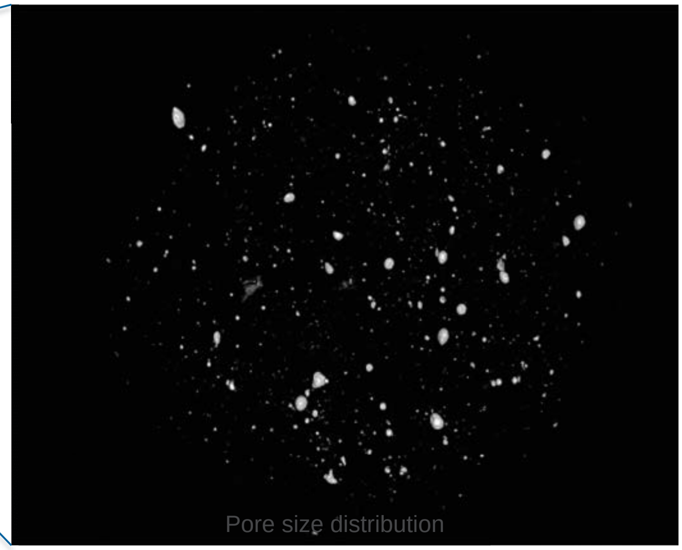


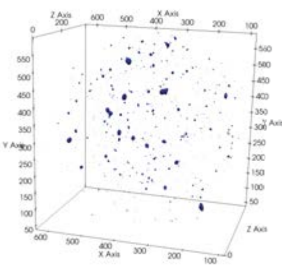
- Compact tension (CT) samples for crack growth testing (CR orientation) and rod samples for synchrotron X-ray tomography measurement were machined from the as-built part
- Porosity is evaluated at the same location as the test plane in the CT specimen

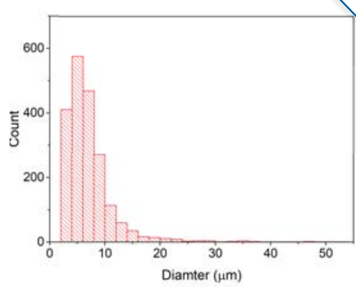
POROSITY



1.8 mm (D) × 1.2 mm (T) (a 3.05-mm^3 volume)

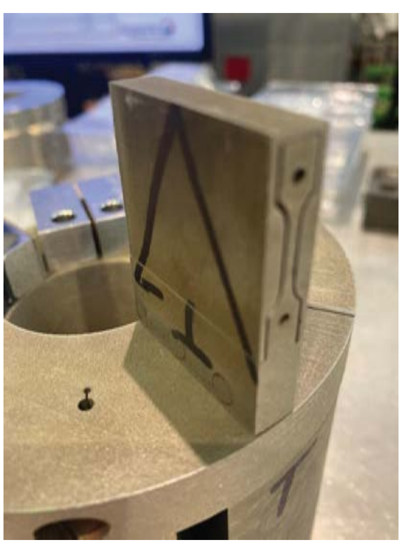


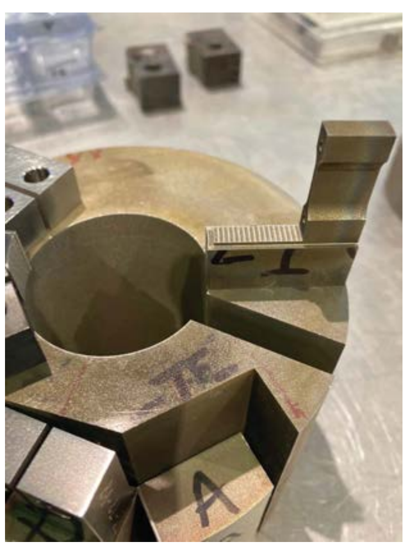


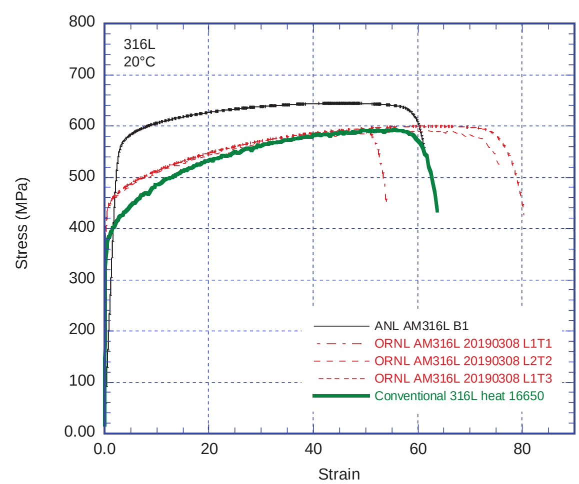


- Porosity measured by X-ray CT: **0.06%**
- Average pore size: **7.2 μm** (with 3 μm detection limit)

AM 316L TENSILE PROPERTIES







- Tensile properties comparable to those of conventional alloy and those of ORNL AM 316L plate (ANL and ORNL use different 3D printers)
- YS 517 MPa, UTS 644 MPa, UEL 43%

SCC CRACK GROWTH TESTING

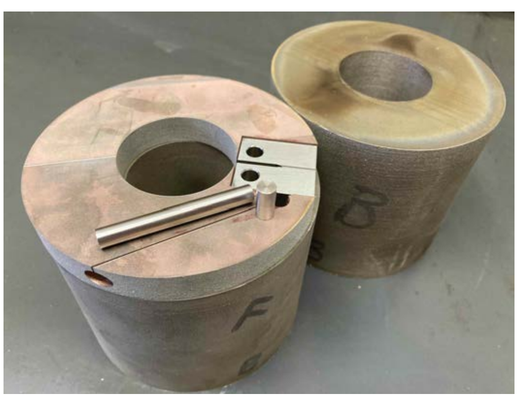
Crack growth rate (CGR) testing was conducted using one of the several dedicated systems at Argonne

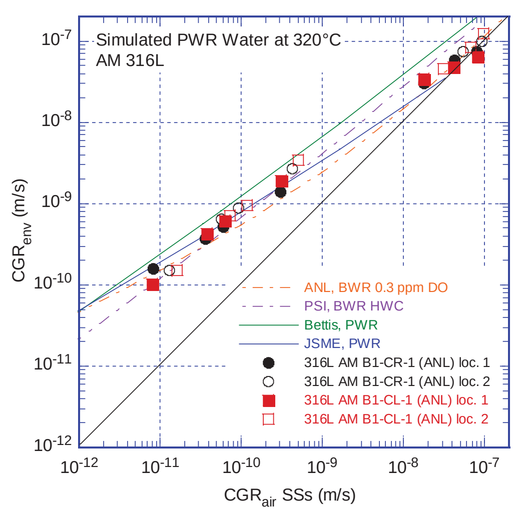
The test on the AM 316L specimen was conducted in primary water environment (HBO_3 and LiOH additions) at 320°C

The test followed a typical sequence for evaluating material performance in LWR environments:

1. Pre-cracking in water at high frequency (mechanical fatigue regime);
2. Transitioning to SCC (corrosion fatigue regime);
3. SCC growth under constant load.

CYCLIC AND SCC CGR RESPONSE OF AM 316L





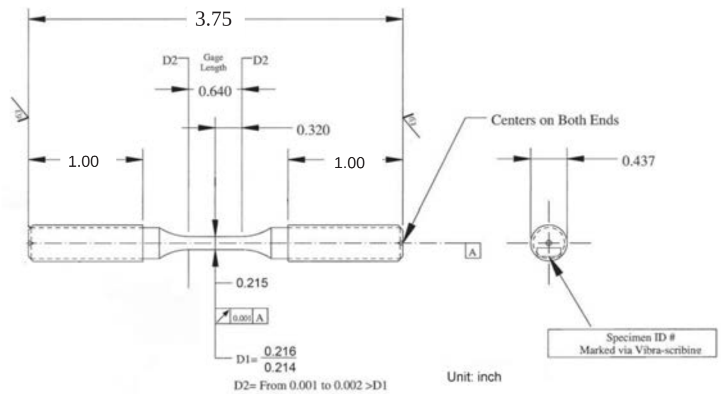
Both CR and CL orientations - results:

- Fatigue and corrosion fatigue CGR response (2 locations along the crack path) is similar to that of conventionally-produced alloy
- AM 316L was resistant to SCC (2 attempts at 2 locations)
- No effect of orientation

FATIGUE TESTING

ASTM standard cylindrical samples:

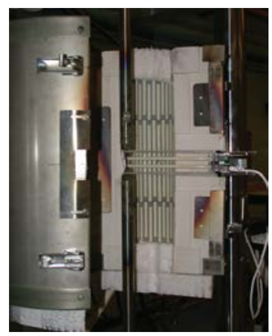
- As-built condition (no post-processing)
- Sample axis along the built direction
- Gauge diameter = 0.215”, Gauge length = 0.64”
- Polished gauge surface, Ra=0.2 μm

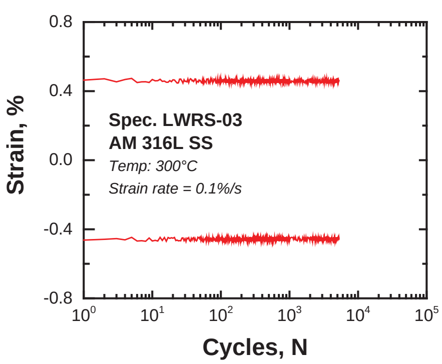


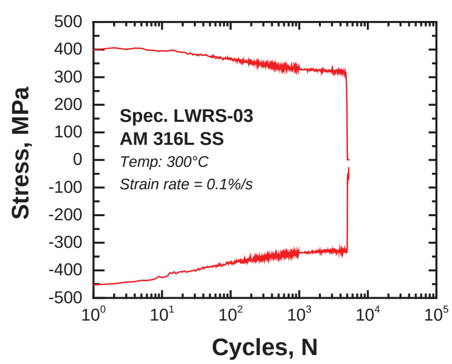
FATIGUE TESTING

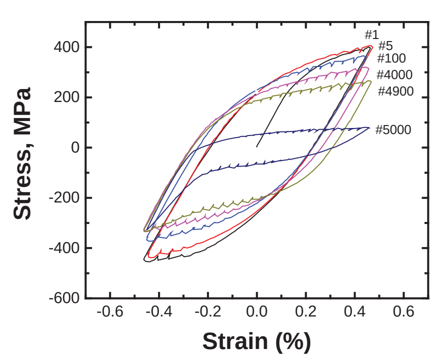
ASME design curves are based on strain-controlled fatigue tests

- Fully-reversed, strain-controlled tests
- In air, at 300°C
- Strain rate: 0.1%/s



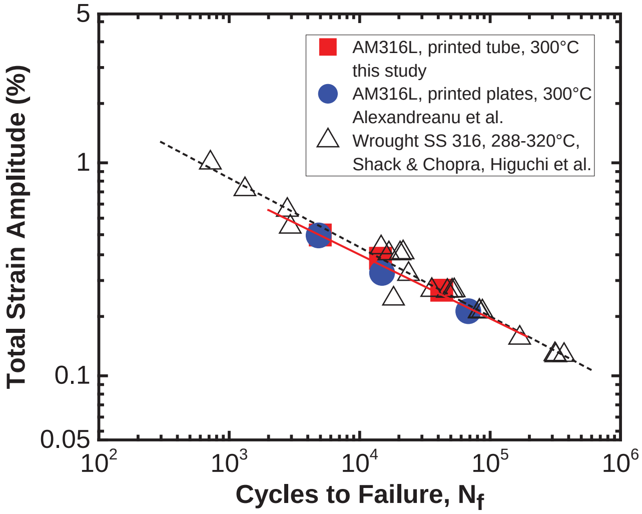






R = -1

STRAIN-LIFE RESULTS



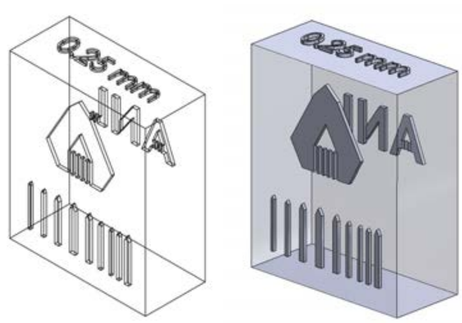
- Strain-life results from two AM prints are nearly identical
- The fatigue performance of AM316L is also similar to that of traditionally manufactured Type 316L SS.

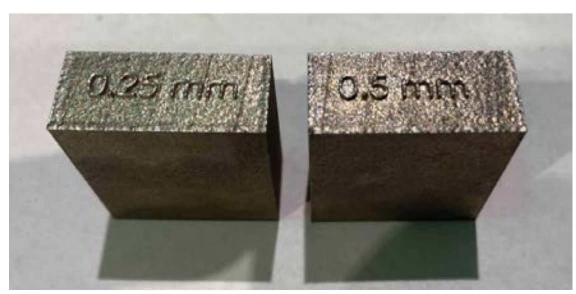
- Porosity at the level of <0.2% does not seem to affect fatigue life in air

EMBEDDED WATERMARKS

Objective: create an embedded watermark in a 3D printed structure to uniquely identify/certify/authenticate a part, e.g. “certified” for use

- Collaboration with NDE group (Dr. Alex Heifetz)



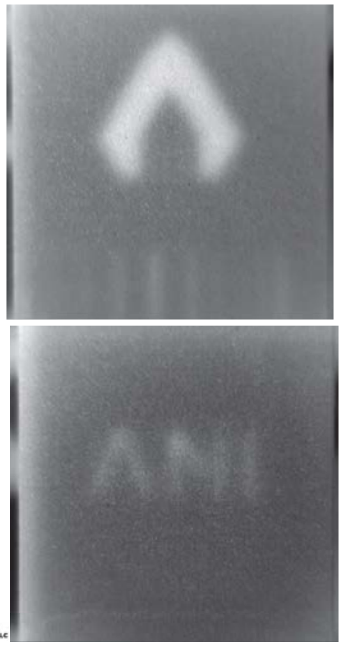


- Blocks with embedded features (ANL logo, bar code) were printed at two depths (0.25 mm, 0.5 mm) underneath the surface
- Detection was via Pulsed Infrared Thermography (PIT) and associated ML-software. Setup is portable and analysis is 6 sec/image

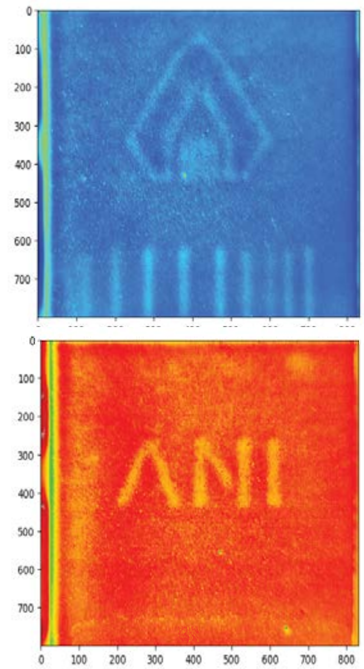
EMBEDDED WATERMARKS

Depth-0.25 mm

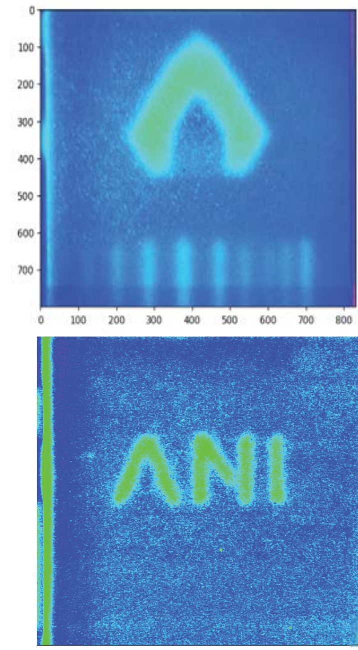
Observed Thermogram after Pulse



Self Learning Calibrated Online STBSS Reconstruction



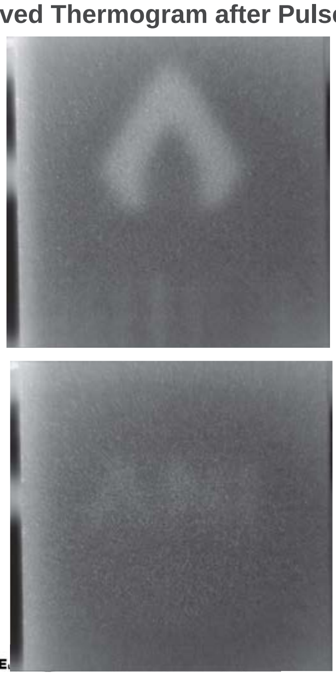
Thermal DefectsNet Reconstruction



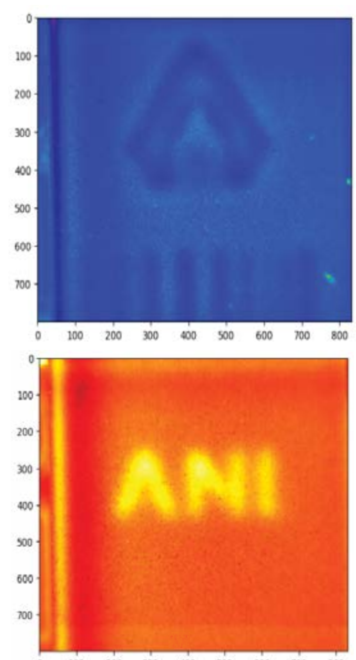
EMBEDDED WATERMARKS

Depth-0.5 mm

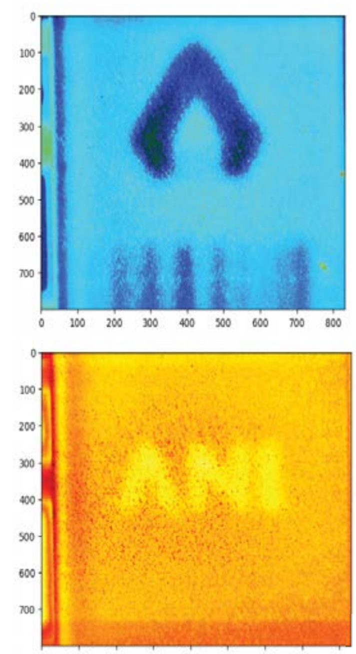
Observed Thermogram after Pulse



Self Learning Calibrated Online STBSS Reconstruction



Thermal DefectsNet Reconstruction



SUMMARY

- A new program to evaluate performance (SCC, EAF, CI) of AM materials was initiated at ANL under US DOE LWRS
- Preliminary (SCC, fatigue) results are encouraging

- Tubes – surrogates for components – were printed and evaluated in as-printed condition

- Microstructural investigations focused on porosity (measured by synchrotron X-ray tomography) and performance testing in LWR-relevant environment.

  - Porosity was found to be small (0.06%), and the average pore size was 7.2 μm

  - SCC CGR response of AM alloy is similar to that of conventionally-produced alloy

  - Fatigue response in air of AM alloys seems similar to that of the conventional alloy. Further evaluation of environmental fatigue is needed

- Preliminary results with embedded watermarking of components are encouraging

ACKNOWLEDGEMENTS

- The authors gratefully acknowledge financial support from US DOE Light Water Sustainability Program (LWRS), PM Frank Chen for assistance developing current program
- The authors gratefully acknowledge financial support from US DOE Advanced Materials and Manufacturing Technologies (AMMT) program and Transformational Challenge Reactor (TCR) program funded by the U.S. Department of Energy, Office of Nuclear Energy under Contract DE-AC02-06CH11357
- The authors gratefully acknowledge financial support from Argonne's LDRD SWIFT programs 2021-0217, 2023-0214, and 2023-0218
- This research used resources of the Advanced Photon Source, a U.S. Department of Energy (DOE) Office of Science User Facility operated for the DOE Office of Science by Argonne National Laboratory under Contract no. DE-AC02-06CH11357
- The authors thank Edward Listwan and Joe Listwan for their assistance with the experimental effort

Generation of a Fatigue Design Curve Suitable for Use on Additive Manufacture Nuclear Plant Components Produced from 316LN Stainless Steel using Laser Powder Bed Fusion

Bill Press
Technical Specialist – Component Design
October 2023

Small Bore Globe Valves (½”, 1” & 2” NB)

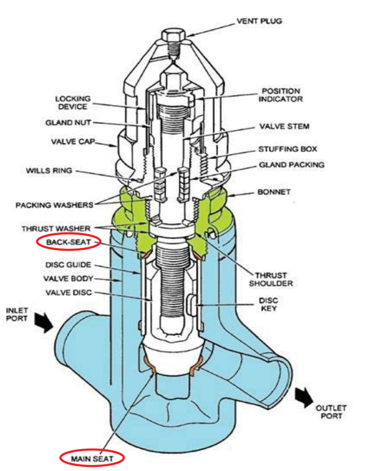
316LN Stainless Steel Body & Bonnet

Tristelle 5183 Main & Back Seats (hard facings)

Method-of-Manufacture includes Hot Isostatic Press (HIP) heat treatment

Background

- Primary application of AM Laser Powder Bed Fusion (LPBF) technology focused on the production of Small-Bore Globe Valve body and bonnet components.
- Pressure Boundary
- Safety Critical
- High Production Volume



Benefits of AM LPBF Approach

Background Cont.

Lead Time Reduction

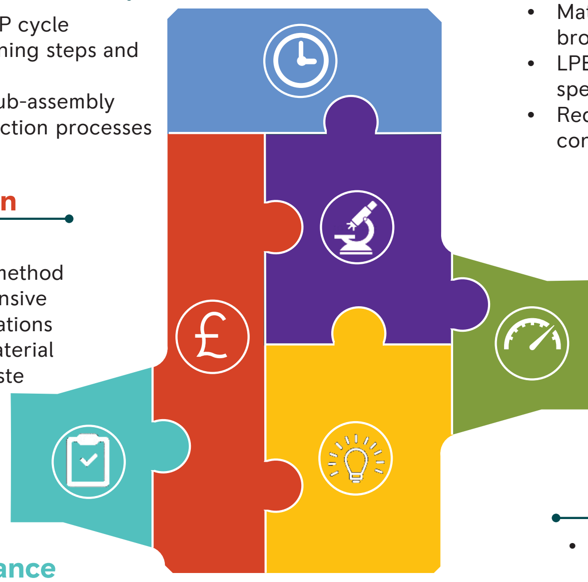
- Removal of a HIP cycle
- Reduced machining steps and timescales
- Elimination of sub-assembly welding & inspection processes

Cost Reduction

- Simplification of manufacturing method
- Removal of extensive machining operations
- Reduced raw material logistics and waste

Quality Assurance

- Each metallic powder batch
- Each build plate (control samples/HIP bond specimens)



Materials & Inspection

- Materials types applicable to broad product range
- LPBF material properties meet specification requirements
- Reduced grain size and consistent microstructure

Performance Testing

- All valve test requirements met
- Tests exceeded design limits to drive out issues
- Tests on forged valves to enable direct comparison

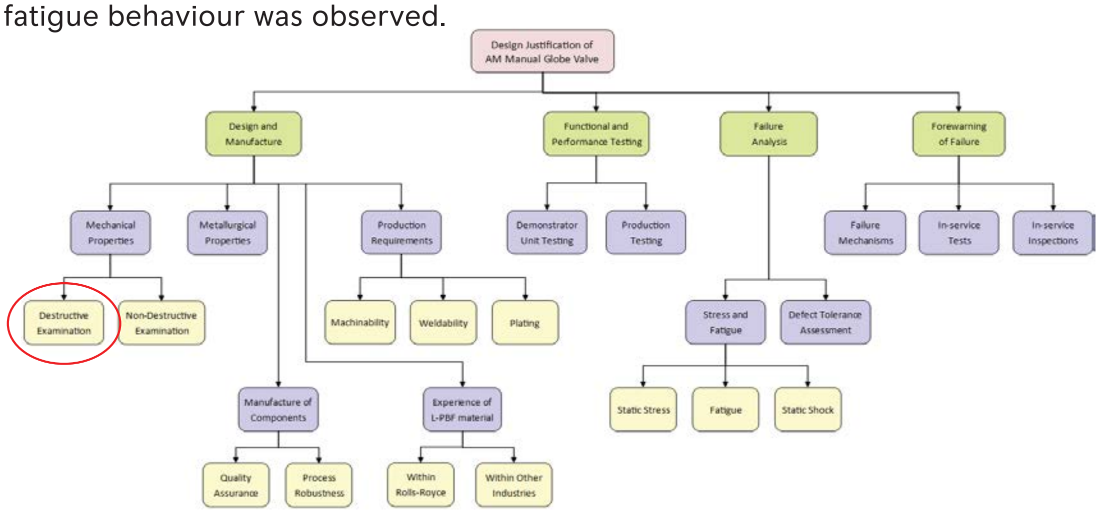
Innovation

- Encapsulation principle patent filed
- Rolls-Royce leading on AM with key partners
- Application on other product ranges

Multi-legged Justification Strategy

Background Cont.

- Multi-legged Justification Strategy set out to demonstrate structural reliability of the material as currently no design basis or code for AM LPBF.
- Leg 1 - Initial in-air fatigue endurance test data on AM LPBF 316LN (single powder batch) was within expected scatter when compared to data on which the NUREG/CR-6909 best-fit is based.
- Following testing on multiple powder batches and builds, a more complex fatigue behaviour was observed.



Overview of Materials Fatigue Testing & Data

- In-air fatigue data generated by testing material covering four different powder batches of AM LPBF 316LN, five different builds at multiple test houses. All tests carried out post HIP heat treatment.
- Constant-amplitude, strain-controlled fatigue testing carried out in accordance with ASTM E606.
- A strain rate of no greater than 0.4%/s was used during the rising and falling portions of the strain cycle.
- Majority of the testing was conducted at room temperature with four data points generated by testing at 300°C

	Test Orientation		
	'X'	45°	'Z'
Number of Valid Data Points	45	17	32
Minimum strain amplitude tested %	0.18	0.20	0.18
Maximum strain amplitude tested %	1.0	0.8	0.9

Overview of Materials Fatigue Testing & Data

Difference in behaviour of the 'X' and 'Z' orientations

Fatigue lives in the 'X' direction appear lower than the NUREG/CR-6909 data in the low cycle regime (N<~10,000 cycles).

For this reason the Rolls-Royce design curve MP5.1.7 (based on ASME design curve) was not considered suitable.

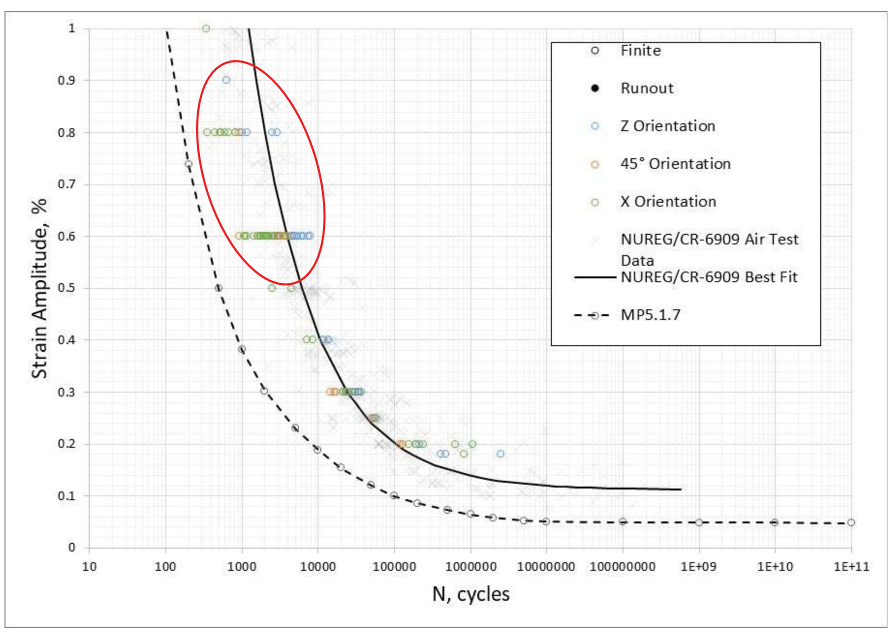
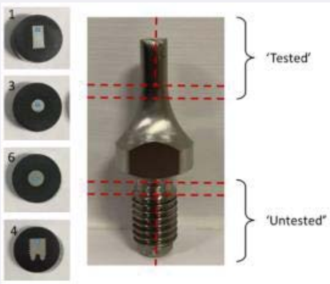
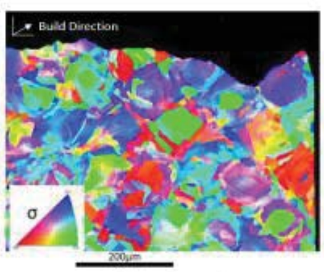


Fig 2: Fatigue Lives of AM LPBF 316LN Specimens Testing in Air at Ambient Temperature Compared to the Rolls-Royce 'Wrought Design Curve' (MP5.1.7) and Associated Best Fit Curve

Microstructural and Failure Characterisation Investigation



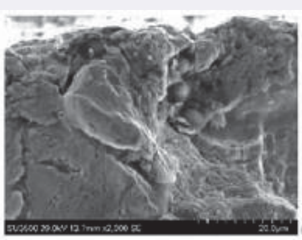


(a) Horizontal

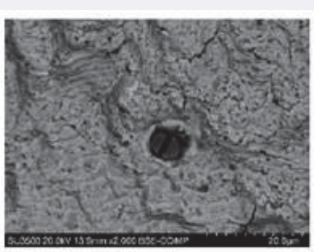
1. Microstructural Characterisation

- Electron Backscatter Diffraction (EBSD) used to examine the microstructure of various broken fatigue test specimens;
  - Transverse and longitudinal directions
  - Inside and outside the gauge length
- Local EBSD misorientation maps for each section and each specimen broadly comparable.
- The grain size and grain size distributions were seen to be comparable (ASTM 9 to 10.5).
- General observation : crack initiation site most likely to occur in colonies of smaller grains, traversing one or two larger grains prior to transgranular cracking under Mode I loading.

Microstructural and Failure Characterisation Investigation



(a) Located at fatigue initiation site



(b) Sheared particle slightly away from failure position

2. Failure Characterisation

- > 50 tested specimens were examined by SEM.
- Failure exclusively because of fatigue initiation near to or at the outer surface of the specimen gauge.
- Particles were observed and determined by EDS to be Manganese (Mn) rich, near-spherical inclusions - origin more likely via the manufacturing process rather than the powder feedstock.
- Despite their presence, not sufficiently apparent that these particles were active in fatigue initiation and growth, or simply a benign underlying feature.
- In all specimens inspected, secondary cracking was observed on the gauge length near to, but not interacting with, the primary crack. More prevalent in higher strain amplitude test specimens.
- Nothing noted outside of the cracking described, i.e. foreign objects, porosity, etc.

Examined fatigue behaviour at the higher strain amplitude of 0.8% (region of concern)

Strain rate reduced by a factor of 10 to limit buckling under compression (0.4 %/s^{-1} to 0.04%/s^{-1})

The ‘control’ 0.6% tests seen to agree with the previous data carried-out at 0.4%/s.

Microstructural and Failure Characterisation Investigation

3. Additional Fatigue Testing

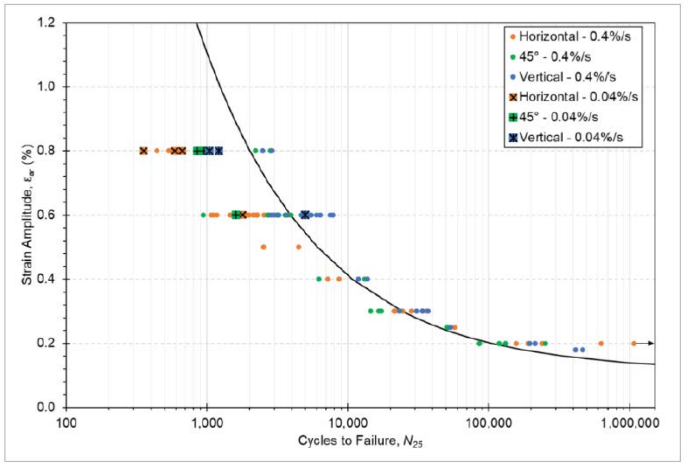


Fig 7: Additional In-air Fatigue Tests at 0.04%/S Strain rates under Ambient Conditions

- Investigation concluded no definitive material or mechanistic attribute identified as a cause for the premature failure of the material at high strain amplitudes, other than the textural microstructural differences (directionality).
- More conservative fatigue design curve required for AM LPBF 316L SS.

Counter-clockwise rotation of the S-N curve observed in heats of wrought Austenitic SS with increasing tensile strength

AM LPBF 316LN appears to display similar behaviour in the limiting ‘X’ orientation

Design Curve Derivation

- A best fit S-N curve was produced for both the ‘X’ and ‘Z’ orientations by using Maximum-Likelihood Estimation (MLE) models fitted to the number of cycles observed.
- In Low Cycle Fatigue (LCF) region the ‘X’ orientation is clearly limiting. In the medium to high cycle region the ‘Z’ orientation is considered limiting.

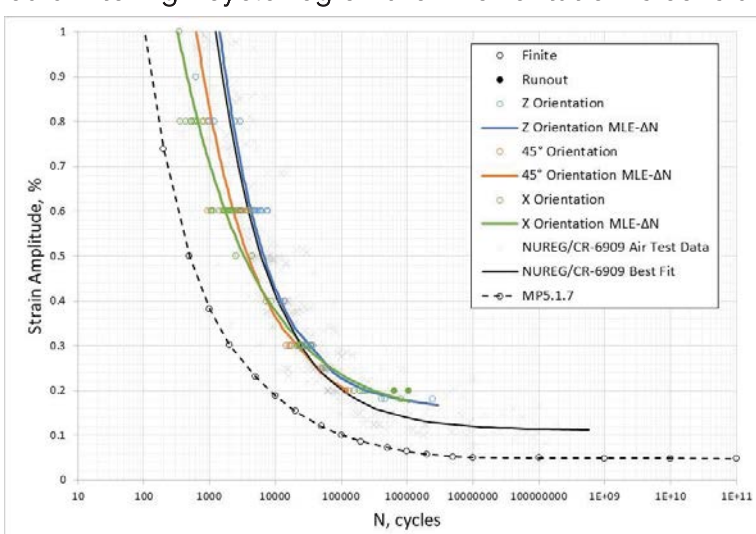


Fig 9: MLE Fits for each Orientation compared to the NUREG/CR-6909 Best Fit Curve

Combined best fit S-N curve produced by;

- N<20,000 cycles - ‘X’ orientation best fit
- N>20,000 cycles - NUREG/CR-6909 best fit was used (as bounding of all orientations in region)

Fatigue Design Curve produced from the best fit S-N curve by;

- Applying a bounding mean stress correction
- Factors of 2 on stress
- Factors of 20 on cycles

Design Curve Derivation - AM LPBF 316LN St. St.

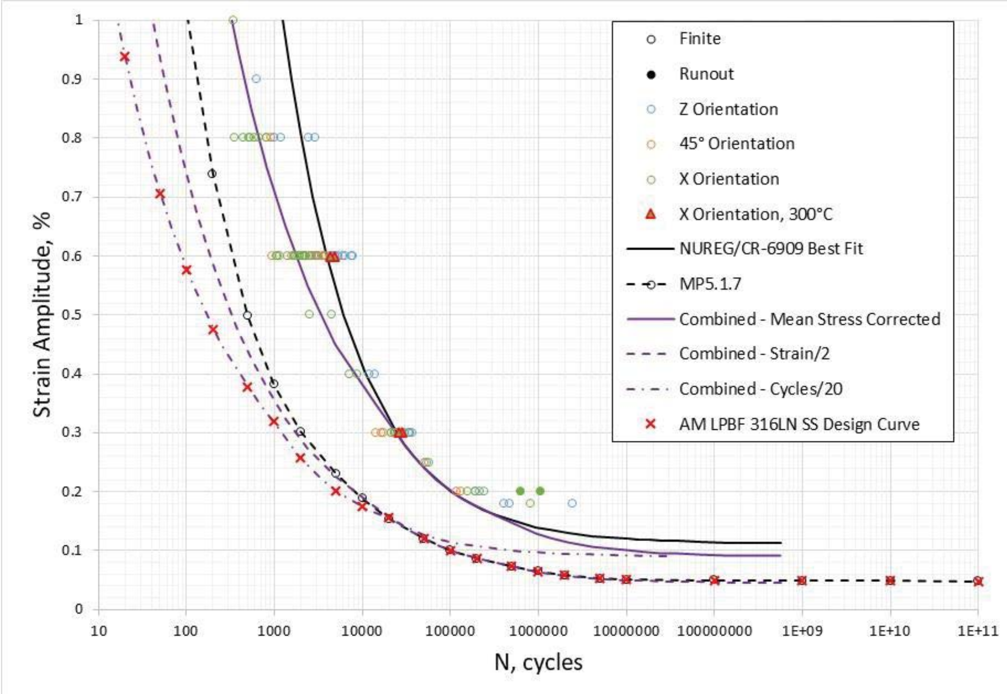
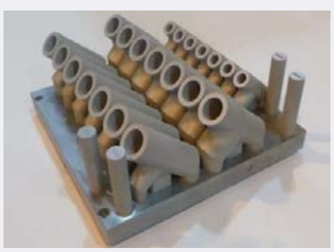


Fig 11: Construction of the AM LPBF 316LN Stainless Steel In-Air Fatigue Design Position

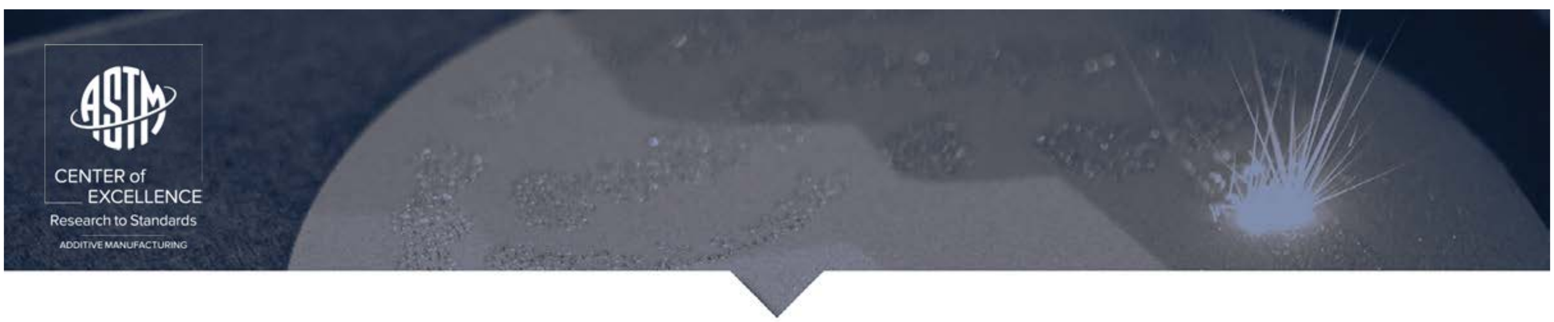


Summary

- In-air fatigue testing on AM LPBF 316LN St. St. on multiple powder batches and builds demonstrated complex fatigue behaviour at high strain amplitude.
- Investigation could not find a definitive material or mechanistic attribute as a cause for the premature failure, other than textural microstructural differences.
- A best fit curve has been constructed by considering each orientation separately and using either a fit to the limiting test orientation, or the NUREG/CR-6909 mean curve at each point across the S-N curve, whichever is lower.
- Fatigue design curve produced from the best fit curve by applying a mean stress correction and then applying conservative transference factors on stress and on cycles.
- AM LPBF 316LN fatigue design curve is judged to be suitably conservative for the assessment of the material on nuclear plant applications, including Small-Bore Globe valves which have also undergone supporting ASME, Section III, Appendix II, thermal cyclic testing.
- Data and approach published externally in ASME PVP 2023 - 106379 *(figure references)*

ROLLS ROYCE

Thank you – Any questions?



ASTM INTERNATIONAL
Additive Manufacturing Center of Excellence

AM Materials Data – Challenges & Opportunities

NRC Workshop on Advanced Manufacturing Technologies for Nuclear Applications
October 24-26, 2023

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ASTM Additive Manufacturing Center of Excellence

CENTER of EXCELLENCE Research to Standards ADDITIVE MANUFACTURING

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Develops comprehensive education and training programs built on standardization and certification expertise that prepares the AM workforce of the future at all levels.

Industry Consortium

Develop and standardize the requirements and best practices for AM material data generation and create high-pedigree shared datasets for use by members to support design and rapid qualification.

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Support successful AM implementation globally through a range of business strategy and technical advisory services from market intelligence, strategy and planning, to operations execution through Wohlers Associates.

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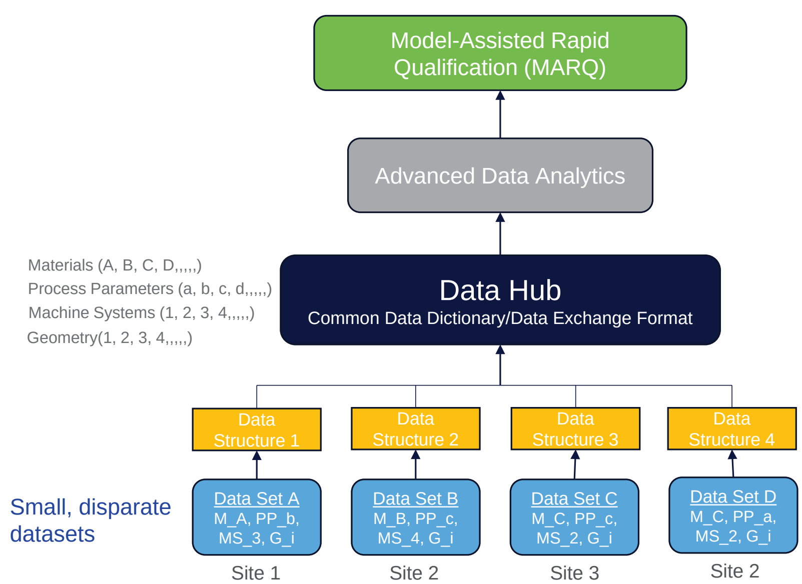
AM Materials Data - Challenges

CENTER of EXCELLENCE Research to Standards ADDITIVE MANUFACTURING

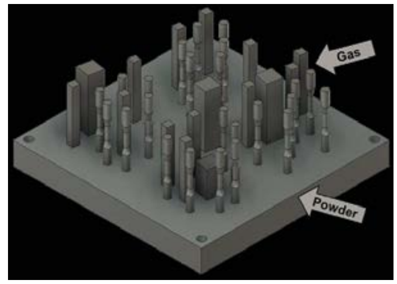
Large Number of AM Systems and Process Variables

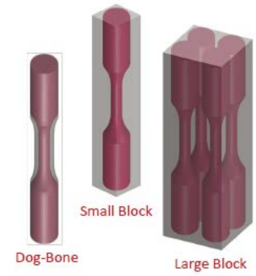
- Powder/Feedstock
  - o Chemistry, Size, Shape
- Part Geometry/Size
- Build Layout
  - o Location, Orientation, Quantity
- Machine Systems
  - o Recoater, Gas Flow, Temperature, etc.
- AM Process Parameters
- Post-processing

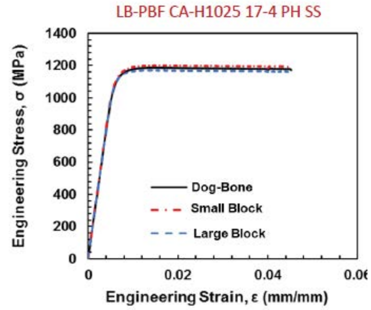


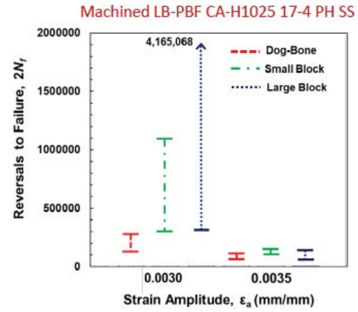
Effects of Geometry, Size and Time

- Three sets of LB-PBF 17-4 PH SS parts (dog-bone, small block, large block)
- All parts machined to similar geometry and polished to minimize surface effects
- CA-H1025 heat treatment was used to homogenize the microstructure
- No effect on tensile behavior was observed, however, effect of geometry on fatigue behavior was noticeable, especially in the high cycle fatigue regime



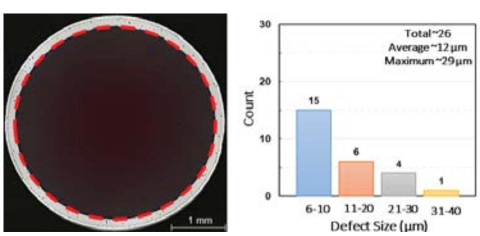




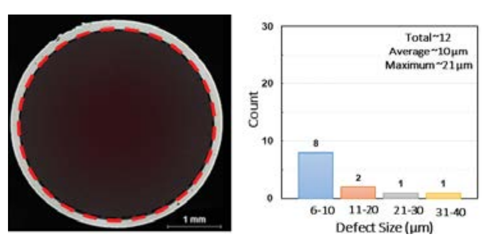


R Shrestha, N Shamsaei, M Seifi, N Phan, "An investigation into specimen property to part performance relationships for laser beam powder bed fusion additive manufacturing." Additive Manufacturing 29, 100807, 2019.

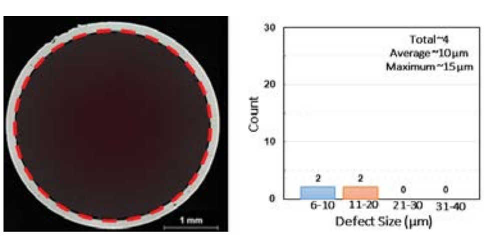
Effects of Geometry, Size and Time



Dog-Bone



Small Block



Large Block

- Highest amount of porosity was observed in dog-bone specimen, followed by small block specimen
- The maximum defect size was smallest in large blocks and largest in dog-bone parts
- Only considered the area within ~100 µm from surface

R Shrestha, N Shamsaei, M Seifi, N Phan, "An investigation into specimen property to part performance relationships for laser beam powder bed fusion additive manufacturing." Additive Manufacturing 29, 100807, 2019.

AM Materials Data - Challenges

Effects of Geometry, Size and Time

AUBURN UNIVERSITY

Dog-Bone	Small Block	Large Block
Total ~ 99	Total ~ 26	Total ~ 8
Max ~ 29 µm	Max ~ 21 µm	Max ~ 17 µm
Density ~ 99.96%	Density ~ 99.98%	Density ~ 99.99%

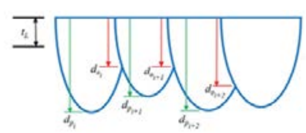
R Shrestha, N Shamsaei, M Seifi, N Phan, "An investigation into specimen property to part performance relationships for laser beam powder bed fusion additive manufacturing." Additive Manufacturing 29, 100807, 2019.

AM Materials Data - Challenges

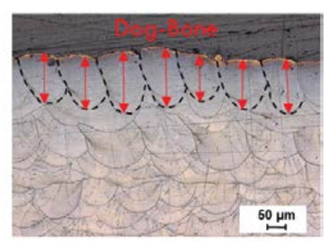
Effects of Geometry, Size and Time

- Some effect of part geometry was noticed in the size of the melt pool
- Longer melt pools were observed in large block specimens, while the shortest melt pools were noticed in dog-bone specimens
- Differences in melt pool size suggest cooling rate is highest in dog-bone specimens and lowest in large block specimens
- Values of dp/tL & do/tL > 1 explain the absence of lack of fusion defects

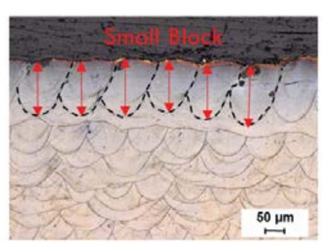
National Aeronautics and Space Administration. (2017). Specification for control and qualification of laser powder bed fusion metallurgical processes. MSFC-SPEC-3717.



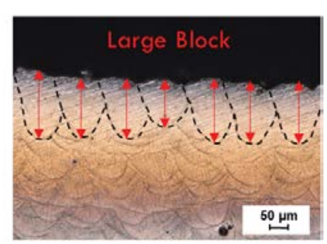
t_L = Layer Thickness
d_p/t_L & d_o/t_L
Melt pool characteristics is indicative of health of the process



Melt pool depth ~ 142 µm
$d_p/t_L = 3.6$ & $d_o/t_L = 2.1$



Melt pool depth ~ 156 µm
$d_p/t_L = 3.9$ & $d_o/t_L = 2.0$



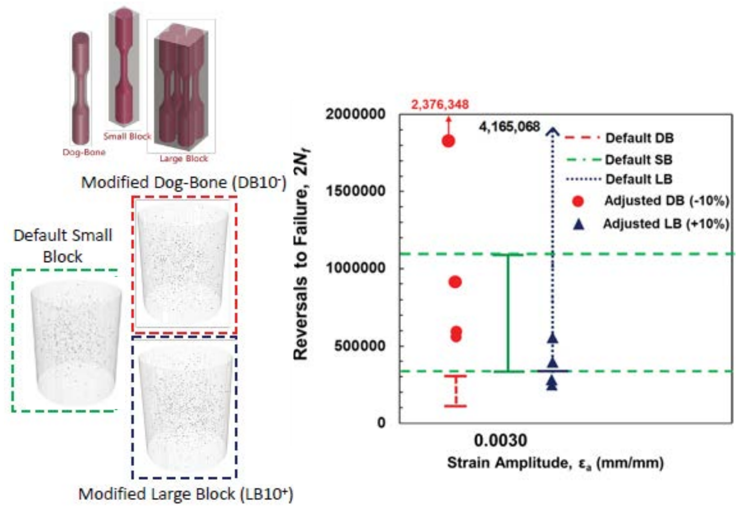
Melt pool depth ~ 162 µm
$d_p/t_L = 4.1$ & $d_o/t_L = 1.9$

R Shrestha, N Shamsaei, M Seifi, N Phan, "An investigation into specimen property to part performance relationships for laser beam powder bed fusion additive manufacturing." Additive Manufacturing 29, 100807, 2019.

AM Materials Data - Challenges

Effects of Geometry, Size and Time

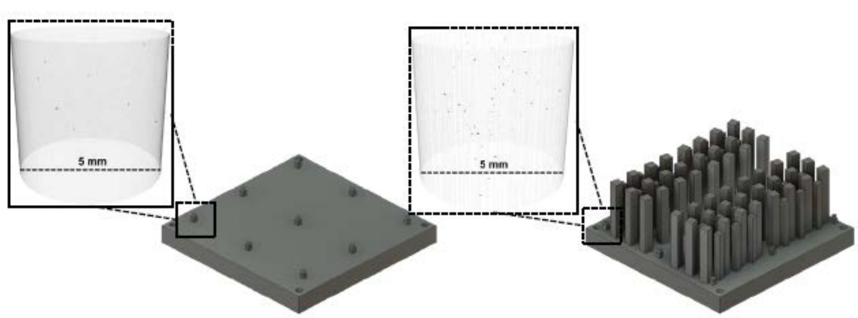
- ➢Similar defect distribution between different geometries was achieved by adjusting the process parameters
- ➢As a result, similar fatigue lives were obtained for these three different geometries
- ➢Achieving similar thermal histories in different geometries can result in comparable defect content as well as part performance
  - – **Optimal parameters are based on the geometry being printed**

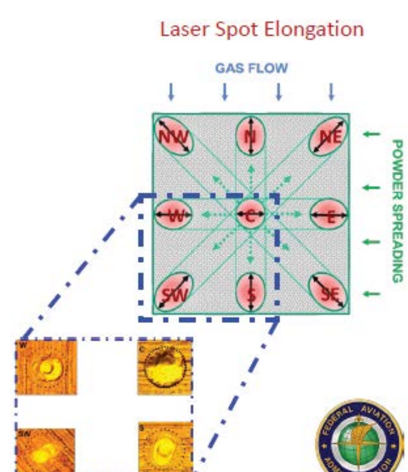


AM Materials Data - Challenges

Build Layout

- ➢ Laser spot elongation (i.e., area, shape), powder packing state, and gas flow can vary at different locations on the build plate
- ➢ The build plate density (i.e., total part area/build plate area) can affect the defect population as a result of varying scan times and spattering

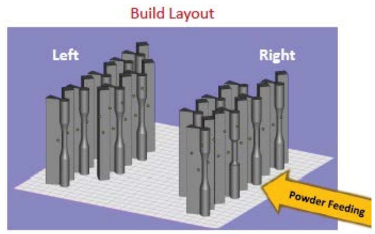


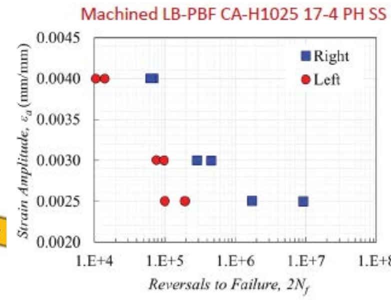


AM Materials Data - Challenges

Build Layout

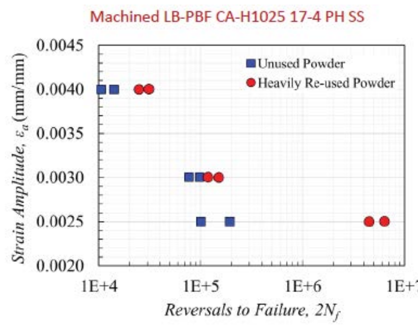
- Fatigue resistance of AM parts, even on the same build plate, was different as a result of powder flowability, packing density and the resultant defect formation
- Tensile properties were insensitive to the location of the parts on the build plate





Powder Reuse

- Effects of powder re-use on tensile properties and fatigue performance in as-built surface condition were negligible
- Re-using the powder did not considerably affect low and mid cycle fatigue regimes of machined specimens due to less sensitivity to process-induced defects
- Fatigue performance of machined specimens was improved significantly in the high cycle fatigue regime due to less presence of smaller particles and agglomerates



Shamsaei et. al., Additive Manufacturing, 36: 101398, 2020.

AM Materials Data - Challenges

- Companies from across a broad range of industries need to develop extensive material datasets to support implementation of Additive Manufacturing into the design and production of innovative products.

Creating datasets is very expensive and can be prohibitive for many companies

Difficult to impossible to directly transfer data and lessons learned between companies and across machine platforms, creating duplicate efforts within and across industry verticals

Lack of standardized approaches to data generation, pedigree and management leads to significant waste

Dataset generated with Method 1 ≠ Dataset generated with method 2 ???

AM Materials Data - Opportunity

➢ ASTM officially launched a Global Consortium for Materials Data and Standardization (CMDS) in 2022, which in coordination with members and with input from regulatory agencies, will accelerate adoption of AM technologies through standardization by:

REQUIREMENTS & BEST PRACTICES

- Terminology, Pedigree, Specimen Geometry, Build & Test Plans
- Identify Process-Structure-Property Relationships
- Equivalency/Combinability of new or existing data

GENERATE HIGH-PEDIGREE DATA

- Consortia-funded R&D projects create *shared* high-pedigree "reference" material datasets to drive process-based material specifications

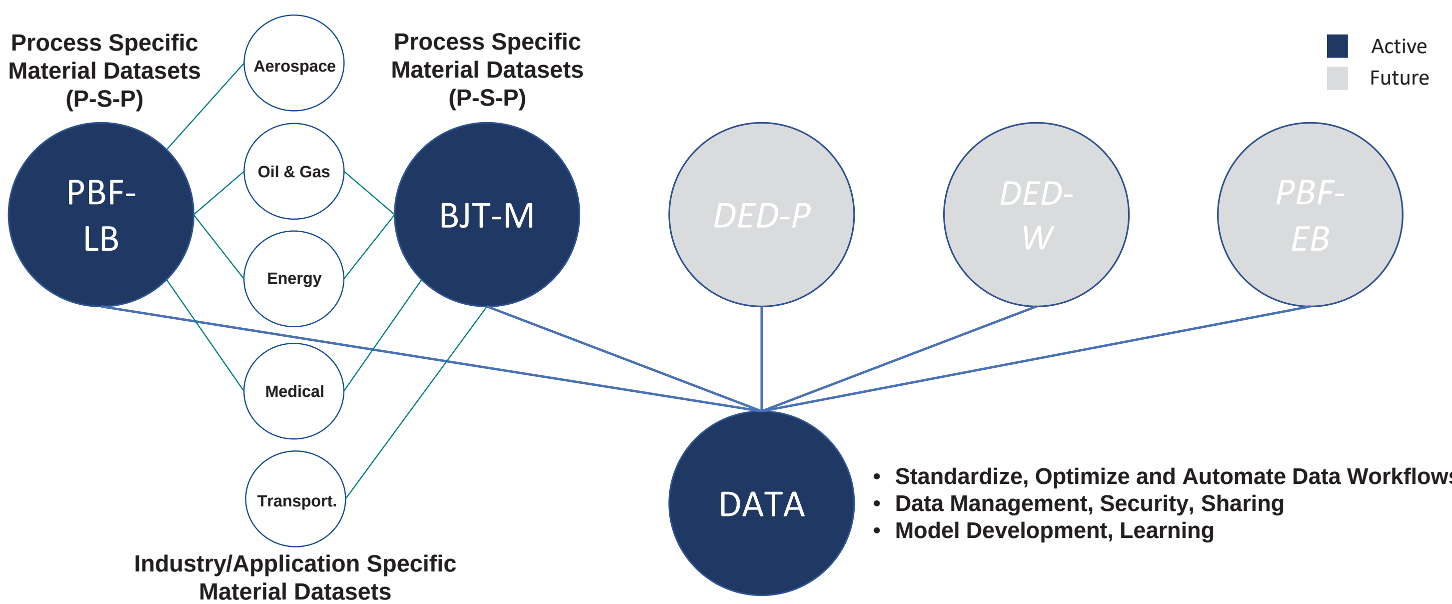
DATA MANAGEMENT SYSTEM

- Secure, Access-controlled Data Management System
- Establishing/Following standard data principles (e.g., CDD, CMD, CDEF, FAIR*)

STANDARDS DEVELOPMENT

- Transferring lessons learned and consortium approved materials data to standardization committees

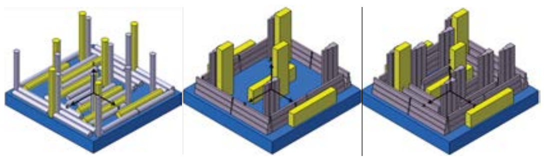
AM CoE CMDS – Workstream Structure

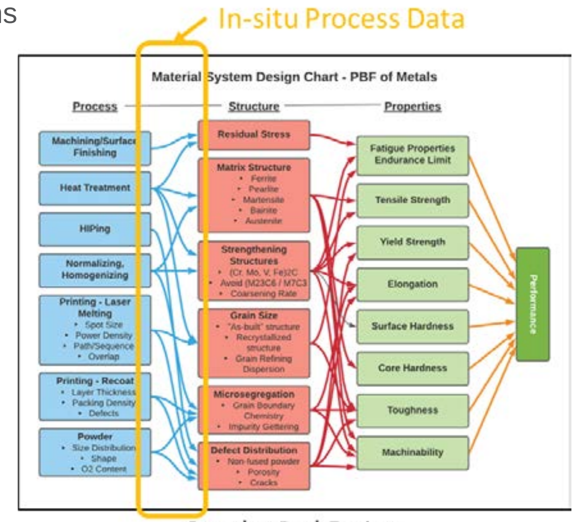


- **Standardize, Optimize and Automate Data Workflows**
- **Data Management, Security, Sharing**
- **Model Development, Learning**

AM CoE CMDS – Process Workstreams

- Define and Generate high-pedigree and high-value AM Materials Data of interest
- Identify Process-Structure-Property (P-S-P) relationships for AM Materials
  - Population of data representing typical process variables/variations
  - Linkage of "specimen" data to "part production" data
    - Geometry Size/Shape
    - Build layout/density
    - Feedstock
    - Machine systems
    - Printing Parameters
    - Post-processing
- Establish "Equivalency" of material data (combinability)
  - Equivalency requires similar microstructure
  - Material is in family with specification/class
- Define material allowables and specification values
- Feature Based Process/Parameter Design
- Model-Assisted Rapid Qualification (MARQ)





Powder Bed Fusion

AM CoE CMDS – Process Workstream Active Projects

Powder Bed Fusion (PBF)

- UNS N07718 Project In-Process
  - Tensile & Fatigue Properties
  - Room Temperature & Elevated Temperature
  - Four (4) different AM machines
  - Study includes size, location and orientation effects on material properties
  - Expected Standardization Deliverables:
    - ***New/Updated material standard with updated structure-property requirements for two heat treat grades.***
    - ***New guide for materials data generation for ASTM material specifications***
- UNS A03600 Project In-Process
  - Tensile & Fatigue Properties
  - Two (2) AM machine platforms
  - Study includes size, location and orientation effects on material properties
  - Expected Standardization Deliverables:
    - ***New/Updated material standard with updated structure-property requirements for additional stress relief condition.***


Build A – EOS M290/1

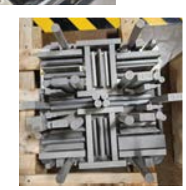

Build B – EOS M290/2


Build C – EOS M290/1


Build D1 – EOS M400-4


Build D2 – EOS M400-4


Build E1 – FormUp 350


Build E2 – FormUp 350

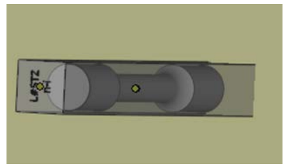
CMDS UNS N07718 PROGRAM			AM MACHINE							
			M290			M400-4		FormUp 350-2		
	TEST CONDITION	HEAT TREATMENT	Build A	Build B	Build C	Build A	Build C	Build A	Build C	TOTALS
TENSILE TEST	Room Temp	P-TS 101/102	32	2	2	10	5	10	5	66
TENSILE TEST	Room Temp	P-TS 103/102				9		9		18
TENSILE TEST	Elevated Temp	P-TS 103/102				25	9	25	9	68
TENSILE TEST (2 mm DB)	Room Temp	P-TS 101/102		40	12		3		3	58
TENSILE TEST (4 mm DB)	Room Temp	P-TS 101/102			12		3		3	18
TENSILE TEST (6 mm DB)	Room Temp	P-TS 101/102			12		3		3	18
LOW CYCLE FATIGUE TEST	Room Temp	P-TS 101/102	12	12	12	12	12	12	12	84
HIGH CYCLE FATIGUE TEST	Room Temp	P-TS 101/102				10	20	10	20	60
LOW CYCLE FATIGUE TEST	Elevated Temp	P-TS 103/102				12	12	12	12	48
CREEP	Elevated Temp	P-TS 103/102				6	6	6	6	24
		TOTALS	44	54	50	84	73	84	73	462

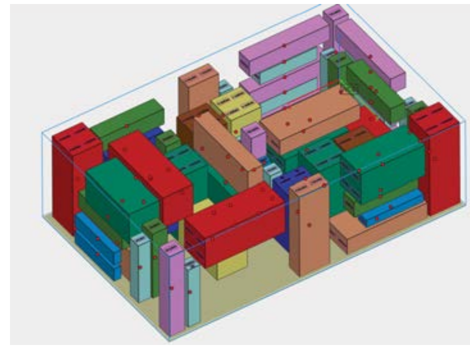
AM CoE CMDS – Process Workstream Active Projects

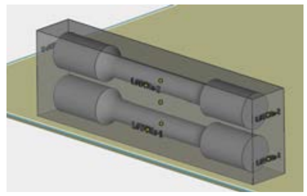
CENTER of EXCELLENCE Research to Standards ADDITIVE MANUFACTURING

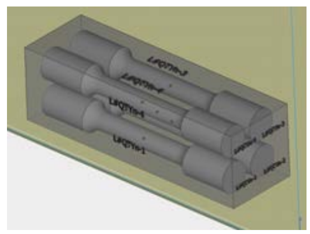
Binder Jetting Technology (BJT)

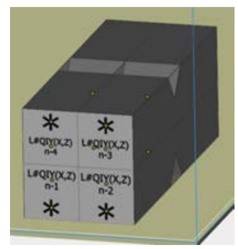
- UNS S17400 Type 630 Project In-Process
  - Tensile, Fatigue, Impact and Corrosion room temperature Properties
  - Three (3) different AM machine platforms
  - Study includes size, location and orientation effects on material properties
  - Expected Standardization Deliverables:
    - ***New (first) BJT material standard with two heat treat grades.***
    - ***Input from BJT perspective on guide for materials data generation for ASTM material specifications***

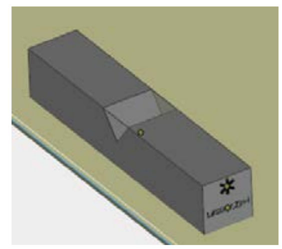






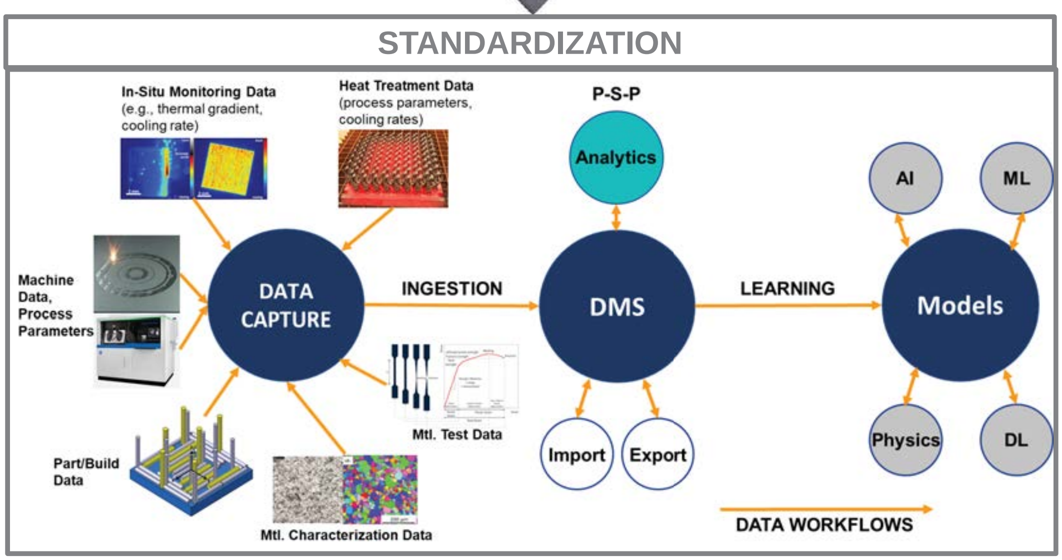






AM CoE CMDS – Data Workstream

CENTER of EXCELLENCE Research to Standards ADDITIVE MANUFACTURING



- **Standardize, Optimize and Automate Data Workflows**
- **Data Management, Security, Sharing**
- **Model Development, Learning**
- **Utilize FAIR, CDD, CDM, CDEF principals**

AM CoE CMDS – Data Acquisition

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

Common Data Dictionary (CDD)

- The objective of the AM CDD is to provide definitions of a common set of concepts, data elements in a domain which define the basis of AM data collection, integration, management and exchange.
  - Use of common data dictionaries supports the ease of data collection, curation, analysis, storage and exchange.
  - Build a foundation for the subsequent development of common data exchange formats and standard data governance for a more streamlined AM development lifecycle and value chain management.

- ASTM F4390 - Standard Practice for Additive manufacturing -- General principles -- Overview of data pedigree

This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.

INTERNATIONAL Designation: F3490 – 21

Standard Practice for Additive Manufacturing — General Principles — Overview of Data Pedigree[1]

This standard is issued under the fixed designation F3490; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 The scope of this document outlines the interpretation of additive manufacturing (AM) data. Currently, legacy AM data is stored in different databases or data management systems, each of which uses its own data dictionary. A common data dictionary allows AM data pedigree to be discovered, mapped, federated, and analyzed to improve both the understanding and qualification of AM processes and parts.

1.2 A common data dictionary facilitates the interoperability, searchability, and reusability of AM data by *(1)* identifying the general AM data pedigree elements already defined in a standardized terminology and *(2)* defining those salient terms with indisputable semantics (meanings). The goal of this document is to provide a first subset of the common data dictionary by which AM data may be collected, curated, and shared, regardless of which technology platform and software are used for data storage and exchange.

1.3 The common data dictionary also specifies a way to group AM data pedigree into fifteen information modules pertaining to different aspects of the entire additive manufacturing process.

1.4 The common data dictionary approach specifies data element names that serve to uniquely identify the AM data elements. The data type, value domain, and term definition for each data element are also specified in this practice. References are provided for those data elements with established definitions in existing standards.

1.5 The data elements identified in this common data dictionary are considered essential, because they are most frequently encountered in AM, process agnostic and technology independent. They are broadly applicable to all the process categories defined in ISO/ASTM 52900. It is intended to be a starting point, not all-encompassing.

1.6 The common data dictionary does not specify:

1.6.1 A complete set of data items to be exchanged through AM development lifecycle and value chains.

1.6.2 A minimum set of data items to be exchanged for AM lifecycle and value chain activities.

1.6.3 A common AM data exchange format.

1.6.4 The details associated with how the common descriptions of data items should be implemented for the development of new data systems or data federations among heterogeneous data systems.

1.7 Additional data elements beyond those defined in existing ASTM, ISO, AWS, NASA and SAE standards have been introduced to provide increased utility for AM. These new data items are generally common-sense and frequently used in the AM industry.

1.8 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.9 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

A1080 Practice for Hot Isostatic Pressing of Steel, Stainless Steel, and Related Alloy Castings

E1338 Guide for Identification of Metals and Alloys in Computerized Material Property Databases

E2077 Specification for Analytical Data Interchange Protocol for Mass Spectrometric Data

E2339 Practice for Digital Imaging and Communication in Nondestructive Evaluation (DICONDE)

[1] This practice is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.08 on Data.

Current edition approved Dec. 15, 2021. Published March 2022. DOI: 10.1520/F3490-21.

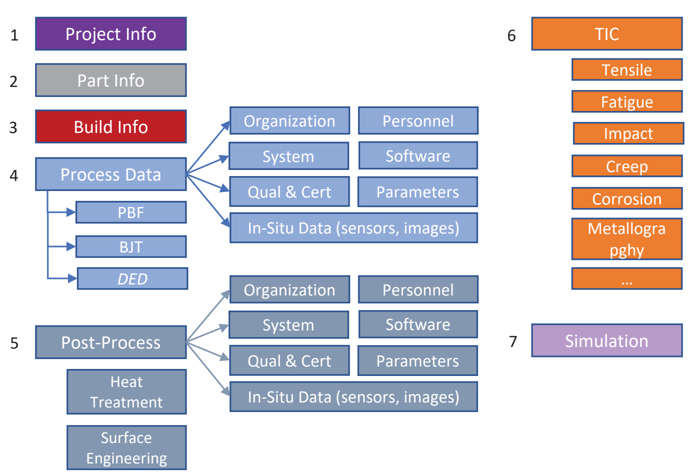
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

AM CoE CMDS – Data Acquisition

CENTER of EXCELLENCE
Research to Standards
ADDITIVE MANUFACTURING

Common Data Dictionary (CDD) Template

2000+ data elements are being collected by CDD

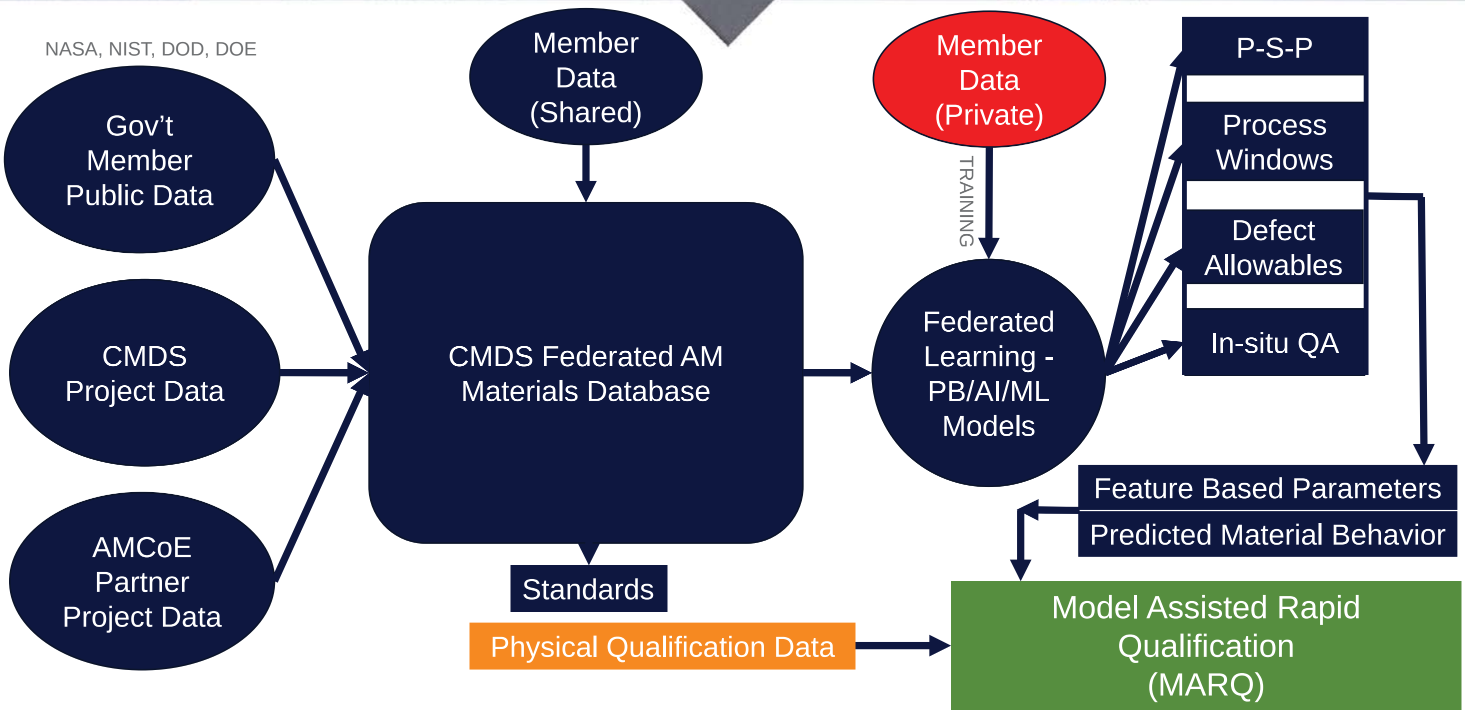


- CMDS leveraged this standard (ASTM F3490, Overview of Data Pedigree), and has developed a standard template for data acquisition.

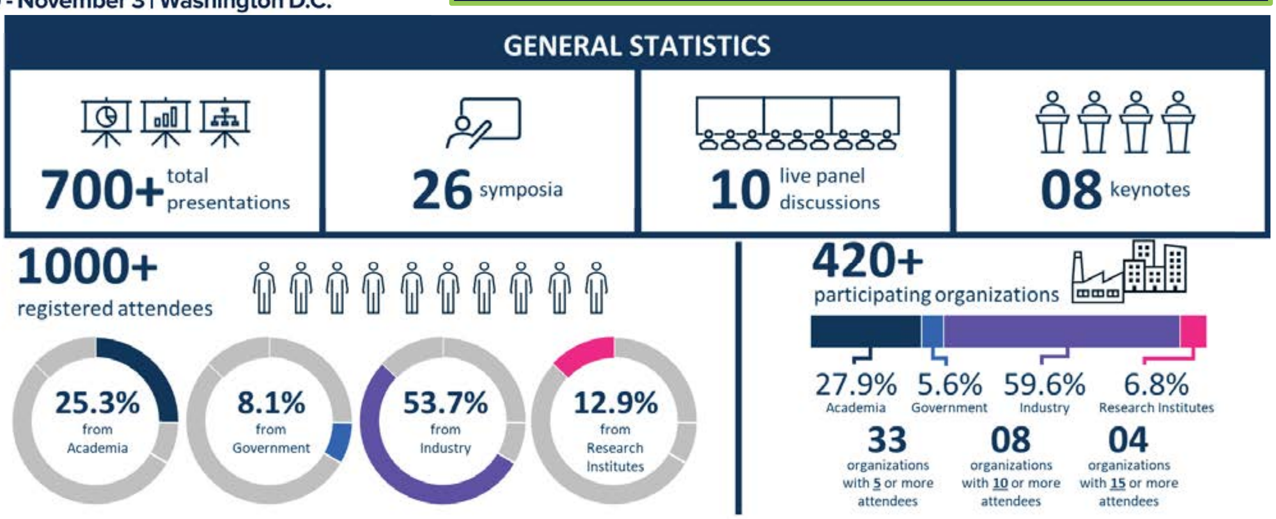
Return to Introduction

Data Element Name	Data Type	Value Range, Value Set or Primary Units	Definition / Standard	Data Entry
AM Production Operation				
Organization Name	string	free text	The name of an organization.	
Organization ID	string	free text	The unique identifier of the organization.	
Organization Type	string	Organization Type Enumeration	The type or roles of an organization, whether it is a manufacturer, vendor, supplier, or contractor. One organization may have many types.	
Organization Qualification/Certifications		free text	Details of the organization's qualifications and certifications, encompassing the facility where the build cycle was produced	
Organization Location	globalAddressFormat		The address of the organization. Postal Address Standards	
AM Operations Project Lead	string	free text	Identification of the Project Lead for the Additive Manufacturing operations	
AM Machine Operator/Technician	string	free text	Identification of the AM machine operator or technician that runs the AM machine	
AM Facility	string	free text	Name of the facility where an AM system is installed	
AM Machine and Auxiliaries Information				
AM Machine				
AM Machine Manufacturer	string	Organization ID	Manufacturer's name of an AM Machine	
AM Machine Model Name	string	Searchable vendor defined AM machine model name	Manufacturer's model name of an AM Machine	
AM Machine Serial Number	string	free text	Serial number of an AM machine defined by the machine manufacturer	
AM Machine Acceptance Date	date	The date is specified in the following form "YYYY-MM-DD(Time Zone)" defined by ISO 8601	Date when an AM machine is certified or Installation Qualified (passes the site acceptance test, or Installation qualification)	
Machine Control Firmware Version	string	free text	The version number of the Firmware installed in the AM Machine	
Machine Software Version	string	free text	The version number of the Control Software installed in the AM Machine	
Number of Lasers	integer		The number of lasers available in the AM Machine	
Nominal Laser Power	real	Watts	The nominal laser power of installed laser(s) in the AM Machine	
AM System Installation Qualification - Date	date	The date is specified in the following form "YYYY-MM-DD(Time Zone)" defined by ISO 8601	ISO/ASTM 52930 Additive manufacturing Qualification Principles - Installation, Operation and Performance (IQ/OQ/PQ) of PBF-LB Equipment	
AM System Operation Qualification - Date	date	The date is specified in the following form "YYYY-MM-DD(Time Zone)" defined by ISO 8602	ISO/ASTM 52930 Additive manufacturing Qualification Principles - Installation, Operation and Performance (IQ/OQ/PQ) of PBF-LB Equipment	
AM Machine Installation Qualification Data /Report	document/anyURI	Link to document	A document or data reporting evidence of AM machine installation qualification (IQ)	
AM Machine Operation Qualification Data /Report	document/anyURI	Link to document	A document or data reporting evidence of AM machine operation qualification (OQ)	
Machine calibration date	date	The date is specified in the following form "YYYY-MM-DD(Time Zone)" defined by ISO 8601	Date of machine calibration	
Machine calibration report	document/anyURI	Link to document	Technical report from the calibration	
AM System Last Maintenance Date	date	The date is specified in the following form "YYYY-MM-DD(Time Zone)" defined by ISO 8601	Date of last AM System Maintenance	
AM System Last Maintenance Report	document/anyURI	Link to document	Technical report from the latest maintenance routine	
Building Volume Shape	string	Build Volume Shape Enumeration	Shape of a building volume (i.e., BOX or CYLINDER)	
Building Volume Width	real	mm	Width of a box building volume	
Building Volume Depth	real	mm	Depth of a box build volume	
Building Volume Height	real	mm	Height of a box build volume	
Building Volume Diameter	real	mm	Diameter of a cylinder build volume	
Total Build Volume	real	mm^3	The total usable volume available in the AM System in mm^3	
Build Platform				
Build platform ID	string	free text	Identifier of the build platform used to manufacture the build	
Build Platform Material	string	Metal Specific Material Type Enumeration	Material type of a build platform	
Build Platform Part Process Methods	string	free text	Part processing methods of a build platform, eg, hot rolled and annealed	
Build platform Surface finish	string	free text	Surface roughness description of the build plate	
Build platform flatness	real	mm		
Build Platform Material Grade	string	Searchable	Standard grade the build platform material product conforms to	

AM CoE CMDS – To-Be Vision



Addressing application specific requirements of various industry sectors in addition to covering the fundamentals of advanced manufacturing processes with the goal of transitioning *research to application through standardization*.



AM Standards Forum

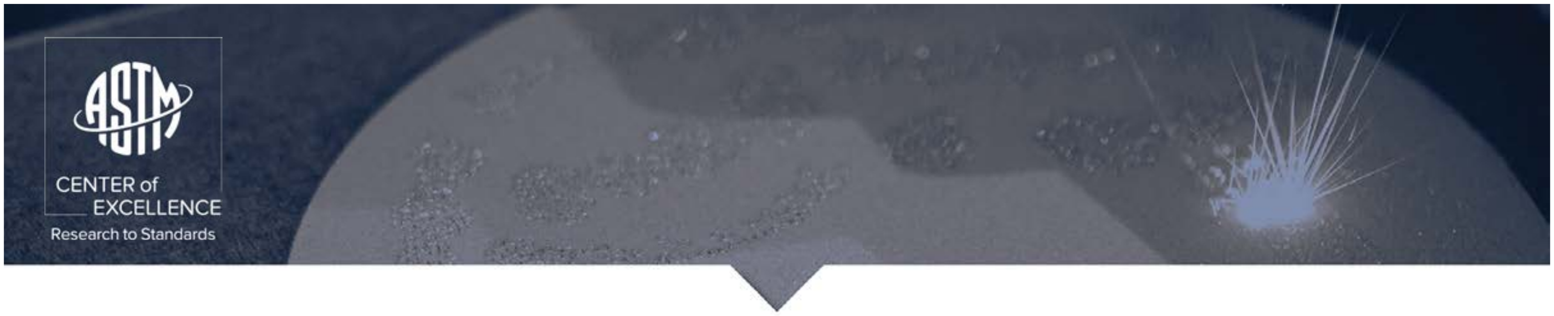
➢ This one-day workshop at Formnext 2023 is dedicated to discussing the standardization needs for additive manufacturing and will enable you to engage with experts to discuss standard practices and overcome implementation challenges.

Organized by:

Consortium for Materials Data & Standardization (CMDS)

➢ Global Consortia for Materials Data & Standardization enables companies of all sizes from across the entire Additive Manufacturing ecosystem to collaborate on standardizing the requirements and best practices for high-pedigree materials data generation and creating, curating and managing the data needed to accelerate the industrialization and full adoption of AM technologies.

- OEM/LSI End Users
- AM Equipment Manufacturer
- AM Contract Manufacturer/Supplier
- AM Materials/Feedstock Producer
- AM Post-processing and Testing Service Provider
- AM Software
- AM Process/Health Monitoring
- Industrial Equipment Producer (e.g., Furnace, Powder Handling Equipment,…)
- Government Agencies and Laboratories (DoD, DOE, NASA, NIST)



ASTM INTERNATIONAL
Additive Manufacturing Center of Excellence

Thank you.

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America Makes

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The Current State of Additively Manufactured Ni-Based Superalloys and a Future Look at AMT's within the Casting and Forging Industries

Oct. 26, 2023

John Martin
Additive Manufacturing Research Director, America Makes
john.martin@ncdmm.org

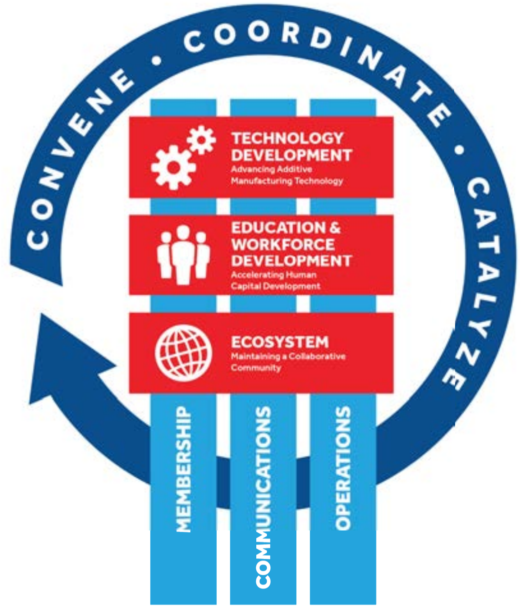
Overview

The three core activities of the Institute are:

- **Develop Additive Manufacturing Technology:**
  Projects, Innovation, Technology Transfer, Implementation
- **Accelerate Human Capital Development:**
  Workforce, Education, Training, Outreach
- **Energize Collaborative Ecosystem:**
  Government, Membership, Community

These focus areas are enabled by:

- **Membership:** Driving engagement and collaboration with our nation's brilliant minds from government, industry and academia to advance Additive Manufacturing
- **Communications:** Driving awareness and spreading the word to government, members, stakeholders, community
- **Operations:** Run by a not-for-profit organization with a lean and collaborative structure



America Makes
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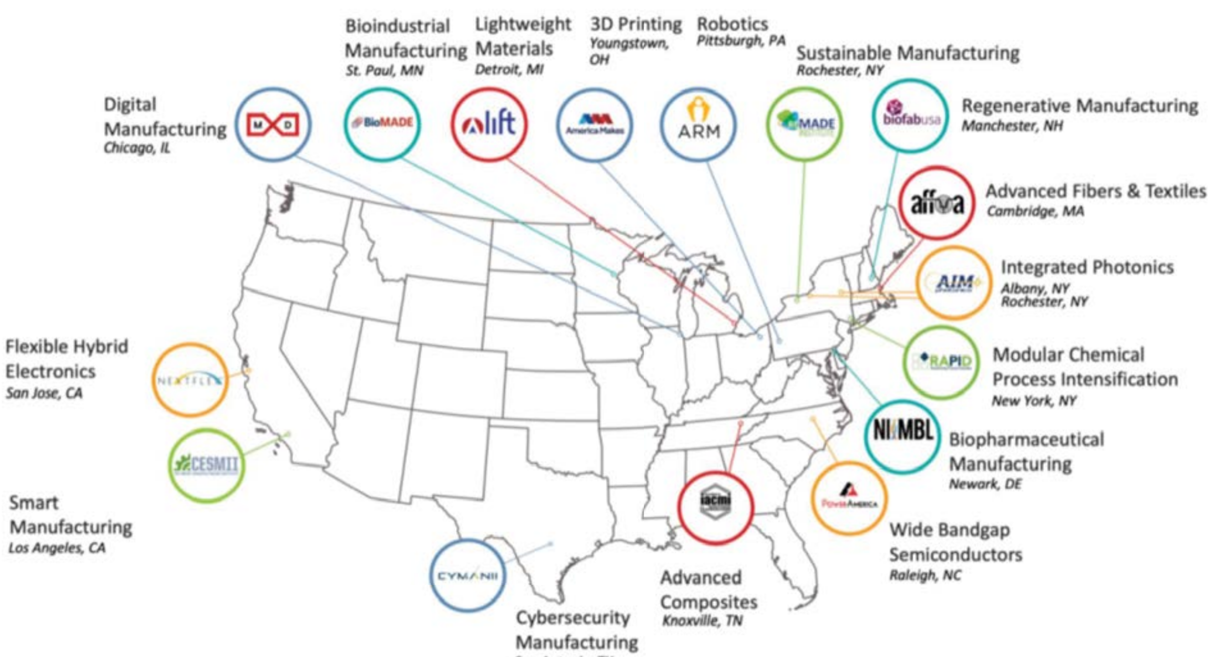
Manufacturing USA Network



Geographic Representation of America Makes Membership

- 42 States are represented by America Makes members.
- More information is needed to more accurately represent the additive manufacturing ecosystem.

NCDMM

HQ

Satellite Centers

Project Team – Roles and Responsibilities

NIST National Institute of Standards and Technology; AFRL The Air Force Research Laboratory	• Technical oversight
America Makes	• Program management • Customer interface
Colorado School of Mines	• Technical management • Data management • Testing & characterization
Renishaw, EOS, Open Additive, 3D Systems, Xact Metal, AddUp, Concept Laser (a GE Additive company), Velo3D, Aconity3D	• Data pedigree assurance • Specimen manufacturing

Technical Approach

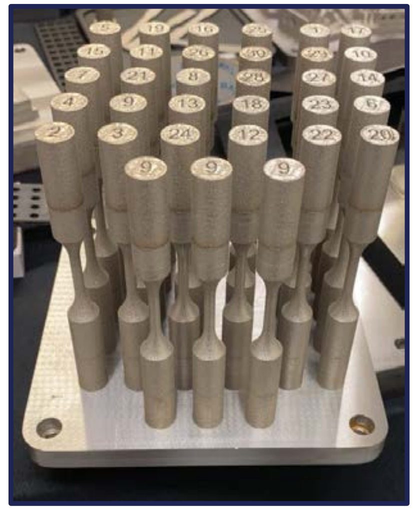
- The project aims to investigate cross-platform consistency in PBF-LB technologies.
- We will engage with 9+ different PBF-LB original equipment manufacturers (OEMs)
  - Develop a neutral manufacturing plan to establish consistency across platforms
  - Determine methods for analyzing and improving the consistency of PBF-LB processes.
- This project will provide the industrial supply chain with the knowledge of cross-platform printing for broad implementation

Technical Approach

- Focus on the tensile properties of PBF-LB IN 718
  - Establish **processing control data requirements** for multiple PBF-LB platforms
  - Conduct a **round-robin test** for tensile properties across 9+ different PBF-LB platforms
  - Evaluate the **effect of heat treatments** to create process consistency
  - Analyze the influence of **process parameters and machine features**
  - **Document recommendations** for test methods and data requirements for qualification and future standards needs
- *The raw data will be made available to the America Makes community for further analysis*

Task 1 – Test Method Development

- Develop the test method for the **data collection and printing strategy** for the round robin tests
  - Prior lessons learned from NIST round robin testing
  - The overall test architecture will be developed in collaboration with NIST, AFRL and America Makes.
- Focus on tensile properties
  - Including the influence of post processing heat treatment
  - Net shape geometry using best practice processing
- All proposed test methods will be reviewed with the NIST/AFRL team
  - A sample dataset from Mines will be validated with the NIST AM team to ensure compatibility and suitability.

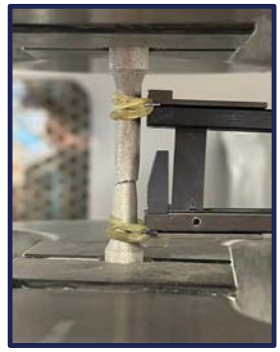


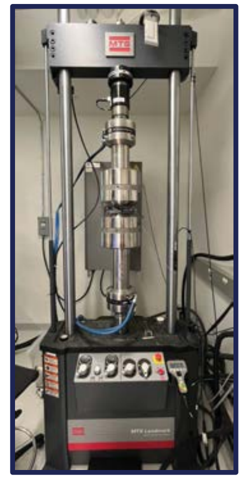
Task 2 – Definition of Processing Pedigree

- Identify what processing pedigree is documented from the different platforms
  - Collaborative discussions to identify the machine process control parameters for at least 9 different platforms
  - Bridge gaps in terminology between all the OEMs leveraging the ASTM Common Data Dictionary
  - Ensures consistency in data reporting during the round robin studies.
  - Definition of post-processing steps

Task 3 – Round Robin Studies

- Obtain a minimum of **40 tensile bars from each platform** and tensile test to failure
  - A minimum of 9 platforms will be tested
  - Powder feedstock characterization
- Analyze the **microstructure and porosity** through cross-sections
- Optional fatigue bars depending on project time
- Gather all process control data as well as any in-process data
- A summary report will be developed
  - Raw data will be delivered to the America Makes community



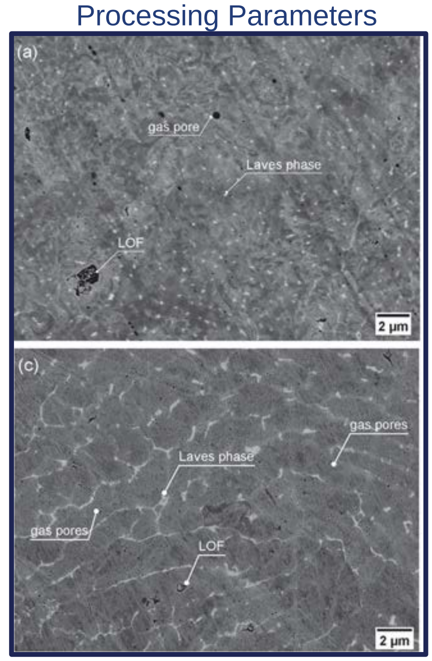


Test Matrix
(Number of bars per platform: total)
As-built (3: 27)
Standard Heat Treatment (15: 135)
Full Recrystallization (15: 135)

Task 5 – Data Analysis

- Correlative analysis of processing inputs to tensile properties
  - Processing and machine variables
- Microstructural analysis of as-built and both heat treatments
  - Influence of starting microstructure on heat treatment response
- Microstructure impact on tensile properties

718 Microstructure at Different Processing Parameters



Lesko, C.C., Sheridan, L.C. and Gockel, J.E., 2021. *Journal of Materials Engineering and Performance*, *30*(9), pp.6630-6639.

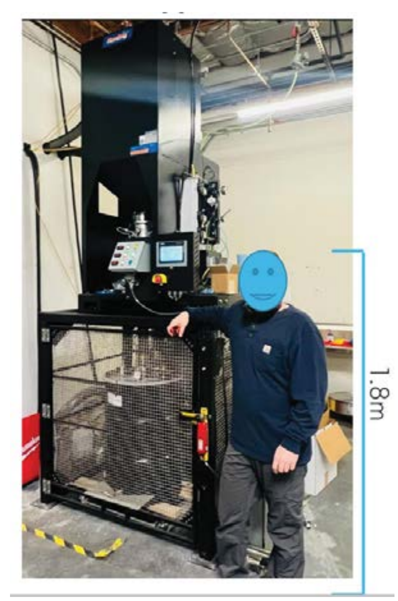
Task 6 – Measurement Method Specification

- Develop a measurement method specification that may be used for analyzing consistency of various PBF-LB equipment
  - Expose future gaps and needs for standards development and new America Makes roadmap requirements.

Velo Sapphire 1MZ Install and Qualification

Summary:
- Build Module Docking and Sealing
  - Cable routing updated
  - Software update for communication issue
  - Sealing/docking fix
- Herding Integration (3rd party system)
  - Velo design for improved discharge bin/lid
  - Procedure created for discharge bin removal
  - Safer, more reliable, ergonomic operation

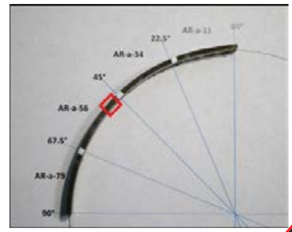
For Reference:
- 4 XC 1MZ systems fielded
- >400,000 layers of accumulated printing

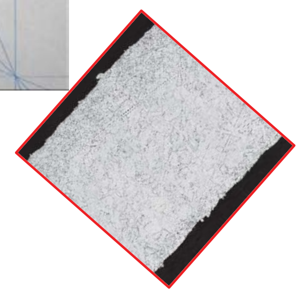


Technical Approach

Goal: Checkout machine and process for program use.

- Evaluate to determine if in family to specifications or need to generate additional procedures
- Consistent, repeatable and controllable fabrication





- Machine operations
- Material and Parameter checkouts
  - Microstructure (As-built and Heat Treated)
  - Tensile properties are in family of other Velo and conventional
  - 3 ranges: 0°< Angle < 20°, 21°< Angle < 44°, 45°<Angle
- Geometry checkouts – Feature builds, residual stress distortion
- Limit builds – Hole sizes, wall thicknesses

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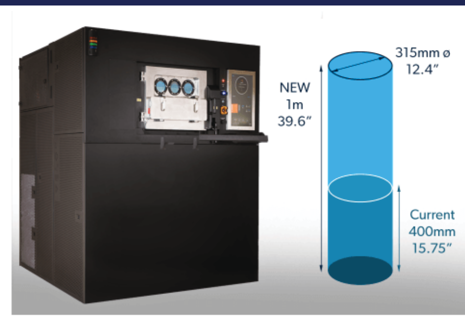
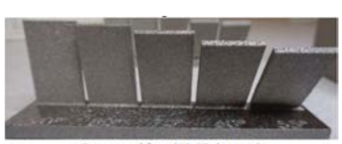
Velo Material Checkouts

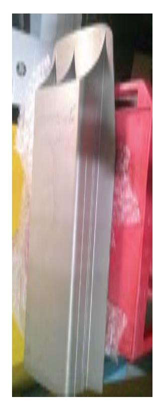


- At the build plate:
  - Microstructure samples around the build plate
  - Horizontal, Vertical, and 45° tensile tests
  - Design and build impossible samples
- Vertical checkouts:
  - Full height samples – Microstructure evaluation
  - Iteration 2 samples

- Geometry Samples
  - Flat plate samples
  - Feature build samples (Tough to build sections)
  - Full geometry
  - Test unit geometry

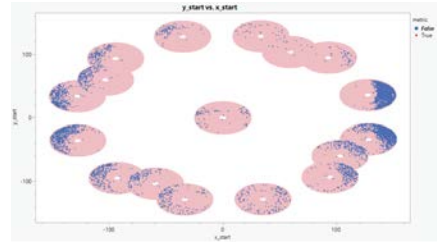


Downward face (90-55 degrees)

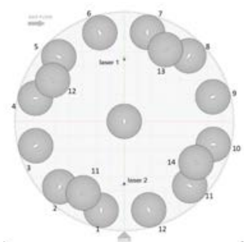


DISTRIBUTION STATEMENT A. Approved for public release: Distribution is unlimited. (AFRL-2023-4642) 20 Sep 2023 AmericaMakes.us

Build 1 – Velo Head Quarters



- Goal: Review consistency of multiple parameter microstructure around the build envelope and response to heat treatment. Heat Treatment development
- Clocking is not important on the samples
- At Build plate:
  - 4X Process Tree – Center
  - 8X Process Tree – Edge
- At Top of envelop:
  - 4X Process Tree – Center
  - 4X Support bar, .5" OD



Overhang angles:

Sample arrayed as on build plate, viewed from below build plate

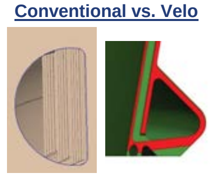
Geometry Demonstration Plan

Air

Side View: Fluid Schematic

Goals:
- Make sample that meets 1m z-height
- Utilize Velo capabilities
  - "Cavity Feature" >45°
  - Injector holes ID .010"
  - Manifold features >1.5" OD
  - Thin walls .030" Min
- Demonstrate joining elimination
- Test geometric distortion □→○
- Complex contouring

Conventional vs. Velo



Detail Requirement:
- Inlet to Combustor
- Balance realism vs. inherent design

Submitted for review to feature or de-feature

CAD-toon of notional envelope geometry

Problem Statement

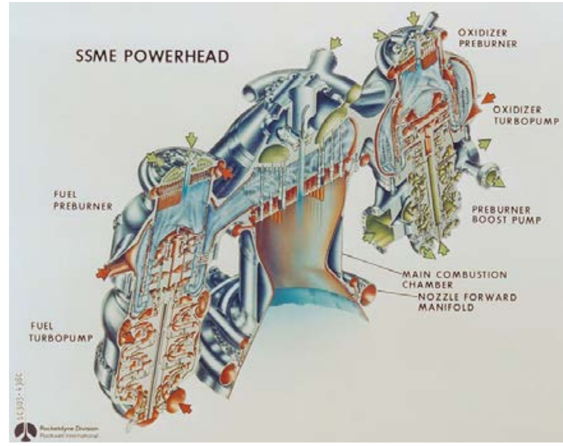
- Joining is often required to leverage LPBF. This requires additional manufacturing steps, tooling, post-processing, and inspections.
- Enabling large-scale LPBF eliminates the need for joining operations, reduce associated cost, weight, part defects, and lead times.

GE's Project ATLAS beta machine

- Build envelope:
  - 1,000mm x 900mm x 300mm
- 1 kW laser
- 3D scanner translates with laser
- Optimal air flow over the print area
- Geometric flexibility/versatility
- Scalable platform (multi-laser)

GE ATLAS 2019 (85 days)

GE ATLAS 2020 (54 days)



SSME/RS-25 – Powerhead
"Backbone of the Engine"

- Technology demonstration
- Representative size, joining, and fine feature risks
- Representative material certification requirements

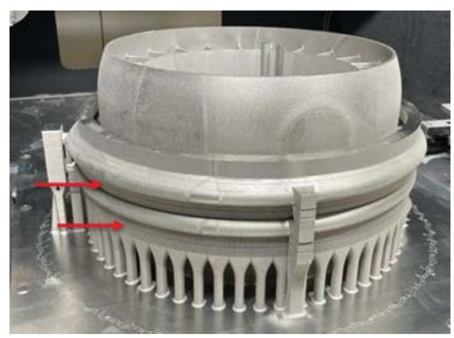
ATLAS removes >1000 parts and >500 joints

Phase 4 – Full Scale Component Build

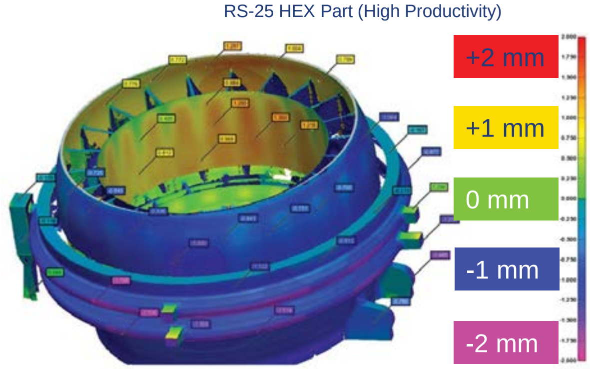
- Goals
  - Demonstrate feasibility for ATLAS platform (large, jointless components)
  - Provide accompanying mechanical data
  - Demonstrate productivity improvement on "real world" large format part
- Build Preparation
  - Identical build layout to HEX Print on ATLAS platform in 2020
  - Updated bulk parameter (Phase 1) and downward surface parameter (Phase 3a)
- Results
  - RS-25 HEX successfully printed (600mm OD, 300mm height)
  - Reduction in total build time of ~43%
  - Dimensional deviations associated with global part shrinkage
  - Tensile, HCF, and LCF all similar to previous results in this program

RS-25 HEX Build on ATLAS	Baseline Parameter (2020)	High Productivity (2022)	% Difference
Scan Time	35.8 days (859 hrs)	19.0 days (455 hrs)	**-47.0%**
Total Build Time	53.9 days (1295 hrs)	30.8 days (739 hrs)	**-42.9%**

Support Structure



RS-25 HEX Part (High Productivity)



Dimensional scan with point cloud (mm)

The U.S. casting and forging industry faces challenges related to capability and capacity, workforce, and U.S. Government policies

Reductions Across Foundries

- With a **67% reduction in the number of U.S. foundries since 2000**, the U.S. Castings and Forgings ecosystem supply chain is clearly dwindling

Customer Prioritization

- High-quality, domestic purveyors of castings and forgings tend to **prioritize high-value/high-quantity customers** such as in automotive and other high-demand industries

DoD Supply Chain Implications

- The **DoD's high mix/low volume quantities** are **not as profitable for domestic foundry operations**

The challenges with the CF supply chain can pose immediate risks to our national security interests and wartime readiness for critical platforms

Fortunately, AM has shown potential to improve CF lead times

America Makes is leading the way by convening AM and CF ecosystems to strategically assess opportunities for augmenting casting and forging with additive manufacturing.

Roadmap Objectives:

Identified the significant issues affecting CF supply chains and their common characteristics

Prioritized and mapped AM opportunities to those issues, defined the **scope and investment** required

Examples may include:

- Leveraging AM for Tooling
- Leveraging AM for Replacement Parts
- Hybrid Manufacturing

Determined what infrastructure is needed to address the challenges identified

America Makes

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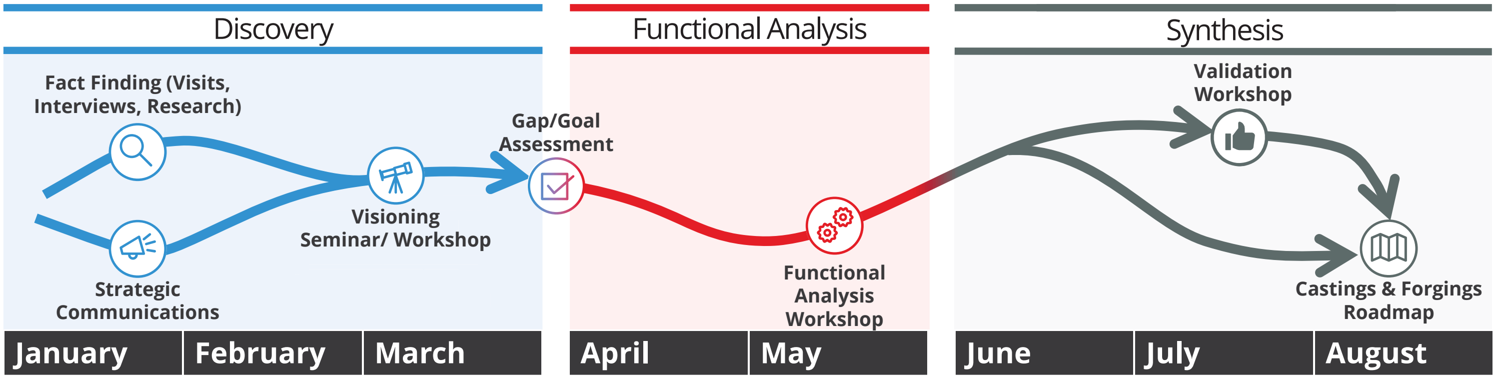
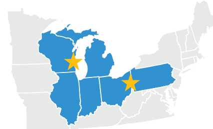
The Journey



- *Identified **100** articles and peer-reviewed them for **technical solutions***
- *Conducted **41 expert** interviews*

*Identified industry **Pain Points** and **Opportunities** for AM*

***4 workshops** in Milwaukee and Youngstown; representing casters, forgers, and the DIB*



** Blue illustrates where the casters and forgers who participated are located*

131 Workshop Participants

96 Organizations Represented

4 Swim Lanes

21 Technical Projects

America Makes

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Insights + Key Discoveries

KEY THEMES:

AM for Tooling	**AM for tooling is the most feasible solution** as the final part is not being altered, easing qualification requirements while speeding up the time to get tooling and lowering the cost
Confidence in AM	Due to underdeveloped standards and limited characterization of the material properties, there is a **general lack of confidence in the repeatability of AM** compared to casting and forging
Modeling and Simulation	Desire to **improve modeling and simulation tools** to improve decision-making, increase confidence in part performance, and speed up the qualification process
Assisted 3D model creation	Desire for **improved tools** to assist with converting **2D drawings to 3D CAD models** when the drawing exists and **tools for reverse engineering** when it does not
Workforce Enablement	**Workforce enablement** was cited as a current pain point with CF, and as a gap to implementing AM solutions

TOP PAIN POINTS

- The qualification process is challenging, lengthy, and costly
- The wealth of knowledge in the DIB is declining
- Converting 2D drawings to 3D CAD models
- Bidding on low volumes is too risky
- Tooling can be difficult to manage

TOP OPPORTUNITIES

- Modeling & simulation to improve the design process
- Printed tooling for forgings and castings
- AM for tool & equipment repair to keep manufacturing “in the fight”
- AM for hybrid manufacturing
- Tools/guides to assist with technology selection and design

What Is Needed to Succeed

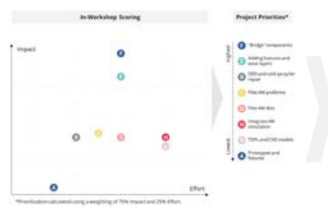
KEY INGREDIENTS:

- **Path to Print** — Playbooks to deploy AM technology for patterns, molds, dies, and repairs
- **Shared Understanding** — Common guidance on when to print, capable vendors, and how to measure performance
- **Integrated Tools** — AM material property predictions as input to broadly used software
- **Digital Foundation** — Common TDP structure with processes to build digital stockpiles
- **Sustainable Training** — Accessible AM resources contained and grown within Casting and Forging communities

Casting Project Priorities and Impact

- Reduced NRE cost
- Reduced variation
- Removed bottlenecks with parallel path
- Improved confidence in AM outcomes

Forging Project Priorities and Impact



- Extended tooling life
- Simplified supply chain
- Reduced cost/time of tooling repair
- Increased process flexibility

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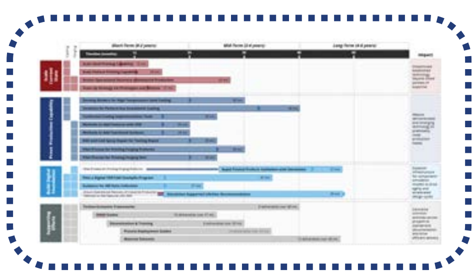
Elements of a U.S. Casting and Forging Roadmap

The Roadmap consists of 5 key elements: 1) swim lanes demonstrating the focus areas; 2) stages organized into 3 phases; 3) projects that collectively enable a capability; 4) ecosystem(s) that the projects apply to; and 5) impact in support of DoD's mission



Swim Lanes

Focus areas that structure the implementation of initiatives and facilitate organization of resources to execute

Stages

Time horizons broken into three distinct phases: near-term (0-2 years), medium-term (2-4 years), and long-term (4+ years)

Projects

Targeted actions in support of program objectives through strategic alignment and drive the planning and execution phases

Ecosystem(s)

Designation of whether the individual projects apply to the casting and/or forging industry

Impact

Comprehensive value that each swim lane will drive; includes stakeholder benefits and aligns with the future vision

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The Roadmap Structure

1 Roadmap

21 Projects

4 Swim Lanes

Scale Current State	**Disseminate established technology beyond siloed pockets of expertise**
Prove Production Capability	**Mature demonstrated and emerging technology to predictably meet production needs**
Build Digital Foundation	**Establish infrastructure for component/simulation models to drive agility and accelerated design cycles**
Supporting Efforts	**Centralize shared activities across projects to standardize documentation and drive efficient delivery**

Making the Roadmap Actionable

Implementation Activities
Identified over three stages: near-term, mid-term, and long-term

Impact, Output, and Outcomes
Results and products of project delivery

Interdependencies
Connectivity outlined across projects, lines of effort, and sub-tasks

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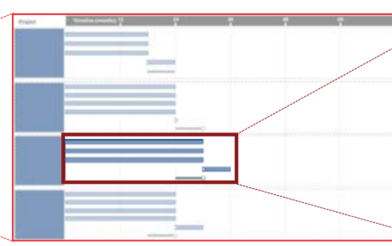
Navigating the Roadmap

ROADMAP LEVEL

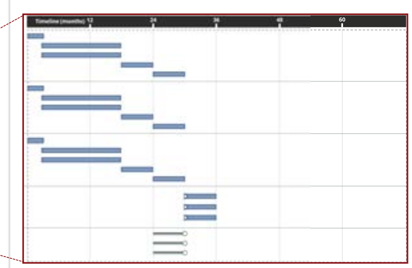
The highest level depicts the multi-year view of all projects, summarizing their attributes and impacts. It provides the framework for down-selecting projects and their activities for funding, organizing the overall projects by applicable ecosystem (casting/forging) and area of focus (swim lane).

SWIM LANE LEVEL



The swim lane level organizes projects that aim to achieve similar outcomes, and are delineated along the lines of technology maturity and the digital-physical nature of AM. This level of the roadmap presents a deeper look into each swim lane and its projects.

PROJECT LEVEL



The project level details execution plans that drive individual activities to a specific application domain and outcome. They provide a structured and comprehensive breakdown that describes the attributes of priority, schedule, and results (output, outcomes, and impact).

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Casting Projects Overview

Scale Sand Printing Capability	Disseminate leading practices and promote adoption of 3D printed sand molds/cores
Scale Pattern Printing Capability	Develop and disseminate leading practices and promote adoption of 3D printed patterns for casting
Develop Binders for High Temperature Sand Casting	Develop enhanced binder materials and strategies to drive processing efficiency of 3D printed sand
Ceramics for Pattern-less Investment Casting	Mature ceramic AM technology to enable rapid pours into integrated shell and cores
Conformal Cooling Implementation Tools	Develop and disseminate performance-enhancing tools for implementing AM conformal cooling

Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts

Forging Projects Overview

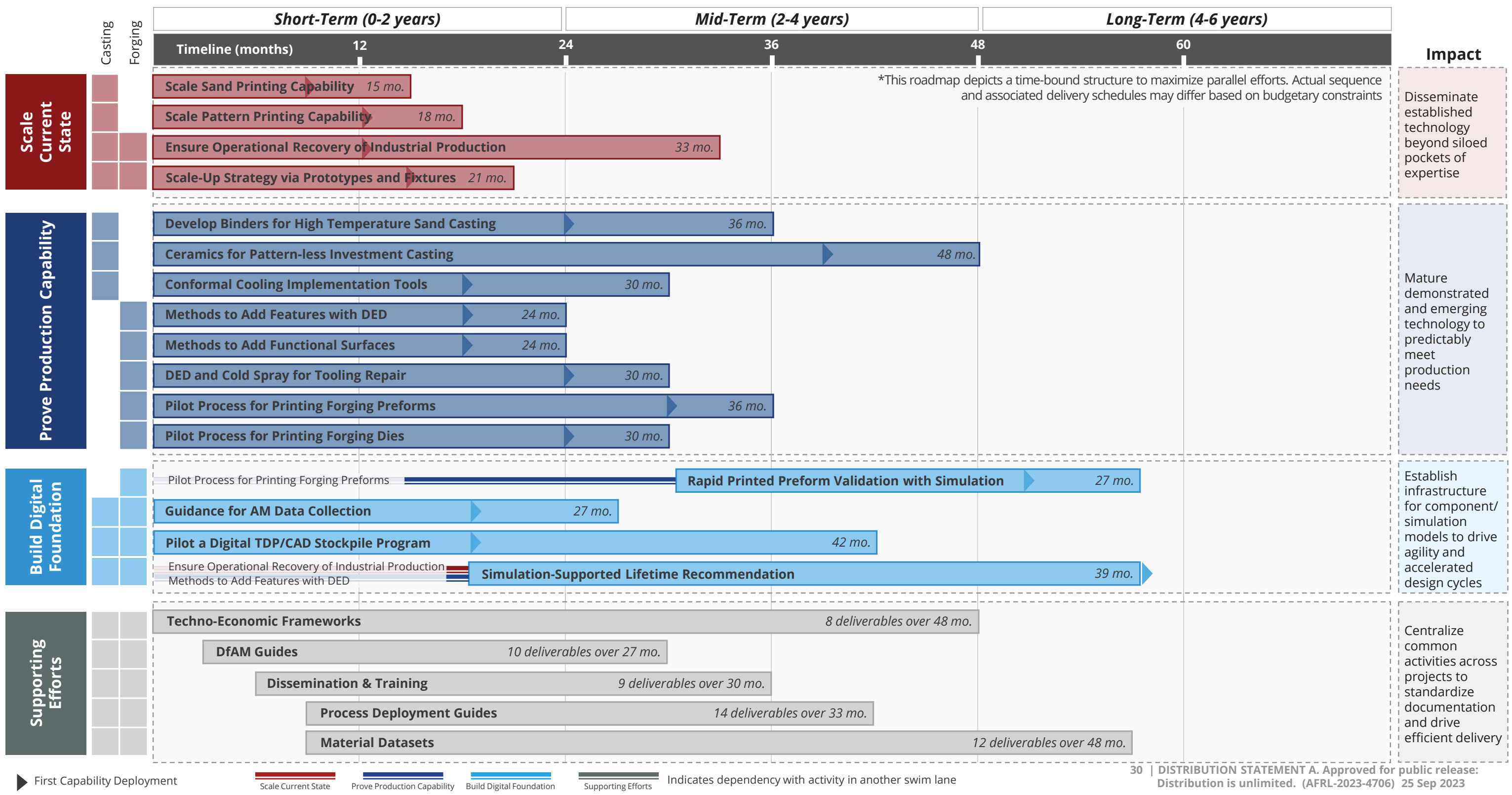
Methods to Add Features with DED	Established, assess, and demonstrate transferable capability to add complex geometric features to forgings
Methods to Add Functional Surfaces	Established, assess, and demonstrate transferable capability to add functional surfaces to forgings
DED and Cold Spray for Tooling Repair	Establish methods for planned and unplanned tooling repair and modification applications
Pilot Process for Printing Forging Preforms	Pilot the industrialization of AM preforms to expedite the forging process for low volume components
Pilot Process for Printing Forging Dies	Pilot the industrialization of AM dies to expedite the forging process for low volume components
Rapid Printed Preform Validation with Simulation	Enable optimized process setups with predictable performance using preforms with heterogenous microstructures

Shared Projects Overview

Ensure Operational Recovery of Industrial Production	Establish scalable sourcing model for AM industrial equipment replacement parts to keep critical production equipment running
Scale-Up Strategy via Prototypes and Fixtures	Define an optimal dissemination strategy for design/deployment guides through prototypes & fixtures
Guidance for AM Data Collection	Establish data infrastructure and application-based guidance to collect store data spanning AM process flows
Pilot a Digital TDP/CAD Stockpile Program	Accelerate the creation of TDPs and CAD models for legacy components by building a program of record for continued conversion
Simulation-Supported Lifetime Recommendation	Develop material and geometric performance software solutions to integrate into DoD process flows
Techno-Economic Frameworks	Drive AM utilization by establishing frameworks that clearly define when, where, and how to print feasibly and economically
Design for Additive Manufacturing Guides	Enable confident and efficient usage of AM by documenting proven design rules across parts, tooling, and accessories
Dissemination & Training	Scale the adoption of technical development with focused and strategic communication to build a pipeline of SMMs ready to leverage AM capabilities
Process Deployment Guides	Build delivery mechanisms for technical development by documenting clear and tested procedures for implementing and controlling AM processes on the shop floor
Material Datasets	Enable cross-functional sharing with standardized management and storage of material data gathered during development activities

Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts

Additive Manufacturing Technology Roadmap for Castings and Forgings



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No Regrets Next Steps

It is imperative to enhance national security by maturing our industrial base with investments that free up CF capacity and streamline throughput

Lower adoption risk by disseminating resources and tools to make informed decisions for when to use AM.

Invest in technology deployment by transferring key capabilities and outcomes to the shop floor

Incentivize knowledge sharing by early adopters to replicate advanced capabilities at scale across the industrial base

Incorporate non-technical solutions to policy and workforce issues that will generate long-term success

To improve our nation's wartime readiness, we must address CF supply chain challenges and build on the momentum generated during roadmap development through continued ecosystem collaboration and targeted investment

Scale Current State

Roadmap | **Scale Current State** | Prove Production Capability | Build Digital Foundation | Supporting Efforts

Scale Current State

	Short-Term		Mid-Term		Long-Term		
Project	Timeline (months) 12	24	36	48	60	**Time to Deployment & Total Duration (months)**	**Impact**

Project	Activities	Time to Deployment & Total Duration (months)	Impact
Scale Sand Printing Capability (Casting)	Molds for Aluminum Sand Casting Molds for Magnesium Sand Casting Supporting Efforts Transferability Demonstration	• First Deployment: 9 • Total Duration:15	• Increase supply base quoting for low-volume DoD parts • Realize 20%+ improvement in throughput
Scale Pattern Printing Capability (Casting)	Patterns for Aluminum Investment Casting Patterns for Nickel Investment Casting Supporting Efforts Assess Scalability of Post-Processing Automation Transferability Demonstration	• First Deployment: 12 • Total Duration:18	• Reduced engineering development cost by 10%+ • Demonstrate 25%+ lead time reduction potential
Ensure Operational Recovery of Industrial Production (Casting and Forging)	Supplier Network Risk-Based Selection Framework Techno-Economic Framework Common Data Model Deployment - Shop 1 Deployment - Shop 2 Deployment - Shop 3 Deployment - Shop 4 Deployment - Shop 5 Supporting Efforts	• First Deployment: 12 • Total Duration: 33	• Drive reduction in equipment downtime • Build common understanding of when and how to implement industrial equipment replacement parts

First Capability Deployment | Deliverable | Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts | **Indicates this activity is interdependent of an activity in another swim lane**

Roadmap | Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts

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Scale Current State

Project	Short-Term / Mid-Term / Long-Term — Timeline (months) 12, 24, 36, 48, 60	Time to Deployment & Total Duration (months)	Impact
Scale-Up Strategy via Prototypes and Fixtures (Casting and Forging)	Machining Fixtures Inspection Fixtures Assembly Fixtures Prototypes for Parallel Path Development Strategy Assessment Supporting Efforts	• First Deployment: 15 • Total Duration: 21	• Shorten development cycles by 10%+ by parallelizing activities • Build a common training and knowledge dissemination strategy

First Capability Deployment | Deliverable | Scale Current State | Prove Production Capability | Build Digital Foundation | Supporting Efforts | **Indicates this activity is interdependent of an activity in another swim lane**

Scale Sand Printing Capability

Disseminate leading practices and promote adoption of 3D printed sand molds/cores

Casting Forging

Timeline (months) 12, 24, 36, 48, 60

Molds for Al Sand Casting	As-Cast Model & Mold Generation Model-Assisted Design Methods FAI
Molds for Mg Sand Casting	As-Cast Model & Mold Generation Model-Assisted Design Methods FAI
Supporting Efforts	Techno-Economic Framework DfAM Guide for Printing Sand Molds Dissemination & Training
Transferability Demonstration	Aluminum Sand Casting Magnesium Sand Casting

First Capability Deployment | Deliverable | Supporting Efforts

Priority, Cost, & Duration

Priority: 1
Casting Projects

15 Months
Total Duration

Output, Outcomes, and Impacts

Output
- Techno-Economic Framework
- DfAM Guide for Printing Sand Molds

Outcomes
- 2 material systems characterized: Aluminum and Magnesium
- 2 tailored products designed, manufactured, and validated

Impact
- Increase supply base quoting for low volume DoD parts
- Realize 20%+ improvement in throughput

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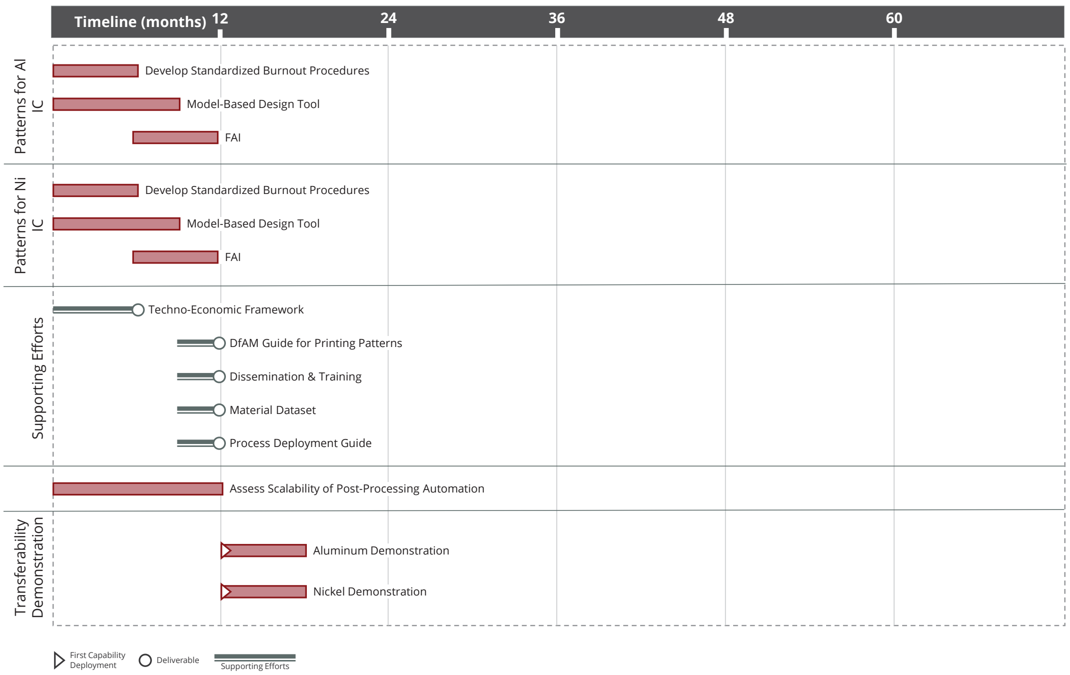
Scale Pattern Printing Capability

Develop and disseminate leading practices and promote adoption of 3D printed patterns for casting

Casting Forging



Priority, Cost, & Duration

Priority: 5
Casting Projects

18 Months
Total Duration

Output, Outcomes, and Impacts

Output
- Techno-Economic Framework
- DfAM Guide for Printing Patterns
- Material Dataset
- Process Deployment Guide

Outcomes
- 2 material systems characterized: Aluminum and Nickel
- 2 products assess through FAI
- Transferability of outcomes assessed

Impact
- Reduced engineering development cost by 10%+
- Demonstrate 25%+ lead time reduction potential

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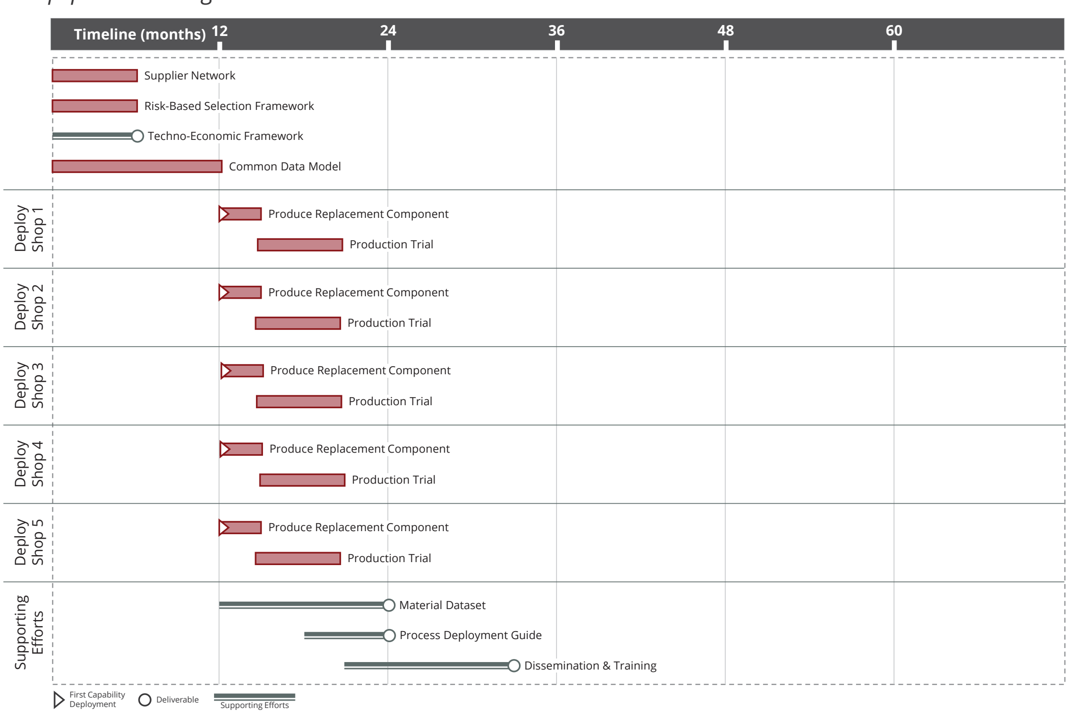
Ensure Operational Recovery of Industrial Production

Establish scalable sourcing model for AM industrial equipment replacement parts to keep critical production equipment running

Casting Forging



Priority, Cost, & Duration

Priority: 1
Shared Projects

33 Months
Total Duration

Output, Outcomes, and Impacts

Output
- Common Data Model for Industrial Equipment Replacement Parts
- Techno-Economic Framework
- Process Deployment Guide for Industrial Equipment Replacement Parts (including process selection)

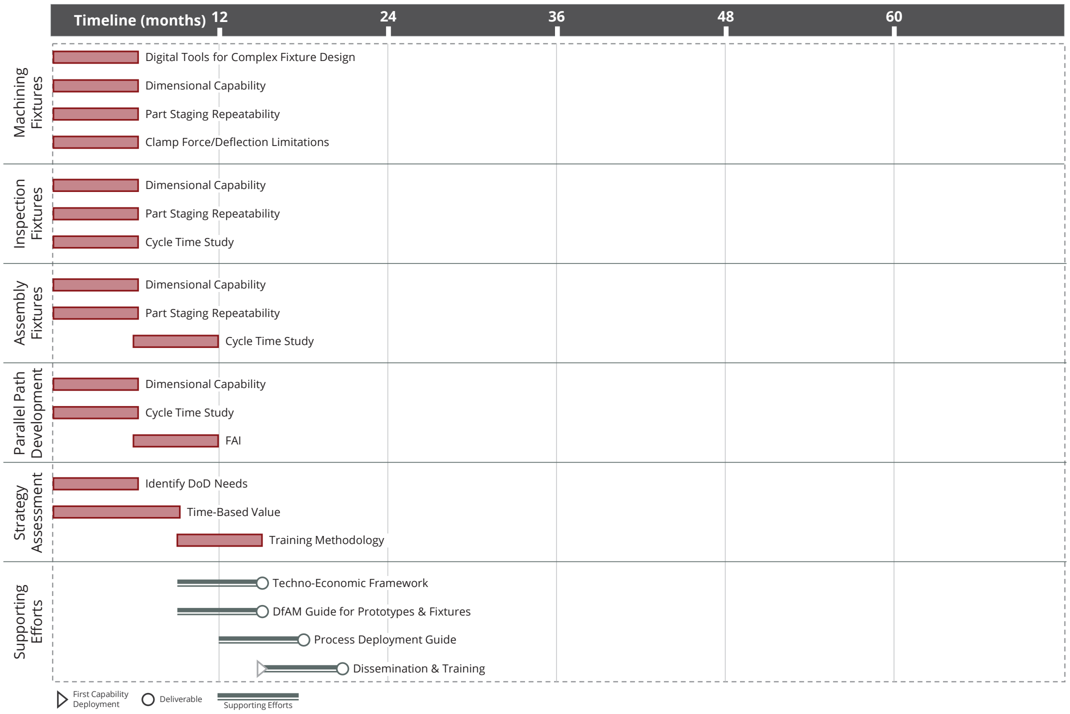
Outcomes
- Produce and Validate 5 Components
- Deploy to 5 production facilities

Impact
- Drive reduction in equipment downtime
- Build common understanding of when and how to implement industrial equipment replacement parts

Scale-Up Strategy via Prototypes and Fixtures

Define an optimal dissemination strategy for design/deployment guides through prototypes & fixtures

Casting Forging



Priority, Cost, & Duration

Priority: 4
Shared Projects

21 Months
Total Duration

Output, Outcomes, and Impacts

Output
- Techno-Economic Framework
- DfAM Guide for Prototypes and Fixtures
- Process Deployment Guide

Outcomes
- 5 products assessed through stages of development cycle
- 3 AM materials assessed through stages of development cycle
    - 2 polymer (ABS/Nylon)
    - 1 composite

Impact
- Shorten development cycles by 10%+ by parallelizing activities
- Build a common training and knowledge dissemination strategy

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When America Makes America Works

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ASME Additive Manufacturing Codification Workshop on Advanced Manufacturing Technologies for Nuclear Applications

October 26, 2023
Rockville, Maryland

George Rawls
GBR Consulting
Aiken, SC
Teresa Melfi
Lincoln Electric Corp.
Cleveland, OH

ASME
SETTING THE STANDARD

ASME Codification of Additive Manufacturing

- The ASME goal is to have AM requirements in ASME Construction Codes and Product Standards with the 2025 Editions with Code Cases preceding the 2025 Edition.
- The ASME Special Committee on AM has drafted criteria for two Code Cases for Additive Manufacturing.
  - AM Construction of Pressure Equipment using the Direct Energy Deposition Process with Wire Feedstock.
    - Includes Gas Metal Arc Process.
  - AM Construction of Pressure Equipment using the Powder Bed Fusion AM Process.
    - Includes Laser and Electron Beam Energy Sources.
    - The material property verification testing in the PBF Code Case is being update to be parallel to the DED Criteria.
- The maximum design temperature shall be at least 50°F (25° C) colder than the temperature where time-dependent material properties govern.

Tee Built using PBF
4" Diameter x 8" Tall ≅ 50 lbs.
(Rolls-Royce)

Valve Built Using Gas Metal Arc DED
8" Valve ≅ 1000 lbs.
(EPRI/ Lincoln Electric)

ASME
SETTING THE STANDARD

ASME Codification of Additive Manufacturing

- **PBF and DED Criteria**
- Both the PBF and DED criteria provide the needed requirements for the materials, design, fabrication, examination, inspection, testing and quality control.

  - Powder Bed Fusion
  - Scope
  - Additive Manufacturing Specification
  - Materials
  - Thermal Treatment
  - Powder Requirements
  - Design Requirements
  - PBF Procedure
  - Procedure Qualification Builds
  - Production Builds
  - Chemical Composition Testing
  - Mechanical Property Testing
  - Metallographic Evaluation
  - Referenced Standards
  - Definitions
  - Records
  - Quality Program

  - Direct Energy Deposition
  - Scope
  - Additive Manufacturing Specification
  - Materials
  - Thermal Treatment
  - Design Requirements
  - Welding Qualification (Section IX, Article VI)
  - Procedure Qualification Builds
  - Production Builds
  - Chemical Composition Testing
  - Mechanical Property Testing
  - Metallographic Evaluation
  - Referenced Standards
  - Definitions
  - Records
  - Quality Program

ASME SETTING THE STANDARD

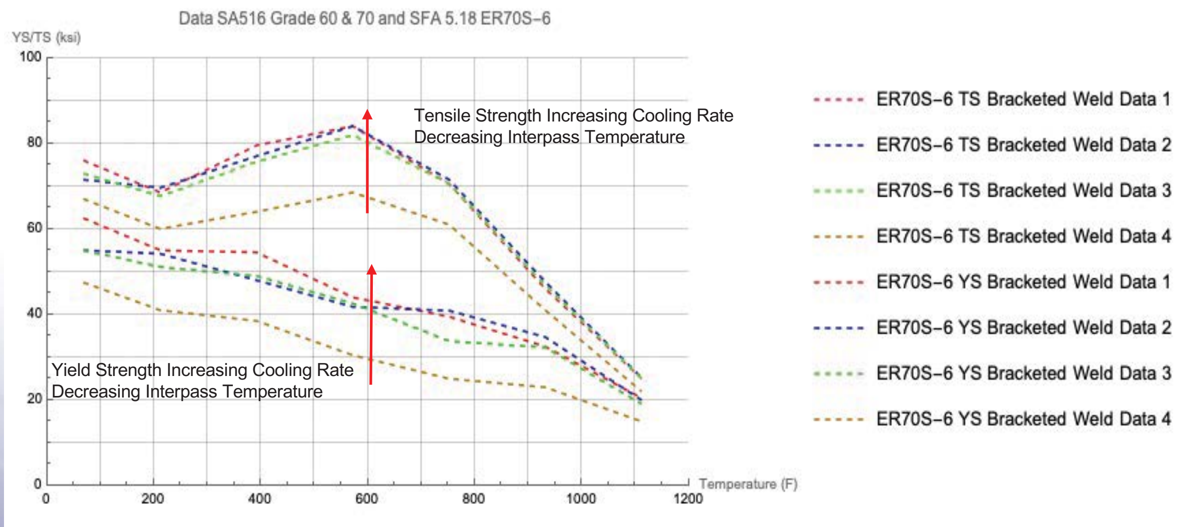
ASME Codification of Additive Manufacturing

- **Allowable Stress Values for DED AM Weld Metal**
- The ASME AM Committee and BPVC Section II have developed criteria for verification testing AM Material to ensure mechanical properties.
  - What criteria and verification testing is needed to enter the allowable stress tables in ASME BPVC Section II Part D and use base metal property data for the allowable stress values for AM deposited weld metal?
    - Tensile data for deposited weld metal needs to show the same trends with temperature for properties between the deposited metal and base metal.
    - Verification testing to address heat input and cooling rates for the AM deposited weld metal.
    - ASME BPVC has an extensive successful experience with welding in a wide verity of materials and services.
- Heat input and cooling rate, which are Additive Manufacturer process dependent, and PWHT control the final tensile properties.
  - Different criteria are needed for acceptance of AM material because of the variability in tensile properties for a given filler material with heat input and cooling rate.
  - The current Section II Appendix 5 process for new materials is impractical for AM because of the variability in heat input and cooling rate.

ASME SETTING THE STANDARD

ASME Additive Manufacturing

- **Tensile Properties for Weld Metal and DED Sample Builds**
  - Data for ER70S-6 Filler - Variability in material properties for a given filler material with heat input and cooling rate.
  - Lincoln Electric Design of Experiments Project

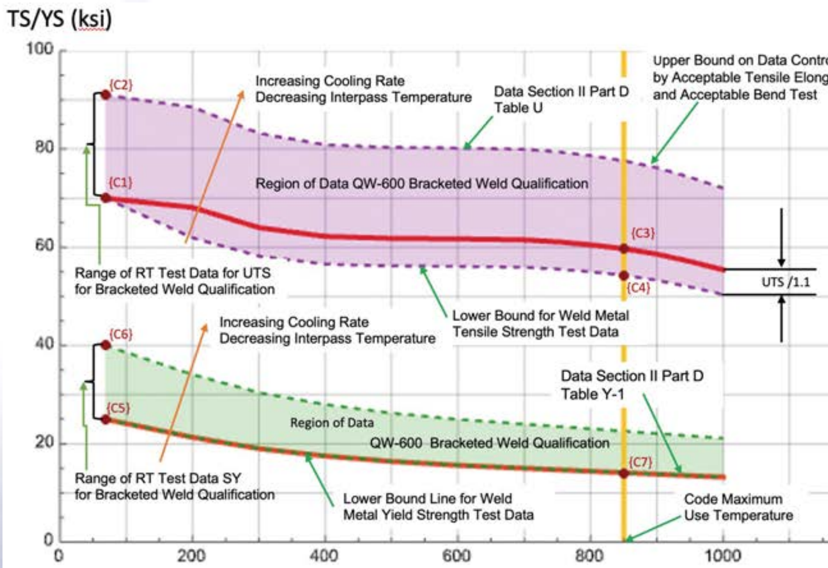


ASME Codification of Additive Manufacturing

- **Tension Test Requirements in ASME BPVC Section IX Article VI Bracket Weld Qualification is required in the DED Criteria.**
- Additive Material Manufacturing Procedure Qualification Requirements.
  - Required for each filler material.
  - Minimum of 4 Tension Tests – 2 High Cooling Rate – 2 Low Cooling Rate.
  - Minimum of 4 Bend Tests – 2 High Cooling Rate – 2 Low Cooling Rate.
- Additional Testing Required by the AM DED Criteria.
  - One (1) additional high temperature tension test from low cooling rate temperature QW-600 weldment.
  - Analyze tensile test data to calculate the minimum required room temperature tensile properties for the AM Qualification Builds and Production Builds.

ASME Codification of Additive Manufacturing

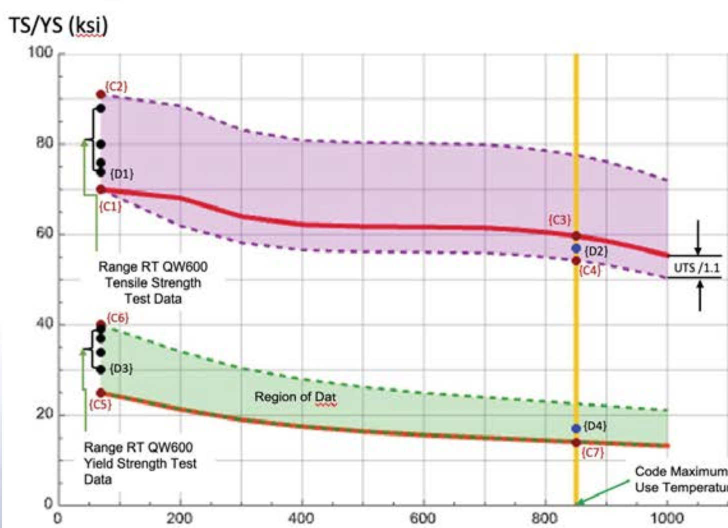
- **Bounding Criteria for DED Bracketed Weld Qualification**



Point	Temperature (°F)	Strength (ksi)	Description	Criteria
C1	Room	TS	Specified Minimum Tensile Strength	Specified Minimum Tensile from Material Specification
C2	Room	TS	Upper Bound of Tensile Strength	Elongation from Tension Test data is Equal to the Specified Minimum Value in the Material Specification
C3	Maximum Use	TS	Value from Table U at Maximum Use Temperature	From Section II Part D Table U
C4	Maximum Use	TS	Minimum Acceptable Value of Tensile Strength for High Temperature Test	Point 3/1.1 Value from Table U at Maximum Use Temperature Divided by 1.1
C5	Room	YS	Specified Minimum Yield Strength	Specified Minimum Tensile from Material Specification
C6	Room	YS	Upper Bound of Yield Strength	Elongation from Tension Test data is Equal to the Specified Minimum Value in the Material Specification
C7	Maximum Use	TS	Value from Table Y-1 at Maximum Use Temperature Minimum Acceptable Value of Yield Strength for High Temperature Test	From Section II Part D Table Y-1

ASME Codification of Additive Manufacturing

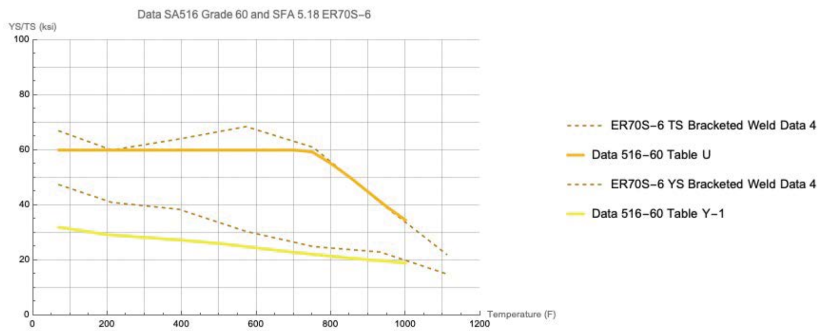
- **Bounding Criteria for DED Bracketed Weld Qualification**
  - Showing Example Test Data

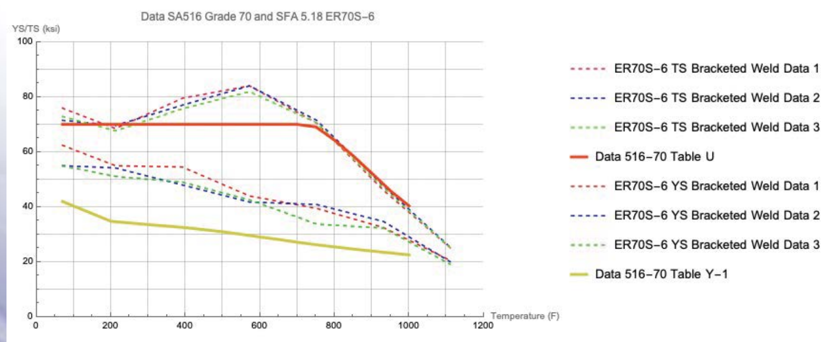


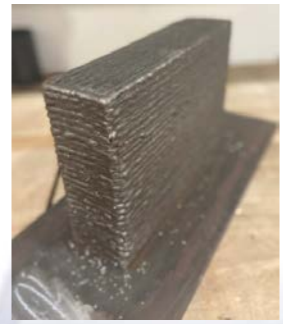
Point	Temperature (°F)	Strength (ksi)	Description	Criteria
D1	Room	TS	Minimum Value of Tensile Strength from QW 600 Data	Minimum Tensile Strength and Elongation from the QW-600 Tests Shall Equal or Exceed the Specified Minimum Tensile Strength in the Material Specification (Point C1)
D2	Maximum Use	TS	High Temperature Tensile Strength Test Data Point	Minimum Tensile Strength Value from QW-600 Test Shall Equal or Exceed Value Calculated for Point C4
D3	Room	YS	Minimum Value of Yield Strength from QW 600 Data	Minimum Yield and Elongation from the QW-600 Tests Shall Equal or Exceed the Specified Minimum Yield Strength in the Material Specification (Point C5)
D4	Maximum Use	YS	High Temperature Yield Strength Test Data Point	Minimum Yield Strength and Elongation from QW-600 High Temperature Test Equal or Exceed Value of C7
ALL	RT	TS/YS	Range of QW 600 Tensile Data	Elongation from Tension Test is Below Specified Minimum in the Material Specification

ASME Codification of Additive Manufacturing

- ER70S-6 can be qualified for either SA516-60 or SA516-70.
- The effect of heat input and interpass temperature must be addressed for AM
- Verification testing and controls are required at the AM facility.



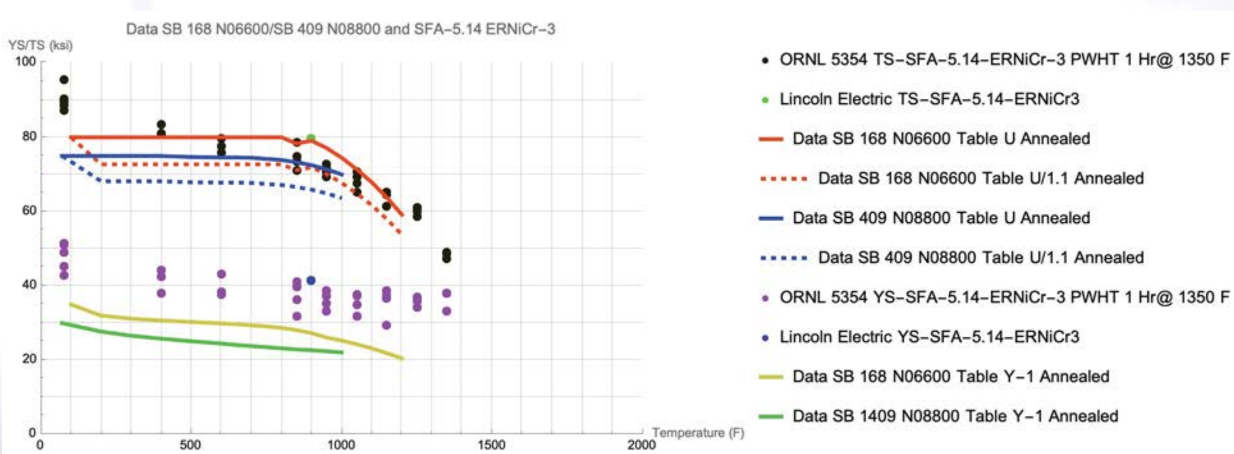




ASME SETTING THE STANDARD

ASME Additive Manufacturing

- ERNiCr-3 compared to SB 168 N06600 and SB 409 N08800
- The ERNiCr-3 Data is from manual welding not DED AM

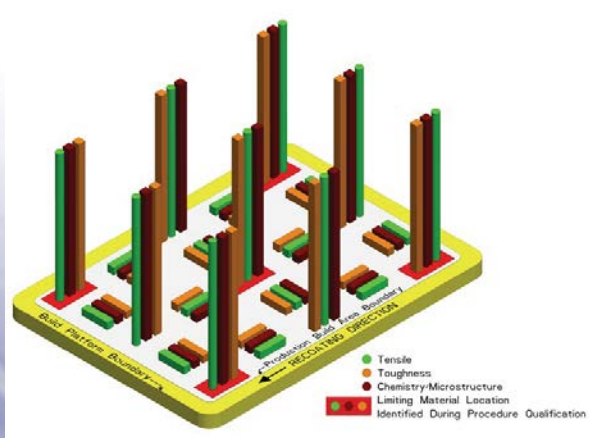


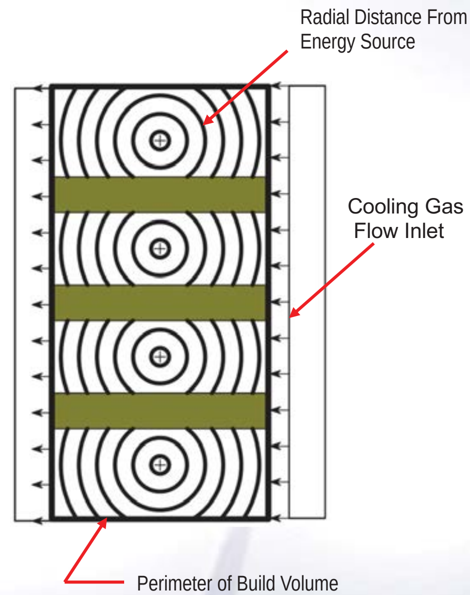
ASME SETTING THE STANDARD

ASME Codification of Additive Manufacturing

- **Additive Manufacturing Procedure**

- The Additive Manufacturer shall identify the locations of limiting material conditions for each energy source
- The qualification builds shall include a minimum of 3 powder lots.
- Understanding material cooling rates





Specimens for PBF Additive Manufacturing Procedure Qualification

ASME Codification of Additive Manufacturing

- The ASME Special Committee AM document “Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing” was published in Pressure Technology Book-13 in May 2021.
- The criteria in PTB-13 has been applied to develop an ASME BPVC Section I Code Case for pressure relief valve bodies using PBF AM

Revisions needed to PTB-13

- The same material property verification testing will be used for PBF that has been developed for DED.
- PTB-13 will be revised to address the PBF process for one-off components vs multiple duplicate components.
- PTB-13 will be used to document the work done to develop the technical baseline for both the PBF and DED AM Processes

ASME Codification of Additive Manufacturing

- **Integration of AM into ASME Codes and Standards**
- **ASME Nuclear and Pressure Technology Code Committee Activities**
- **Section I (Power Boilers)**
  - AM Task Group meeting to incorporate DED AM
  - Issued a PBF Code Case for relief valve parts
- **Section III (Nuclear Facility Components)**
  - AM Task Group has begun incorporation of PBF and DED AM
  - Balloted Code Cases for DED and LPBF for Grade 316L material
- **Section VIII (Pressure Vessels)**
  - AM Task Group has begun incorporation of DED AM
- **B31 (Code for Pressure Piping)**
  - AM Task Group to begin incorporation of AM
  - B31 has issued a review and comment ballet for using DED AM
- **B16 (Standards for Pipes and Fittings)**
  - Formed a Task Group to begin incorporation of AM

ASME SETTING THE STANDARD

Questions ???

ASME SETTING THE STANDARD