In Situ Monitoring for Defect Detection and Certification of AM

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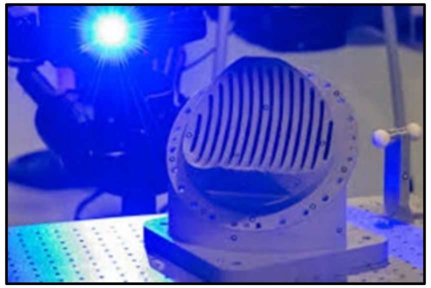
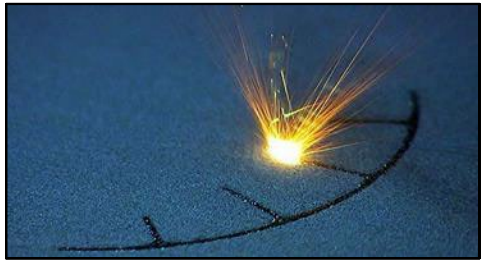
Qualification of In Situ Process Monitoring for Certification of AM Space Hardware

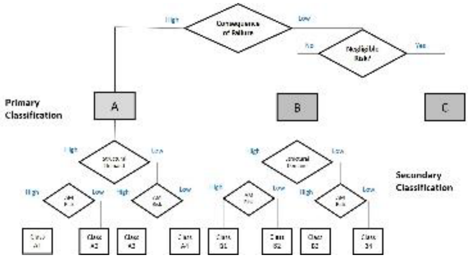
We will discuss NASA's interest in qualifying NDE and in situ monitoring methods for certification of AM space hardware.



NASA's involvement and approach



Qualification of NDE and in situ monitoring

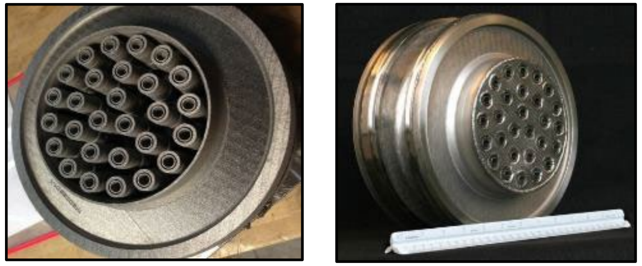


Certification framework

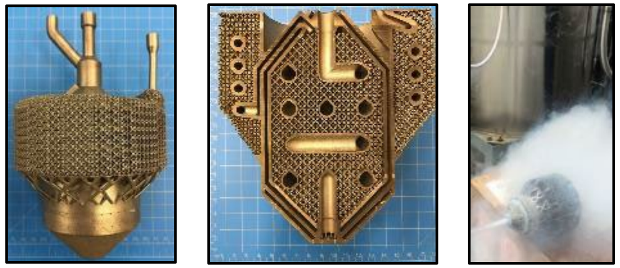
Qualification of In Situ Process Monitoring for Certification of AM Space Hardware

NASA is interested in qualifying in situ monitoring for complex, critical parts that are difficult to inspect using traditional NDE.

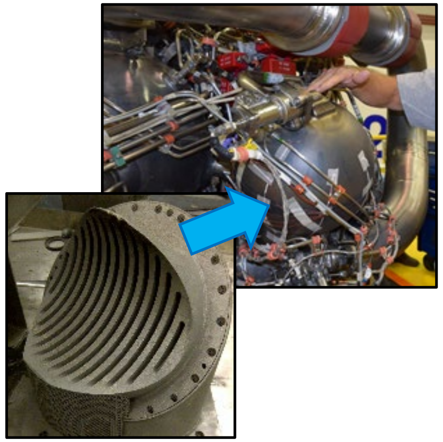
28-Element Inconel® 625 Fuel Injector
Reduced 163 parts to 2
Schedule reduced from 1 year to 4 months
70% cost reduction



Cryogenic Heat Exchanger-Injector-Condenser Demo



Injector Assembly
MSFC Project with Army Air and Missile Defense (AMD)



RS-25 Pogo Accumulator Z-Baffle
Over 100 Welds Eliminated
Nearly 35% Cost Reduction

In Situ Process Monitoring Functions

There are two main functions of in situ process monitoring:

Process Control Function

- Real-time warning of build problems
- Use to check for process drift
- Monitor effects of parameter changes, spatter, etc.

- **Not** counting on it for quantitative part quality metrics or defect detection
  - May help tell you where to look for a problem, but would require verification with NDE

vs.

Part Quality Function

- **Quantitative analysis of part quality**
- Requires a known correlation between indications, physics of the process, and actual defects in the finished part
- Need to know probability of detection
  - Extra step – verify actual size, location of created defects

- Need to **treat it like NDE** – believe and investigate every indication
  - Can't dismiss anything as a false positive unless proven

Challenge Current Paradigm

When considering the use of in situ process monitoring for part qualification, there are a few aspects that challenge the current paradigm.

In-process vs. post-process NDE

- Often, defect observations are indirect
  - Directly observing process variation, inferring final defect
  - Must understand physical basis for measured phenomena
  - Need to prove a causal correlation from measured indications to defect state
- Probability of detection (POD) study must include secondary verification of created defects

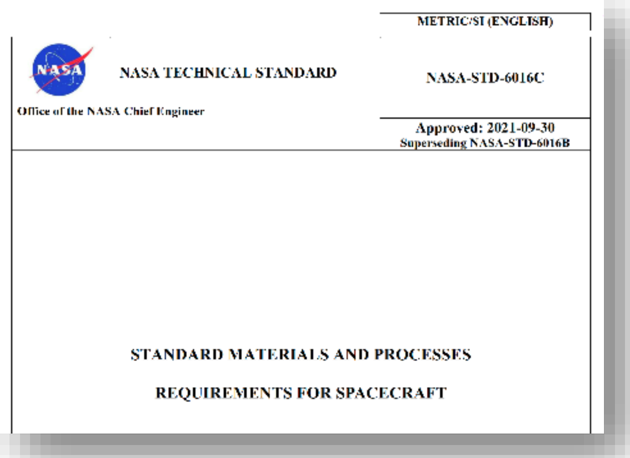
Closed-loop process control

- Current NASA qualification logic based on a locked process
- For real-time parameter changes, a new approach is needed

no longer nondestructive

NASA AM Certification Approach

The current logic of additive manufactured part certification is outlined in NASA-STD-6016C, NASA-STD-6030, and NASA-STD-6033.



METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

NASA-STD-6016C

Office of the NASA Chief Engineer

Approved: 2021-09-30
Superseding NASA-STD-6016B

STANDARD MATERIALS AND PROCESSES
REQUIREMENTS FOR SPACECRAFT

NASA-STD-6016C

General M&P requirements

MSFC-STD-3716

Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

MSFC-SPEC-3717

Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

NASA-STD-6030

NASA Technical Standard

Additive Manufacturing Requirements for Spaceflight Systems

NASA-STD-6033

NASA Technical Standard

Additive Manufacturing Requirements for Equipment and Facility Control

Handbook coming soon with more specifics on implementation.

Qualified In Situ Process Monitoring

Passive in situ process monitoring may be used as a quantitative indicator of part quality, if qualified.

Language:

> "Prior to use as a quantitative indicator of part quality for part acceptance, passive in-situ process monitoring technologies **shall** be ***qualified*** by the CEO to the satisfaction of NASA in a manner analogous to other NDE techniques."

Rationale:

- "All processes that are used to establish quantifiable quality assurance metrics are qualified against established criteria to verify detection reliability, calibration, and implementation. If in-situ monitoring techniques are employed for such purposes, the need for such qualification is unchanged."

(emphasis added)

Qualified In Situ Process Monitoring

Passive in situ process monitoring may NOT replace NDE.

Rationale (cont.):

- "Certification of a passive in-situ monitoring technology relies upon a thorough understanding of the physical basis for the measured phenomena, a proven causal correlation of the measured phenomena to a well-defined defective process state, and a proven level of reliability for detection of the defective process state."
- "If qualified in the manner stated above, an in-situ process monitoring technique can be used to complement NDE in the Integrated Structural Integrity Rationale of the PPP. At this time, even a qualified in-situ process monitoring method cannot be considered a complete replacement for NDE."
- "Even if qualification is not desired, the use of in-situ process monitoring is encouraged as a source of process control data. This data can also be used to help guide targeted inspection."

(emphasis added)

Overview of the In Situ Process Monitoring Qualification Study Efforts

- What: The In-Situ Project
  - Correlating In-situ monitoring data and Non-Destructive Evaluation (NDE) methods to characterize defect populations in Laser Powder Bed Fusion (L-PBF) material
- How: Analyze defect detection capabilities of in-situ monitoring by comparison to traditional NDE using flaws created with controlled off-nominal build parameters and verified by metallography
  - Create samples with known defects on EOS M290
  - Record layer to layer AM process quality with EOState Optical Tomography Monitoring system
  - Compare results using North Star Imaging X5000 Mini-/Micro-Focus CT and UES RoboMet serial sectioning system
- Why:
  - Supports developing roadmap for qualifying in-situ monitoring technologies to support NASA-STD-6030 certification approach
    - Proven causal correlation between indications in in-situ monitoring data and final state of the part
  - Supports Agency Lunar Infrastructure objectives

Context

INFRASTRUCTURE OBJECTIVES

Lunar

Mars

Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

LI-1^{L}:	Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.
LI-2^{L}:	Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs.
LI-3^{L}:	Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs.
LI-4^{L}:	Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.
LI-5^{L}:	Demonstrate precision landing capabilities in support of continuous human lunar presence and a robust lunar economy.
LI-6^{L}:	Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.
LI-7^{L}:	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.
LI-8^{L}:	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.
LI-9^{L}:	Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.

https://www.nasa.gov/sites/default/files/atoms/files/m2m-objectives-exec-summary.pdf

- Certification of Additively Manufactured (AM) parts
  - Advancement on Process Qualification
    - V&V of in-situ monitoring
      - The in-situ project
        - Inadequate traditional NDE methods
        - AM parameters & quality
          - Many, variable results
        - In-Situ monitoring + Machine learning
          - Defect prediction

Introduction

- Current L-PBF process, like any process, can generate material that contains defects:
  - gas porosity trapped in the powder feedstock
  - random fluctuations in laser power output
  - error in the build process: skipped layer or short feed
- Defects have detrimental effect on the properties of the material produced:
  - crack initiation sites
  - reduce safe-life of the component
- Traditional NDE methods are not fully adapted to AM:
  - Limitations in reliably detecting defects in large or complex part geometries
- Development of new approach is necessary:
  - Pairing data from in-situ monitoring with NDE

Objectives

1. Develop L-PBF material defect detection and characterization methodologies
2. Understand the influences of build parameter variations on the resulting material defect populations.
3. Correlate detected defect populations with tensile and fatigue properties.
4. Characterize the effect of heat treatment on the defect populations and their detectability with mini-CT.
5. Evaluate part-to-part and build-to-build defect population repeatability.
6. Establish a preliminary probability of detection for the available in-situ monitoring tools and for mini-CT.
7. Evaluate seeded defect methodologies for realistic defect creation.
8. Baseline defect populations for an established AM process as defined in NASA-STD-6030 Qualified Material Process (QMP).

Simulated Flaws

0%
nominal

Unfused powder

75%
nominal

Lack of fusion

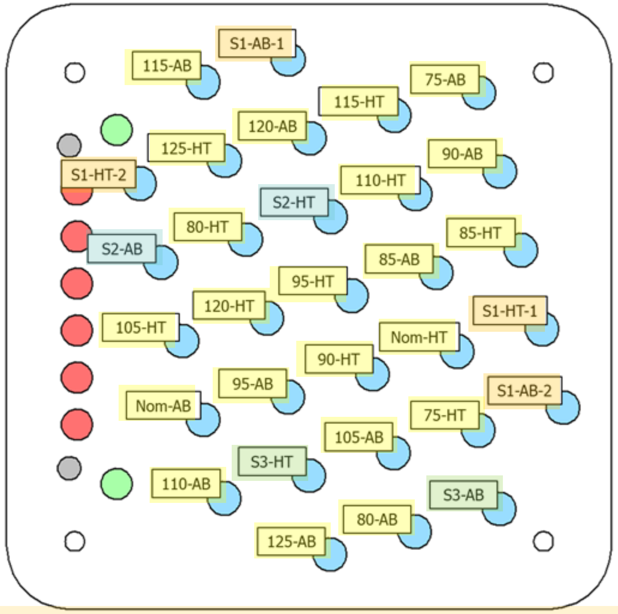
125%
nominal

Keyhole voids

Different laser powers in seeded flaws simulate different flaw conditions

Material: NASA HR-1

Test Plan



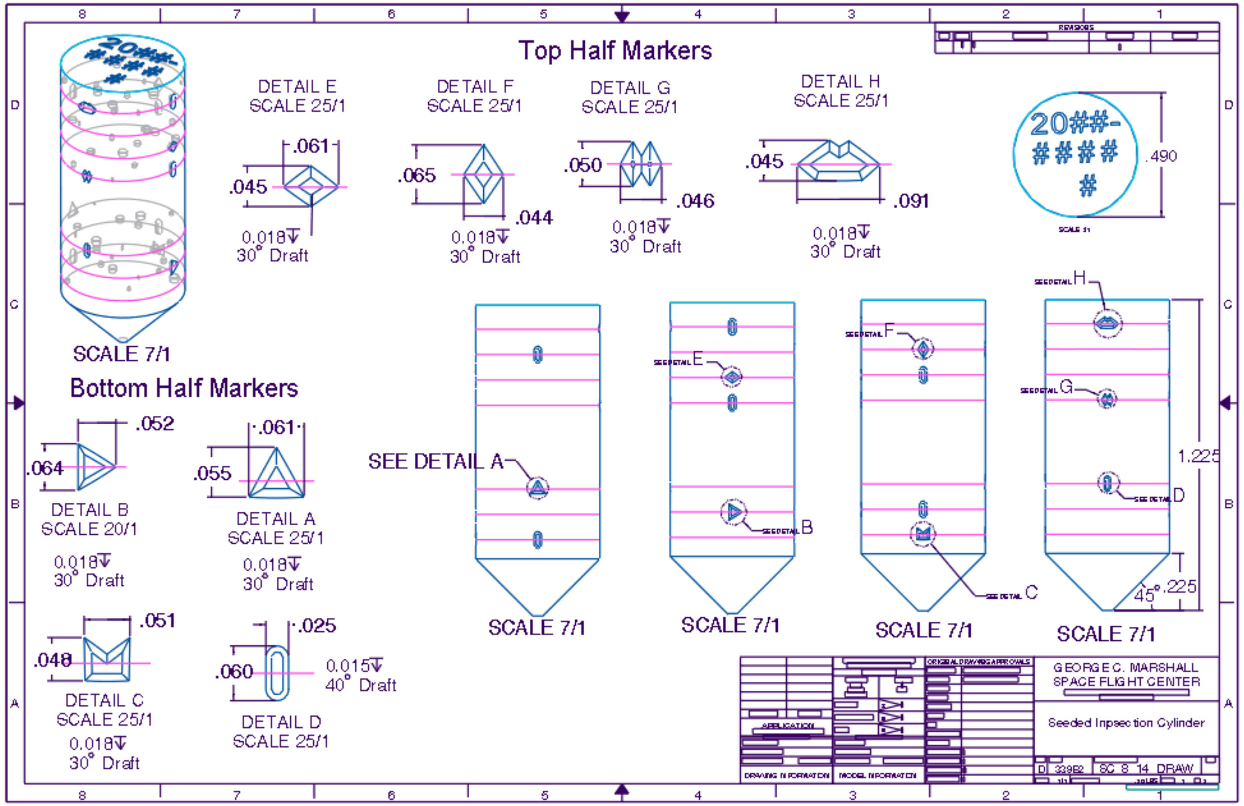
Specimens		
Type	**Qty**	**Color**
Inspection Cylinder	30	🟦
Witness Tensile	6	🟥
Witness HCF	2	🟩
Metallography	2	⬜

S1 samples: Skipped Layer (Unfused Powder) Defects = 0% Laser Power

S2 samples: Low Power (Lack of Fusion) Defects = 75% Laser Power

S3 samples: High Power (Keyhole) Defects = 125% Laser Power

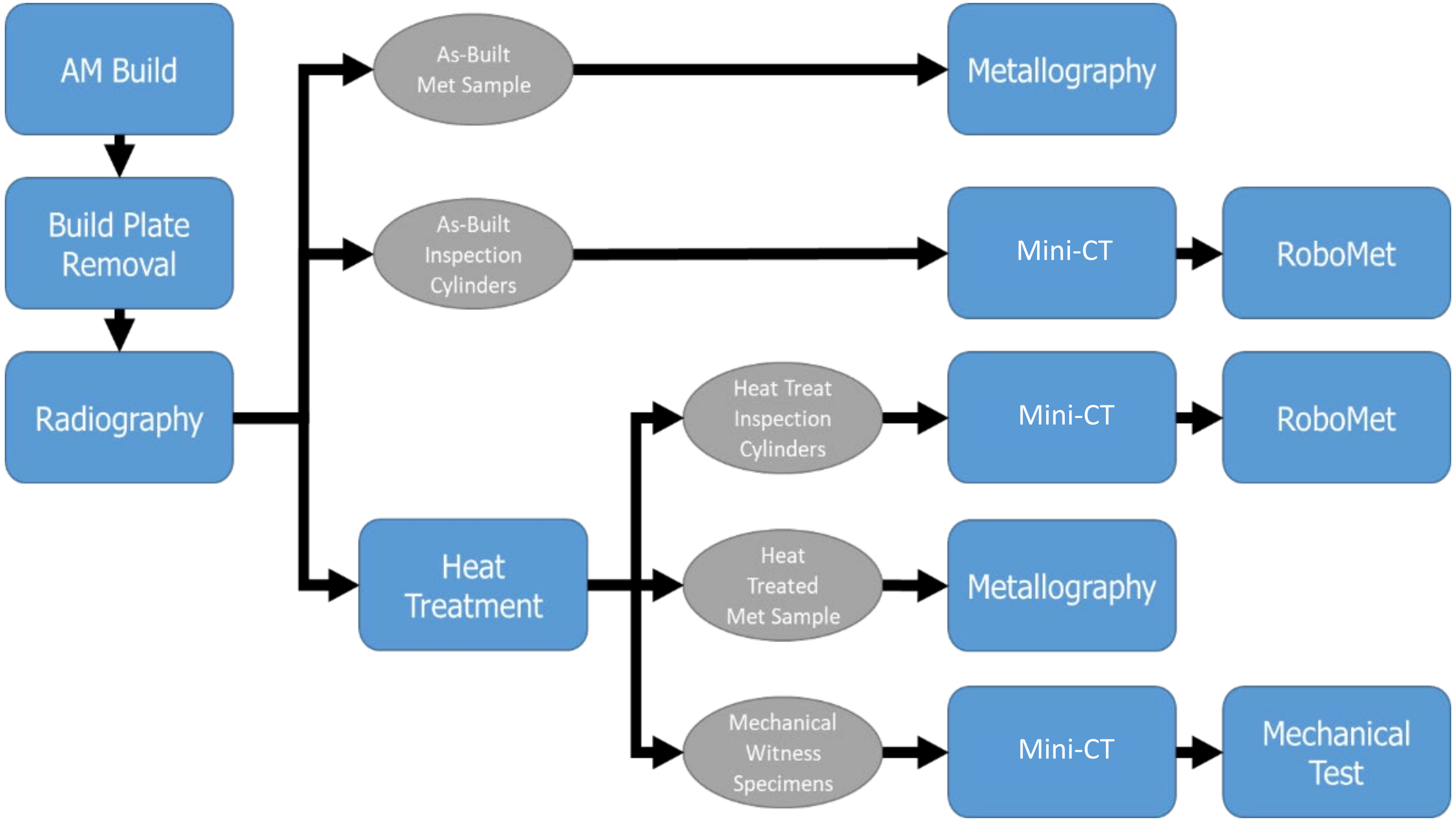
Laser Power Variation samples 75% to 125%



Test Plan

- HR-1 Sample population

- 2 kinds of inspection cylinders
  - Seeded defects (3 types)
    - 7 planes, 7 defects
    - Different thicknesses and diameters
  - Laser power variation
    - 75% to 125%
- Data Collection on samples
  - In-situ monitoring:
    - Optical Tomography
  - NDE
    - Computed Tomography (CT)
  - Metallography
    - RoboMet Serial Sectioning



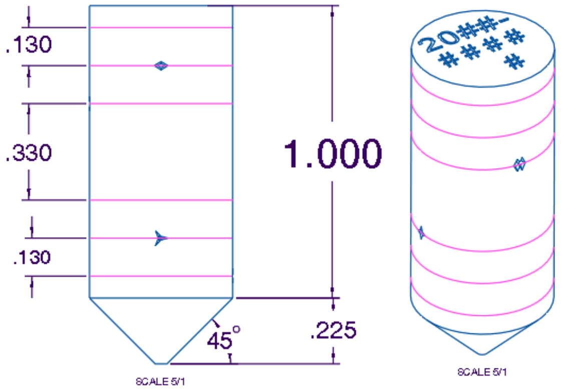
History

- 2 Builds so far
  - First build built with In718 parameters
    - 6 flaws per plane, 6 planes of flaws
    - Seeded flaws 2 to 7 build layers thick
  - Second build built with HR-1 parameters
    - 7 flaws per plane, 7 planes of flaws
    - Seeded flaws 8 to 14 build layers thick

Build 1 Defect Samples Design

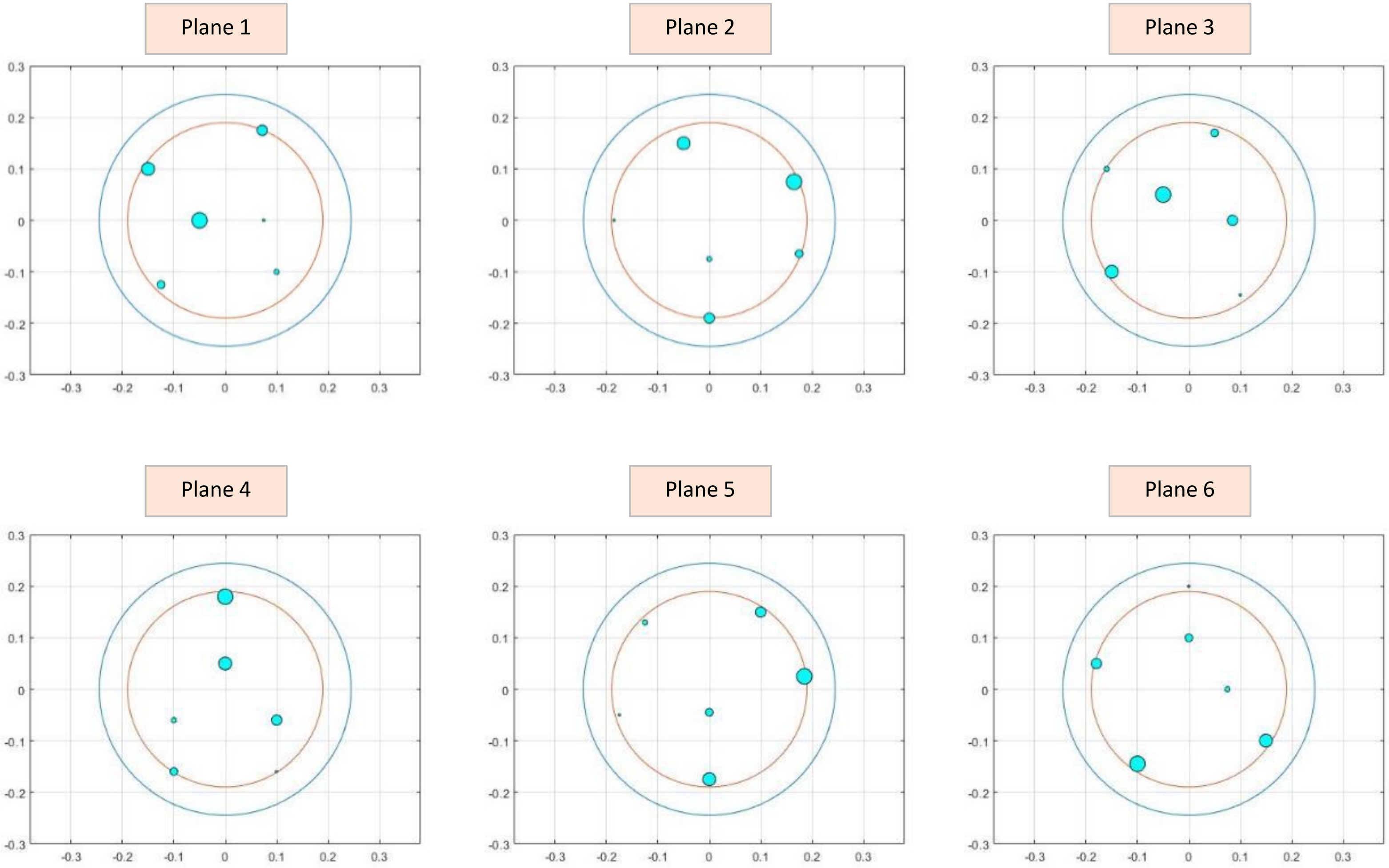
Ø0.490 x 1.0 inch
Inspection Cylinder

Ø0.38 where defects
can be found



All possible Defect Diameters	All possible Thicknesses (in)	Corresponding Thicknesses (µm)	# Layers
0.005"	0.00472”	80	2
0.01"	0.00315”	120	3
0.015"	0.00630”	160	4
0.02"	0.00787”	200	5
0.025"	0.00945”	240	6
0.03"	0.0110”	280	7

Defect Layer Cross Sections (Top View)


Plane 1

Plane 2

Plane 3

Plane 4

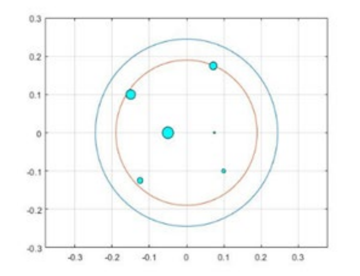
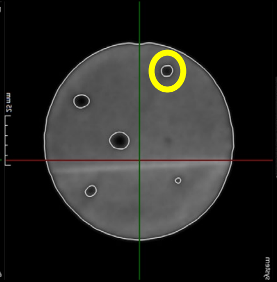
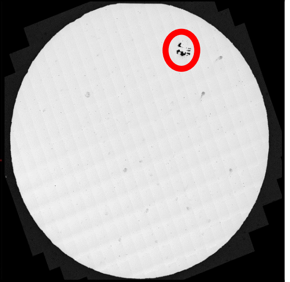
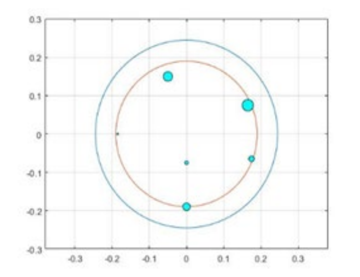
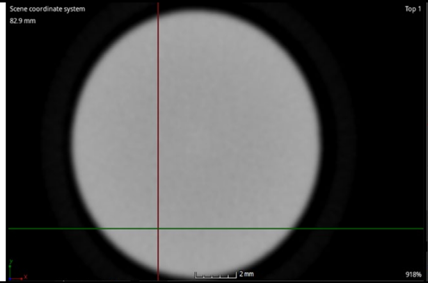
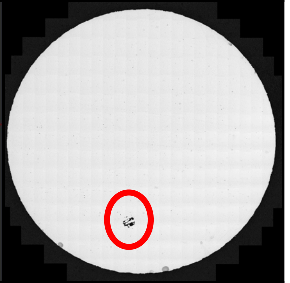
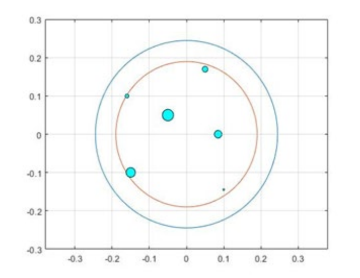
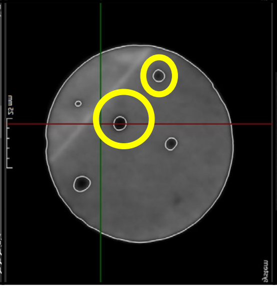
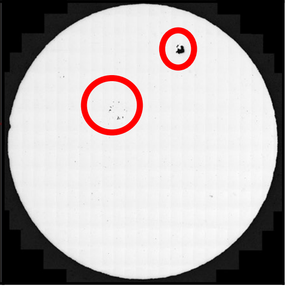
Plane 5

Plane 6

Summary Of Results Build 1 [Pre HT]

- CT showed only one seeded defect
- In-situ monitoring captured an image for every layer showing insertion of seeded defects as designed
- RoboMet slices seeded defect sample at planes 1, 2 & 3
  - 1 or 2 defect remnants per plane: only the higher thicknesses remain

Comparison of Detection Methods for S1-AB-1 (Skipped Layer)

	MATLAB	Mini CT	In-situ	RoboMet
Plane 1				
Plane 2				
Plane 3				

1. S1 samples: Skipped Layer (Unfused Powder) Defects = no power
2. S2 samples: Low Power (Lack of Fusion) Defects = 75% Laser Power
3. S3 samples: High Power (Keyhole) Defects = 125% Laser Power

HT: Heat Treated
AB: As Built

Summary of Build 1 Findings

- Seeded defects were not thick enough to be picked up by NDE methods
  - Mini-CT does not offer high enough resolution to pick up that size defect (~0.00315”-0.00945” = 80-240 microns thickness)
  - To be verified with next build with thicker (more layers) seeded defects: 8 to 14 layers
- Defects “heal” during AM build process
  - Meltpool was deep enough that remaining unfused powder within thinner defects melted with the rest of the part, “healing” the sample

All possible Thicknesses (in)	Corresponding Thickness (µm)	# Layers	Total defects identified by Robomet	Total defects identified by CT	Out of
0.00315”	80	2	0	0	9
0.00472”	120	3	2	0	9
0.00630”	160	4	2	0	9
0.00787”	200	5	7	0	9
0.00945”	240	6	7	0	9
0.0110”	280	7	9	1	9/216

Modifications For Build # 2

Previous designed defects’ thickness ranging from 2 to 7 layers (~40 microns/layer), new build with thickness ranging from 8 to 14 layers (320 – 560 microns) will be created

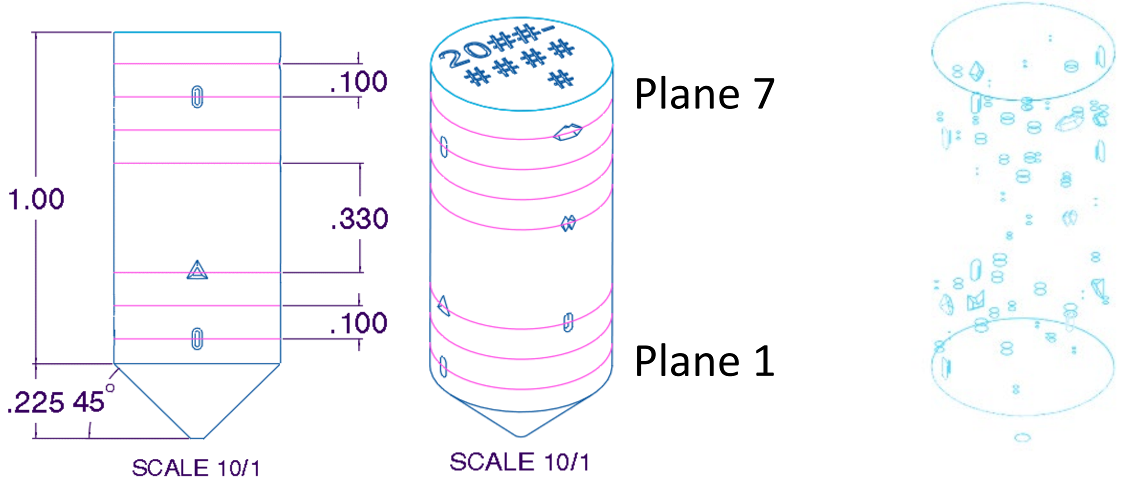
Build 1

All possible Defect Diameters	All possible Thicknesses (in)	Corresponding Thicknesses (µm)	# Layers
0.005"	0.00472”	80	2
0.01"	0.00315”	120	3
0.015"	0.00630”	160	4
0.02"	0.00787”	200	5
0.025"	0.00945”	240	6
0.03"	0.0110”	280	7

Build 2

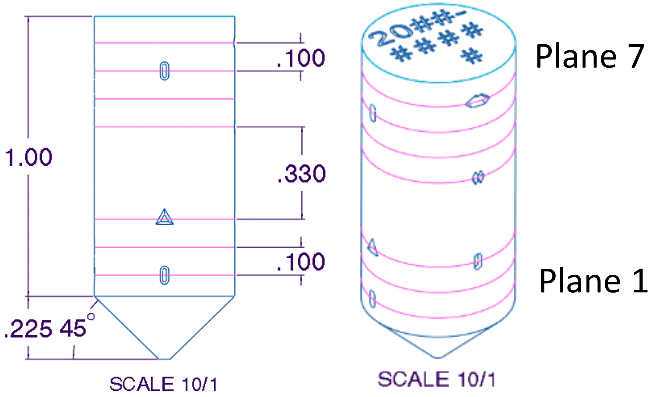
All possible Defect Diameters	All possible Thicknesses (in)	Corresponding Thicknesses (µm)	# Layers
0.005"	0.0126	320	8
0.01"	0.01417	360	9
0.015"	0.01575	400	10
0.02"	0.01732	440	11
0.025"	0.0189	480	12
0.03"	0.02047	520	13
0.035"	0.02205	560	14

Ø0.490” x 1.0”
Inspection Cylinder



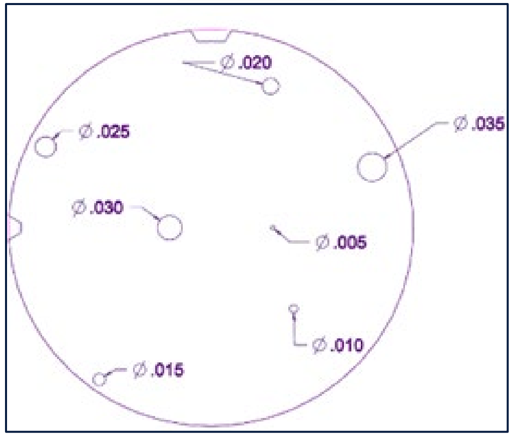
Build 2 Defect Samples Design

Ø0.490” x 1.0”
Inspection Cylinder

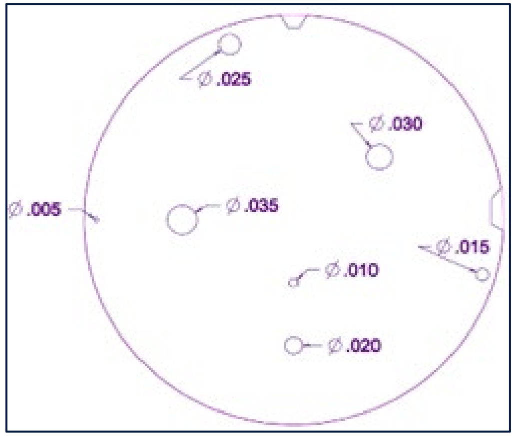


Defect Layer Cross Sections (Top View)

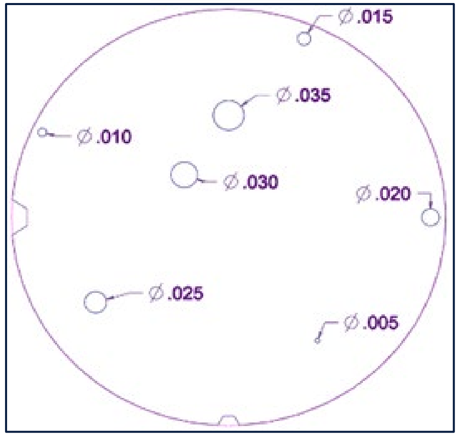
Plane 1



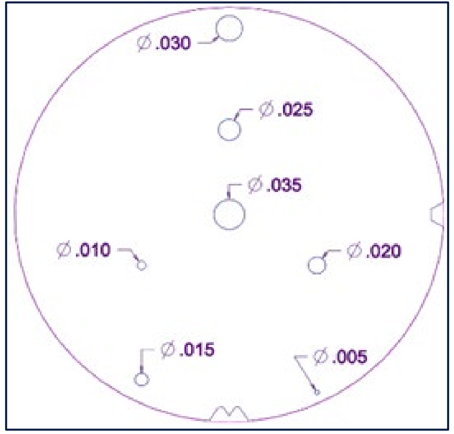
Plane 2



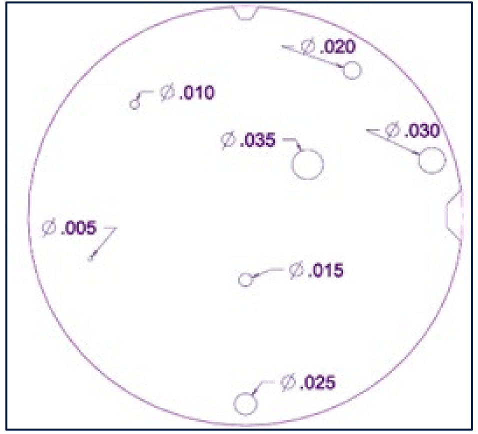
Plane 3



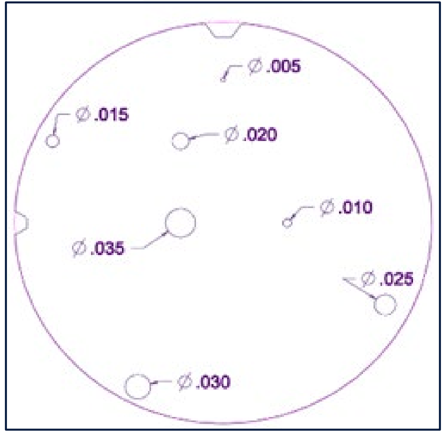
Plane 4



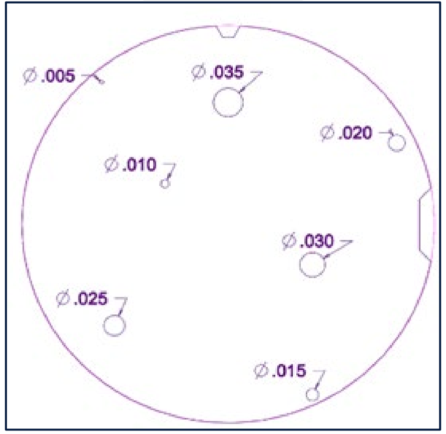
Plane 5



Plane 6



Plane 7



S1-AB-1 In Situ Reconstruction [Pre HT]

S1-AB-1 CT Data Reconstruction [Pre HT]

CT data

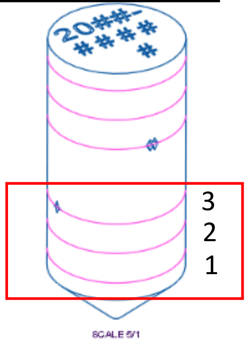
S1-AB-1 [Pre] and S1-HT-1 [Post] HT

S1-AB-1 Robomet Data [Pre HT] - Planes 1, 2 & 3

Plane 1

Plane 2

Plane 3



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3. S3 samples: High Power (Keyhole) Defects = 125% Laser Power

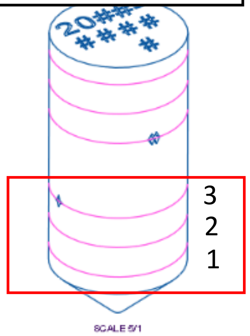
HT: Heat Treated
AB: As Built

S1-HT-1 Robomet Data [Post HT] - Planes 1, 2 & 3

Plane 1

Plane 2

Plane 3



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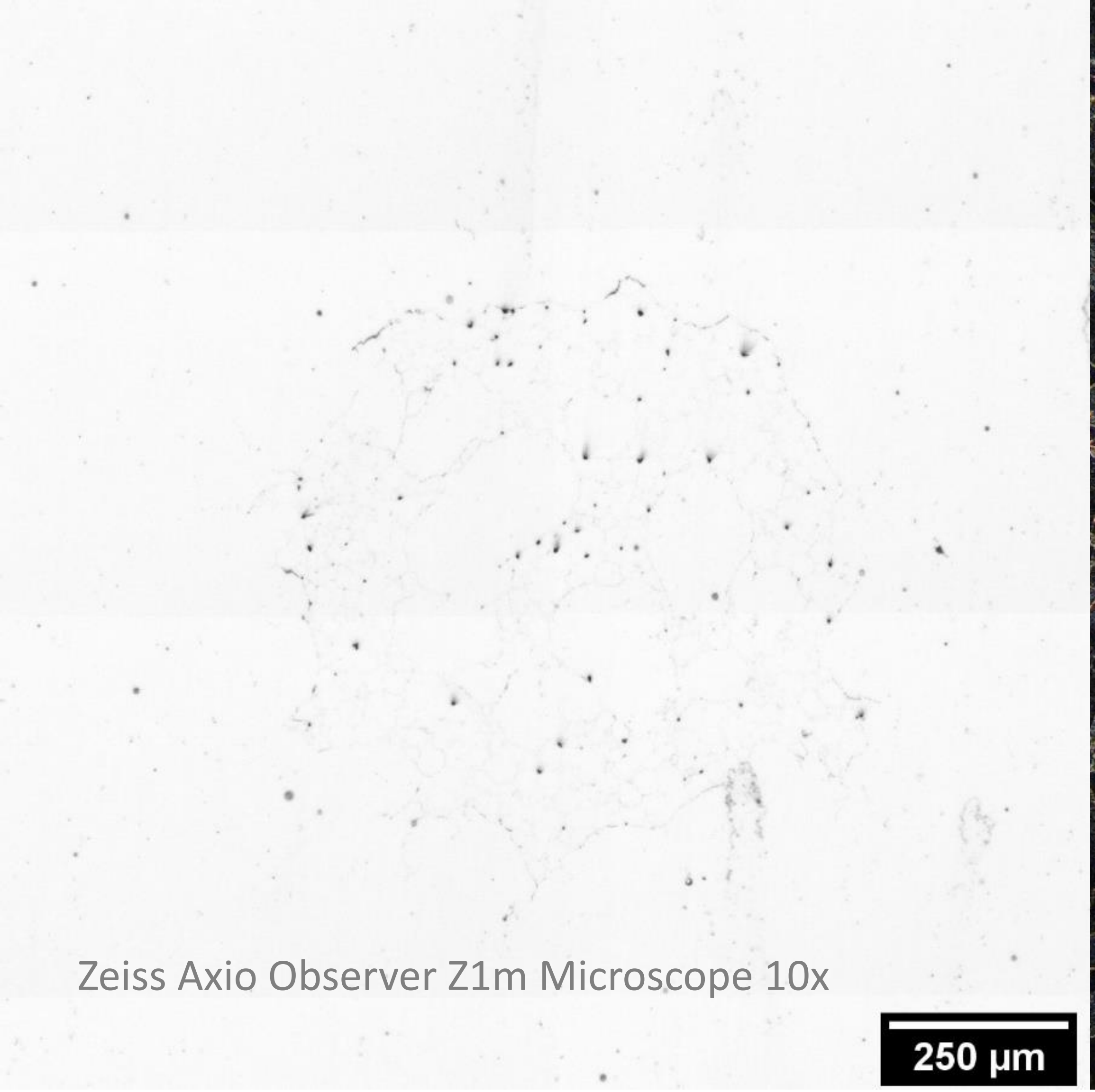
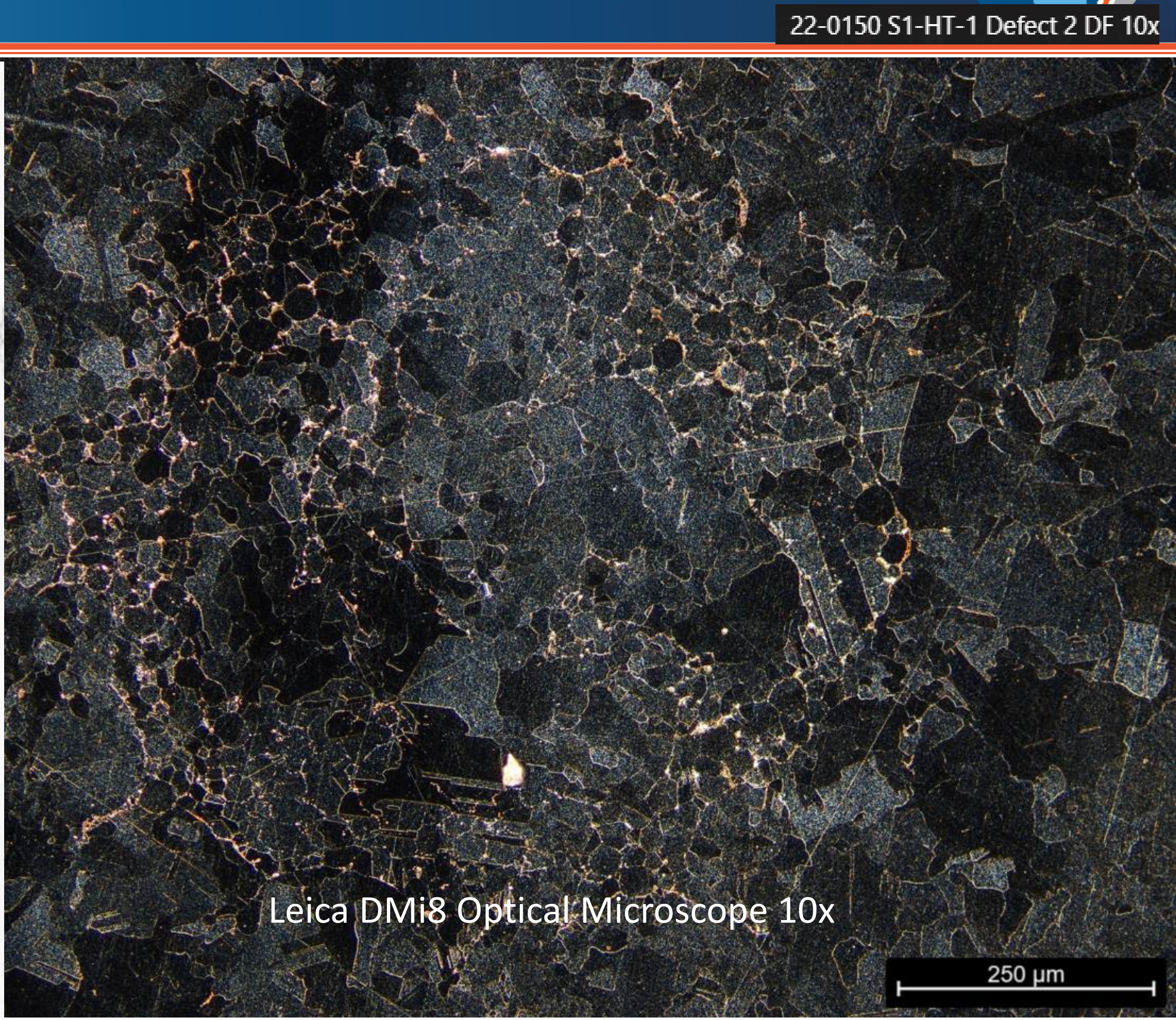
S1-HT-1 [Post HT] (Top View)

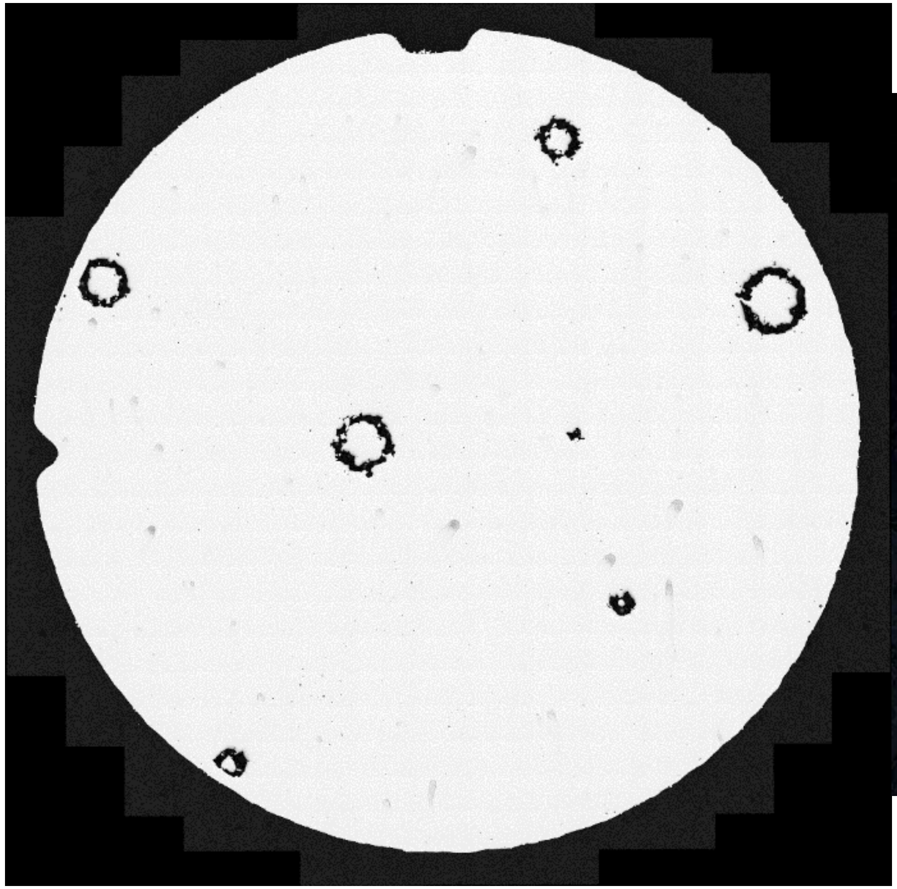


Zeiss Axio Observer Z1m Microscope 10x

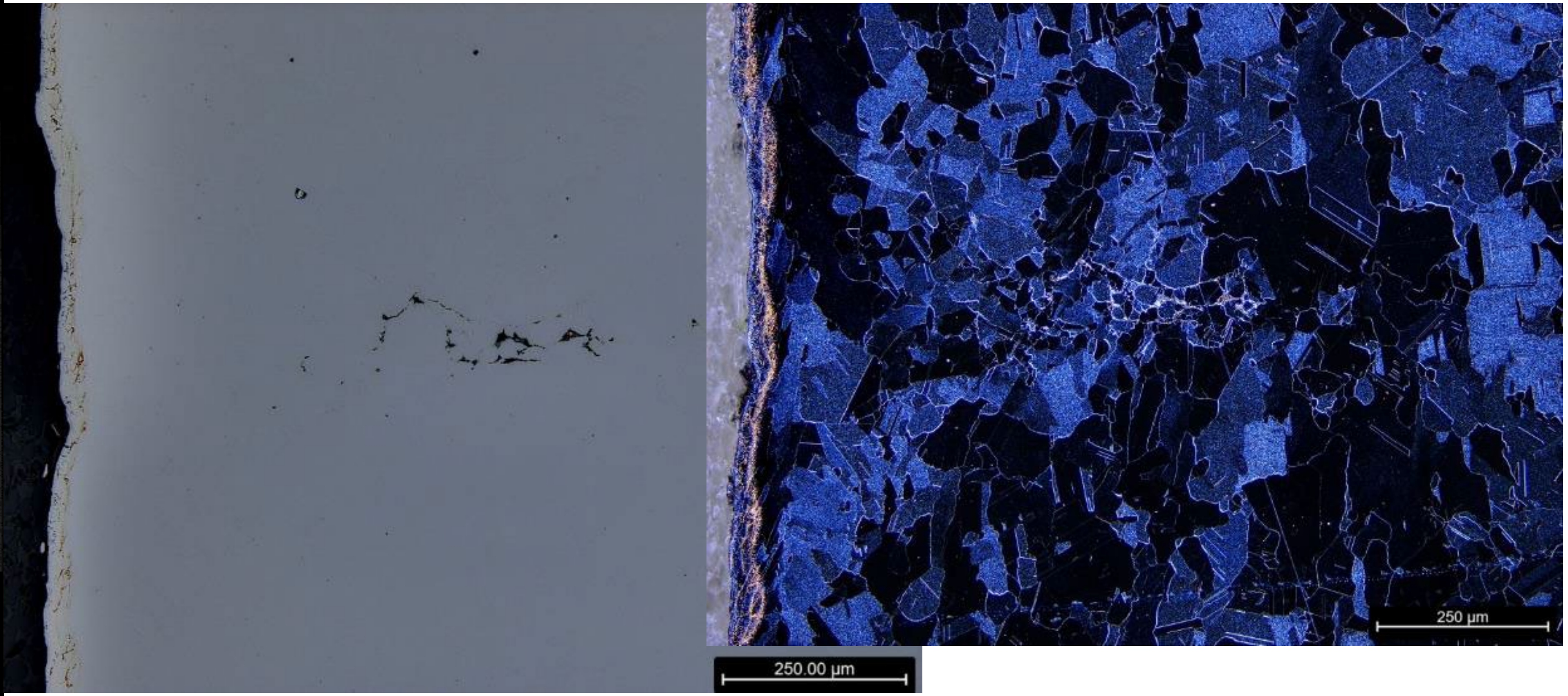


Leica DMi8 Optical Microscope 10x

S2-AB [Pre HT] & S2-HT [Post HT]



RoboMet Pre HT



Leica DMi8 Optical Microscope 10x Post HT (Z axis view)

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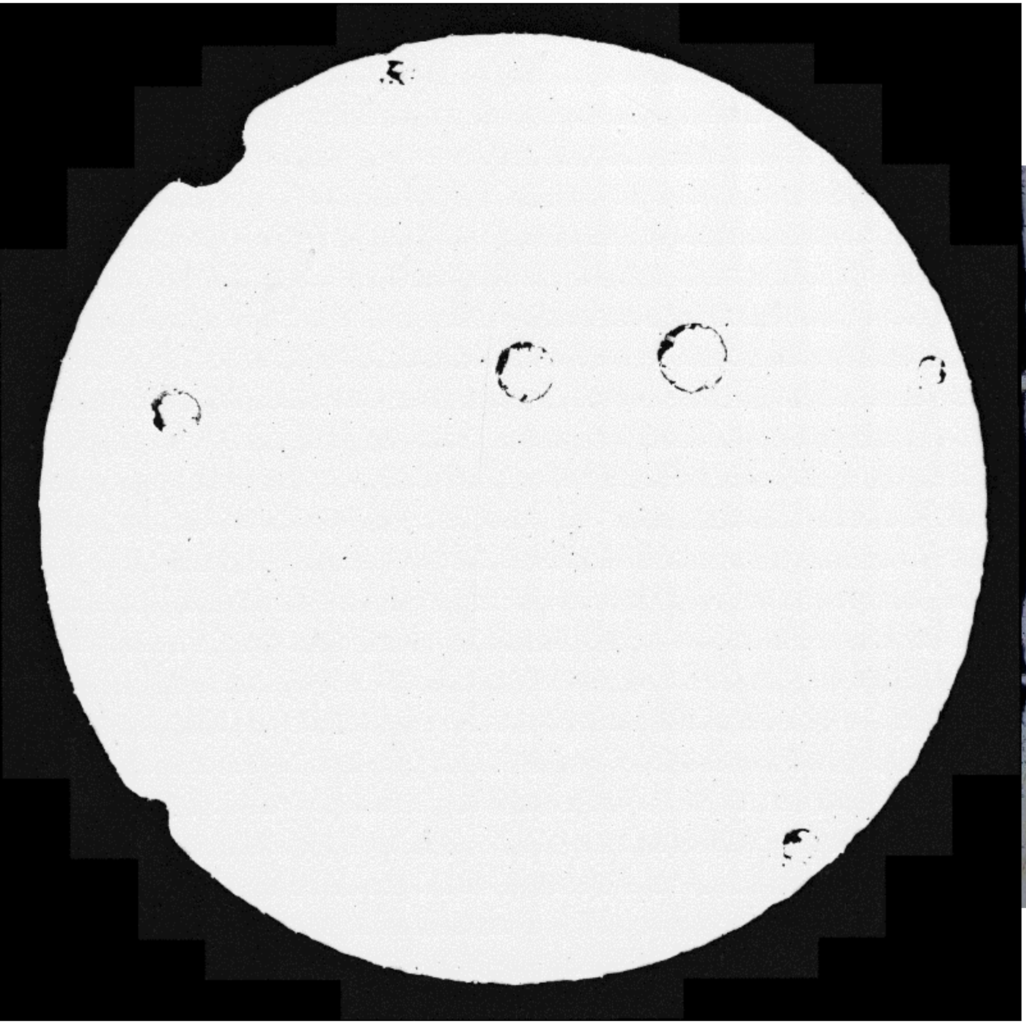
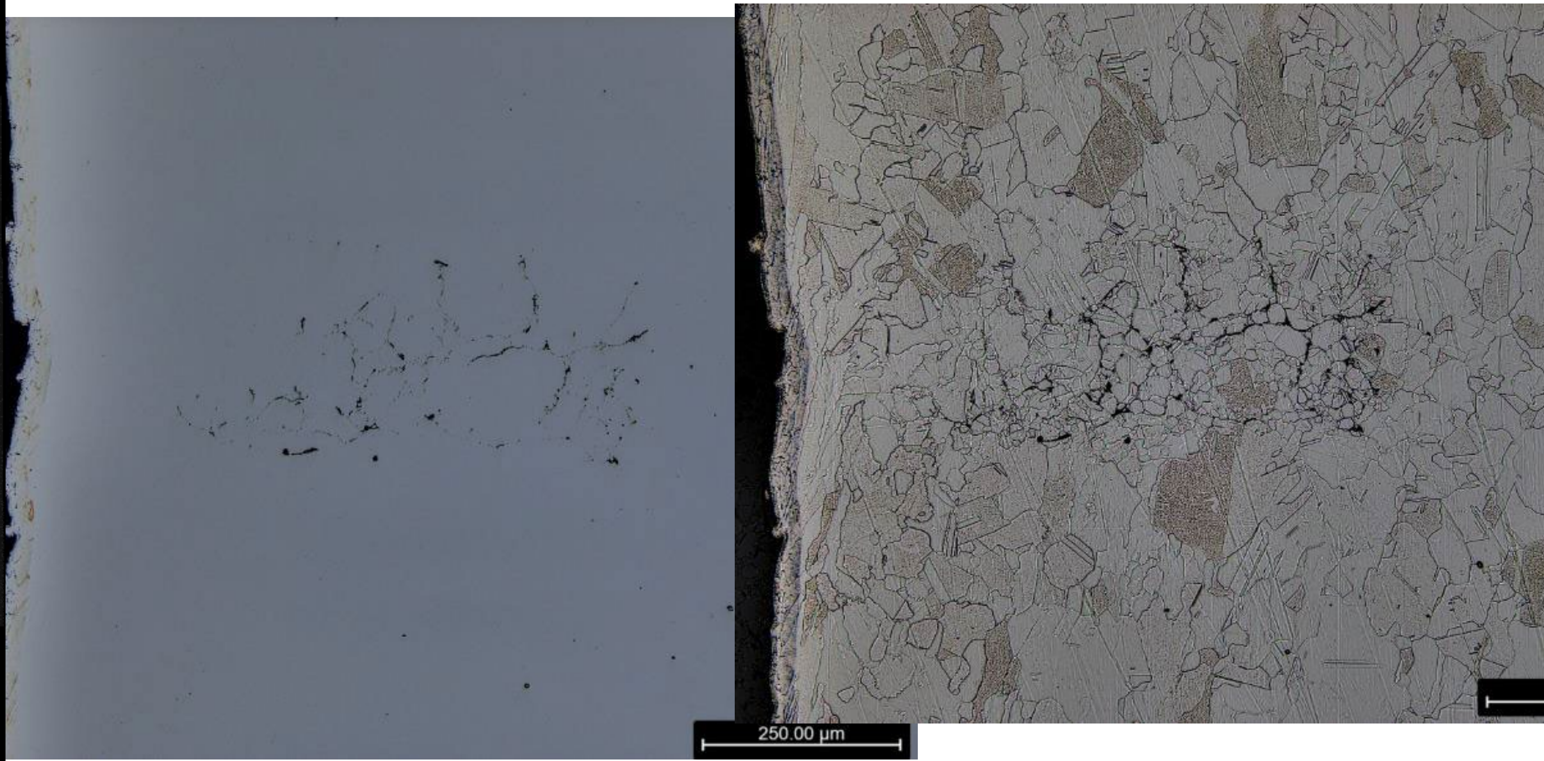
HT: Heat Treated
AB: As Built

S3-AB [Pre HT] & S3-HT [Post HT]



RoboMet Pre HT

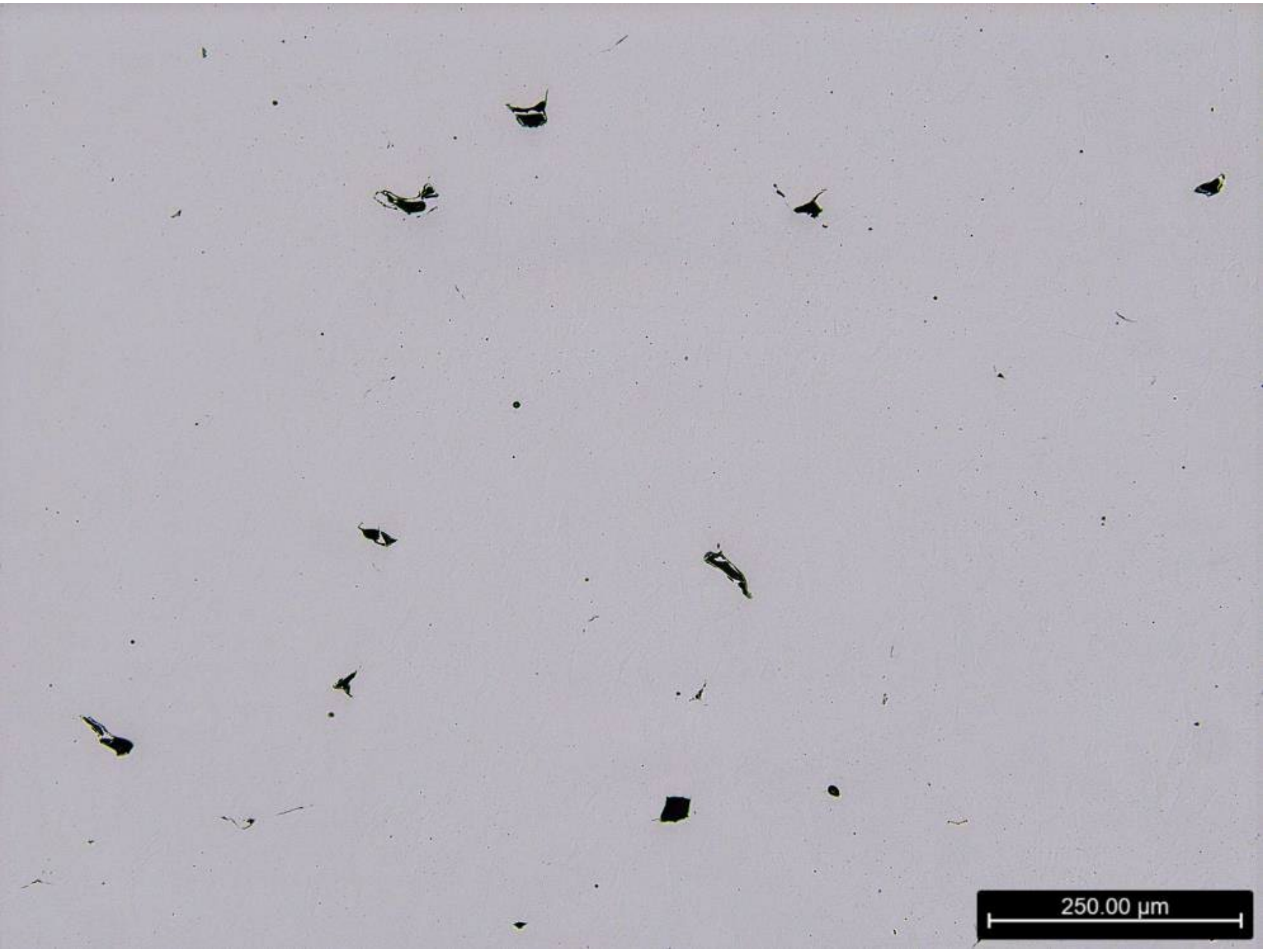


Leica DMi8 Optical Microscope 10x   Post HT (Z axis view)

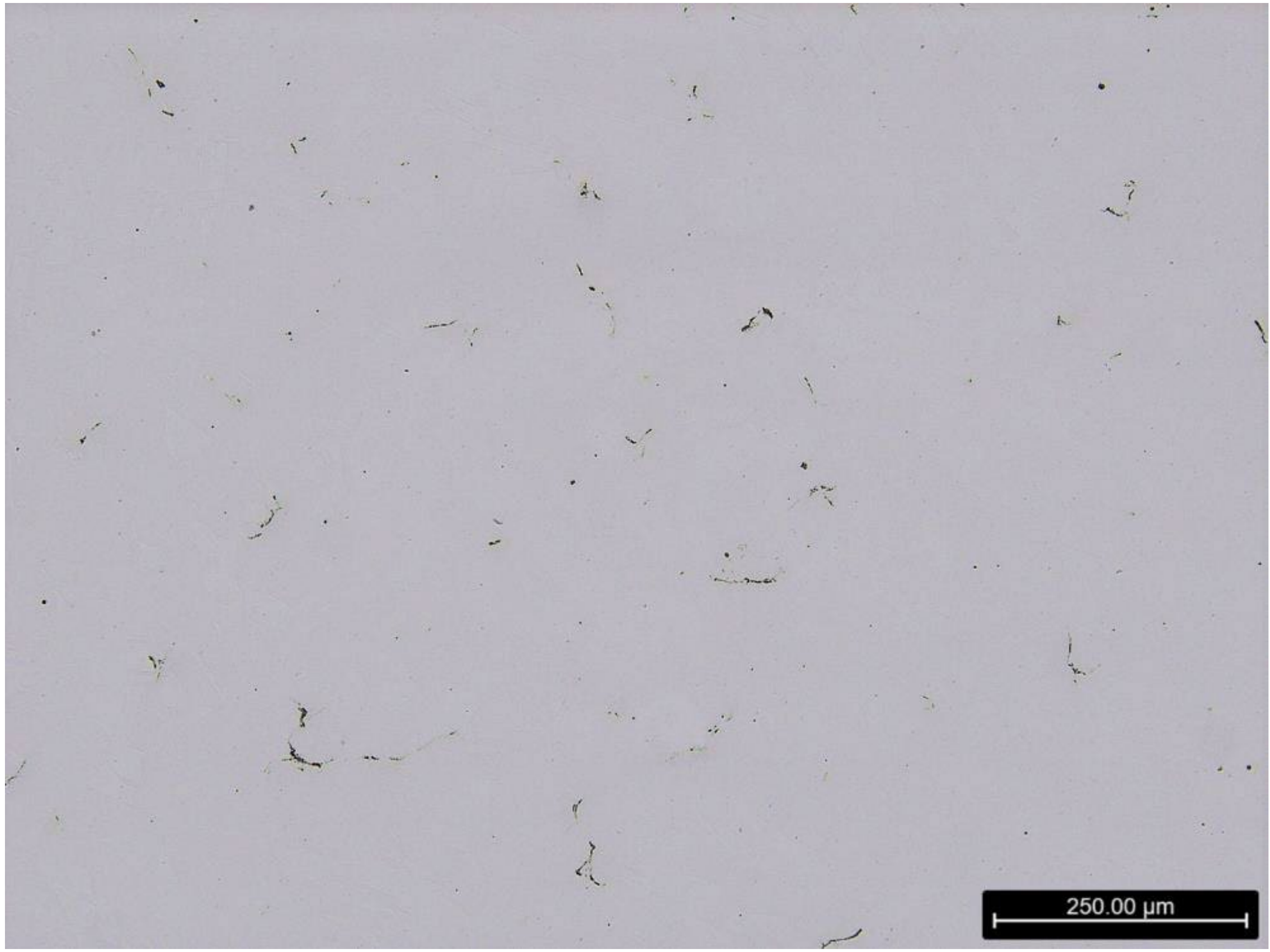
1. S1 samples: Skipped Layer (Unfused Powder) Defects = no power
2. S2 samples: Low Power (Lack of Fusion) Defects = 75% Laser Power
3. S3 samples: High Power (Keyhole) Defects = 125% Laser Power

HT: Heat Treated
AB: As Built

75% Laser Power Sample

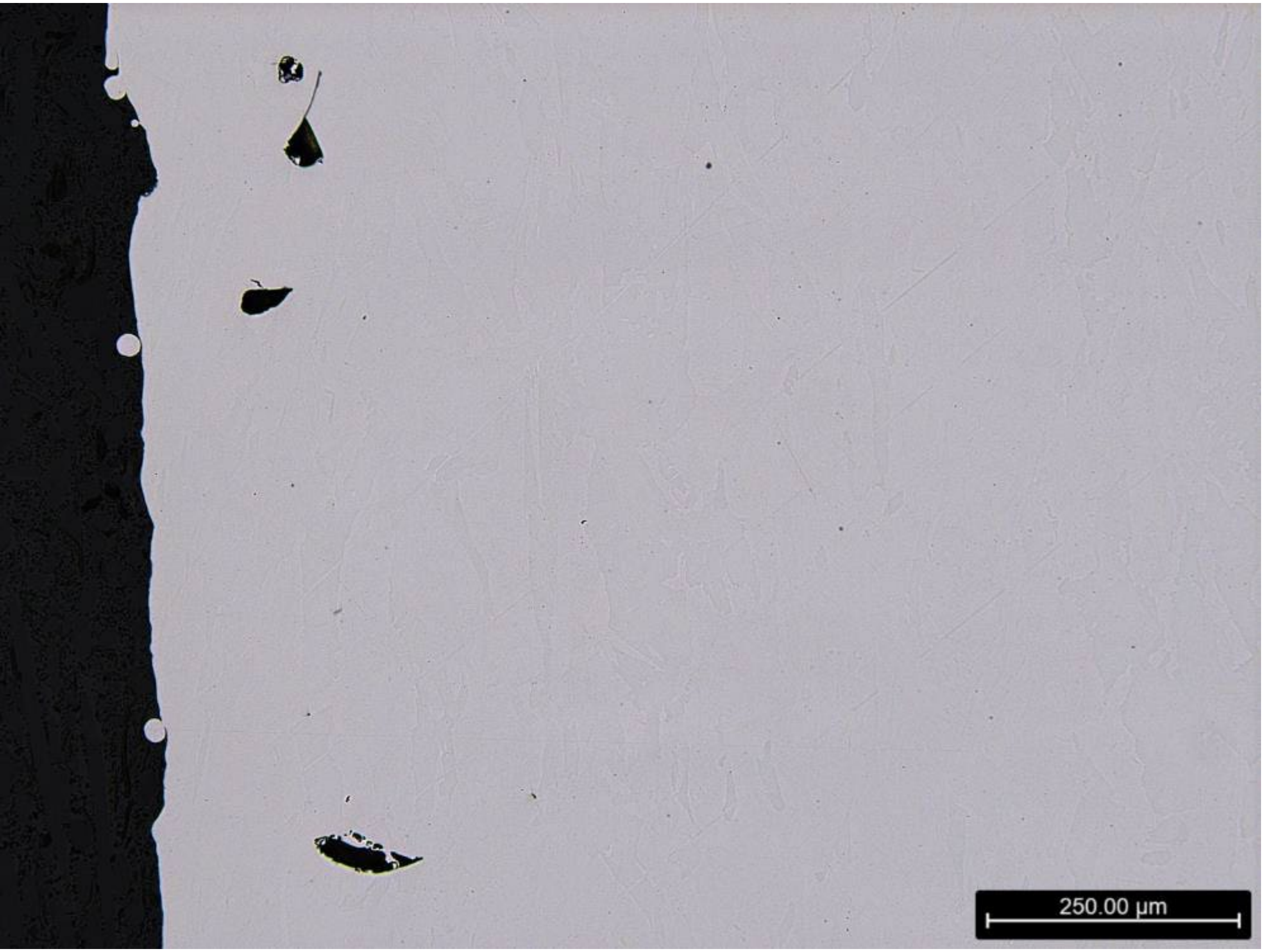


75% Pre HT

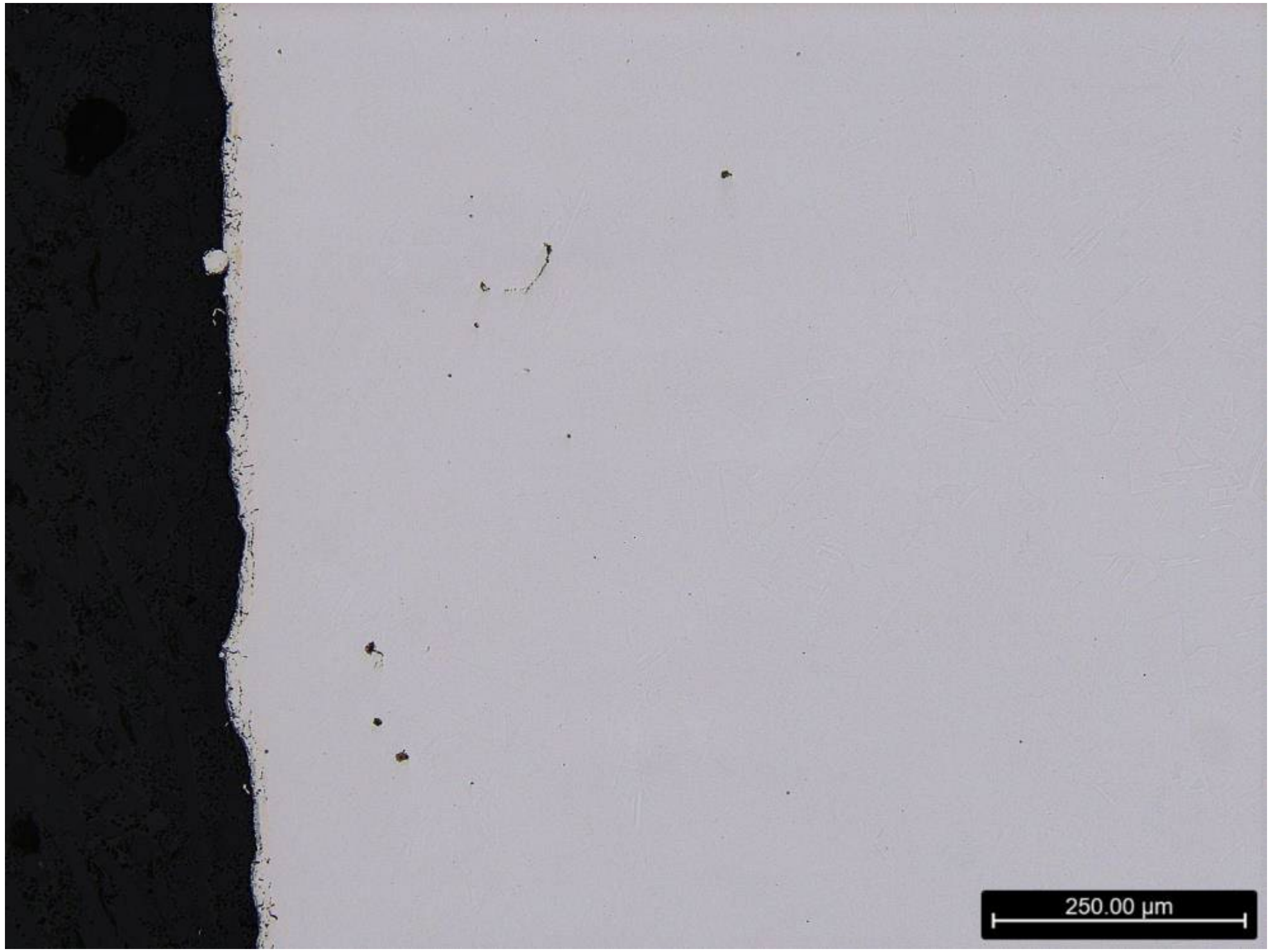


75% Post HT

125% Laser Power Sample



125% Pre HT



125% Post HT

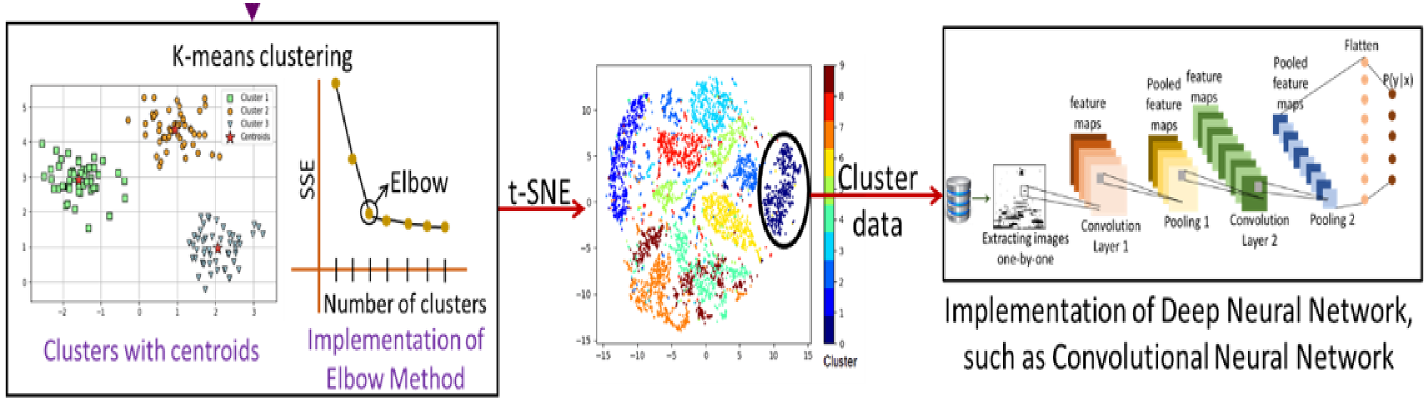
MSFC Machine Learning (ML) Tools for Defect Detection and Prediction

- Current ML tools at MSFC:
  - Autoencoder-based algorithm for defect detection
  - Autoencoder is an unsupervised machine learning method that can be trained to process thermal and optical tomography images and produce a generalized reconstruction for defect detection

- Video(left) shows defect defection of induced skipped layer flaws in a part. Video(right) showing CAE isolating spatter marks and short feed indications from in-situ images

- Developing ML Tools:
  - Development of Convolutional Neural Network (CNN) for defect detection

  - Development of ML platform for detection and labeling in-situ images



Implementation of Deep Neural Network, such as Convolutional Neural Network

What’s Next?

- In Situ Process Monitoring Probability Of Detection
  - Uncharted territory -> first step: CT POD to understand the process using collected data
- Multi sensor data post processing using machine learning
  - Evaluate the range of flaw detection
  - Expand machine learning software for classification and labeling
  - Investigate processing of different data types using machine learning
- Include thermal modeling to better target regions of heat concentration
- Study flaw distribution on coupons and its effect on material properties determined by performing mechanical tests
  - The data collected can be used to calculate transfer function to help relate coupons to real components of similar geometry. This will inform future NDE standards

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- Erin Lanigan
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- Will Tilson
- James Walker

Back-Up Slides

Scope Of Results

S1-AB-1; S1-HT-1
S2-AB; S2-HT
S3-AB; S3-HT

75-AB; 75-HT
125-AB; 125-HT

1. S1 samples: Skipped Layer (Unfused Powder) Defects = no power
2. S2 samples: Low Power (Lack of Fusion) Defects = 75% Laser Power
3. S3 samples: High Power (Keyhole) Defects = 125% Laser Power

HT: Heat Treated
AB: As Built

NASA HR-1

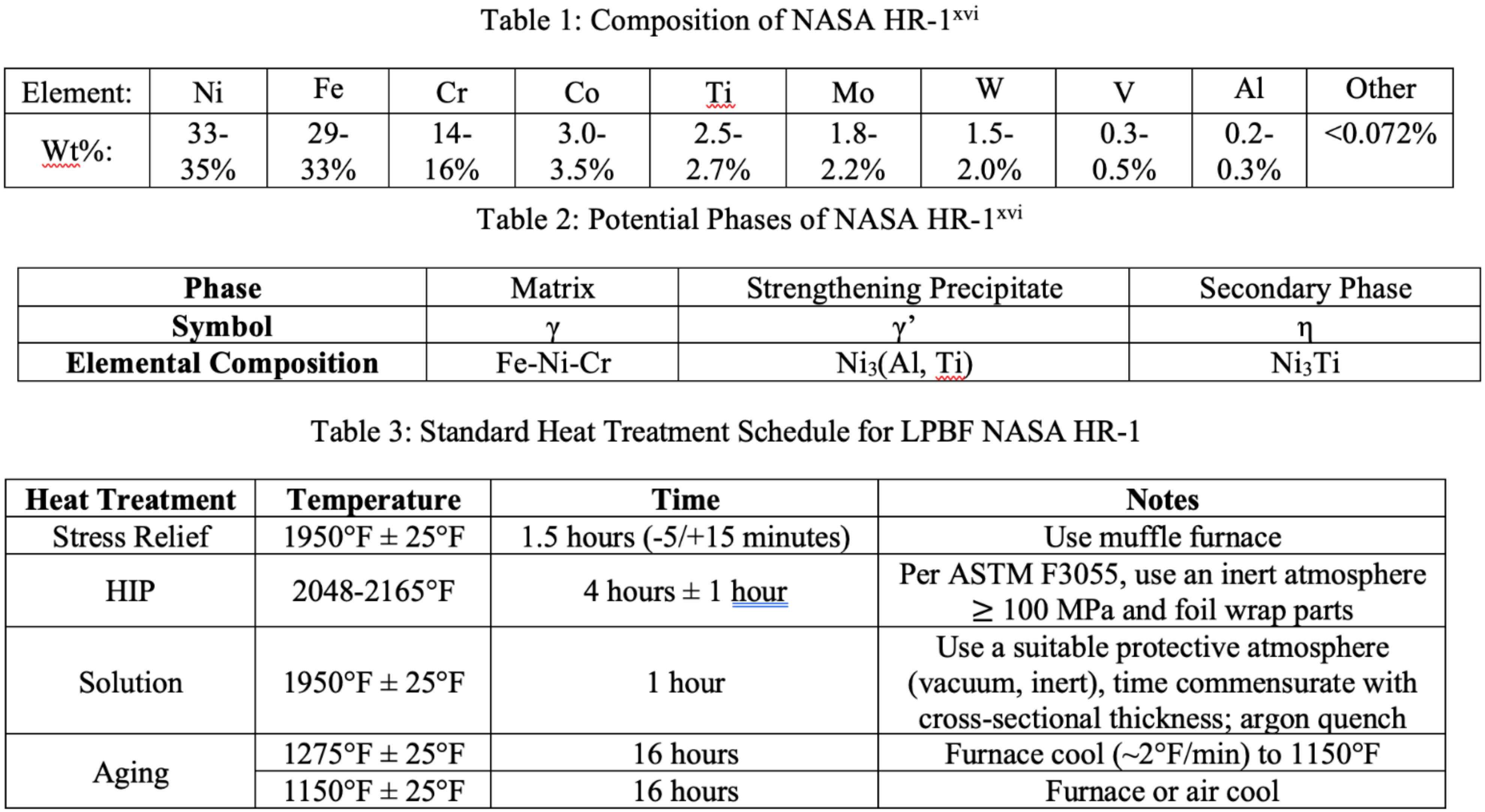


Table 1: Composition of NASA HR-1[xvi]

Element:	Ni	Fe	Cr	Co	Ti	Mo	W	V	Al	Other
Wt%:	33-35%	29-33%	14-16%	3.0-3.5%	2.5-2.7%	1.8-2.2%	1.5-2.0%	0.3-0.5%	0.2-0.3%	<0.072%

Table 2: Potential Phases of NASA HR-1[xvi]

Phase	Matrix	Strengthening Precipitate	Secondary Phase
Symbol	γ	γ'	η
Elemental Composition	Fe-Ni-Cr	$Ni_3(Al, Ti)$	Ni_3Ti

Table 3: Standard Heat Treatment Schedule for LPBF NASA HR-1

Heat Treatment	**Temperature**	**Time**	**Notes**
Stress Relief	1950°F ± 25°F	1.5 hours (-5/+15 minutes)	Use muffle furnace
HIP	2048-2165°F	4 hours ± 1 hour	Per ASTM F3055, use an inert atmosphere ≥ 100 MPa and foil wrap parts
Solution	1950°F ± 25°F	1 hour	Use a suitable protective atmosphere (vacuum, inert), time commensurate with cross-sectional thickness; argon quench
Aging	1275°F ± 25°F	16 hours	Furnace cool (~2°F/min) to 1150°F
	1150°F ± 25°F	16 hours	Furnace or air cool

List of all samples with AM process variation

Table 1. Machine Parameter Settings for Phase I Build

Specimen ID	Laser Power (% of nominal)	Laser Power (W)	Heat Treatment	Notes
75-AB	75	213.75	As-Built	---
75-HT	75	213.75	Full HT	---
80-AB	80	228	As-Built	---
80-HT	80	228	Full HT	---
85-AB	85	242.25	As-Built	---
85-HT	85	242.25	Full HT	---
90-AB	90	256.5	As-Built	---
90-HT	90	256.5	Full HT	---
95-AB	95	270.75	As-Built	---
95-HT	95	270.75	Full HT	---
Nom-AB	100	285	As-Built	Nominal
Nom-HT	100	285	Full HT	Nominal
105-AB	105	299.25	As-Built	---
105-HT	105	299.25	Full HT	---
110-AB	110	313.5	As-Built	---
110-HT	110	313.5	Full HT	---
115-AB	115	327.75	As-Built	---
115-HT	115	327.75	Full HT	---
120-AB	120	342	As-Built	---
120-HT	120	342	Full HT	---
125-AB	125	356.25	As-Built	---
125-HT	125	356.25	Full HT	---
S1-AB-1	100	285	As-Built	Seeded 1
S1-HT-1	100	285	Full HT	Seeded 1
S1-AB-2	100	285	As-Built	Seeded 1
S1-HT-2	100	285	Full HT	Seeded 1
S2-AB	100	285	As-Built	Seeded 2
S2-HT	100	285	Full HT	Seeded 2
S3-AB	100	285	As-Built	Seeded 3
S3-HT	100	285	Full HT	Seeded 3

1. S1 samples: Skipped Layer (Unfused Powder) Defects = no power
2. S2 samples: Low Power (Lack of Fusion) Defects = 75% Laser Power
3. S3 samples: High Power (Keyhole) Defects = 125% Laser Power

HT: Heat Treated
AB: As Built

Build 2 Defect Samples Per Plane

Plane 1	Defect Diameter	Thickness
Circle 1	0.005"	0.01260
Circle 5	0.01"	0.01417
Circle 4	0.015"	0.01575
Circle 2	0.02"	0.01732
Circle 3	0.025"	0.01890
Circle 6	0.03"	0.02047
Circle 7	0.035"	0.02205

Plane 2	Defect Diameter	Thickness
Circle 3	0.005	0.02205
Circle 2	0.01	0.01260
Circle 5	0.015	0.01417
Circle 4	0.02	0.01575
Circle 1	0.025	0.01732
Circle 6	0.03"	0.01890
Circle 7	0.035"	0.02047

Plane 3	Defect Diameter	Thickness
Circle 3	0.005	0.02047
Circle 1	0.01	0.02205
Circle 4	0.015	0.01260
Circle 5	0.02	0.01417
Circle 2	0.025	0.01575
Circle 6	0.03"	0.01732
Circle 7	0.035"	0.01890

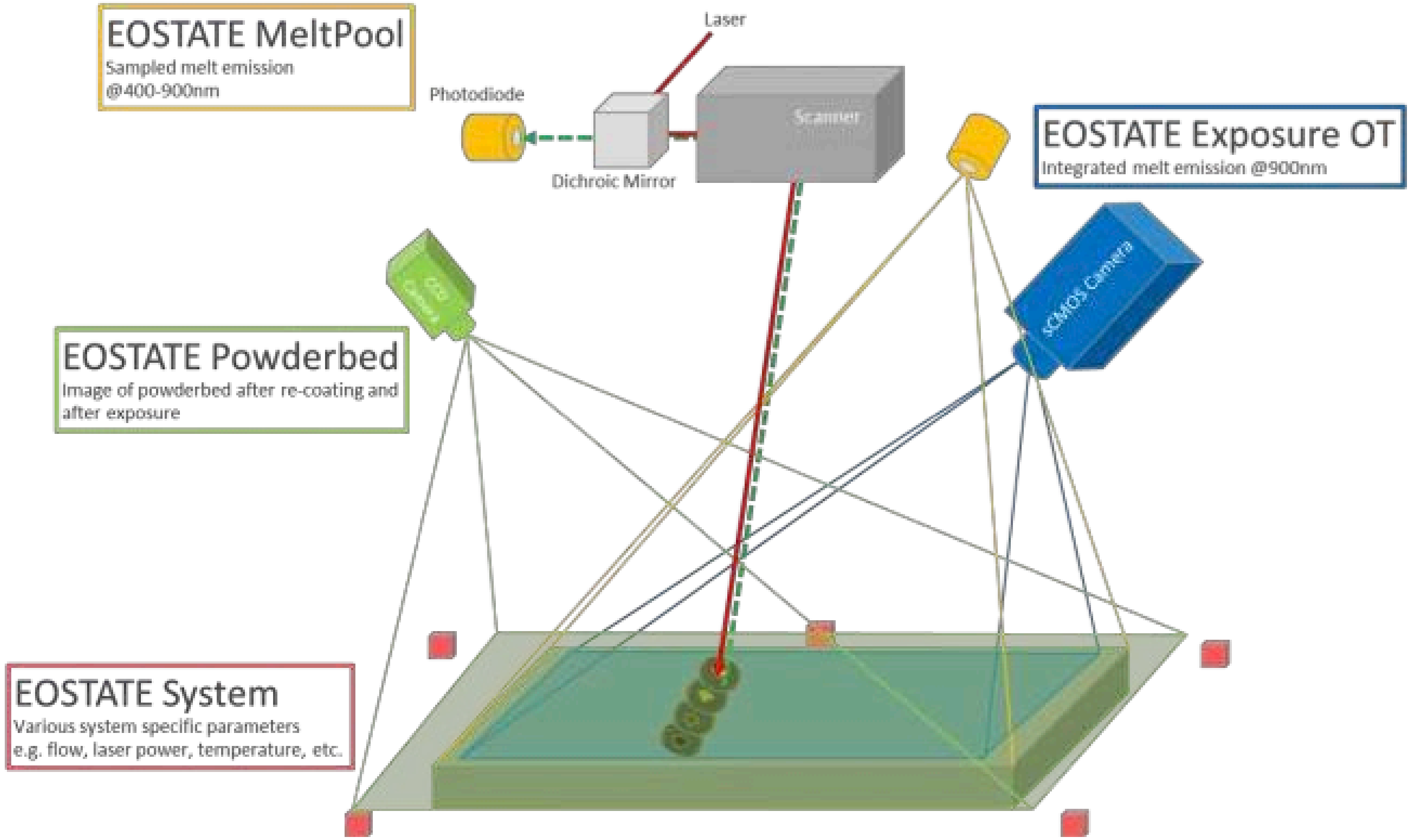
Plane 4	Defect Diameter	Thickness
Circle 5	0.005	0.01890
Circle 1	0.01	0.02047
Circle 2	0.015	0.02205
Circle 4	0.02	0.01260
Circle 3	0.025	0.01417
Circle 6	0.03"	0.01575
Circle 7	0.035"	0.01732

Plane 5	Defect Diameter	Thickness
Circle 4	0.005"	0.01732
Circle 1	0.01"	0.01890
Circle 3	0.015"	0.02047
Circle 5	0.02"	0.02205
Circle 2	0.025"	0.01260
Circle 6	0.03"	0.01417
Circle 7	0.035"	0.01575

Plane 6	Defect Diameter	Thickness
Circle 4	0.005"	0.01575
Circle 2	0.01"	0.01732
Circle 1	0.015"	0.01890
Circle 3	0.02"	0.02047
Circle 5	0.025"	0.02205
Circle 6	0.03"	0.01260
Circle 7	0.035"	0.01417

Plane 7	Defect Diameter	Thickness
Circle 4	0.005"	0.01417
Circle 2	0.01"	0.01575
Circle 1	0.015"	0.01732
Circle 3	0.02"	0.01890
Circle 5	0.025"	0.02047
Circle 6	0.03"	0.02205
Circle 7	0.035"	0.01260

EOS M290 In-Situ Monitoring System



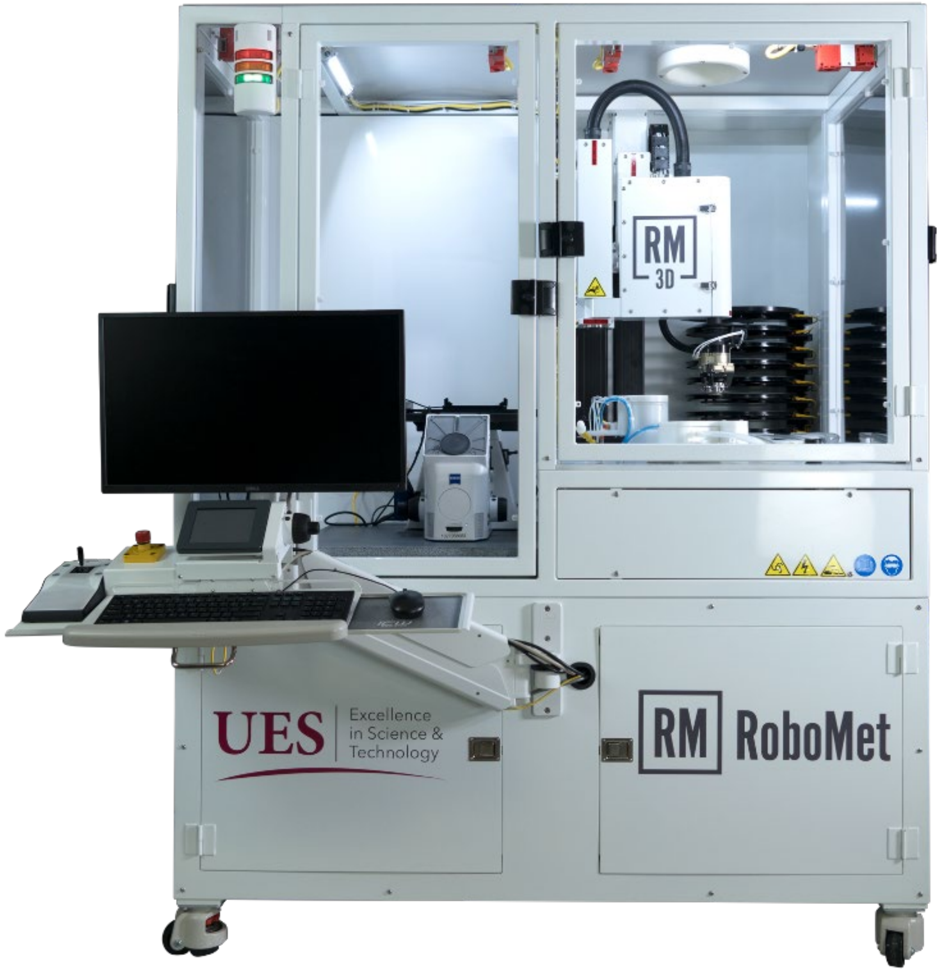
EOSTATE MeltPool
Sampled melt emission
@400-900nm

EOSTATE Exposure OT
Integrated melt emission @900nm

EOSTATE Powderbed
Image of powderbed after re-coating and after exposure

EOSTATE System
Various system specific parameters
e.g. flow, laser power, temperature, etc.

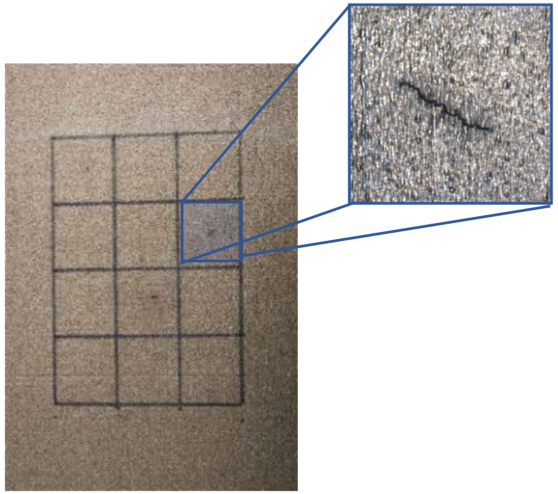
Serial Sectioning w/ Robomet



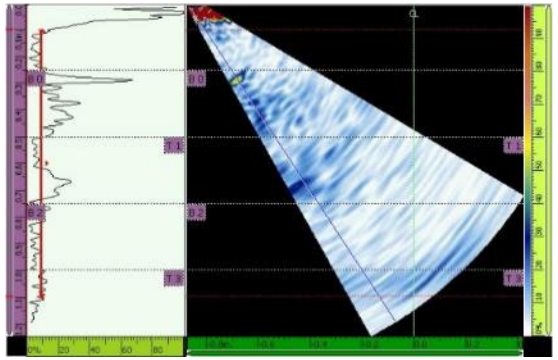
What’s Next?

- How big can we expect a defect to close off after HT?
  - Can we predict based on in-situ data which will close off, which will not?
- Mechanical testing of all those samples and comparing mechanical test w/ nominal parameters
  - Understanding what flaw size will affect the material properties
- Crossing data w/ melt pool monitoring data
- Confirming limitations of NDE tools
    - Minimum flaw size detected
- Calculating probability of detection
    - Based on CT data
- L-PBF HR-1 Defect Characterization is just a piece of the bigger in situ project
  - Next step is to practice the methodology on AM complex parts/ propulsion components
  - Study natural flaws in complex geometries (e.g. heat concentration)
  - Machine learning (defect prediction)

Computed tomography (CT) is the most capable NDE method for AM but still has limitations due to mass and complexity.

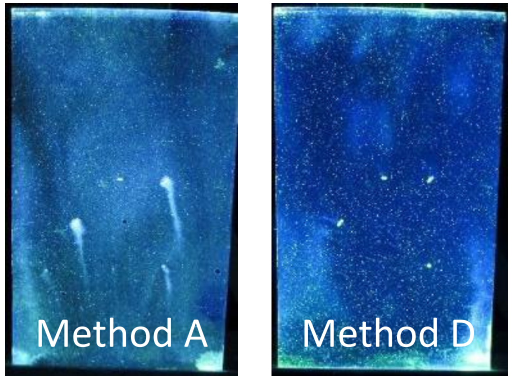


Laser notches in as-built LPBF In 718 panels

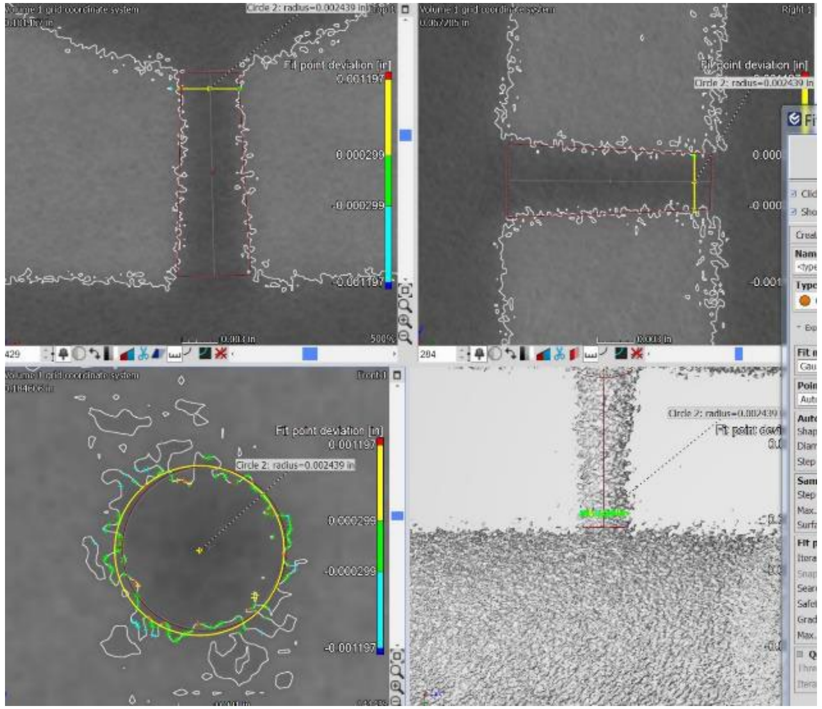


Ultrasonic

Radiography



Penetrant



Computed Tomography (CT)

MSFC has investigated in situ process monitoring through various mechanisms.

Small Business Innovation Research

Monitoring Systems

EOS | Optical Tomography & Meltpool Monitoring

ARCTOS | Thermal Tomography & High-Speed Spatter Imaging

ASTM Working Group WK73289

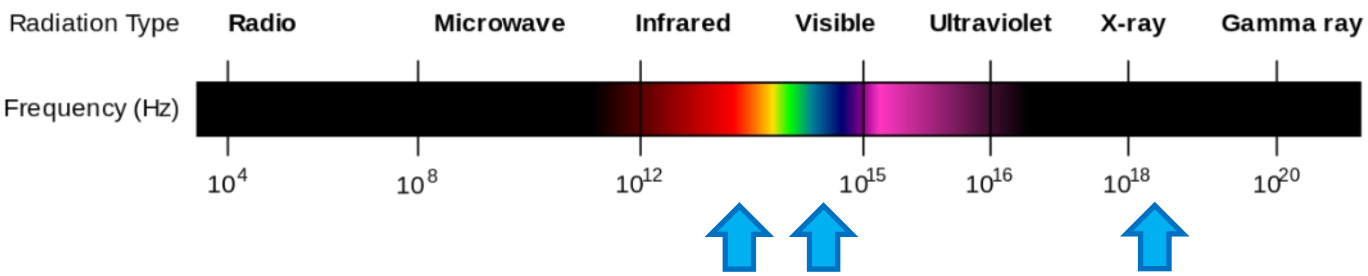
"Standard Guide for In-Situ Monitoring of Metal Additive Manufactured Parts"

ASTM AM Center of Excellence

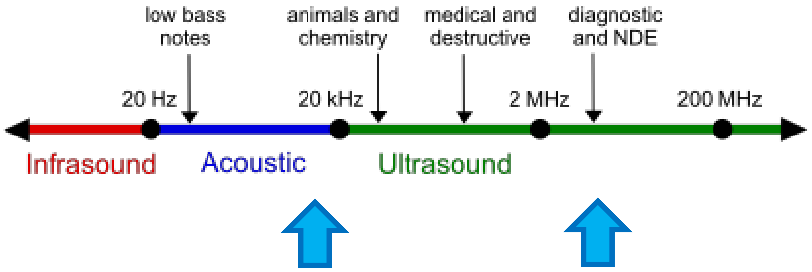
Completed a landscape survey and workshop with road mapping session

There are many different in situ process monitoring technologies which observe different physical phenomena.

Electromagnetic Frequency Spectrum



Ultrasonic Frequency Spectrum

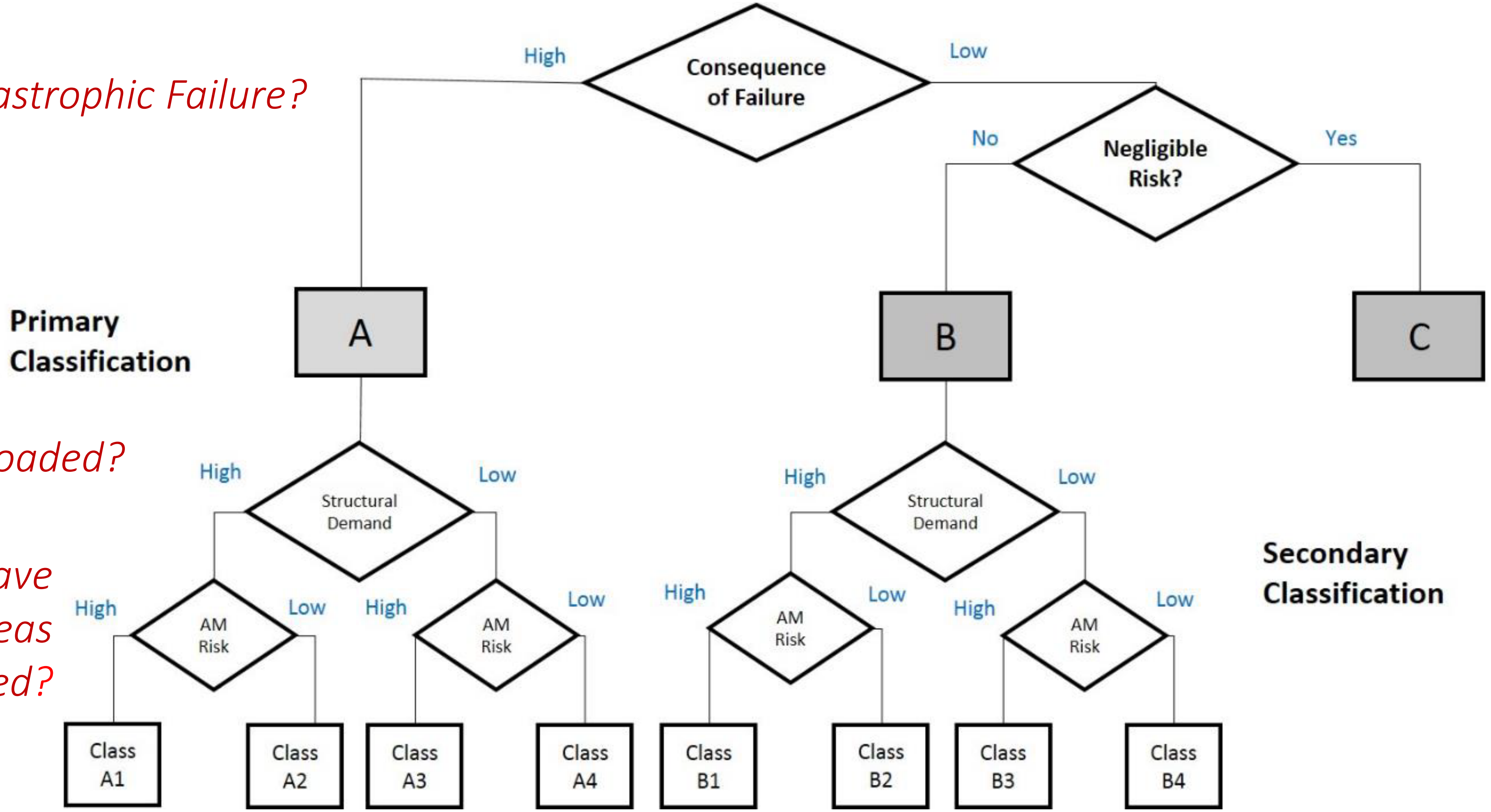


	Monitor During Build Process	Inspection Between Build Layers
Passive (No external excitation)	Infrared/near-IR melt pool monitoring	Visual Laser profilometry
Active (Added excitation)	-	Laser ultrasonic X-ray

There are also different additive manufacturing technologies that can be monitored.

	Powder Bed Systems	Freeform Fabrication
Process:	Laser Powder Bed Fusion (L-PBF) Electron Beam Melting (EBM) Selective Laser Sintering (SLS)	Laser Directed Energy Deposition (DED) Electron Beam Free Form Fabrication (EBF^3) Rapid Plasma Deposition Additive Friction Stir Weld Fused Filament Fabrication (FFF)
Feedstock:	Metals: Nickel alloys, copper alloys, titanium alloys, etc. Polymers: nylon, polyamide	Metal powder/wire/chips Filament: polymer, carbon fiber, biological, etc.

Classifications for AM parts consider the risk of AM manufacturability and inspectability.



Catastrophic Failure?

Heavily Loaded?

Does the build have challenging aspects or areas that cannot be inspected?

Consequence of Failure

High

Low

Negligible Risk?

No

Yes

Primary Classification

A

B

C

Structural Demand

High

Low

AM Risk

Secondary Classification

Class A1

Class A2

Class A3

Class A4

Class B1

Class B2

Class B3

Class B4

The NASA standard requires *quantitative* NDE with full coverage of the surface and volume for Class A Parts.

Language:

"All Class A parts **shall** receive ***quantitative NDE*** with full coverage of the surface and volume of the part, including verifiable detection of critical initial flaw size in critical damage tolerant parts, with any coverage limitations due to NDE techniques(s) and/or part geometry documented in the PPP"

Rationale:

- "NDE provides a necessary degree of quality assurance for AM parts in addition to the process controls of this NASA Technical Standard."
- "No methodology currently exists to preclude all AM process failure modes through the available manufacturing process controls."

(emphasis added)

For Class A parts, the NDE approach must comply with the Special NDE requirements in NASA-STD-5009.

Language:

"The NDE approach for Class A parts **shall** meet the Special NDE requirements of NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture Critical Metallic Components, and be documented in the PPP."

Rationale:

- "The defects of interest in AM are of a different nature than those listed in Tables 1 and 2 of NASA-STD-5009, and AM microstructures can impact the effectiveness of NDE methods. Therefore, all inspection of fracture critical AM hardware should be treated as Special NDE."
- "Alternative flaw screening methods for Class A parts (e.g., proof testing) may be feasible with full justification provided in the PPP."

The NASA standard requires NDE *for process control* with full coverage of the surface and volume for Class B Parts.

Language:

"All Class B parts **shall** receive ***NDE for process control*** with full coverage of the surface and volume of the part, ~~including verifiable detection of critical initial flaw size in critical damage tolerant parts~~, with any coverage limitations due to NDE techniques(s) and/or part geometry documented in the PPP"

Rationale:

- "NDE for process control requires the use of physical reference standards for calibration and acceptance criteria based on the capability of the NDE technique but does not require quantitative validation of flaw detection.
- "Targeted approaches for NDE can be proposed and approved per the PPP."

(emphasis added)

For Class B parts, the NDE approach must meet the requirements in NASA-STD-5009.

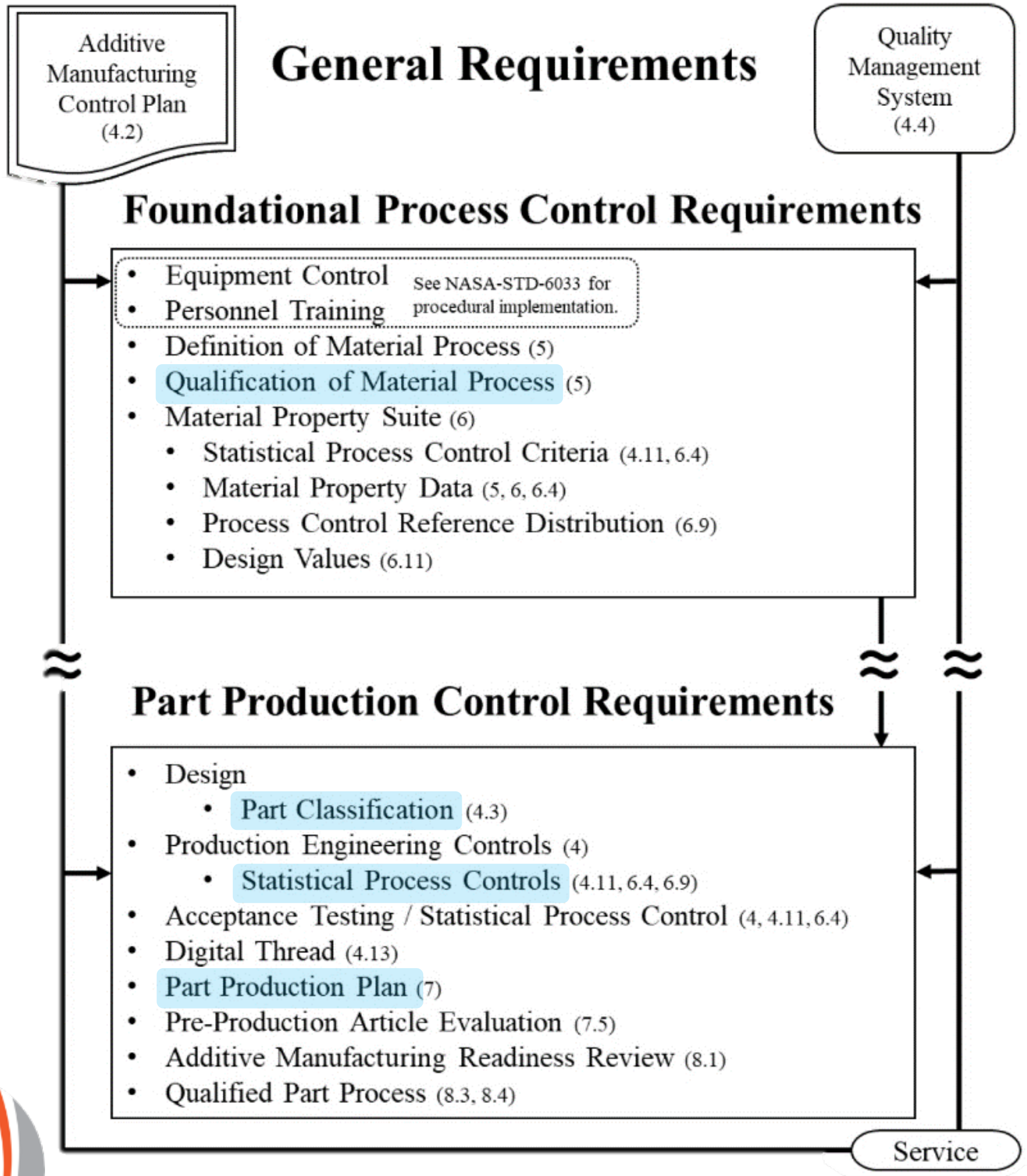
Language:

"The NDE approach for Class B parts **shall** meet the ~~Special NDE~~ requirements of NASA-STD-5009 and be documented in the PPP."

Rationale:

- "The requirements in NASA-STD-5009 establish important controls, including the definition, validation, documentation, and approval of all NDE procedures, standards, methods, and acceptance criteria […]"
- "Alternative post-build quality assurance methods for Class B parts (e.g., proof testing), as well as a reduction in NDE scope for Class B parts, may be feasible with full justification provided in the PPP."

In situ monitoring can be used in several aspects of certification:



Additive Manufacturing Control Plan (4.2)

General Requirements

Quality Management System (4.4)

Foundational Process Control Requirements

- Equipment Control
- Personnel Training

See NASA-STD-6033 for procedural implementation.

- Definition of Material Process (5)
- Qualification of Material Process (5)
- Material Property Suite (6)
  - Statistical Process Control Criteria (4.11, 6.4)
  - Material Property Data (5, 6, 6.4)
  - Process Control Reference Distribution (6.9)
  - Design Values (6.11)

≈ ≈ ≈

Part Production Control Requirements

- Design
  - Part Classification (4.3)
- Production Engineering Controls (4)
  - Statistical Process Controls (4.11, 6.4, 6.9)
- Acceptance Testing / Statistical Process Control (4, 4.11, 6.4)
- Digital Thread (4.13)
- Part Production Plan (7)
- Pre-Production Article Evaluation (7.5)
- Additive Manufacturing Readiness Review (8.1)
- Qualified Part Process (8.3, 8.4)

Service

Qualification of Material Process (QMP)

- Use with process development

Part Classification

- Improve inspectability for better AM risk posture
- Inspection process must be qualified by cognizant engineering org. (CEO)

Part Production Plan

- Integrated Structural Integrity Rationale (ISIR):
  - Can be specified as a defect screening action
  - Must be qualified by CEO

Production Controls

- Could develop certain metrics to track over time

The current certification approach does not accommodate the use of adaptive systems.

"Closed-loop process control based on adaptive in-situ monitoring technologies that alter the defined AM process in response to monitored phenomena are not currently applicable technology per this NASA Technical Standard and cannot be used without prior approved tailoring."

Adaptive (Closed-Loop) Systems

- Monitor the process using sensors (e.g. meltpool thermal signature) and change a machine/process parameter (e.g. laser power) to optimize the response
- Currently available in many directed energy deposition (DED) systems

Two issues for verification:

1. Verify the sensor performance, algorithm and machine response ***(control system)***
2. Verify the physics – does controlling this parameter result in a good part? ***(materials)***

For certifying closed-loop control systems, NASA can leverage the expertise of the spacecraft control systems community.

Verification of a control system:

1. Verify the accuracy of the sensor data
2. Verify the software/algorithm processing and response
3. Verify that the changed parameter responds correctly

Black box issue:

- For commercial systems, machine parameters may not be known, algorithms may not be accessible
- Ideal approach: collaborate with machine manufacturers
- Can also develop transfer function by studying inputs/outputs

Verifying that the adaptive system results in good material is a challenge that will require further study.

What is being monitored, and to what end?

Assume you're monitoring the meltpool thermal emissions

Are you looking to keep it constant, or vary it based on part geometry?

What does it really tell you about the process and the material?

Is this a good indicator of material quality?

Is the resulting microstructure/morphology consistent and repeatable?

What parameter will you change?

More complex if monitoring multiple signals and/or changing multiple parameters

Qualify process for each different system, alloy, part?

In summary, NDE and in situ monitoring both have a role in certification of AM space hardware.

To use for ***quantitative part quality*** function, monitoring system must be qualified.

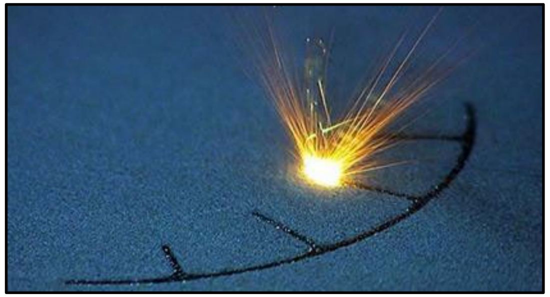
→ Main challenge: developing correlation of indication to verified defect

Qualifying ***closed-loop, adaptive*** systems will require a new approach to the QMP.

NDE is still vital for verification of post-build quality.

Thank you for your time!

Questions?



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