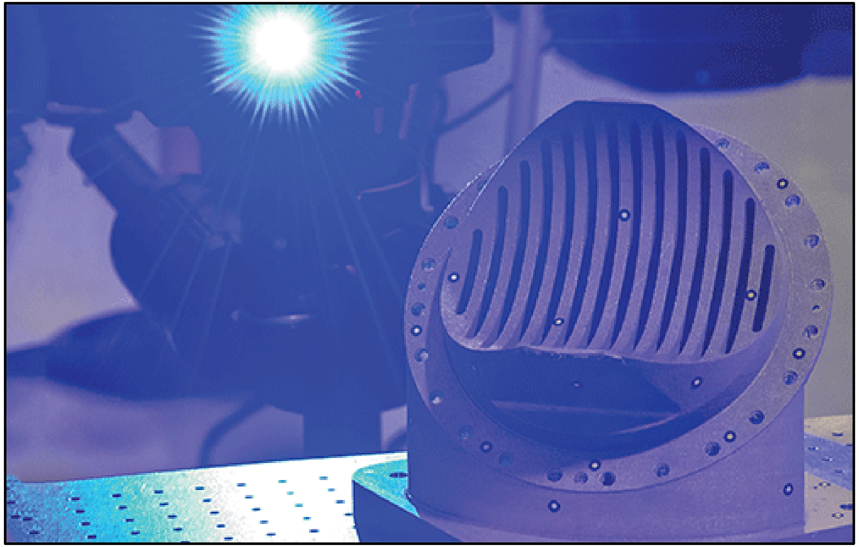
A NASA Perspective on the Growing Role of In-Situ Process Monitoring in Managing Risk of AM Hardware

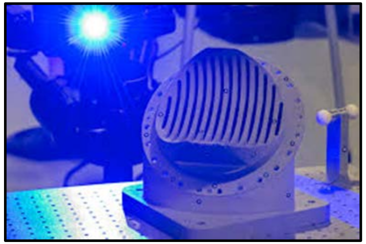
Erin Lanigan
NASA Marshall Space Flight Center
Nondestructive Evaluation Team



Manufacturing Problem Prevention Program (MP3)
The Aerospace Corporation
El Segundo, California

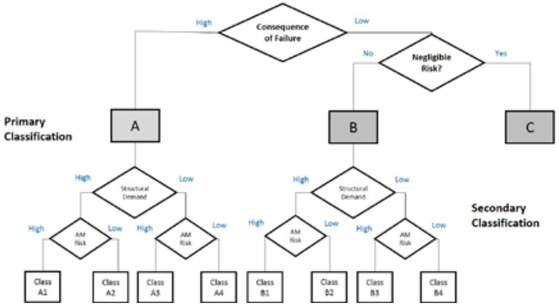
November 5th, 2019

This presentation focuses on NASA's interest in developing in-situ process monitoring as a tool for managing risk.



NASA's investment

Use of the technology

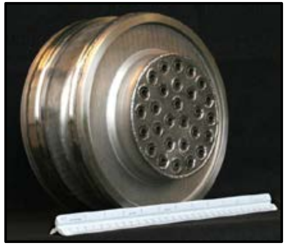


Qualification considerations


NASA TECHNICAL STANDARD

National Aeronautics and Space Administration

NASA is most interested in in-situ monitoring for high criticality, complex parts that cannot be inspected using traditional NDE.



28-Element Inconel® 625 Fuel Injector

Built using laser powder bed fusion (L-PBF)

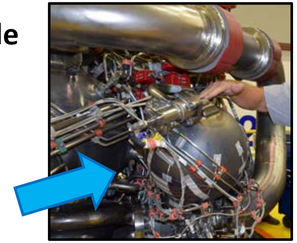
- Using traditional manufacturing methods:
    - 1 year, 163 parts
- Using L-PBF AM:
    - 4 months, only 2 parts
    - 70% cost reduction

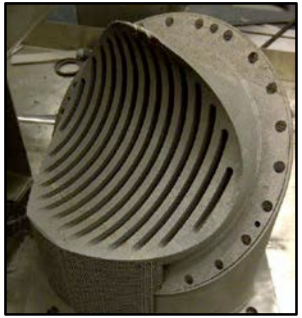
Injector Assembly

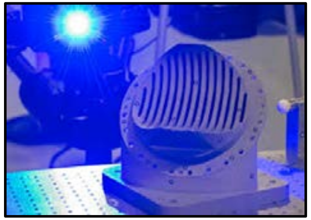
MSFC Independent Research and Development (IRAD) project with Army Air and Missile Defense (AMD)

RS-25 Pogo Accumulator Z-Baffle

- Over 100 Welds Eliminated
- Nearly 35% Cost Reduction







Cryogenic Heat Exchanger-Injector-Condenser Demo

NASA has investigated in-situ process monitoring through various mechanisms.

Small Business Innovation Research Grants

SBIR · STTR
America's Seed Fund™
POWERED BY NASA

OEM Commercial Systems

eos
e-Manufacturing Solutions

QM RT
meltpool 3D®

ASTM Working Group WK62181

ASTM INTERNATIONAL

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

ASTM AM Center of Excellence

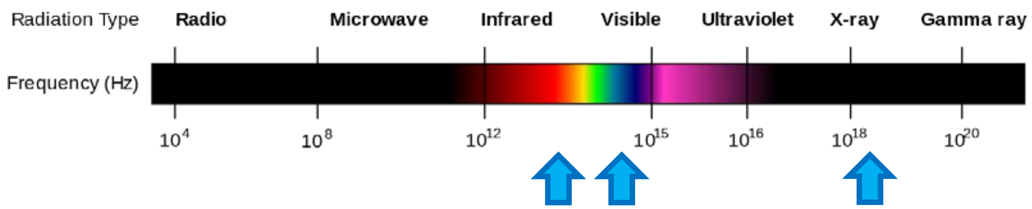
CENTER of EXCELLENCE
RESEARCH TO STANDARDS
Additive Manufacturing

Kicked off a study to survey the landscape of in-situ monitoring technologies.

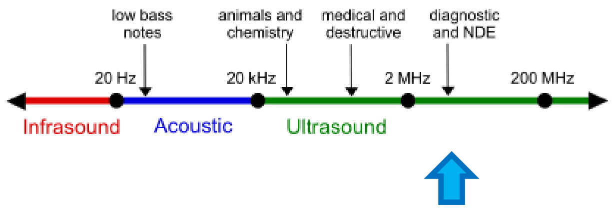
NASA MSFC ENGINEERING

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

Electromagnetic Frequency Spectrum



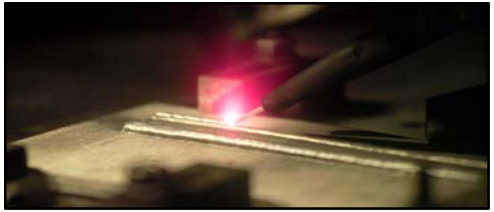
Ultrasonic Frequency Spectrum



	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.



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

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 study must include secondary verification of created defects

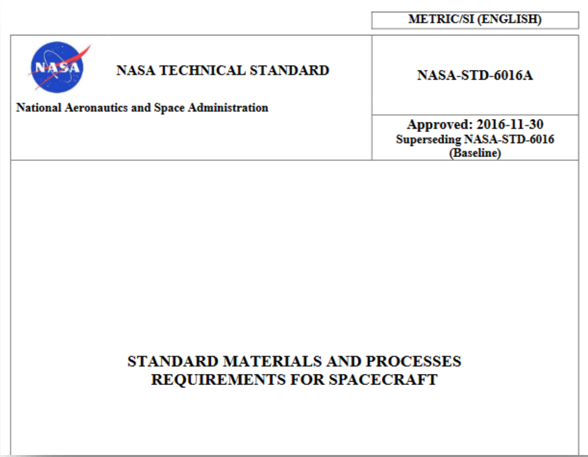
no longer nondestructive

Closed-loop process control

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

MSFC ENGINEERING

The current logic of additive manufactured part certification is outlined in NASA-STD-6016A, MSFC-STD-3716, and MSFC-SPEC-3717.


METRIC/SI (ENGLISH)

NASA TECHNICAL STANDARD

National Aeronautics and Space Administration

NASA-STD-6016A

Approved: 2016-11-30
Superseding NASA-STD-6016 (Baseline)

STANDARD MATERIALS AND PROCESSES REQUIREMENTS FOR SPACECRAFT

NASA-STD-6016A

Requirements for traditional manufacturing – also apply to AM

Policy

MSFC-STD-3716

MSFC Technical Standard

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

↓

NASA-STD-6030

NASA Technical Standard

Additive Manufacturing Requirements for Crewed Spaceflight Systems

Procedure

MSFC-SPEC-3717

MSFC Technical Standard

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

↓

NASA-SPEC-6033

NASA Technical Standard

Additive Manufacturing Requirements for Equipment and Facility Control

The new NASA standards require comprehensive NDE for surface and volumetric defects, *unless otherwise substantiated*.

Language:

"All AM parts **shall** receive ***comprehensive nondestructive evaluation*** (NDE) for surface and volumetric defects within the limitations of technique and part geometry ***unless otherwise substantiated*** as part of the Integrated Structural Integrity Rationale of PPP [Part Production Plan] per section 7.3"

Rationale:

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

(emphasis added)

However, passive in-situ process monitoring may be used as a quantitative indicator of part quality, if qualified by the CEO.

Language:

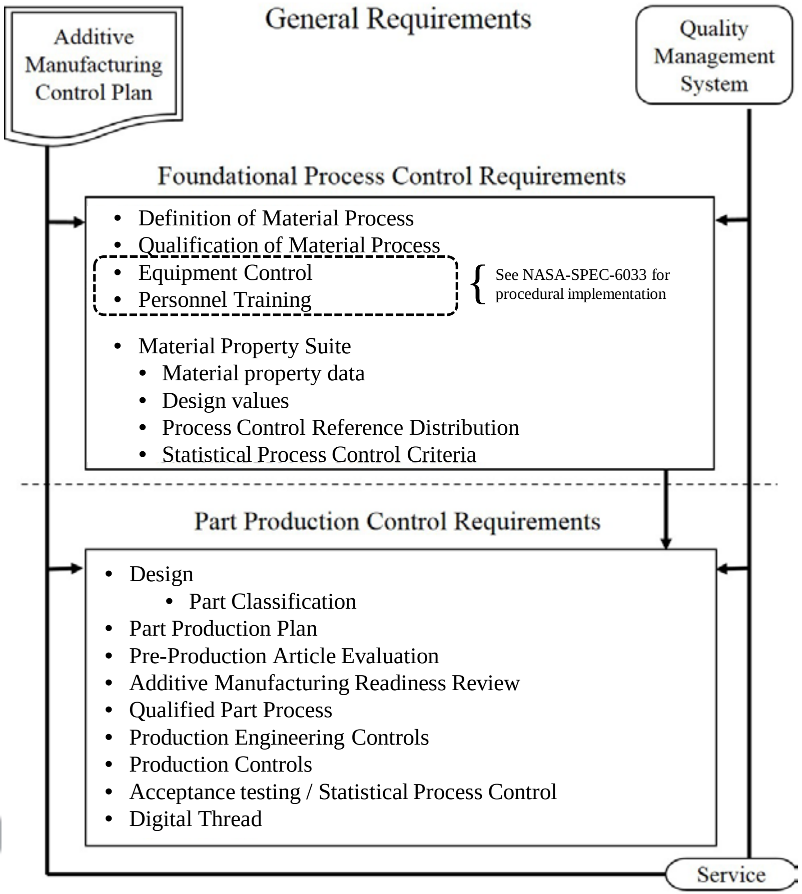
"Prior to use as a quantitative indicator of part quality, passive in-situ process monitoring technologies ***shall be qualified*** by the CEO to the satisfaction of NASA in a manner analogous to other NDE technologies."

Rationale:

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

(emphasis added)

In-situ monitoring can factor into several aspects of part certification.



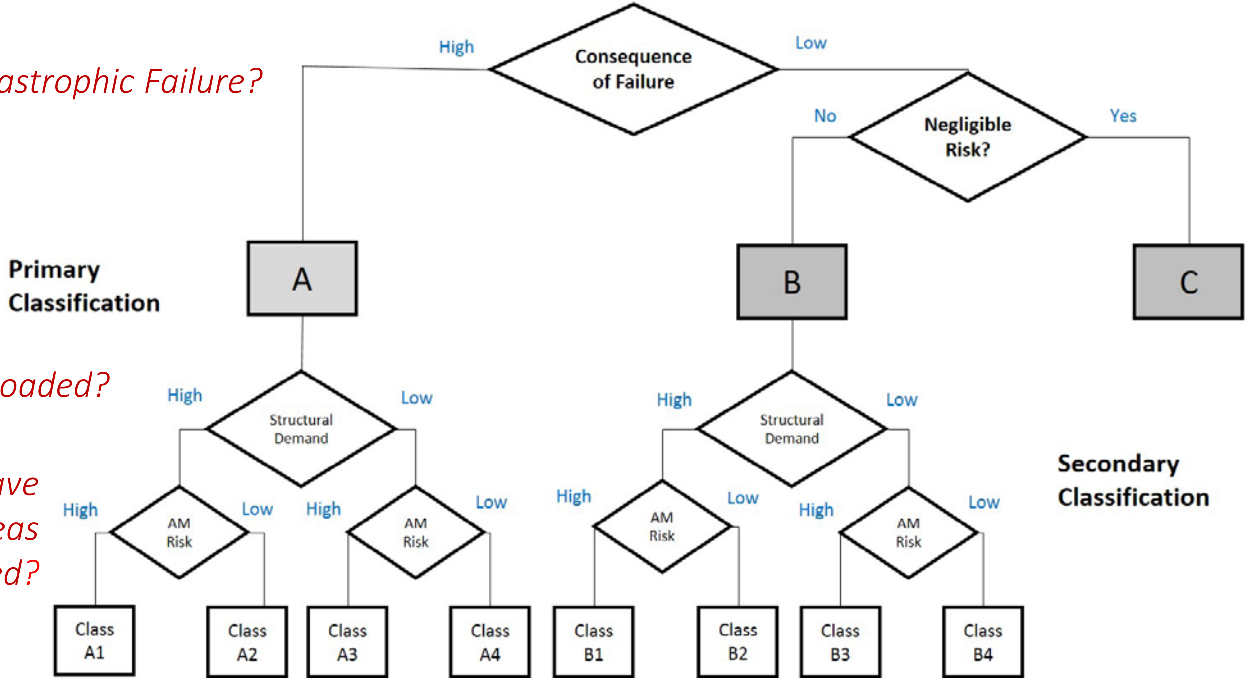
- **Qualification of Material Process (QMP)**
  - Use in sync with process development
- **Part Classification**
  - Improve inspectability for better risk posture
  - Inspection process must be qualified by CEO
- **Part Production Plan**
  - Integrated Structural Integrity Rationale (ISIR):
    - Can be specified as a defect screening action
    - Must be qualified by CEO
- **Production Controls**
  - Could develop certain metrics to track over time

Risk-based part 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?



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

"Active in-situ monitoring technologies that alter the defined AM process in response to monitored phenomena are ***not currently acceptable*** per this NASA Technical Standard."

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, NASA encourages and wants to help enable the use of in-situ process monitoring for AM certification.

Use for process monitoring is ***highly encouraged.***

→ Will help inform, develop, and prepare for part quality function

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.

Thank you for your time!

Questions?