National Aeronautics and Space Administration
Marshall Space Flight Center

Reliability of Mechanical Behavior in Metallic Additively Manufactured Parts for Critical Applications

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ASTM/NIST Workshop on
Mechanical Behavior in
Additive Manufactured parts

May 4, 2016

There is more to AM than manufacturing

AM machines create a unique material product form – typically purview of the foundry or mill

Subtractive Forging Process

1. Ingot Making 2. Cutting 3. Heating 4. Forging 5. Heat Treating 6. Machining 7. Inspection 8. Delivery with CoC

Additive SLM Process

1. Powder Making 2. Printing 3. HIPing 4. Heat Treating 5. Machining 6. Inspection 7. Final Part

As the 'mill', the AM process must assure manufacturing compliance throughout the build process and material integrity throughout the volume of the final part.

AM Reliability Challenges

- AM responsibility serving as the material mill gives rise to additional reliability concerns
  - Low entry cost compared to typical material producers
  - New players in AM, unfamiliar with the scope of AM, lacking experience
  - Fabrication shops not previously responsible for metallurgical processes
  - Research labs converting to production

Concept Laser X-line Material Mill in a Box

- **AM machines operate with limited process feedback!**
  - **Reliability depends upon the quality and care taken in every step of AM operations => rigorous and meticulous controls**

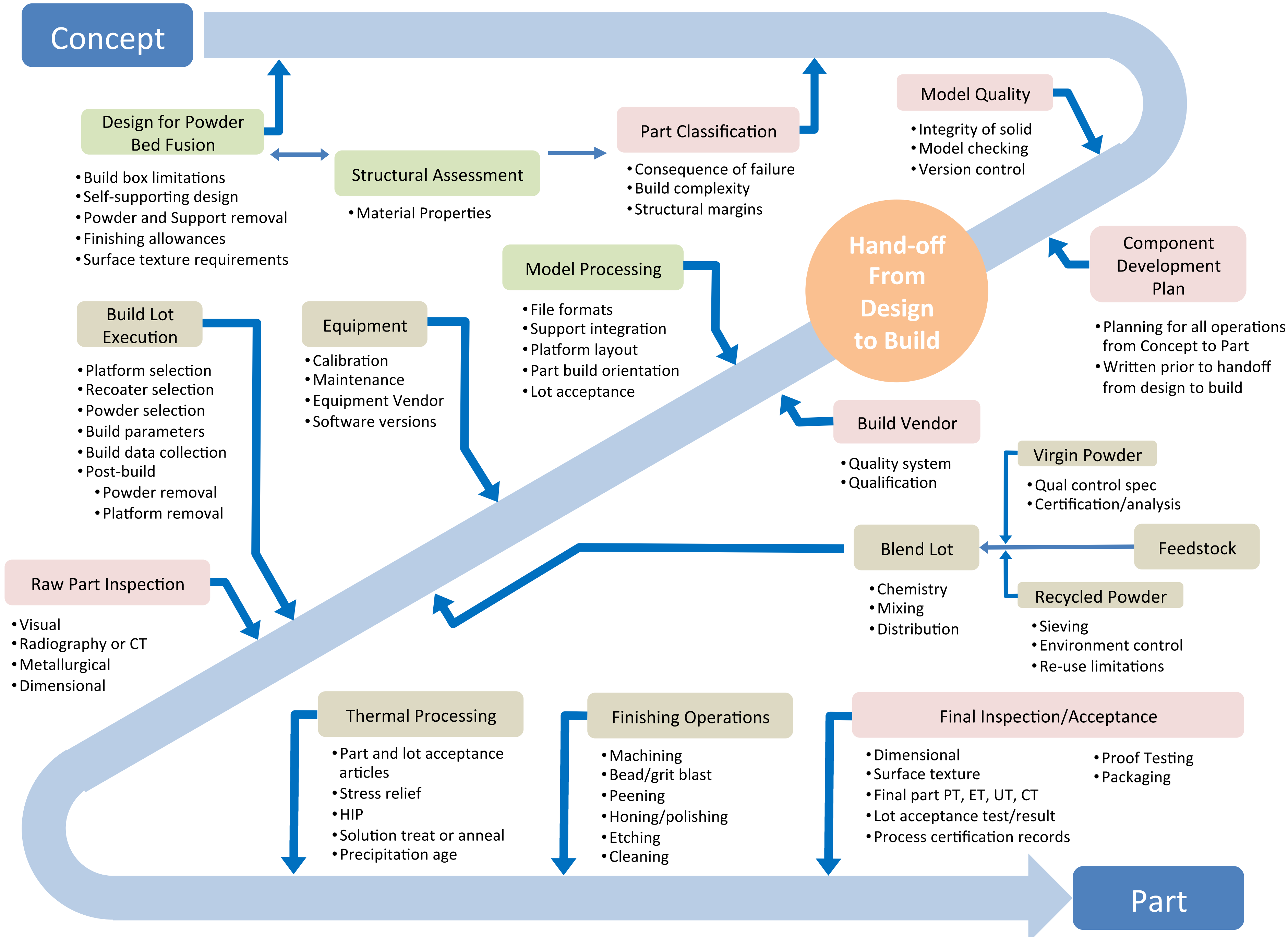
Opportunities to Secure AM Reliability

Two primary opportunities to ensure AM reliability

1. In-Process Controls, (Control what you do)
   - Understanding fundamentals of the process
   - Knowing the process failure modes (pFMEA)
   - Identifying observable metrics and witness capabilities
   - Meticulous process scrutiny
   - *Future to provide detailed process feedback for post-process evaluation or even closed-loop controls.*
2. Post-Process Evaluation (Evaluate what you get, NDE)
   - Extensive subject, ASTM E07 and many partners involved
   - Not covered in this discussion

Part reliability rationale comes from sum of both in-process and post-process controls, weakness in one must be compensated in the other

The AM Process: Concept to Part



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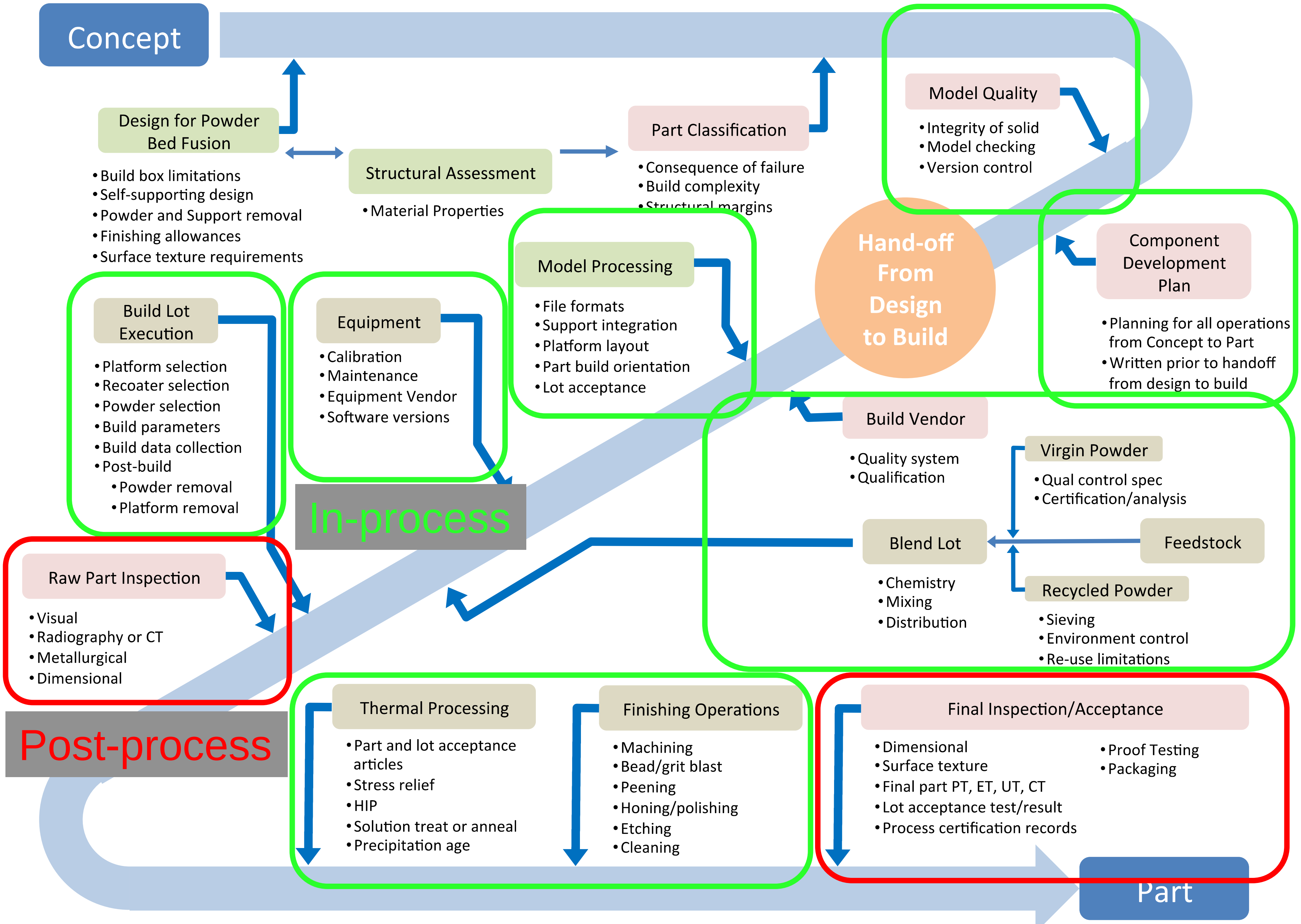


Standardization for AM Mechanical Reliability

- Systematic and controlled execution of AM processes is required to achieve requisite mechanical reliability
- Standardization of AM processes is actively pursued by private industry, government organizations, and standards development organizations worldwide.
  - ASTM F42, ISO collaboration
    - Only SDO with open, published AM standards
  - SAE AMS-AM
  - AWS
- NASA works with SDOs to bring open industry standards to AM
- Currently available open industry standards do not levy sufficient controls for spaceflight applications

Standardization for AM Mechanical Reliability

National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

- Draft NASA MSFC Standard
- Current methodology for AM reliability for critical applications
  - Space Launch System
  - Commercial Crew Program

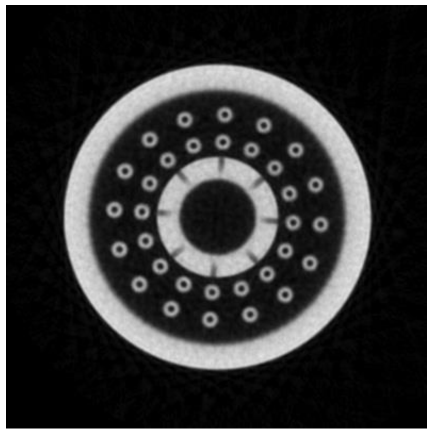
Aerojet Rocketdyne RS-25

SpaceX SuperDraco

Aspects of Process Control

Draft NASA MSFC Standard implements four fundamental aspects of process control for AM:

Metallurgical Process Control



Part Process Control

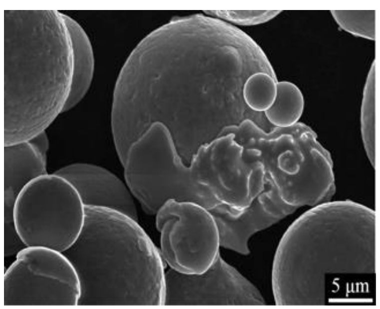
Equipment Process Control

Build Vendor Process Control

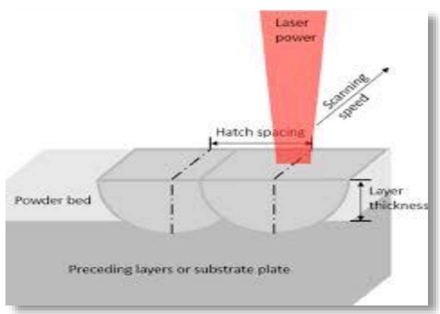
- Each aspect of process control is essential to the production of critical AM parts with reliable mechanical behavior
- Discussion here focuses on process control fundamentals for production of mechanically reliable AM materials

Foundation: Qualified Metallurgical Process

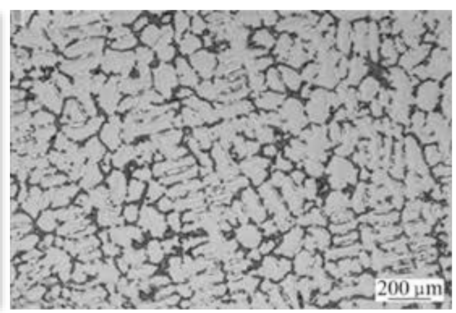
- Draft NASA MSFC Standard identifies AM as a unique material product form and requires the metallurgical process to be qualified on ***every*** individual AM machine
- While aspects of this foundation are present in, for example, ASTM F3055 (IN718 AM spec), rigor, qualification, and traceability are currently lacking.



Powder



Process Variables



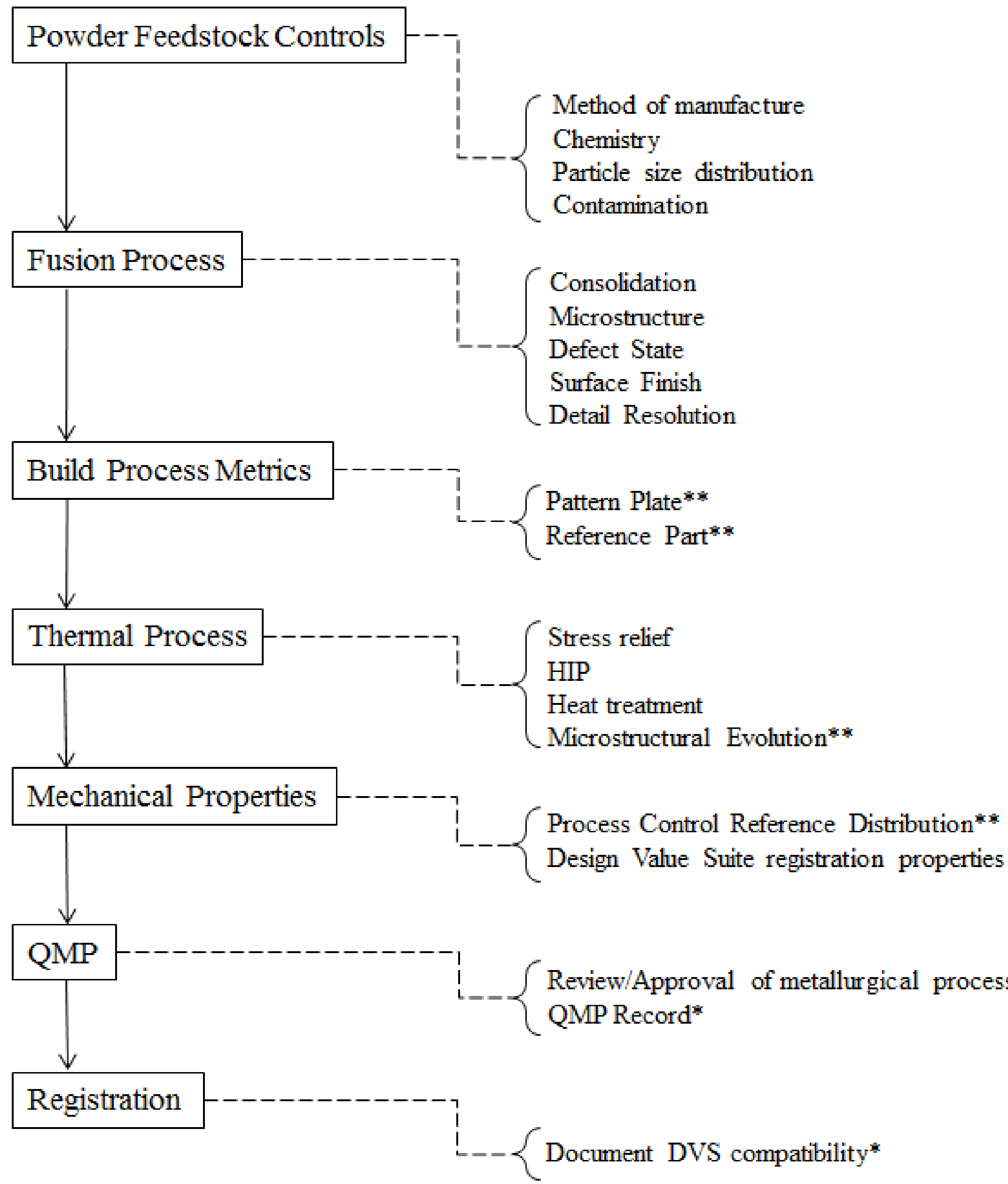
Microstructure

Properties

Foundation: Qualified Metallurgical Process

Qualified Metallurgical Process (QMP)

- Feedstock control or specification
- AM machine parameters, configuration, environment
- As-built densification, microstructure, and defect state
- Control of surface finish and detail rendering
- Thermal process for controlled microstructural evolution
- Mechanical behavior reference data
  - Strength, ductility, fatigue performance



*Quality management system record
**Acceptance criteria metric

Foundation: Qualified Metallurgical Process

As Built

Stress Relieved

HIP & Final

Qualified Metallurgical Process (QMP)

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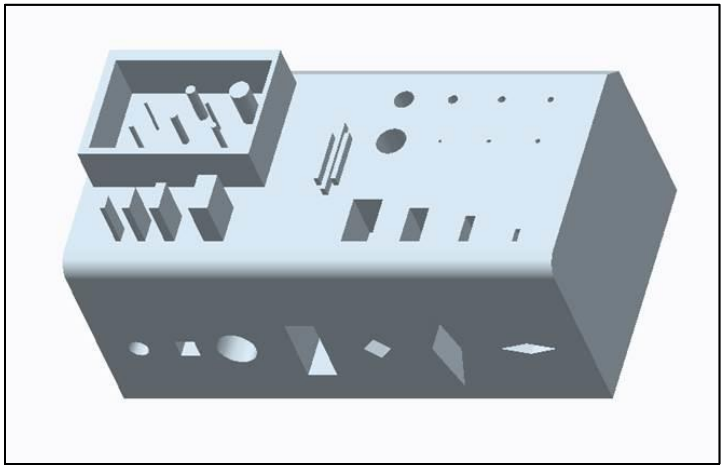
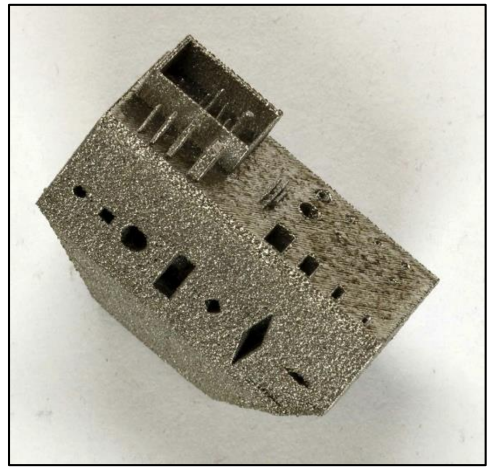
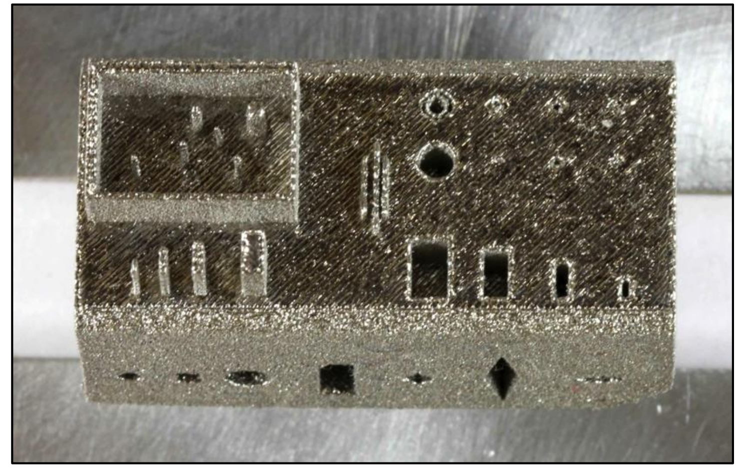
- Thermal process for controlled microstructural evolution

Foundation: Qualified Metallurgical Process







Reference parts:

Metrics for surface texture quality and detail rendering

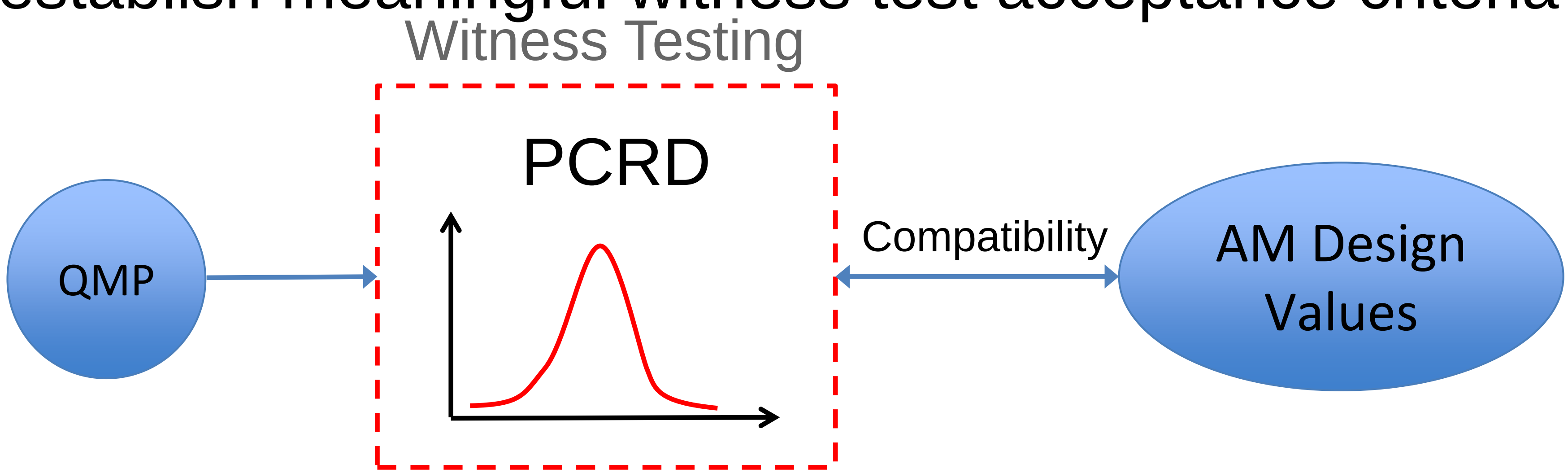
Overhanging, vertical and horizontal surface texture, acuity of feature size and shape

Qualified Metallurgical Process (QMP)

- Reference Parts
- Control of surface finish and detail rendering
- Critical for consistent fatigue performance if as-built surfaces remain in part

Foundation: Qualified Metallurgical Process

- Mechanical behavior reference data
  - Strength, ductility, fatigue performance
  - Process Control Reference Distributions (PCRD)
- Establish and document estimates of mean value and variation associated with mechanical performance of the AM process per the QMP
  - Will evolve with lot variability, etc.
- Utilize knowledge of process performance to establish meaningful witness test acceptance criteria



Foundation: Qualified Metallurgical Process

Types of AM build witness specimens

- Metallurgical
- Tensile (strengths and ductility)
- Fatigue
- Low-margin, governing properties

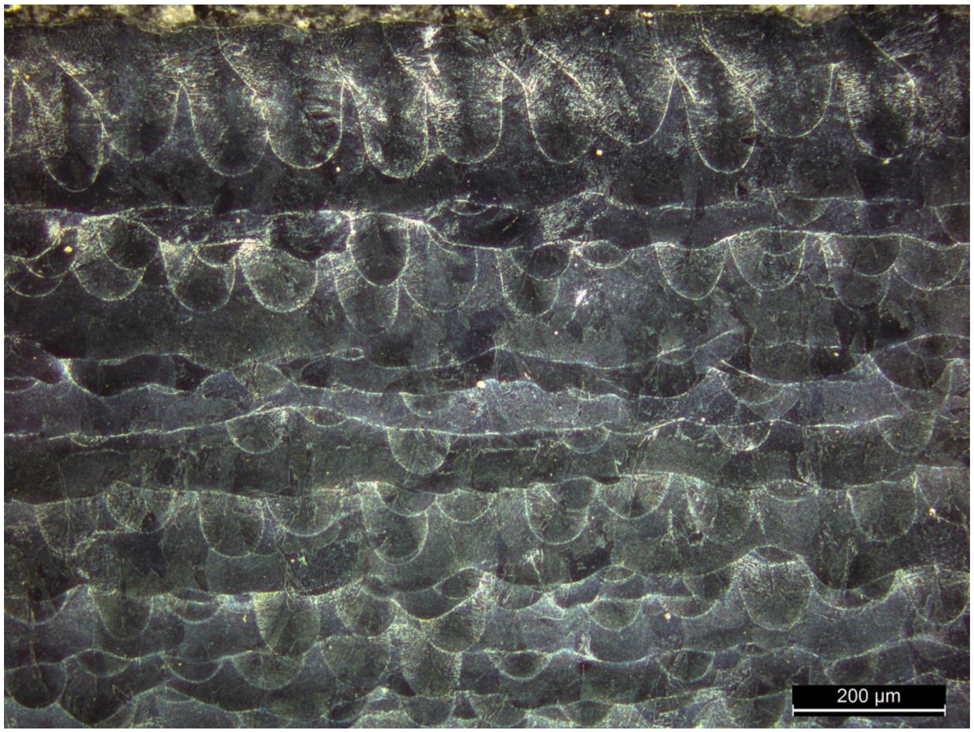
What is witnessed?

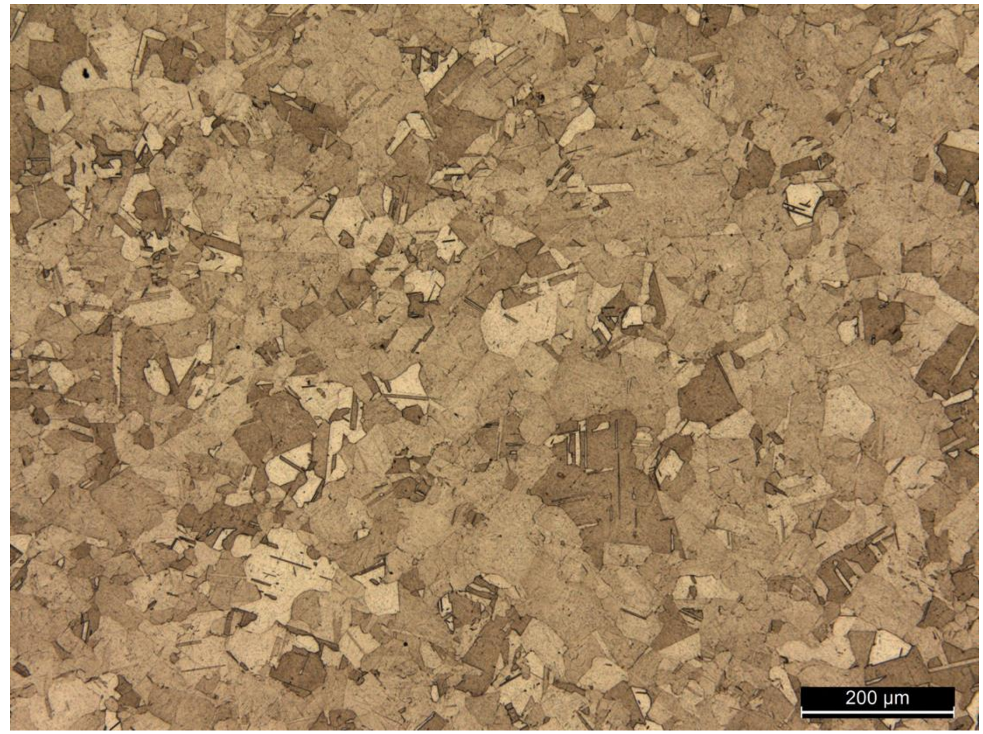
- Witness specimens provide direct evidence only for the systemic health of the AM process during the witnessed build
- Witness specimens are only an in-direct indicator of AM part quality through inference.

Foundation: Qualified Metallurgical Process

Types of AM build witness specimens

- Metallurgical





Example acceptance criteria - as-built state:

- Weld penetration depth and shape
- Grain nucleation patterns
- Porosity
- Lack of fusion / Cracks

Example acceptance criteria - final state:

- Grain size
- Expected phases or carbide sizes
- Grain boundary cleanliness
- Porosity
- Lack of fusion / Cracks

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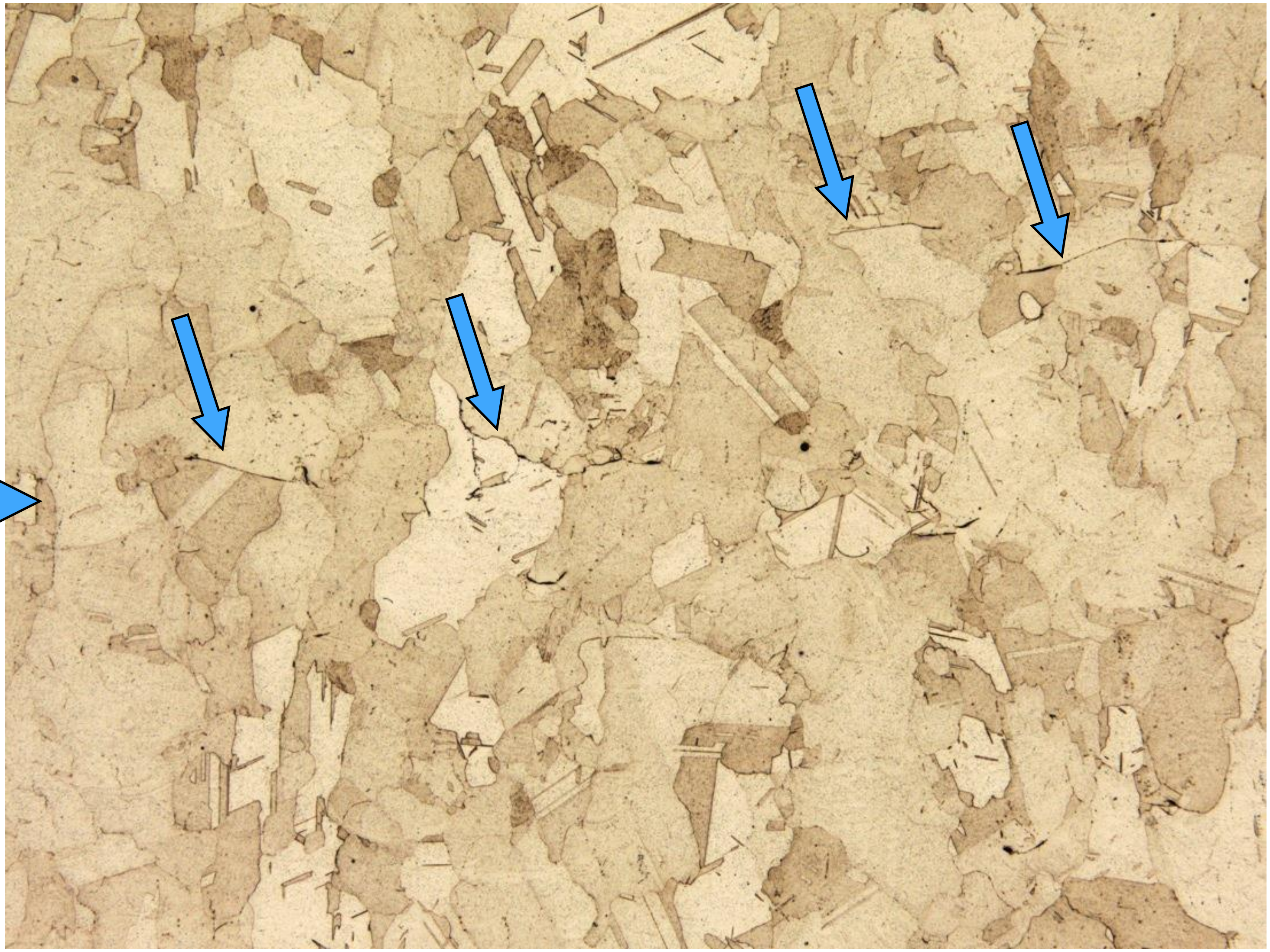


Foundation: Qualified Metallurgical Process

Types of AM build witness specimens

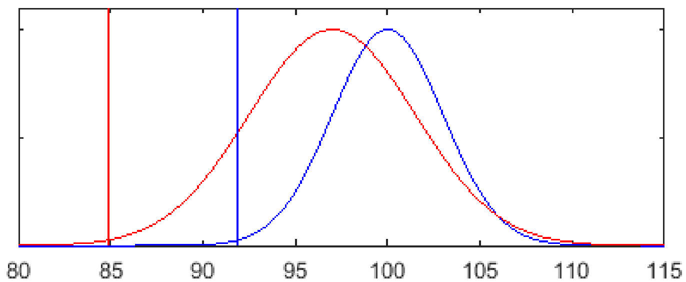
- Mechanical
  - Move away from spot testing with acceptance against 99/95 or specification minimums
  - Evaluate with sufficient tests to determine if the AM build is within family
  - Compromise with reasonable engineering assurance
  - Proposed
    - Six tensile
    - Two fatigue

Evaluate against the PCRD of the QMP

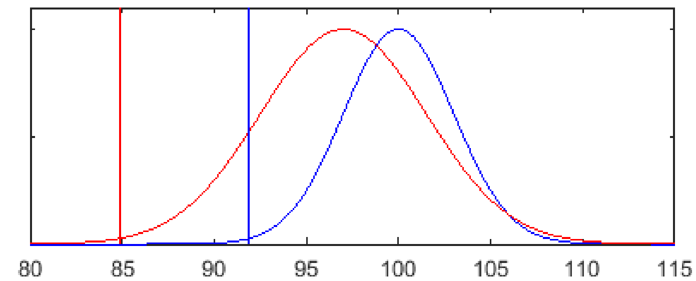
- **Ongoing evaluation of material quality substantiates the design allowable**
- **Only plausible way to maintain design values**

Example of AM build witness specimen evaluations

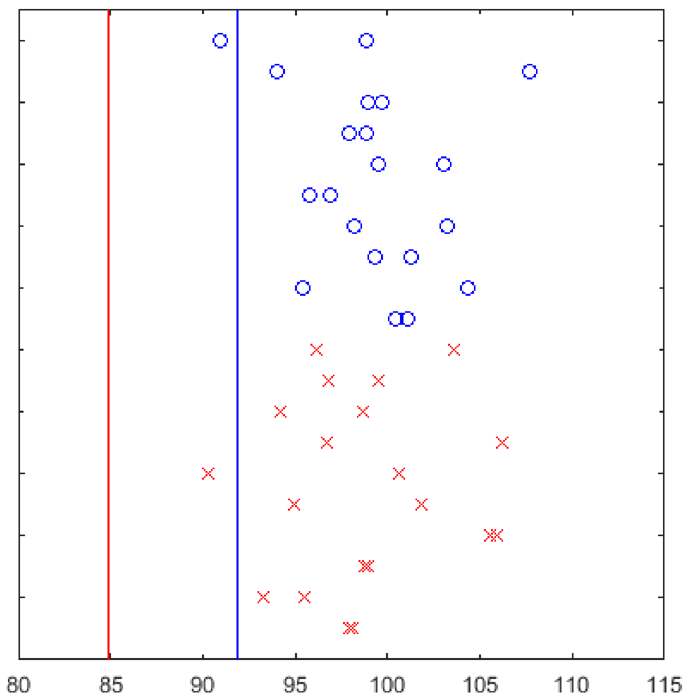
Nominal process is blue, off nominal in red



Two (2) witness tests per build



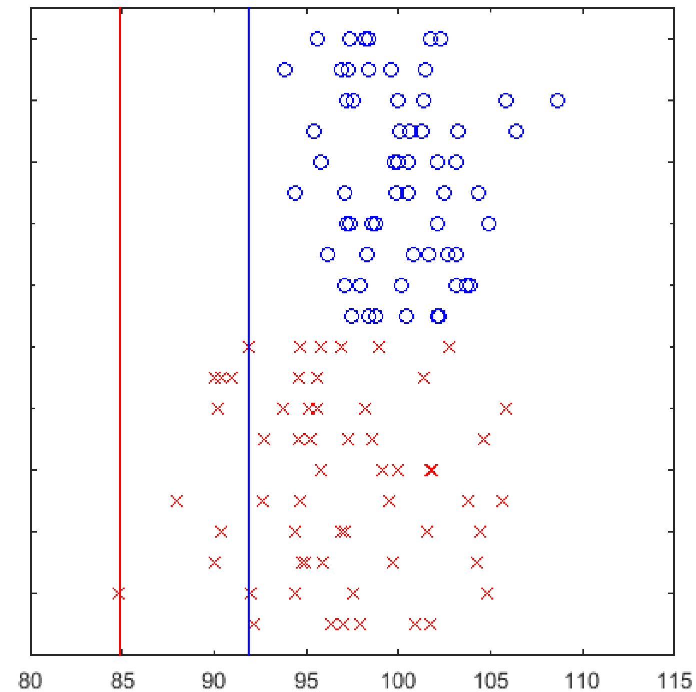
Six (6) witness tests per build



Process shift hard to discern

Random draw from nominal process 10 times

Random draw from off-nominal process, 10 times



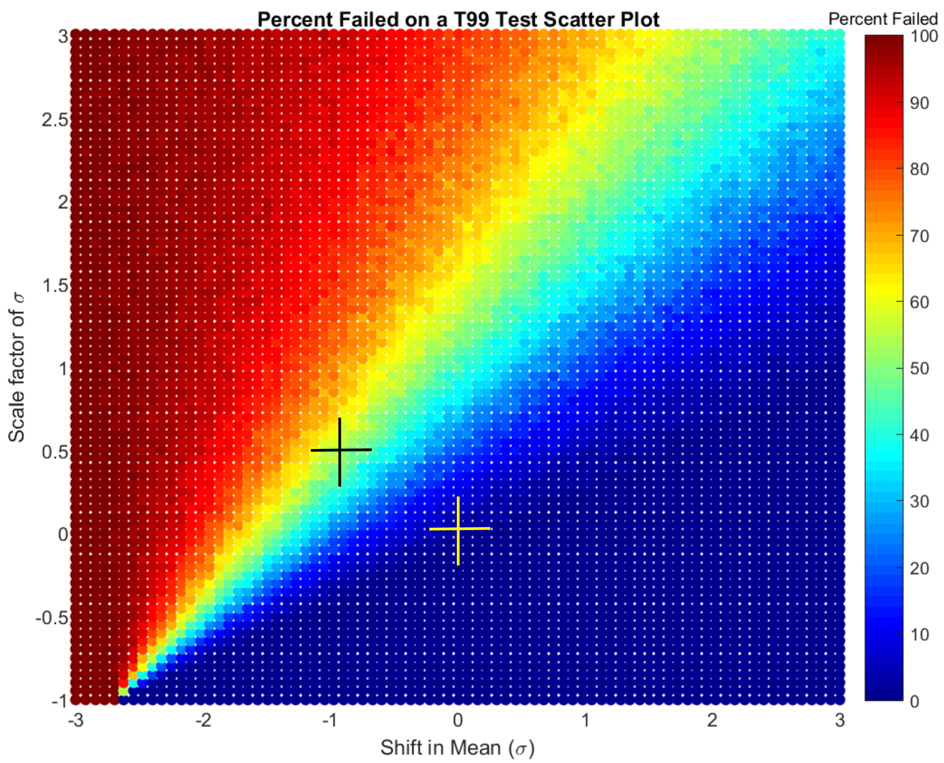
Process shift discernable with analysis of mean and variation

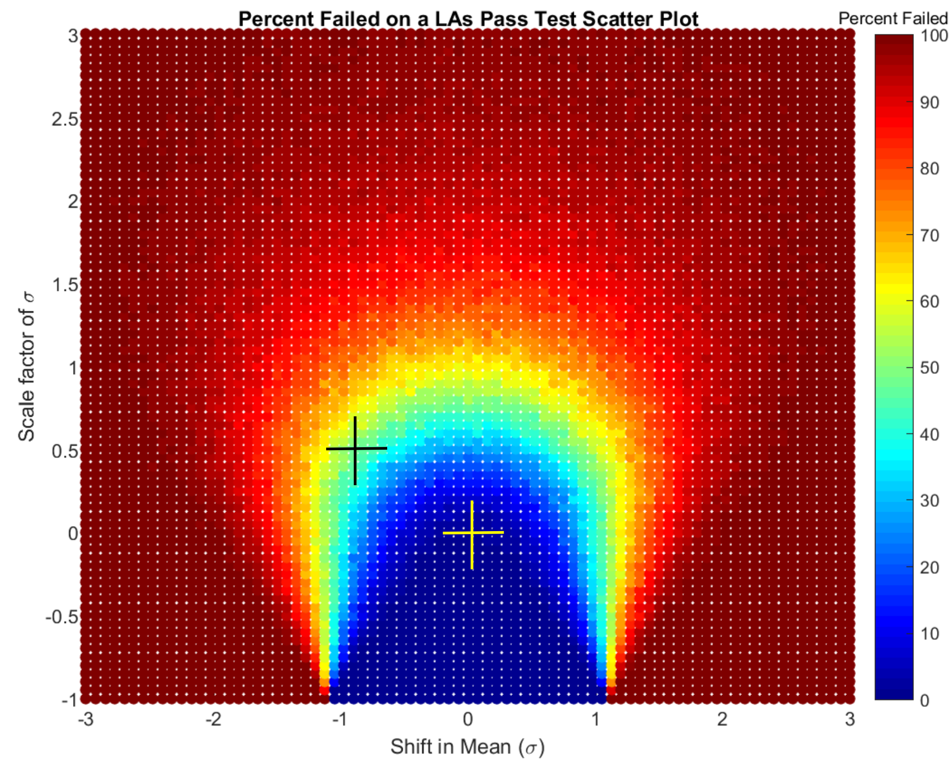
Witness for Statistical Process Control

Simulation is used to evaluate small sample statistical methods for witness specimen acceptance

Design acceptance criteria for the following:

- Keep process in family
- Minimize false negative acceptance results
- Protect the design values witnessed
- Protect the inferred design values





Role of Quality Management System

AM process controls cannot be meaningfully implemented without oversight and integration with strong Quality Management System

- Example, SAE AS9100

Mechanical reliability in AM cannot be established until:

- Process is defined and understood – Concept to Part
- Failure modes identified
- QMS engaged to monitor process and defeat failure modes

Standardization is key to developing a consistent approach

Summary of Points

To ensure mechanical reliability in AM:

- Requires thorough understanding and control of the process - Just as would be expected from a mill, foundry, or manufacturing house
- Requires sufficient process standardization to produce reliable parts in a routine fashion
- Requires quality management systems be in place
- Requires In-Process controls
  - Start with a solid foundation
    - Qualified metallurgical Process
  - Ensure mechanical reliability
    - Process witnessing, statistical evaluations
- Requires Post-Process controls
  - NDE
  - Proof testing
  - Etc.

Thank You

Additive Manufacturing at MSFC

Witness for Statistical Process Control