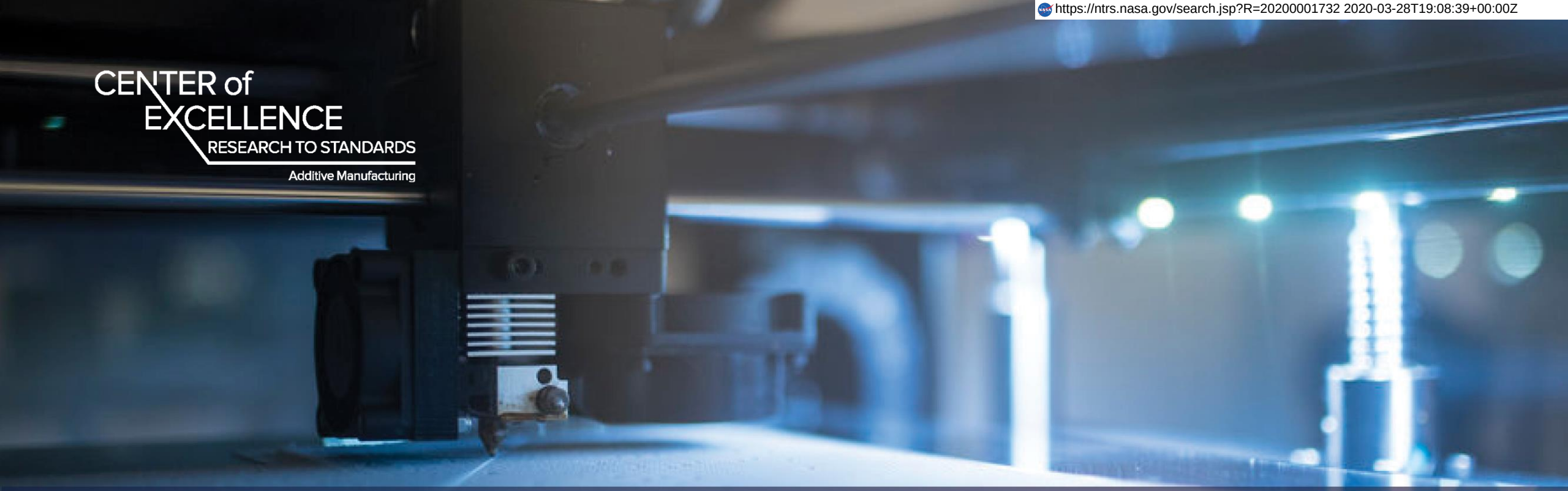


3rd ASTM AM CoE Snapshot Workshop

Additive Manufacturing Machine/Process Qualification

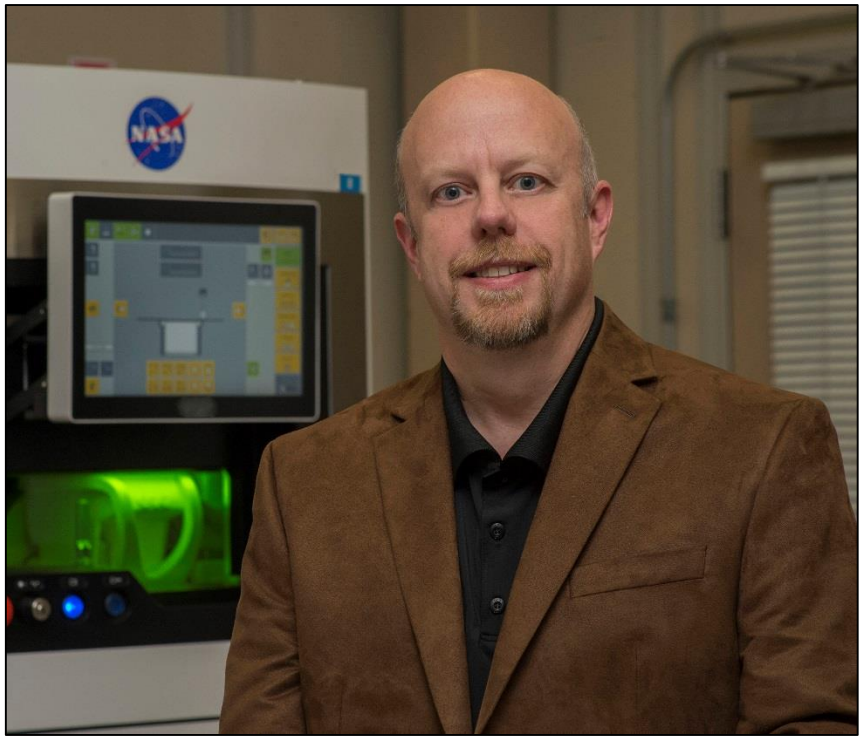
Douglas N. Wells, NASA Marshall Space Flight Center

Presenter Bio

Douglas Wells

NASA - Marshall Space Flight Center

- Structural Materials Engineer, Materials and Processes Laboratory
- 25+ years experience in fatigue, damage tolerance, and fracture control of flight structures.
- 8+ years developing methodologies for the qualification and certification of additively manufactured spaceflight hardware
- Developed first NASA standards to establish requirements for incorporating additively manufactured hardware into flight vehicles



Introduction and Overview

Additive Manufacturing Machine/Process Qualification

- ***Machine and Process Qualification are Fundamental.***
- For any manufacturing process that is dependent upon continuous and ardent control to produce quality-critical products, companies, purchase stakeholders, and regulatory agencies anchor their confidence in the most basic aspect of process control:

The foundational act of qualifying the process to demonstrate it meets a well-defined degree of quality and stability.

Introduction and Overview

AM Machine/Process Qualification

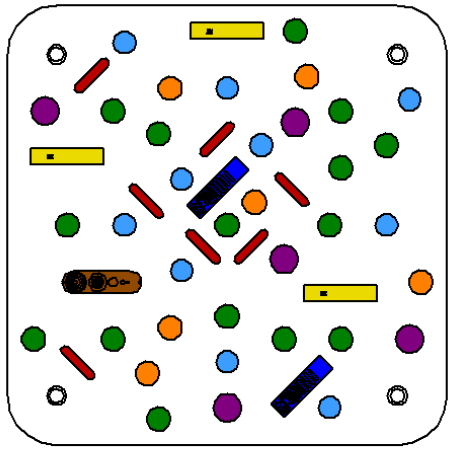
- Lack of standardization for AM machine and process qualification
- Commonly treated as proprietary information
- Current declarations of machine and process qualification have little meaning because the declaration lacks definition
- Proprietary process qualification standards are evaluated on a case-by-case basis, leading to significant burden on vendors, purchasers, and regulatory bodies to continuously evaluate the rigor of unique and varied methodologies of qualification.
- For safety-critical applications, this non-standardized, vendor-unique qualification review adds risk related to potential unidentified shortfalls in the unique qualification scheme

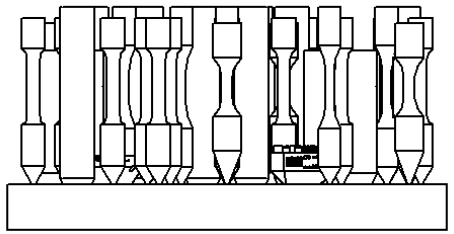
Introduction and Overview

Additive Manufacturing Machine/Process Qualification

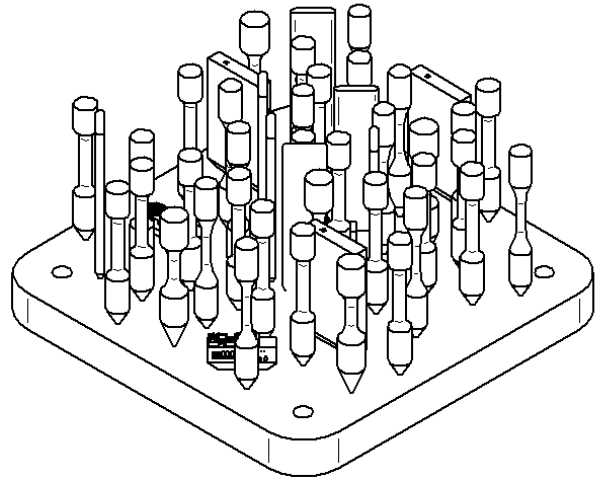
Key Challenges

- Time and expense of qualification are significant – efficiency is critical
- Consensus lacking on the scope, proper metrics, and evaluation criteria
- Part criticality influence on qualification
- Re-qualification needs are frequent
  - How and when
  - Maintenance / troubleshooting
  - Relates to monitoring and efficiency of witness feedback





Specimen Type	Qty	Name	Key
High Cycle Fatigue	10	HCF-1 thru HCF-10	
Low Cycle Fatigue	5	LCF-1 thru LCF-5	
Tensile (RT)	15	TN-1 thru TN-15	
Tensile (Cryo, ET)	6	TN-16 thru TN-21	
Fracture Toughness	3	FT-1 thru FT-3	
Metallographic Samples	7	MET-1 thru MET-7	
Dimensional Samples	2	D-1 thru D-2	
Contour Analysis Samples	1	C-1	



Standardized Practices

Limited standardization has been established for LB-PBF qualification

- Needs are discussed in the America Makes/AMSC Standardization Roadmap for Additive Manufacturing, Version 2.0, Section 2.3.3.1 on "Processes on Procedures."
- Overview of current standardization for AM machine/process qualification
  - ASTM/ISO standards
  - SAE AMS AM standards
  - AWS D20
  - Open Government standards: MSFC-SPEC-3717
- Two trends:
  1) deferral to "as agreed upon" language, and
  2) lack of consensus on scope and approach

Standardized Practices

- ASTM F42 AM standards have qualification requirements only by agreement
- F42 "Finished Part" standards: F3055 IN718, F3302 Ti, F3184 316ss, etc.
  - Requires a manufacturing plan that includes
  - A machine, manufacturing control system, and qualification procedure as agreed upon by the part supplier and purchaser;
  - NOTE—Qualification procedures typically require qualification build cycles in which mechanical property test specimens are prepared and measured in accordance with Section 11 or other applicable standards. Location, orientation on the build platform, build parameters/exposure strategies, number of test specimens for each machine qualification build cycle, and relationship between specimen test results and part quality shall be agreed upon by the part supplier and purchaser.
- ISO 52901 *Additive manufacturing — General principles — Requirements for purchased AM parts*
  - Silent on requiring machine/process qualification prior to purchase
  - Guidance provided for Qualification Parts, and their acceptance procedures

Standardized Practices

- ISO 52904 *Additive manufacturing — Process characteristics and performance — Practice for metal powder bed fusion process to meet critical applications*
- Most definitive ASTM/ISO standard directly addressing machine/process qualification:
  - Machine, Process, and Part Qualification
    - …consolidated material shall be evaluated for chemical composition, microstructure, porosity and mechanical properties as specified by an *appropriate standard* or as agreed upon by the component manufacturer and customer.
    - …a reference part that is an indicator of build quality shall be produced and dimensionally measured as part of the qualification procedure

An "appropriate standard" for machine/process qualification is needed.

Standardized Practices

- SAE AMS AM 7000 series requires machine qualification, but also defined only by agreement
- Common language for L-PBF Machine Approval in the 7000 series:
  - For each individual L-PBF machine, the Producer shall demonstrate that the items fabricated in the L-PBF machine conform with all requirements of the applicable material specification. The CEO shall define the requirements (number of specimens, analysis method and acceptance criteria) and the Producer shall meet those requirements. This substantiation shall be authorized by the CEO prior to implementation into production.
    - Material testing is performed using specimens built within the extents of the build envelope defined in the PCD including the extremes of the x, y, and z positions and orientations in the x-y plane and z direction.

Standardized Practices

AWS D20.1 *Specification for Fabrication of Metal Components using Additive Manufacturing*

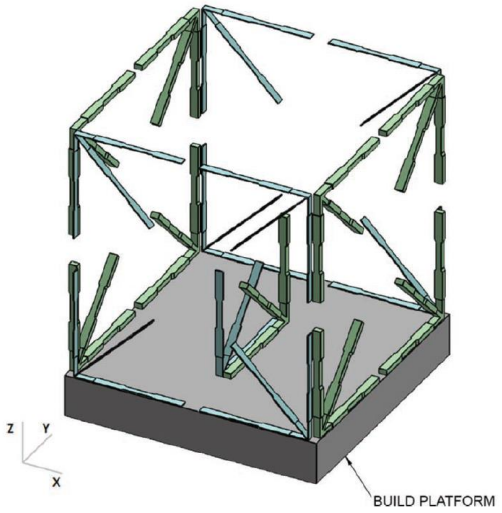
- Most comprehensive, open-industry standard addressing process qualification
- Clause for "Additive Manufacturing Machine and Procedure Qualification"
  - …The purpose of an AM machine qualification is to demonstrate that an AM machine is capable of producing specimens that meet required properties throughout the build envelope within which components are to be fabricated using a qualified AM procedure.
  - Machine Qualification Record (MQR)
  - Machine qualification is required for Class A and Class B components and requires the fabrication and testing of a standard qualification build (5.2.1, 5.2.2). Machine qualification is not required for Class C components.
- Incorporates part classification into qualification requirements

Standardized Practices

AWS D20.1 *Specification for Fabrication of Metal Components using Additive Manufacturing*

Classes A & B, focus on tensile tests: bounding box, multiple orientation, statistically significant quantity, thick and thin cross-sections.

Figure C1:



Excerpt: Table 5.1, Inspection and Testing Requirements for Machine and Procedure Qualification

Test Method		Powder Bed Fusion		
		Class A	Class B	Class C
Machine Qualification Standard Qualification Build(s)	Visual Examination	Yes	Yes	—
	Dimensional Inspection	Yes	Yes	—
	Radiographic Examination	Yes	Yes	—
	Density Testing	Yes	Yes	—
	Tension Tests	54	54	—
	Metallographic Examination	Yes	Yes	—

Standardized Practices

- Publically available government standards:
  - 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”
- Documents soon to be superseded by NASA-STD-6030 *Additive Manufacturing Requirements for Crewed Spaceflight Systems*
  - Incorporates part classification-based machine/process qualification
- The MSFC documents serve as a “point of departure” for the evaluation of AM process qualification in the ASTM CoE Process Qualification project.
- Current CoE Process Qualification project focused only on single-laser, LB-PBF

Standardized Practices

Current evaluations required for Machine/Process Qualification in -3717 include:

Prerequisites: adequate feedstock control, completely defined and locked process variables.

a) Quality of material microstructure as-built by the machine/process
   i. Consistency throughout build area
   ii. Demonstration to tolerance to thermal history extremes
   iii. Restart layer interfaces (if allowed)
   iv. Interfaces in scan patterns, surface contours, or cosmetic passes
   v. Melt pool evaluations for process characterization

b) Microstructural evolution controlled by post-build thermal processing

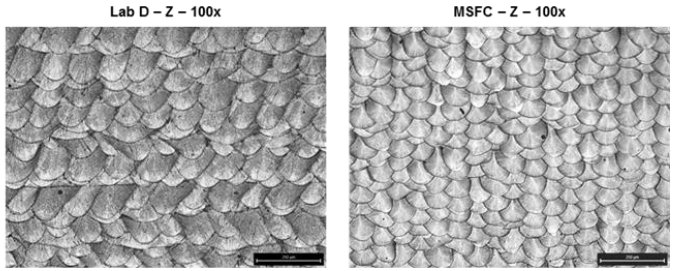
c) Reference parts providing evaluation of surface texture and detail resolution metrics

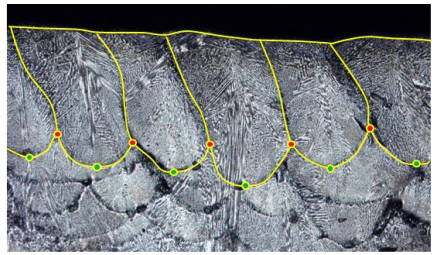
d) Mechanical properties that demonstrate the process achieves material capability in family with data used to establish and monitor process control and develop design values.

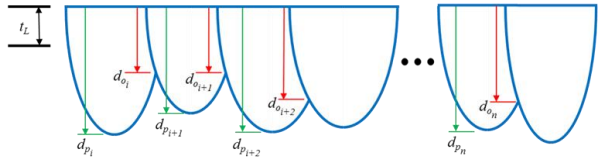
The Starting Foundation

Current evaluations required for establishing the QMP in -3717 include:

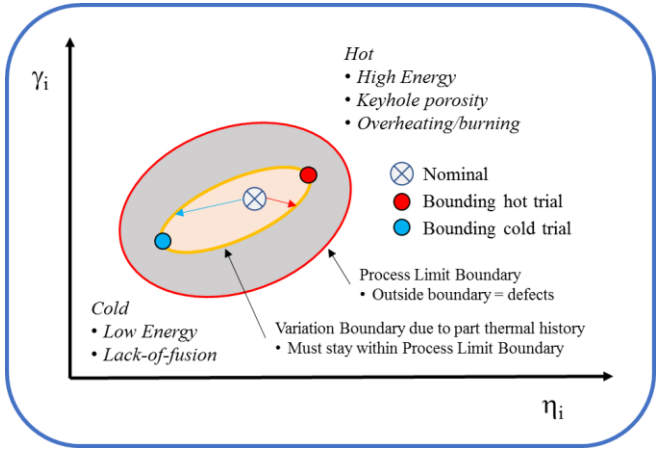
a) Quality of material microstructure as-built by the machine/process
   i. Consistency throughout build area
   ii. Demonstration to tolerance to thermal history extremes
   iii. Restart layer interfaces (if allowed)
   iv. Interfaces in scan patterns, surface contours, or cosmetic passes
   v. Melt pool evaluations for process characterization

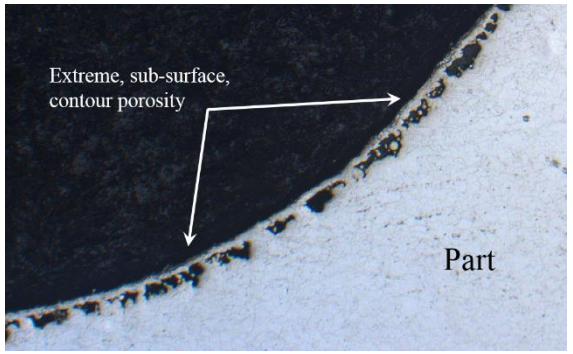






Melt Pool Evaluation



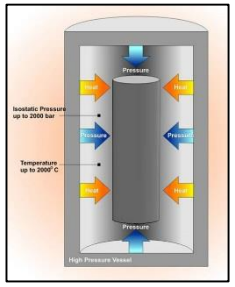


The Starting Foundation

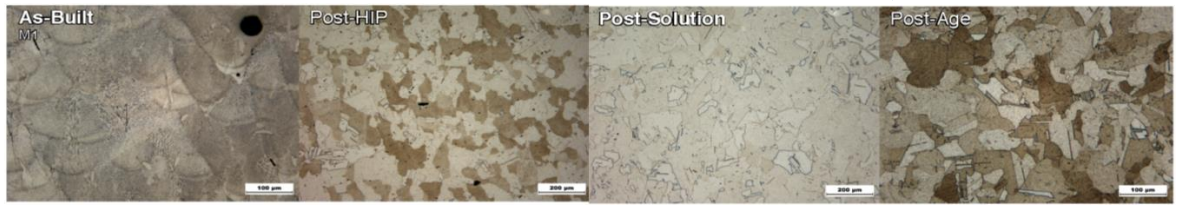
Current evaluations required for machine/process qualification in -3717 include:

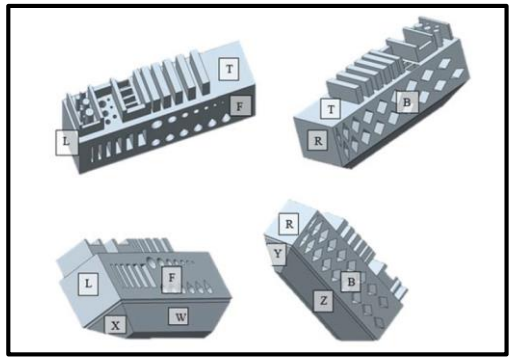
b) Microstructural evolution caused by post-build thermal processing

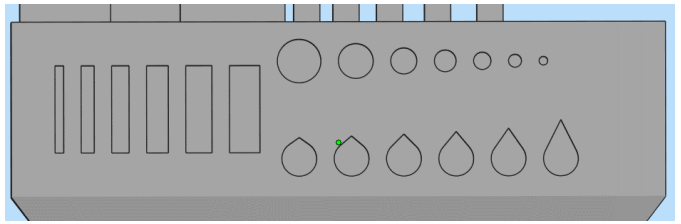
c) Reference parts providing evaluation of surface texture and detail resolution metrics

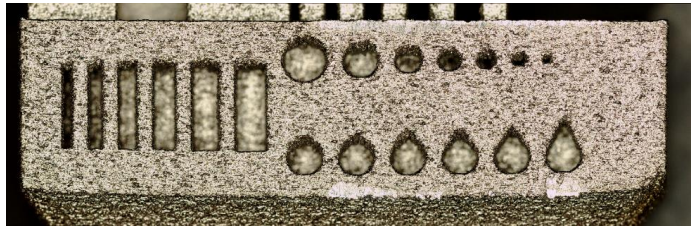


IN718 Microstructural Evolution





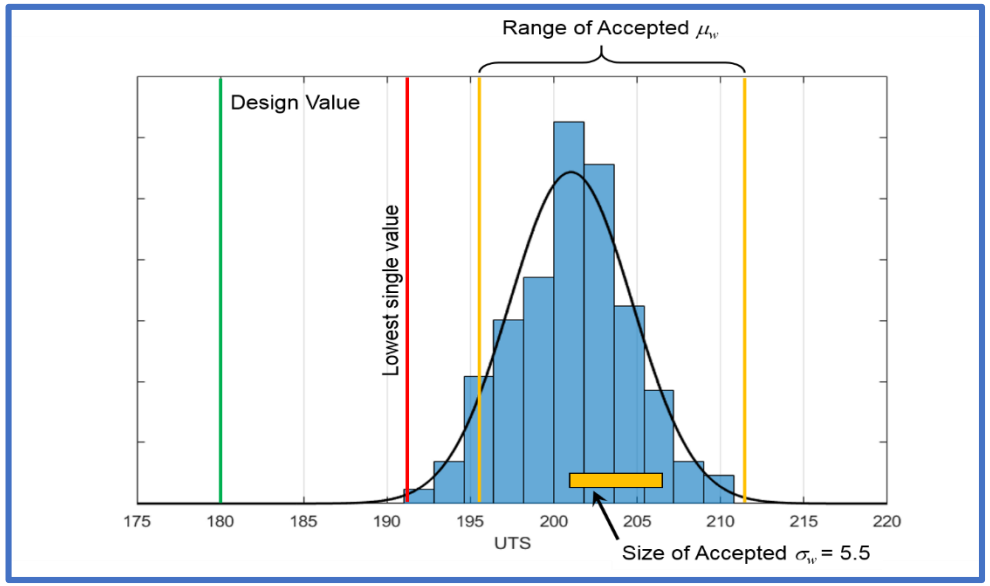


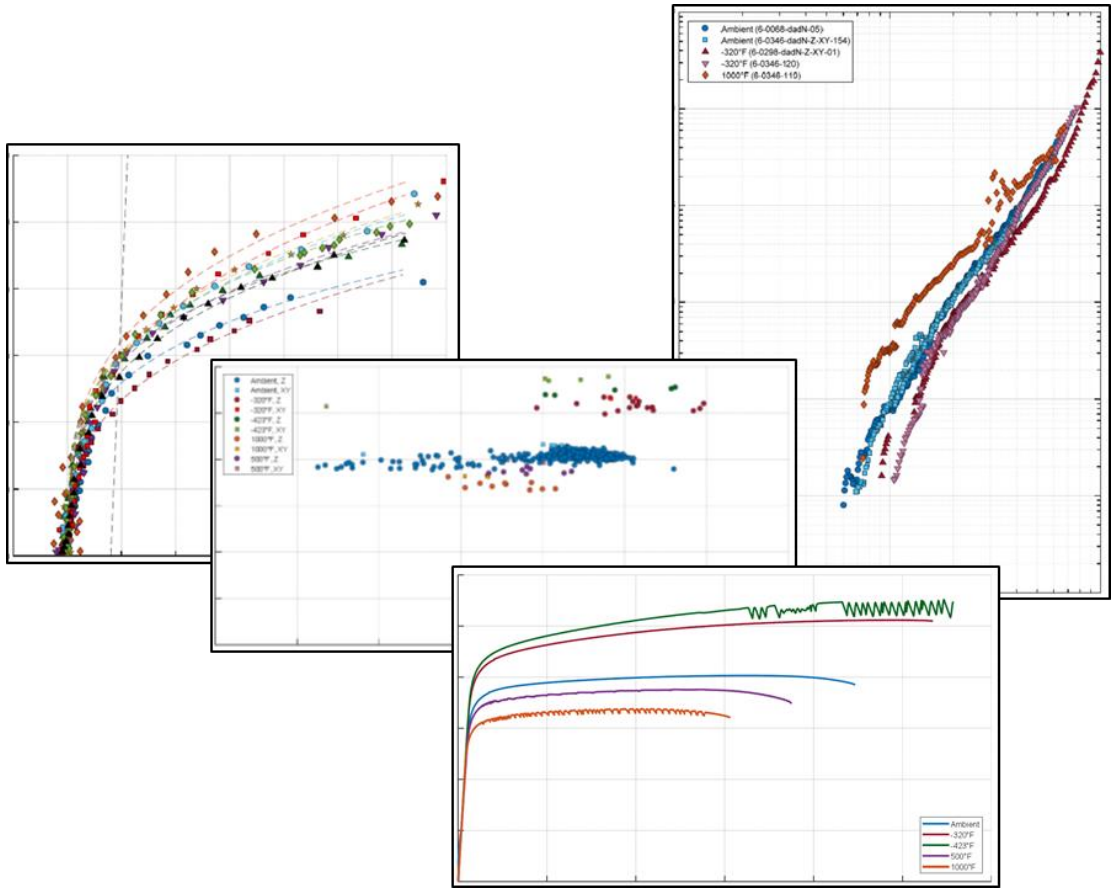


The Starting Foundation

Current evaluations required for machine/process qualification in -3717 include:

d) Mechanical properties that demonstrate the process achieves material capability in family with data used to establish and monitor process control and develop design values.





Gaps in Standards

- Primary gap is the lack of a consensus standard defining the objectives, procedures, metrics, and criteria for AM machine/process qualification
- A common definition for AM machine/process qualification provides a foundation for significant gains in uniformity in the quality of AM processes and parts
- AM machine/process qualification standards must provide clear distinction for roles
  - Interdependence of machine and process parameters
  - Role of fixed parameter sets, and allowance for parameter changes
  - AM machine calibration (machine operates correctly as commanded)
  - AM part qualification
    - Companion standard needed for AM part qualification procedures
  - Events and circumstances invalidating qualification and need for re-qualification

Solutions

Objectives of the LB-PBF Process Qualification CoE Activity

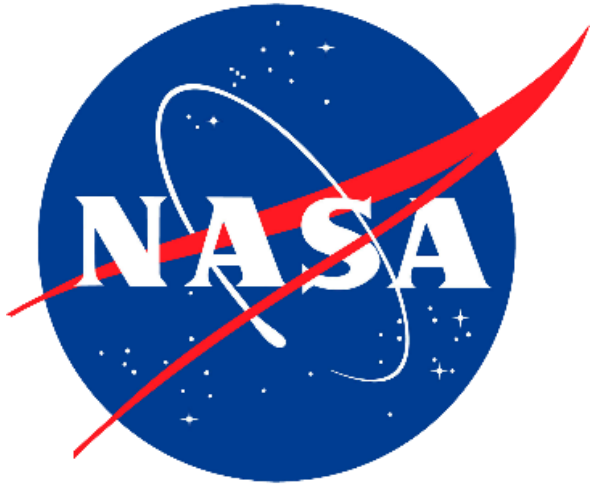
1. Develop consensus within the ASTM CoE community regarding minimum requirements for the qualification of L-PBF machines/processes.
2. Establish a standard set of procedures, test methods, and evaluations used to establish L-PBF qualification based on fundamental objectives.
3. Establish quantitative and/or qualitative metrics applicable to each evaluation to define successful machine and process qualification.
4. Conduct development and round-robin-style trials of the qualification evaluations and associated metrics.
5. Establish a set of recommendations to appropriate F42 sub-committees for standards implementation.

Current Status: CoE LB-PBF Qualification Project

- LB-PBF Project is directed by NASA/MSFC for the CoE
- Multi-partner project by definition
- CoE partners and participants Auburn, EWI, MTC, NIAR are engaged
  - Includes input from CoE US Industry Consortia
- CoE has conducted a review of the MSFC AM standards
  - No disagreements or gaps noted in the foundational concepts
  - Numerous potential gaps in implementation of qualification procedures sited
    - Feedstock control, microstructural evaluations, thermal process controls and allowances
  - Need for improved clarity and generalization for non-NASA applications
  - Methodology for part classification-based qualification, requires decision on classification system
  - Increased flexibility desired
- Currently working to establish means of establishing consensus
- Next step is CoE partners developing potential procedures and beginning round robin activities

Q&A

Questions?



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Next Topic: LB-PBF, Process and Monitoring

- The goal of consistent machine/process qualification is to establish a basis definition of acceptable machine/process performance
- The operational objective is to maintain the same consistent performance throughout production
- This is traditionally done through a variety of post-build process witness specimens (dimensional, metallurgical, mechanical)
- A rapidly growing opportunity is to maintain awareness and traceability of process health through means of monitoring the process in situ.