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MSFC TECHNICAL STANDARD

SPECIFICATION FOR CONTROL AND QUALIFICATION OF LASER POWDER BED FUSION METALLURGICAL PROCESSES

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FOREWORD

This Marshall Space Flight Center (MSFC) Technical Standard is published by the National Aeronautics and Space Administration (NASA), MSFC to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for MSFC programs and projects, including requirements for selection, application, and design criteria of an item. This MSFC Technical Standard is classified as type “Specification” because its primary purpose is to convey procedures and practices for process qualification and control. Henceforth, this document is referred to as a “MSFC Specification.” This MSFC Specification may be cited in contract, program, project, and other Agency documents, and applies only to the extent specified or referenced in those documents.

This MSFC Specification is an applicable document to MSFC-STD-3716 “Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals” (henceforth, MSFC-STD-3716) and implements the requirements for qualification of the laser powder bed fusion (L-PBF) metallurgical process, control of L-PBF equipment and associated facilities, and training of personnel. Though L-PBF is a highly automated process, vigilant qualification and control of the process is essential. In addition to manufacturing parts, by its nature, the L-PBF process also serves a critical role in the production of the material itself.

Qualification of the L-PBF process on each additive manufacturing machine is essential—just as is required in the commonplace qualification of welding processes in aerospace practice. The methodology for qualification of the metallurgical process in L-PBF has not yet been standardized by the industry. This MSFC Specification identifies the basic requirements needed to evaluate the quality of the L-PBF metallurgical process and provide metrics for use in continuous process monitoring and part acceptance. Process qualification depends upon a known state of calibration and qualification of the L-PBF machine as well as the quality of controls over the supporting facility, such as the storage and handling of feedstock powder. Regardless of the level of automation, L-PBF is a complex and meticulous process, requiring practitioners with proper education, experience, and skills to achieve the expectations of quality for aerospace applications.

1. Scope

1.1 Purpose

This MSFC Specification is an applicable document to MSFC-STD-3716. It defines procedural requirements for foundational aspects of process control in L-PBF: definition and qualification of the L-PBF metallurgical process; maintenance, calibration, and qualification of L-PBF equipment and facilities; and training of personnel for L-PBF operations.

1.2 Applicability

This MSFC Specification is applicable to the control and qualification of L-PBF processes as governed by MSFC-STD-3716.

In conjunction with MSFC-STD-3716, this MSFC Specification may be levied to govern the development and production of L-PBF hardware at the discretion of NASA programs or projects.

Verifiable requirement statements are numbered and indicated by the word "shall." Explanatory or guidance text is indicated in italics with further commentary provided in Appendix A.

1.3 Tailoring

[PCQR-1] Tailoring of this MSFC Specification for application to a specific program or project shall be formally documented as part of program or project requirements and approved by the responsible Technical Authority in accordance with NPR 7120.5, NASA Space Flight Program and Project Management Requirements.

[Rationale: Tailoring of the requirements of this MSFC Specification is allowed to provide flexibility in implementation. Undocumented tailoring results in loss of process control and AM part reliability; therefore, all tailoring is approved and documented.]

Tailoring of requirements in this MSFC Specification are intended to be documented in the Additive Manufacturing Control Plan (AMCP) required by MSFC-STD-3716.

The tailoring process is intended to allow for other approaches that will meet the intent of these requirements without meaningfully altering the level of risk. Commentary is provided throughout the standard to assist in interpretation of intent for each requirement.

1.4 Summary of Methodology

Figures 1 and 2, (reproduced from MSFC-STD-3716) illustrate how the content of this MSFC Specification relates to MSFC-STD-3716. See MSFC-STD-3716 for a detailed discussion of these figures. In Figure 1, the content of this MSFC specification is contained within the dashed-line box and the content of MSFC-STD-3716 is deemphasized and shown in grey.

The focus of this MSFC Specification is qualification and control of L-PBF metallurgical processes. Before any candidate L-PBF metallurgical process can be qualified, it must be adequately defined. As represented in Figure 1 and described in Section 4.1, the three required elements that define a candidate L-PBF metallurgical process according to this MSFC specification are (1) a powder feedstock specification, (2) control factors governing the fusion process, and (3) requirements for thermal processing.

Once a candidate L-PBF process is defined, it is then systematically evaluated for qualification as a Qualified Metallurgical Process (QMP). The qualification process ensures the implementation of the L-PBF process on any given machine renders material of appropriate metallurgical quality, provides appropriate surface texture and detail resolution to parts, and achieves mechanical properties commensurate with those used to establish the design values in the Material Properties Suite.

Candidate L-PBF metallurgical processes are typically qualified to an existing Master QMP that has similar L-PBF machine characteristics to the candidate. This concept simplifies qualification for multiple similar machines and ensures consistency in qualification standards. If a Master QMP does not exist for the candidate process, then the candidate is qualified as a Master QMP, which entails the additional evaluations and the development of acceptance criteria for qualifying future candidate processes. Once established, all QMPs are documented in the form of a QMP Record that is maintained as a quality record in the Quality Management System (QMS).

This MSFC Specification defines minimum requirements for control of L-PBF equipment and facilities. These controls are defined and implemented by the L-PBF Process Vendor through an Equipment and Facility Control Plan unique to the L-PBF facility. This plan defines procedures and work instructions for production operations such as powder feedstock management, contamination control, computer security, and the maintenance, calibration, and qualification of L-PBF machines.

This MSFC Specification requires certified operators based upon an operator training and certification program to ensure L-PBF operations are executed by personnel with proper knowledge of the L-PBF process, all related equipment, procedural controls levied by qualified processes, and engagement of the QMS.

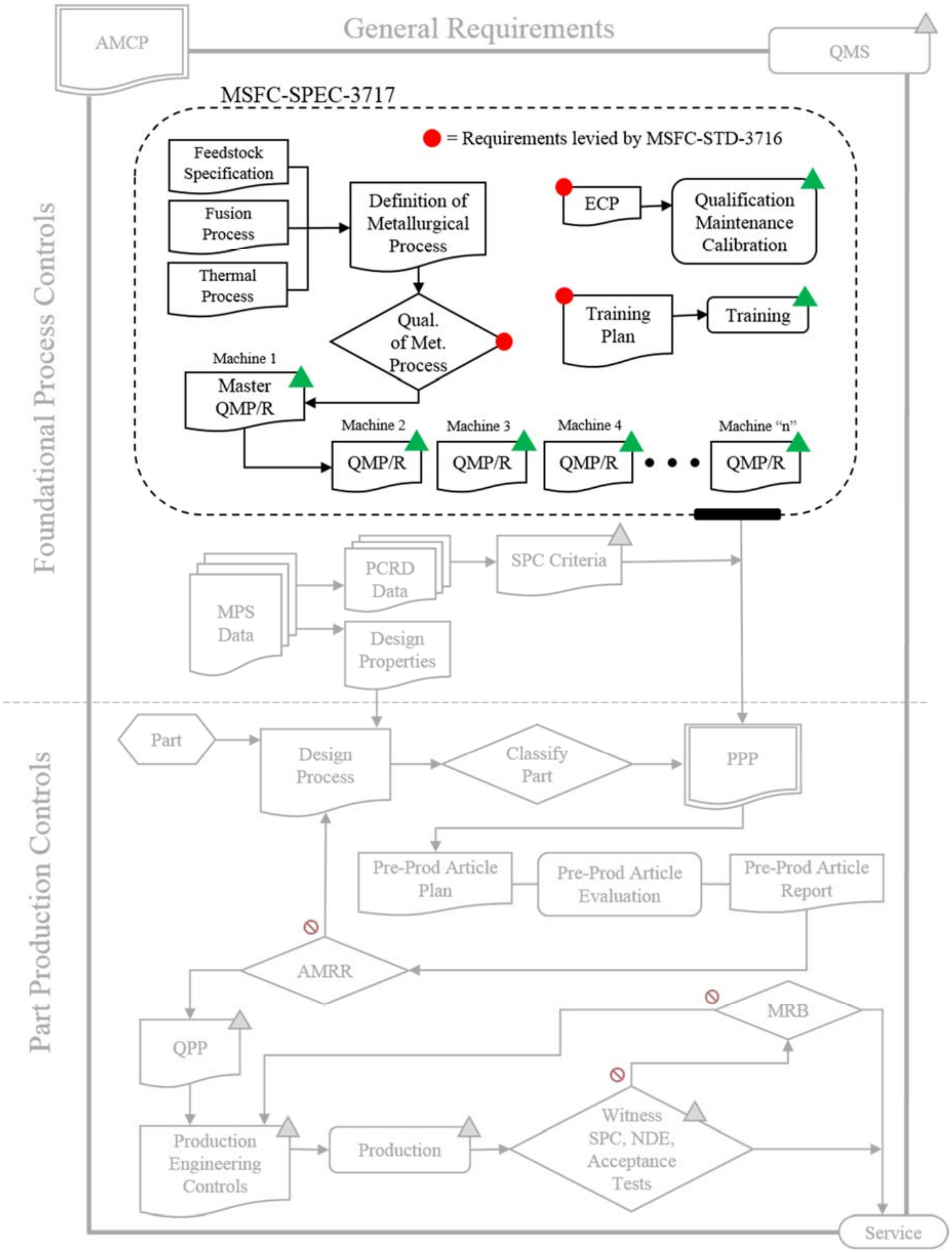

FIGURE 1. Content of this MSFC Specification relative to MSFC-STD-3716

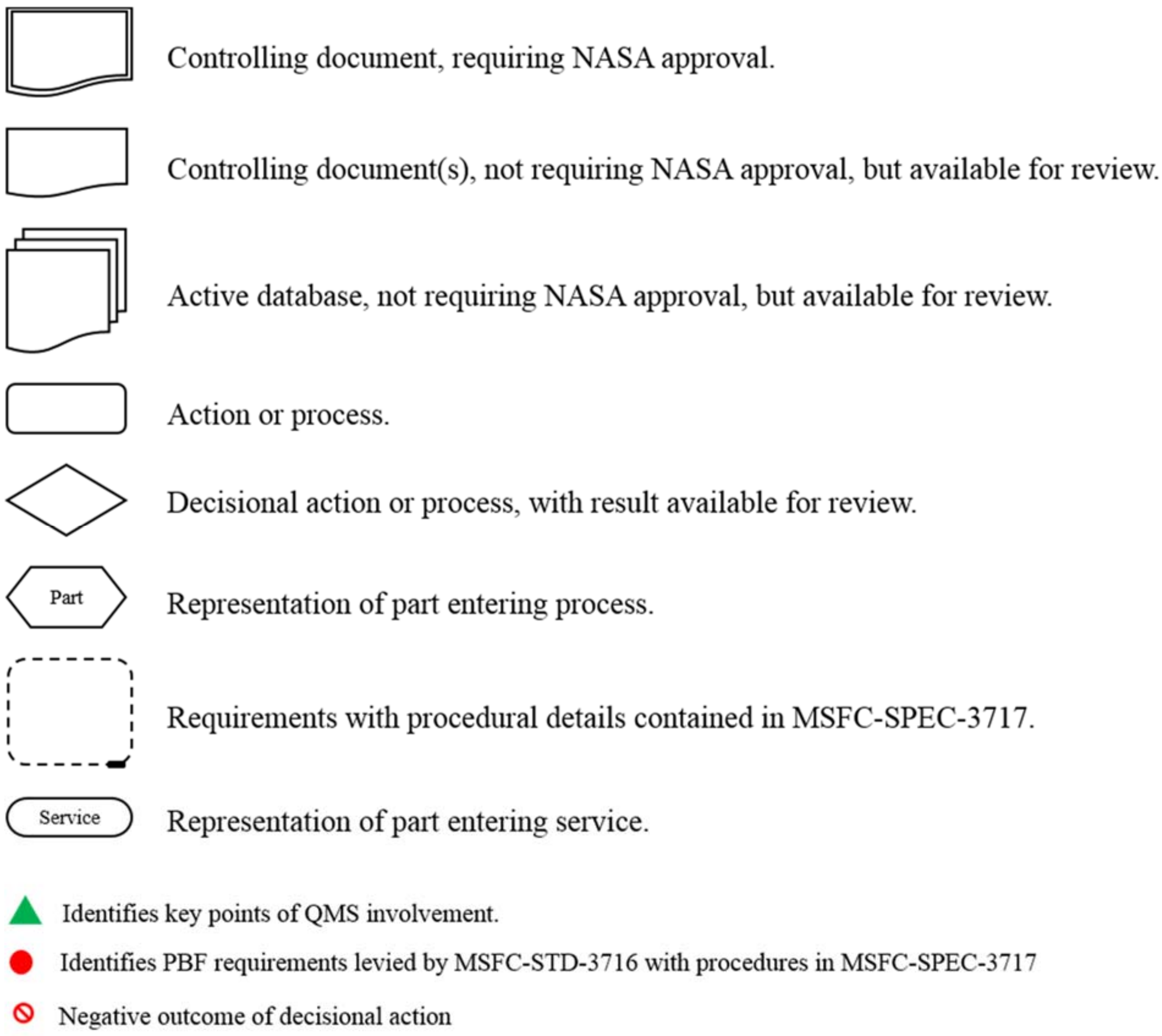

FIGURE 2. Symbol legend for content of Figure 1.

2. Applicable Documents

2.1 General

The documents listed in this section contain provisions that constitute requirements of this MSFC Specification as cited in the text. The latest issuances of cited documents apply unless specific versions are designated.

The applicable documents are accessible at https://standards.nasa.gov, may be obtained directly from the Standards Developing Body or other document distributors, or information for obtaining the document is provided. Reference documents are listed in Appendix C.

2.2 Government Documents

MSFC-STD-3716	Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

2.3 Non-Government Documents

ASTM E8/E8M	Standard Test Methods for Tension Testing of Metallic Materials
ASTM E21	Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials
ASTM E399	Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials
ASTM E466	Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials
ASTM E606/E606M	Standard Test Method for Strain-Controlled Fatigue Testing
ASTM E1450	Standard Test Method for Tension Testing of Structural Alloys in Liquid Helium
ASTM E1820	Standard Test Method for Measurement of Fracture Toughness
ISO/ASTM 52921	Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies

3. Acronyms and Definitions

3.1 Acronyms

AM	Additive Manufacturing (and variants)
AMCP	Additive Manufacturing Control Plan
CEO	Cognizant Engineering Organization
d_o	Melt-pool overlap depth (see Figure 3)

d_p	Melt-pool full depth (see Figure 3)
EAR	Export Administration Regulations
EFCP	Equipment and Facility Control Plan
HIP	Hot Isostatic Pressing
ITAR	International Traffic in Arms Regulations
L-PBF	Laser Powder Bed Fusion
MPS	Material Property Suite
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NIST	National Institute Of Standards and Technology
PSD	Particle Size Distribution
PCRD	Process Control Reference Distribution
PCQR	Process Control and Qualification Requirement
QMP	Qualified Metallurgical Process
QMS	Quality Management System
SPC	Statistical Process Control
t_L	L-PBF layer thickness

3.2 Definitions

Additive Manufacturing: process of creating objects from three-dimensional computer models incrementally, typically layer by layer, from material stock. This is contrasted with subtractive manufacturing technologies that remove material to create the object, such as machining. *Adj*., additively manufactured

Build: a single, complete operation of the powder bed fusion process to create objects in the powder bed. Multiple objects are commonly created during a build.

Build area: the area in the build plane where the fusion process is controlled and qualified to a QMP per MSFC-SPEC-3717. The build area may be defined smaller than the full reach of the laser if needed to maintain the quality of the fusion process.

Build box/build volume: the volume in which parts may be reliably produced in the powder bed. The build volume is defined by the build area and maximum Z-position.

Build lot: all objects created during a single build operation.

Build plane: plane in which fusion takes place during powder bed fusion. Commonly, the build plane is fixed and the build platform is incrementally lowered to create the powder bed.

Build platform: flat, solid material base upon which powder bed fusion objects are built.

Cognizant Engineering Organization: (CEO), the organization responsible for establishing and maintaining the certified design state of the hardware and delivering hardware compliant with all levied requirements.

L-PBF Process Vendor: the entity responsible for production of powder bed fusion parts to meet the requirements of the certified design state. The L-PBF process vendor may be synonymous with the CEO or a sub-vendor to the CEO.

Nadcap™: formerly NADCAP (National Aerospace and Defense Contractors Accreditation Program), a global cooperative accreditation program for aerospace engineering, defense, and related industries.

Operator: personnel involved directly in the production of L-PBF parts, from manipulation of the digital product definition in preparation for the L-PBF build through the completion of the L-PBF build process.

Part: fundamental unit or object defined by the design state. A Qualified Part Process may include multiple parts in a build.

Powder Bed Fusion: an additive manufacturing process that uses a high-energy source to selectively fuse, layer-by-layer, portions of a powder bed.

Powder Lot: (also powder blend lot) a quantity of powder supplied by a certified powder producer that was manufactured by the same process and equipment, and blended simultaneously. The blended powder lot may contain multiple heats of powder when all heats independently meet the powder specification.

Self-supporting structure: (unsupported limit) part features that may be built in an overhanging condition without the need for support structure below it. The maximum angle at which overhanging part features may be reliably built without supporting structure is the unsupported limit.

Support Structure: supplementary, sacrificial material built along with a part used to anchor overhanging geometry, provide dimensional stability, and promote proper thermal management within the powder bed during a build.

To the extent possible, this standard uses terminology as established by, or consistent with, international standards organizations. See ISO/ASTM 52921.

4. Definition and Qualification of L-PBF Metallurgical Processes

Requirements for defining a candidate L-PBF metallurgical process are given in Section 4.1, Definition of a Candidate L-PBF Metallurgical Process. Once defined, the candidate L-PBF *metallurgical process is then qualified through metallurgical evaluation and capability demonstration to establish a QMP. Requirements to qualify the metallurgical process are given in Section 4.2, Qualification of the L-PBF Metallurgical Process.*

The QMP is a foundational L-PBF process control—enabling parts to be built with a process of verified metallurgical quality. The use of a QMP provides the rationale for the assumed material capability of a part (only partially verified in first article assessments) and provides quantifiable metrics to monitor the quality of the metallurgical process over time.

4.1 Definition of a Candidate L-PBF Metallurgical Process

This section specifies the methodology for defining a candidate L-PBF metallurgical process in three parts:

a. *Powder feedstock specification and associated controls per Section 4.1.1 and sub-sections,*
b. *Fusion process controls and restart procedures per Section 4.1.2, and sub-sections;*
c. *Thermal processing requirements per Section 4.1.3, and subsections.*

4.1.1 Powder Feedstock

4.1.1.1 Virgin Powder Requirements

[PCQR-2] A configuration controlled material specification used in all powder feedstock acquisition shall levy comprehensive requirements that ensure consistent performance in the L-PBF process and govern, at a minimum, the following aspects of virgin powder production and procurement:

a. Requiring powder producers and suppliers to operate under a QMS conforming to AS9100, or an equivalent approved by the CEO,
b. Specifying unambiguously the method of powder manufacture,
c. Specifying powder chemistry requirements, including acceptable methods of measurement and tolerance,
d. Specifying particle size distribution (PSD) requirements and the acceptable methods of powder sampling and determining the PSD, including explicit limits in weight percent on the quantity of coarse and fine particles outside the PSD range,
e. Specifying, at least qualitatively, the mean particle shape (powder morphology) and limits on satellite particles
f. Controlling the blending of powder heats into powder lots by requiring each blended powder heat individually meet all requirements of the feedstock specification
g. Prohibiting post-production additions to the powder lot for control of PSD or chemistry, (doping)
h. Providing requirements for powder cleanliness and contamination control,
i. Providing requirements for powder packaging, labeling, and environmental controls,

j. Specifying a certificate of compliance be provided for all levied requirements along with identifiers for each powder heat and blended lot and the date and location of powder production.

[Rationale: Control of powder feedstock is essential to consistent performance of the L-PBF metallurgical process. Each of these controls are specified to minimize the likelihood of known L-PBF process failures related to the powder feedstock.]

An important aspect of powder feedstock not directly addressed in these requirements is an objective, quantifiable metric controlling the necessary rheological (flow and spreading) behavior of the powder. The objectives are proper flow through the L-PBF machine powder handling mechanisms and a smooth, uniform layer spreading across the bed by the recoater. These rheological behaviors are currently controlled indirectly through particle size distribution and qualitative control of morphology and satellite particles. The L-PBF process vendor should vigilantly observe the spreading characteristics of each powder lot for inconsistencies. Further commentary is provided in Appendix A.

4.1.1.2 Powder Reuse Requirements

Feedstock powder reuse may be allowed when the requirements of this section are met and the reuse protocol for the feedstock is clearly specified in the QMP feedstock definition. Without the implementation of the powder feedstock reuse protocol required of this section, only virgin powder feedstock is permitted in part production.

[PCQR-3] To enable the reuse of powder feedstock under a QMP, a powder reuse protocol governed by the following rules shall be defined and implemented:

a. Metrics are defined for tracking the progression of powder reuse that are applicable to the L-PBF machine of interest and the capabilities of the L-PBF process vendor;
b. Limits on powder reuse are defined and enforced based upon the metrics;
c. The performance of L-PBF material produced from reused feedstock powder up to the defined limit of reuse is substantiated through material characterization in the Material Property Suite (MPS) per the requirements of MSFC-STD-3716;
d. Powder at the defined limit of reuse continues to meet all requirements of the original feedstock specification;
e. After every cycle through the powder bed, used powder is sieved in accordance with the coarse particle limits of the PSD and blended to remove segregation prior to reuse;
f. Once a portion of a powder feedstock reuse blend reaches the reuse limit, the powder blend is no longer used in part production under the auspices of the QMP, with the exception of material characterization builds used to evaluate reuse limits on material properties;
g. Reuse limits may be re-evaluated and expanded as long as the requirements of items “c” and “d” of this section are met;

h. For machines with build volume capacity greater than 0.05 m^3 (1.75 ft^3), the reuse limits of item "b" and blending requirements of item "e" (but NOT sieving) of this section may be replaced with a powder sampling plan if the L-PBF machine is maintained under continuous statistical process control (SPC) as defined in MSFC-STD-3716 and, as part of the SPC process, feedstock powder is regularly sampled and evaluated according to the requirements of the original feedstock specification, without evidence of detrimental segregation.

[Rationale: Feedstock powder can degrade through reuse due to changes in chemistry and morphology, each of which can affect the quality of the metallurgical process and the resulting part integrity. The acceptability of allowing feedstock powder reuse has been demonstrated, when proper controls are maintained.]

Metrics for tracking powder reuse include machine operation hours, the number of days powder is present in the machine, the number of build operations, or likely a combination of such metrics. Other metrics for monitoring powder reuse may be proposed. As a starting point, the following reuse limits are recommended: for non-reactive powders, every 1000 hours of machine operation, 60 days, or 30 build operations, whichever is first; for powders that readily oxidize, (e.g., titanium or aluminum alloys) 500 hours of machine operation, 30 days, or 10 build operations. Note that powder degradation may be a function of fusion parameters and part demands, with hot process conditions tending to accelerate degradation.

Powder reuse blends exceeding the reuse limit may be used in developmental or non-production builds.

The powder feedstock reuse protocol may be specified in the QMP or levied more generally by the AMCP required by MSFC-STD-3716.

4.1.2 Fusion Process

[PCQR-4] The L-PBF fusion process shall be defined by a comprehensive list of control factors of known influence on the fusion process for a given L-PBF machine, with the control factors listed in Table I, at a minimum, addressed in the definition.

TABLE I. Defining the L-PBF fusion process, minimally required control factors

Equipment	L-PBF machine: make, model, and serial number
	Date of fusion process definition (machine configuration)
	Versions for machine software and firmware
	Recoater geometric configuration and material
	Recoater speed (range)
	Build platform material and configuration
	Build platform pre-heat temperature

	Nominal powder dosing (range)
Build Chamber Atmosphere	Purge / ventilation gas composition
	Ventilation gas flow rate and corresponding machine settings
	Ventilation diffuser configuration
	Dew point / moisture control
	Oxygen limits
	Temperature limits
Fusion Parameters	Layer thickness
	Laser power
	Laser spot size / shape
	Scan speed
	Hatch spacing / overlap
	Contour spacing / overlap
	Laser timings (on-off delays and related controls)
	Laser scan strategy

Identifying the set of fusion control factors for a specific L-PBF machine makes the metallurgical process unique to that machine—the machine configuration, parameter settings, firmware and software versions are all important to the process. Any additional factors beyond those postulated in Table I that are identified with potential to influence the fusion process are intended to be included in the definition of the fusion controls. Controls related to the laser and scanning system are typically defined by an electronic parameter file on the L-PBF machine. This file may be developed by the L-PBF Process Vendor or may be supplied as a non-editable parameter set by the machine manufacturer. These controls are preferably defined as a set using this parameter file. The values of the parameters may remain undisclosed and proprietary. To establish the metallurgical process definition using the fusion control parameter file, the file name and its cryptographic hash is included as the fusion control part of the metallurgical process definition. See discussion of the cryptographic hash and its use in MSFC-STD-3716.

4.1.2.1 L-PBF Process Restart Procedures

To enable the L-PBF process to be restarted following a planned or unplanned stop, the criteria and procedures enabling such restarts are defined as part of the L-PBF metallurgical process.

[PCQR-5] If capability to restart the L-PBF process is intended, criteria for determining the suitability for process restart and the detailed procedures for restarting the L-PBF process shall be defined as part of the candidate metallurgical process specific to the L-PBF equipment for which the metallurgical process applies.

[Rationale: Restart of a stopped L-PBF process represents a significant risk to part integrity. These risks can only be mitigated if the soundness of the restart procedure is evaluated to

established criteria and then, if restarted, such operations are controlled by detailed, qualified procedures.]

Examples of restart criteria include, but are not limited to, the reason for the process stop, maximum allowed stop time, powder bed cooling limits, and the condition of the powder bed and last part layer. The restart procedures are specific to the L-PBF equipment for which the metallurgical process is being defined and exist in the form of a detailed procedure or check-list. These criteria and procedures may be documented directly with the metallurgical process definition, or the metallurgical process may reference criteria and procedures established in other version-controlled documentation within the QMS.

Establishing and qualifying a process restart capability does not imply parts built to the QMP may always be successfully restarted; therefore, all planned restarts are qualified in the development of the Qualified Part Process and all unplanned restarts are given non-conformance status in the QMS pending disposition of the part. Successful process restarts in parts may be influenced by part geometry and the thermal state of the build.

4.1.3 Thermal Processing

[PCQR-6] The thermal process for the candidate metallurgical process shall be defined with all steps needed to manage microstructural evolution from the as-built state to the final microstructure, including a mandatory hot isostatic pressing (HIP) step for application of the metallurgical process to Class A parts.

[Rationale: This MSFC Specification requires post-build thermal processes to evolve part microstructure toward a uniform and orderly state to mitigate risks, known and unknown, associated with material performance due to the complex as-built microstructure from the L-PBF process.]

A typical L-PBF thermal process includes stress relief, HIP, and post-HIP heat treatments appropriate to the alloy, such as annealing or a solution treatment and aging cycle.

Stress relief thermal cycles are not mandatory for a L-PBF metallurgical process. HIP is mandatory for all L-PBF metallurgical processes that are used to produce Class A parts per MSFC-STD-3716, thus use restrictions for the metallurgical process are needed when HIP is not included in the thermal process. HIP conditions are chosen to provide a time and temperature appropriate to fully homogenize and recrystallize the as-built microstructure as well as to close the majority of microporosity present from the build process. Further heat treatment following HIP is performed as required to achieve the proper final microstructure for the alloy.

See commentary for Section 4.1.3 in Appendix A.

4.1.3.1 Control of Thermal Processes

[PCQR-7] The following controls shall be applied to all steps of the thermal process:

a. The thermal process definition explicitly identifies all control parameters, including but not limited to, temperatures, hold times, heating and cooling rates, atmosphere, and pressure, each with compatible tolerances.
b. Aerospace quality specifications are in place to control the execution of all thermal processes;
c. Vendors used for thermal processing are Nadcap™ accredited or approved equivalent by the CEO and operate under a quality management system conforming to AS9100 or an appropriate equivalent QMS approved by the CEO.
d. Part cleanliness requirements are enforced, such that
   (1) L-PBF parts are confirmed free of residual powder prior to thermal processing;
   (2) L-PBF parts are cleaned to remove any contaminants such as dirt, grease, or oils prior to thermal processing, or protected from such contamination in all processes following completion of the build.

[Rationale: Essential controls on the thermal process are necessary to ensure part reliability.]

See commentary for Section 4.1.3.1 in Appendix A.

4.1.3.2 Variations in Thermal Process

Variations on the thermal process may be included in the definition of the metallurgical process if the variations in process are qualified to provide material of equivalent capability.

[PCQR-8] Variations on the thermal process which are included in the definition of the candidate metallurgical process shall be independently qualified per Section 4.2 through demonstration that the performance of the resulting material is equivalent to that of the baseline.

[Rationale: Allowing for variations in the thermal process definition of the candidate metallurgical process reduces the burden of developing independent metallurgical processes for each variant. However, allowing such variants is acceptable only when equivalent material is produced; otherwise, part reliability could be compromised relative to performance expectations.]

An example of an acceptable thermal process variation is the addition of a second solution treatment cycle following welding processes prior to aging a welded assembly. In such case, the L-PBF material unaffected by the weld must not be adversely affected by the second solution heat treatment. Variations to heat treatment that affect material properties or result in L-PBF material with a different microstructure than the baseline are intended to be qualified separately as different L-PBF metallurgical process.

4.1.4 Customized Metallurgical Processes

[PCQR-9] Any candidate metallurgical process requiring specific controls or unique witness testing to achieve and/or demonstrate particular material performance characteristics shall be identified as a Customized Metallurgical Process, and include the following in the definition of the candidate metallurgical process:

a. Description of the desired performance characteristics,
b. Definition of the unique process controls used to achieve the desired material performance characteristics, if any,
c. Definition of the requisite witness tests and acceptance criteria used to confirm the desired performance characteristics of the material.

[Rationale: The identification and definition of customized metallurgical processes prevents the loss of unique process controls that may be critical to part integrity.]

Customized metallurgical processes are those which require specific controls or unique witness testing, beyond the basic controls levied by this MSFC Specification, to achieve a particular performance characteristic important to successful use in design. When these unique process controls and witness testing procedures are required to achieve a performance characteristic that is reflected in the MPS and assumed present by the structural design assessment, then the metallurgical process is identified as a Customized Metallurgical Process. Once qualified per Section 4.2 the process is considered a Customized QMP.

See commentary for Section 4.1.4 in Appendix A for further discussion and examples.

4.2 Qualification of the L-PBF Metallurgical Process

[PCQR-10] All candidate metallurgical processes shall be qualified as either a Master QMP or a QMP prior to production use.

[Rationale: The qualification process ensures the defined candidate metallurgical process yields material of the intended quality and reliability.]

The candidate L-PBF metallurgical process defined in Section 4.1 is qualified through demonstrations of capability regarding the following:

a. Metallurgical requirements of Section 4.2.3,

b. Surface texture and detail resolution per Section 4.2.4,

c. Mechanical properties per Section 4.2.5.

The requirements for qualification of candidate L-PBF metallurgical processes in Section 4.2 are established to allow the resulting QMP to produce L-PBF parts of any classification (A1-B4) of MSFC-STD-3716. The evaluations for qualification in Section 4.2 are intended to mitigate the likelihood of known failure modes in the L-PBF process, even if subtle, that may be critical to part functionality in high performance, safety-critical parts. For parts of lower class where criticality and structural demand are minimal, the CEO may tailor these qualification requirements through the AMCP in a manner that reduces burden and still *achieves process qualification commensurate with parts of lower classifications. Such tailoring would result in QMPs that are specific to part classification, and therefore would need to be accompanied by the requisite restrictions on use.*

4.2.1 Master Qualified Metallurgical Process

[PCQR-11] A Master QMP shall be developed for any candidate L-PBF metallurgical process that does not meet all of the following commonality criteria for an existing Master QMP:

a. Powder feedstock controls are identical;
b. Fusion controls are equivalent, meaning
   (1) Same make of L-PBF machine with equivalent configuration and bed size,
   (2) Same make and model of laser and scanner head hardware,
   (3) Same scheme for setting laser scan patterns,
   (4) Same layer thickness;
c. Thermal process definition is identical.

[Rationale: The use of a Master QMP ensures consistent criteria are used to qualify processes that should be consistent based upon machine and process commonality, resulting in reduced burden for qualification of processes with commonality.]

If a Master QMP does exist for a candidate metallurgical process meeting the commonality criteria, then the candidate process is qualified as a QMP to the acceptance criteria of the Master QMP. Using the Master QMP as a template for qualifying subsequent QMPs allows for qualification with reduced documentation of microstructural evolution and reduced mechanical evaluation for registration to the MPS.

The Master QMP is unique because it specifies the acceptance criteria for metallurgical quality, microstructure, and reference part metrics to be used in the qualification of subsequent candidate processes sharing commonality. Qualification of subsequent QMPs based on a Master QMP is intended to simplify the re-occurring qualification practice for similar L-PBF processes.

The Master QMP implementation may be adapted to fit the documentation framework of the CEO and/or L-PBF Process Vendor. The creation of Master QMP is similar to establishing a metallurgical process specification to ensure consistency across nominally equivalent processes based on the compatibility criteria.

4.2.2 Standardized Qualification Build Set

[PCQR-12] A standardized set of qualification builds shall be defined and used in the evaluations required by this section for establishing a Master QMP or QMP.

[Rationale: Standard qualification builds establish necessary consistency and uniformity in the qualification and re-qualification methodology for L-PBF processes and machines.]

Each standard qualification build set is intended to be cooperatively defined by the CEO and the L-PBF process vendor and should be designed to efficiently and consistently achieve the required qualification evaluations. These standard qualification builds are also used to maintain the active status of QMPs by qualifying (or re-qualifying) L-PBF machines and implementing re-occurring SPC builds.

4.2.3 L-PBF Metallurgical Qualification

4.2.3.1 Quality of the As-built Microstructure

[PCQR-13] The as-built microstructure shall be demonstrated free of detrimental defects when evaluated for each of the following cases with metallurgical cross-sections at a minimum magnification of 50x and an area of evaluation $\geq 6cm^2$ ($0.93\ in^2$) when combined across all cases:

a. Survey of consistency throughout the build area
b. Demonstration of tolerance to thermal history extremes
c. Restart layer interfaces
d. Interfaces in scan patterns (striping, islands, multi-laser zones), surface contours, cosmetic passes, including any interface associated with a unique fusion parameter set (such as down-facing surfaces)

[Rationale: The quality of the as-built microstructure establishes the basis for L-PBF part integrity; therefore, the L-PBF process is required to demonstrate refinement that precludes detrimental defects in the base process.]

For this requirement, defects in the L-PBF as-built structure are considered detrimental not only if they impact material performance, but also if they result from a fusion process that is either inconsistent or operating beyond the limits of an acceptable process box.

To meet the intent of this requirement, detrimental defects include, but are not limited to, evidence of unmelted powder particles, lack-of-fusion defects, micro-cracking, organized porosity related to scan strategy, weld melt-pool keyhole defects, overall porosity fraction greater than 1% by volume, individual porosity greater than 100μm (0.004 inch), and epitaxial grain growth greater than five layer thicknesses. Randomly dispersed porosity representing less than 1% by volume in the as-built microstructure is considered typical to the L-PBF process and is not cause for rejection.

For most of these evaluations, metallurgical cross-sections are made parallel to the axis of build, (Z-Axis as defined in ISO/ASTM 52921). Interface evaluations in bulk material may also benefit from evaluations in a plane parallel to the build platform (normal to Z).

See further commentary in Appendix A regarding each of these evaluations.

4.2.3.2 Top Layer Melt-Pool Characterization

[PCQR-14] The weld melt-pool geometry of the as-built microstructure shall be characterized using the top layer of specimens representing the nominal process conditions evaluated in Section 4.2.3.1 part "b" using the characterization metrics d_p/t_L and d_o/t_L as represented in Figure 3, where d_p/t_L is the ratio of full melt-pool depth to nominal layer thickness and d_o/t_L is the ratio of melt-pool overlap depth to nominal layer thickness and each of the ratios is based upon the average of ten or more measurements.

[Rationale: The melt-pool geometry characterization provides a quantifiable tracking metric for monitoring L-PBF process consistency over time and during process or machine re-qualification. Melt-pool geometry characteristics are indicative of the health of the process and its tolerance to variation.]

The average ratios are recorded in the QMP Record for engineering evaluation. Establishing acceptance criteria for the melt-pool characterization is recommended, but not required.

See commentary in Appendix A

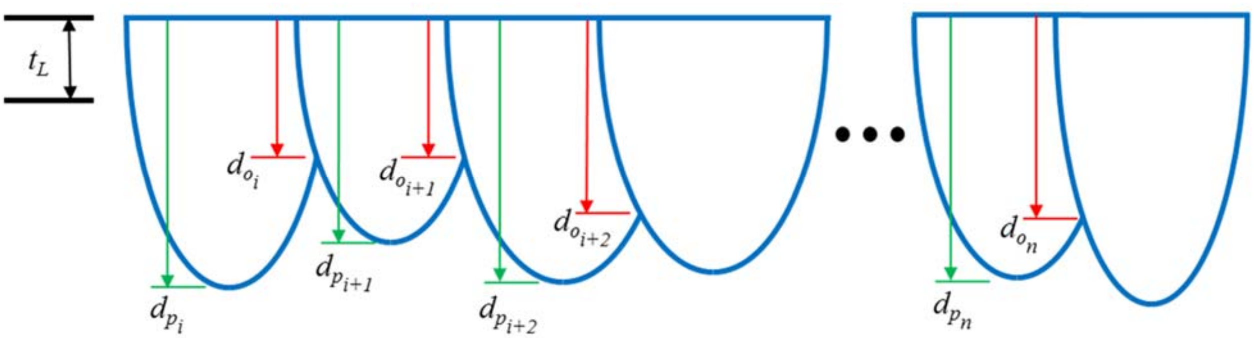

FIGURE 3. Top surface melt-pool geometry measurements

4.2.3.3 Microstructural Evolution

[PCQR-15] The metallurgical process shall demonstrate controlled evolution of the microstructure from the as-built state to the final state, with the final state consisting of predominantly uniform and non-directional recrystallized grain structure, free of remnants of the as-built structure, and reflecting proper homogenization, grain boundary quality, and strengthening mechanisms appropriate to the alloy.

[Rationale: The requirements levied in this MSFC Specification and MSFC-STD-3716 are predicated upon metallurgical processes which evolve the microstructure in a consistent manner from the complex, as-built state to a final state more closely representing familiar structure of common product forms. This requirement is enforced to minimize potential

failure mechanisms associated with native L-PBF microstructures such as strong anisotropy, complex residual stress states, and fatigue and crack growth characteristics.]

For a Master QMP, the microstructure is documented at each step of the thermal process, including the as-built state, each intermediate stage revealing recrystallization and evolution, and the final microstructure. Subsequent QMPs following a Master QMP may document only as-built and final microstructures.

4.2.3.4 Microstructural acceptance criteria

[PCQR-16] For a Master QMP, microstructural evolution shall be documented at each step of the thermal process with microstructural acceptance criteria provided for, at a minimum, the as-built and final microstructural conditions.

[Rationale: Microstructural acceptance criteria defined by the Master QMP are required to maintain consistent process control by establishing uniform acceptance metrics for subsequent QMPs and parts requiring microstructural evaluation for witness test acceptance.]

To maintain consistency in process, subsequent QMPs are evaluated based upon the acceptance criteria of the applicable Master QMP.

The defined acceptance criteria are intended to be appropriately adapted to the alloy and be sufficiently complete to ensure reliable metallurgical process control is maintained. Examples of appropriate microstructural acceptance criteria in the as-built state include interpretation of the criteria required by Sections 4.2.3.1 and 4.2.3.2 as rendered by the alloy and L-PBF machine. For the final state microstructure, acceptance criteria should include metrics such as average grain size, grain shape, grain boundary appearance, presence of (or lack of) certain phases (e.g. precipitates, carbides), or other features appropriate to the alloy.

4.2.4 Surface Texture and Detail Resolution Metrics (Reference Parts)

[PCQR-17] Surface texture and detail resolution capability of the L-PBF process shall be evaluated using Reference Part(s) from a minimum of two locations in the build area:

a. The near center of the build area,
b. The furthest location for beam reach or other location identified with reduced build quality.

[Rationale: Rendering capability of the L-PBF process is commonly not uniform across the build area due to influences such as laser incidence angle. These two evaluation locations are intended to bound the process capability.]

This MSFC Specification does not levy specific quality metrics for surface texture and detail resolution for purposes of qualifying a metallurgical process. The Master QMP should be *refined regarding these metrics to meet part performance goals or to satisfy material property performance goals, such as fatigue life.*

The Reference Part is intended to provide quantitative criteria to judge process performance and repeatability in future development of QMPs, in part builds, and in L-PBF machine qualification. When used for such purposes, reference part metrics defined by the Master QMP process are used as acceptance criteria.

4.2.4.1 Surface Texture and Detail Resolution Acceptance Criteria

[PCQR-18] For a Master QMP, surface texture and detail resolution metrics and acceptance criteria shall be defined.

[Rationale: To maintain consistency in the L-PBF process, surface texture and detail resolution for subsequent QMPs are evaluated with Reference Parts using the acceptance criteria of the applicable master QMP. In many cases, consistency in surface texture and detail are critical to part performance.]

4.2.4.2 Reference Parts

In this MSFC Specification, a reference part is any standardized part, or parts, used to evaluate the capability of the L-PBF metallurgical process regarding the quality of surface texture and detail resolution. These aspects of quality in the L-PBF process influence the performance of parts, just as the "bulk" metallurgical properties evaluated in Section 4.2.3. The quality of surfaces and the level of detail resolved are a representation of the overall health of the L-PBF process. Changes in these build characteristics often provide the earliest indicators of changes in the L-PBF process.

The design of the reference part(s) is not specified and may vary with the design needs and priorities of the organization. The objective is to design the reference part(s) to include features that readily enable establishing quantitative metrics for surface texture and detail resolution performance. A reference part need not be large and is preferably of size and shape that it can be produced in the furthest locations in the build area and easily placed at various orientations relative to the beam and recoater system.

Reference parts may also provide material for requisite metallographic evaluations.

See further commentary for Section 4.2.4.2 in Appendix A.

4.2.5 Mechanical Properties

[PCQR-19] Mechanical properties for the candidate metallurgical process shall be evaluated in accordance with Table II to establish a Master QMP or Table III for a QMP based upon an existing Master QMP.

[Rationale: Mechanical property evaluation is required to ensure the candidate metallurgical process is capable of the intended mechanical performance and can be registered to a MPS.]

Mechanical property evaluations for the Master QMP have been set to investigate common failure modes related to tensile strength, ductility, cyclic fatigue initiation, and fracture toughness per Table II. Subsequent QMPs, based upon an existing Master QMP meeting the commonality criteria, are qualified with a reduced quantity of mechanical property evaluation requirements, as shown in Table III.

For candidate metallurgical processes defined to allow process restart, mechanical tension and fatigue tests with process restart as specified

Table III is also used for periodic evaluation of process quality to meet the SPC requirements of MSFC-STD-3716, if applicable.

Acceptance of mechanical properties is handled in the registration process to a MPS per Section 4.2.6.

TABLE II. Minimum mechanical property evaluation requirements for qualification of candidate metallurgical processes as a Master QMP.

Item	Property	ASTM Standard*	Quantity	Notes
1	Tensile	E8/E8M	15	Survey of build area and materials from "hot" and "cold" processes variants per Section 4.2.3.1 (b)
2	Tensile, With process restart	E8/E8M	5	Required if process restart is allowed. Tensile testing of process restart interface. Item 2 tests not required if restart is included in testing for Item 1
3	High Cycle Fatigue	E466	10	Five (5) tests to MPS PCRD fatigue condition, and five (5) tests at cyclic stress range producing failure > 10^6 cycles that replicate R-ratio and stress range of existing MPS data enabling comparison
4	Low Cycle Fatigue	E606/E606E	5	Five (5) tests at a cyclic strain range represented in MPS data
5	Fatigue, With process restart	E466, E606/E606E	5	Required if process restart is allowed. Fatigue testing of process restart with HCF or LCF, five (5) tests at the MPS PCRD fatigue condition. Item 5 tests not required if restart is included in tests from Item 3 and/or 4.
6	Fracture Toughness	E1820, E399	3	Tests with crack parallel to build plane, loading in Z direction.
7	Tensile (at Temperature)	E21, E1450	6	Three (3) tests per temperature at two or more temperatures – either the high and low bounding temperatures of the MPS or other applicable temperatures.
8	Customized QMP	As specified	2	Test at conditions defined by the candidate metallurgical process required for acceptance, minimum two (2) tests at condition.

*Other test standards approved by the CEO may be used.

TABLE III. Minimum mechanical property evaluation requirements for qualification of candidate metallurgical processes as a QMP or for reoccurring statistical process control evaluation builds.

Item	Property	ASTM Standard*	Quantity	Notes
1	Tensile	E8/E8M	10	Survey of build area locations
2	Tensile, With process restart	E8/E8M	5	Required if process restart is allowed. Tensile testing of process restart interface. Item 2 tests not required if restart is included in testing for Item 1
3	High Cycle Fatigue	E466	5	Five (5) tests to MPS PCRD fatigue condition,
4	Low Cycle Fatigue	E606/E606M	—	Not required for QMP (only Master QMP)
5	Fatigue, With process restart	E466, E606/E606M	5	Required if process restart is allowed. Fatigue testing of process restart with HCF or LCF, five (5) tests at the MPS PCRD fatigue condition. Item 5 tests not required if restart is included in tests from Item 3.
6	Fracture Toughness	E1820, E399	2	Tests with crack parallel to build plane, loading in Z direction.
7	Tensile (at Temperature)	E21, E1450	—	Not required for QMP (only Master QMP)
8	Customized QMP	As specified	2	Test at conditions defined by the candidate metallurgical process required for acceptance, minimum two (2) tests at condition.

*Other test standards approved by the CEO may be used.

4.2.6 Registration of a Candidate Metallurgical Process to a Material Properties Suite

[PCQR-20] Each candidate metallurgical process shall be registered to a MPS through confirmation of the following:

a. Powder chemistry controls are consistent with those of the MPS;
b. Documentation is available to verify the metallurgical process definition was established and adhered to continuously during the development of evaluation materials;
c. Metallurgical and microstructural characteristics are consistent with those of the MPS;
d. Tensile strengths and ductility are accepted to the tensile PCRDs of the MPS;
e. Measured high cycle fatigue life is accepted to the fatigue PCRD of the MPS;
f. For Master QMP only, high cycle fatigue life > 10^6 cycles is in family with MPS data;
g. For Master QMP only, low cycle fatigue life is in family with MPS data;
h. Measured fracture toughness is in family with MPS data;

i. For Master QMP only, tensile properties at temperature are in family with MPS data;
j. For Customized QMP only, defined custom witness tests meet their acceptance criteria.

[Rationale: The material property registration process ensures the metallurgical process is producing material compatible with those materials used to establish the design values that are to be used for parts made to the metallurgical process. Due to the sensitivity of the L-PBF process implementation, without this confirmation, it is not legitimate to assume prior established design values are applicable. The registration process evaluates the key failure mechanisms for compatibility: strength, ductility, cyclic damage, and fracture toughness. While often correlated, these failure modes may act independently.]

Upon successful registration, the material property data should be added to the MPS database.

The CEO is responsible for the registration process and eventual final approval of the candidate process as a QMP. For property evaluations where PCRD criteria are not established, candidate data is determined to be "in family" with the MPS if the average result of the candidate data lies within the statistical range of existing data in the MPS. If outlier data exists, such test results and associated specimens should be evaluated to determine cause. If outlier data is the result of systemic process issues, registration should be withheld pending correction and reevaluation. Other metrics for determining data to be "in family" may be proposed. The CEO has latitude in making the final determination of registration of a metallurgical process to a MPS. If aspects of registration data do not fully meet the criteria above, but the MPS appropriately accommodates the difference, such rationale may be provided in the QMP Record. If the data do not register to the MPS, the CEO may opt to gather additional data, continue improving the process, or develop a new MPS that represents the measured material performance.

4.2.6.1 Bootstrapping a Master QMP and MPS

When new L-PBF processes are first established, an MPS may not yet exist to conduct the registration process. In such cases, a Master QMP is established simultaneously with the MPS (i.e., bootstrapping) and the Master QMP is registered to the new MPS by default. Additional data generated from the Master QMP is used to populate preliminary MPS PCRDs (See MSFC-STD-3716) and other material properties to enable registration of additional QMPs.

4.3 Qualified Metallurgical Process Record

[PCQR-21] After being determined complete and satisfactory, and approved as a QMP, all information used to define and qualify a candidate metallurgical process per Sections 4.1 and 4.2 of this MSFC Specification shall be documented in a configuration controlled QMP Record within the QMS.

[Rationale: The QMP is a core governing document of L-PBF process control and as such must be properly substantiated, approved, and documented.]

This requirement intends the following. The CEO approves QMPs. Once approved and documented, a QMP Record defines a locked process such that no changes are allowed without formal re-evaluation and approval. A QMP may be treated as proprietary information. NASA may review a QMP and its supporting data at any time.

The development of candidate QMPs is typically the responsibility of the L-PBF Process Vendor. A partnership between the CEO and L-PBF Process Vendors, if not the same entity, is required for successful implementation of these requirements.

A check-list for QMP development and an example template of a QMP record is provided in Appendix C.

4.4 Qualification Builds for Continuous Production SPC

[PCQR-22] Periodic qualification builds for SPC required for continuous production witness sampling in MSFC-STD-3716 shall consist, at minimum, of the following evaluations:

a. Evaluation of as-built microstructure per Section 4.2.3.1, parts “a” and “d” only,
b. Measurements of top layer melt-pool geometry per Section 4.2.3.2,
c. Evaluation of as-built microstructures (from part “a” of this section) and final microstructures to acceptance criteria of the Master QMP per Section 4.2.3.4,
d. Evaluation of Reference Parts for surface texture and detail resolution per Section 4.2.4.1,
e. Evaluation of Mechanical properties required in Section 4.2.5 Table III for QMP/SPC qualification to the registration requirements of Section 4.2.6.

[Rationale: MSFC-STD-3716 allows for reduced witness sampling on a per-part basis when machines are under continuous production with SPC monitoring of witness data and periodic SPC qualification builds to demonstrate the process is under control. These evaluations, slightly less than those needed to qualify a QMP are the minimum considered adequate to evaluate the overall health of the L-PBF process periodically to substantiate process control.]

4.5 Equipment and Facility Process Control

[PCQR-23] The equipment control requirements of this section shall be in place and verifiable through the QMS of the L-PBF Process Vendor prior to production of L-PBF parts under auspices of MSFC-STD-3716.

[Rationale: Controlled part production can only occur once equipment and facility controls are in place and enforced.]

4.5.1 Equipment and Facility Control Plans

[PCQR-24] An Equipment and Facility Control Plan (EFCP) shall be developed and maintained within the QMS that addresses, at minimum, the implementation of the requirements of L-PBF equipment and facility control of Section 4.5 and its subsections.

[Rationale: The EFCP provides for consistent definition and implementation of equipment and facility controls necessary for reliable L-PBF part production.]

The L-PBF Process Vendor is intended to develop and maintain the EFCP with the concurrence of the CEO. The requirement for the EFCP may be met by leveraging existing documentation for control of equipment and facilities if all the requirements of this section are addressed, all documents are configuration controlled in the QMS, and the documents comprising the EFCP are identified in the AMCP per MSFC-STD-3617.

4.5.2 Powder Feedstock Management

Proper control of powder feedstock is essential to safe and reliable L-PBF processes. This section provides requirements for storage and handling, material lot control in L-PBF machines, and blending operations.

4.5.2.1 Powder Feedstock Storage and Handling

[PCQR-25] The EFCP shall specify policies and procedures controlling the storage and handling of powder feedstock material including, at minimum, the following aspects:

a. Health and safety hazards
b. Clarity of material and lot number identification by container
c. Storage—control of atmosphere, control of access
d. Control of opened, partially used feedstock containers
e. Control of contamination and feedstock cross-contamination
f. Control of material certifications
g. Procedural implementation of feedstock reuse controls required by Section 4.1.1.2
h. Disposal procedures

[Rationale: Proper management of powder feedstock is essential to ensuring safety in the facility, control of raw materials for the process, and the overall reliability of the L-PBF process.]

4.5.2.2 Alloy Exclusivity

[PCQR-26] Each L-PBF machine shall be dedicated to a single alloy.

[Rationale: The presence of different powder alloys within the machine presents an unacceptable risk of cross-contamination of feedstock powders.]

4.5.2.3 Powder Feedstock Lot Control Requirements in L-PBF Machines

[PCQR-27] The number of powder feedstock lots present in a L-PBF machine at any given time shall follow these rules based on maximum machine build volume:

i. One powder feedstock lot is allowed in L-PBF machines with build volume capacity less than or equal to 0.05m^3 (1.75ft^3);
j. A maximum of two powder feedstock lots is allowed in L-PBF machines with build volume capacity greater than 0.05m^3 (1.75 ft^3).

[Rationale: Maintaining unique traceability in powder lot for AM parts is essential to managing the scope of potential feedstock non-conformance. For small volume machines, the cost and effort of maintaining a single powder feedstock lot in the machine is negligible and provides clear containment bounds for a feedstock non-conformance. For larger volume machines, it is acknowledged that limiting to a single powder feedstock lot may impede operation. The two lot limitation balances non-conformance risk against operational necessity.]

At changing of feedstock lots, this requirement intends a nominal cleaning of the L-PBF machine to remove the prior lot of material, but does not intend a disruptive cleaning throughout the machine for small residuals of the prior powder lot, unless the prior lot was found to be non-conforming.

4.5.2.4 Powder Feedstock Blending at the L-PBF Process Vendor

[PCQR-28] Powder blending operations occurring at the L-PBF Process Vendor shall be controlled by procedures in the EFCP to prevent contamination, cross-contamination of powder alloys or powder lots, and to provide for safety in operations.

[Rationale: Blending operations, such as those required in Section 4.1.1.2, are intended to ensure uniformity in powder particle distribution by reducing segregation as a result of handling, sieving, and other operations that tend to segregate powders. The blending process at the L-PBF vendor must follow established procedures, otherwise required control of the feedstock material may be lost.]

4.5.3 Contamination and Foreign Object Debris Control

[PCQR-29] Plans and polices for the prevention of contamination and foreign object debris, as prescribed by the EFCP, shall be actively enforced during all operations of L-PBF machines and associated equipment.

[Rationale: Contamination and foreign object debris can easily undermine the integrity of the L-PBF process and frequently are the result of unintended and unnoticed actions; therefore, the requirement to formalize and enforce plans and policies to preclude such contamination are essential to the long-term integrity of the L-PBF process.]

Contamination control policies are intended to address the specifics of all operations within the L-PBF machine environment to mitigate the risk of process contamination, particularly during off-nominal operations (atypical maintenance or repair) that may bring unusual opportunities for contamination. These policies should specifically be addressed in the training for all personnel with unsupervised access to the L-PBF machine environment.

4.5.4 Computer Security

[PCQR-30] Continuous, active computer security (cybersecurity or information technology security) shall be established and maintained on all computer systems and associated devices that are associated with any aspect of the L-PBF part design and build process, including storage devices used to transfer files.

[Rationale: The L-PBF process is fully dependent upon digital programs and digitally stored and manipulated data. The integrity of the L-PBF process cannot be assured if the computer systems associated with all aspects of the process are not properly secured.]

The CEO and L-PBF Process Vendor share responsibilities in maintaining computer security that is commensurate with data integrity requirements. L-PBF machines should not be connected to a computer network.

4.5.5 Sensitive Data

[PCQR-31] All L-PBF related data that is designated as sensitive shall be handled with commensurate protections during all stages of transfer and storage.

[Rationale: Implementing the L-PBF process involves the transfer, manipulation, and storage of data, electronic or otherwise, that are potentially deemed sensitive and protected by law from unauthorized disclosure; therefore, this requirement ensures all entities are aware that such precautions may be necessary.]

The CEO is responsible for assigning proper sensitivity designations. Both CEO and L-PBF Process Vendor are responsible for implementing the requirement across all facilities and data transfer operations. This requirement applies to any data, including but not limited to drawings, models, and build files, which the CEO deems sensitive.

Policies and designations for data marking continuously evolve and vary by organization. Examples of designations for sensitive data include: Sensitive But Unclassified, Proprietary, Limited-Rights, International Traffic in Arms Regulations (ITAR), Export Administration Regulations (EAR), or Controlled Item per the United States Munitions List.

4.5.6 Operational Procedures and Checklists

[PCQR-32] Detailed operational procedures for all L-PBF machines and associated equipment shall be documented, or referenced, in the EFCP in the form of checklists or other suitable means that ensure facility operations are standardized to the fullest extent possible and that provide operators a convenient method to ensure all procedural steps are completed.

[Rationale: Consistency in the execution of sensitive processes, such as L-PBF, is critical to maintaining control. Formalized procedures and checklists for complex operations are the key to achieving operational consistency.]

Development of these procedural work instructions or checklists is the responsibility of the L-PBF Process Vendor and may be implemented in any manner suiting the operational norms of the facility. Procedures or checklists are intended to be sufficiently detailed that they are fully specific to a given machine or piece of equipment and are intended to be in place for all standard and readily foreseen contingency situations arising in normal operations such as powder handling/filling, build set up and execution, build completion and removal of parts, powder removal from parts, machine cleaning, and other such common operations.

4.5.7 Configuration Management of L-PBF Machines

[PCQR-33] A configuration management log for each L-PBF machine shall be maintained in the QMS and include, at minimum, the following events:

a. Maintenance, calibration, and qualification,
b. Machine manufacturer service calls,
c. Repairs or other changes to machine,
d. Updates to Software and firmware versions.

[Rationale: Maintaining an accurate record of machine configuration is necessary to 1) establish the state of the L-PBF machine at the time of qualification, 2) track or identify machine changes that may influence qualification status and the quality of the L-PBF process and 3) prevent unplanned or unintended loss of configuration control. Loss of L-PBF machine configuration control negates the process control logic at the foundation of these requirements.]

4.5.8 Maintenance

[PCQR-34] Comprehensive preventive maintenance schedules shall be established and enforced for all L-PBF machines, facility, and associated equipment.

[Rationale: Sustaining a continuously controlled L-PBF process is only feasible if maintenance for the facility and all associated equipment is performed consistently and adequately.]

Facility and equipment maintenance is intended to be implemented through the EFCP under the auspices of the L-PBF Process Vendor. The preventive maintenance schedules should include, at minimum, the recommended maintenance items identified by the L-PBF machine manufacturer and other items unique to the installation or facility. The maintenance schedule *should be reviewed periodically for each L-PBF machine to ensure all maintenance needs and intervals are properly set, proactively taking into account observations of process quality and machine health during operations and prior maintenance activity. Critical associated equipment may include sieve equipment, measuring or calibration instruments, cleaning tools, or other such apparatus that are influential to continued, successful operation of the L-PBF process.*

4.5.9 Calibration

Calibration of L-PBF machines and associated equipment is central to establishing the qualification of machines for production. This section provides minimum requirements for managing calibrations.

4.5.9.1 Calibration Schedules

[PCQR-35] Each L-PBF machine shall have comprehensive calibration schedules defined and implemented that meet the following minimum criteria:

a. Addresses all mechanical, optical, electrical, software, and firmware systems involved in controlling or monitoring the L-PBF process;
b. Defines each calibration metric with nominal value(s) and acceptable tolerances;
c. Defines calibration intervals for each metric;
d. Utilizes NIST-traceable standards for all calibration measurements, unless otherwise documented in the EFCP.

[Rationale: Equipment calibration is essential to reliable control of the L-PBF process.]

Equipment calibration procedures are intended to be implemented through the EFCP under the auspices of the L-PBF Process Vendor. Calibration may also include or be limited to verification of state, such as in the case of software or firmware versions. All aspects of the L-PBF machine that are controlled, commanded, or monitored during execution of the L-PBF process are intended to be included in the calibration and verification process. These include, but are not limited to, the ventilation system, oxygen sensing, motion and alignment of mechanical systems, such as the recoater and build platform. Setting calibration metrics and tolerances for all aspects these systems requires a combination of equipment manufacturer information, monitoring over time, and engineering judgement.

4.5.9.2 Optical System Calibration

[PCQR-36] As part of the calibration schedule of Section 4.5.9.1, calibration of the optical system(s) (lasers, scanner heads, and associated optical path) of each L-PBF machine shall include, at minimum for each laser/scanner combination, the following metrics evaluated at the center and furthest attainable extremes of the build area (or individual laser scan area) in the build plane:

a. Laser power,
b. Laser spot size, shape, and profile,
c. Laser alignment (X, Y) to the build area, and additional lasers
d. Laser plane of focus alignment to the plane of the build area
e. Accuracy and precision of scanner head beam steering and laser timing

[Rationale: The L-PBF process is wholly dependent upon optical system performance; however, L-PBF machines are typically incapable of active feedback monitoring of optical system performance. These calibration requirements are established to provide consistent monitoring of optical system health.]

Depending upon the capabilities of the L-PBF Process Vendor, optical system calibration is likely a set of measurements to verify that the health of the laser and optics system is consistent with metrics provided by the equipment manufacturer and consistent over time. Lasing purposeful markings into a flat, solid plate and evaluating the marking against metrics (based upon past performance) may provide sufficient evidence of scanner head health.

4.5.9.3 Calibration Intervals

[PCQR-37] Maximum calibration intervals shall be as follows:
a. Optical system(s), 90 days,
b. All other systems, 180 days.

[Rationale: Calibration is effective only when maintained continuously. For pragmatic reasons, confirming calibration is not feasible on a per-build basis. This time-based calibration interval is set as a compromise between production efficiency and process assurance.]

To accommodate part build times and schedules, these calibration intervals may be acceptably implemented at the completion of the last build started within the interval. Policies for interpreting the calibration interval are intended to be clearly defined in the EFCP.

4.5.9.4 Calibration State

[PCQR-38] L-PBF machines shall be considered in a calibrated state only when
a. All scheduled maintenance items of Section 4.5.8 are completed within their prescribed maintenance intervals,
b. All calibration metrics of Section 4.5.9.1 are evaluated within their defined calibration intervals (maximums per Section 4.5.9.3) and verified within specification limits, and
c. Maintenance and calibration records are documented as required by Section 4.5.6.

[Rationale: An established and documented state of calibration is necessary to establish L-PBF machine qualification for the production of parts.]

4.5.9.5 Calibration Non-conformance

[PCQR-39] Upon calibration, if any calibration metric is not within specification limits, all parts produced since the last calibration shall be given non-conformance status in the QMS.

[Rationale: Calibration metrics outside specification limits are a non-conformance to section 4.5.10.]

This requirement may influence the choice of calibration intervals to mitigate programmatic risk, particularly for L-PBF machines whose calibration stability is not well characterized. Part non-conformance can be resolved at the discretion of the program, preferable once root cause of the calibration error and its influence on the L-PBF process is understood.

4.5.10 L-PBF Machine Qualification

[PCQR-40] L-PBF machines shall have active qualification status only when

a. The L-PBF machine is documented to be in the calibrated state per Section 4.5.9.4, and
b. A Master QMP or QMP has been successfully established within 12 months or the L-PBF machine has been under continuous SPC monitoring as defined by MSFC-STD-3716, and
c. No event has occurred to negate the active qualification status of the machine as follows:
   (1) Changes to the machine other than predefined preventative maintenance
   (2) Updates to software or firmware
   (3) Replacement, repair, or alteration of essential components
   (4) Moving the machine
   (5) Changes to the machine set-up or configuration within the facility
   (6) Any similar, or unforeseen event which may credibly alter or influence the L-PBF machine performance.

[Rationale: A clearly implemented definition of L-PBF machine qualification status ensuring machine health is critical to the reliable production of L-PBF parts.]

Pre-determining an exhaustive list of events that negate the active qualification status of a machine is not practical and determining which disruptive events reach this threshold can be subjective. Accurate documentation of all events, regardless of magnitude, in the machine configuration management log (Section 4.5.7) are important. Unforeseen events of questionable impact to qualification state should be arbitrated among the L-PBF Process Vendor, CEO, and the customer.

4.5.10.1 Establishing Initial Qualification

[PCQR-41] Active qualification status of a L-PBF machine shall be established initially through the following:

a. Verifying the L-PBF machine to be in a calibrated state per Section 4.5.9.4, and

b. Successfully evaluating one QMP (or Master QMP, as applicable) for the machine to the requirements of Section 4.2
c. Recording the active qualification status in the L-PBF machine configuration log.

[Rationale: These requirements represent the minimally acceptable evaluations of L-PBF machine performance prior to production of parts.]

4.5.10.2 Re-establishing Qualification

[PCQR-42] Active qualification status of a L-PBF machine shall be re-established following any event which negates its active qualification status through a minimum of the following:

a. Verifying the event negating active qualification is resolved,
b. Verifying the L-PBF machine to be in a calibrated state per Section 4.5.9.4, and,
c. Successfully evaluating the L-PBF process using the SPC verification requirements of Section 4.4,
d. Recording all related events in the L-PBF machine configuration log.

[Rationale: These requirements represent the minimally acceptable evaluations of L-PBF machine performance to re-qualify the machine for production of parts following an event that negates an active qualification status.]

A L-PBF machine may have multiple QMPs associated with it, for example QMPs developed for various layer thicknesses. A L-PBF machine without active qualification status may not produce to any of its associated QMPs. However, re-establishing active qualification status, enabling all associated QMPs, requires re-evaluation of the machine capability per Section 4.4 for only one if the associated QMPs.

As discussed in the commentary of Section 4.5.10, a broad variety of events may occur to negate the qualification status of a L-PBF machine. The scope of re-qualification activities may be tailored to fit unique scenarios with written agreement of the L-PBF Process Vendor, CEO, and NASA customer.

4.5.10.3 L-PBF Machine Qualification Status for Production

[PCQR-43] L-PBF parts shall only be produced to a QMP if the associated machine has active qualification status and such qualification status is posted directly on the machine.

[Rationale: The qualification of a L-PBF machine and the qualification of its associated metallurgical processes are largely synonymous, given the machine is in a calibrated state. Verification of the quality of the metallurgical process establishes the L-PBF machine's qualification; thus, events which negate a machine's qualification status negate the ability to produce parts to associated QMPs until machine qualification status is reestablished. Posting of machine qualification status ensures operators are noticeably aware of a machine's status prior to use.]

4.6 Operator Certifications

[PCQR-44] L-PBF operations, defined in the context of this requirement as those actions spanning from the manipulation of the digital product definition to prepare for the build through removal of the completed part from the L-PBF machine, shall only be performed by operators with applicable certifications.

[Rationale: Though highly automated, the L-PBF process is highly sensitive and dependent upon the inputs of the operators at all stages of the process. Operator certifications are essential to minimizing the risk of human error in the process.]

4.6.1 Training Program

[PCQR-45] An active operator training program shall be defined, maintained, and implemented to meet the following objectives:

a. Provide a consistent framework for training and certification requirements
b. Provide clear delineations of abilities and responsibilities associated with granted certifications
c. Provide operators with all necessary skills, knowledge, and experience to execute the responsibilities of their certification safely and reliably
d. Provide for operator evaluations that demonstrate adequacy in skills, knowledge, and experience to grant certifications to personnel, ensuring only properly trained and experienced personnel have appropriate certifications
e. Incorporate content regarding the importance, purpose, and use of the QMS for all certifications.

[Rationale: Operator certifications are only meaningful if granted from a properly structured and adequate training program.]

The CEO and L-PBF Process Vendors are jointly responsible for the adequacy of the implemented training program.

There is currently no openly defined system for operator certifications in AM technologies. The intent of this requirement is to ensure appropriate depth in the knowledge and skills of the AM workforce involved in the production of aerospace parts per these MSFC Technical Standards. Programs are developing within the industry and if suitable may be used in lieu of an internally structured program.

A list of key topics for training and an example of a training program can be found in extended commentary of Appendix A.

APPENDIX A. EXTENDED COMMENTARY

This appendix is non-mandatory. All content is guidance only. This appendix provides extended commentary and guidance specific to the noted sections.

A4.1.1.1 Virgin Powder Requirements

The chemistry requirements for virgin powder feedstock are controlled to render the proper chemistry in the final metallurgical state. Control and specification of powder chemistry for an AM alloy generally will not be unique relative to available standardized powder chemistries. If the powder is gas-atomized, then the use of inert (argon) gas is recommended. If atomized in nitrogen, controls on nitrogen content may be important. Unique controls of chemistry may be more common with a Customized QMP. The distribution of particle size and shape is influential to the quality of the L-PBF process. For L-PBF processes applicable to this MSFC Specification, large particle control and verification is typically feasible with a sieve process. The quantity of the smallest particles (fines) will influence the powder rheology characteristics and therefore also requires control. Verification of particle size distribution below 45 microns requires methods such as light scattering, sedimentation, or image analysis. Examples include ASTM B215 (sampling), ASTM B214 (sieving), ASTM B822 (light scattering), and ISO 13322 (image analysis).

A4.1.3 Thermal Processing

The stress relief cycle is most commonly employed prior to removal of parts from the build platform as a means to reduce residual stresses in the as-built part while the part is dimensionally constrained by the platform and its built support structure. This aids in geometric stability of the parts during platform and support structure removal. A potential secondary benefit is that the stress relief cycle moderates macro-scale residual stresses at a temperature below the onset of rapid grain growth kinetics. Depending upon the alloy system, the as-built residual stress state may provide much of the necessary energy to drive the desired recrystallization; however, without some measure of stress relief, non-uniform grain growth may occur within parts when exposed to the thermal cycle used to affect recrystallization. Achieving a proper balance between stress relief and the hot isostatic pressing cycle should result in a uniformly recrystallized microstructure while avoiding non-uniformities in grain growth caused by macro-scale stored elastic energy in the part.

The HIP process is the most common means of achieving microstructural recrystallization to fully remove the as-built microstructure. It is common to utilize established HIP processes that have been defined for classes of alloys within the industry. Due to the mass of HIP equipment, fast cooling rates can be difficult to achieve for alloys with microstructure sensitive to quench rates from such temperatures. If HIP is not included within the definition of the thermal process, then the metallurgical process is only applicable to Class B parts. This does not absolve the requirements on evolution of the final microstructure. To maximize the applicability of metallurgical processes to parts of all classes, and preclude the need for restrictions on the QMP, it is recommended that all thermal processes include HIP.

Most alloys will require further heat treatment following the HIP process to control the final stages of microstructural evolution. The cooling rates obtainable from most HIP equipment will be relatively slow. Depending upon alloy system, the slow cooling rate from HIP is typically not compatible with the quench rates needed to achieve a proper solution state of microstructure for further response, such as precipitation hardening.

A4.1.3.1 Control of Thermal Processes

Specifications such as the following or their equivalents are suitable to control AM thermal processes: SAE AMS 2801, Heat Treatment of Ti Alloy Parts, and SAE AMS 2774, Heat Treatment of Ni and Co Alloy Parts. Thermal processing conditions may be adapted as required for the AM process and are not required to conform to the time and temperature profiles in existing heat treating specifications such as the above examples. The intent is for the heat treating process to be properly controlled through the procedures of such documents, mainly as enforced by their second tier requirements such as SAE ARP1962, Training and Approval of Heat Treating Personnel, and SAE AMS 2750, Pyrometry. Consistent heat treatment is critical to reliable quality of AM parts. Knowledgeable heat treatment providers who are properly equipped and trained are essential.

A4.1.4 Customized Metallurgical Processes

A Customized Metallurgical Process is defined when there is a need to impose additional process controls to achieve a desired material performance characteristic or if there is simply a need to confirm a particular material performance characteristic is met. An example of a situation requiring a Customized Metallurgical Process would be the development a L-PBF metallurgical process to achieve optimal ductility and toughness in the Ti-6Al-4V alloy at cryogenic conditions. The Customized Metallurgical Process definition will state the material performance objective (cryogenic ductility and toughness) and the controls imposed to achieve it, which in this case could entail unique controls on the oxygen and other interstitial content in the feedstock powder and final product as well as uniquely controlled thermal processing. In addition, the Customized Metallurgical Process definition establishes the type of witness test and acceptance criteria to confirm the process is successful at qualification as well as in future witness testing to occur during the production of parts. In this example, a cryogenic fracture toughness test or notched tensile test may be specified along with an appropriate acceptance criteria.

Another example of a Customized Metallurgical Process would be a need to confirm stress rupture capability has been achieved in a high-temperature, heat-treatable alloy. In this case, there may not be unique process controls levied to achieve the result (nominal chemistry and heat treatments), but the stress rupture test is a performance characteristic not confirmed by the normal witness tests imposed by this MSFC Specification; therefore, the Customized

Metallurgical Process is used to ensure these unique and requisite tests are performed when the metallurgical process is qualified as well as in future witness testing to occur during the production of parts.

A4.2.3.1 Quality of the As-built Microstructure

There are four evaluations of as-built microstructure required to demonstrate proper control of the fusion process on each L-PBF machine for process qualification:

a. Survey of consistency over the powder bed area
b. Demonstration of tolerance to thermal history extremes
c. Restart layer interfaces
d. Interfaces in scan patterns (striping, islands, multi-laser zones), surface contours, cosmetic passes, and any other interfaces associated with a unique fusion parameter set, such as down-facing surfaces.

Commentary for the intent of each of these evaluations is provided below.

Powder Bed Area Survey:

The survey of the powder bed area is intended to identify regions of the bed where the as-built microstructure differs meaningfully. Numerous factors may contribute to such differences—examples include high laser incidence angle at extremes of the bed area, impeded beam focus and profile control, and poor ventilation flow allowing by-products to linger in the purge gas and attenuate the laser. In addition to evaluating areas in the center and corners of the bed area, observation of surface quality in build trials and the ventilation characteristics across the bed will inform where such survey evaluations are needed. If areas in the bed are identified where melt-pool characteristics differ, these areas will be a focus of the further evaluations in thermal history tolerance, surface and detail resolution quality, and mechanical evaluations. If an area of the bed is found to perform poorly, the QMP should identify that area as a "keep-out" zone for builds.

Tolerance thermal history extremes:

The requirement to demonstrate tolerance to thermal history extremes is a result of the methodology of this MSFC Specification (and MSFC-STD-3716) relying on a fixed set of parameters applied uniformly throughout the build volume regardless of part geometry and other content in the build—parameters are not adapted to changing conditions in the bed. (Adaptive parameter methodologies may bring advantages, but quality assurance challenges under such changing process conditions are significant; therefore adaptive methodologies are not currently allowed.) The goal is to have a nominal fusion parameter set that is sufficiently centered in the process limits that shifts in process due to thermal history in the part/bed/machine cannot move the process beyond its limit.

A simplistic representation of the L-PBF process box is shown in Figure A1. The L-PBF process limit is a function of numerous parameters governing laser power, speed, and scanning strategies. Figure A1 represents a space defined by these parameters with a process limit boundary, beyond which detrimental defects occur in the build. The nominal parameter set needs to lie comfortably within the process limit boundary. Throughout the build, local conditions in the L-PBF bed change due to part geometry (fused fraction area), time between laser passes, planned build stops, ventilation changes, or other such influences. The nominal fusion parameter set is uniformly applied atop these varying conditions. This variation is shown as the variation boundary in Figure A1. The intent of this requirement is to evaluate the expected extremes of this variation in local powder bed conditions and demonstrate the nominal parameter set can accommodate the variation without leaving the process limit boundary. It is not required to define either the process limit boundary or the variation boundary as a function of parameters—this is intractable. The intent is to develop conditions in the powder bed which push the variation to practical limits for a qualification build and to evaluate the quality of material at “hot” and “cold” variations represented in Figure A1. The requirement is that material produced under these extremes demonstrates the parameter set remains within the process limit boundary by not having detrimental defects.

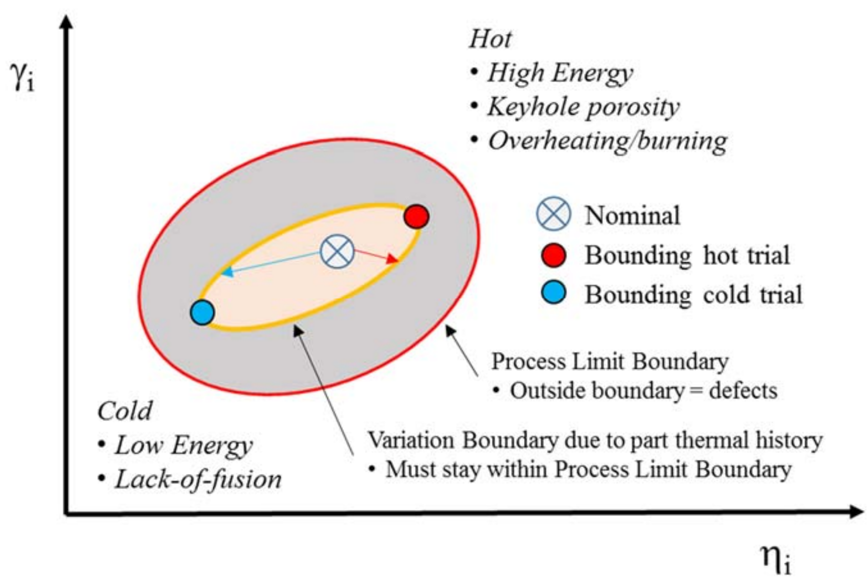

FIGURE A1. L-PBF Process Box

The nominal, hot, and cold conditions are evaluated by planning the qualification builds to reproduce such conditions to a reasonable extent. The nominal condition should be represented consistently. A recommended form is a uniform, vertical, rectangle or cylinder of approximately 10-12mm diameter or side dimension, scanned individually. There are numerous ways to develop the hot and cold test conditions. For testing the cold condition, recommendations for developing the test material include maintaining good thermal conduction in the test artifact, stopping the cold test artifact early before bed temperature rises, having long laser inter-pass time by including artifacts in the same scan set at extreme locations in the bed, allowing cooling time between recoating with zero-power "ghost parts." Note that tolerance to cold process conditions is important because cold conditions may be exacerbated by laser attenuation due to conditions of poor ventilation or contaminated optics developing during the build. For testing the hot condition, the opposite recommendations apply. A hot test artifact may be one of considerable solid cross-section that is scanned individually resulting short inter-pass times. The hot test artifact may be more thermally insulated to retain heat and timed for when the bed has accumulated temperature. Unsupported, down-facing surfaces with edges or corners may be sensitive areas for overheating and good indicators of tolerance (or lack thereof) to the hot condition.

Restart interface:

For a metallurgical process that is to have a qualified process restart procedure, the metallurgical quality at the interfacing layers where the restart occurs must be evaluated under the prescribed, limiting restart conditions defined in the restart procedure or check-list for the L-PBF equipment. The restart of the qualification build should be timed to be included in convenient metallurgical and mechanical test evaluations. The intent of the evaluation is to demonstrate the restart interface is not unique and does not contain detrimental defects.

Other interfaces:

Numerous other interfaces may result from the scan pattern employed by the parameter set. The objective of this interface evaluation is to ensure the implementation of the scan pattern on the L-PBF machine being qualified renders these interfaces without systemic defects. Within the bulk material, interfaces with potential for defects occur at the lowest level (hatch spacing) up to a macro level between patterns of larger scanning regions (islands, stripes, or multi-laser zones). Scan strategies typically apply shifts and rotations to avoid repeated interface locations from layer to layer. This evaluation should ensure the strategy is working and no systemic defects, typically linear porosity, follow these interfaces.

The more critical interface of concern in this evaluation occurs between the surface contour pass and fill pattern. Figure A2 illustrates this interface region where heightened potential for porosity exists due to scan pattern effects. The integrity of this interface is a combination of the geometry of the scan pattern at the boarder of the fill, the parameters used in the fill and contour passes, the offset between the fill and contour passes, and the number of contour passes. The intent of the evaluation is to ensure that the fill and contour passes are well integrated, without porosity or other defects at the interface. This evaluation should occur at vertical surfaces where the interface is always aligned as well as over-hanging (down-facing) surfaces where the interface is built partially over free powder. Sub-surface porosity is a particular concern for fatigue performance of parts. Figure A3 illustrates an extreme example of poor surface contour interface integrity.

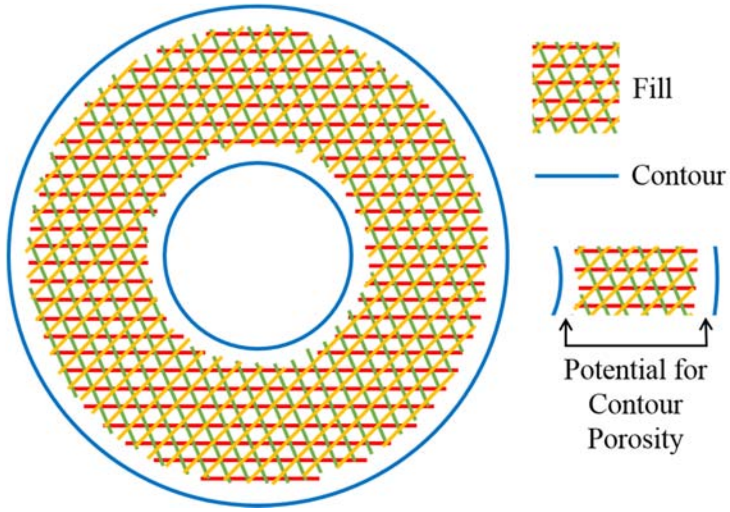

FIGURE A2. Scan pattern layers with fill and contour passes

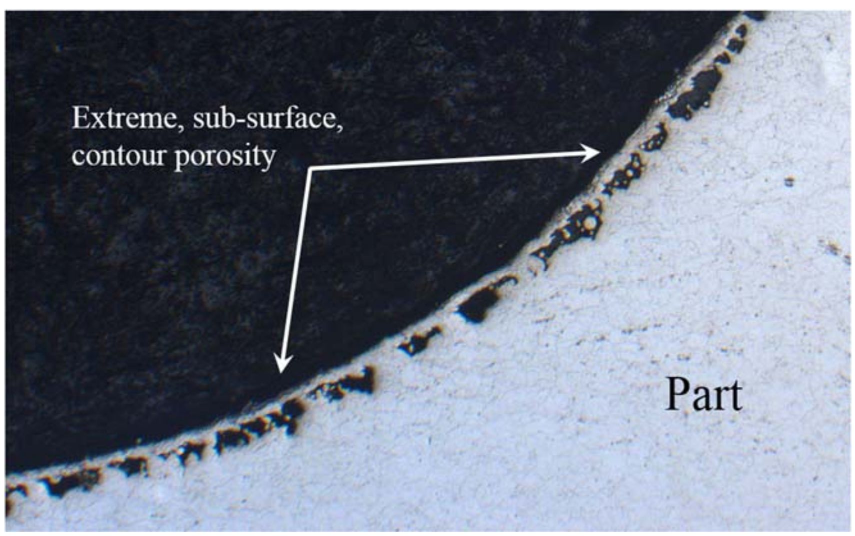

FIGURE A3. Extreme example of sub-surface contour porosity

A4.2.3.2 Top Layer Melt-Pool Characterization

As an extension of the as-built microstructural evaluation, qualification of a candidate metallurgical process requires documentation of the typical melt-pool geometry as measured at the top, or final, layer of a specimen. If the scan strategy of the L-PBF machine includes the use of a cosmetic pass for top-facing surfaces, this needs to be disabled for this evaluation. The intent is for the evaluated melt-pools to be typical of the nominal process state. The metrics identified, averages of d_p/t_L and d_o/t_L, are intended to be simple to obtain yet informative of process health. The requirement is to record these values at qualification and observe consistency over time at re-qualification or SPC builds. There is currently not a requirement for acceptance regarding the value of these ratios. An example of making these measurements in an actual microstructure are shown in Figure A3.

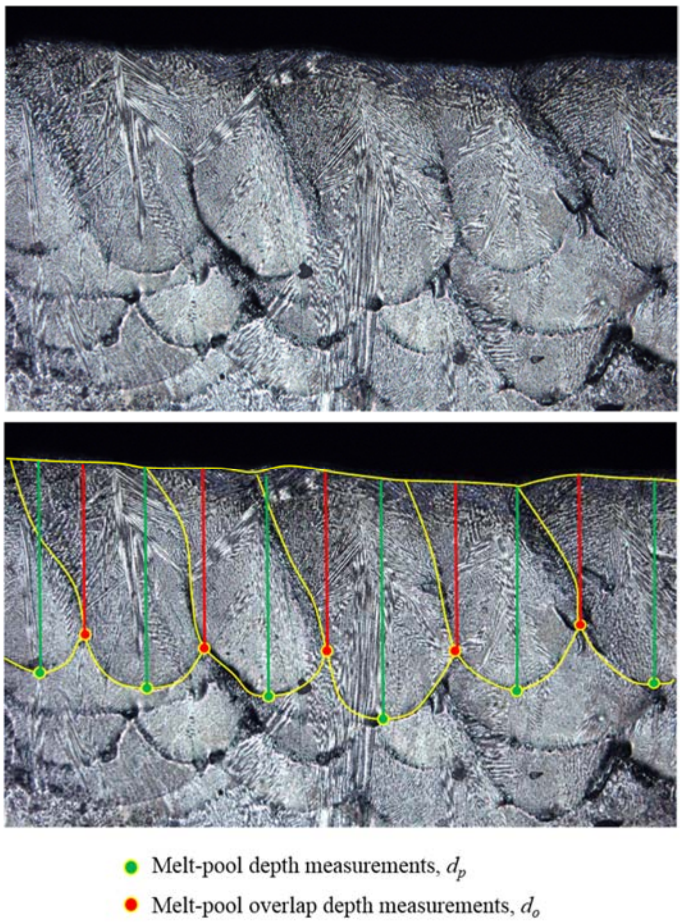

FIGURE A3. Example of melt-pool depth measurements

A4.2.4.2 Reference Parts

While process control inspections of parts provide considerable recurring evidence of build quality, a standardized article optimized to that intent more readily provides evidence, both qualitative and quantitative, to the quality of the geometric rendering of the process and subsequently serving as a potential indicator of developing optical or mechanical issues in the L-PBF machine. The primary intent is to have surface texture (or roughness) measurements on indicative surfaces such as horizontal surfaces, vertical surfaces, 45-degree overhanging surfaces, and open-passage free ceilings. Methods for quantifying detail resolution capability may be as simple as a series of holes, protrusions, or radii of decreasing size, such that the smallest size maintaining its form may be used as the metric. There may be many more useful or informative options for measuring detail resolution appropriate to the intended purpose of the

QMP. Once established, the reference part and inspection method along with the resulting metrics are documented as part of a Master QMP or, if preferable, may be in a standalone, configuration-controlled document referenced by the Master QMP.

The insight provided by reference parts may be used for a variety of needs beyond establishing the QMP, such as comparing the build quality of new powder lots. NASA, National Institute of Standards and Technology (NIST), and other organizations have proposed articles intended to serve as reference parts.

A4.6.1 Operator

The following are examples of key topics expected to be included in a training program. This does not represent a comprehensive list:

- Health and Safety
- Understanding and using the QMS
- Documentation requirements
- Maintaining configuration control of digital files and equipment
- Working with the digital product definition
- The cryptographic hash and its use
- Build files, support structures, slicing
- Feedstock handling
- Machine functionality: setup, operations, restarts, maintenance, calibration
- L-PBF process monitoring: understanding failure mechanisms in the process and the ability to identify and properly troubleshoot build errors
- Understanding build capability: overhangs, surface quality, detail resolution
- As-built part inspections for build quality and anomalies
- Contamination and foreign object debris control
- Execution and evaluation of Standard Qualification Build Sets (4.2.2) for QMP and SPC purposes
- Establishing Master QMPs and QMPs

The following example represents a training protocol for L-PBF machine operators with tiered implementation meeting the objectives of Section 4.6.1.

Note: a similar training regimen, though perhaps not tiered, would be needed to cover topics related to working with the digital product definition: assembling builds, slicing, support generation, and related tasks.

Trainee

Prerequisites:

- No prior experience needed

Typical Duties:

- Trainee may participate in the day-to-day operations of L-PBF machines and associated equipment. A trainee is not to operate L-PBF machines or associated equipment unsupervised by at least a Level I.

Level I Certified Operator

Prerequisites:

- Minimum of three months experience under direct supervision of a Level II or III.
- Must pass written and practical test administered by a Level III
- Completed all basic training offered by the L-PBF machine manufacturer
- Full understanding of applicable QMS and associated responsibilities

Typical Duties:

- Machine cleaning, operational checks
- Basic machine operations,
- Execution of established builds
- Operates under supervision of Level II or III

Level II Certified Operator

Prerequisites:

- All Level I requirements
- One year minimum experience under direct supervision of a Level II or III.
- Must pass written and practical test administered by a Level III
- Completed all advanced training offered by the L-PBF machine manufacturer
- Comprehensive knowledge of all machine functions

Typical Duties:

- Set-up and trouble-shooting of L-PBF equipment
- Execution and analysis of Standard Qualification Build Sets
- Trouble-shoots and iterates build schemes to optimize build performance

- Build file generation in accordance with Qualified Part Process requirements
- Develops machine operation checklists
- Operates under supervision of Level III

Level III Certified Operator

Prerequisites:

- All Level II requirements
- Minimum three years of experience
- Understanding of the physics and metallurgy of the L-PBF process
- Must pass written and practical test administered by another Level III

Typical Duties:

- Developing QMPs
- Establishing proper QMS oversight for all L-PBF activities
- Development, implementation, and approval of production planning records
- Sets machine calibration metrics and intervals
- Develops training and administers certification written and practical tests

Separate from operator training, there is also an expected training investment for metallurgical evaluation techniques needed to qualify processes or evaluate builds, Expertise in L-PBF metallurgical evaluations, particularly in as-built microstructures, requires experience and fundamental process knowledge.

APPENDIX B. REFERENCE DOCUMENTS

The documents listed in this Appendix have been referenced within this MSFC Specification as examples or recommendations. These documents are not directly applicable to fulfilling the requirements of this MSFC Specification.

Non-Government Documents:

ASTM B214	Standard Test Method for Sieve Analysis of Metal Powders
ASTM B215	Standard Practices for Sampling Metal Powders
ASTM B822	Standard Test Method for Particle Size Distribution of Metal Powders and Related Compounds by Light Scattering
ISO 13322	Particle size analysis—Image analysis methods—Part 1: Static image analysis methods
SAE AMS 2750	Pyrometry
SAE AMS 2774	Heat Treatment of Wrought Nickel Alloy and Cobalt Alloy Parts
SAE AMS 2801	Heat Treatment of Titanium Alloy Parts
SAE ARP 1962	Training and Approval of Heat Treating Personnel. Standard:

APPENDIX C. QMP CHECKLIST AND QMP RECORD TEMPLATE

This appendix is non-mandatory. All content is guidance only. This appendix summarizes the steps used to define and qualify the L-PBF metallurgical process.

Definition of the Candidate Metallurgical Process

Identify:

- Powder feedstock specification
  - Chemistry
  - Particle size distribution / morphology
  - Feedstock reuse protocol, if allowed
- Fusion process controls
  - Equipment configuration
  - Build Chamber
  - Fusion parameters
- Process Restart
  - Criteria
  - Procedures
- Thermal Process
  - Stress relief
  - HIP
  - Heat treatment
- Customized Metallurgical Process, as needed
  - Objectives of the customized process
  - Controls levied to obtain objective
  - Witness requirements used to verify objectives

Qualification of the Candidate Metallurgical Process

Determine:

- For the candidate process, does a Master QMP exist meeting commonality criteria?
  - If yes, identify the Master QMP and qualify the candidate to its criteria
  - If no, develop Master QMP with acceptance criteria

Identify:

- Proper qualification build set
  - Execute build according to the defined candidate process

Qualify:

- As-built microstructure
  - Survey of powder bed area
  - Thermal history tolerance
  - Restart layer interface (if restarts are allowed)
  - Interfaces in scan patterns (contours and related)
  - Top layer melt-pool characterization

- Microstructural Evolution
    - For Master QMP, microstructure at each step is documented
        - Establish acceptance criteria for as-built and final
    - For QMP, document as-built and final microstructure
        - Confirm quality meets acceptance criteria of Master QMP
- Surface Texture and Detail Resolution
    - Using defined reference parts, near center and edge of build area
    - For Master QMP, evaluate reference parts
        - Establish metrics and acceptance criteria
    - For QMP, evaluate reference parts
        - Confirm quality metrics meet acceptance criteria of Master QMP
- Mechanical Properties
    - Evaluate mechanical properties from the qualification build set
    - Tests defined in Table II.
- Register metallurgical process to a Material Property Suite
- QMP Record
    - Documents qualification evaluations
    - Records approval of L-PBF Process Vendor and CEO
    - Configuration controlled record in the QMS

The following pages contain a template for the QMP Record. The template is provided only for reference. Its use is not mandatory. It is expected that the QMP Record document will be adapted to fit the documentation system of the CEO and L-PBF Process Vendor.

Notes are provided in brackets with red text in the template to provide guidance regarding expectations for QMP record content.

L-PBF Qualified Metallurgical Process Record

QMP Title: [Name to associate with QMP and QMP Record Number, if desired.]	
QMP Record Number: [Identifier for referencing the QMP in QMS records]	
Check as applicable: □ Master QMP □ QMP, based upon Master QMP: [If checked, identify Master QMP Record number] □ Customized QMP (Complete Customized L-PBF Metallurgical Process Definition Section)	
General Description: [Provide process description for quick reference: machine, alloy, heat treatment…]	
RESTRICTIONS ON USE: [Note restrictions, such as only Class B hardware if no HIP included]	
QMP Approval Statement: All necessary data for qualification of this metallurgical process to the requirements of MSFC-SPEC-3717 has been reviewed, judged acceptable, and archived.	
L-PBF Process Vendor Approval:	Date:
CEO Approval:	Date:

L-PBF Metallurgical Process Definition

Powder Feedstock			
Feedstock Specification:	[Reference to powder specification, version specific]		
Reuse protocol:	[State reuse protocol or reference specification/policy for reuse protocol.]		
Fusion Process Controls			
Machine ID:		Model/Model:	
Serial Number:		Configuration Date:	[Date of QMP build]
Software Version:		Firmware Version:	
Recoater Configuration:	[Geometry, material, other]		
Build platform material:			
Preheat temperature:			
Nominal dosing range:	[Standard range of settings for powder dosing]		
Purge Gas composition:			
Ventilation flow rate:	[Nominal flow rate as measured in standardized location]		
Ventilation setting:	[L-PBF machine setting to achieve nominal flow rate]		
Diffuser configuration:			
Dew point limit:			
Oxygen limit:			
Temperature limits:			
Fusion Parameter File:	[File name]	Hash:	[Cryptographic hash of parameter file]
Layer thickness:	[Fundamental information, needed for melt-pool depth ratios]		
Other:	[If not proprietary, listing other key parameters such as laser power, speeds, hatch spacing, may be helpful.]		
Thermal Process	[Provide detailed thermal process or reference complete thermal process specification.]		

Process Restart
Restart of process allowed? Y/N [Identify if restarts allowed for this QMP, yes or no]
Restart criteria: [State criteria required of the stopped build state to permit restart to occur (time limits, other)]
Restart procedure: [Provide reference to established restart procedure evaluated for this QMP. (in QMS)]

Customized L-PBF Metallurgical Process Definition	
Desired Attributes:	[State required unique material performance attributes (cryogenic ductility, stress rupture)]
Controls:	[State unique controls applied (chemistry, thermal process, other)]
Witness Requirements:	[Describe witness test requirements needed to confirm performance attributes.]

Metallurgical Process Qualification

Qualification Build Set Utilized:
[Identify the build file used for the qualification build. Suggest including a CAD image for reference.]

As-built Microstructure Evaluations: Build Area Survey
[Images] [May reference a separate metallurgical report, if the report is documented in the QMS]
Acceptance Statement: [Provide a statement, or comments as needed, regarding the uniformity and consistency of the as-built microstructure surveyed around the build area—no detrimental defects.]

As-built Microstructure Evaluations: Thermal History Tolerance		
Nominal:	Cold:	Hot:
[Images] [(or reference)]	[Images] [(or reference)]	[Images] [(or reference)]
Acceptance Statement: [Provide a statement, or comments as needed, regarding the tolerance of as-built microstructure to variation in thermal history—no detrimental defects.]		

As-built Microstructure Evaluations: Restart Interface (If process restart allowed)
[Images] [May reference a separate metallurgical report, if the report is documented in the QMS]
Acceptance Statement: [Provide a statement, or comments as needed, regarding the acceptability of the as-built restart interface quality—no detrimental defects.]

As-built Microstructure Evaluations: Interfaces (Contours and scan patterns)
[Images] [May reference a separate metallurgical report, if the report is documented in the QMS]
Acceptance Statement: [Provide a statement, or comments as needed, regarding the acceptability of the as-built interface quality—no detrimental defects.]

As-built Microstructure Evaluations: Top Layer Melt-Pool Evaluations	
Average of d_p/t_L =	Average of d_o/t_L =
[Provide micrographs documenting melt-pool evaluation.] [May reference a separate metallurgical report, if the report is documented in the QMS.]	

Microstructural Evolution (Thermal Process)
[Provide micrographs documenting microstructural evolution. All steps for Master QMP, only as-built and final for QMP.] [May reference a separate metallurgical report, if the report is documented in the QMS.]
For Master QMP—Establish metrics and acceptance criteria for as-built and final microstructures
For QMP—Acceptance Statement, Microstructures meet Master QMP criteria.

Surface Texture and Detail Resolution
[Report evaluation metrics from reference parts: surface texture, build quality, detail resolution.] [Include photographs for reference.] [May reference a separate reference part evaluation report, if the report is documented in the QMS.]
For Master QMP—Establish metrics and acceptance criteria for surface texture and detail resolution
For QMP—Acceptance Statement, Texture and resolution meet Master QMP criteria.

Mechanical Properties
[Report properties required for either Master QMP or QMP, as appropriate.] [May reference a mechanical property test report, if the report is documented in the QMS.]

Registration—Material Properties Suite
Material Property Suite: [Identify the MPS to which the QMP is registered]
All properties meet requirements of registration (Y/N) Comments:

APPENDIX D. SUMMARY TABLE OF REQUIREMENTS

This appendix is non-mandatory. All content is guidance only. This appendix summarizes the requirements of this MSFC Specification.

TABLE D1. Summary of Requirements

Category	Requirement	Abbreviated Requirement Description	Section	Page
—	PCQR-1	Tailoring of this MSFC Specification	1.3	7
Metallurgical Process Definition	PCQR-2	Feedstock Specification, Virgin Powder Requirements	4.1.1.1	14
	PCQR-3	Feedstock Specification, Powder Reuse Requirements	4.1.1.2	15
	PCQR-4	Fusion Process Definition	4.1.2	16
	PCQR-5	L-PBF Process Restart Procedures	4.1.2.1	17
	PCQR-6	Thermal Process Definition	4.1.3	18
	PCQR-7	Controls for Thermal Processes	4.1.3.1	18
	PCQR-8	Variation in Thermal Processes	4.1.3.2	19
	PCQR-9	Customized Metallurgical Processes	4.1.4	19
Qualification of Metallurgical Processes	PCQR-10	Qualification of Candidate Metallurgical Processes as a Master QMP or QMP	4.2	20
	PCQR-11	Master QMP and commonality requirements	4.2.1	21
	PCQR-12	Standardized Qualification Build Sets	4.2.2	21
	PCQR-13	Quality of As-Built Microstructure	4.2.3.1	22
	PCQR-14	Top Layer Weld Melt-Pool Characterization	4.2.3.2	23
	PCQR-15	Microstructural Evolution	4.2.3.3	23
	PCQR-16	Microstructural Acceptance Criteria for Master QMP	4.2.3.4	24
	PCQR-17	Surface Texture and Detail Resolution Using Reference Parts	4.2.4	24
	PCQR-18	Surface Texture and Detail Resolution Acceptance Criteria for Master QMP	4.2.4.1	25

	PCQR-44	Operator Certifications	4.6	39
	PCQR-45	Training Program	4.6.1	39