

D-101742

Supplier Quality Requirements for Powder Bed Additive Manufacturing

Revision A

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Definitions

Additive Manufacturing (AM) – Process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methods.

As-built – the state of parts made by an additive process before any post processing, besides, if necessary, the removal from a build platform as well as the removal of support and/or unprocessed feedstock

Build Strategy – The AM machine’s strategy for building the part

Condensate – Vaporized material, created while the laser is firing, that condenses into nanometer-sized particles

Pre-production Article Inspection – Qualification report of the first part produced that ensures the specifications are met

ITAR – International Traffic in Arms Regulations. Regulation of the export and import of defense related parts

Powder 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.

Material Process Record – A configuration-controlled document detailing a set of machine parameters, feedstock, and post-processing specifications that constitute a material process.

Material Family – Alloys classified under the same Unified Numbering System (UNS) series.

Melting Device – The device used to fuse the powder together to form layers, often an electron beam or a laser

Powder Bed – The build area in an additive manufacturing process in which the powder is deposited and selectively melted with a heat source to build up components

Powder Manufacturer – The organization that produces the powder

Recoater Blade – The part of the powder distribution system that spreads a thin, level layer of powder across the build platform

Supplier – Additive manufacturing vendor producing parts or providing post-processing for JPL

Support Structure – Supplementary, sacrificial material built along with a part to provide thermal management within the powder bed, dimensional stability, and overhanging geometry support

Used Powder – Powder that has been processed in at least one previous build cycle

Virgin Powder – Unused powder from a single powder lot

1. Purpose

The purpose of this document is to provide the supplier quality requirements for additively manufactured space-flight parts using powder bed fusion technologies.

2. Applicability

This document applies to any suppliers who conduct activities involving additively manufactured JPL flight parts using powder bed fusion technologies. This document does not apply to any other additive manufacturing methods. For the purpose of this document, “supplier” refers to the subcontracted organization fabricating additively manufactured parts for JPL or performing post-processing of additively manufactured parts. In this document, “contract” refers to the contract between JPL and the supplier, not the contract between NASA and JPL. JPL approved suppliers are responsible for flowing down requirements as stated in this document to sub-tier suppliers.

This document includes the minimum requirements needed for production of additively manufactured parts. Supplier shall see the contract or drawing for any additional applicable requirements. For guidance regarding additional requirements included outside of this document, refer to the NASA-STD-6030.

3. Applicable Documents

The following documents, of the issue specified in the contractual instrument, or as specified for use within JPL, form a part of this specification to the extent specified herein.

3.1. ASTM Publications

ASTM B213 – Standard Test Methods for Flow Rate of Metal Powders Using the Hall
Flowmeter Funnel

ASTM B214 – Standard Test Method for Sieve Analysis of Metal Powders

ASTM B215 – Standard Practices for Sampling Metal Powders

ASTM B243 – Standard Terminology of Powder Metallurgy

ASTM B311 – Standard Test Method for Density of Powder Metallurgy (PM) Materials
Containing Less Than Two Percent Porosity

ASTM B946 – Standard Test Method for Surface Finish of Powder Metallurgy Products

ASTM E8/E8M – Standard Test Methods for Tension Testing of Metallic Materials

ASTM E9 – Standard Test Methods of Compression Testing of Metallic Materials at
Room Temperature

ASTM E539 – Standard Test Method for Analysis of Titanium Alloys by X-Ray
Fluorescence Spectrometry

ASTM E1409 – Standard Test Method for Determination of Oxygen and Nitrogen in

Titanium and Titanium Alloys by Inert Gas Fusion

ASTM E1447 – Standard Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by Inert Gas Fusion Thermal Conductivity/Infrared Detection Method

ASTM E1742 – Standard Practice for Radiographic Examination

ASTM E2371 – Standard Test Method for Analysis of Titanium and Titanium Alloys by Direct Current Plasma and Inductively Coupled Plasma Atomic Emission Spectrometry

ASTM E2465 – Standard Test Method for Analysis of Ni-Base Alloys by Wavelength Dispersive X-Ray Fluorescence Spectrometry

ASTM E2594 – Standard Test Method for Analysis of Nickel Alloys by Inductively Coupled Plasma Atomic Emission Spectrometry (Performance-Based Method)

ASTM E3061 – Standard Test Method for Analysis of Aluminum and Aluminum Alloys by Inductively Coupled Plasma Atomic Emission Spectrometry

ASTM E606/E606M – Standard Test Method for Strain-Controlled Fatigue Testing

ASTM F2924 – Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion

ASTM F3056 – Standard Specification for Additive Manufacturing Nickel Alloy with Powder Bed Fusion

ASTM F3122 – Standard Guide for Evaluating Mechanical properties of Metal Materials Made via Additive Manufacturing Processes

3.2. ISO Publications

ISO/ASTM 52900 – Standard Terminology for Additive Manufacturing

3.3. JPL Standards

D-106325 - Elementum Al6XRAM2 Feedstock Powder Specification for Laser Powder Bed Fusion Additive Manufacturing

D-106326-Heat Treatment for Al6061RAM2 Additively Manufactured QCI Parts

D-107777-Heat Treatment for UNS R56400 (Ti-6Al-4V) Additively Manufactured QCI Parts

D-107778-Titanium 6Al-4V ELI (Grade 23) Feedstock Powder Specification for Laser Powder Bed Fusion (L-PBF) Additive Manufacturing

3.4. NASA Standards

NASA-STD-6030 Additive Manufacturing Requirements for Spaceflight Systems

NASA-STD-6033 Additive Manufacturing Requirements for Equipment and Facility Control

3.5. NFPA Publications

NFPA 484 – Standard for Combustible Metals

3.6. SAE Publications

AMS 2750 – Pyrometry

4. General

All JPL requirements and specifications shall take precedence over manufacturer recommendations and supplier processes. Supplier processes should be in accordance with the machine manufacturer's machine recommendations. If manufacturer's recommendations are unavailable, the supplier will be responsible for establishing processes to meet requirements. In regards to requirements listed in the contract and the drawing, the contract will always supersede the drawing. Supplementary specifications or standards that are required in addition to this standard will be referenced in the drawing or contract. If the supplier is not capable of meeting one or more requirements in this document, they will need to request a deviation prior to accepting the work.

5. Material Process Control

5.1. Material Process Record

The supplier shall manufacture JPL parts using a material process record approved by JPL consistent with the requirements provided in subsequent sections of this document.

The material process record shall, at minimum, address the following:

- Control of powder feedstock
- Definition of fixed, key process variables of known influence on the AM build process for any given AM machine.
- Control of secondary processing if applicable

The material process record shall be controlled by the supplier's Quality Management System (QMS), configuration controlled, and require JPL approval of initial release and all changes.

5.2. Material Properties

All required material properties needed to substantiate the manufacturability of the design shall be documented prior to beginning production of JPL flight parts. Material properties may be documented via JPL provided Material Property Suite (MPS) or other documentation approved by JPL Materials and Processes (M&P).

Supplier shall provide evidence, supported through the use of statistics, for material that they are certifying to meet mechanical properties. Mechanical properties may consist of, but not limited, to the following:

- Tensile
- Compression

- Flexural
- Stress Rupture / Creep
- Fatigue
- Fracture Toughness

6. Powder

6.1. General Powder Requirements for Supplier and Powder Manufacturer

6.1.1. Powder Quality

The powder shall be uniform in color and quality, dry, and free from agglomerated masses, foreign materials, and imperfections detrimental to its performance.

6.1.2. Powder Sampling

Unless otherwise stated by JPL, all powder sample collecting shall be performed in accordance with ASTM B215.

6.1.2.1. Particle Size Distribution

If required on the contract, particle size distribution testing shall be performed in accordance with ASTM B214.

6.1.2.2. Powder Composition

Powder chemical composition results shall conform to the material specification that is listed in the contract or drawing, see Section 6.2.1 and 11.2.

If material specification is not provided in the contract or drawing, reference Appendix 1.

6.1.2.3. Rheology

If required by contract, the rheology measurement shall be delivered with the shipment. Rheology measurement methods include hall flowmeters, used in accordance with ASTM B213, and Revolution Powder Analyzers. Additional methods may also be used if approved on the contract.

6.1.3. Powder Identification

All material containers used for production shall have identification that includes, at a minimum:

- Manufacturer identification

- Purchase order number
- Production method
- Material type and grade
- Lot number
- Manufacturing date

6.1.4. Storage and Handling

Supplier shall have a process that ensures the powder is stored in a sealed moisture resistant container that permits long term storage without affecting its characteristics or properties.

The supplier and powder manufacturer shall have documented processes in place to address possible moisture contamination and prevention of electro static discharge (ESD) during storage and handling.

Any powder found in damaged packages, potentially allowing exposure to the outside environment, or that has been wet, shall be segregated and properly disposed of.

Suppliers shall have a documented process for feedstock disposal in accordance with the material manufacturer's instructions for cleanup and disposal.

Documentation of the safe processing and storage of reactive materials, such as titanium or aluminum, shall be maintained to prevent accidental ignition.

Proper PPE shall be used for handling the reactive materials per safety data sheets (SDS) and other regulating bodies. See NFPA 484 for further reactive material handling information.

Identification and traceability of the powder shall be maintained throughout the transferring of packages. The supplier should have a documented process to minimize the time that unused powder is exposed to open air in order to reduce possible contamination of the stored powders.

The supplier shall have a documented process for the control of opened, partially used feedstock containers including documenting the individual responsible for controlling access to powders and tracking usage.

6.2. Powder Manufacturer

Suppliers shall have a process to determine a powder manufacturer's ability to provide powder that meets all requirements of this standard and any other required by the supplier.

As a part of that process, the supplier shall ensure that the powder manufacturer maintains a documented process for:

- Procurement of raw material for powder
- Sampling and testing
- Identification
- Storage

6.2.1. Procurement of Raw Material for Powder

Procured raw material used to produce powder shall meet the compositional requirements specified in the contract or the engineering drawing.

A powder lot is defined as powder produced by a certified supplier in one production run, using the same process, equipment, and one type of powder.

Raw material not purchased directly from the manufacturer shall provide traceability all the way to the original manufacturer.

All procurements shall comply with the most current JPL Designated Countries List.

6.3. Supplier Powder Usage

6.3.1. Documentation Verification

Before releasing the powder for production, the supplier shall verify that the powder is in accordance with the powder specification indicated on the drawing.

6.3.2. Feedstock Conditioning

The supplier shall have a method for verifying if powder conditioning is required prior to loading feedstock into the PBF machine. Feedstock conditioning methods include, but are not limited to: sieving, filtering, mixing, and powder recovery.

6.3.3. Powder Reuse

Powder shall not be reused, unless approved on the contract.

6.3.4. Single Lot

A single powder lot shall be used for each build, unless approved by JPL.

6.3.5. Material Exclusivity

The supplier shall ensure that each AM machine using powder feedstock is dedicated to a single material family.

7. Machine

7.1. Machine Identification

The supplier shall maintain documented identification information on the machine.

The register shall include the equipment type, unique identification, location, and the calibration or verification method, calibration frequency, and acceptance criteria. It is acceptable to include the machines in the monitoring and measuring device register required by the quality management systems.

7.2. Environmental Parameters

The supplier shall ensure the machines' surrounding environment (temperature, humidity) does not affect the build environment within the machine during operation by documenting temperature and humidity measurements of the surrounding area during the build.

7.3. Machine Selection

All manufacturing requests for an individual JPL part shall be manufactured on the same qualified model of machine.

7.4. Machine Qualification

The supplier shall have a documented process for machine qualification.

AM machines shall have an active qualification status only when:

- The machine is documented to be in the calibrated state (Reference Section 7.6)
- The machine meets the supplier's acceptance criteria for proving the capability of each machine to meet specifications. The supplier's process should at minimum, test:
 - Print consistency between prints
 - Print consistency across build plate
 - Printing quality
 - Scale and Dimension
 - Geometric Validation
- The machine has no associated unresolved nonconformances.

- The machine maintains SPC specific to the material and material process record approved by JPL.

7.5. Machine Requalification

Requalification of the machine shall occur when there are, at minimum, changes in:

- Rastering strategy
- Melting device
- Power supply
- Software and firmware
- Location (Reference Section 7.2)

Software changes include any update of software that changes the build strategy (including laser path or tool path of the machine) and any update of software due to machine calibration or preventive maintenance.

Requalification of the machine shall be established by completing the following at minimum:

- Verify the event negating active qualification is resolved
- Verify the AM machine to be in a calibrated state
- Verify process control limit falls within control limit range established at time of initial qualification.
- Record all related events in the AM machine configuration log or similar record.

7.6. Machine Calibration

Machines and machine components shall be calibrated and/or verified at specified intervals against measurement standards traceable to international or national measurement standards.

When no such standards exist, the basis used for calibration or verification shall be retained as documented information.

The following machine specific calibrations will be in accordance with manufacturer's recommendations or supplier defined frequency ensuring the maximum calibration interval not to exceed 90 days for optical systems, 180 days for all other systems, or after any maintenance, repair, or replacement of any system, including but not limited to:

- Machine leveling
- Inert gas system
- Power supply
- Melting device
- Machine hardware (powder distribution mechanism, build plate lowering mechanism, etc.)
- Monitoring and measuring equipment (including in situ monitoring systems)
- Optical system

AM Machines shall be considered calibrated when all scheduled maintenance items are completed within their prescribed intervals, all calibration metrics are evaluated and verified to be within specification limits, and the associated maintenance and calibration records are documented.

If any calibration metric is not within specification limits, a nonconformance together with a potential product impact analysis shall be reported to JPL for all JPL parts produced since the last calibration.

7.7. Machine Operation

The supplier shall utilize detailed operational procedures and checklists for all AM machines and associated equipment to ensure facility operations are standardized to the fullest extent possible, to provide operators with a proactive method to ensure all procedural steps are completed, and to provide traceability to the relevant QMS documents and forms. See Section 8.3 for details regarding the pre-build checklist.

Prior to beginning production on an AM machine, the supplier shall assure hazard mitigation systems and ventilation needs/byproducts produced by AM equipment are consistent with OEM recommendations and all applicable environmental and safety standards.

7.8. Machine Maintenance

Suppliers shall follow a maintenance schedule for machines and ancillary equipment.

Maintenance records including what maintenance was performed, when it was performed, and technician identification shall be retained.

The replacement of any components listed in Section 7.6 shall result in requalification of the machine.

7.8.1. Preventative Maintenance

The supplier shall maintain a documented process for performing preventative maintenance and calibration of each of the following:

- Sintering Device Condition
- Powder Distribution System
- Heating Chamber Components
- Machine Hardware (filters, mechanical components, etc.)

7.8.2. Unplanned Maintenance

All unplanned maintenance shall be documented and the responsible personnel will make the determination whether the repairs require additional actions, such as a new pre-production article inspection, a machine calibration, etc.

If unplanned maintenance occurs during the manufacturing process of a JPL part, the supplier shall notify the JPL QA Representative.

7.9. Machine Cleaning

The supplier shall have a documented process for cleaning the machine and for evaluating cleanliness of the machine.

The machine shall be thoroughly cleaned in accordance to the manufacturer's recommendations. The cleaning should consist of decontaminating and removing all residual powder prior to introducing new material lots per the material exclusivity requirements of Section 6.3.5 or when thorough cleanouts associated with removing nonconforming lots or material changeover are required. For guidance regarding build chamber cleaning prior to each build, see Section 8.3.2.

7.9.1. Cleaning for Material Changes within the Same Family

The supplier shall have a documented process for the cleaning of machines following a change in material of the same family. Any cross contamination is strictly prohibited. Replace all components that interacted with the previous material.

7.10. Machine Configuration Management

A configuration management log for each AM machine used in the production of JPL parts where this document is imposed shall be controlled by the QMS and include, at a minimum, the following events:

- Maintenance, calibration, and qualification events
- Machine manufacturer service calls
- Repairs or other changes to machine
- Changes to associated computers used in production of files for printing (e.g. changes in computer-aided design and slicing software).
- Updates to software and firmware versions.

8. Build

8.1. Support Structure and Part Orientation

Support structure designs and part orientation shall be included in the pre-production article inspection.

Part orientation shall be approved by JPL upon review of the pre-production article inspection report.

If JPL furnishes a support structure and/or orientation in the part design, it shall be used in a build and included in the pre-production article inspection.

8.2. Build Configuration Management

All builds, build revisions, and build documents shall be controlled and retained as documented information.

8.3. Pre-Build Setup

The supplier shall have a pre-build checklist, checking and documenting each of the following:

8.3.1. Machine Qualification Status

The machine shall have an active qualification status. See section 7.4 for details regarding Machine Qualification.

8.3.2. Build Chamber Cleaning

The build chamber shall be cleaned before every build to remove residual powder and condensates from all accessible surfaces.

8.3.3. Build Plate

Build plate material shall be adequate to ensure the build of an acceptable part.

The build plate shall be visually inspected to check for surface damage and contamination. Before inserting the build plate into the machine, it must be free of oil, grease, burrs, and metallic chips.

The build plate shall be a level surface capable of being leveled to the recoating device.

8.3.4. Recoater Device

The recoater device shall be visually inspected to be free of chips, tears, or other signs of wear and then leveled prior to every build.

The recoater device material shall not contaminate the build while it is distributing the powder.

8.3.5. Build Environment

For each of the following resources required during the AM build process, the supplier shall

ensure the appropriate quantity and rating are available, and the levels are properly monitored and maintained for the entire duration of the build.

- Power
- Inert gas
- Chilled/cooling water
- Vacuum

8.3.6. Powder Loading

The supplier should maintain a documented process in accordance with manufacturer's recommendations on how to load powder into the machine.

8.4. Build Record

A data package referencing all build parameters that may affect part quality shall be retained as documented information.

Build parameters shall be consistent across qualification parts, pre-production articles, and production parts.

Suppliers shall notify JPL if build parameters change during the process.

JPL parts shall have their own build lot, not shared with any non-JPL parts. Witness coupons used by supplier for process monitoring may be included in the build with prior JPL approval.

All parameters monitored by the machine that may affect part quality shall be recorded throughout the build process. Machine monitored parameters include, but are not limited to:

- Oxygen levels
- Vacuum measurements (in EBM systems only)
- Build plate temperature

In addition to machine monitoring, build parameters include:

- Environmental parameters (See Section 7.2)
- Scan speed, pattern, and strategy
- Laser power
- Layer thickness

Any unplanned modifications to the build file on the machine during the AM process setup and/or execution shall be cause for nonconformance subject to JPL approval.

8.5. Process Interruptions

Process interruptions, defined as an unplanned pause or stoppage during the build that is outside the normal working operation of the machine, shall be cause for nonconformance subject to JPL approval.

The build record shall include evidence that there were no process interruptions.

All visual monitoring processes shall be in compliance with ITAR restrictions.

In case of a failed build, the supplier shall verify no powder depleted from the powder reservoir or supply is reused.

8.6. Contamination Control

Clothing, tools, or equipment used to handle powder and parts shall be clean and free of oil, loose particles, or debris that could contaminate the part.

9. Post-Processing

The supplier shall document the sequence of post-processing performed to JPL parts, including part removal from the build plate.

9.1. Part Separation

The supplier shall have a documented process for separating the part, support structures, and build plate.

9.2. Heat Treatment

Heat treatments, including stress relief, shall be performed in accordance with the specification on the drawing or contract.

Heat treat certifications shall include the following: furnace identification for the treatments performed, time, temperature, atmosphere profiles, and the location of any load thermocouples used during the heat treatment.

The supplier shall provide furnace temperature charts.

9.2.1. Hot Isostatic Pressing (HIP)

If parts require HIP, it shall be performed in accordance with the specification on the drawing or contract.

HIP certifications shall include the part and thermocouple location in the vessel, as well as temperature and gas profiles for each process performed for a given part.

If required by the contract, the HIP cycle shall only include JPL parts.

10. Inspection

10.1. Source Inspection

If source inspection is required by the contract, the supplier shall be responsible for all JPL contractual source inspections and must plan for these inspections accordingly.

10.2. Visual Inspection

Visual inspection shall be performed prior to and after post-processing. Visual inspection of final parts is to be performed using normal or corrected-to-normal vision under ambient light.

The visual inspection shall look for visual evidence of a failed print, cracks, and any deviation from the drawing.

10.3. Dimensional Inspection

Dimensional inspection shall be performed before and after post-processing to verify the part meets specified dimensions, geometry, and tolerances as specified in the drawing.

11. Testing

11.1. Mechanical Testing

If required by contract, suppliers shall perform mechanical testing in accordance with the respective standard shown in Table 1.

Test records shall include actual test values and standard used.

Test coupons shall be from the same build and powder as the parts.

Any additional tests required by JPL shall be in accordance with standards specified in ASTM F3122.

Table 1. Mechanical Testing Requirements

Test	Required Standard
Tensile	ASTM E8/E8M
Compression	ASTM E9
Fatigue	ASTM E606/E606M or ASTM E466
Fracture Toughness	ASTM E1820

11.2. Chemical Composition

If required by contract, the supplier shall perform chemical composition testing on the as-built parts in accordance with the appropriate test standard from Appendix 2.

Results shall meet the compositional requirements for the material as specified in the contract or drawing.

In the case where the compositional requirements differ between the drawing and the contract, the contract requirements supersede the drawing.

11.3. Radiographic Inspection

If required by contract, radiographic examination shall be performed in accordance with ASTM E1742, Sensitivity 2-2T.

11.4. Density

If required by contract, part density shall be measured in accordance with ASTM B311.

11.5. Surface Finish

If required by contract, surface finish procedures shall be in accordance with ASTM B946.

12. Rework and Repair

If repair is required, the supplier shall obtain written JPL approval.

If rework is required, the supplier shall report the rework to JPL.

The supplier shall not perform rework that involves deforming or straining a part in order to meet requirements.

13. Packaging, Handling, and Shipping

The supplier shall maintain a documented process for packaging, handling, and shipping the final part to JPL. The packaging shall include:

- Identification of the part
- Purchase order number
- Part number
- Quantity

14. Traceability

A certificate of conformance (CoC) shall be a prerequisite for acceptance of the part by JPL.

Traceability shall be provided back to the powder lot.

JPL parts and coupons shall be traceable throughout the manufacturing process with a minimum of:

- Engineering Drawing / Revision Number
- Production Order / Batch Number
- Serial Build Cycle
- Part Serialization / Manufacturer's Control Number
- Machine Process Number

The identification of the witness coupons shall be traceable to their location and orientation within the build volume per ASTM F2971, if not defined otherwise on contract.

The part and witness coupons shall be adequately marked such that they maintain their identity following removal from the build plate.

15. Data Sensitivity

Treat AM computer systems and related devices that are associated with any aspect of the AM part design and build process of JPL parts as operational IT systems, whose cybersecurity risk shall be characterized, controlled, assessed, and monitored throughout its life cycle.

Digital records considered to be part of the production engineering record shall be retained in accordance with the contract or supplier's QMS requirements. Any AM related data identified as sensitive on the contract will require special attention as directed on the contract.

All files necessary to reproduce fully all aspects of the part design, preparation for the build, and the build and post-build processes for JPL AM parts shall be subject to full version control.

16. Operator Training

AM operations, defined in the context of this section 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 AM machine, shall only be performed by operators with applicable training competencies traceable via a records management system controlled by the QMS and to minimum training requirements defined by the machine's OEM.

The supplier shall define, maintain, and implement an active operator training program to meet the following objectives:

- Provide a consistent framework for training requirements.
- Provide clear delineations of abilities and responsibilities associated with proven competencies.
- Provide operators with all necessary skills, knowledge, and experience to safely and reliably execute the responsibilities of their role.
- Provide for operator evaluations that demonstrate adequacy in skills, knowledge, and experience, ensuring only properly trained and experienced personnel are granted appropriate competencies.
- Incorporate content regarding the importance, purpose, and use of the QMS.

17. Deliverable Matrix

If required, the following deliverables shall be included with the delivered parts (Table 2). Refer to the associated section within the standard for further details of the deliverable.

The supplier shall be responsible for obtaining all the deliverables and flowing down the requirements to the mill and powder manufacturer.

Table 2. Deliverable Matrix

Deliverable Type	Section	Deliverable
Powder Test Results	6.1.2.1	Particle Size Distribution Measurements
	6.1.2.2	Powder Chemical Composition Measurements
	6.1.2.3	Rheology Measurements
Part Test Results	11.1	Mechanical Testing Results
	11.2	As-built Parts Chemical Composition Results
	11.3	Radiographic Inspection Results
	11.4	Density Measurements
	11.5	Surface Finish Measurements
Certificates of Conformance (CoC)	6	Powder CoC
	9.2	Heat Treat CoC

	9.2.1	HIP CoC
	14	Part CoC
Inspection Report	10	Inspection Reports
Build Record	8.4	Build Record

18. Records Retention Matrix

The supplier shall retain the following records and be prepared to provide these records upon request. Refer to the associated section within the standard for further details of the records.

Table 3. Record Retention Matrix

Deliverable Type	Section	Record
Machine Records	7.4	Machine Qualification Records
	7.6	Machine Calibration Records
	7.8	Machine Maintenance Records
Machine Operational Documentation	8.3	Pre-build Checklist
	7.7	Machine Operational Procedures
	7.9	Machine Cleaning Procedures

19. Appendixes

19.1. Appendix 1. Material Composition Standards

Material	Reference Standard
Ti-6Al-4V	ASTM F2924
Inconel 625	ASTM F3056 or AMS 7000
Inconel 718	ASTM F3055
AlSi10Mg	ASTM F3318

19.2. Appendix 2. Material Composition and Elemental Analysis Methods

Material	Element	Analysis Method
Titanium Alloys	Composition	ASTM E539 or ASTM E2371
	Carbon	ASTM E1941
	Hydrogen	ASTM E1447
	Oxygen, Nitrogen	ASTM E1409
Nickel Alloys	Composition	ASTM E1473, ASTM E1019, or ASTM E1941
	Carbon, Sulfur, Nitrogen, Oxygen	ASTM E1019
	Other Elements	ASTM E354
Aluminum Alloys	Composition	ASTM E1479 or ASTM 3061

19.3. Appendix 3. Requirement Matrix

This matrix summarizes all requirements in this document.

In case of conflicting requirements, requirements within the purchasing document and the drawing supersede requirements within this document.

Section	Description	Requirement
2	Applicability	This document includes the minimum requirements needed for production of additively manufactured parts. Supplier shall see the contract and/or drawing for any additional applicable requirements.
4	Requirement / Specification Precedence	All JPL requirements and specifications shall take precedence over manufacturer recommendations and supplier processes.
5.1	Material Process Record	The supplier shall manufacture JPL parts using a material process record approved by JPL consistent with the requirements provided in subsequent sections of this document.
5.1	Material Process Record Contents	The material process record shall, at minimum, address the following: <ul style="list-style-type: none"> - Control of powder feedstock - Definition of fixed, key process variables of known influence on the AM build process for any given AM machine. - Control of secondary processing if applicable
5.1	Material Process Record Control	The material process record shall be controlled by the supplier's QMS, configuration controlled, and require JPL approval of initial release and all changes.
5.2	Material Properties	All required material properties needed to substantiate the manufacturability of the design shall be documented prior to beginning production of JPL flight parts.
5.2	Evidence of Mechanical Properties	Supplier shall provide evidence, supported through the use of statistics, for material that they are certifying to meet mechanical properties. Mechanical properties may consist of, but not limited, to the following: <ul style="list-style-type: none"> - Tensile - Compression - Flexural - Stress Rupture / Creep - Fatigue - Fracture Toughness
6.1.1	Powder Quality	The powder shall be uniform in color and quality, dry, and free from agglomerated masses, foreign materials, and imperfections detrimental to its performance.
6.1.2	Powder Sampling	Unless otherwise stated by JPL, all powder sample collecting shall be performed in accordance with ASTM B215.
6.1.2.1	Particle Size Distribution	If required on the contract, particle size distribution testing shall be performed in accordance with ASTM B214.
6.1.2.2	Chemical Composition	Powder chemical composition results shall conform to the material specification that is listed in the contract or drawing, see Section 6.2.1 and 11.2.
6.1.2.3	Rheology	If required by contract, the rheology measurement shall be delivered with the shipment. Rheology measurement methods include hall flowmeters, used in accordance with ASTM B213, and Revolution Powder Analyzers.
6.1.3	Powder Identification	All material containers used for production shall have identification that includes, at a minimum: <ul style="list-style-type: none"> - Manufacturer identification - Purchase order number

Section	Description	Requirement
		<ul style="list-style-type: none"> - Production method - Material type and grade - Lot number - Manufacturing date
6.1.4	Powder Container	Supplier shall have a process that ensures the powder is stored in a sealed moisture resistant container that permits long term storage without affecting its characteristics or properties.
6.1.4	Powder Moisture and ESD Prevention	The supplier and powder manufacturer shall have documented processes in place to address possible moisture contamination and prevention of electro static discharge (ESD) during storage and handling.
6.1.4	Wet Powder Disposal	Any powder found in damaged packages or that has been wet, shall be segregated and properly disposed of.
6.1.4	Powder Disposal Process	Suppliers shall have a documented process for feedstock disposal in accordance with the material manufacturer's instructions for cleanup and disposal.
6.1.4	Safe Processing and Storage Documentation	Documentation of the safe processing and storage of reactive materials, such as titanium or aluminum, shall be maintained to prevent accidental ignition.
6.1.4	PPE for Reactive Materials	Proper PPE shall be used for handling the reactive materials per safety data sheets (SDS) and other regulating bodies. See NFPA 484 for further reactive material handling information.
6.1.4	Identification and Traceability	Identification and traceability of the powder shall be maintained throughout the transferring of packages. The supplier should have a documented process to minimize the time that unused powder is exposed to open air in order to reduce possible contamination of the stored powders.
6.1.4	Control of Opened Powder Containers	The supplier shall have a documented process for the control of opened, partially used feedstock containers including documenting the individual responsible for controlling access to powders and tracking usage.
6.2	Powder Manufacturer Requirements	Suppliers shall have a process to determine a powder manufacturer's ability to provide powder that meets all requirements of this standard and any other required by the supplier.
6.2	Powder Manufacturer Requirements Verification Process	As part of that process, the supplier should ensure that the powder manufacturer maintains a documented process for: <ul style="list-style-type: none"> - Procurement of raw material for powder - Sampling and testing - Identification - Storage
6.2.1	Powder Compositional Requirements	Procured raw material used to produce powder shall meet the compositional requirements specified in the contract or the engineering drawing.
6.2.1	Material Traceability	Raw material not purchased directly from the manufacturer shall provide traceability all the way to the original manufacturer.
6.2.1	Procurements	All procurements shall comply with the most current JPL Designated Countries List.
6.3.1	Powder Verification	Before releasing the powder for production, the supplier shall verify that the powder is in accordance with the powder specification indicated on the drawing.
6.3.2	Feedstock Conditioning	The supplier shall have a method for verifying if powder conditioning is required prior to loading feedstock into the PBF machine.
6.3.3	Powder Reuse	Powder shall not be reused, unless approved on the contract.
6.3.4	Single Powder Lot	A single powder lot shall be used for each build, unless approved by JPL.

Section	Description	Requirement
6.3.5	Single Material Family	The supplier shall ensure that each AM machine using powder feedstock is dedicated to a single material family.
7.1	Machine Identification	The supplier shall maintain documented identification information on the machine.
7.1	Machine Register	The register shall include the equipment type, unique identification, location, and the calibration or verification method, calibration frequency, and acceptance criteria.
7.2	Machine Environment	The supplier shall ensure the machines' surrounding environment (temperature, humidity) does not affect the build environment within the machine during operation by documenting temperature and humidity measurements of the surrounding area during the build.
7.3	Machine Consistency	All manufacturing requests for an individual JPL part shall be manufactured on the same qualified model of machine.
7.4	Machine Qualification Process	The supplier shall have a documented process for machine qualification.
7.4	Machine Qualification Requirements	<p>AM machines shall have an active qualification status only when:</p> <ul style="list-style-type: none"> - The machine is documented to be in the calibrated state (Reference Section 7.6) - The machine meets the supplier's acceptance criteria for proving the capability of each machine to meet specifications. The supplier's process should at minimum, test: <ul style="list-style-type: none"> - Print consistency between prints - Print consistency across build plate - Printing quality - Scale and Dimension - Geometric Validation - The machine has no associated unresolved nonconformances. - The machine maintains SPC specific to the material and material process record approved by JPL.
7.5	Machine Requalification Events	<p>Requalification of the machine shall occur when there are, at minimum, changes in:</p> <ul style="list-style-type: none"> - Rastering strategy - Melting device - Power supply - Software and firmware - Location (Reference Section 7.1)
7.5	Machine Requalification Process	<p>Requalification of the machine shall be established by completing the following at minimum:</p> <ul style="list-style-type: none"> - Verify the event negating active qualification is resolved - Verify the AM machine to be in a calibrated state - Verify process control limit falls within control limit range established at time of initial qualification. - Record all related events in the AM machine configuration log or similar record.
7.6	Machine Calibration Standards	Machines and machine components shall be calibrated and/or verified at specified intervals against measurement standards traceable to international or national measurement standards.
7.6	Machine Calibration Standards	When no such standards exist, the basis used for calibration or verification shall be retained as documented information.
7.6	Machine Calibration Status	AM Machines shall be considered calibrated when all scheduled maintenance items are completed within their prescribed intervals, all calibration metrics are evaluated and verified to be within specification limits, and the associated maintenance and calibration records are documented.

Section	Description	Requirement
7.6	Machine Calibration Nonconformance	If any calibration metric is not within specification limits, a nonconformance together with a potential product impact analysis shall be reported to JPL for all JPL parts produced since the last calibration.
7.7	Facility Operational Procedures and Checklists	The supplier shall utilize detailed operational procedures and checklists for all AM machines and associated equipment to ensure facility operations are standardized to the fullest extent possible, to provide operators with a proactive method to ensure all procedural steps are completed, and to provide traceability to the relevant QMS documents and forms.
7.7	Hazard Mitigation	Prior to beginning production on an AM machine, the supplier shall assure hazard mitigation systems and ventilation needs/byproducts produced by AM equipment are consistent with OEM recommendations and all applicable environmental and safety standards.
7.8	Maintenance Schedule	Suppliers shall follow a maintenance schedule for machines and ancillary equipment
7.8	Maintenance Records	Maintenance records including what maintenance was performed, when it was performed, and technician identification shall be retained.
7.8	Machine Component Replacement	The replacement of any components listed in Section 7.6 shall result in requalification of the machine.
7.8.1	Preventative Maintenance and Calibration	The supplier shall maintain a documented process for performing preventative maintenance and calibration of each of the following: <ul style="list-style-type: none"> - Sintering Device Condition - Powder Distribution System - Heating Chamber Components - Machine Hardware (filters, mechanical components, etc.)
7.8.2	Unplanned Maintenance	All unplanned maintenance shall be documented and the responsible personnel will make the determination whether the repairs require additional actions, such as a new pre-production article inspection, a machine calibration, etc.
7.8.2	Unplanned Maintenance during Manufacturing	If unplanned maintenance occurs during the manufacturing process of a JPL part, the supplier shall notify the JPL QA Representative.
7.9	Machine Cleaning and Cleanliness Evaluation	The supplier shall have a documented process for cleaning the machine and for evaluating cleanliness of the machine.
7.9	Machine Cleaning Recommendations	The machine shall be thoroughly cleaned in accordance to the manufacturer's recommendations.
7.9.1	Cleaning following Material Change	The supplier shall have a documented process for the cleaning of machines following a change in material of the same family.
7.10	Machine Configuration Management	A configuration management log for each AM machine used in the production of JPL parts where this document is imposed shall be controlled by the QMS and include, at a minimum, the following events: <ul style="list-style-type: none"> - Maintenance, calibration, and qualification events - Machine manufacturer service calls - Repairs or other changes to machine - Changes to associated computers used in production of files for printing (e.g., changes in computer-aided design and slicing software). - Updates to software and firmware versions.
8.1	Pre-production Article Inspection	Support structure designs and part orientation shall be included in the pre-production article inspection

Section	Description	Requirement
8.1	Part Orientation Approval	Part orientation shall be approved by JPL upon review of the pre-production article inspection report.
8.1	JPL Provided Support Structure / Part Orientation	If JPL furnishes a support structure and/or orientation in the part design, it shall be used in a build and included in the pre-production article inspection.
8.2	Build Configuration Management	All builds, build revisions, and build documents shall be controlled and retained as documented information.
8.3	Pre-Build Checklist	The supplier shall have a pre-build checklist, checking and documenting each of the following: (See subsections 8.3.1-8.3.6)
8.3.1	Machine Active Qualification Status	The machine shall have an active qualification status. See section 7.4 for details regarding Machine Qualification.
8.3.2	Build Chamber Cleaning	The build chamber shall be cleaned before every build to remove residual powder and condensates from all accessible surfaces.
8.3.3	Build Plate Material	Build plate material shall be adequate to ensure the build of an acceptable part.
8.3.3	Build Plate Visual Inspection	The build plate shall be visually inspected to check for surface damage and contamination.
8.3.3	Level Build Plate	The build plate shall be a level surface capable of being leveled to the recoating device.
8.3.4	Recoater Device Visual Inspection	The recoater device shall be visually inspected to be free of chips, tears, or other signs of wear and then leveled prior to every build.
8.3.4	Recoater Device Contamination	The recoater device material shall not contaminate the build while it is distributing the powder.
8.3.5	Available Resources	For each of the following resources required during the AM build process, the supplier shall ensure the appropriate quantity and rating are available, and the levels are properly monitored and maintained for the entire duration of the build. <ul style="list-style-type: none"> - Power - Inert Gas - Chilled/Cooling Water - Vacuum
8.4	Build Record	A data package referencing all build parameters that may affect part quality shall be retained as documented information.
8.4	Build Parameters	Build parameters shall be consistent across qualification parts, pre-production articles, and production parts.
8.4	Build Parameter Changes	Suppliers shall notify JPL if build parameters change during the process.
8.4	Build Lot	JPL parts shall have their own build lot, not shared with any non-JPL parts.
8.4	Machine Monitored Parameters	All parameters monitored by the machine that may affect part quality shall be recorded throughout the build process.
8.4	Build File Modifications	Any unplanned modifications to the build file on the machine during the AM process setup and/or execution shall be cause for nonconformance subject to JPL approval.
8.5	Process Interruptions	Process interruptions, defined as an unplanned pause or stoppage during the build that is outside the normal working operation of the machine, shall be cause for nonconformance subject to JPL approval.

Section	Description	Requirement
8.5	Evidence of No Process Interruptions	The build record shall include evidence that there were no process interruptions.
8.5	Visual Monitoring Systems	All visual monitoring processes shall be in compliance with ITAR restrictions.
8.5	Failed Builds	In case of a failed build, the supplier shall verify no powder depleted from the powder reservoir or supply is reused.
8.6	Contamination Control	Clothing, tools, or equipment used to handle powder and parts shall be clean and free of oil, loose particles, or debris that could contaminate the part.
9	Post Processing Documentation	The supplier shall document the sequence of post-processing performed to JPL parts, including part removal from the build plate.
9.1	Part Separation Process	The supplier shall have a documented process for separating the part, support structures, and build plate.
9.2	Heat Treatments	Heat treatments, including stress relief, shall be performed in accordance with the specification on the drawing or contract.
9.2	Heat Treat Certifications	Heat treat certifications shall include the following: furnace identification for the treatments performed, time, temperature, atmosphere profiles, and the location of any load thermocouples used during the heat treatment.
9.2	Furnace Temperature Charts	The supplier shall provide furnace temperature charts.
9.2.1	HIP Specification	If parts require HIP, it shall be performed in accordance with the specification on the drawing or contract.
9.2.1	HIP Certifications	HIP certifications shall include the part and thermocouple location in the vessel, as well as temperature and gas profiles for each process performed for a given part.
9.2.1	HIP Cycle	If required by the contract, the HIP cycle shall only include JPL parts.
10.1	Source Inspection	If source inspection is required by the contract, the supplier shall be responsible for all JPL contractual source inspections and must plan for these inspections accordingly.
10.2	Visual Inspection	Visual inspection shall be performed prior to and after post-processing. Visual inspection of final parts is to be performed either under normal or corrected-to-normal vision under ambient light.
10.2	Visual Inspection	The visual inspection shall look for visual evidence of a failed print, cracks, and any deviation from the drawing.
10.3	Dimensional Inspection	Dimensional inspection shall be performed before and after post-processing to verify the part meets specified dimensions, geometry, and tolerances as specified in the drawing.
11.1	Mechanical Testing	If required by contract, suppliers shall perform mechanical testing in accordance with the respective standard shown in Table 1.
11.1	Test Records	Test records shall include actual test values and standard used.
11.1	Test Coupons	Test coupons shall be from the same build and powder as the parts.
11.1	Additional Testing	Any additional tests required by JPL shall be in accordance with standards specified in ASTM F3122.
11.2	Chemical Composition Testing	If required by contract, the supplier shall perform chemical composition testing on the as-built parts in accordance with the appropriate test standard from Appendix 2.
11.2	Compositional Requirements	Results shall meet the compositional requirements for the material as specified in the contract or drawing.

Section	Description	Requirement
11.3	Radiographic Examination	If required by contract, radiographic examination shall be performed in accordance with ASTM E1742, Sensitivity 2-2T.
11.4	Density	If required by contract, part density shall be measured in accordance with ASTM B311.
11.5	Surface Finish Procedures	If required by contract, surface finish procedures shall be in accordance with ASTM B946.
12	Repair	If repair is required, the supplier shall obtain written JPL approval.
12	Rework	If rework required, the supplier shall report the rework to JPL.
12	Prohibited Rework	The supplier shall not perform rework that involves deforming or straining a part in order to meet requirements.
13	Packaging, Handling, and Shipping Process	The supplier shall maintain a documented process for packaging, handling, and shipping the final part to JPL. The packaging shall include: <ul style="list-style-type: none"> - Identification of part - Purchase Order Number - Part Number - Quantity
14	Part CoC	A certificate of conformance (CoC) shall be a prerequisite for acceptance of the part by JPL.
14	Traceability	Traceability shall be provided back to the powder lot.
14	Parts and Coupons Traceability	JPL parts and coupons shall be traceable throughout the manufacturing process with a minimum of: <ul style="list-style-type: none"> - Engineering Drawing / Revision Number - Production Order / Batch Number - Serial Build Cycle - Part Serialization - Machine Process Number
14	Witness Coupon Traceability	The identification of the witness coupons shall be traceable to their location and orientation within the build volume per ASTM F2971, if not defined otherwise on contract.
14	Parts and Coupons Marking	The part and witness coupons shall be adequately marked such that they maintain their identity following removal from the build plate.
15	Cybersecurity	Treat AM computer systems and related devices that are associated with any aspect of the AM part design and build process of JPL parts as operational IT systems, whose cybersecurity risk shall be characterized, controlled, assessed, and monitored throughout its life cycle.
15	Records Retention	Digital records considered to be part of the production engineering record shall be retained in accordance with the contract or supplier's QMS requirements. Any AM related data identified as sensitive on the contract will require special attention as directed on the contract.
15	Electronic Files Version Control	All files necessary to reproduce fully all aspects of the part design, preparation for the build, and the build and post-build processes for JPL AM parts shall be subject to full version control.
16	Training Competencies	AM operations, defined in the context of this section 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 AM machine, shall only be performed by operators with applicable training competencies traceable via a records management system controlled by the QMS and to minimum training requirements defined by the machine's OEM.
16	Operator Training Program	The supplier shall define, maintain, and implement an active operator training program to meet the following objectives:

Section	Description	Requirement
		<ul style="list-style-type: none"> - Provide a consistent framework for training requirements. - Provide clear delineations of abilities and responsibilities associated with proven competencies. - Provide operators with all necessary skills, knowledge, and experience to safely and reliably execute the responsibilities of their role. - Provide for operator evaluations that demonstrate adequacy in skills, knowledge, and experience, ensuring only properly trained and experienced personnel are granted appropriate competencies. - Incorporate content regarding the importance, purpose, and use of the QMS.
17	Deliverable Matrix	If required, the following deliverables shall be included with the delivered parts (Table 2).
17	Deliverable & Requirement Flow-down	The supplier shall be responsible for obtaining all the deliverables and flowing down the requirements to the mill and powder manufacturer.
18	Records Retention Matrix	The supplier shall retain the following records and be prepared to provide these records upon request (Table 3).