

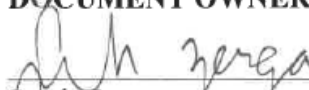
JPL D-101742

Supplier Quality Requirements for Powder Bed Additive Manufacturing

Initial Release

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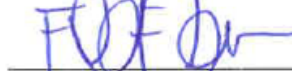


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Definitions

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 part's form after it has been built but before secondary processing

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

First Article Inspection (FAI) – 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 – Powder produced by a certified supplier in one production run, using the same process, equipment, and one type of powder

Manufacturing Plan – The supplier's plan to manufacture a JPL part, including all steps performed to the part from start to finish

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

Part Cake – The combination of sintered powder and part on the build plate after the part has finished building

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 additive manufacturing space-flight parts using powder bed fusion technologies. This document does not apply to any other additive manufacturing methods.

2. Applicability

This document applies to any suppliers who conduct activities involving additively manufacturing JPL flight parts using powder bed fusion technologies. A separate document will exist for internal production parts. For the purpose of this document, “supplier” refers to the subcontracted organization delivering additively manufactured parts to JPL. 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 the powder manufacturer, mill, and post-processing facilities.

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 – 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 – 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 52900 – Standard Terminology for Additive Manufacturing

3.3. MSFC Standard

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

3.4. NFPA Publications

NFPA 484 – Standard for Combustible Metals

3.5. 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. The supplier will maintain documented information of the machine manufacturer's recommendations. The supplier may establish their own processes that differ from manufacturer's recommendations, but justification and rationale may be required. 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, the drawing, and the Statement of Work (SOW), the contract will always supersede the drawing and the drawing will supersede the SOW. Supplementary specifications or standards that are required in addition to this standard will be referenced in the drawing, contract, or SOW.

5. Powder

5.1. General Powder Requirements for Supplier and Powder Manufacturer

5.1.1. 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.

5.1.2. Powder Sampling

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

5.1.2.1. Particle Size Distribution

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

5.1.2.2. Powder Composition

Powder chemical composition results shall conform to the material specification that is listed in the contract or drawing, see Section 5.2.1 and 10.2. In the case where the compositional requirements differ between the drawing and the contract, the contract shall supersede the drawing

5.1.2.3. 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.

5.1.3. Powder Identification

All material used for production, including raw material and powder, should have identification that includes, at a minimum:

- Manufacturer identification
- Purchase order number
- Production method
- Material type and grade
- Lot number

5.1.4. Storage

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. Supplier will use methods of reducing moisture inside the containers e.g. desiccant packs or inert gas.

The powder should be stored in a cool, dry area. The supplier and powder manufacturer should 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 or that has been wet shall be segregated and properly disposed of. See 6.2 for additional information on Environmental Parameters.

Documentation of the safe processing and storage of reactive materials, such as titanium or aluminum, shall be maintained to prevent accidental ignition and the proper PPE should be used for handling the reactive materials. See NFPA 484 for further reactive material handling information.

Identification and traceability of the powder should 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.

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

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

5.2.1. 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. In the case where the compositional requirements differ between the drawing and the contract, the contract requirements shall supersede the drawing. A powder lot shall be designated as powder produced by a certified supplier in one production run, using the same process, equipment, and one type of powder. In addition, all procurements shall comply with the most current JPL Designated Countries List.

5.3. Supplier Powder Requirements

5.3.1. Documentation Verification

Before releasing the powder for production, the supplier should verify that the powder is in accordance with the data provided in the CoC from the powder manufacturer. All powder verification should be retained as documented information.

5.3.2. Virgin Powder

All virgin powder should be conditioned by the supplier such that it is suitable for use in their manufacturing process, including but not limited to: sieving, filtering, mixing, and powder recovery, etc. If the conditioning procedure changes, the JPL purchaser must be notified.

5.4. Reuse

5.4.1. Powder Recovery

Powder shall not be reused, unless approved on the contract. Applicable methods of powder removal include, but are not limited to:

- Dry ultrasonic
- Wet ultrasonic
- Shaker tables
- Compressed air
- Vacuuming

5.4.2. Lot Mixing

Used powder may be refreshed with powder from additional powder lots of the same alloy produced by the same manufacturer and process (i.e. gas atomization using the same gas). Powder lot traceability shall reflect the mixed lots. If a single lot requirement is specified on the contract or drawing, all powder used shall be from the same lot. The requirements on the contract shall supersede the drawing. Higher grades of the alloy may be used to modify the presence of alloying elements e.g. oxygen. Higher grade powder shall meet the compositional requirements of the powder being refreshed. Refer to Appendix 3 for more information on Titanium powders.

5.4.3. Reused Powder Testing

All reused powder shall be tested before or concurrent to the part build to ensure the properties meet the requirements at the time of build. Testing should include powder composition, particle size distribution, and rheology measurements in accordance with, and acceptable to, virgin powder requirements. All test data should be retained as documented information. The supplier should also have a documented process for mixing powder that successfully meets the specifications and has uniform mixing of the powders.

6. Machine Requirements

6.1. Machine Identification

The organization shall maintain documented 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.

6.2. Environmental Parameters

The machine should be stored in a cool, dry area where temperature and humidity are controlled. The supplier should have a documented moisture prevention and ESD program, as stated in 5.1.4. Temperature and humidity measurements should be retained as documented information during the build.

6.3. Machine Selection

All manufacturing requests for an individual JPL part shall be manufactured on the same qualified model of machine. The supplier shall use the same model of machine to build the final part and the first article part.

6.4. Machine Qualification

The supplier shall have a procedure and acceptance criteria for proving the capability of each machine to meet specifications. The supplier's machine qualification process shall, at minimum, test:

- Print consistency between prints
- Print consistency across build plate
- Printing quality
- Scale and Dimension
- Geometric Validation

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 6.1)

Any update of software, both machine and slicing, that changes the build strategy, including laser path or tool path of the machine, shall result in requalification of the machine. Updates of software due to machine calibration or preventive maintenance require requalification of the machine.

6.5. 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:

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

Calibration or verification of monitoring and measuring equipment shall be carried out under suitable environmental conditions, and documented information shall be retained in accordance with the supplier's quality management system.

6.6. Machine Maintenance

All maintenance recommendations from the machine manufacturer should be performed. Suppliers shall retain maintenance records including what maintenance was performed, when it was performed, and technician identification. The replacement of any components directly associated with manufacturing a part shall result in recalibrations and requalification of the machine.

6.6.1. 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.)

6.6.2. Unplanned Maintenance

All unplanned maintenance shall be documented and the responsible personnel, including the supplier QA organization, shall make the determination whether the repairs require additional actions, such as a new FAI, a machine calibration, etc. If unplanned maintenance occurs during the manufacturing process of a JPL part, the supplier shall notify the JPL QA Representative.

6.7. Cleaning

The supplier shall have a documented process for cleaning the machine. The machine shall be thoroughly cleaned in accordance to the manufacturer's recommendations and the cleaning should consist of decontaminating and removing all residue powder from all accessible parts throughout the build chamber and filters. For build chamber cleaning prior to each build, see Section 7.3.1.

6.7.1. Cleaning for Material Changes

The supplier shall have a documented process for the cleaning of machines following a change in material. When switching materials, the supplier must clean the machine and replace all components that interacted with the previous material. Any cross-contamination is strictly prohibited.

7. Build

7.1. Support Structure and Part Orientation

Support structure designs and part orientation shall be included in the FAI. Part orientation shall be approved by JPL upon review of the FAI 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 FAI.

7.2. Build Configuration Management

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

7.3. Pre-Build Setup

The supplier shall have a pre-build checklist, checking and documenting each of the following, including but not limited to 7.3.1-7.3.5.

7.3.1. Build Chamber Cleaning

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

7.3.2. Build Plate

Build plate material shall be adequate to ensure the build of an acceptable part. Before inserting the build plate into the machine, it must be free of oil, grease, burrs, and metallic chips. It shall be visually inspected to check for surface damage and contamination. The build plate shall be a level surface capable of being leveled to the recoating device.

7.3.3. 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.

7.3.4. Build Atmosphere

For processes that rely on the use of inert gas, as required in the SOW, the supplier shall assure that there is a sufficient supply of gas for the entire duration of the build and that gas levels during the build do not fluctuate greatly. For processes that rely on vacuum, the supplier shall be able to monitor the vacuum the in same way.

7.3.5. Powder Loading

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

7.4. Build Record

A data package referencing all critical build parameters shall be retained as documented information. Build parameters shall be consistent across qualification parts, first articles, and final 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. All critical parameters monitored by the machine 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 6.2)
- Scan speed, pattern, and strategy
- Laser power
- Layer thickness

7.5. 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 shall include evidence that there was no process interruptions. All visual monitoring processes shall be in compliance with ITAR restrictions.

7.6. Part Handling

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. JPL parts must be handled with gloves at all times.

7.7. Part and Witness Coupon Identification

The part and witness coupons shall be identified by part number and serial number. The identification of the witness coupons shall be traceable to their individual build location and the supplier shall use the witness sample configuration provided or approved by JPL.

8. Secondary Processing

8.1. Part Separation

The supplier shall have a documented process for separating the part, support structures, and build plate. The manufacturing plan shall state the sequence of post processes and part removal from the build plate.

8.2. Heat Treatment

Heat treatments, including stress relief, shall be performed in accordance with the specification on the drawing or SOW. 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. When furnace cooling rates are specified in the contract or the drawing, the supplier shall provide temperature charts.

8.2.1. Hot Isostatic Pressing (HIP)

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.

9. Inspection

9.1. 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.

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

9.3. Dimensional Inspection

Dimensional inspection should be performed prior to post-processing to verify the part meets specified dimensions, geometry, and tolerances. The final, post-processed part shall meet the dimensions and tolerances as specified in the drawing. The supplier shall not perform rework that involves deforming or straining a part in order to meet dimensional requirements.

10. Testing

10.1. Mechanical Testing

If required by contract, suppliers shall perform the following mechanical testing, in accordance with the respective standard (Table 1). Test records shall include actual test values and standard used and 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
Compression	ASTM E9
Fatigue	ASTM E606

10.2. 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 shall supersede the drawing.

10.3. Radiographic Inspection

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

10.4. Density

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

10.5. Surface Finish

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

11. 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

12. Traceability

Traceability shall be provided back to the raw material 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

13. 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

Deliverables Matrix			
Deliverable	Section	Type of Document	Notes
Particle Size distribution measurements	5.1.2.1	Test Results	If required by contract
Powder Chemical Composition	5.1.2.2	Test Results	Powder Composition results from pre-build
Rheology measurements	5.1.2.3	Test Results	If required by contract
Single Powder Lot	5.4.2	CoC	If required by contract or drawing. Contract supersedes drawing
Part Orientation and Support Structure	7.1	FAI Report	Approval required on FAI Report
Final Part Orientation and Support Structure	7.1	Build Report	
Pre-build Checklist	7.3	Pre-build Checklist	Including but not limited to 7.3.1 - 7.3.5
Critical Parameters from build	7.4	Build Report	Critical parameters listed in standard (environmental and machine)
Part and Witness Coupon Identification	7.7	Build Report	Traceability to individual build location required
Heat treat Certifications	8.2	CoC	See standard for required information
HIP Certifications	8.2.1	CoC	See standard for required information
Visual Inspection	9.2	Inspection Report	Prior to and after post-processing
Dimensional Inspection	9.3	Inspection Report	Should be performed prior to post-processing and shall be performed after post-processing
Mechanical Testing	10.1	Test Results	If required by contract. Test records including actual test values and standard used
Chemical Composition on as-built parts	10.2	Test Results	Shall meet the requirements in the contract and/or drawing
Radiographic Inspection	10.3	Test Results	If required by contract. ASTM E1742, Sensitivity 2-2T
Density	10.4	Test Results	In accordance with ASTM B311, if required by contract
Surface Finish	10.5	Test Results	In accordance with ASTM B946, if required by contract

14. Appendixes

Appendix 1. Material Composition Standards

Material	Reference Standard
Ti-6Al-4V	ASTM F2924
Inconel	ASTM F3056

Appendix 2. Elemental Analysis Methods

Element	Analysis Method
Carbon	ASTM E1409
Hydrogen	ASTM E1447
Nitrogen	ASTM E1409
Oxygen	ASTM E1409
Titanium alloys	ASTM E539 and E2371
Aluminum alloys	ASTM E3061
Nickel based alloys	ASTM E2594 and E2465

Appendix 3. Extra Low Interstitial Grade 23

Mixing Grade 5 with Grade 23 Extra Low Interstitial (ELI) version of Ti6Al4V is permitted to maintain an oxygen level below the specification limit. The powder manufacturer and the powder production process shall be the same as the original powder lot. ELI powder shall go through the same process and requirements stated in this document as that of non-ELI powder. If ELI powder is mixed, the supplier shall include appropriate documentation for the powder.

Appendix 4. Requirement Tailoring Matrix

This matrix will be used as a tool to summarize the tailorable requirements of this document that will be indicated on the contract, drawing, or SOW (Table 2). The contract shall supersede the drawing, and the drawing shall supersede the SOW. Requirements that are not dependent on the contract, drawing, or SOW are not included in this matrix.

Table 3. Requirement Tailoring Matrix

Requirement Tailoring Matrix				
Requirement	Section	Contract	Drawing	SOW
1 Powder sampling will follow ASTM B215	5.1.2	X		
2 Particle size distribution (following ASTM B214)	5.1.2.1	X		
3 Powder composition match material spec	5.1.2.2	X		
4 Rheology measurements	5.1.2.3	X		
5 Raw material for powder composition	5.2.1	X	X	
6 Powder reusal not allowed	5.4.1	X		
7 Single lot requirement	5.4.2	X	X	
8 JPL support structure and/or orientation	7.1		X	
9 Process relying on use of inert gas	7.3.4			X
10 Heat treatments specification (including stress relief)	8.2		X	X
11 HIP cycle of only JPL parts	8.2.1	X		
12 Source inspection	9.1	X		
13 Mechanical Testing	10.1	X		
14 Chemical composition testing	10.2	X		
15 Radiographic Inspection	10.3	X		
16 Density	10.4	X		
17 Surface Finish	10.5	X		