

Engineering Considerations for Powder Bed Fusion Additively Manufactured Parts

This document does not provide guidance for the certification of an AM part. The engineering considerations in this document are a good starting point for a certification discussion with an applicant that may be documented in an Issue Paper (IP). The contents of this document are taken from R. Grant, Engineering Considerations for Powder Bed Fusion Additively Manufactured Parts, FAA General Memorandum AIR100-16-130-GM18 (July 7, 2016).

1. **Definitions.**

Additive Manufacturing: Describes the process of joining materials to make objects from three dimensional (3D) model data using layer upon layer technique/method, as opposed to subtractive manufacturing methodologies.

Build: A complete operation of the powder build fusion process to create objects, including parts as defined in the 3D build model. It is common for multiple parts, witness specimens, etc. to be produced in a single build.

Build area: The area of the build platform where the fusion process is qualified to produce parts. This area may be less than the full capability of the powder bed fusion (PBF) machine.

Build chamber: The volume in which parts may be produced in the powder bed. This volume is defined as the build platform area and maximum height off the build platform.

Build platform: A flat plate upon which the parts are built.

Powder bed fusion (PBF): An additive manufacturing process that uses a high-energy source (e.g., laser or electron beam) to selectively fuse, layer by layer, portions of a powder bed.

Powder blending: The process of combining powders, of the same nominal composition, originating from more than one heat or more than one lot of powder.

Powder Heat: The product of one vacuum melt cycle and gas atomization run.

Process specification: The applicants' process specification that controls the manufacturing of an AM part, including the PBF machine process parameter settings. In some cases, the parameter values may be defined in a separate document (e.g., Technical Plan or Process Control Document).

Powder recycling (or reuse): The use of powder in a build that has been exposed to one or more previous builds in a powder bed fusion machine.

Significant process: A process that, if changed, could affect physical, mechanical, metallurgical, or chemical properties.

Support structure: Is built with the part to provide dimensional stability to overhung surfaces and to transfer heat away from the part as new layers are added.

2. **General Description.** To assess an applicant's proposal to use a PBF process to manufacture parts, a general understanding of the PBF process is necessary. An illustration of the PBF method is provided below. In general, the feedstock powder is loaded in a hopper. The build chamber is pre-heated to a pre-determined temperature depending on the process, around 100°C for laser based PBF systems and 700-1100°C for the electron beam (e-beam) based PBF systems. A recoater blade sweeps a thin layer of powder over the build platform with the excess swept into an overflow hopper. A directed energy source, such as a laser or e-beam, is used to selectively fuse portions of the powder bed (based on the 3-D model of the build) to the build platform. Once a layer is complete, the build platform is lowered and a fresh layer is swept over the build platform by the recoater blade and that layer is fused by the energy source to the previous layer. This process is repeated layer after layer until the final part is fully formed. The build chamber is fully enclosed to control the build environment and to draw off any volatiles which the process may generate that could contaminate the final part.

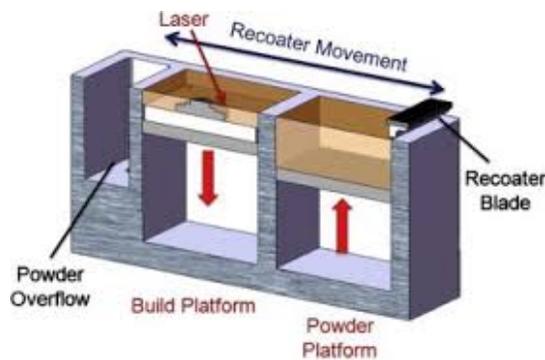


Illustration of Powder Bed Fusion Process

Support structures may be used to help transfer heat away from the part as new layers are added, and to help support the part's shape as it is being formed layer by layer. These supports are machined away once the part is built. In the example illustration below, the orientation of the part does not coincide with the build platform. The part's orientation to the build platform may have an affect on the material properties of the final part.

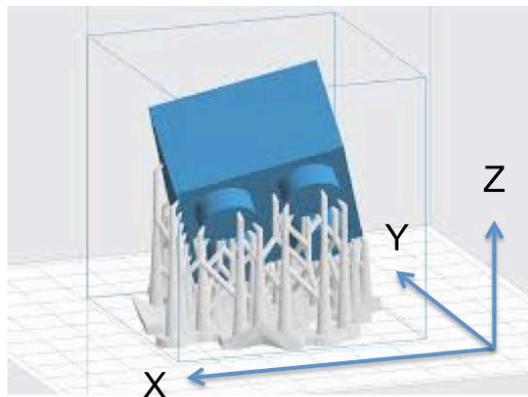


Illustration of a PBF part (blue) and Support Structure (white) on the Build Platform

3. **Component Design Considerations.** Components manufactured using PBF require unique considerations not typically pertinent when using traditional manufacturing techniques. For example, layer-by-layer processing tends to generate directionally-oriented microstructure that may result in both location dependent and directionally dependent property variations. Support structures are used to help transfer heat away from the part as new layers are added and also help hold the part's shape as it forms. Additionally, the surface texture of the part can vary based on the features (holes, fillets, slots, etc.) and orientation to the build plate. The following questions should be considered:

- How is the component oriented on the build platform?
- What considerations led to this orientation?
- How is the component supported (support structure)?
- Does the component orientation affect the support structure needed, and what affect does that have on the component?
- Is warpage of the part a concern, and if so how is it accounted for and controlled?
- How are residual stresses created by the PBF process accounted for in the structural analysis?
- Does the component have features that overhang or have internal unsupported features such as “unsupported roofs” as shown in the illustration below?
- Do any unsupported roof surfaces have properties different than the rest of the component, and how is that accounted for in the design?
- Are there any other unique considerations for these unsupported features?
- How is the surface finish controlled, and how is fatigue, form, fit and function affected?
- How are dimensional tolerances compared to the AM process dimensional capabilities?
 - What is the dimensional capability of the essential features (e.g., minimum and maximum wall thicknesses, fillet radii, etc.)? What are the limits and why?
 - Are there special design considerations for using the part with as-built surface roughness (normally higher than conventional manufacturing), for example, aerodynamics/fluid dynamics, etc.?
- Have you included prolongs to the part or test specimens in the build for metallurgical evaluations?



Illustration - Unsupported "roof" and overhanging surfaces

4. **Powder Feedstock Considerations.** Control of the powder feedstock is essential to a quality fusion process. The powder shape and statistical distribution of particle sizes in the powder bed affect whether the powder can consistently be spread uniformly along the powder bed, with the proper density, to support a quality fusion process. Factors such as powder chemistry, particle shape, particle size distribution (including size limits), cleanliness and powder flow characteristics can be defined in a material specification. The following questions should be considered:
- What is the chemical composition of the alloy?
 - What powder characteristics are controlled by a material specification?
 - What cleanliness and contamination controls are specified for the powder?
 - What environmental controls are specified for the powder?
 - How are the controlled powder characteristics defined?
 - What tests and inspections are performed on the powder to verify that the powder meets the specification requirements?
 - How is a powder lot defined?
 - How are powder lots identified, what information is retained for each powder lot, and how is it retained?
 - What controls and requirements are in place regarding blending of powder heats into a single lot?
 - Is powder heat blending limited to occur at just the powder supplier?
5. **Powder Bed Fusion Process Considerations.** The fundamental goal of fusion process control is to achieve consolidation of the powder to the greatest extent possible without the presence of fusion-related defects. The fusion process parameters specified to control the PBF machine are set to achieve the desired material density, geometric detail, microstructure, surface texture, and other fusion-related characteristics of the as-built structure. The process must be properly controlled to produce stable and reproducible dimensions, properties, and quality.
- 5.1 *Process Controls.* Greater than 100 parameters are used to control the PBF process. Examples of fusion process parameters include laser power, scan speeds, layer thickness, and fill patterns. Other process elements that can influence the outcome of the PBF process include the chamber atmosphere, recoater blade material/configuration, and the build plate alloy. Elements of the PBF process, including the process parameters, that can influence the outcome of the PBF process (e.g., mechanical, tensile, metallurgical, or chemical properties) are identified as significant process elements and are frozen and require requalification if changed. The following questions should be considered:
- What PBF process parameters are specified for the control of the PBF machine during the build process?
 - What process parameters are classified as significant and how are they defined?
 - What other process elements (e.g., recoater blade material, build plate material) affect the outcome of the PBF process (i.e., are significant process elements)?
 - What is the procedure used to determine the values set for the PBF process parameters?

- Were the PBF process parameters and other process elements that can affect the outcome of the PBF process defined and frozen in a process specification?
- Is the same process specification used for each PBF machine of the same make and model building a specific part number?
- What is the temperature of the build chamber and why?
- How is the temperature of the build chamber measured and monitored, including number and locations on the build plate?
- What is the build chamber atmosphere?
- How is the build chamber atmosphere measured and monitored?
- How is the quality of PBF process evaluated and monitored?
- Is in-situ monitoring of the PBF process performed?
- If in-situ monitoring is performed, what aspects of the PBF process (e.g., the melt pool) are being monitored and why (e.g., quality of the build)?
- If in-situ monitoring is performed, how is the monitored data used (e.g., for post build accept/reject evaluation, active process control, or for informational purposes only)?

5.2 *Powder Blending*. Powder blending can be a source of contamination that should be evaluated and controlled. The following questions should be considered:

- Is more than one powder lot permitted in the PBF machine at a time?
- Is blending of powder from more than one supplier permitted?
- What is the process for blending of powder?

5.3 *Powder Recycling (Reuse)*. It is expected that PBF process specifications will allow the use of recycled powder. Examples of recycle limits include the number of build operations, number of machine operation hours, or the days the powder is allowed to remain in the PBF machine. The following questions should be considered:

- Is powder recycling allowed?
- What is the process for recycling of powder?
- What are the limitations on powder recycling?
- How were the above limitations established and validated?
- What requirements does the recycled powder have to meet?
- What document contains the limitations on powder recycling?
- How are changes to the limitations on powder recycling controlled?
- How is the powder recycling status, for each recycle limit, tracked and identified for each machine?
- How are unusable powders (e.g., contaminated, exceeds maximum reuse cycles, or doesn't meet specification requirements) disposed of to ensure that said powders are not reintroduced into the supply chain?

5.4 *Energy Source Performance*. The performance of the energy source and associated control systems, based on the frozen fusion process controls, should be documented reflecting performance over the entire build area. The following questions should be considered:

- How will the performance of the energy source and associated control systems, governed by the frozen fusion parameters be evaluated?
- What are the metrics used to evaluate the performance of the energy source and associated control systems?
- How was the allowed variation of the metrics established?

5.5 *Surface Texture and Detail Resolution.* Inspections of parts provide reoccurring evidence of build quality, but a standardized reference part may be optimized to more readily provide qualitative and quantitative evidence of the quality of the geometric rendering of the process. The following questions should be considered:

- How is the performance of the PBF machine with respect to surface texture and detail rendering documented?
- What metrics are used to evaluate surface texture and detail resolution?
- How was the allowed variation of the metric established?

In some circumstances a reference part may be used to address these concerns. A reference part, if used, would be designed with purpose built features that serve as metrics of build quality, dimensional accuracy, and process stability and would be produced in the furthest locations on the build plate.

6. **Post Build Considerations.** The post build operations, including the sequence of the operations must be clearly stated. The post build sequence of operations may affect the final part microstructure, material characteristics, residual stress, and dimensional control.

6.1. *General*

- What is the post build sequence of operations?
- How is the residual stress in the part after post build processing assessed?
- What surface finish enhancements are used on the AM part?

6.2. *Powder removal*

- How is powder removed from the part?
- How is removal of all powder confirmed?

6.3. *Build Plate and Support Structure Removal*

- Is the method and sequence of removal of each part from the build plate and temporary support structures clearly defined?
- What processes are used to remove the part from the build plate?
- What processes are used to remove the support structure from the part?

6.4. *Thermal Processing.* It is expected that parts manufactured using PBF will require thermal processing operations to evolve the as-built microstructure into a final form providing proper and predictable material performance. The following questions should be considered:

- Is a stress relief thermal cycle used?
- Is the part Hot Isostatic Pressed (HIPed)?

- Is additional heat treatment performed post HIP?
- What heat treatment cycle(s), if any, are specifically aimed at improving material microstructure (e.g., reduced anisotropy, improved homogeneity, etc.)?
- Are there specific requirements defined with regards to the desired output of this post-processing step(s) (e.g., final microstructure attributes, acceptable levels of anisotropy, remaining level of residual stress etc.)?

7. **Inspection Method Considerations.** AM parts may require the use of multiple non-destructive inspection (NDI) techniques to achieve full coverage. A combination of radiography, dye penetrant, eddy current, or ultrasonic techniques may be used on a single part. The physics of the layered AM process does not tend to produce defects with significant height in the build direction. Planar defects, such as aligned or chained porosity or cracks, tend to form along the build plane. The as-built surfaces can be rough and mask the presence of typically unallowable surface defects. The following questions should be considered:

- What NDI methods are used on the as-built part?
- What NDI methods are used on the final part?
- What is the specific objective of each NDI method used?
- What flaw type, if any, is each NDI method intending to detect?
- What is the inspection threshold for each NDI method and flaw type?
- What are the Probability of Detection (POD) assumptions for each NDI method and flaw type?
- In production, for each NDI inspection method, at what frequency (every part, sampling plan) will the inspection be performed?
- How is micro-sectioning of parts and microstructural evaluation of designated locations used in the production inspection program?

8. **Other Considerations.**

8.1 *Part Models, Build Assemblies, and Associated Electronic Data.* The variety of files required to execute the AM process can be large. This includes, but is not limited to, part computer aided design (CAD) files, test specimen geometry files, the assembled part build file (parts, test specimens, and support structures), stereolithography (STL) files, slice files, parameter files, log files, and execution scripts. The following questions should be considered:

- What electronic files are required to execute the AM process?
- How are the electronic files identified and referenced in AM process?
- Describe the configuration control, traceability, and security of these electronic files.
- What test specimens are included in the build file?

8.2 *Part Process Control.* Part process control encompasses all part production processes beginning with the PBF machine through final part acceptance. This should include the content of the part drawing, specifications, and a part traveler system. The following questions should be considered:

- How is part process control documented and implemented?
- How is part process control validated?
- Are the part process control documents under configuration control?

8.3 *Build Interruptions.* The build should run to completion without unplanned intervention. The following questions should be considered:

- What build interruptions are expected and planned for?
- How was the acceptable time limit for planned interruptions determined?
- What is the procedure for evaluating a build interruption beyond the allowed limit dispositioned?
- What is the procedure for evaluating unplanned interruptions?

8.4 *Contamination and Foreign Object Debris Control.* A plan to address the control of contamination and foreign object debris during all operations of the PBF machine and associated equipment is necessary. Airflow in the build chamber is important to prevent the by-products of the fusion process from falling into the powder bed. The following questions should be considered:

- What forms of contaminants were considered and how were they mitigated?
- How is the risk of powder contamination mitigated for all aspects of operation such as during handling, storage, blending, sieving, machine loading, or any other operation?

8.5 *Traceability.* A list of records associated with each part produced may be necessary. For Material Review Board (MRB) considerations, there may be a need to trace back to root cause of the issue. Records such as powder heat, lot, powder condition (e.g., virgin or recycle count), machine serial number (S/N), and build number, etc. may need to be retained for each part produced. The following questions should be considered:

- What records, specimens, etc. are retained for each build?
- What records are retained for each part?

9. **Process Validation Considerations.** Process validation is the methodology used to verify that a component manufactured to a specific process, process sequence, and drawing requirements meets design intent. Process validation requirements may include, but are not limited to part cutups, metallurgical examinations, manufacturing sequence sheets, first article inspections, chemistry, dimensional, and mechanical properties. Aspects of variability to be considered include, but are not limited to feedstock variability, machine variability, and variability within the build volume. Upon establishment of a robust process that is determined to meet design intent, the process is frozen. All significant process changes to frozen process specifications must undergo a similar qualification to that of the initial process validation described above prior to their introduction in the manufacturing process. The following questions should be considered:

- What process validation requirements are used to substantiate that the PBF process and post build processing are stable and repeatable, such that parts produced consistently meet design intent?

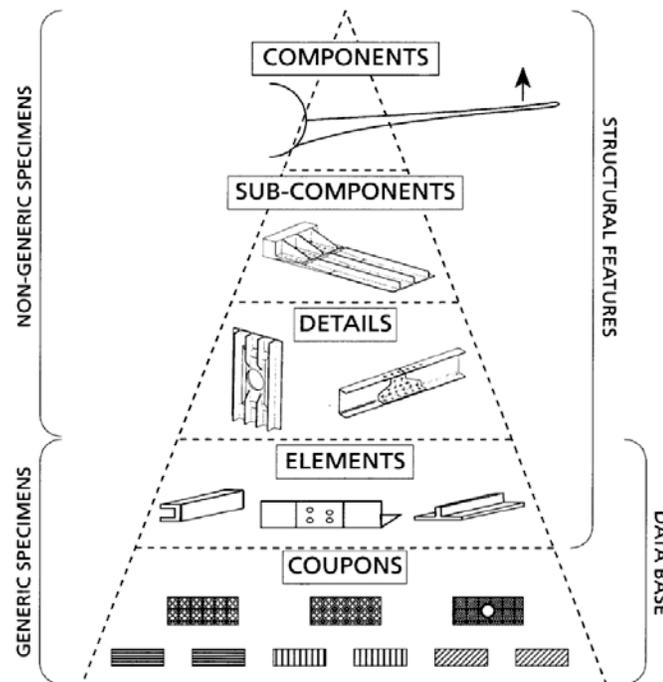
- What is the definition for significant process changes?
- What procedure is in place to ensure that the significant process parameters and significant process elements of the fusion process are not changed (i.e., frozen)?
- What disciplines review and approve the data used to substantiate that the frozen process specifications result in a part that meets design intent?
- What is the procedure for evaluating and approving changes to a frozen process specification?
- Is there a procedure in place to require approval of changes to a frozen process specification prior to their introduction in the manufacturing process and that revision control is maintained?
- What changes result in a requalification to a frozen process specification?

10. **Material Design Values Development Considerations.** Material strength and design values used for AM components that require structural analysis need to account for the variability due to the materials and the production methods used to manufacture the part. The physics of the layered AM process may produce anisotropic material properties. In general the variability of the material in the final component is accounted for by using statistical tools to analyze data obtained from testing of specimens either extracted from actual components, or in cases where specimens cannot be extracted from actual components, purpose built specimens. The following questions should be considered:

- Is the material specification the material is being purchased to finalized?
- Were the material design values determined using test specimens produced in accordance with frozen material, process, and part specifications?
- How is the material from which test specimens are extracted shown to be representative of the material expected to be seen in the final production components?
- If purpose-built witness coupons are used for material characterization, how are the coupon material properties determined to be representative of the part's material properties?
- How does the test plan being used to obtain data to derive design values encompass sufficient lots of material and production builds to capture the variability of the final production material?
- How was the effect of anisotropy accounted for in establishing the material design values?
- What are the key types of material anomalies (e.g., porosity, lack of fusion, etc.) that may result in component's performance debit (e.g., tensile properties, low cycle fatigue, high cycle fatigue)?
- How are such anomalies characterized?
- How is their effect on component properties established and reflected in the design allowables?
- What design values, if any, are derived properties?
- Can the applicant provide a matrix (e.g., number of heats, lots, specimens for each specimen type, orientation, location on build plate, surface texture, and condition) that summarizes the testing performed to develop the mechanical, fatigue, fracture mechanics, and other design values?

- How was the effect of recycled powder accounted for in establishing the material design values?
- How are allowable pauses in the PBF machine operation accounted for in the material design values?
- Is the process used for developing design allowables for AM parts different from the company's traditional methodologies for conventional material forms? If so what are the differences?

Considering that PBF methods are best suited to produce smaller, typically thin walled components it may be difficult to extract test specimens representative of the mechanical properties of that component. In these cases an ACO engineer may have to assess the strength and design values being proposed by an applicant in a manner similar to the building block approach used for composite materials (Composite Materials Handbook 17). The building block approach is illustrated below:



Building Block Approach

The building block approach is intended to address complex material systems where design values may require more extensive testing than strictly at coupon level. For parts produced using PBF methods some element level testing may be required to capture the mechanical behavior of elements or higher levels. For the sample sited above, (a thin wall complex part) the building block approach may put more reliance on element or detail component testing instead of the more traditional coupon level of tests. It will be crucial for the ACO engineer to assess the level of testing required for deriving appropriate design values for parts manufactured by PBF methods.