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INTRODUCTION TO THIS GUIDE

This guide is intended to help manufacturers through the Operational Qualification (OQ) process as it relates to Laser Powder Bed Fusion (LPBF) machines. The guide attempts to supplement the qualification structure presented in AMS 7003 and AMS 7032 and seeks to provide additional insight and industry best practices. The recommendations included within this document may not coincide with the current AMS version (year 2024) but are in line with proposed edits to the AMS specifications with anticipated release dates within the next few years. Aerospace Material Specifications (AMS), the International Organization for Standardization (ISO), and the American Society for Testing and Materials (ASTM) provide several specifications that are integral to the qualification process. Figure 1 below illustrates how these specifications are applied throughout the qualification process.

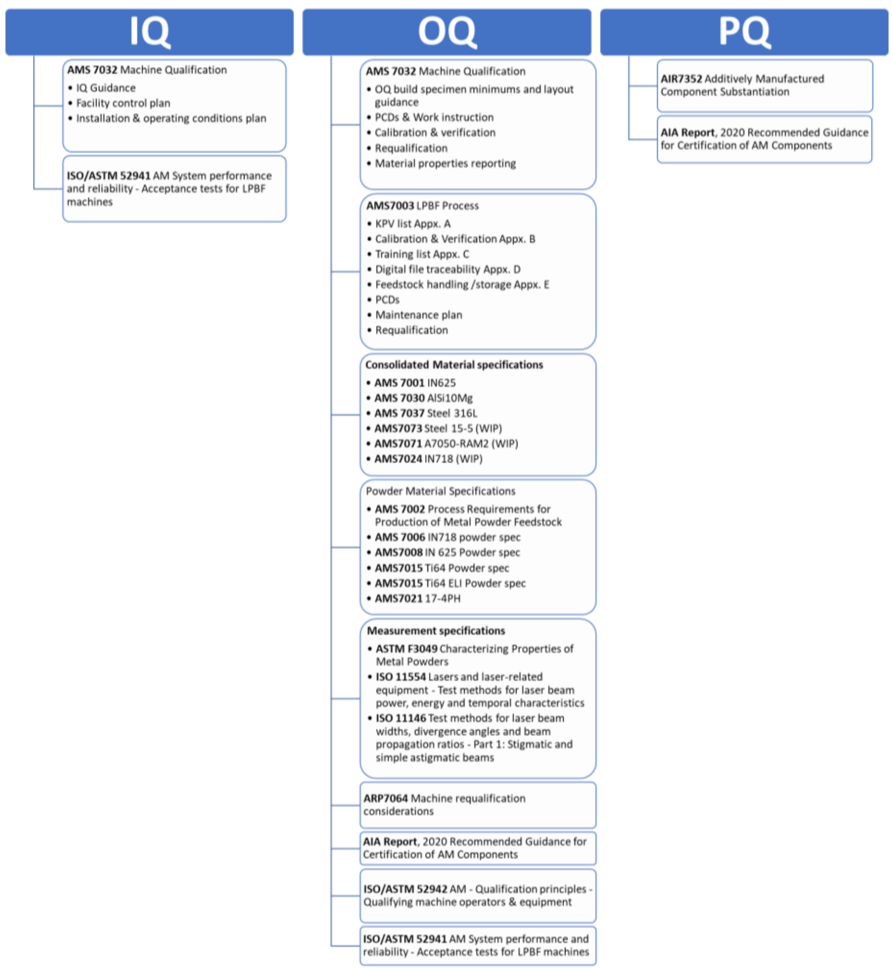

Figure 1: Specifications within the IQ, OQ, PQ Process

As LPBF technology and the regulatory landscape around Additive Manufacturing (AM) continue to evolve, this guide may not accurately reflect those changes. Each manufacturer is responsible for understanding their technology, processes, facility, and industry-specific requirements to determine the necessary actions they need to take to ensure they produce compliant parts. This approach to OQ described in this guide is largely geared towards qualifying for the aerospace industry.

INTRODUCTION TO OPERATIONAL QUALIFICATION (OQ)

Operational Qualification is a validation process that ensures equipment operates within predetermined limits, demonstrating its ability to produce materials with conforming properties. In the context of AM, OQ involves a series of tests and procedures to confirm that the equipment performs reliably and produces material according to material specifications. OQ is one step in the larger qualification process. This process includes Initial Material Qualification (IMQ), Installation Qualification (IQ), Operational Qualification (OQ) and Performance Qualification (PQ). The relationship between these qualification stages is depicted in Figure 2 below.

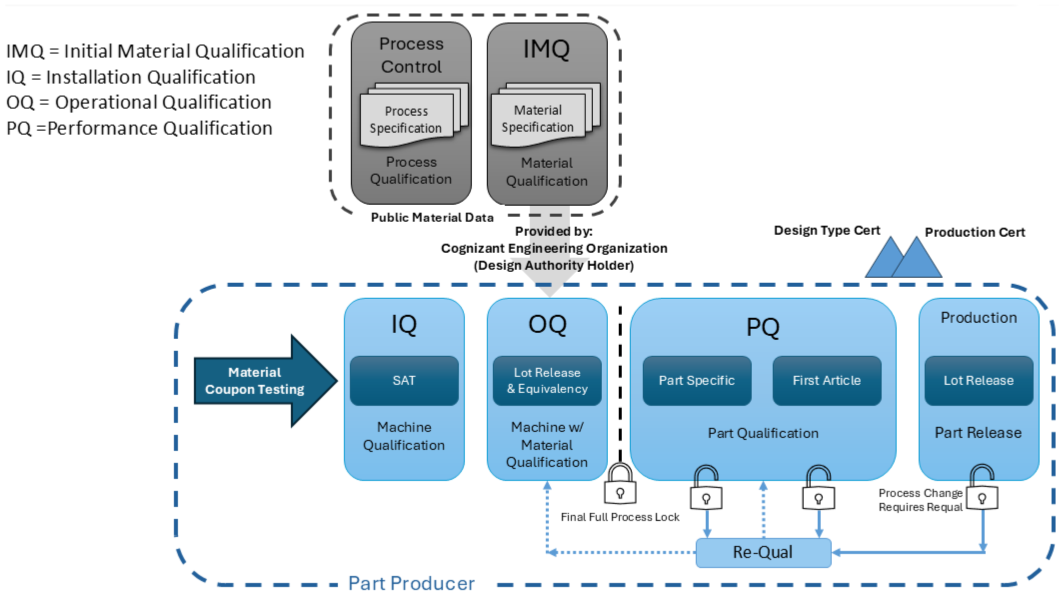

Figure 2: IQ, OQ, PQ Process

The material and process specification requirements for OQ may vary based on the target application. However, the goal of OQ is to demonstrate that a machine, material, and material parameter combination can produce quality material. The process by which to approve this combination (OQ) is based on a generally accepted procedure across most industries and applications.

The post processing qualification and control will not be covered in this guide; however, it is assumed that all material is tested in its final heat-treated condition unless otherwise specified by the cognizant engineering organization (CEO) or customer.

Individual final applications may require additional testing which would be laid out during the PQ for that application. Additional testing will be required to ensure ongoing product quality over a longer period. Those testing measures and PQ are not addressed in this document.

The OQ process for AM involves several critical steps:

- **Equipment Calibration and Maintenance**: Ensuring that the AM equipment is properly calibrated and maintained to operate within specified parameters.
- **Key Process Variable Verification**: Verifying that all key process variables (KPVs) are set and controlled within acceptable limits.
- **Material Control**: Confirming that the materials used in the AM process are consistent in quality and properties.
- **Process Control**: Creating processes and work instructions to ensure that the process inputs are consistent.
- **Test Builds and Validation**: Conducting test builds to validate the AM process. This involves producing and testing coupons to ensure they meet the intended mechanical and physical properties.
- **Documentation and Traceability**: Maintaining detailed records of all OQ activities, including test results, equipment settings, and any deviations or corrective actions taken.

Additional resources and guidance on qualifying the AM process for aerospace can be found in the Aerospace Industries Association (AIA) Report "Recommended Guidance for Certification of AM Components."

OQ Checklist

- Installation Qualification is complete
- Process control documents created
    - Facility operating conditions plan
    - Operator training
    - Process work instruction plan
    - Digital file and software configuration control plan
    - KPV plan
        - Process Input Variables (PIV) determined and values recorded
        - Key Process Variables (KPV) determined and target values determined
        - KPV Capability/control tolerances determined
        - Determine variable control plan – SPC or PM
        - SPC plan determined for KPVs
    - Machine configuration plan created
    - Preventative Maintenance Plan
        - Verification items are decided on
        - Intervals of PM items are determined
        - PM work instructions
        - Documents for recording PM results are created
    - Calibration verification plan
    - Machine requalification plan
    - Process interruption plan (if applicable)
    - Material feedstock specification
    - Powder management and handling procedures
    - Powder reuse procedures (if applicable)
    - Moisture and contamination control plan
    - Alloy change contamination avoidance plan (if applicable)
- Consumables management
- KPV Process window study
- OQ material requirements and test plan (e.g. material spec)
- OQ build layouts determined
- OQ builds and post processing complete
- OQ material testing complete

GUIDANCE DOCUMENT OVERVIEW – STEPS TO COMPLETE IQ AND OQ

This guide walks through the steps required to complete IQ and OQ. Detailed recommendations for each step are discussed within the remaining sections of this document. At a high level, the required steps are outlined below:

1. **Machine Installation and Installation Qualification (IQ)**
   This section guides the user on how to perform an IQ, recommended additional measurements, and what to do if there is a time gap between install and OQ.
2. **Process Control Documents (PCDs)**
   This section touches on the different types of machine and process specific documents that need to be in place before preforming an OQ, including work instructions, training. This also includes facility control documents that may not be machine specific, including environmental control, feedstock storage, and feedstock management.
3. **Variables Review**
   This section explains how to determine if a variable in the process needs to be monitored and controlled.
4. **Measuring KPVs**
   This section helps users determine the measuring frequency and tolerance ranges of identified process variables.
5. **Preventative Maintenance (PM) Plan**
   This section provides guidance on what tasks are required at each PM and what validation is necessary when the PM is complete. This section also covers documentation of any calibration and testing results.
6. **Material Requirements and Testing Plan**
   This section explains the requirement of establishing the target material properties (usually provided by a material specification) that the OQ build will be tested against and offers guidance on the creation of testing plans.
7. **Layout OQ Build**
   This section discusses the guidelines in AMS 7032 and the considerations for laying out an OQ build.
8. **Requalification vs Verification Events and Testing**
   This section will assist the reader on deciding which events require a full requalification, a partial requalification, or a simpler set of verification steps.
9. **Material Testing**
   This section and step are where OQ and material property requirements come together. The testing plan is executed upon build and post-processing completions, and results are compared back to original requirements to verify machine, material, and parameter sets meet expectations.

1 Machine Installation and Installation Qualification (IQ)

This section relates to AMS 7032 3.1.

IQ must be performed before a machine goes through the OQ process. The purpose of the IQ is to ensure installation conditions for the machine are met and the machine is installed and functioning correctly. An IQ typically starts by preparing an area for machine arrival and is completed after the Site Acceptance Test (SAT) build is analyzed. The SAT build can be an original equipment manufacturer (OEM) standard build or a build that is mutually agreed upon between the parts manufacturer and the OEM. All installation testing and SAT results should be compared back to the Factory Acceptance Test (FAT) to check for consistency. The FAT is testing performed at the OEM before machine shipment.

Most of the data required from IQ can be attained from the machine OEM during install and SAT. However, it is important that the measurement techniques and equipment type used to establish IQ are the **same** that will be used for future checks (i.e. PMs and KPV tracking) as this will allow future checks to be compared to the baseline. If the machine has already gone through IQ but has been operating for an extended timeframe between IQ and starting OQ, then machine pre-checks are recommended to reduce the risk of an unsuccessful OQ. These checks are similar to a PM and are covered in Section 1.3.

1.1 Performing IQ

This section relates to AMS 7032 3.2.1.4.

All IQ checks should be done with calibrated instrumentation per AMS 7032 3.2.1.4. It is recommended that the same Calibration and Verification Plan from IQ be used in OQ. Appendix 4: Discussion on Measuring Techniques provides more detailed information.

The following is a list of common checks that may be included in IQ and shall be documented appropriately:

- Machine is installed correctly per OEM site installation guide
    - Facility power hookups are correct
    - Floor thickness, levelness, and vibration requirements are met*
    - Machine is leveled
    - Facility environmental conditions meet specification (temp & humidity)*
- Calibrations completed
    - Laser Power
    - Location of focus
    - Beam profiling
    - Scan field
    - Gas flow*
- Documentation complete
    - Serial numbers recorded
        - Machine
        - Lasers
        - Scanners
        - Collimators

        - 3D scanner (if applicable)
        - Peripherals (chillers)
    - Firmware versions recorded
        - Lasers
        - Scanners
        - Chillers
        - PLCs
    - Software versions recorded
        - On machine software
            - Machine control software
        - Other machine software*,1
        - Offline software
            - Slicing or setup software
    - Certification documents collected
        - Laser factory acceptance
        - Scanner factory acceptance
        - Oxygen sensor calibration
        - Flow sensor calibrations
        - Other sensor calibrations*
    - PM schedule created
- Additional discretionary checks
    - Safety*
    - OEM training documents*
    - OEM Pre build checklists*
    - Continuity of powder transportation hoses*,2
- SAT build
    - Part dimensional accuracy
    - Material properties

[1] Other machine software may include process monitoring (Meltpool, Optical tomography, recoat monitoring), data acquisition or machine health software
[2] Continuity of powder transportation hoses is relevant in systems that transport powder during process such as systems with internal sieving. These systems often include flexible hoses which must be grounded properly to the surrounding metal piping. A continuity check on either side of the flexible hose can be used to check this. Failure to ground these hoses can be an explosion hazard or can result in static buildup which can cause electrical components to malfunction.
* Recommended but not required

1.2 CONFIRMING CALIBRATION

This section relates to AMS 7032 3.2.1.4

Before an IQ is ran, the machine should be in a known state. It is recommended that you work with the machine OEM to ensure the machine install and SAT include enough data to certify the machine's working condition. This will provide a baseline to compare against when doing calibration checks during PM.

Machine calibration checks will vary from one OEM to the next, so it is important that each manufacturing facility set a standard of what calibrations are expected to be verified. The manufacturing facility should work with the OEM to ensure those calibrations are performed or that the facility performs these checks themselves after installation. These checks are similar to PM verifications. The recommended baseline verifications are:

Laser Power – A verification that commanded laser power for each laser matches the power recorded in the chamber.

Location of Focus – This is the location of the center of the beam waist relative to the working plane. See diagram of working plane in Other Discussions.

Beam Profiling (Beam Caustic measurement) – a check that laser beam size and shape is as expected. It is important to check the quality of the beam after machine movement to ensure no drift within the optical train or contamination of the lenses during shipping. From the beam profiling the following should be reported out for a standard fiber laser with a gaussian beam output:

- Minimum spot size
- Location of focus relative to the working plane
- Spot size at working plane (may be the same as min spot size)
- Thermal shift
- Beam quality (M2 Value)

Scan Field Calibration – A measurement of the commanded vs actual location of the laser at the working plane. The output of this measurement is typically max error and average error across the build area at the working plane.

Gas Flow – Gas flow velocities will vary across the build platform. Some OEMs have allowable ranges for this variation and will check multiple defined points across the build plate. At minimum, it is recommended that the machine should be tested to confirm that the commanded airflow velocity results in the expected velocity in at least one defined place on the platform or near the airflow outlet. This will minimize machine to machine variation.

More about these checks can be found in Appendix 4: Discussion on Measuring Techniques. If the facility's measurement techniques vary from the OEM's, then these checks should be repeated using the facility's methodology before OQ begins.

1.3 Machines Without a Recent IQ

If the IQ was not completed recently or did not include a full check of calibration, then the calibration of the machine should be checked before starting OQ. In this case it is recommended that the yearly PM be performed, including the check of any verification items included in Section 1.2. If no yearly PM plan exists, use this document, any applicable machine manuals, AMS 7003, and AMS 7032 to guide in the development of one.

1.4 Machines Without Historical Material Data

Before beginning OQ, there should be confidence that the final mechanical properties from the OQ build will meet expectations. If the machine type and parameter set have no historical mechanical testing data, or new mechanical data is being required (such as fatigue), it is recommended that a spot check build be run to verify that the parameter and machine combination will perform as expected before incurring the expense of a full OQ. The spot check build should involve at a minimum, a mechanical test coupon at the extents of the laser reach, and at the lowest and highest airflow regions of the build area. Metallography and surface samples at these extents will also provide an indication of platform stability. The goal is to get enough data to ensure that material properties will buy-in across the full intended build area. Across the platform, the quality of airflow, spot size, beam shape, laser angle of incidence and powder packing density can change. The spot check aims to verify that this variation will not result in a failing OQ.

2 PROCESS CONTROL DOCUMENTS (PCDS)

PCDs consist of required work instructions and operating procedures. PCDs should be created for any part of the manufacturing process which requires process control to meet product requirements. Therefore, any part of the process that could affect Key Process Variables (KPVs) or result in an altered Process Input Variable (PIV) should have PCDs associated with it. PCDs will include:

Machine:

- Facility operating conditions plan — AMS7032 3.2.1.3
- Operator training — AMS7032 3.2.1.6
- Process work instruction plan — AMS7032 3.2.1.1
- Digital file & Software configuration control plan — AMS7003 3.1.3
- KPV plan — AMS7003 3.1.1
- Machine configuration plan — AMS 7032 3.2.1.2
- Preventative Maintenance Plan — AMS 7032 3.2.1.5 & AMS7003 3.1.5
- Calibration verification plan — AMS7032 3.2.1.4 & AMS7003 3.1.4
- Machine requalification plan
- Process interruption (if applicable) — AMS7003 3.1.2

Material:

- Material feedstock Specification
- Powder management and handling procedures — AMS7003 3.1.6
- Moisture and contamination control plan — AMS7003 3.1.7
- Alloy change contamination avoidance plan (if applicable)
- Consumables management

Further details on these required PCDs can be found in subsequent sections.

2.1 MACHINE AND FACILITY PCDS

The creation of these documents may consider the topics in the subsections below and may be coordinated (if applicable) with individuals responsible for quality, safety, facilities, CEO, manufacturing team and/or operations. It is recommended that facility PCDs be integrated into the companies Quality Management System (QMS).

2.1.1 Facility Control Plans

This section relates to AMS 7032 3.2.1.3.

A part of a facility control plan establishes requirements for measuring and controlling key environmental conditions that may affect the process. It is required, at a minimum, that any environmental conditions called out in the installation manual be monitored and controlled. This document should include locations of sensors, frequency of measurement, and control limits.

At a minimum the following should be measured and controlled:

- Temperature

- Humidity

The following should be considered for measurement and control:

- Process gas pressure and flow
- Air/CDA pressure and flow
- Vibration
- Power stability
- Electro-magnetic interference

A facility control plan may also encompass policies on general cleanliness, hazardous material storage, ventilation requirements, environmental health and safety (EHS), and personal protective equipment (PPE) requirements.

2.1.2 Operator Training

For more information, see AMS7032 section 3.2.1.6.

Operator training programs should include for:

- Powder storage and safety
- Powder handling
- Peripheral use and safety (i.e. vacuum, lifts)
- Powder reuse procedures (if applicable)
- Build file setup
- Preparing a machine for build and build start
- Pulling a finished build
- Build restart (if applicable)
- Build data collection pre or post build (if applicable)
- Recording build information for traceability per facility QMS
- Preventative maintenance

It is also recommended that all machine users are trained to identify events that may trigger requalification or verification procedures.

2.1.3 Process Work Instruction Plan

This section is written to be in accordance with AMS 7032 3.2.1.1.

It is recommended that there are work instructions and checklists for the following:

- Powder reuse procedures (if applicable)
- Build file setup
- Preparing a machine for build and build start
- Pulling a finished build
- Build restart (if applicable)
- Build data collection pre or post build (if applicable)
- Recording build information for traceability per facility QMS system
- Preventative maintenance

2.1.4 Digital File & Software Configuration Control Plan

This section is written to be in accordance with AMS 7003 3.1.3.

A configuration control system should be put in place for:

- Firmware versions
    - Lasers
    - Scanners
    - Chillers
    - PLCs
- Software versions
    - On machine software
        - Machine control software
        - Other machine software, Process monitoring, data acquisition or machine health software (recoat monitoring, meltpool monitoring etc.)*
    - Offline software
        - Slicing or setup software
- Part files
    - Original customer CAD file
    - CAD files after modifications (scale, supports, stock-add)
    - Build setup files
    - Sliced vector files
- Machine parameters

More guidance can also be found in AIA report Figure 6.

2.1.5 KPV Plan

This section is written to be in accordance with AMS 7003 3.1.1.

A KPV plan will include:

- Process Input Variables (PIV) determined and values recorded
- Key Process Variables (KPV) determined and target values determined
- KPV Capability/control limits determined
- Determine variable control plan – SPC or PM
- SPC plan determined for KPV's

More details can be found in Section 4 of this document

2.1.6 Machine Configuration Plan

This section is written to be in accordance with AMS 7032 3.2.1.2.

The machine configuration shall be fixed once qualification is completed. The machine configuration includes all critical component serial numbers recorded in IQ.

2.1.7 Preventative Maintenance (PM) Plan

This section relates to AMS 7003 3.1.5 and AMS 7032 3.2.1.5.

The following should be completed as part of making a PM plan:

- Items which require verification determined
- Intervals of PM items are determined
- PM work instructions
- Documents/templates for recording PM results are created

PM plan is further discussed in Section 5 of this document.

2.1.8 Calibration Verification Plan

AMS 7003 section 3.1.4 lays out what a calibration and verification plan is while AMS 7032 section 3.2.1.4 gives specifics on what items must be included in this plan. A calibration plan should be created as soon as calibration test methods and tools are determined.

2.1.9 Machine Requalification Plan

Machine requalification events and procedures determined. See Section 8 for more detail.

2.1.10 Process Interruption (if applicable)

Per AMS 7003 3.1.2

If process interruptions are approved, a plan detailing the restart procedure and allowable stoppage time should be created. Data must be present to prove that there are no adverse effects to process interruption. This should be part of PQ.

2.2 Material Control Documents

This section relates to AMS 7002

Material control documents should include all required controls to ensure that the feedstock going into a machine meets predetermined quality standards.

2.2.1 Feedstock Material Specification

This section relates to AMS 7002

The guidance of *AIA Report: Recommended Guidance for Certification of AM Components* was leveraged to distill out the following key requirements of a material specification.

Feedstock specifications are typically alloy-specific with appropriate provisions for various additive processes (i.e., powder bed, wire-fed, or powder-fed) and energy sources (i.e., plasma, electron-beam, or laser). Powder specification requirements should include, but may not be limited to:

- Chemistry
- Production Method
- Particle size distribution
- Morphology
- Lot definitions

Additional plans to be considered:

- Entrapped porosity limits
- Morphology
- Moisture
- Powder flow
- Tap and apparent density
- Repose angle, and/or spreadability

Wire feedstock material specification requirements should include, but may not be limited to:

- Chemistry
- Melting practice
- Surface condition, including surface quality
- Size and tolerance
- Fabrication method
- Lot definition
- Traceability requirements
- Packaging requirements

Industry standards organizations are actively developing specifications for powder feedstock materials and production processes; some of these relevant to aerospace products can be found in **Error! Reference source not found.**.

2.2.2 Powder Management and Handling Procedures

Per AMS 7003 3.1.6 a powder management Process Control Document (PCD) is required. The following topics should be addressed when drafting your powder management PCD and may be divided into multiple PCDs if necessary.

- Incoming powder management
    - Inspection & approval process
    - Labeling
- Powder storage
    - Environmental control/monitoring (humidity, temperature)
    - Labeling (lot, powder type, uses)
    - Contamination controls
    - Segregation/labeling of approved, awaiting approval and scrap powder
- Lot control strategy
- General shop labeling, segregation and other contamination controls for containers, machines and peripheral equipment
- Peripheral powder equipment controls
- Controlling external tools to prevent contamination
- Disposal of scrap powder

2.2.2.1 Powder Reuse (if applicable)
If powder reuse is approved, the following should be considered for the powder reuse PCD:

- Methodology
  - Virgin add – external to system
    - When and how much virgin is added?
    - How is it blended?
  - Virgin add – internal to system
    - When and how much virgin is added?
    - Is a sampling plan needed?
    - Internal sieve inspection frequency
  - Reuse counting
    - Are powders of the same powder lot, with the same reuse quantity allowed to be combined to create a new sub-lot? Does this apply regardless of which machine the powder was used in?

- Definition of what constitutes a "use"
- How powder is handled, sieved and transported
- How powder is labeled and when reuse on given powder is incremented
- Sieving work instruction
- Sieve inspection and PM plan
- Blending work instructions (if applicable)
- Environmental control/monitoring plan (temp/humidity)

2.2.3 Consumables Management
A plan detailing the management of key consumables such as build platforms and recoaters. The following at minimum is recommended:

- Build platform
  - Material labeling to prevent contamination
  - min thickness requirements
  - Flatness requirements
- Recoater
  - Labeling (if multiple recoater types are being used in facility)
  - Profile requirements
  - Hardness requirement (if applicable)
  - Pre-build inspection

3 Variables Review

3.1 Identifying KPVs
Before OQ can begin, it is important that critical aspects of the process remain fixed, and it is understood which variables are important to monitor. AMS 7003 and 7032 define KPVs as "aspects of the manufacturing process that may impact the capability to meet the specified requirements. These include physical, chemical, metallurgical, mechanical property, or dimensional requirements."

For the purposes of this document, we define KPVs as "aspects of the manufacturing process that may impact the capability to meet the specified material requirements, referred to as Key Characteristics (KC)." **KCs include chemical, metallurgical, and mechanical properties that are controlled by the appropriate material specification**. It should be noted that for the purposes of this document, dimensionality is excluded from this list, because that is controlled via dimensional inspection.

In Appendix A of AMS 7003, potential process variables are listed. Many of the variables identified as KPVs in that list are defined as Process Input Variables (PIVs) since the called value does not change during the process. As technology evolves and allows for closed-loop parameter control, variables that are currently PIVs may become KPVs. Therefore, in any new process and technology, all process variables should be assessed for that specific technology to understand if they are KPVs. Currently, there are five (5) minimum variables that are identified as KPVs. See Figure 3 below for a graphical representation on how variables are categorized.

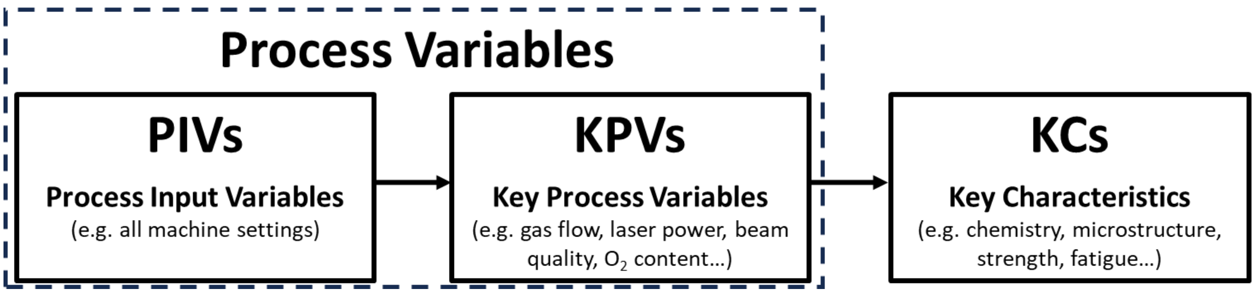

Figure 3: Process Variables

The minimum required KPVs that should be considered are scan field calibration, shielding gas flow rate, oxygen content, power of each laser, and beam spot size/shape of laser. Those KPVs are further defined in The Minimum KPVs. The remainder of this section acts as a guide to determining if any additional PIVs are considered KPVs for unique situations. To identify KPVs, the following questions should be answered:

1. Could variation in this variable impact the capability to meet the specified key characteristics?
2. Is this a fixed input variable or is it a measurable output variable?
3. Does the measurable output of the variable fluctuate within my process to the degree that it can impact the key characteristics?

If the parameter is fixed within a locked production process and the output does not vary significantly, then that variable will remain a PIV. Fixed PIVs must be locked, documented, and verified during initial qualification, requalification, and verification tasks, but will not be monitored. It is dependent on a facility's process controls to ensure that these fixed PIVs cannot change in a qualified process.

Figure 4 provides a decision tree to assist in KPV determination in unique situations.

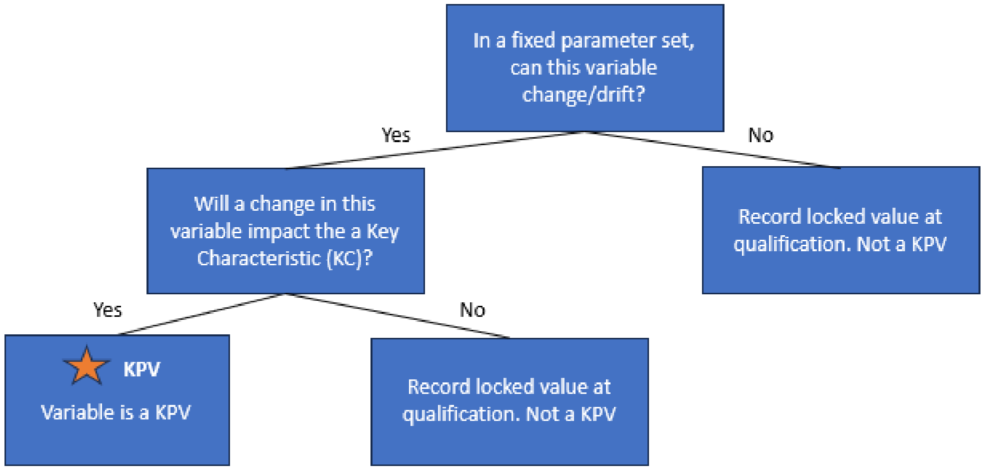

Figure 4: KPV Decision Tree

Considering the first question (Could variation in this variable impact the capability to meet the specified key characteristics?), it is helpful to understand what machine controls prevent variation. If the movements of the machine are well controlled and monitored by encoders, you could conclude that it is unlikely to change the key characteristics without the machine signaling an error. If something like airflow is close loop controlled (ex. PID controlled), further investigation may be needed to prove that the control loop is correctly adjusting and stabilizing in a way that does not affect the process. This example is discussed further in Section 4.4.

Example 1: Laser power – The called value for laser power is constant for a qualified process, making it a fixed variable. However, the laser power received at the working plane can fluctuate during a process or over time due to optical contamination, an aging laser, or other causalities. Therefore, laser power is at minimum, a KPV. It is important to the final part quality and may fluctuate in an unintended but meaningful way.

Example 2: Hatch spacing – Hatch spacing is considered a process input variable (PIV) because it is a fixed setting in a typical LPBF process, assuming adaptive parameters are not used. This is a parameter that is locked down and controlled within the software, so with a locked software and a set parameter, it should not change in a meaningful way if the minimum wall thickness used is significantly larger than the hatch spacing. Some minor fluctuations may occur based on rounding error, but quick and simple math can show if the difference in spacing would be meaningful enough to affect properties. If a part has strength or leak critical thin walls, additional application specific testing may be required in PQ.

Varying PIVs should be done in a parameter development effort before OQ is started. Any parameter development effort should result in:

- A locked final parameter
- A parameter that can build the intended part reliably and consistently
- A parameter that will meet the required KCs of the intended part

Before starting an OQ with a newly developed parameter set, it is recommended that a spot check build be run to verify that the parameter and machine combination will perform as expected before incurring the expense of a full OQ. This is discussed further in Section 1.4.

4 MEASURING KPVS

According to AMS 7032, “The initial machine(s) of a particular make and model that are qualified shall develop the ranges for the process window of the Key Process Variables (KPVs), which are generally listed in the applicable AMS process specification (see *GN7*). To ensure consistent performance, KPVs shall be identified [see Section 3.1], associated tolerance bands determined [see Sections 4.3, 4.4, and 4.5] and the impact of variation through each tolerance band should be understood [see Section 4.6].” If your KPVs measure outside the established limits, an action plan is required for remediation.

4.1 MEASUREMENT FREQUENCY – STATISTICAL PROCESS CONTROL (SPC) VS PREVENTATIVE MAINTENANCE (PM) IDENTIFYING KPVS3.1

SPC is the use of statistical techniques to control a process. SPC involves utilizing relevant quantitative data to determine if a process changes (a shift in average values) or goes out of control limit. Control charts with upper and lower limits are typically used to quickly show and alert if a process goes out of range.

If the variable changes frequently (e.g. build to build variation) then that variable should be controlled with frequent measurements (SPC). If the variable changes slowly (e.g. over months or years) than that variable should be monitored less periodically (PM).

Machine OEMs may be able to provide guidance on how tightly their machines are controlled and how often variables should be checked for drift. A machine stress test can also help guide in this determination. Check with your OEM for additional information.

When determining the measurement frequency of any variable, it is important to consider the quantity of product at risk if the variable is out of tolerance. Measuring too frequently incurs additional cost and time, but too infrequently can result in months of at-risk builds. Additionally, any at-risk builds will require a secondary part quality verification to ensure the product meets requirements. The balance of time, cost, and risk should be considered carefully. If a variable is found to be out of the control limit, the corresponding action plan should be documented within the PCD.

To assist in determining the appropriate measurement frequency (e.g. SPC vs PM), use the decision tree illustrated in Figure 5.

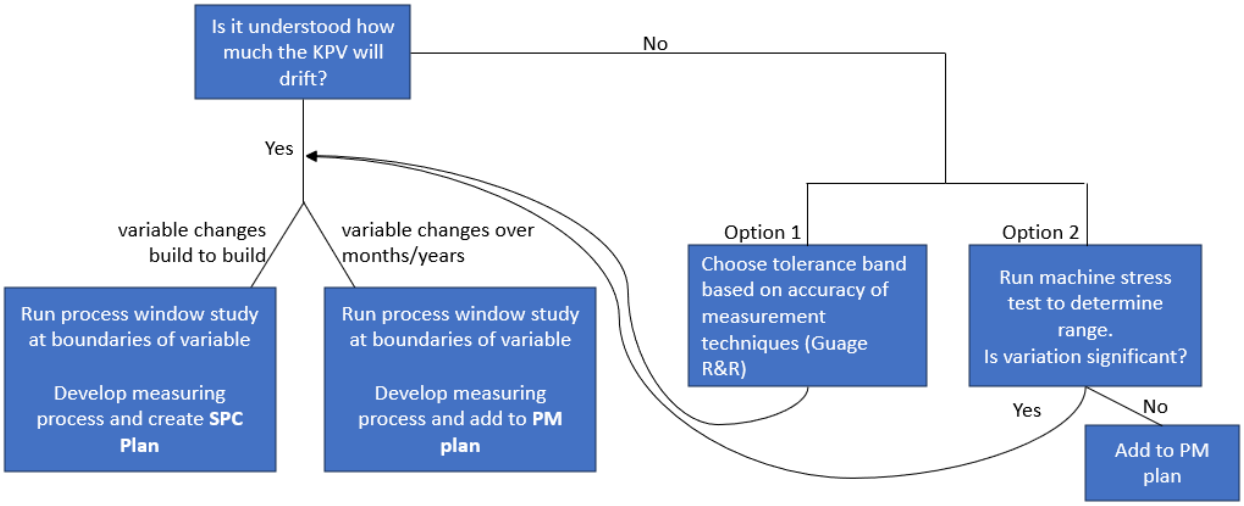

Figure 5: Measurement Frequency Decision Tree

4.2 Choosing How to Measure Variables

To determine how to measure the identified KPVs, it may be helpful to first determine the impact to the KCs and work backwards to understand what inputs must be controlled.

Further, many variables interact with each other; one example is multi-laser alignment. There are several approaches to measuring the aforementioned variable. One would be to use calibration checks before a build starts. Another approach would be to use a coupon on each platform to quantify laser mismatch. A facility may choose this in-build measurement method over a pre-build method due to its direct measurement of the final process. This in-build measurements accounts for additional factors that can change during a build, such as temperature and working distance impacting laser mismatch.

As discussed in AMS 7003 Section 9.5, there are several other examples of direct and indirect measurement methods. It is recommended that if indirect methods are being used, such as the weld width discussed in this section, these methods must first be characterized so that their sensitivity and the reliability is understood. In the case of using weld width, if the weld is unstable on the plate, resulting in weld width changes throughout the weld bead, this indirect method may not be valid. However, if the weld is stable, this method may be used as an indicator of total input energy density (power, scan speed, and spot size). In this situation, it should also be verified that weld width is also an acceptable proxy to weld depth for the given parameter set.

4.3 Determining Variable Limits

The chosen limit should be tested using a process window study to show that the product still meets specifications, even when operating at the limits. This process window study should be completed **before** OQ begins. A process window study only needs to be completed once for each machine model and material combination. Once you've identified KPVs that may impact KCs within the process the next three questions to ask are:

1. How accurately can I measure this KPV?
2. How much can this KPV vary in the process?
3. Will the resulting limit result in a product that meets requirements?

An alternative method to determine KPV limits is proposed in *AIA Report: Recommended Guidance for Certification of AM Components.* Section 6.3 of that document proposes setting the limits by running a design of experiment (DOE) in which the parameter is varied to find the range in which the parameter begins to affect material properties. Then use that minimum as the tolerance range. Assuming the identified range can be measured with the set tools, this is also a valid method. In the following section of this document, we propose using known variation and measurement accuracy ranges to reduce the number of specimens ran.

4.4 How Accurately Can I Measure This KPV?

It is critical that the chosen tolerance range is never smaller than the accuracy of the tools. Start by deciding how the variable will be measured, then decide what tools will be used and record the accuracy of each of the tools. If the accuracy of the tool is unknown or operator variation may be a factor, run a gauge repeatability and reproducibility (gauge R&R) study to determine the measurement variation.

4.5 How Much Can a KPV Vary?

The first step in understanding how much a KPV may vary is to ask the machine OEM if they already have this data. If not, determine if this information is known from past experience. If neither the OEM nor your organization understand the KPV's possible variation, inquire to the OEM how that variable is controlled and then perform a test. To decrease the cost and time associated with a full DOE, one approach would be to first identify the measurement technique of the KPV and the associated gauge repeatability and reproducibility (Gauge R&R). Then test that tolerance, or beyond that range in a process study window to determine if the chosen range results in acceptable material properties. A generally accepted rules for Guage R&R is that the measurement system is acceptable if the variability is less than 30% of the tolerance range, but ideally less than 10% of the tolerance range.

$$Minimum\ tolerance = \frac{Study\ variation}{Tolerance}$$

Example: If the measurement tool for laser power has a tolerance of ± 3% and there are no other factors that contribute to error within the measurement technique, then the tool's measurement variability (study variation) is 6%. So, to reach a minimum acceptable range of the tool contributing less than 30% of the tolerance range, my equation would be:

$$Minimum\ tolerance = \frac{0.06}{0.3} = 0.2 = 20\%$$

Therefore, the minimum specification range for this laser power would be ± 10%, so in the process window study you would test +10% laser power from your nominal setting and –10% laser power from your nominal setting. In this same example if I wanted to use the ideal range of 10% of study variation, then the tested laser range in the process window study would be ± 30%, so you may decide that a more accurate tool is needed.

If the operating condition boundaries of the machine impact the parameters, another approach would be to run a machine stress test to see how much the process variable actually varies during the process. Examples of operating condition boundaries would be temperature, humidity, pressure in the system, filter status, length/scan time of build etc.

Example: You discuss with the OEM and find out that the machine's airflow is close looped controlled. As the filters get full, it causes pressure buildup in the system so the pump works harder to achieve the same velocity at a sensor located in the airflow loop. In this system, airflow velocity is staying constant while pump speed increases. Therefore, the boundaries of operation conditions are a clean filter vs an empty filter. If the desired measurement is airflow, you would measure the airflow in one location on the platform, then simulate a clogged filter and measure again in the same place. If the goal is to prove that the output key characteristics are not affected, then you could build bars with a new filter and with a full (or simulated full) filter. Consistent results would prove that airflow does not need to be a KPV and does not need monitored beyond initial machine IQ checks as long as machine control software remains fixed. If variation is significant, pump speed, filter pressure, or airflow at sensor may be SPC values or airflow may become a PM check item. Which of the aforementioned checks are preformed depends on which variable can be correlated to the final part variation.

4.6 Is My KPV Tolerance Range Acceptable? (Process Window Study)

Once the KPVs and corresponding tolerance ranges are determined from sections 4.1-4.5 above, the extents of those ranges should be tested to prove they don't affect the key characteristics, using a Process Window Study. Like Material Qualification and the machine stress test, this also only has to be performed once per machine model and parameter set combination. Subsequent machines will only involve an IQ followed by an OQ build and material testing.

Mechanical bars should be built with the worst-case parameters at the extremes of the platform. It is recommended that density/surface finish coupons also be built with the same parameters. These recommended density/surface finish coupons may result in visual defects that are leading indicators of issues that impact the desired key characteristics. For example, If the specimen built with power at the low end of the tolerance and spot size at the high end of the tolerance shows noticeable and measurable surface finish changes, then an inexpensive surface finish coupon may help flag problems before they drift out of tolerance.

If all mechanical bars buy-in to the material curve, then the parameters, variable limits, and measurement frequencies can be locked in, control documents finalized and OQ builds can begin.

5 Preventative Maintenance (PM) Plan

A Preventative Maintenance (PM) plan should describe what tasks are completed at each PM and what validation is needed when the PM is complete. This should also include documentation of any calibration and testing results. A PM can either be based on a set period of time or based on a machine metric such as number of layers run, laser hours, or total accumulated build time.

See *AMS7003 3.1.5 Maintenance Plan* for general guidelines on creating a PM plan.

The KPV decision tree found in Figure 4 should also aid in identifying which KPV checks should be added to a maintenance plan. For guidance on selecting appropriate measurement techniques during PMs, see Appendix 4: Discussion on Measuring Techniques.

Any maintenance items that include part replacement or recalibration should be assessed for risk to the process. A requalification or verification may be needed when the PM is complete if major components are affected (see Section 8). Any unexpected machine alterations that results from issues found during a PM should also be assessed for potential impact to the key characteristics.

Often preventative maintenance will be performed by the machine OEM. Discuss with your machine OEM the measurements that need to be added to their typical PM to meet internal requirements.

The output of every PM should be a document that includes a record of any tools used to measure and calibrate the machine as well of a record of all maintenance that was performed on the machine.

6 MATERIALS REQUIREMENTS AND TESTING PLAN

The actions that need to be completed in this segment are:

- Establish target material properties for OQ
- Define heat treatments
- Determine any additional post processing such as surface finish treatments, if required
- Define testing methods

Leveraging existing material data and specifications, establish the target material properties that the OQ build will be tested against. A test plan should also be established based on existing testing practices.

The specifications found in Appendix 3: Material Specifications should aid in the development of the target material properties if an internal material curve does not already exist.

7 OQ BUILD LAYOUT

This section is in reference to AMS 7032.

AMS7032 provides guidance for the build layout of the OQ build. Figure 6 below provides a summary of the discussion within AMS7032 to assist in decision making as it relates to the build layout.

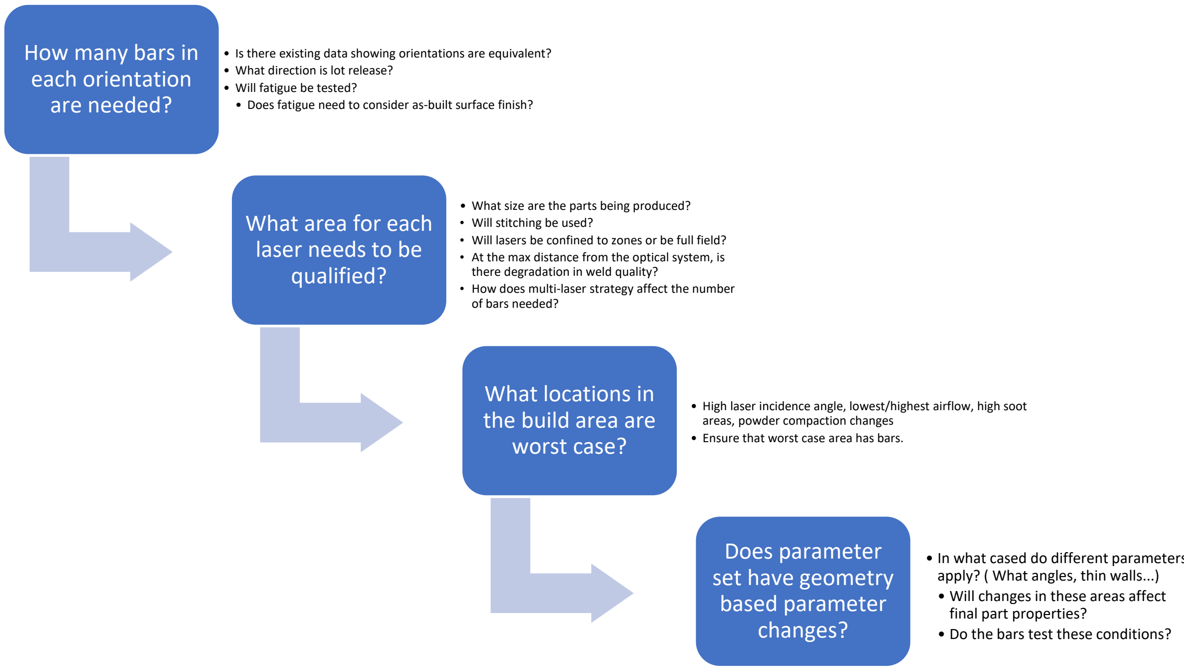

Figure 6: OQ Build Layout Determination

An example two laser and full field operational qualification build layout is shown below in Figure 7.

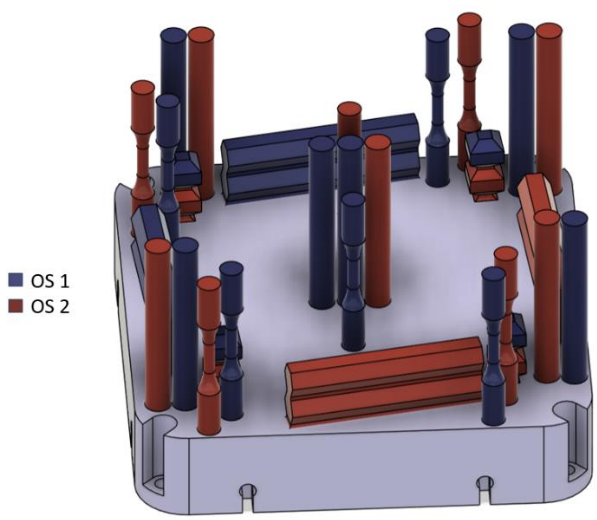

Figure 7: OQ Build Layout Example

In this example, both lasers were qualified full field. This build would be built three (3) times and would qualify the full XY of the machine but only the total Z height of the tallest bar included. This build layout also includes as-built fatigue specimens.

7.1 BUILD ORIENTATION/DIRECTION

AMS 7032 refers to test direction as lot release and requires most test bars be built in the lot release direction. This will be the same orientation that will be built alongside production parts to spot check each build. Therefore, lot release is typically determined by the part owner with the direction specified within the material specification.

As a clarification to AMS 7032, the primary build orientation tested is directed within the specification. Additional orthogonal build direction test requirements are directed within AMS 7032. If the part/application requires additional direction and property requirements, additional bar builds and testing would be required within PQ and **not** within the OQ approach.

7.2 LASER/BUILD STRATEGY

The following sections can help determine how the number of lasers on the machine will impact the OQ build layout. To design a build layout, the following questions may be considered:

- Will stitching be used?
- Will lasers be confined to zones or be full field?
- At the max distance from the optical system, is there degradation in weld quality?

A few factors to consider when choosing worst case bar locations are:

- Laser angle of incidence
- Gas flow velocity and direction
- Focal or beam shape change across the platform

7.2.1 Laser Zones vs Full Field

In a multi laser system, it is important to choose a laser strategy upfront. While the full laser reach can be qualified, there are reasons why only one laser zone would be qualified. If the manufacturer or the machine uses a zone strategy, then the extent of that zone should be qualified. If a specific process, controlled by training and control documents, has all builds setup such that lasers are never assigned to parts outside of a specific zone, then only that zone needs to be qualified even if lasers are capable of reaching the full field.

Considerations:

- What size are typical parts?
    - Can parts be divided amongst the lasers, while staying in the zones without sacrificing capacity?
- Where is the center point of each optical system?
- Is there part degradation at the extremes of the optical field?
    - As laser incidence angle gets large, the spot can lose its circular gaussian shape, leading to changes in the weld pool which can affect material properties.

  - Weld angle can have a strong effect on surface finish, leading to greater variation.
  - Laser angle into or away from gas flow and the resulting smoke can affect material properties.
- How would gas flow and the smoke plume affect parts being built in the strategy?

As seen in these points, there are risks and considerations to account for before choosing a laser zone strategy. Preliminary testing is recommended to judge if pushing lasers to the extents of their reach could risk material buy-in.

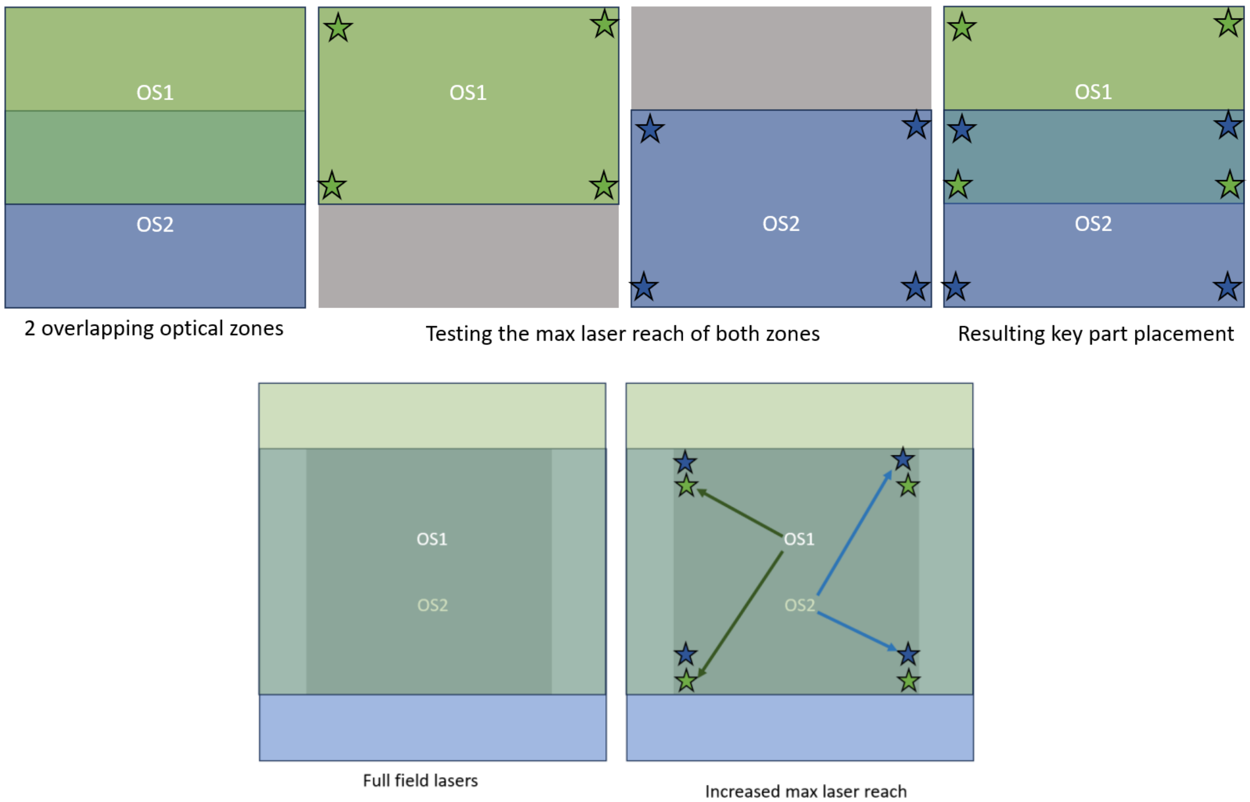

Figure 8: Zone Strategy Examples

Figure 8 demonstrates the increased max reach of having the lasers go full field. It is important to remember that in many multi laser systems where multiple lasers are used, these lasers are offset to eachother, resulting in drastically different distances and resulting laser angles. Calibration and characterization work will show if this difference causes issues.

One common issue that may degrade laser quality at the extents of a zone is a potential difference in focus in that area. This is further described in the measurement section under the Location of Focus section.

Platform variation is further discussed in Checking Parameter Performance Across the Platform.

7.3 STITCHING

7.3.1 Key Considerations in Multi-Laser Stitching

The qualification of laser stitching may be performed in either OQ or PQ. The originally issued AMS7032 required stitching qualification within OQ, however it is likely that it will be moved to PQ in later revisions.

In the case of stitching, it is important to identify worst case areas in the overlap zone. What is designated worst-case will be influenced by the optical layout, airflow and control methodology of the given machine. Things to consider:

- How could airflow and the direction and velocity of smoke travel impact stitching quality?
- How will distance from an optical system affect the quality
- How will the difference in laser incidence angle affect the quality?
- How would a small shift in the working plane due to thermal expansion, or new recoater installation affect the quality?

Stitching should be tested extensively in mechanical property bars if it is being used. A method to check stitching alignment on or before every build is recommended if the machine does not automatically check alignment during the process. If stitching is used, SPC (statistical process control) is recommended to track how stitching drifts and to catch if it has gone outside of the determined tolerance.

The current version of AMS7032 states that each laser should "contribute to building the gauge area of at least three tensile coupons". If stitching is used, "the stitched region should contribute to the gauge section of at least three coupons."

7.4 DETERMINING NUMBER OF BARS

Table 1 in AMS7032 lists the total number of bars recommended across at least three (3) builds to meet AMS OQ requirements. Section 3.2.2 further details the minimum requirements of an OQ build.

The current version of AMS7032 describes fatigue as optional. A revision to AMS7032 may require fatigue and specify a different quality and orientation requirement.

Review the requirements within the current version of AMS7032 carefully as they are undergoing change at the time of this writing.

Note that chemistry and microstructure can be taken from the same coupon or any coupon on the platform such as the tip of a tensile bar.

7.5 TYPE OF BARS

7.5.1 As Built Bars

This section only applies to cases where fatigue testing is required as part of OQ. As built bars will perform worse than machined bars due to their rough surface finish. The type of bar selected should consider what the machine is capable of building and what geometries and angles the machine will be running in production.

7.5.1.1 Verticals

Vertical as-built bars are the most common form. With high-contact recoaters like steel blades or rollers, these bars often need supports so the gauge section does not become bent. It is important that the support does not touch or sinter to the as-built gauge section. The gap needed between supports and parts will vary based on parameter set and angle of parts.

7.5.1.2 Angled As-Built Bars

The goal of non-vertical as-built bars would be to capture the effect of down facing surfaces on fatigue life. There are several aspects to this. Note that a support system would likely be needed on any angled bar if using a high contact recoater.

1) What is the maximum angle on the part where an “as-built” surface will be left on a final part?
2) At what angle does a different downskin parameter apply?
3) Are there multiple downskin parameters that apply?
4) Are there channels in the part that would be fatigue limiting?

Examples:

Example 1: Simple parameter

Parameter has no separate downskins that go into effect. All surfaces steeper than 45 degrees are supported. There are no holes or channels in the part where fatigue would be a concern. In this case consider building angled bars that correspond with the steepest as-built, unsupported surface that will be allowed. The neck of these bars will exceed the tested angle and therefore can be an issue to build.

Example 2: Complicated parameter

Parameter has downskin parameter that takes affect at 20 degrees and second downskin parameter that takes effect at 30 degrees. Because the parameter is using a different strategy (power, speed, scan direction) at different angles, the resulting porosity and fatigue growth characteristics could be different. It is important to carefully inspect the build files before starting to ensure the parameters are taking affect as many machines won’t perfectly apply the parameter directly at the intended angle.

- Build 19* degree bars
- Build 45 degree bars

* The first set of bars should be built at the steepest angle where the parameter fully applies on every layer of the gauge section. Review scan files carefully to ensure intended test is valid. It is recommended that these types of tests be moved to PQ because they are part specific and would add additional costs to OQ.

7.5.1.3 “Horizontal” As-Built Bars

If machines can build unsupported as-built bars, then these bars should be included if Fatigue testing is required. Building horizontal as-built bars is not typically possible on LPBF machines because support would be required on the gauge section, negating the effectiveness of what is being tested. If there are holes or channels in the part where fatigue would be a concern, and these holes have downfacing closeouts (are not build in Z direction), then a discussion should be had with the part owner on the best way to design a test bar to represent this surface.

Due to the difficulty of building angled as-built bars, horizontal bars with holes through the center can potentially be used. The center hole represents the as-built downskin surface, and the outside of the bar is machined. It is recommended that you discuss how to machine and test these with your testing vendor.

It is recommended that these types of tests be moved to PQ because they are part specific and would add additional costs to OQ.

7.5.2 Microstructure/Chemistry

Microstructure and chemistry specimens can be combined into one specimen or taken from other parts of the build such as extra stock on a tensile bar. Similar to mechanical property specimens, both microstructure and chemistry should be evaluated after all heat treatments are complete. Microstructure should be cut and examined in at least two orientations, the XY and an orientation that looks at the Z direction. These specimens can also be used to measure density or characterize porosity if they are cut and polished.

7.5.3 Other Measurements

Dimensional coupons as well as surface finish coupons are also helpful to gauge the quality and consistency of the process. Surface finish coupons, especially those that include down facing surface, can be a way to characterize variation as surface finish is often sensitive to airflow and laser angle of incidence variation.

8 REQUALIFICATION VS VERIFICATION EVENTS AND TESTING

Before implementing any changes to the machine, procedures, or surrounding environment, it is essential to assess the potential impact on the machine's output. This includes any maintenance activities, such as recalibration or replacement of parts. A thorough analysis of the potential effects of these changes should be conducted, and the changes must be approved by technical leadership.

Table 1 in the current version of AMS 7032 lists some changes and the level of requalification needed for each.

Verification events are not discussed in AMS 7032; however, it is worth noting that there may be some small changes that only require a verification effort, and not a full requalification, because the risk incurred by the change is minimal.

Verification Example 1: A change in setup software where the release notes state that the changes are to make the software more stable. Here, if one can validate on a vector level that vectors are applied the same (for all feature types, at all angles), the scan order doesn’t change and the actual build time doesn’t change, then to implement such a change may not require a build but may require customer and leadership approval.

Verification Example 2: At PM intervals, hoses on the machine are changed out. Here you might implement a check that everything is grounded correctly after the change with a check of continuity, but no build would be needed.

The verification events will be further validated through the on-going lot release testing.

8.1 MOVING A MACHINE

Moving machine is considered a major requalification event for several reasons. A new machine environment can change the temperature, humidity, and vibrations a machine experiences. Additionally, machine movement can cause movement of the lenses and in extreme cases, bending of the machine frame or optical train. In some machines when the machine is turned off to be moved, it is missing critical components of its optical cleanliness protection such as a pressurized optical cabinet. It is recommended that after any movement, a full beam caustic be performed before beginning the requalification process.

8.2 OTHER REQUALIFICATION EVENTS

Other requalification events, not previously discussed, should be determined based on the machine and the exact nature of the change. Each change should be evaluated carefully and assessed for potential impact those changes may have on Key Characteristics.

Here, a “Full OQ” is defined as a repeat of the full qualification process, including all calibration checks and all three OQ builds with the corresponding testing. A “Partial OQ” is considered a subset of the full suite of checks. These should include calibration checks on any items that may be adversely affected by the change and then one or two builds to check any Key Characteristics that may have been adversely affected by the change. “Verification” is defined as specific checks of calibration of functionality to make sure the change had no effect on any process variable and therefore could not possibly affect downstream material properties or machine performance.

A general recommendation is shown below in Table 1.

Table 1: Requalification vs Verification Events

Full OQ	Partial OQ	Verification
Move machine	Critical SPC or PM items are out of tolerance and need recalibration.(beam shape, focus location)	Minor adjustment of power curve
A change in inert gas	Software or firmware that influences meltpool (vector strategy, cooling firmware, control loop modification)	Small setup software updates
New powder ordered to different specification	New powder vendor ordered to same specification	New powder heat (Quality testing)
Change in material parameter	An increase in size of laser zones (builds should	Change is hardware that does not affect

(speed, vector spacing/strategy, power etc)	focus on new area added to laser zone)	weldpool (platform assembly, hoses, sieves)
Change in laser pulse characteristics	Machine has not been used for extended period of time	Machine has not been used for predetermined period of time
Replacement of hardware that influences meltpool (Optical train components)		Minor PM items are out of tolerance (scan field calibration on single laser systems) but drift has not caused material or part tolerances to be out of spec.
Use of multi-lasers on single part where it was not qualified previously		A change in parameter that does not affect part and would not show up in test bars (support change, first layer parameter change). Verification may involve building of parts and should be discussed with part owner

9 MATERIAL TESTING

Once the bars have been built and completed post-processing, the next step is to send the bars out to test the mechanical properties. The plan laid out in section 6: Material Requirements and Testing Plan should be implemented. Mechanical properties such as tensile, LCF and compression should be tested using a certified vendor with calibrated equipment. Internal testing, measurements and analysis will also be done during this phase. Check with vendors before the use of any sub-scale or non-standard specimens to ensure they have the capability to test those parts.

Appendix 1: AMS KPV List and Discussion

The Minimum KPVs

In a LPBF machine, there will be five primary KPVs.

The minimum KPVs are shown Table 2 below.

Table 2: Minimum KPVs

	Variable	Description	Impact to Process
1	Scan field calibration	The calibration of the scanner that ensures the positional accuracy of the laser at the working plane.	Impacts component geometrical /dimensional accuracy as well as scan speed.
2	Shielding gas flow rate	Flow rate of gas entering the build chamber that is used to remove smoke and condensate while building	Shielding gas evacuates smoke from the chamber, preventing the smoke from interfering with power delivery to the working plane. Gas flow can also move weld pool ejections, disturb the powder bed and impact cooling rate. Gas flow changes primarily affect porosity and surface finish.
3	Oxygen content	Oxygen content in the build chamber and the recycled atmosphere.	High oxygen content can lead to oxidation of certain materials. Oxide formation primarily affects mechanical properties.
4	Power of each laser	The commanded power and the delivered power at the build surface.	Fundamental to the process. Impacts the material quality (surface finish, mechanical properties) Changes in the power result in a change in power density which can fundamentally change the weld pool.
5	Beam spot size and shape of each laser	Properties include: Shape of the beam, refers to the powder distribution within the laser spot (top hat, Gaussian, astigmatism etc.) Thermal stability – effect of heating of the optics (thermal lensing) on the size and shape of the beam Spot size at focus – the smallest spot size capable of the beam Spot size at working plane- spot size use at the working plane called by the intended parameter set.	Fundamental to the process. Impacts the material quality (surface finish, mechanical properties). Changes in the beam result in a change in power density which can fundamentally change the weld pool.

AMS KPV List

While we identified the five (5) minimum KPVs, other variables are fully listed in Appendix A of AMS 7003.

APPENDIX 2: INDUSTRY STANDARDS FOR MATERIAL

GENERAL FEEDSTOCK REQUIREMENTS

Published:

- AMS7031 Batch Processing Requirements for the Reuse of Used Powder in Additive Manufacturing of Aerospace Parts
- AMS7025 Metal Powder Feedstock Size Classifications
- ARP7044 Powder History Scoring Metric and Labeling Schema
- AMS7002A Process Requirements for Production of Metal Powder Feedstock for Use in Additive Manufacturing of Aerospace Parts
- AMS 7002 "Process Requirements for Production of Metal Powder Feedstock for use in Laser Powder Bed Additive Manufacturing of Aerospace Parts"
- ASTM F3049 "Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes"

Work in Progress:

- ARP7302 Powder Sampling Strategies for Closed Loop Additive Manufacturing Equipment
- GA_AM-M20-C General Agreement: CP-Ti or Ti-alloy Powder Template
- AIR7359 Additional Guidance for Metal Powder Feedstock for Additive Manufacturing
- AS7040 Requirements for powder distributors
- AMS7052 Continuous, Closed-Loop Process Requirements for the Reuse of Used Powder in Additive Manufacturing of Aerospace Parts

POWDER FEEDSTOCK REQUIREMENTS

Published:

- AMS7018 Aluminum Alloy Powder 10.0Si – 0.35Mg
- AMS7033 Aluminum Alloy Powder, 4.6Cu – 3.4Ti – 1.4B – 0.75Ag – 0.27Mg
- AMS7020 Aluminum Alloy Powder, 7.0Si – 0.55Mg – 0.12Ti
- AMS7023 Gamma Titanium Aluminide Powder for Additive Manufacturing, Ti – 48Al – 2Nb – 2Cr
- AMS7008 Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 47.5Ni – 22Cr – 1.5Co – 9.0Mo – 0.60W – 18.5Fe
- AMS7013 Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 60Ni – 22Cr – 2.0Mo – 14W – 0.35Al – 0.03La
- AMS7001 Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 62Ni – 21.5Cr – 9.0Mo – 3.65Nb
- AMS7006 Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 52.5Ni – 19Cr – 3.0Mo – 5.1Cb (Nb) – 0.90Ti – 0.50Al – 18Fe
- AMS7021 Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 15.0Cr – 4.5Ni – 3.5Cu – 0.30Nb
- AMS7012 Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 16.0Cr – 4.0Ni – 4.0Cu – 0.30Nb

- AMS7035 Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Binder Jet Additive Manufacturing, 16.0Cr – 4.0Ni – 4.0Cu – 0.30Nb
- AMS7037 Steel, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 17Cr – 13Ni 2.5Mo (316L)
- AMS7017 Titanium 6-Aluminum 4-Vanadium Powder for Additive Manufacturing, Extra Low Interstitial (ELI)
- AMS7015 Titanium 6-Aluminum 4-Vanadium Powder for Additive Manufacturing
- AMS7014 Titanium Alloy, High Temperature Applications, Powder for Additive Manufacturing, Ti – 6.0Al – 2.0Sn – 4.0Zr – 2.0Mo
- AMS7026 Titanium Ti-5553 (Ti – 5Al – 5Mo – 5V – 3Cr) Powder for Additive Manufacturing

Work in Progress:

- AMS7012A Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 16.0Cr – 4.0Ni – 4.0Cu – 0.30Nb
- AMS7054 Aluminum Alloy Powder, 6A61.50 (A6061-RAM2, composition similar to UNS A96061)
- AMS7070 Aluminum Alloy Powder, 7A50.50 (composition similar to UNS A97050)
- AMS7055 Steel Powders 3.5Cr – 7.5Ni – 16.3Co – 1.75Mo – 0.2W – (0.10 – 0.15 C) Inert Gas Atomized
- AMS7021A Precipitation Hardenable Steel Alloy, Corrosion and Heat Resistant, Powder for Additive Manufacturing, 15.0Cr – 4.5Ni – 3.5Cu – 0.30Nb
- AMS7063 Aluminum Alloy Powder, HPA1 (12Si-4Cu-0.4Mg-0.5Fe-1.0Ti)
- AMS7045 Aluminum Alloy Powder, 5.3Zn – 3.3Mg – 1.7Zr – 1.6Cu (composition similar to 7A77.50)
- AMS7058 Laser Powder Bed Fusion Produced Parts, Aluminum Alloy Powder Al-1.0Mg-0.6Si-0.28Cu-0.2Cr-0.7B-0.2C-2.4Ti (composition similar to 6061), T6
- AMS7059 Copper Alloy Powder for Additive Manufacturing, Cu – 1Cr – 0.15Zr
- AMS7060 Niobium Alloy Powder for Additive Manufacturing, Nb – 10Hf – 1Ti
- AMS7001A Nickel Alloy Powder for Additive Manufacturing, 62Ni – 21.5Cr – 9.0Mo – 3.65Nb

APPENDIX 3: MATERIAL SPECIFICATIONS

CONSOLIDATED MATERIAL SPECIFICATIONS:

Published:

AMS 7001 (IN625) Nickel Alloy, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 62Ni - 21.5Cr - 9.0Mo - 3.65Nb
AMS 7030 (AlSi10Mg) Aluminum Alloy, 10.0Si - 0.35Mg Stress Relieved, Hot Isostatic Pressed (HIP), Solution Treated and Artificially Aged, Produced by Laser Powder Bed Fusion (L-PBF)
AMS 7037 (Steel 316L) Steel, Corrosion and Heat-Resistant, Powder for Additive Manufacturing, 17Cr - 13Ni - 2.5Mo (316L)
ASTM F2924 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
ASTM F3001 Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
ASTM F3055 Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion (IN718)
ASTM F3184 – Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion (17-4PH)
ASTM 3213 Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion
ASTM F3302 Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Titanium Alloys via Powder Bed Fusion
ASTM F3318 Standard for Additive Manufacturing – Finished Part Properties – Specification for AlSi10Mg with Powder Bed Fusion – Laser Beam

Work in Progress:

AMS7073 Laser-Powder Bed Fusion (L-PBF) Produced Parts, Steel, Corrosion and Heat-Resistant, 15.0Cr - 4.5Ni - 3.5Cu - 0.30Nb (15-5), Solution and Precipitation Heat Treated (Steel 15-5)
AMS7071 Laser Powder Bed Fusion Produced Parts, Aluminum Alloy 7A50.60L (A7050-RAM2, composition similar to UNS A97050), Hot Isostatic Pressed and T74 Aged
AMS7024 Inconel 718 L-PBF Material specification

Testing Requirement Specifications:

ASTM E8/E8m-24 Standard Test Methods for Tension Testing of Metallic Materials
ASTM E9 Standard Test Methods of Compression Testing of Metallic Materials at Room Temperature.
E606/E606M-21 Standard Test Method for Strain-Controlled Fatigue Testing
ASTM E18 – Standard Test Methods for Rockwell Hardness of Metallic Materials.
ASTM F2971 Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
ASTM F3049 – Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes.

APPENDIX 4: DISCUSSION ON MEASURING TECHNIQUES

MEASUREMENT TERMINOLOGY AND NOTES

The working plane is defined by where the top plane of the powder is after a recoat; therefore, in most systems it is safe to assume the working plane is defined by the bottom of the recoater. Figure 9 shows the working plane as defined within this document.

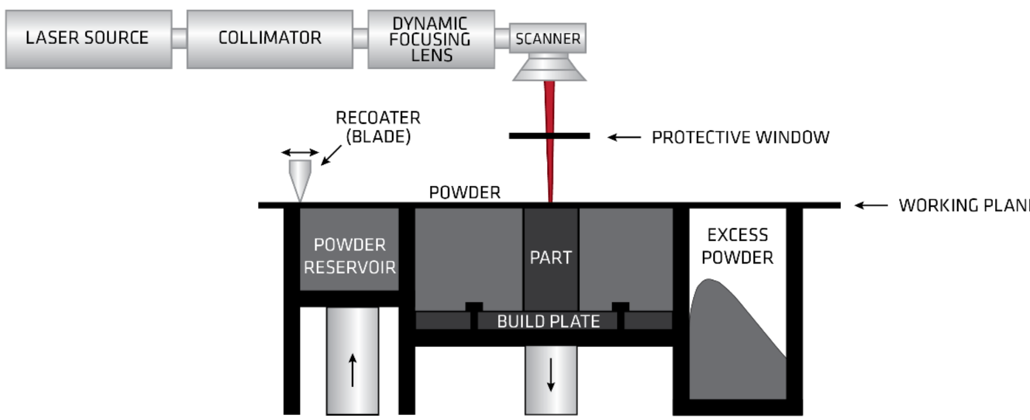

Figure 9: Working Plan Identification

Different machines and machine OEMs allow different level of access. Discuss with machine OEM about the measurements that need to be recorded and make sure they provide the access or can perform these measurements for you.

MEASUREMENT FREQUENCY

Understanding the appropriate measurement frequency of a variable will help determine if that variable should be measured and tracked as part of SPC, or less frequently as part of preventative maintenance. This is discussed in Section 4.1.

Example Measurement Frequency Decision Tree: Scan Field

Scan field calibration is an item typically controlled at preventative maintenance intervals. A drift in scan field calibration would cause parts to be incorrectly sized, out of round, or curved when they should be straight. Therefore, the tolerance put on this item should be based on the tolerance of parts, the capability of the scanner and the accuracy with which the scan field can be measured.

If a single laser is being used in the process, then deviations in this KPV would be caught in dimensional inspection of parts and therefore, a process window study is not strictly needed.

If a multi laser system is used and stitching is being qualified, deviation in scan field would contribute to the misalignment between lasers. Lasers that are not correctly aligned to each other will often result in porosity and surface defects on parts. Therefore, to qualify laser stitching, including laser to laser misalignment, the use of a process window study to understand at what point it affects material and part properties is recommended. Where stitching is being applied, scan field calibration becomes a more frequent check than a PM item. Here, particularly where automatic calibration units are used, scan field calibration and laser to laser alignment would become an SPC item as the drift in laser to laser overlap and maximum calibration error should be measurable.

Figure 10 displays a decision tree to help determine the frequency in which scan field calibration should be checked.

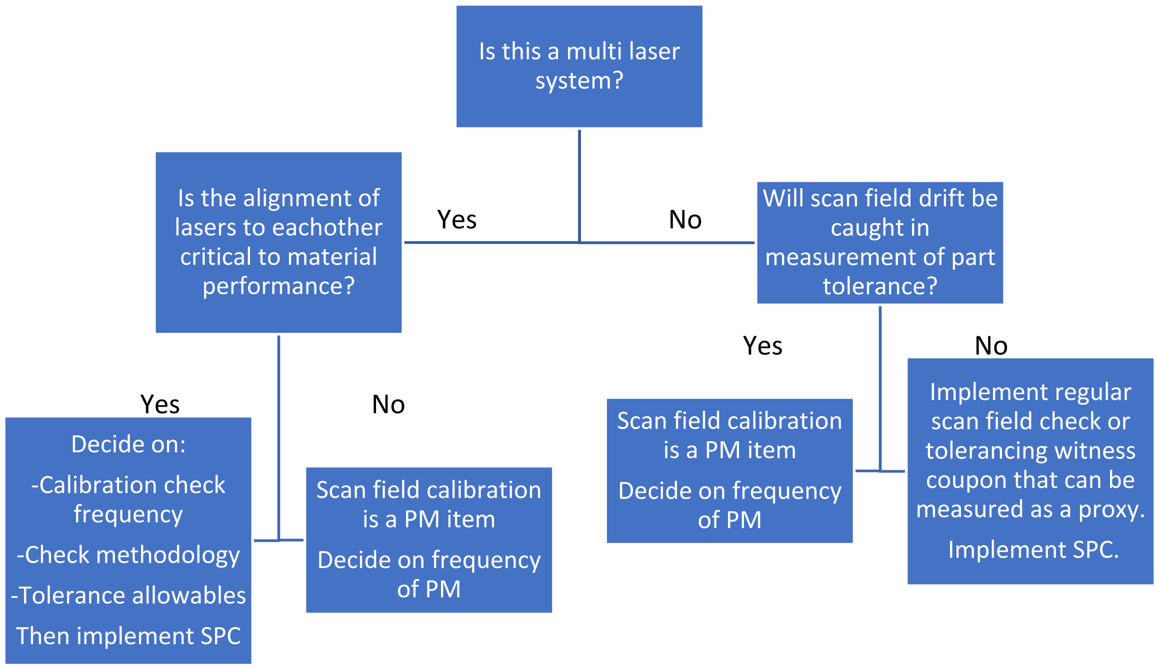

Figure 10: Example Decision Tree for Scan Field Calibration

Machine Data and Log Files

Most modern machines output some basic data that may be tracked to indicate issues with the machine. While most of this data is basic and does not directly track KPVs, there still may be enough data to indicate machine problems. It is advisable to understand all data tracked by the machine to understand if any of that data may be useful in early detection of issues. At a minimum, most machines track total build time. In production, a change in total build time could signal an unintended change in process that may warrant investigation.

Laser Power

Background Information

Lasers should be checked at a range of powers to ensure accuracy. It is important that the checked range include the min and max power used in the parameter set that will be qualified.

If parameter set has not been determined, it is important to note that most lasers should not be operated below a certain threshold as they become unstable. The general rule of thumb is 10% of max laser power, but this should be determined based on the laser OEM. It is also advisable that parameters never call the max stated power of the laser, as lasers will degrade over time, meaning the max available power after a few years can be lower than the stated max power of the laser.

Laser Power Equipment

There is a variety of laser power equipment on the market. Before specifying equipment for a shop, first verify a few key points:

- Machine allows access to take the measurement (beam straight down, beam on for commanded period of time).
- Quoted device accuracy
  - This will control SPC/PM tolerances for your process
- Device is capable of measuring at machine's laser wavelength
- Device is capable of measuring at machine's max/min power
- Device is capable of measuring at laser's energy density
  - User may have to defocus laser or move device out of laser focus to use
- Are there cables that must be run outside of the machine
  - Does machine setup allow for this to be done safely?
  - If not, consider wireless options
- Will device require cooling for intended use?

Frequency of Checks

It is important to double check the called verses actual power output at a minimum of every 6 months to ensure the laser output is still as expected. Quick checks of two to three key power calls are recommended more often, depending on application. The frequency for higher criticality applications can range from before every build to once a month. Discuss with your machine OEM on how to get access to do these checks.

BEAM QUALITY

When discussing beam quality, it is helpful to understand the anatomy of the laser beam.

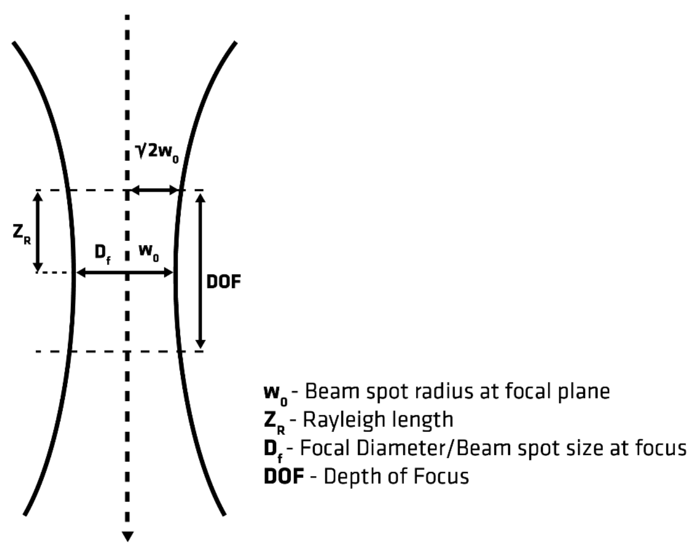

Figure 11: Basic Laser Anatomy

Figure 11 show the profile of a laser as it goes into and out of focus. The focal diameter, Df, is the diameter of the beam at the smallest point in the beam waist, often referred to as minimum spot size, or the smallest diameter the laser can achieve in a system with a stationary collimator.

Beam Profiling Equipment

Beam profiling, also sometimes referred to beam caustics, is a set of measurements that analyze the size, shape and quality of a laser beam as well as power distribution and total input power. Beam profiling equipment is generally expensive and often require special machine access granted by the OEM which is why these measurements are often performed by the OEM. If the OEM does allow access to take this measurement, the device should be chosen carefully considering what connections the profiler requires and if there are wires and cooling, how can be safely run into the system. It is important to understand the tolerances around this equipment, especially as it pertains to the location of focus.

A beam caustic can help diagnose issues including optical misalignment, thermal lensing, location of focus and variation between lasers as well as issues pertaining any device that is adjusting focus such as a 3D scanner. The majority of beam profilers do not allow the beam to enter at an angle, therefore, this is a measurement taken directly below the optic. To infer beam quality at the extents, weld comparisons on plate or specimen comparisons can be used.

Figure 12 is a photo from Cinogy showing a high-quality laser beam profile.

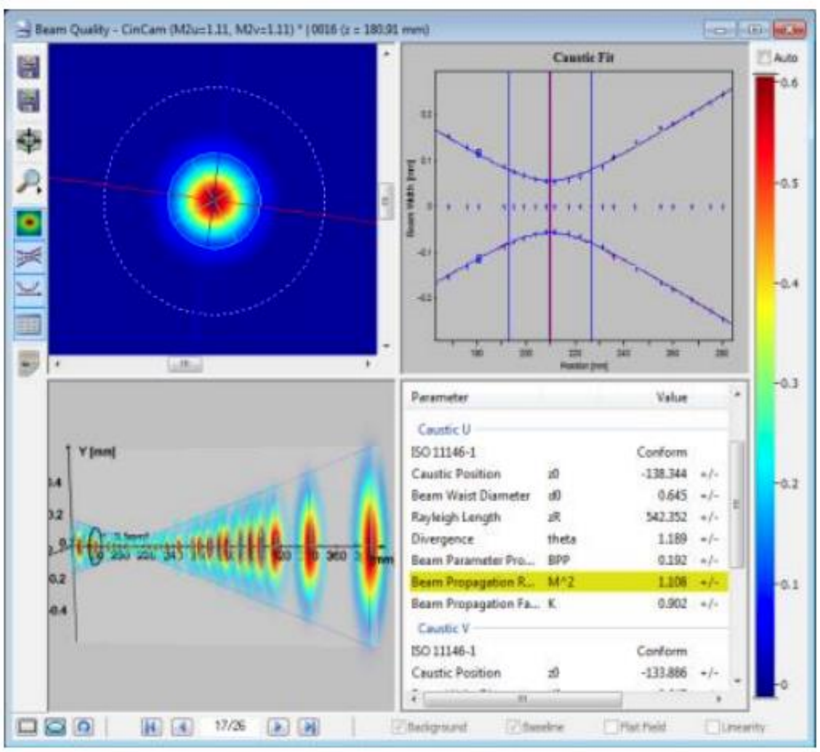

Figure 12: High Quality Laser Beam Profile[3]

[3] "https://www.cinogy.com/html/measurement_tool.html

Thermal Shift

The same beam profiling equipment can be used to determine thermal shift. Thermal shift, also called thermal lensing is a change in size of the beam when the components in the optical train heat up. Some thermal lensing is typical and should be characterized on a new system. A portion of the thermal lensing can come from the measurement device itself, so it is important to always use the same device model to set baseline and preform PM checks. The amount the beam size is expected to change should be considered as spot size tolerances are determined for the process study window.

Thermal lensing that is larger than normal is often caused by lens or window contamination.

Minimum Spot Size and Spot Size at Working Plane

The same beam profiling equipment can be used to determine min spot size, the spot size at set defocus commands, the spot size at the working plane and the beam quality. In some systems that operate "in focus" (i.e. At the smallest area of the beam waste) the min spot size will be the same as the spot size at the working plane. Beams spot variation is minimal within the Rayleigh length but changes faster outside of this length. This is why it is important to understand both what the system's potential unintended working plane variation may be and how much that may change the spot size so that these values can be considered within the process study window. Thermal lensing combined with this shift would provide the worst-case scenario for spot size change.

Some systems will shift focus within the parameter or as a standard. Figure 13 shows why a change in Z, or working distance, changes the spot size. This is discussed further in Location of Focus.

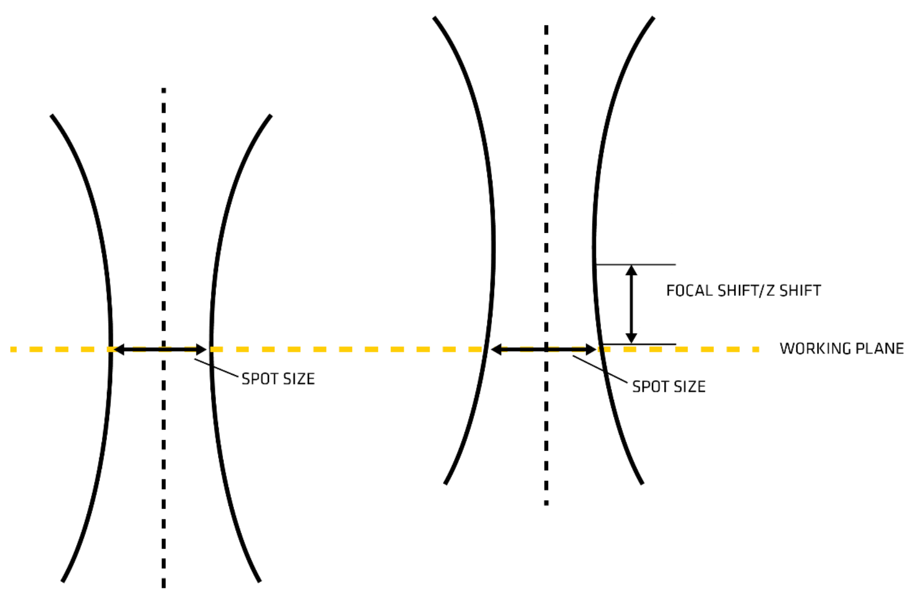

Figure 13: Spot Size Example

Beam Quality

The beam quality metrics would change for beams that are not gaussian in profile and for non-traditional laser sources. If the beam is a gaussian beam, beam quality can include the M2 value and astigmatism. The M2 value, also called beam quality factor or beam propagation factor, is a unitless measure of deviation from a nominal gaussian profile. Checking that this value is consistent between lasers, between machines and over time will help keep the machine performing as expected.

Astigmatism, as it is referred to in AMS 7003, is when a beam size measures differently in one axis than the other rather than being perfectly circular.

LOCATION OF FOCUS

A typical laser beam on an AM machine with a single mode fiber laser has a profile shown below in Figure 14.

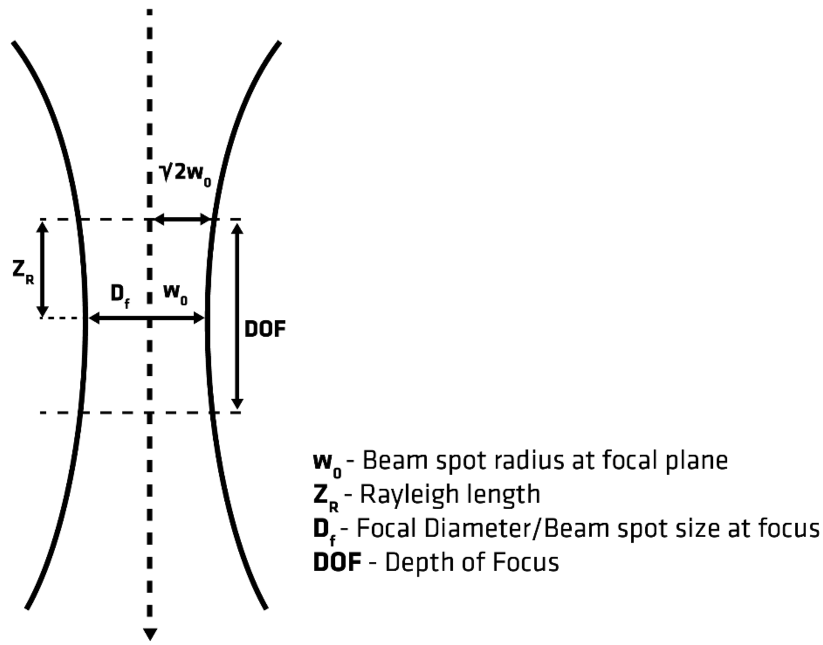

Figure 14: Laser Beam Profile

Figure 14 shows that if the working plane is aligned in the Z direction with the smallest diameter of the beam waist, i.e. the location of the focal diameter (D_f), small movements in Z will have a limited effect on beam spot size because the beam diameter has the lowest variation within the Rayleigh length (Z_r). Therefore, if the parameter being used works exclusively with the beam in focus, the allowable Z shift tolerance may be higher than if the beam is defocused in the parameter set. In other words, the same shift in Z would result in a more significant change in spot size if the laser is operating outside the Rayleigh length. There are many potential ways to set the initial tolerance on focal shift that will later be checked in the process window study, but the key question to ask is: “How much is it likely to shift?” A starting point would be to assume that it is likely to shift at least as much as the thermal z-shift recorded during the caustic measurement at installation. This is the difference between the location of focus of the laser at minimum power, and the location of focus at the maximum power. Figure 15 shows how a shift in the location of focus changes the beam spot size at the working plane.

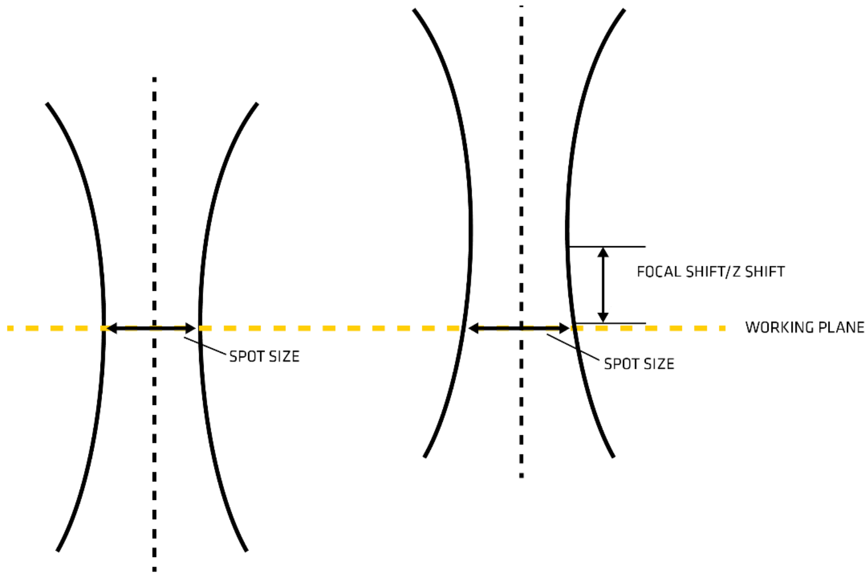

Figure 15: Thermal Lensing Causing a Shift in Focal Location

Setting up for measurement:

The working plane is defined by the top surface of the powder after a recoat*, therefore, in most solid recoater systems it is safe to assume the working plane is defined by the bottom of the recoater. To start this measurement, first align a flat plate to the bottom of the recoater, taking care to check that the plate is in the same plane as the bottom of the recoater throughout the full build area. Often this is done using a ground build plate, however it should be noted that a build plate does not always hold tight tolerances to the full working plane in both the X and Y direction.

* In soft recoater or "non-contact" systems, this may not be the case.

Reason focus might vary across the build platform:

The location of focus across the working area can vary. As demonstrated in Figure 16, the beam must travel different distances to hit each location on the build platform. 3D scanning optics and Fthetas attempt to compensate for this, but don't always perfectly "flatten" the scanfield.

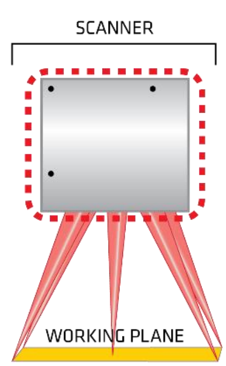

Figure 16: Variation in Laser Travel Distance Across the Platform

While using a beam profiler to measure the location of focus in the center of the field is the most accurate, these measurement tools can't typically be used if the beam is at an angle to the measuring device. Therefore, other methods of comparing the focal location at the center of the platform vs the edges must typically be used.

As the beam goes out of focus, the spot size gets larger resulting in the same amount of power being spread over a larger area. This results in

- A change in weld pool size
- A change in weld pool depth
- A change in energy density

Therefore, one can use the Z axis or command the 3D scanner (if applicable) to move through the laser's focal area and either measure the resulting weld pools on a metal plate, or using an anodized plate determine where the energy density surpasses a minimum threshold. If using the 3D scanner to control focal changes for this test, it is advised that results are compared against physical movements once on the system to check that the results are the same.

Scan Field Calibration

Scan field calibration describes the process of making sure the energy source is accurate at the working plane. In typical LPBF machines, the laser is controlled using a scanner with two mirrors that translate their rotational movement to linear movement on the platform.

Uncalibrated scanners will draw an arc rather than a straight line. There are a variety of tools offered by scanner companies and some machine OEMs that make preforming a scanfield calibration easier. Here are a few additional resources on scan fields:

https://novantaphotonics.com/calibration-accuracy-for-laser-scan-head-sub-systems/

https://www.raylase.de/en/products/image-processing-and-measurement-systems/scan-field-calibrator.html

If automatic calibration is not available for the system, the process can be performed by the machine OEM or vendor using a pattern drawn by the machine that is then checked by an optical CMM. It is critical that any calibrations be performed at the working plane.

The primary data that should be recorded when scan field is checked is the average deviation and max deviation values.

Stitching quality

Stitching quality can be checked with machine or scanner OEM supplied calibration units, done with welds on a plate or checked during a build with parts. Each of these has advantages and disadvantages. Calibration and plate checks can be run before a built to ensure build quality but are often dependent on an operator to correctly find the working plane which often has gauge errors. Parts during a build are the most representative of the actual process but are subject to distortion or the part and built plate as well as rough surface finish that may make measurements or visual judgements challenging.

Airflow – Directly Outside of Inlet and/or Across the Platform

Airflow is typically measured by a sensor in the gas flow loop. Check the sensor for factory calibration and calibration expiration dates. If an airflow sensor needs to be removed to be recalibrated, it is recommended the machine OEM performs this task. A requalification should be completed in the event that the internal airflow sensor is modified, replaced or removed/reinstalled.

Airflow will technically be validated by the mechanical properties of OQ build, however, to reduce risk of a machine not buying into the mechanical properties, it is advisable to check the airflow consistency on a new machine. The OEM may already do this during the factory calibration or site acceptance testing.

Because mechanical properties are sensitive to airflow, one way to verify the airflow would be to build parts at the extremes of the airflow and compare surface finish and density to a machine that has previously passed OQ. To find the worst and best-case areas, take note of if the airflow comes in at an angle and where the outlet to the chamber airflow is to make educated guesses of areas of maximum variation.

Another, more direct, way to test airflow would be by using an anemometer in the chamber. For low airflows, a hot wire anemometer or an ultrasonic anemometer are two options that can be found for the low velocities seen in a chamber environment. Critical to this setup would be the repeatability of the location of the anemometer each time gas flow is checked.

Airflow can typically be monitored, and values recorded by the machine. Relevant values are airflow velocity, pump speed or current draw, and pressure in the system or across the filter. A machine that is close loop controlled will increase pump speed to maintain airflow as the filter gets clogged. On a machine type that is new to the facility, it is recommended that a stress test is preformed to prove that airflow is stable and to generate the tolerances in which airflow, as measured by the machine, may vary. This is also discussed in the example in Section 4.5.

Oxygen Content

Oxygen values are monitored in at least one, but often multiple places in the machine. The oxygen values are typically recorded by the machine and can be accessed through log files or machine APIs. Oxygen content does not typically require an on-machine calibration if the sensors are factory calibrated and certified. Typically, this means that on a yearly basis, these oxygen sensors must be changed and sent out for OEM recertification.

It should be noted that it is challenging to test the top of the oxygen range using a process study window. In this case it is recommended that oxygen be tracked with SPC and the limits established over time. After running the extent of a single filter’s life, there should be enough data to understand the average oxygen content during runtime and flag an investigation if oxygen drifts significantly or if the standard deviation of oxygen values begins to grow.

Scan Speed

Equipment to measure scan speed accurately is prohibitively expensive. Methods such as using a stop watch are also highly inaccurate and don’t account for vector delays. While industry currently lacks a standard process in how to account for scan speed, the following logic is generally understood as true by some industry members:

While scan speed can change throughout a vector as the scanner accelerates, it is highly unlikely to change from build to build if the scanner control is time-based and the parameters are not adaptive (controlled in a closed loop by the machine). The scan speed might not be exactly equal to the set value, but it will be consistent build to build and machine to machine if the scan field is accurate. Therefore, if the machine passes mechanical and dimensional testing during OQ, one can say the scan speed is good. A change is scan speed would likely come out as a dimensional change in parts and would show up in inaccuracies in scan field calibration.

Checking Parameter Performance Across the Platform

As discussed in the corresponding sections above, the part quality can vary across the platform due to airflow differences, beam spot size variation, beam shape variation and laser incidence angle. Therefore, a recommended pre-check to OQ would be to understand weld pool width and alignment at the extents of each laser zones. If the weld pool changes or the distance between the fill and external vectors changes significantly, then it may be safest to qualify a smaller laser zone. A further step in this check would be to build small parts at the extents that include overhangs and then cut and polish them to assess the porosity in these parts to assess variation. Remember that weld width is a function of power delivered, speed, spot size and beam shape.

OTHER DISCUSSIONS

PQ MEASUREMENTS

It is notable that very thin parts with extremely short vectors may show different microstructure, density and mechanical properties due to a variety of factors. Therefore, if thin walls are a part of the final product, it is recommended they are tested separately in PQ.

Other considerations for PQ testing:

- As build angles outside of OQ testing
- As-built holes that are fatigue critical
- Surfaces with support removal that is fatigue critical
- Surface finish post processing fatigue affect if post processing varies from OQ

DIFFERENT MACHINE SETUP TERMINOLOGY

Figure 17 shows the terms typically used when referring to a system that uses an F-Theta lens to flatten the field. An F-Theta lens, also called flat field lens, is a specialized lens that focuses the laser beam to ensure consistency in spot size across the working plane. An F- theta system is a static system, requiring no moving parts to flatten the focal plane. If focus is to be adjusted, an additional lens would be added prior to the scanner.

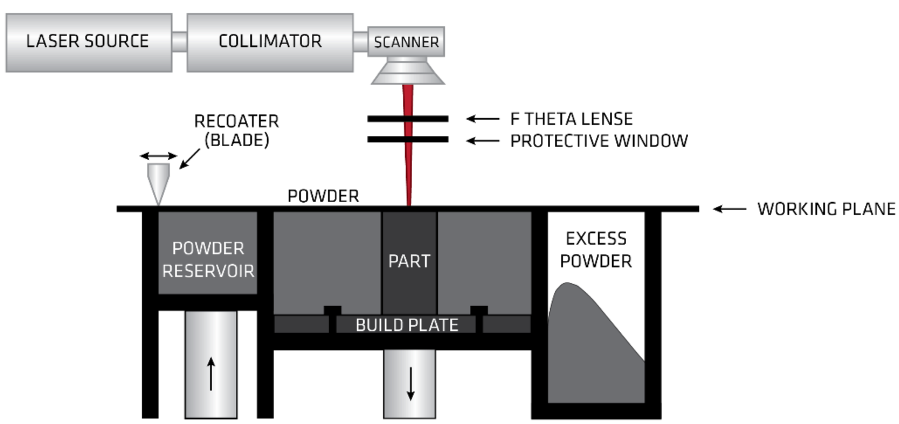

Figure 17: F Theta Setup

The following diagram shows the terms typically used when referring to a system that uses a Dynamic Focusing lens, also called a 3D Scanner, to flatten the field dynamically. A focusing lens moves anytime the laser changes position to account for changes in working distance and ensure a consistent spot size. The Dynamic Focusing Lens also allows for spot size changes of the laser beam.

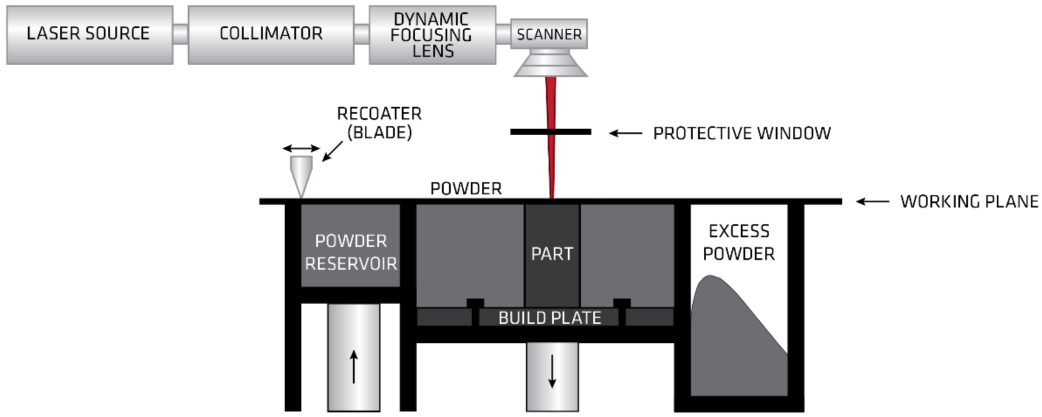

Figure 18: Dynamic Focus/3D Scanner Setup

GLOSSARY

As-built – this refers to bars with a surface finish that has not had any secondary processes or machining applied to it out of the LPBF machine. In this document it is assumed that "as-built" bars go through the same heat treatments as all other bars.

FAT – Factory acceptance test – A series of tests run by the Original Equipment Manufacturer to ensure that the machine's performance falls within expected tolerance defined by that manufacturer. This is the final check that a machine is functioning correctly before shipment from the factory to the customer.

Full OQ – A repeat of the full qualification process, including all calibration checks and all three OQ builds with the corresponding testing.

IQ – Installation Qualification – The set of tests performed to verify that a machine is installed correctly.

KCs (Key characteristics) - KC's include chemical, metallurgical, and mechanical properties that are controlled by the appropriate material specification.

Lot release – The coupons that will be built on the platform with parts to monitor key characteristics. Typically, these parts are built in the worst-case orientation for properties.

LPBF – Laser Powder Bed Fusion

OEM – Original Equipment Manufacturer, in this document OEM refers to the manufacturer of the LPBF machine being used.

OQ – Operational Qualification - The set of tests to show that a machine can produce materials that meet a predefined standard.

Partial OQ - Considered a subset of the full suite of checks. These should include calibration checks on any items that may be adversely affected by the change and then one or two builds to check any Key Characteristics that may have been adversely affected by the change

PCDs – Process control documents. All documents that control a process including work instructions, training documents and documents that control quality.

PIV – Process Input Variable – Machine settings that are controlled in a fixed process such as machine parameters whose called values should not change once qualified.

PM – Preventative maintenance – Maintenance performed at a set interval to maintain full machine functionality and prevent machine failure.

Powder heat – All the powder atomized at the same time by the powder vendor.

Powder lot – All powder from a single heat received at the same time by a manufacturer.

Powder sub-lot – Reused powder that has seen the same conditions/ build or powder that has been reused and blended with other reused or virgin powder to create a new sublot.

PPQ - Process Performance Qualification – Ongoing testing that shows that a process consistently meets key characteristics during production.

PQ – Product Performance Qualification - A set of tests to show that a machine can produce a production part that meets the key characteristics as defined by the part drawing and other related part requirement documents.

SAT – Site acceptance test – A series of quantitative tests that determines if a machine is operating as intended. Results are often compared back to the Factory Acceptance Test (FAT) to show that the machine functionality is equivalent to the performance of that same machine prior to its shipment from the manufacturer.

SOP – Standard Operating Procedures – A set of written instructions that outline how to perform a specific task in a manner that maintains quality and consistency.

SPC – Statistical process control – The use of statistical techniques to monitor and control a manufacturing process.

Verification - is defined as specific checks of calibration of functionality to make sure the change had no effect on any process variable and therefore could not possibly affect downstream material properties or machine performance

Witness coupon – A part that is used to verify an aspect of quality for the build platform.

Working distance – The distance from the scanners to the working plane.

Work Instructions -(WIs) Documents that describe how a procedure or task should be performed. Work instructions are created for process steps that must be performed the same way each time in order to ensure final part quality.

Working plane – The plane where the lasers are melting. This should be the same as the calibration and recoat plane.