



GUIDANCE NOTES ON

ADDITIVE MANUFACTURING

SEPTEMBER 2018

**American Bureau of Shipping
Incorporated by Act of Legislature of
the State of New York 1862**

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Foreword

As introduced in the *ABS Advisory on Additive Manufacturing*, the latest innovation in manufacturing is additive manufacturing (AM), wherein parts are fabricated by adding material layer-by-layer. AM technologies allow designers and builders to re-think the way parts are designed, constructed, and delivered. The rapid development of AM technologies has indicated that the marine and offshore industries may greatly benefit from AM's capacity to support a flexible fabrication facility.

The goal of a flexible fabrication facility based upon an AM system (machinery and software) is to enable production of a variety of qualified parts in a highly versatile manner. In this way, a single AM service provider (AMSP) can act as the equivalent of multiple qualified factories with disparate production lines under one roof, serving many different clients. A single AMSP may produce a wide range of parts, from many different materials, to meet diverse quality and critical service requirements.

These Guidance Notes introduce a qualification scheme that defines AM processes with sufficient clarity to achieve consistent, repeatable results while accommodating frequent changes to the factory configuration and product requirements.

Like traditional manufacturing, quality in AM relies on a clear understanding of the process, from design through manufacturing. Consistent quality involves an up-front understanding of the effects that the material, the process selection, and manufacturing configuration have on the specific part design, build sequence, and manufacturing parameters. Management of each of these aspects is necessary to effectively control variability and anticipate the effects of process changes.

As standardization for AM develops, it is important to understand that the definition of a “qualified” AM process changes between industries and users, and that there may be different qualification requirements, methods, and metrics. The ABS AM qualification structure outlined in these Guidance Notes represents a recommended standardized method that targets the needs of the maritime and offshore industries.

These Guidance Notes become effective on the first day of the month of publication.

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GUIDANCE NOTES ON ADDITIVE MANUFACTURING

CONTENTS

SECTION 1	General	1
1	Scope	1
2	Purpose	1
3	Acronyms and Definitions	2
3.1	Acronyms	2
3.2	Definitions	3
SECTION 2	Structure of ABS AM Qualification	5
1	Documentation Overview	5
1.1	Process Configuration and Workflow Diagram (PCWD)	6
1.2	Part Design Package (PDP)	7
1.3	Part Manufacturing Description (PMD)	9
1.4	Part Inspection & Testing Package (PITP)	15
2	AM Qualification Process	17
TABLE 1	Documentation Structure for Qualifying AM Systems, Processes, and Parts	6
TABLE 2	Nomenclature for Items in the Build Volume Model	11
TABLE 3	Example Features/Properties for Test Artifacts	13
FIGURE 1	Example PBF or BJ Build Volume Model, Showing Build Volume Containing One Production Part, Reference Part, Test Sample, and Test Artifact	10
FIGURE 2	Example DED Build Volume Model, Showing Build Volume Containing One Production or Reference Part with Integral Build Platform	10
FIGURE 3	NIST Test Artifact for PBF	12
FIGURE 4	ABS Additive Manufacturing Qualification Process	17
FIGURE 5	Additive Manufacturing Qualification Stage Goals	17
SECTION 3	Feasibility Stage	18
1	Initial C2G Population	18

SECTION 4	Verification Stage	19
1	Critical and Auxiliary Parameters.....	19
2	Part and Process Design	20
2.1	AM Modeling and Simulation	20
3	In-Process Monitoring and Control during Production	21
3.1	Process Intervention	21
4	Material Reuse (Metal Powders).....	22
5	Witness and Hold Points in PCWD Process Nodes	22
6	Part and Process Risk Analysis	22
SECTION 5	Pre-Production Validation Stage	24
1	Confirmation of Manufacturing System.....	24
2	Testing and Inspection Results.....	25
3	Ongoing Process Database	25
SECTION 6	Production Stage.....	26
1	Re-Establishing AM Process Maturity	26
2	Installation and Operation	27
3	Cybersecurity and Digital Manufacturing	27
4	Ongoing Production Risk Assessment	28
APPENDIX 1	Example PCWD with Supporting Information	29
FIGURE 1	Example Process Configuration Workflow Diagram Outline for a DED-GMAW (WAAM) Process with Outsourced Heat Treatment, Inspection, and Testing, Showing Typical Node Structure.....	30
FIGURE 2A	Example Feedstock Facility Node.....	31
FIGURE 2B	Example Feedstock C2G Documentation.....	32
FIGURE 3A	Example Part Design Owner Node	33
FIGURE 3B	Example Part Design Owner C2G Documentation.....	34
FIGURE 4A	Example AM Service Provider Node.....	35
FIGURE 4B	Example AM Service Provider C2G Documentation	36
FIGURE 5A	Example Heat Treatment Node	37
FIGURE 5B	Example Heat Treatment C2G Documentation	38
FIGURE 6A	Example Machining Node	39
FIGURE 6B	Example Machining C2G Documentation	40
FIGURE 7A	Example Nondestructive Evaluation Node	41
FIGURE 7B	Example Nondestructive Evaluation C2G Documentation	42
FIGURE 8A	Example Destructive Testing Node.....	43
FIGURE 8B	Example Destructive Testing C2G Documentation	44
FIGURE 9A	Example Part Design Owner Acceptance and Installation Node	45
FIGURE 9B	Example Part Design Owner Acceptance and Installation C2G Documentation.....	46
APPENDIX 2	References	47



SECTION 1 General

1 Scope

These ABS *Guidance Notes on Additive Manufacturing* (AM) outline a procedure for systematically qualifying AM parts, processes, systems, and materials primarily intended for marine and offshore use. The scope of these Guidance Notes includes AM processes that are capable, either directly or indirectly, of producing metallic parts, including the following as outlined by ASTM F42: Directed Energy Deposition (DED), Powder Bed Fusion (PBF), and Binder Jetting (BJ). These Guidance Notes can be used to assess the capability of an AM process to produce an existing design, as well as new designs that may be specific to AM. These Guidance Notes follow a multi-staged approach to qualification similar to the ABS *Guidance Notes on Qualifying New Technologies* (NTQ). Each stage is designed to build upon the previous stage to develop a more complete understanding of the process.

2 Purpose

Evaluating the performance of AM parts is dependent on knowledge of the entire manufacturing process workflow including: material selection, part model design, part/build orientation, parameter selection, processing conditions, post processing, inspection, acceptance criteria, and operator knowledge. The purpose of these Guidance Notes is not to exhaustively outline the requirements and risks of using AM designs in marine and offshore applications. It is a tool to guide would-be users of AM through the process of defining an AM procedure with sufficient detail to produce parts consistently, attain the required properties, and regulate process changes for the:

- System (machinery and software)
- Process (fabrication steps, order, and parameters)
- Part (geometry, functional requirements, material)

Generally, all AM parts should meet or exceed the design requirements of their non-AM equivalents⁽¹⁾. Alternatively, AM parts complying with national or proprietary specifications may be accepted, provided such specifications give reasonable equivalence to these requirements and also adequately account for the unique features of AM. Typically, metal AM part properties range between those of cast and forged counterparts. However, process variation, the location and type of defects, and metallurgical anisotropy are unique to the individual processing conditions of AM and should be considered in the design of the part.

AM's value lies in its ability to produce a low number of complex parts faster than traditional manufacturing methods. Additional benefits include the ability to process high performance materials while reducing the industrial footprint and increasing the flexibility of a fabrication facility. AM gives manufacturers significant control over the build process. This amount of control has benefits and drawbacks, because as opposed to manual techniques, there is little room for human intervention once building begins. The AM system controls the designated parameters once building begins.

Note:

- 1 For parts required by ABS Rules to be unit certified, reference is to be made to the ABS *Rules for Materials and Welding Rules (Part 2)* and the applicable sections of Parts 3 and 4 of the ABS *Rules for Building and Classing Marine Vessels (Marine Vessel Rules)* including manufacturer qualification and survey. ABS may identify additional survey witness/hold points, indicating requirements above and beyond unit certification. Where the ABS Rules do not require unit certification, recognized international standards should be referenced as applicable. To establish equivalency, the relevant Rules for products made by traditional (non-AM) processes apply together with the guidance herein. For additional guidance on determining the applicable requirements, refer to 2/1.4.

3 Acronyms and Definitions

3.1 Acronyms

AMSP	Additive Manufacturing Service Provider
ABS	American Bureau of Shipping
AM	Additive Manufacturing
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
AWS	American Welding Society
BJ	Binder Jetting
C2G	Cradle to Grave
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CFD	Computational Fluid Dynamics
CNC	Computer Numerical Control
DED	Directed Energy Deposition
FAT	Factory Acceptance Testing
FDA	Food and Drug Administration
FDS	Functional Design Specifications
FEA	Finite Element Analysis
FMECA	Failure Mode Effect Criticality Analysis
GN	Guidance Notes
HIP	Hot Isostatic Pressing
ISO	International Organization for Standardization
ML	Manufacturer's Log
NASA	National Aeronautics and Space Administration
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
NTQ	New Technology Qualification
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PCWD	Process Configuration and Workflow Diagram
PDO	Part Design Owner
PDP	Part Design Package
PITP	Part Inspection & Testing Package
PMD	Part Manufacturing Description
PO	Purchase Order

PSD	Particle Size Distribution
QMS	Quality Management System
SAE	Society of Automotive Engineers
TDS	Technical Design Specifications
UL	Underwriters Laboratories

3.2 Definitions

Additive Manufacturing. Manufacturing technologies that fabricate parts by adding material layer by layer as opposed to removing material.

Additive Manufacturing Service Provider. The organization responsible for operating an AM system (machinery + software) to produce the design.

American Society of Mechanical Engineers. Standards development organization. Multiple committees relate to AM.

American Society for Testing and Materials. Standards development organization. Committee F42 covers AM.

American Welding Society. Standards development organization. Committee D20 covers AM.

Binder Jetting. An AM process that uses binder to bind loose powder particles into a desired shape followed by additional post-processing steps to achieve the desired part properties.

Cradle to Grave File. The data package detailing the entire design, production, inspection, and testing information for the AM part.

Computer Aided Design. Computer software and the process used to design 3D solid or surface models creating a digital definition of the part.

Computer Aided Engineering. Modeling and simulation software used to help designers and engineers analyze performance of parts and systems virtually.

Computer Aided Manufacturing. Computer software designed to control/operate tools or other manufacturing machinery such as some AM machines, lathes, mills, etc.

Computational Fluid Dynamics. Computer modeling and simulation software used to analyze the properties and performance of fluid based systems.

Computer Numerical Control. Computer-controlled machine tools that create a part or feature by following a sequence of motion and machine function commands. See CAD, CAM.

Directed Energy Deposition. An AM technology that deposits material by providing energy to a feedstock delivered by a nozzle, welding fixture, etc.

Factory Acceptance Testing. A series of tests conducted to confirm that a part or system meets the agreed functional and technical design requirements.

Feedstock Facility. The facility that will produce the material used for building the parts, reference parts, and all other items in the build volume for both the qualification and production builds.

Food and Drug Administration. Regulatory authority on AM medical devices.

Functional Design Specifications. A document or series of documents that describe the required properties and functions of the design.

Finite Element Analysis. Computer modeling and simulation software used to analyze thermal and mechanical effects, stresses and strains in materials, parts and systems.

Failure Mode Effect Criticality Analysis. Technique used for assessing the severity, frequency, effect, and mitigation for design risk.

Guidance Notes. ABS non-mandatory guidance document designed to direct users towards standards and regulatory compliance.

Hot Isostatic Pressing. A post-processing technique involving pressure and temperature used to remove or reduce stresses and porosity from AM parts.

International Organization for Standardization. An international standards development organization. Technical committee TC 261 covers AM.

Manufacturer's Log. A series of documents included in the PMD that describes the calibration, maintenance, and qualification status of AM systems and processes.

National Aeronautics and Space Administration. An organization that has published technical standards for metal powder bed fusion qualification and quality for aerospace applications.

National Institute for Occupational Safety and Health. NIOSH operates under the Centers for Disease Control and Prevention and generates knowledge and programs that improve workplace health and safety.

National Institute of Standards and Technology. US Government organization for measurement science, standards, and technology.

New Technology Qualification. An ABS five-stage procedure for qualifying new technologies using a risk-based approach.

Original Equipment Manufacturer. The organization that originally created the machine or software of interest.

Powder Bed Fusion. An AM process that uses a laser or electron beam energy source to sinter or melt loose powder particles in the desired shape.

Process Configuration and Workflow Diagram. A roadmap of a specific AM process, depicting nodes, connections, and a sequence of operations.

Part Design Owner. The organization that owns the design of the part to be built.

Part Design Package. The sum of design documents that describe the part to be built, including drawings, functional and technical design specifications, models, etc.

Part Manufacturing Description. Supplementary information for each process step indicated as a node in the PCWD. Explains "how" each procedure is conducted.

Purchase Order. AM feedstock supplier document indicating the required properties for a certain type of product. Individual feedstock orders contain certificates of compliance for the given PO.

Particle Size Distribution. A statistical representation of the range of particle sizes within a sample of metal powders used in AM.

Part Inspection and Testing Package. Describes the standards and metrics used to evaluate the design's performance, including testing and inspection results.

Quality Management System. See ISO 9001 or equivalent standard.

Society of Automotive Engineers. Standards development organization, AMS committee covers AM.

Technical Design Specifications. A document or series of documents that describe how the required properties and functions of the design are met.

Underwriters Laboratories. A standards development organization, UL has published information regarding AM facility safety.



SECTION 2 Structure of ABS AM Qualification

AM qualification relies on a clear understanding of the entire manufacturing workflow from initial digital product definition and material feedstock characterization through AM fabrication, post-processing, acceptance, and installation on the asset. This family of documents and data is referred to as the “cradle to grave” (C2G) file, and defines the qualification method, processing parameters, design requirements and material properties for the part in its intended application.

Using the same make and models of a machine, even if provided by the same AM original equipment manufacturer (OEM), does not guarantee consistent performance from machine-to-machine or build-to-build. AM processes require numerous pieces of machinery, software, material interactions, and workflow steps, each with their own performance metrics.

Therefore, it is critical to have a clear and unambiguous understanding of the AM system, process parameters, inputs, outputs, and workflow to systematically track and improve quality. The C2G file defines and constrains the AM process, material, and part to be qualified to an acceptance range in accordance with the available Rules, standards and practices.

While various OEMs, operators, and national labs may have individual resources to gauge a machine’s performance, there is currently no single standardized test coupon that can validate an AM system’s performance as being “in-spec”. Standards for validating individual AM systems and builds are not yet available or well-developed. Interim documents and procedures may require development on a case-by-case basis until standardization matures.

To accommodate the flexibility of AM systems, processes, and parts, the C2G file is built with collaboration among the Part Design Owner (PDO), Additive Manufacturing Service Provider (AMSP), and ABS, as well as other relevant interested bodies. The ABS C2G methodology contains four sub-packages, detailed in Subsection 2/1.

1 Documentation Overview

The C2G file structure for qualifying AM processes and parts is divided into four packages, which are summarized and described in 2/1.1 through 2/1.4. The purpose of the C2G file is to develop a single source that provides a complete description of the final product, including production parts, reference parts, test samples, test artifacts, manufacturing parameters, tests, inspections, and applicable standards.

The C2G file outlined in Section 2, Table 1 is a living file; sub-packages will be referenced and updated regularly throughout the AM qualification process and during ongoing operations. Relevant information to populate the C2G should be included as linked documents with clear revision history.

TABLE 1
Documentation Structure for Qualifying AM Systems, Processes, and Parts

<i>Name</i>	<i>Acronym</i>	<i>Purpose</i>	<i>Contents</i>
Cradle to Grave File	C2G	A master reference file that is retained for the life of the part.	Contains the unique PCWD, PDP, PMD, PITP, and any other relevant information to the part and manufacturing process.
Process Configuration and Workflow Diagram	PCWD	Describes the order of operations for the overall AM process. An example PCWD is shown in Appendix 1.	A single workflow diagram where each major ⁽¹⁾ manufacturing step is listed as a separate 'node', each connected by their respective inputs and outputs.
Part Design Package	PDP	Describes the design's functional and technical requirements, including the materials basis.	Contains the production part drawings, test sample and test artifact drawings, functional design specifications, technical design specifications, CAE/CAD models, etc. The PDP also contains the material basis, which provides the material selection for the design, along with the environmental conditions and feedstock requirements.
Part Manufacturing Description	PMD	Describes the process (fabrication steps, order, and parameters) used by the relevant personnel and AM system to produce the part, including the manufacturer's log (ML) ⁽²⁾ .	The PMD contains the AM procedure specification ⁽³⁾ , build volume model, and process monitoring and control details for all items included in each build cycle (production parts, reference parts, test samples, and test artifacts). The ML contains the relevant information and documentation for machinery calibration and maintenance and worker qualification(s).
Part Inspection & Testing Package	PITP	Describes how the parts, test specimens and artifacts are inspected and tested, what metrics will be used to gauge initial part and AM process performance, and what data will be used for maintaining a qualified process.	The PITP contains the list of Rules, codes, and standards used to evaluate parts, test specimens, and test artifacts. The PITP also includes the results and criteria for the testing and inspections, such as test reports, inspection results, or other files.

Notes:

- 1 Major manufacturing steps include design and CAD/CAE file creation, feedstock production, AMSP operations, heat treatment, machining, inspection, mechanical/chemical testing, and installation at end-application. Each AM process node indicated on the PCWD that includes a witness/hold point should be witnessed by ABS for each initial qualification as well as reestablishing qualification. Witness/hold points, once established, should be indicated on the PCWD for ease of reference. Ongoing process examination should be agreed upon between the PDO and AMSP, and depends on the frequency of AM part production, the size and criticality of the parts, and C2G requirements.
- 2 Refer to 2/1.3.5, "Process Confidentiality".
- 3 An AM procedure specification (AMPS) is similar to a welding procedure specification (WPS) for AM. See American Welding Society (AWS) D20.

1.1 Process Configuration and Workflow Diagram (PCWD)

The roadmap for the AM process is contained in the process configuration and workflow (PCWD) diagram. The PCWD allows the PDO, AMSP and ABS to divide an AM process into individual manufacturing steps. Each organization conducting a manufacturing step in the AM part's workflow should be identified in the PCWD as its own "node", including all suppliers and subcontractors. The PDO and AMSP should identify and agree which manufacturing capabilities are available in-house, and which are considered outsourced, such as heat treatment, hot isostatic pressing (HIP), nondestructive evaluation (NDE), and machining. An example PCWD is shown in Appendix 1 for a process where the PDO has requested an AMSP to fabricate a part, and the AMSP has then subcontracted the heat treatment, testing, and inspection.

Each manufacturing node contains six blocks: header, input, machinery, software, process information, and outputs.

- i) The header block contains an outline of the general information for each organization/facility, such as name, location, applicable QMS type, and experience with similar parts and/or AM.
- ii) The input block contains the raw materials or information used to produce the product. For example, a feedstock facility may use barstock to produce wire, while a PDO may use field data to design a new part.
- iii) The AM system (machinery) block contains a description of the machines and other equipment used to process materials and parts, such as AM machine make, model, serial number, etc.
- iv) AM system (software) block contains a description of the software programs and packages used to supply information to, or otherwise control and/or monitor the AM process.
- v) The process (fabrication steps, order, and parameters) information block describes what processes are conducted at the location described in the header block to convert the inputs into outputs.
- vi) Outputs provide a description of the physical and/or digital deliverables between nodes. The outputs and inputs of different PCWD nodes are connected using arrows.

The PCWD is meant to be a “living” document and will be updated as more information becomes available.

Note: The QMS may employ a different quality scheme for the PDO, AMSP, and AM feedstock provider. In general, the QMS should at least govern specific functions, including worker training for AM, process revision control, change of/new supplier, data storage/management, data security, addressing AM nonconformance, material handling, powder storage, anti-contamination procedures, and material disposal.

1.2 Part Design Package (PDP)

The first group of documents in the C2G file includes comprehensive product definition with description, functional and technical specifications, and standards that must be met according to the PDO for the design to be considered adequate.

This information is contained in the part design package (PDP), which includes the part drawing(s), models, digital design definition, functional design specifications (FDS), technical design specifications (TDS), engineering calculations, drawings, design models, examples of similar approved designs, etc.

The PDP documents should also describe the architecture and function for the system into which the AM part will be installed. Initial details about the physical and functional interface requirements, such as mechanical fit, hydraulic/pneumatic interface, and electrical continuity should be provided along with associated requirements and tolerances. The PDO should consider the effect of service environment on the part when considering system performance. AM processing may create parts with different long-term material properties such as fatigue, corrosion, creep, and wear than non-AM counterparts.

AM-produced parts may use different materials and have different/alternative geometries than parts produced by traditional manufacturing methods. The PDO should address the use of AM-specific design modifications such as topological optimization, generative design, functionally graded (strengthened, corrosion-enhanced, etc.), and combining parts in assemblies. The PDO should also indicate prior experience and/or instances of similar existing designs in other systems, regardless of whether they were produced with AM or traditionally. Examples could include prior certifications, successful applications, case studies, analyses, etc. The AMSP should also provide proof of authorization by the PDO to build the intended parts.

The design is to be initially proven by first principles, calculations, prior experience, and testing, and then checked for compliance with Rules, codes, and standards that may specify additional design features. The reason for this is that standards should not be used as a replacement for first engineering principles. Rather, they should be used to augment acceptable first principle designs.

Note: The PDP is meant to be a “living” document and will be updated as more information becomes available.

1.2.1 Material Basis

The PDO and AMSP should specify the material selection for the design, the material feedstock, and the environmental conditions to which the design will be exposed. This material basis should include the type and grade of material, final heat treated/post processed condition of part (i.e., as-built, annealed, HIP, etc.), and the material properties used in the design specifications. A description of the required mechanical properties in specific locations and directions is to be submitted. Accounting for anisotropic properties early in the design process can help designers and materials engineers build testing and inspection plans that will establish the properties that best meet the design requirements.

Note: Modeling software for mechanical properties may not adequately account for anisotropic behavior of AM-processed materials.

Note: Hotspot locations, regions of localized thermal or mechanical effect concentration, and other areas such as rapid changes in cross-section, sharp changes in deposition process parameters, deposition direction, etc., should be identified and assessed and may require additional testing, inspections, or subsequent design model modifications.

For both wire and powder manufacturers, the PDO, AMSP, and AM feedstock provider should agree on a purchase order (PO) that denotes the following:

- i) Supplier name and address
- ii) Feedstock product name
- iii) Purchase order reference number
- iv) Certificates of compliance for each order made to that PO
- v) Feedstock lot number
- vi) Feedstock production process
- vii) Chemical composition
- viii) Representative micrograph or picture of product morphology
- ix) Packaging and storage requirements
- x) Feedstock production date/Expiration date

Note: The feedstock should not be used if the:

- Feedstock marking is damaged such that it is unreadable.
- Feedstock packaging is damaged such that there is doubt as to whether the feedstock remains in an acceptable condition per the manufacturer's recommendations.
- Feedstock manufacturer/OEM requirements for storage conditions and/or shelf life are not met.

Note: AM system OEMs may also prescribe OEM-sourced materials (e.g., powders for PBF machines).

Feedstock requirements may depend on the AM feedstock type (e.g., powder, wire, etc.), the AM OEM requirements, and the service criticality of the part. For both wire and powder manufacturers, the purchase order should have a unique identification number and include material grade, chemical composition, heat/lot designation, and applicable product standards. Measurement techniques and relevant measurement standards for all feedstock properties should also be listed.

Powder manufacturers should list the following, along with associated measurement techniques and standards, as applicable:

- i) Production type (e.g., Plasma Atomization, Gas Atomization, Plasma Rotating Electrode Process, etc.)
- ii) Particle size distribution (PSD)
- iii) Powder sampling methodology
- iv) Limits on the amount of particles outside the designated PSD range

- v) Density, including measurement technique (e.g., skeletal, tap, apparent, etc.)
- vi) Mean particle shape (morphology), limits on satellite particles, and porosity (hollow particles) should be listed, and a representative picture provided if possible

Wire manufacturers should list the following, along with associated measurement techniques and standards, as applicable:

- i) Feedstock storage conditions (e.g., atmosphere, temperature, separation, cleanliness, etc.)
- ii) Coating or lubrication on wire, which may require removal prior to fabrication
- iii) Wire surface roughness

The material supplier is to be included in the PCWD, as some AM requirements may entail a configuration-controlled virgin powder material specification. For wire manufacturers, the product form (e.g., diameter, coated wire, uncoated wire, etc.) and acceptable surface roughness should be provided. Additional feedstock requirements may be required by guidance documents, such as AWS A5.XX or ASME IIC. The properties listed above are minimum details. Application-specific requirements may involve additional information.

Feedstock documents should account for the unique requirements of AM processing, such as tight process configuration, high material quality, and revision control of all manufacturing processes. Currently, there is a limited selection of AM-specific material grades relative to non-AM alternatives. If the feedstock supplier has certified AM feedstock for previous processes, the details of same and any applicable previous experience can be submitted for reference.

The material basis should include, as applicable, the relevant details for the build platform or substrate material for the build process, including material thickness, grade, surface preparation, and markings. In addition, the relevant details for inert or other process gases should include vendor, type, grade, purity or other information regarding the gas supply source.

The PDO, AMSP, and feedstock supplier should agree on the feedstock properties and establish an initial purchase order certificate/template that takes into account all noted requirements and measurements. This document will be reviewed by ABS.

After the pre-production validation series of builds that includes parts, reference parts, test samples, and test artifacts, a feedstock property check should be conducted to determine if additional feedstock requirements should be specified.

1.3 Part Manufacturing Description (PMD)

The purpose of the PMD is to contain the parameters for the AM process and other associated processes in the PCWD. The PMD should include the manufacturing system capabilities, including the applicable AM category (e.g., PBF-L, PBF-Electron Beam, DED-Laser, DED-Gas Metal Arc, BJ-Direct, and BJ-Indirect), machine make and model, and basic machine details such as the technical specifications provided by the AM machine OEM (e.g., build volume, material compatibility, feature resolution capability, and surface roughness).

The PMD should describe the deposition plan, build volume model, build platform description (if applicable), support arrangement, heat treatment, machining, surface modification (e.g., peening, carburization), and other information required for manufacturing not included in the PDP. The location, orientation, and dimensions with tolerances of all production parts, reference parts, test samples, and test artifacts in the qualification, pre-production, and production build volumes should also be specified. Section 2, Figure 1 shows an initial build volume model for a PBF or BJ system. Section 2, Figure 2 shows an initial build volume model for a DED system.

FIGURE 1
Example PBF or BJ Build Volume Model, Showing Build Volume Containing One Production Part, Reference Part, Test Sample, and Test Artifact

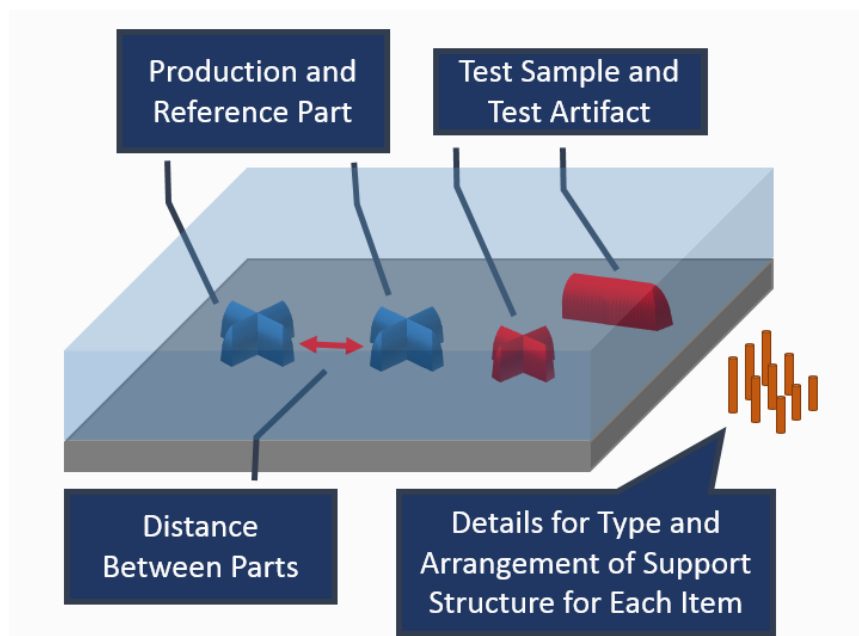
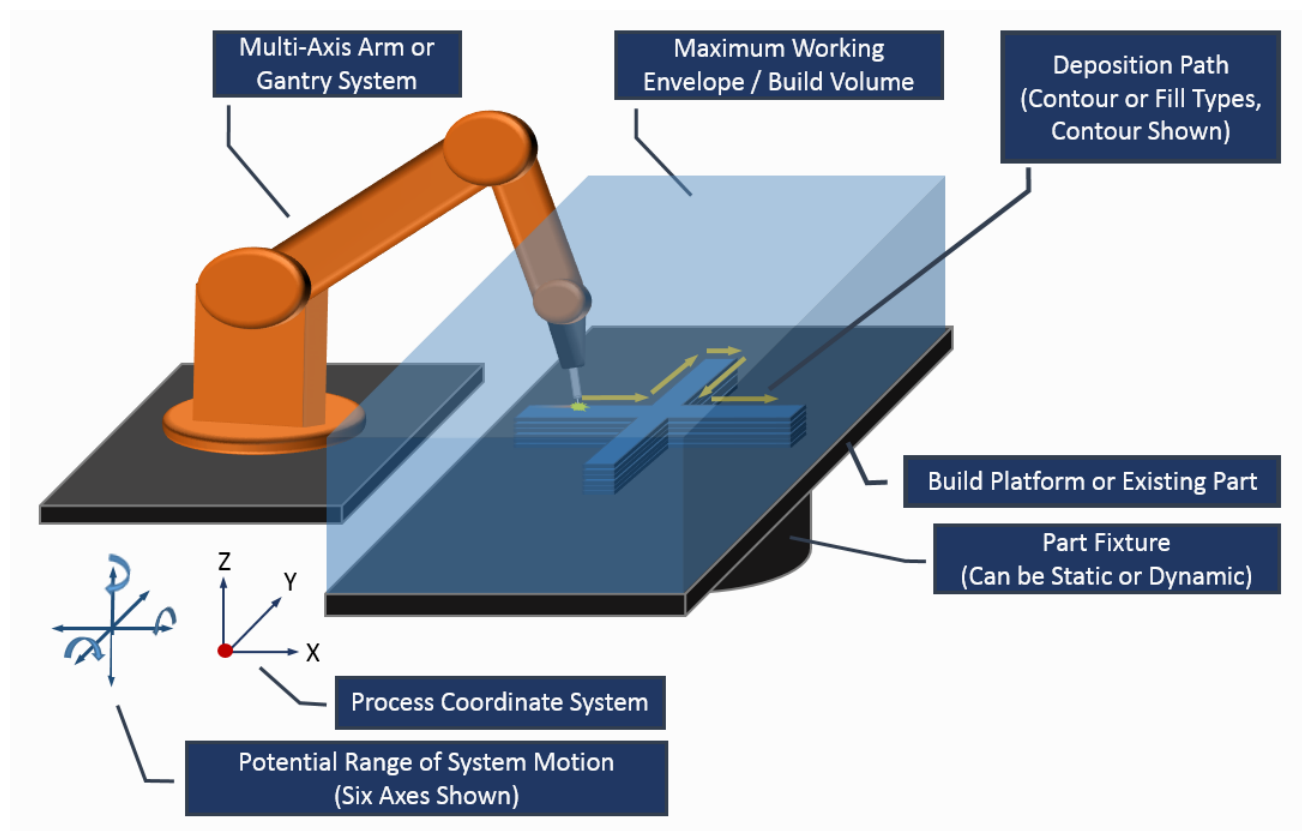


FIGURE 2
Example DED Build Volume Model, Showing Build Volume Containing One Production or Reference Part with Integral Build Platform



In general, the PMD should define the steps required to manage the physical, chemical, and microstructural property evolutions of parts from the as-built to final state. The PMD should also account for residual stresses accumulated during the build process and indicate post-processing activities required to achieve desired surface finish of final part(s).

Post processing is required to improve properties of as-built parts, which may have:

- Lower tensile elongation
- Fewer fatigue cycles to failure
- Lower creep rupture lifetime
- Less corrosion resistance
- Higher surface roughness or “near-net” shape

Note: Removing parts from support structures prior to stress relief can cause severe distortion, cracking, and premature part failure. Parts should not be removed from fixtures or build platform/support structures until the appropriate stress relief procedures have been performed. The build orientation and support structure may be designed to accommodate AM post-build operations such as heat treatment and machining.

Deposition process parameters (e.g., scan plan, deposition plan, etc.) are critical to each qualified AM process. Refer to 2/1.3.4 for process confidentiality. Changes in process parameters may require requalification and/or proof of equivalence by testing and inspection methods, as agreed among the PDO, AMSP, and ABS. As such, version control should also be specified for machine software used to run the build file. In addition to the process parameters for the production part, the PMD should include processing parameters for the items referenced in Section 2, Table 2 at a minimum.

TABLE 2
Nomenclature for Items in the Build Volume Model

Production Part	The AM part to be qualified.
Reference Part	Sacrificial part with identical geometry to the production part.
Test Samples	Material from which test specimens will be obtained, including mechanical, chemical, and microstructural properties.
Test Artifacts	Test artifacts are objects that can be fabricated either in each build cycle or during qualification builds that contain multiple features that aid in monitoring or measuring process repeatability or quality. Examples include reference geometries, NDE calibration and reference blocks, or archive samples.

Whenever possible, technical specifications and associated measurements for AM systems (machinery and software) and processes should be provided with tolerances and associated measurement techniques. The PDO and AMSP should also indicate how many units are intended to be manufactured and how many units per build cycle, for example: one-off, set number/range, or ongoing production. PMD documents may be supplied by the PDO, AMSP, or other relevant bodies indicated in the PCWD.

Note: Manufacturers new to AM may not have a well-developed, robust understanding of the intended AM process and its associated critical parameters. Therefore, information not available initially will be populated in subsequent stages. The PMD is meant to be a “living” document and will be updated as more application-specific knowledge is gained.

1.3.1 Process Monitoring and Control Criteria

AM is variable intensive, so actively tracking, testing, and inspecting for all process variables and part properties during regular build operations may be impractical due to computational limitations. The ability to detect errors early within builds is crucial. Undetected defects in the build process may cause parts to be rejected. Since it may not be possible to fully monitor and/or control all process variables in real-time, the AMSP may therefore choose to track certain part properties that are sensitive to fluctuations in critical and/or auxiliary process parameters as a way of inferring or tracking process stability. These are referred to as process stability variables.

Process control variables relating to the energy source and build environment (such as preheat and atmosphere) have a large impact on process stability. This may manifest in physical characteristics such as variable surface roughness and dimensional fluctuations, and possibly influence mechanical properties. Tracking process stability variables could provide an early indication of builds being out-of-spec by providing indicators that are sensitive to process fluctuations. Establishing a list of process variables and part properties that are process-sensitive may reduce the cost and time of production by enabling an AMSP to recognize and stop “failed” builds early in the build cycle.

The PMD should provide a description of process stability variables and artifacts used to monitor the build process, as well as the applicable measurement techniques. Examples could include measuring surface roughness or accuracy on worst-case surfaces, such as overhangs, abrupt geometrical changes, or high-aspect ratio geometries, such as posts, thin walls, or holes.

Note: Listing variables that are held constant or assumed to be constant and not under the direct control of the machine or operator may aid in analyzing and improving the stability of the AM process.

Note: Not all manufacturers may have the ability to track and/or anticipate AM process parameters with advanced algorithms or machine learning. Therefore, these capabilities are not mandatory requirements, but are intended to assist the PDO and AMSP in process design and optimization. It is anticipated that there will be significant industrial focus on developing these features.

1.3.2 Design of Test Artifacts

A valuable practice to aid in establishing, tracking, and maintaining build quality is the use of test artifacts. Test artifacts are samples that can be fabricated either in each build cycle or during qualification builds that contain multiple features that aid in monitoring or measuring process repeatability or quality. Use of test artifacts that demonstrate multiple different types of features is recommended, such as the NIST demonstration artifact for PBF, which includes numerous features and is shown in Section 2, Figure 3 and Section 2, Table 3.

Note: The use of test artifacts is also discussed in the *ABS Advisory on Additive Manufacturing*.

FIGURE 3
NIST Test Artifact for PBF

(Left: top view; right: oblique view)

