

Requirements for

Additive Manufacturing



July 2022



REQUIREMENTS FOR

ADDITIVE MANUFACTURING
JULY 2022

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Foreword (1 July 2022)

Additive manufacturing (AM), also known as 3D printing, is a process of fusion/joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. AM can fabricate 3D parts by creating multiple 2D cross sections and increase the flexibility of designs for complex shapes, some of which were not previously feasible in traditional manufacturing.

During the past several decades, academia and industry have performed many studies on the AM process and equipment for various materials, designs, and applications. The early AM processes were established in the 1980s to rapidly produce prototypes to test form, fit, and function. Later, the AM process was applied to molds and fixtures to support traditional manufacturing.

The increased uptake of the technology has driven AM technology from prototype to end use, from non-metallic materials to metal materials, and from fabrication of small parts created by desktop machines to large parts created by computer numerical control (CNC) machines or robotic arms. The expanded capability of AM makes it feasible to implement metal AM parts to marine and offshore end use applications.

For marine and offshore applications, metal AM may add value in the following areas:

- i)* Manufacturing on demand with shorter lead time in the supply chain (e.g., changing from management of physical parts to management of a computer aided design (CAD) model and manufacture on demand where and when it is needed)
- ii)* Manufacturing end use parts with more flexibility in design (e.g., reducing traditional machining costs for complex shapes, integrating multiple pieces into a single part with reduced installation costs, and optimizing parts using the topology method by adding materials where needed for reduced weight or improved performance)
- iii)* Small batch production (e.g., adding more value for small batch production by avoiding high tooling costs, ability to fabricate obsolete parts, self-sustaining for vessels at sea or in port)
- iv)* Hybrid metal AM process with traditional manufacturing (e.g., applying AM process for repair, applying AM features to traditionally manufactured parts, adding functional or new materials for improved resistance to corrosion, erosion, or wear)

However, there are still challenges and gaps between current metal AM technology and marine and offshore applications. The first challenge is the cost of metal parts manufactured by the AM process, especially for the large and heavy metal parts used in marine and offshore assets. The second challenge is possible static loading and cyclic loading experienced by AM parts due to static load and wave action, storms, or other special loads. The third challenge is potential physical defects in the materials such as lack of fusion, porosities, distortion, cracking and anisotropy in the microstructure, and more scattered mechanical properties. The fourth challenge is lack of standardization, qualification, and certification for the overall metal AM process in AM design, material, process, inspection, and testing for quality control.

While considering the challenges of using AM in marine and offshore applications, this document focuses on two main categories of metal AM processes, namely Powder Bed Fusion (PBF) and Directed Energy Deposition (DED). This document standardizes AM design, feedstock, AM pre-build and build process, post-build process, inspection, and testing by implementing specification control for production to support approval for AM facilities and approval and certification for AM parts.

The July 2022 version changes the document type from “Guide” to “Requirements”. “Requirements” documents contain mandatory criteria for Classification and issuance of Class Certificates, while Guides contain only requirements for optional Notations (see 1-1-4/1.5 of the *ABS Rules for Conditions of Classification (Part 1)*). The title is changed from “*Guide for Additive Manufacturing*” to “*Requirements for Additive Manufacturing*”. Accordingly, editorial changes are made throughout this document.

This document becomes effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version is the most current.

We welcome your feedback. Comments or suggestions can be sent electronically by email to rsd@eagle.org.



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ADDITIVE MANUFACTURING

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1 Introduction

1.1 Metal AM Process

There are two primary metal Additive Manufacturing (AM) categories intended for end use in accordance with ISO/ASTM 52900:

- i)* Powder Bed Fusion (PBF), wherein thermal energy selectively fuses regions of a powder bed.
- ii)* Directed Energy Deposition (DED), wherein focused thermal energy is used to fuse materials by melting as they are deposited.

Based on the building platform and joining/fusion method, the metal AM process is subcategorized and described in accordance with AWS D20.1 as follows:

- i)* LB-PBF: Laser Beam Powder Bed Fusion
- ii)* EB-PBF: Electron Beam Powder Bed Fusion
- iii)* LB-DED: Laser Beam Directed Energy Deposition
- iv)* EB-DED: Electron Beam Directed Energy Deposition
- v)* PA-DED: Plasma Arc Directed Energy Deposition
- vi)* GTA-DED: Gas Tungsten Arc Directed Energy Deposition
- vii)* GMA-DED: Gas Metal Arc Directed Energy Deposition

In addition, the DED process is further differentiated into powder DED and wire DED based on the type of the feedstock materials used.

Note:

Other designations are also used in the AM industry, such as Selective Laser Melting (SLM) for LB-PBF, Laser Aided Additive Manufacturing (LAAM) for Powder L-DED, Wire Arc Additive Manufacturing (WAAM) for Wire PA/GTA/GMA-DED.

1.2 AM Process Chain

The purpose of the AM process chain is to integrate the AM process for AM parts and materials using CAD modeling, specifications, and quality procedures with revision control. The AM process chain is typically composed of the following steps:

- i)* Conceptualization, such as design the part for AM
- ii)* Computer Aided Design (CAD) model

- iii)* Feedstock, such as selection of feedstock
- iv)* Build platform material
- v)* Conversion to digital file: STL, AMF, STEP, 3MF or other
- vi)* Transfer and manipulation of STL or alternative digital file on AM machine
- vii)* Machine setup
- viii)* Build
- ix)* In-process monitoring
- x)* Post-build processing including part removal, cleanup, support removal, heat treatment, and surface and feature finish
- xi)* Inspection and testing
- xii)* Application
- xiii)* Maintenance, Repair, Overhaul (MRO), Recycle or Disposal, if applicable

Notes:

- 1 Different AM technologies may use other breakdown steps and sequence for the AM process chain.
- 2 Repair may be applicable to DED process but is not applicable to PBF process.

2 Scope

This document outlines the AM process, approval for AM facilities, and approval and certification for AM parts.

- i)* Section 2: Design review, if applicable
- ii)* Sections 3, 4 and 5: Factors to be considered for the AM process

Note: Factors include essential parameters and non-essential parameters. Essential parameters are to be defined in the specification and are required by ABS. Non-essential parameters need not be defined in the specification and are to be documented by AM facilities.

- iii)* Section 6: Requirements for inspection and testing
- iv)* Section 7: Requirements for AM facility approval
- v)* Sections 8 and 9: Requirements for AM parts approval and certification

Specifications for production, approval for AM facilities, approval and certification for AM parts are to demonstrate at least an equivalent level of safety and integrity to traditionally manufactured parts and materials.

This document covers seven subcategorized PBF and DED metal AM processes in accordance with 1/1.1 or equivalent, intended for marine and offshore applications.

Other AM processes, materials, and applications may be submitted for review and will be specially considered by ABS. Some of the qualification and testing principles contained herein may be applicable. Examples of other cases are listed as follows:

- i)* Binder jetting, materials extrusion, sheet lamination, etc.
- ii)* Non-metallic materials such as ceramic, composite, plastic
- iii)* Prototype new design, tooling, fixtures, etc.

Note:

AM is an emerging and developing technology for marine and offshore applications. Metal AM parts may cover a wide range of applications and use various designs, materials, and processes. Accordingly, special consideration and case-by-case decisions by ABS may be called out during engineering review and manufacturing survey.

The verbal forms are used to express provisions in this document as follows:

- i)* “is to be” or “are to be” denotes the minimum requirements
- ii)* “should” denotes a recommendation, which is advised but not required
- iii)* “may be” is used for permission or option
- iv)* “can be” is used for possibility or capability

3 Approval and Certification Process

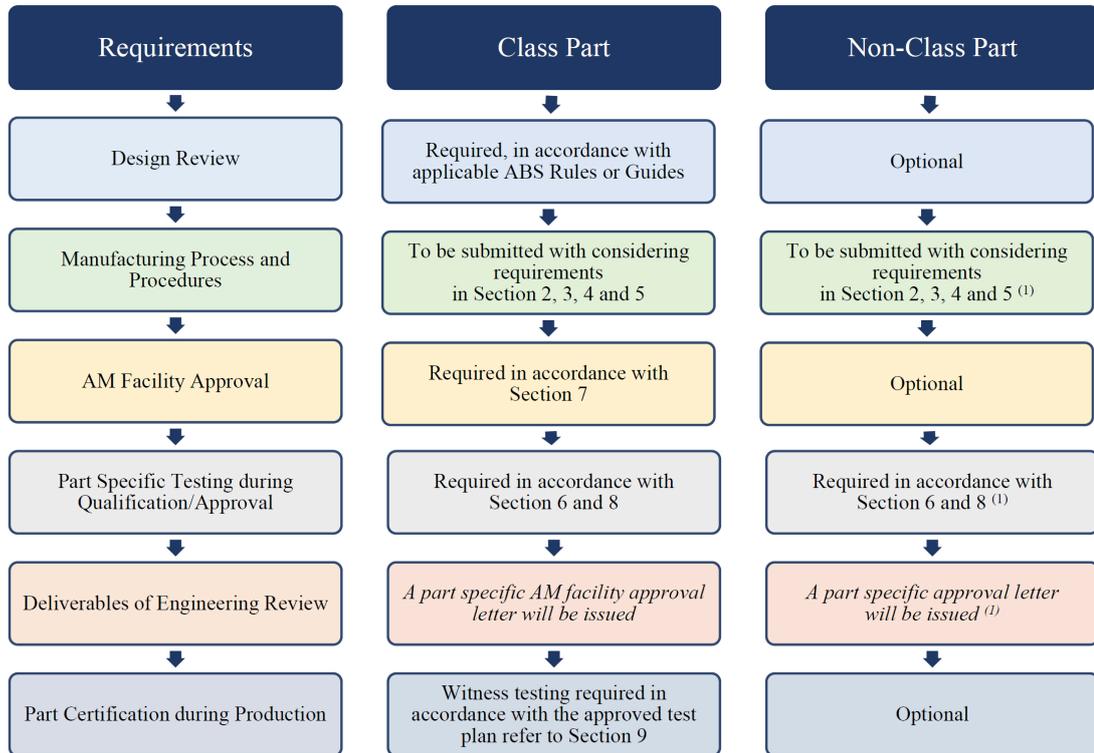
Approval for an AM facility verifies the manufacturer’s capability of furnishing products in a consistent manner under effective process and quality controls for fabrication or production (refer to 2-1-1/1.2.2 of the *ABS Rules for Materials and Welding (Part 2)*). Approval for an AM part indicates that the design and material properties can meet the part’s intended functional and system requirements. Both require ABS review and witness by an attending ABS Surveyor. Certification indicates an individual product has been surveyed and found to be within specifications as defined in Subsection 8/5.

Components/parts where ABS Rules apply are to be certified by ABS (termed as “Class Parts”) and are to be produced at an ABS approved AM facility with witnessed qualification and production tests. Components/parts where ABS Certification is not required if manufactured by conventional process (termed as “Non-Class Parts”), at the option of the client, can be produced by an ABS approved AM facility and certified by ABS with witnessed qualification and production tests. For non-class parts, it is not mandatory that manufacturers be ABS approved or that ABS witness all production tests. However, the manufacturer is to submit the manufacturing description and ABS witnessed qualification tests are necessary.

The approval and certification process for AM parts and facility is shown in Section 1/ Figure 1 and listed as follows:

- i)* Request for approval from client, along with submittals and detailed test plan (refer to Section 7 and/or Section 8)
- ii)* Engineering review and agreement of test plan and scope of approval
- iii)* Surveyor to witness qualification/approval tests and plant survey of the facility
- iv)* Engineering review of the test results and plant survey report
- v)* Issuance of the approval letter giving extent of qualification/approval and limitations
- vi)* Part certification

FIGURE 1
Approval and Certification Process



Note:

- 1 Non-class parts are not mandatory to be approved by ABS. However, if ABS approval is requested by clients for non-class parts, the AM facility/matrix is to submit the manufacturing process and procedures, and part specific qualification/approval testing report with ABS witnessed qualification/approval tests.

4 Terms and Abbreviations

The following acronyms and abbreviations are used in this document:

- AM Additive Manufacturing
- AMF Additive Manufacturing Format
- AMPS Additive Manufacturing Procedure Specification
- ASME American Society of Mechanical Engineers
- ASTM American Society for Testing and Materials
- API American Petroleum Institute
- AWS American Welding Society
- CAD Computer Aided Design
- CNC Computer Numerical Control
- CT Computerized Tomography
- DED Directed Energy Deposition
- EC Eddy Current
- GMA Gas Metal Arc

GTA	Gas Tungsten Arc
HIP	Hot Isostatic Pressing
IP	Intellectual Property
ISO	International Organization for Standardization
LAAM	Laser Aided Additive Manufacturing
LB	Laser Beam
LP	Liquid Penetrant
EB	Electron Beam
MP	Magnetic Particle
MSDS	Materials Safety Data Sheet
NDI	Nondestructive Inspection
OEM	Original Equipment Manufacturer
PA	Plasma Arc
PBF	Powder Bed Fusion
PQR	Procedure Qualification Record or Part Qualification Record
QP	Quality Procedure
SLM	Selective Laser Melting
STEP	Standard for the Exchange of Product Model Data
STL	Surface Tessellation Language
SWI	Standard Work Instruction
WAAM	Wire Arc Additive Manufacturing
3MF	3D Manufacturing Format

5 Definitions

Additive Manufacturing. A process of fusion/joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Also known as 3D printing.

AM Machine. The additive manufacturing system including hardware, machine control software, required set-up software, and peripheral accessories necessary to complete a build cycle for producing parts and materials.

AM Procedure Specification. A document stating all operating variables to provide requirements for producing a component/part using an additive manufacturing process.

AM Process Chain. The sequence of additive manufacturing processes necessary for the part or material to achieve all its desired properties.

Approval. Approval for an AM facility indicates that the manufacturer's capability of furnishing products in a consistent manner under effective process and quality controls for fabrication or production (refer to 2-1-1/1.2.2 of the *ABS Rules for Materials and Welding (Part 2)*) has been verified. Approval for an AM part indicates that the design and material properties meet the part's intended functional and system requirements. Both require ABS review and witness by an attending ABS Surveyor.

Build. A single and complete operation of the AM process to create objects in the build platform (single or multiple objects).

Build Lot. All objects created during a single build operation.

Build Platform. Flat/Shaped solid material based upon which AM objects are built.

Build Volume/Envelope. The volume in which parts may be reliably produced in the build platform, defined by the build area in X/Y and the maximum Z-position.

Build Volume Model. A model containing the design part geometry and orientation for the entire build volume including support structure, machining stock and test samples.

Certification. Certification indicates an individual product has been surveyed and found to be within the range of approval as defined in Subsection 8/5.

Class Part. Parts required to be certified in accordance with the applicable ABS Rules for target material or specific application (e.g., parts are class parts if equipment/components require unit certification; refer to 4-1-1/3.1 and 4-1-1/Table 1 to Table 8 of the *Marine Vessel Rules*, or other applicable sections of the *ABS Rules for Building and Classing Mobile Offshore Units (MOU Rules)* etc.).

Essential Parameters. Any parameter considered as essential if the applied parameter out of qualified range will affect the mechanical properties or final part quality. Essential parameters are to be defined in the specification and are required by ABS for review and survey. Any change of essential parameters out of the qualified range requires requalification.

Factory Acceptance Tests. The set of tests agreed to between part supplier, part purchaser, and ABS according to documented procedures. The factory acceptance tests and results are to meet predetermined design/functionality requirements and are overseen/witnessed by ABS.

Feedstock. The bulk raw material used by the AM building process, typically supplied in various forms such as powders, filaments/wires, or sheets.

Integrated Build Platform. DED material will be added on the build platform and the build platform is not removed for service. When qualifying DED procedures for production, additional requirements are considered for the interface between AM build materials and build platform and for the build platform heat affected zone (HAZ) and any potential substrate distortion (e.g., DED for repair of a component or DED for feature addition on the traditional material).

Machine Qualification Record. A record of the variables used to produce an acceptable standard qualification build and corresponding test results to support an AM machine qualification and approval for AM facilities.

Non-Class Part. Part not required to be certified by ABS if manufactured by conventional process in accordance with the applicable ABS Rules but may be subject to ABS's AM part approval process depending upon functionality and criticality. Non-class parts can refer to the *ABS Rules for Materials and Welding (Part 2)* for the material requirements, if applicable. Requirements for non-class parts may also be provided by shipyards, OEM, or the applicable industry standards (e.g., ASTM for materials requirements, ASME for pressure vessels, API for offshore or others).

Part Approval Test Build. A build fabricated using the same AM procedure for the entire build envelope as production of an intended AM part. The part approval test build is to be used to retrieve approval test samples for testing and evaluation. One purpose is to verify dimensions and material properties between approval test samples and the intended AM part for quality control during production.

Part Qualification Record. Evidence documented by the validation of the control boundaries through qualification tests for production across a specified range of input and environmental parameters. The qualified part is to be verified by evaluation of functionality/engineering requirements and is to be validated by evaluation of conformance with class Rules and Guides, industry standards, or designer/OEM's specification for the installed equipment/system.

Procedure Qualification Record. A record of the procedure used for production of an acceptable part approval test build and the corresponding test results carried out to support an AM pre-build, build and post-build procedure.

Production Part. The AM part to be qualified.

Reference Part. Sacrificial part with identical/representative geometry to the production part.

Standard Qualification Build. A build used to retrieve approval test samples for testing and evaluation. The standard qualification build is to support qualification of the AM machine and is also applicable to materials qualification to support approval for the AM facility.

Self-supporting Structure. Part features that may be built in an overhanging condition without the need for support structure below them. The maximum angle is the unsupported limit, at which overhanging part features may be reliably built without support structure.

Support Structure. Supplementary, sacrificial material built along with a part used to anchor overhanging geometry, provide dimensional stability and promote proper thermal management during a build.

Test Samples/Coupons. Material from which test specimens will be obtained, including mechanical, chemical, and microstructural properties.

Test Artifacts. 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.

1 Technical Requirements

This Section covers solid model/drawing and material specification of additively manufactured parts for design review. Class parts are required in accordance with applicable ABS Rules or Guides for design review. Non-class parts are optional for design review, which are to be specially considered and agreed to by ABS on a case-by-case basis.

1.1 Engineering Design

Engineering requirements of AM parts and materials are to be defined to verify the compliance with intended functional and system requirements. The following factors are to be considered:

- i)* Part functionality for equipment/system to be installed
- ii)* Loading condition, such as static loading, cyclic loading, shock loading
- iii)* Operation environment, such as high or low temperature, sea water, corrosive mediums or sour service

Depending upon the application, the engineering design is to adhere to the applicable ABS Rules and Guides, recognized industry standards, or designer/OEM specifications.

1.2 Traditional Manufacturing

If the product was previously manufactured by traditional approaches, original engineering design details are to be provided for reference:

- i)* Part description with part functionality, including if machined or if welded for assembly
- ii)* Part engineering design requirements
- iii)* Drawing or CAD model
- iv)* Material property requirements of final delivered condition
- v)* Semi-finished materials requirements including material grade, composition, and manufacturing process such as rolling, casting, forging
- vi)* Heat treatment procedure from semi-finished to finished material
- vii)* Nondestructive testing methods, standards, quality level, test locations, and acceptance criteria
- viii)* Reliability or performance report, if available

2 Submittals

The following are to be submitted for engineering design of AM parts:

- i) Part categorization: class part or non-class part
- ii) Identification of the applicable ABS Rules/Guides for class parts and the applicable industry standards or designer's specification for non-class parts
- iii) The applicable AM process workflow and manufacturing plan
- iv) CAD model or drawing with revision number
- v) If applicable, engineering calculation or simulation to support structural integrity
- vi) Materials specification with revision number

3 Parts Categorization

Part criticality levels are defined as the possible consequence or loss due to parts failure. Criticality levels are referenced in the applicable sections of the *Marine Vessel Rules*. The following definitions from AWS D20.1 are applicable for reference.

- i) *Critical application.* A component whose failure would cause significant danger to personnel, loss of control, loss of a system, loss of a major component, or an operating penalty.
- ii) *Semi-critical application.* A component whose failure would reduce the overall strength of the equipment or system or preclude the intended functioning or use of equipment, but loss of the system or the endangerment of personnel would not occur.
- iii) *Non-critical application.* A component whose failure would not affect the operation of the system or endanger personnel.

In this document, a part is categorized as a class part if requirements for the part are contained in the applicable Rules for the target material or specific application. A part is categorized as a non-class part where ABS Certification is not required if manufactured by conventional process and design requirements for the part may not be available in accordance with the ABS Rules. Requirements for non-class parts can be provided by shipyards, OEM, or the applicable industry standards (e.g., ASTM for materials requirements, ASME for pressure vessel, API for offshore, etc.).

Unless otherwise agreed to, a class part is considered as a critical application. A non-class part is considered either a semi-critical or non-critical application, depending upon the system/equipment to be installed.

4 Engineering Design for AM

4.1 CAD Model for AM

ASTM 52910 can be referred to for general design. ASTM 52911 Part 1 and Part 3 can be referred to for LB-PBF and EB-PBF, respectively. ASTM 52922 can be referred to for DED.

Due to the inherently digital characteristic, data requirements for AM parts are to be established on model-based requirements, as opposed to drawing-based requirements.

The CAD model or drawing is to be defined and identified in accordance with ASME Y14.41 for Digital Product Definition Data Practice and ASME Y14.5 for Dimensioning and Tolerancing.

Specific characteristics for AM are to be defined and identified in accordance with ASME Y14.46 for Product Definition for Additive Manufacturing.

The CAD model or drawing for AM is to include requirements for final geometry, dimensions, and tolerances and the specific characteristics for AM design and optimization. The definition of the CAD model or drawing according to ASME Y14.100 – classification code 3, 4 and 5 is as follows:

- i) Model with classification 3: data set with model and simplified drawing graphic sheet

- ii) Model with classification 4: data set with annotated model and drawing graphic sheet
- iii) Model with classification 5: data set with annotated model and no drawing graphic sheet

If the CAD model or drawing for AM are redesigned, optimized by topology, or generated by design algorithms, the CAD model for AM is to be fundamentally calculated or simulated using engineering software to verify design compliance and structure integrity for service. The applicable procedure and results are to be submitted for ABS review.

The CAD model or drawing for AM is to demonstrate at least an equivalent level of functionality and integrity with traditional manufactured parts. Consideration is to be given to alternative solid models and the materials in accordance with ABS Rules and Guides, recognized industry standards, or designer/OEM specifications, if deemed appropriate.

For class parts, the extent of submittals for design review are to be in accordance with the applicable ABS Rule and Guides. For non-class Parts, CAD models or drawings for AM are to be submitted for information. The revision number of solid models or drawings is to be included in the AM part approval as the range of approval.

4.2 Material Specification

The following items are required in AM material specification for final delivered condition:

- i) Material type and grade
- ii) Manufacturing process, including AM process and any post-build heat treatment process
- iii) Chemical composition
- iv) Microstructure, such as grain size, metallographic analysis
- v) Fusion density, applicable to powder process and not required for wire DED
- vi) Tensile tests
- vii) Charpy tests, if required for application
- viii) Hardness tests, if required for application
- ix) Other special properties such as fatigue, corrosion, etc., if required for application
- x) Nondestructive testing method, test level, quality level, and acceptance criteria

Notes:

- 1 Microstructure and fusion density are required during qualification/approval but optional for production.
- 2 For special applications, other tests or properties may be required such as for fatigue, corrosion, wear, erosion, fracture toughness etc. and alternative inspection and testing requirements may be specially considered and agreed to by ABS on a case-by-case basis.

The material specification is to include material properties for final delivered condition and acceptance criteria for AM parts or materials. The acceptable material properties are to demonstrate an equivalency level to traditional manufactured material, in accordance with *ABS Rules for Materials and Welding (Part 2)* and the applicable requirements provided in other ABS Rules for specific applications or recognized industry standards and designer's specifications, if deemed appropriate.

Due to the inherent morphology of AM builds, consideration may need to be given to applying AM materials with alternative chemistry and enhanced mechanical properties, which are better than the material properties typically required by conventional processes, to improve physical characteristics such as impact, fatigue, wear or corrosion resistance. The selected AM materials are to be appropriate for the components/parts, service, and approved by ABS.

1 General

Refer to ISO/ASTM 17296-2, 52907 or other equivalent standards for feedstock material specification, documentation, handling, and storage.

The feedstock material specification is to define requirements and tolerances for the essential and non-essential parameters to achieve a consistent process and material quality of final delivered AM parts or materials.

2 Submittals

The following documents are to be submitted for AM feedstock:

- i)* Specification with revision number
- ii)* Documentation or feedstock datasheet
- iii)* Quality procedure for handling and storage, if requested by ABS
- iv)* Valid approval or certificate for wire manufacturer

3 Powder

3.1 Specification

Powder characteristics can affect AM process stability, efficiency, quality and cost, applied processing parameters, and part material properties.

Powder specification is to be defined with the applicable manufacturing process, the range of essential parameters, and nonessential parameters.

Unless otherwise agreed, the powder specification is to be qualified by a range of parameters. Any change of essential parameters out of the qualified range requires requalification (refer to Section 7 or Section 8, if applicable).

3.1.1 Essential Parameters

- i)* Material grade
- ii)* Powder manufacturing process, including the melting and atomization process, type of gas used, environmental conditions
- iii)* Post-atomization classification, such as sieving
- iv)* Chemical composition

- v) Powder size range
- vi) Particle size distribution
- vii) Powder morphology and internal microstructure
- viii) Flowability
- ix) The applicable additive manufacturing process (e.g., powder for LB-PBF, powder for EB-PBF or powder for DED)

Notes:

- 1 Refer to ISO 3954 or ASTM B215 for powder sampling. Material grade may be a trade name, common name or typical material designation.
- 2 Chemical composition is to be tested and determined by a suitable testing procedure such as wet chemical process, atomic absorption spectrometry, flame emission spectroscopy, X-ray fluorescence analysis, or other recognized methods. Industry standards may be referenced to determine the content of interstitial elements such as carbon, nitrogen, hydrogen, sulfur, and oxygen.
- 3 Powder size and distribution are to be tested in accordance with ASTM E2651 or other equivalent standards, such as sieving in accordance with ASTM B214 for DED powder, static or dynamic image analysis, light scattering, laser diffraction in accordance with ASTM B822 or other recognized methods. The powder size distribution (PSD) may be described by D10, D50 and D90. D10 is the first decile (e.g., 1/10 of the statistical population is below this value). D50 is the median value (e.g., 50% of the statistical population is below this value). D90 is the last decile (e.g., 90% of the statistical population is below this value). Other powder size distribution methods may also be specified by the powder manufacturer. For the powder DED process, the maximum powder size may be specified depending upon the powder feeding system.
- 4 Morphology can be affected by the powder manufacturing process; the preferred inspection method is by scanning electronic microscopy (SEM), secondary electron imaging, or other recognized methods.
- 5 Flowability can be affected by multiple factors such as powder size and distribution, cohesive strength by moisture, inter-particles friction, powder sphericity, etc. Industry standards, such as ASTM B213, may be referenced to test flowability through piping, nozzle, funnel, etc.

3.1.2 Non-Essential Parameters

- i) Density, such as apparent density, tap density, skeletal density, fusion density
- ii) Thermal properties, such as solidus, liquidus temperature for reference
- iii) Oxygen content
- iv) Moisture content, etc.

3.2 Documentation

The powder manufacturer should issue statements of conformity and document the following information for raw material control and traceability per heat per lot:

- i) Powder manufacturer's contact information
- ii) Heat No.
- iii) Lot No.
- iv) Powder description
- v) Powder manufacturing process, including the melting and atomization process, type of gas used, environmental conditions
- vi) Post-atomization classification, such as sieving
- vii) Sampling

Note: Sampling is to be representative of the powder lot with homogenous splitting. A procedure for sampling and sieving referred to ISO 3954 or ASTM B215 and agreed by feedstock manufacturer and AM facility, is to be included for cleanliness and to prevent cross contamination.

- viii) Testing method, standard, and results required by powder material specification
- ix) Packing date, quantity, handling, and storage instructions
- x) Materials Safety Data Sheet (MSDS)

3.3 Handling, Storage, and Reuse

From a health and safety perspective, powder material can be hazardous for the operator. Handling and storage are to be in accordance with the feedstock supplier's instructions and the applicable international, national industry standards, local regulations, etc.

In addition, powder should be protected against damage, contamination, and deterioration during handling, storage, and reuse.

Powder not deposited after exiting the nozzle in DED is not to be reused.

For the PBF process, powder reuse with mixed lots is not allowed. Powder reuse for the same lot may be allowed for the PBF process in accordance with the implemented standard work instruction (SWI) or quality procedure (QP). The SWI or QP for powder reuse may consider the following factors:

- i) The documented methods for tracking the progression of powder reuse
- ii) Limitation for powder reused cycles
- iii) Performance of the final delivered material property by the reused powder
- iv) The documented control procedures, such as sieving, testing oxygen, moisture, or other best practices
- v) Testing results of the essential parameters within the specified range of virgin powder, if applicable
- vi) Implementation of best practices for prevention of cross contamination on multi-material use machine or linking one machine for one type of material

4 Wire

4.1 Specification

Refer to AWS A5.01, AWS A5.32, ASME BPVC. II. C or other equivalent standards for wire such as ISO 14175.

The wire specification is to be defined with the manufacturing process, the range of essential parameters, and nonessential parameters.

Unless otherwise agreed, the wire specification is to be qualified by the range of parameters. Any change of the following essential parameters out of the qualified range requires requalification (refer to Section 7 or Section 8, if applicable).

- i) Material grade
- ii) Chemical composition
- iii) Wire size
- iv) The applicable additive manufacturing process

Notes:

- 1 Material grade may be a trade name, common name, or typical material designation.
- 2 All wires are to be homogeneous in chemical composition throughout the length. For cored wires, the distribution of core ingredients is to be included.
- 3 The wire type is to be appropriate to the suitable DED process. Solid/cored wire is suitable for EB, Laser, PA, Tungsten Inert Gas (TIG) heating source. Solid/cored wire electrode is suitable for Metal Active Gas (MAG) and Metal Inert Gas (MIG) arc.

4.2 Documentation

The wire material manufacturer is to issue statements of conformity and document the following information for raw material control and traceability per heat per lot.

- i)* Wire is to be sourced from ABS approved welding consumable manufacturers for class parts. Wire can be sourced from approved welding consumable manufacturers by other class societies for non-class parts. Wire manufacturer's contact information
- ii)* Heat No.
- iii)* Lot No.
- iv)* Wire description such as wire size, material grade, AWS designation, F No., A No. if applicable
- v)* Wire manufacturing process
- vi)* Testing method and results required by wire material specification
- vii)* Packing date, quantity, handling and storage instructions
- viii)* MSDS

4.3 Handling and Storage

From a health and safety perspective, wire material is less dangerous, but sufficient measures should be taken to protect against damage, contamination, and deterioration. Handling and storage are to be in accordance with the manufacturer's instructions and the applicable international, national industry standards, local regulations.

1 General

AM procedure specification (AMPS) as required in accordance with Subsection 4/5 is to be documented for controlling and monitoring both the essential parameters and nonessential parameters that may affect final part quality.

AMPS is to be qualified by a range of parameters and applying the approval tests in Section 7 and/or Section 8, and any change of essential parameters beyond the range calls out requalification.

The applicable essential and nonessential parameters are to be documented by AM facilities. Any parameter that affects heat input/source and heat history/deposition is to be considered as an essential parameter (refer to 4/4.1 and 4/4.3 for the PBF process and 4/4.2 and 4/4.3 for the DED process). These parameters are to be reviewed by ABS.

2 Submittals

The following documents are to be submitted for AM pre-build and build process:

- i)* Digital build volume model or the detailed build plan for reference
- ii)* AM procedure specification with revision number
- iii)* If applicable, in-process monitoring and controlling plan
- iv)* Procedure qualification record

3 Pre-Build

3.1 Build Volume Model

The following pre-build process characteristics are to be defined and identified, which may be supported by software for preparation:

- i)* Part location and orientation
- ii)* Test coupon location and orientation
- iii)* Machining allowance for part and test coupon, if applicable
- iv)* Build location and nesting, if applicable
- v)* Build surface, direction and gravity direction
- vi)* Support/infill structure, if applicable

Notes:

- 1 If required, part orientation is to be identified relative to a specified build surface, such as the build platform or incorporated substrate. For the PBF process, the part may be oriented and optimized by software, to reduce the build time or thermal residual stress. For the DED process, parts may be oriented vertically and horizontally and to other angles determined by machine flexibility to manipulate the substrate.
- 2 If applicable and required, build location is to be identified using X, Y, Z directions in accordance with ISO/ASTM 52921. The location of a single part may be specified within a build envelope. If applicable, multiple build locations may be necessary when multiple parts are built simultaneously within the same build envelope. This process is known as nesting. The requirements for build location and nesting are similar with design for assembly.
- 3 Test coupons are to be identified in the build layout with a unique label. If build layout and build surface are depicted, the build location, orientation, and related tolerance for test coupons are also to be indicated in accordance with ISO/ASTM 52921. Test coupons for the DED process may be taken from the prolonged part, if applicable, or a separate test coupon that represents the part features, which can be specially considered and agreed to by ABS on a case-by-case basis. Digital build model of parts and test coupons are to be submitted for reference.
- 4 If applicable, overhangs and sacrificial support structures may be used for support during fabrication. Alternatively, the part may be re-orientated to avoid any overhang, if possible.
- 5 If specified, a bounded surface or volume region may be used to define locations to limit or require support/infill structure. If not specified, a default support/infill structure may be applied depending upon the machine and software.
- 6 For DED, pre-build processor may be customized and linked to the machine.

3.2 Software Workflow

Digital building files are to be exported with accuracy especially for the critical features, documented by facility and submitted, if deemed necessary by ABS. During exporting of digital building files, the conversion of digital building file from solid model should be verified and fixed for any errors automatically by available software or manually by operator, as needed.

ASTM 52950 can be referred to for the overview of data processing.

Digital files may be needed, including derivatives from the original CAD model (e.g., STL, AMF, STEP or 3MF).

Depending upon the machine and software availability, AM modules may be added to commercialized CAD/CAE/CAM software that enables process simulation, residual stress and distortion prediction, build time estimation and potential manufacturability issues.

Additionally, process planning capabilities may be added to some software to provide slicing, toolpath generation, and G code programming.

4 Build

Building parameters related to heat input/source and heat history/deposition are considered as essential parameters and are to be specified in the procedure specification, controlled and qualified in the range. Non-essential parameters should be documented and controlled as much as possible, including build platform, build environment, and any other related parameters.

If process characteristics are required for in-process monitoring during building, those requirements are to be assessed for conformance, such as machine building errors and failures.

4.1 Powder Bed Fusion (PBF)

Refer to ASTM F3303 for process characteristics and performance practices for metal PBF process to meet the intended applications.

EB-PBF has similar capabilities with LB-PBF but demonstrates differences due to different beam sources. Compared with LB-PBF, the beam energy transferred by electron beam is higher. The process may operate at higher temperatures, with faster build rates and with relatively low resolutions. Additionally, the powder bed is preheated to slightly below melting temperature, which results in less thermal induced stress and faster deposition rates.

The parameters to be defined in the LB-PBF or EB-PBF procedure specification include:

4.1.1 Heat Source

- i)* Beam type, such as laser or electron beam
- ii)* Beam power
- iii)* Beam size
- iv)* Beam pulse frequency/waveform control
- v)* Preheating by beam splitting
- vi)* Beam focus setting

4.1.2 Deposition

- i)* Scan pattern/strategy
- ii)* Travel speed
- iii)* Hatch overlap
- iv)* Hatch distance/spacing
- v)* Specific settings affecting edge and surface build conditions
- vi)* Layer thickness

4.1.3 Build Environment

- i)* For LB-PBF
 - a)* Build platform material specification/designation and thickness
 - b)* Build platform preheat temperature
 - c)* Shielding gas composition and flow rate
 - d)* Supplemental gas shielding
 - e)* Build chamber gas composition for
 - f)* Environmental enclosure hardware and configuration
- ii)* For EB-PBF
 - a)* Build platform material specification/designation and thickness
 - b)* Build platform preheat temperature
 - c)* Vacuum pressure
 - d)* Environmental enclosure hardware and configuration

4.1.4 Other Parameters

- i)* Recoater blade type, material or roller wear
- ii)* Powder dosing rate
- iii)* Ambient environment conditions
- iv)* Feedstock condition, such as powder lot number, virgin or reused

4.2 Directed Energy Deposition (DED)

The DED process is to be in accordance with ASTM F3187 or equivalent for standard guide for DED of metals.

The parameters to be defined in the DED procedure specification include:

4.2.1 Heat Source

- i)* Heat input including beam/arc power and size
- ii)* Heat pulse frequency/waveform control
- iii)* Preheating by beam splitting (not applicable to PA-DED, GTA-DED, and GMA-DED)
- iv)* Use of energized (pre-heated) wire (not applicable to Powder DED)
- v)* Beam/arc focus setting (not applicable to PA-DED, GTA-DED, and GMA-DED)

4.2.2 Deposition

- i)* Scan pattern/toolpath
- ii)* Travel speed
- iii)* Hatch overlap
- iv)* Hatch distance/spacing
- v)* Start working distance/nozzle standoff distance (not applicable to PA-DED, GTA-DED and GMA-DED)
- vi)* Specific settings that may affect edge and surface build condition
- vii)* Feed rate
- viii)* Programmed layer thickness (applicable to laser powder DED, not applicable to other DED processes)
- ix)* The applied technique such as weaving, multi-wires or pulse for wire DED, if applicable

4.2.3 Build Environment

- i)* Build platform material specification/designation and thickness
- ii)* Build platform preheat temperature
- iii)* Interpass temperature and interpass cleaning, if applicable
- iv)* Shielding gas composition and flow rate (not applicable to EB-DED)
- v)* Powder carrier gas flow rate, if applicable
- vi)* Supplemental gas shielding (not applicable to EB-DED)
- vii)* Supplemental gas composition (not applicable to EB-DED)
- viii)* Build chamber gas composition, if applicable
- ix)* Vacuum pressure (applicable to EB-DED only)
- x)* Environmental enclosure hardware and configuration

4.2.4 Other parameters

- i)* Orientation of heat source impingement
- ii)* Ambient environment conditions, such as temperature, moisture, etc.
- iii)* Feedstock type, such as powder or wire
- iv)* Wire delivery parameters, such as incidence angle, offset distance from centerline of heat source or path orientation

4.3 In-Process Monitoring or Controlling

Some AM systems may have subsystems/subcomponents using one or more real-time sensors to monitor or control various performance and status indications during building such as melt pool temperature, size, lack of fusion, spattering, and others.

In-process monitoring methods that do not change or control any qualified variables are not required in the AMPS and PQR. In-process monitoring methods that can change or control any qualified variables are required in the AMPS and PQR, including monitoring or controlling type and method, monitoring or controlling system settings and qualified variables affected by in-process monitoring or controlling.

A procedure for planned build interruption is to be included in the AMPS. For example, build interruption is planned to enable interpass temperature requirements, loading of feedstock, or routine cleaning.

Unplanned build interruption is to be categorized and recorded as an in-process correction. Examples of unplanned build interruptions are power outages, unplanned maintenance, or interlock trips. Unplanned build interruption is to be reported, specially considered, and agreed to by ABS on a case-by-case basis.

5 Procedure Qualification Record

The AMPS and PQR are to document all essential/controlled parameters and corresponding test results. Refer to AWS D20.1/Annex A for the different AM processes. Any format of PQR is acceptable if all applicable information is recorded with traceability.

Note: Procedure qualification record can be established and documented during ABS review and survey when requested approval for AM facilities or AM parts depending upon the targeted material grades or specific applications.

SECTION 5 Post-Build Process

1 General

The post-build process is to be provided in the standard work instruction (SWI), quality procedure (QP), or procedure specifications to meet the quality and properties of the final delivered part.

The parameters such as temperature, soak time, and cooling media are to be specified by the AM facility, controlled by heat treatment facility, and referred to industry standards depending upon materials.

If specified, machining allowances are to be in accordance with ASME Y14.36.

The same post-build processes are to be applied to the test coupons and the sacrificial/reference/actual parts.

2 Submittals

The following documents are to be submitted for post-build process:

- i) Specification with revision number for stress-relief, HIP, or other heat treatment process
- ii) SWI or QP for powder removal, part removal, surface or feature finish, if requested by ABS
- iii) Documentations for specification or best practices for SWI/QP

3 Powder Removal

The PBF process is applicable to remove loose powder in the part using different processes in accordance with the facility's best practice. The residual powder in the part may cause health and safety issues for personnel while working during the post processing steps, especially for reactive materials such as titanium-based or aluminum-based powder.

Notes:

- 1 Free of powder is to be verified for the part and build platform. If the part is not planned for stress relief or other heat treatment process, the part is to be removed from the build platform in accordance with Subsection 5/7. If the part is planned for stress relief or any other heat treatment process outside of the AM machine, the part is to be removed from build platform after the stress relief or any other heat treatment process.
- 2 Heated bed may be fitted with PBF machines, which may relieve thermal residual stress during building of the part.
- 3 The heated bed and chamber of EB-PBF may maintain a higher temperature, such as 500-1000°C (932 – 1832°F). Stress relief may not be required for parts built using the EB-PBF process.

4 Stress Relief

4.1 Specification

The purpose of stress relief is to reduce thermal residual stress and to mitigate distortion in parts and materials to an acceptable level. A specification is to be prepared for the stress relief process including the following essential parameters, referred to industry standards depending upon the type/grade of material:

- i)* Stress relief temperature
- ii)* Hold time at stress relief temperature
- iii)* Furnace atmosphere
- iv)* Cooling media, if applicable
- v)* Applied fixturing or restraint to mitigate distortion, if applicable

Notes:

- 1 Heating and cooling rates are to be controlled in accordance with the practices of the heat treatment shop such as slow heating and cooling to mitigate potential distortion or cracking.
- 2 If available, vacuum furnace or inert gas furnace should be used to avoid any unnecessary oxidation on the net-shape parts as it may be difficult to remove the oxide film after the treatment.
- 3 The applied fixturing or restraint for mitigation of distortion depends if parts are still on the build plate. Meanwhile, it may be challenging to design and manufacture fixtures/jigs to hold all the complex features during the stress relief process.

4.2 Documentation

The actual parameters for stress relief are to be documented and recorded for qualification and production.

Other heat treatment parameters/practices are to be documented and audited in accordance with the applicable ABS Rules including furnace type, parts loading map inside the furnace, verification of temperature uniformity in the furnace heat zones, calibration of thermocouples, controlling thermocouple touching to the parts and acquirable heat cycle disk chart.

5 Hot Isostatic Pressing (HIP)

5.1 Specification

The purpose of HIP is to improve density, remove internal voids/defects, and reduce stress concentration and crack initiation locations inside of as-built parts. HIP may also reduce anisotropy in microstructure and the scatter band/standard deviation of final mechanical properties. Additionally, HIP treatment helps to decrease thermal residual stress and improve ductility, fatigue and fracture toughness. A specification is to be prepared for HIP process including the following parameters:

- i)* HIP temperature
- ii)* HIP pressure
- iii)* Hold time at HIP specified temperature and pressure
- iv)* HIP atmosphere (Argon gas may be applied to pressurize the HIP chamber. The purity of argon gas is important to avoid any unnecessary surface carburization/oxidation.)
- v)* Cooling media, if applicable

Note: HIP is applicable to powder process but not required by wire DED process.

5.2 Documentation

The actual parameters for HIP are to be documented and recorded for qualification and production.

Other HIP parameters/practices are to be documented and audited in accordance with the applicable industry standards including the applied fixture/jig for mitigation of distortion, practices to clean carburized or oxidized layer if occurred, chamber with inert gas protection, loading/unloading to avoid any damage, etc.

6 Other Heat Treatment

If applicable, other heat treatment may be applicable to homogenize the microstructure, retain the strengthening phase and tailor the mechanical properties of the final parts (e.g., the industrial parts may need special heat treatment condition such as solution treatment plus aging for Al6061-T6, Ti6Al4V, solution treatment plus double aging for Inconel 718, solution treatment for 316 stainless steel, etc.).

The heat treatment procedure can refer to the relevant industry standard for the specified material. If the existing procedure cannot provide the required material properties, a new heat treatment procedure is to be developed, qualified, and documented.

7 Part Removal

SWI or QP may be prepared for part removal or support structure removal in accordance with the AM facility's best practices. The following information may be documented:

- i) Build platform temperature when part is planned to be removed
- ii) Applicable methods
- iii) Step-by-step instructions
- iv) If applicable, powder removal needs to be verified before heat treatment

Due to residual stresses, stress relief heat treatment is to be carried out before the part is removed. However, this might not be applicable for large parts due to the furnace capacity. Parts may be removed before stress relief heat-treatment depending upon materials, which need special attention to avoid cracking and are specially considered and agreed to by ABS on a case-by-case basis.

The removal of support structures is to avoid detrimental impact on the part or is proactively considered for the ease of removal of the interface between the support structure and the part during the design or building.

8 Surface or Feature Finish

The main purpose of surface finish is to meet tolerance requirements. If required, SWI or QP should be prepared for surface finish in accordance with the AM facility's instruction or procedure. Surface or feature finish is performed after the applicable heat treatment processing due to potential deformation and discoloring/oxidization during heat treatment. Surface or feature finish may be carried out before heat-treatment in accordance with facility's practices, which are specially considered and agreed to by ABS on a case-by-case basis.

PBF is able to produce fine features with relatively well controlled surfaces for smaller parts. It achieves the best surface quality with the surface finish depending upon powder particle size and beam size. Grit/shot/bead/wet blasting may be sufficient for parts through LB-PBF or EB-PBF.

Wire feed DED enables far higher deposition rates and virtually unlimited component size, but the as-deposited surface finish is very rough. The large melt pool results in weld-bead shaped deposits which need machining or grinding to achieve the required dimensional accuracy and surface finish.

Notes:

- 1 One unresolved challenge for AM is surface finish. Components subject to fatigue may be machined or undergo some other surface modification, such as shot peening.

- 2 Additional processes add cost and may prevent the full benefits of AM from being realized.
- 3 Theoretically, AM gives complete freedom to create complex shapes, such as those generated by topology optimization. In practice, surface finish requirements often prevent this.
- 4 If surface machining is required, the same limitations on form apply as for any other machined component.
- 5 If shot peening is used, limitations are placed on thin and slender structures, which may be vulnerable to this process.

Other surface treatments maybe considered and applied depending upon applications, such as electron beam (EB) polishing, electropolishing, drag finishing, stream finishing, vibratory finishing, shot peening, ultrasonic impact treatment, or laser peening for super precision surface finish.

SECTION 6 Inspection and Testing

1 General

The purpose of inspection and testing is to verify the technical design requirements are met repeatedly, accurately, and consistently using sacrificial, reference, and actual parts and/or testing coupons through nondestructive or destructive testing methods.

The inspection and testing of sacrificial, reference, and actual parts and/or testing coupons are to be applied after all post-build processes. Materials testing may be carried out after heat treatment and excludes machining and surface finishing.

The scope and frequency of inspection and testing is to consider the categorization of the part and the potential limitations of the AM process.

The inspection and testing may be affected by part geometry, dimensions, features, materials, and applications. Test samples/coupons are to be representative of the part, representing minimum and maximum feature size within the part and build orientation.

Inspection and testing are to be in accordance with applicable ABS Rules and Guides, industry standards, or designer specification and are to be targeted for quality control during production with an agreed or approved fabrication plan (refer to Section 9).

The extent of testing and frequency for AM facility approval are provided in Section 7 and for AM part approval in Section 8.

2 Submittals

The following documents are to be submitted for inspection and testing:

- i) Inspection and testing plan
- ii) The applicable testing standards in accordance with ABS Rules/Guides for class parts, industry standards or designer's specification for non-class parts
- iii) The nondestructive inspection report
- iv) The functional testing report for first article or prototype part
- v) The materials testing report

3 Material Testing

Refer to Section 2-1-1 of the *ABS Rules for Materials and Welding (Part 2)* for material property testing.

Other equivalent industry standards are also recognized and acceptable including:

- i) ASTM A751 for Standard Test Methods, Practices and Terminology for Chemical Analysis of Steel Products
- ii) ASTM E3 for Standard Guide for Preparation of Metallographic Specimens
- iii) ASTM E407 for Standard Practice for Microetching Metals and Alloys
- iv) ASTM B962 for Standard Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes' Principle
- v) ASTM B311 for Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
- vi) ASTM A370 for Standard Test Methods and Definitions for Mechanical Testing of Steel Products
- vii) ASTM E8 for Standard Test Methods for Tension Testing of Metallic Materials
- viii) ASTM E23 for Standard Test Methods for Notched Bar Impact Testing of Metallic Materials
- ix) ASTM E10 for Standard Test Method for Brinell Hardness of Metallic Materials
- x) ASTM E18 for Standard Test Methods for Rockwell Hardness of Metallic Materials
- xi) ASTM E92 for Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials

3.1 Chemical Composition

Chemical composition is to be analyzed, and the results are to be documented including all elements in the materials specification of the final delivered condition.

3.2 Microstructure

Microstructure is to be examined using optical microscopy or scanning electron microscopy (SEM). The following information is to be documented for qualification and production if required:

- i) Sample ID
- ii) Part thickness at sectioning plane
- iii) Sectioning plane angle relative to build platform
- iv) Pictures at 5X, 100X, 500X or facility's best practices
- v) Description of microstructure with grain size or other observations, as applicable
- vi) Characterization of flaws or defects, such as morphology, type, size, location, frequency

3.3 Fusion Density

Fusion density is to be tested in accordance with ASTM B962 or other equivalent standards and test results are to be documented for qualification and optional for production.

Note: Fusion density is applicable to powder process but not required by wire DED process.

3.4 Mechanical Properties

3.4.1 Tensile

Refer to 2-1-1/Figure 2 and 3 of the *ABS Rules for Materials and Welding (Part 2)* for dimension of tensile testing samples. Other technically equivalent industry standards may also be applied. Subsize samples in accordance with ASTM E8 are acceptable for PBF process with a minimum gage diameter of 6.25 mm (0.25 in.). Other alternative sample sizes may be specially considered and agreed to by ABS on a case-by-case basis.

Test results are to be documented for qualification and production including:

- i) Tensile sample information such as ID, gage length, diameter for round sample or width and thickness for flat sample, and the sample orientation
- ii) Test temperature is to be stated if not room temperature
- iii) Test results such as yield strength, tensile strength, elongation, reduction of area, and tensile failure type and location

3.4.2 Charpy Test

If required by end-used material specification, reference is to be made to 2-1-1/Figure 4 of *ABS Rules for Materials and Welding (Part 2)* for dimension of Charpy testing samples.

Test results are to be documented including the following items:

- i) Charpy sample information such as identification, sample size, and notch orientation
- ii) Test temperature
- iii) Test results such as absorbed energy, percentage crystallinity, and lateral expansion for qualification and production

3.4.3 Hardness

If required, hardness testing is to be carried out in accordance with facility's practices such as microhardness or other applicable hardness testing methods for qualification and production.

3.4.4 Bend Test

If required, refer to 2-4-3/Figure 7 of the *ABS Rules for Materials and Welding (Part 2)* for bend testing samples and bending mandrel. Other technically equivalent industry standards are also recognized, such as ASTM A20.

3.5 Special Properties

Other special properties may need testing depending upon material specification and application. Other tests include fatigue, corrosion, wear, erosion, fracture toughness, high or low temperature, etc. Testing plan and procedures are to be submitted for ABS review. Test results are to be documented for qualification.

As applicable, weldability testing is to be performed depending on the fabrication, installation and build process, etc., which is specially considered and agreed to by ABS on a case-by-case basis.

4 Nondestructive Testing

Nondestructive testing standards, quality level and acceptance criteria are to be defined in accordance with *ABS Guide for Nondestructive Inspection* and documented for qualification and production if required.

Other equivalent industry standards are also recognized and acceptable including:

- i) ISO 3452-1 for Non-destructive testing — Penetrant testing — Part 1: General principles
- ii) ASTM E1417 for Standard Practice for Liquid Penetrant Testing
- iii) ISO 17638 for Non-Destructive Testing of Welds — Magnetic Particle Testing
- iv) ASTM E1444 for Standard Practice for Magnetic Particle Testing
- v) ISO 17636-1 for Non-Destructive Testing of Welds — Radiographic Testing — Part 1: X- and Gamma-Ray Techniques with Film
- vi) ASTM E1742 for Standard Practice for Radiographic Examination
- vii) ASTM E1570 for Standard Practice for Fan Beam Computed Tomographic (CT) Examination
- viii) ISO/ASTM 52905 for Additive manufacturing — General principles — Non-destructive testing of additive manufactured products

4.1 Dimension Examination

100% inspection is required for dimensions and tolerance.

4.2 Visual Examination

100% visual examination is required.

4.3 Surface Examination

When applying surface NDI Liquid Penetrant (LP), Magnetic Particle (MP), or Eddy Current (EC), the as-printed surface of AM parts may give false indications, so if surface NDI is required, the surface is to be made suitable for the NDI method applied.

LP is an acceptable inspection method. MP and EC are alternative testing methods only for ferromagnetic materials.

4.4 Volumetric Examination

If required by specification, ultrasonic or radiographic are acceptable inspection methods for volumetric defects.

Due to the complex shape or the signal decay between layers, internal defects testing results may not be accurate by ultrasonic or radiographic inspection. Computed Tomography (CT) is an acceptable inspection method for estimation of internal defects in accordance with ASTM E1570. If applicable, powder removal from internal volumes is to be verified using CT scan.

5 Functional Testing

Depending upon the intended application, functionality is to be tested in accordance with applicable ABS Rules and Guides, industry standards or design's specifications for qualification and optional for production.

As applicable, functional testing includes hydrostatic testing for Machinery, Boilers, Pressure Vessels and Piping in accordance with 2-3-5/31 of the *ABS Rules for Materials and Welding (Part 2)*.

As applicable, other functional testing is to be carried out such as loading, balancing testing, and FAT in accordance with the applicable section of Part 4 of the *ABS Rules for Building and Classing Marine Vessels*.

Other testing requirements may be specially considered, applied, and agreed to by ABS on a case-by-case basis.

6 Inspection and Testing Report

A material testing report (MTR) is to include all specified requirements in accordance with ABS Rules and Guides, recognized industry standards, or material specification for the final delivered condition.

The nondestructive testing report is to include all specified requirements such as dimensions, position, and features of the AM part for the final delivered condition.

Additionally, surface or volumetric inspections are to be in accordance with the *ABS Guide for Nondestructive Inspection* or other recognized industry standards, depending upon the applied nondestructive techniques.

SECTION 7 Approval of AM Facilities

1 General

AM facilities are to comply with the applicable requirements of ABS Rules and Guides, ABS recognized industry standards, or designer's specifications.

AM materials or parts in final delivered condition are to be prepared using the established manufacturing specifications, qualified using approval tests of standard qualification build, and approved with repeatedly and consistently achievable materials properties for potential application.

The AM facility is evaluated for its quality management system and AM capability. In addition, the sub-suppliers or facilities are to be reviewed using specification as input and documentation as output. The sub-suppliers or facilities may include feedstock supplier, post-build heat treatment, machine shop, lab testing, NDT facilities, or service supplier.

ABS approval involves documentation review and audit of the facility. The approval is valid for 5 years subject to annual verification and/or endorsement by the attending Surveyor. An additional audit may be requested when there is any quality concern.

2 Submittals

The following documents are to be submitted for AM facility approval, to the satisfaction of ABS review and survey:

- i)* Quality management system (refer to Subsection 7/3)
- ii)* Additive manufacturing capability (refer to Subsection 7/4)
- iii)* Machine and operator qualification record, if requested (refer to Subsections 7/5 and 7/6)
- iv)* Build volume model or test plan for standard qualification build (refer to Subsection 4/2)
- v)* Feedstock procurement specification and data sheet with testing results (refer to Subsection 3/2)
- vi)* AM procedure specification including pre-build, build, and post-build (refer to Subsection 4/2 and Subsection 5/2)
- vii)* Procedure specification qualification report (PQR) (refer to Subsection 4/2)
- viii)* Destructive and nondestructive testing standard and testing report (refer to Subsection 6/2)
- ix)* Material specification for final delivered condition, if available (refer to Subsection 2/2)

3 Quality Management System

Quality management system is a set of policies, processes, and procedures required for planning and execution (production/development/service) in the additive manufacturing business area of the facility (i.e., areas that can impact the organization's ability to meet customer requirements). The review and survey of the AM facility by ABS are to be considered from facility description, organization and quality, and AM capability including historical data for AM facility approval, to the satisfaction of ABS review and survey.

3.1 Facility Description

- i) Name and address of AM Facility
- ii) General relevant information and background
- iii) Estimated annual production of finished part for marine and offshore application

3.2 Organization and Quality

- i) Organizational chart
- ii) Staff employed
- iii) Organization of the quality control department and its staff employed
- iv) Qualification of the operator involved in activities related to the quality of the part
- v) Certification of compliance of the quality system with ISO 9001 or equivalent, if any
- vi) Approval certificates/documentation already granted by other Classification Societies, if any

Note:

If recognized certification is not available, then adequate controls are to be demonstrated through a review of the Manufacturer's QMS.

4 Additive Manufacturing Capability

- i) List of machines and materials for approval, refer to Subsection 7/9
- ii) Manufacturing flow chart for the AM Process
- iii) Feedstock handling and storage procedure
- iv) Final delivered part handling and storage procedure
- v) Details of the various equipment or outsourcing facilities, including pre-build, AM build, and post-build activities (e.g., heat treatment)
- vi) Nondestructive and destructive testing facilities or service suppliers intended to be used, if outsourced
- vii) Information about the different types of material grades the facility intends to manufacture with frequency of manufacturing, with any previous examples
- viii) Information about the different types of AM processes the facility intends to use to fabricate with the manufacturing frequency and any previous examples
- ix) Previous examples of the different types of test coupons/manufactured parts at the facility
- x) Information about maximum weights and dimensions the facility is capable of handling
- xi) Management system of engineering specifications, standard work instruction/qualification procedures with revision control and documentation for part/samples labeling and traceability

Note:

If the practice affects the quality of part or material, such as cleaning, cross contamination, multi-materials in the same machine, the AM facility is to take responsibility for powder quality and reuse and handling procedures. Furthermore, the AM facility is to take full responsibility for requirements of ES&H (environment, safety, and health). Any practices related to ES&H are to be documented, controlled, and witnessed.

5 Machine Qualification

The purpose of machine qualification is to establish documented evidence to demonstrate the following (refer to the applicable part of ASTM 52926 depending upon the AM process):

- i)* Process equipment and ancillary systems can operate within the established/specified limits and tolerances
- ii)* Test coupons throughout the build envelope can achieve the required properties by approval tests for standard qualification build in Section 7.
- iii)* Approval tests for Machine Qualification Record

Machine qualification is to consider the actual production conditions and worst-case scenario. The standard qualification builds are to represent the build envelope, within which intended AM parts and materials are to be fabricated using a qualified AM procedure.

- i)* Examination of equipment design
- ii)* Determination of calibration, maintenance, and adjustment
- iii)* Identification of critical equipment features that may affect the process and product

The written quality procedures and machine qualification record are to be documented for equipment calibration, maintenance, monitoring, and control by the AM facility in their quality management system and submitted to ABS if deemed necessary.

Range of approval for machine qualification is to include the following information:

- i)* Machine manufacturer
- ii)* Machine model
- iii)* Machine series number, if applicable
- iv)* Software version
- v)* Major subcomponents of equipment/machine, if applicable

Notes:

- 1 A DED machine may be customized by the AM facility, and it is to be qualified/identified by series number. A PBF machine may be commercialized by the machine manufacturer and may have similar controls for the same model with different series numbers. PBF machine qualification may be waived by series number, with special consideration and agreed to by ABS on a case-by-case.
- 2 Refer to 4/4.3. The in-process monitoring or controlling methods that do not alter or control any essential parameters are not required to be in the range of approval. The in-process monitoring or controlling methods that alter or control any essential parameters are to be documented in procedure specification and required in range of approval as major subcomponents of equipment/machine.

6 Operator Qualification

A qualified operator is to have a knowledge test (such as written exams, internal training, external training and qualification) and operator qualification test samples for the intended range of approval, refer to ASTM 52935.

The operator qualification is to follow qualification for additive manufacturing procedure specification (AMPS) using procedures for part approval qualification builds.

For practical hands-on skills, the operator is to demonstrate the necessary process steps on the machine and demonstrate the necessary capabilities to follow a preliminary/qualified AM procedure specification.

For the procedure, part and material approval or production, the operator is to be assessed based on the practical qualification/approval tests in accordance with the requirements of procedure for material approval in Section 7 and/or part approval tests in Section 8.

The range of approval for operator qualification is to include the combination of process, feedstock material and machine:

- i)* Metal AM process: Change of process is to be requalified
 - LB-PBF
 - EB-PBF
 - L-DED
 - Arc-DED
 - Other identified process
- ii)* Feedstock material group: Change of material group is to be requalified
 - A: Unalloyed, low-alloyed steels and high alloyed ferritic steels
 - B: Austenitic, martensitic and precipitation hardening steels
 - C: Titanium and Titanium alloys, Niobium, Zirconium and other reactive materials
 - D: Aluminum alloys
 - E: Magnesium alloys
 - F: Nickel alloys, cobalt alloys
 - G: Other than above, such as copper alloys, ceramic
- iii)* Machine: Change of machine is to be requalified
 - Machine manufacturer
 - Machine type
 - Software version

The written quality procedures and operator/performance qualification record are to be documented and controlled by the AM facility in their quality management system and submitted to ABS upon request.

7 Approval for AM Facility

7.1 General

Generic procedure qualification is required in accordance with Subsection 4/5.

AMPS and PQR are to be established by specification and documentation control to show that the technical/design requirements are achievable in accordance with ABS Rules and Guides, industry standards, or designer/OEM specification.

Alternative standard qualification builds are acceptable in accordance with the AM facility or designer specification, if deemed as technically equivalent by ABS.

- i) The test coupons with or without a sacrificial/reference part are to be built and are to achieve the required material properties by approval tests using standard qualification builds.
- ii) Test samples are to represent the intended AM parts and applications or worst-case scenario, such as edge of the build platform with fast cooling rate.
- iii) The relationship between input variables and output results is to be established for the specific combination of parameters by Procedure Qualification Record for Facility Approval.
- iv) Test quantities are to be specially considered and agreed to by ABS on a case-by-case basis, if the AM facility can provide the historical test results for the technically same combination of machine, feedstock, procedure, and materials of the final delivered condition.

If part approval and facility approval are carried out concurrently, the procedure qualification for part approval and facility approval are to be combined in one build lot, or the test methods, quantities, and acceptance criteria for approval tests are to meet the requirements, whichever is more stringent.

7.2 Approval Tests

Test samples are to be evenly distributed over the overall build platform and represent a worst-case scenario for samples during production.

Approval tests, test methods, and acceptance criteria are to be referred to the materials specification of the final delivered condition and agreed upon before testing samples are prepared. Alternative tests may be specially considered and agreed to by ABS. Unless otherwise agreed, the following tests in Section 7/ Table 1 are to be performed.

TABLE 1
Approval Tests for AM Facility Approval

<i>Test Method⁽¹⁾</i>	<i>Powder Bed Fusion (PBF)</i>		<i>Directed Energy Deposition (DED)⁽⁷⁾</i>	
	<i>Class</i>	<i>Non-Class⁽⁸⁾</i>	<i>Class</i>	<i>Non-Class⁽⁸⁾</i>
Visual Inspection	Y	Y	Y	Y
Dimensional Inspection	Y	Y	Y	Y
Penetrant Inspection	Y	Y	Y	Y
Radiographic Inspection	Y	Y	Y	Y
Density Testing, if applicable	3	3	3	3
Metallographic Examination ⁽⁵⁾	Y	Y	Y	Y
Chemical Analysis	Y	Y	Y	Y
Tensile Tests (Test Coupons)	15 ⁽²⁾	5 ⁽²⁾	9 ⁽³⁾	3 ⁽³⁾
Charpy Tests (Test Coupons)	3 ⁽⁴⁾ sets	1 ⁽⁴⁾ set	3 ⁽⁴⁾ sets	1 ⁽⁴⁾ set
Hardness Tests ⁽⁵⁾	Y	Y	Y	Y
Bend Tests	NA	NA	4 ⁽⁶⁾	4 ⁽⁶⁾

Notes:

- 1 Depending upon the intended parts and applications, other tests may be required, such as for fatigue, corrosion, wear, erosion, weldability, and residual stress.
- 2 For LB-PBF and class application, a total of 15 tensile samples produced and tested with 5 each in the X, Y and Z directions (refer to Section 7/ Figure 2). For LB-PBF and non-class application, a total of 5 tensile samples produced and tested in the Z axis (refer to Section 7/ Figure 3). For the EB-PBF process, tensile test directions and quantities are to be specially considered and agreed to by ABS on a case-by-case basis.
- 3 For DED and class application, a total of 9 tensile samples are to be tested. For DED and non-class applications, a total of 3 tensile samples are to be tested. The above tests can also be specially considered and agreed to by ABS on a case-by-case basis. The examples are given in Section 7/ Figure 4 for straight wall and Section 7/ Figure 5 for cylinder wall, respectively.
- 4 Alternative testing to the test quantities in Section 7/ Table 1 may be specially considered and agreed to by ABS, depending upon materials, designed temperature, and build process.
- 5 Unless otherwise required, hardness and metallographic tests are to be carried out in accordance with the facility's practice, reported and specially considered by ABS on a case-by-case basis.
- 6 For class and non-class applications, two bend tests in Z and two bend tests either X or Y directions for the wire/powder arc DED process (refer to 6/3.4.4 for sample thickness and bend mandrel radius).
- 7 If the DED procedure is qualified for an integrated build platform (refer to Section 7/ Figure 5), the AM material is not to be removed from the build platform for the final delivered condition. As a minimum, six tensile samples are to be retrieved and tested for each integrated build platform material. Three tensile samples are to represent the interface and heat affected zone (HAZ). The other three samples are to represent the AM build materials in the gage length. Charpy tests for the integrated build qualification are to be specially considered and agreed to by ABS on a case-by-case basis. The interface and HAZ are also to be characterized (refer to traditional welding procedure qualification).
- 8 It is not mandatory for non-class parts to be fabricated by ABS approved facility/manufacture. However, if ABS approval is requested by clients, the facility/manufacture is to submit the manufacturing process and procedures with ABS witness and qualification/approval testing report with ABS witnessed qualification/approval tests.

8 Examples of Qualification Builds

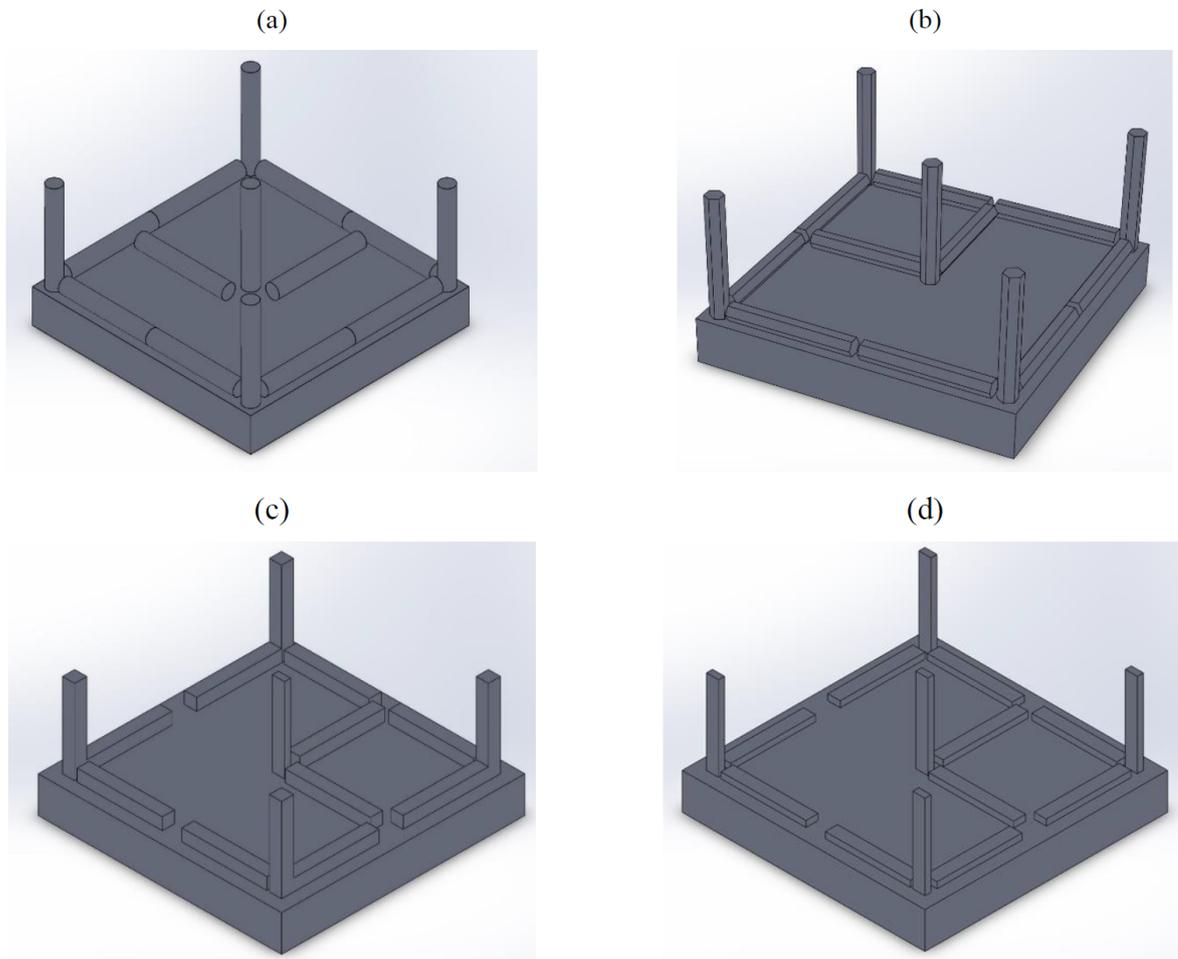
Examples of standard qualification builds are shown in the following figures. The figures show the distribution and direction of tensile samples. Other samples for approval tests are to be optimized in accordance with facility's practice. Alternative standard qualification builds are acceptable if test coupons represent the actual part or the worst-case scenario of the build platform/build direction.

8.1 PBF

For the PBF process, examples of a qualification build are provided in Section 7/ Figure 1 for class applications and Section 7/ Figure 2 for non-class applications.

FIGURE 1
Example for Facility Approval using PBF (Class Application)

Build Platform: 250 mm by 250 mm (10 inch by 10 inch)

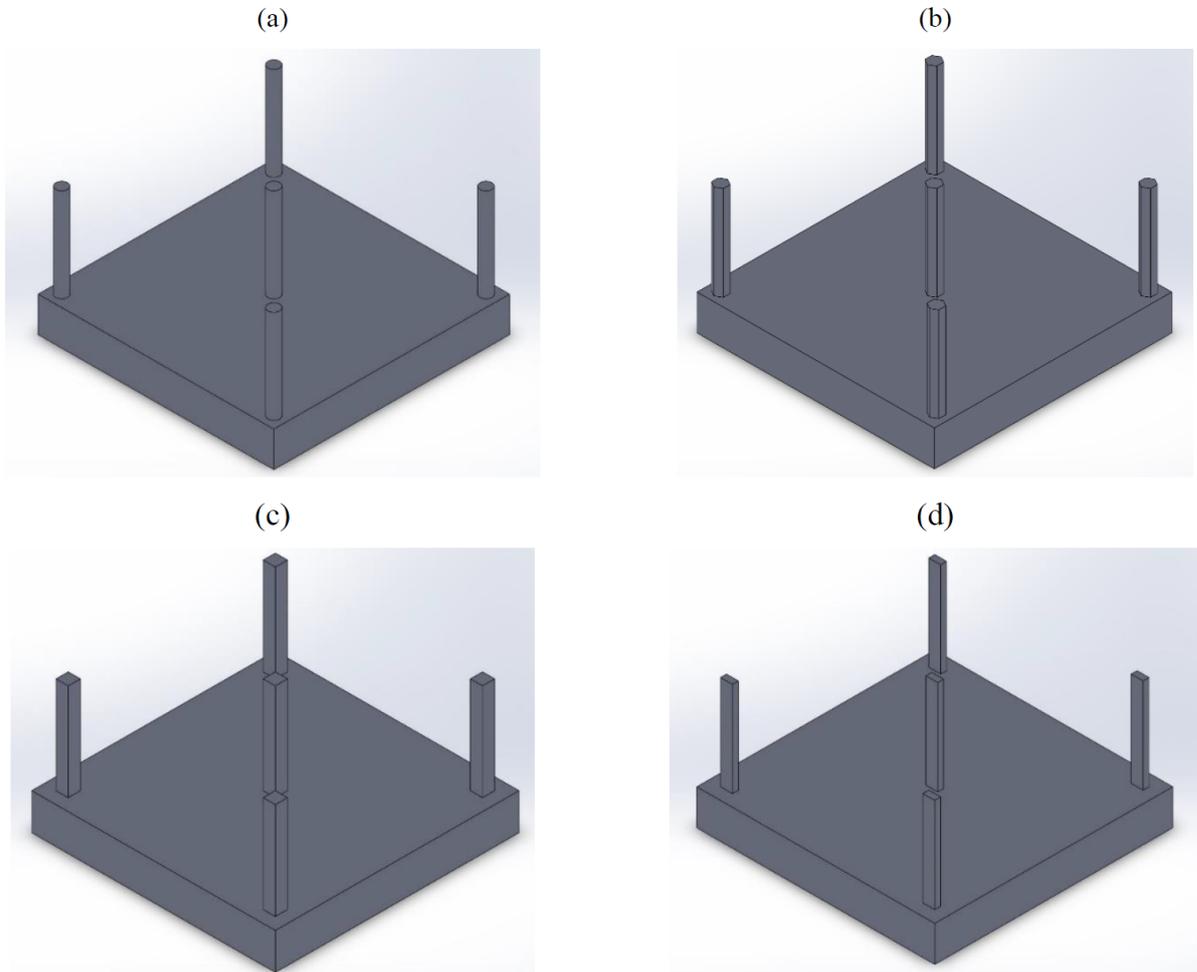


Notes:

- 1 The example represents test samples for class application and the procedure qualification for facility approval. According to AM facility's best practice, as-built samples may be round (a), hexagonal (b), square (c), or flat (d) shapes.
- 2 For LB-PBF and class applications, a total of 15 tensile samples are to be produced and tested with 5 each in the X, Y and Z directions. For the EB-PBF process, tensile test directions and quantities are to be specially considered and agreed to by ABS on a case-by-case basis.
- 3 Alternative test samples and quantities may be specially considered and agreed, depending upon the historical test data of AM facility for target material.
- 4 Reduced tensile sample size is acceptable with the minimum gage diameter of 6.25 mm (0.25 in.) or equivalent, in accordance with ASTM E8.

FIGURE 2
Example for Facility Approval using PBF (Non-Class Application)

Build Platform: 250 mm by 250 mm (10 inch by 10 inch)



Notes:

- 1 The example represents test samples for a non-class part application and the procedure qualification for facility approval. According to AM facility's best practice, as-built samples may be round (a), hexagonal (b), square (c) or flat (d) shapes.
- 2 For LB-PBF and non-class applications, a total of 5 tensile samples produced and tested in the Z axis. For the EB-PBF process, tensile test directions and quantities are to be specially considered and agreed to by ABS on a case-by-case basis.
- 3 Alternative test samples and quantities may be specially considered and agreed, depending upon the historical test data of AM facility for target material.
- 4 Reduced tensile sample size is acceptable with the minimum gage diameter of 6.25 mm (0.25 in.) or equivalent in accordance with ASTM E8.

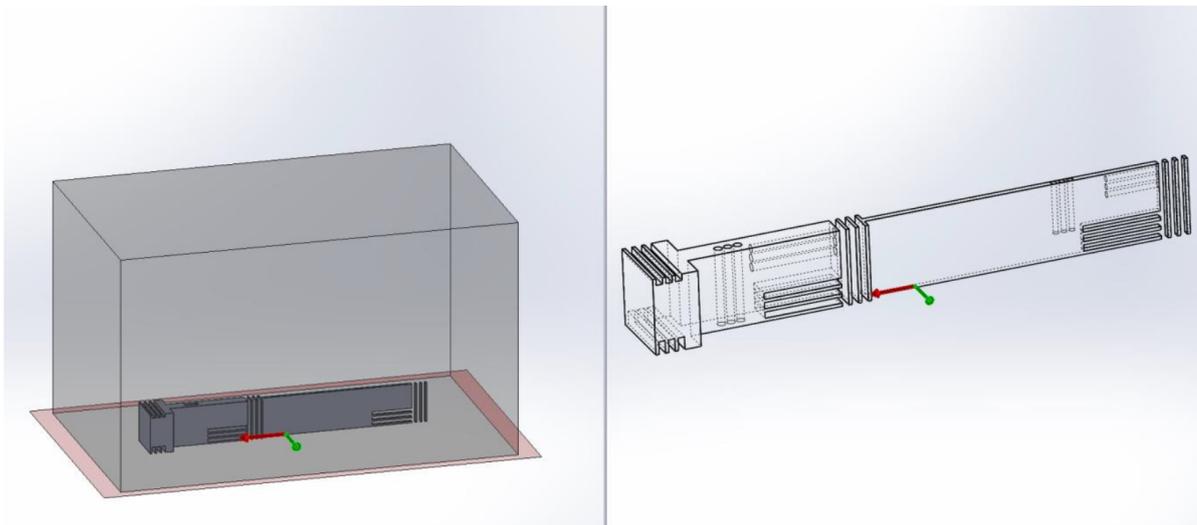
8.2 DED

For the DED process, examples of a qualification build are provided in Section 7/ Figure 3 for straight wall, Section 7/ Figure 4 for cylinder wall, and Section 7/ Figure 5 for integrated build platform.

For DED, test pieces are to mimic the final geometry. Changes in geometry may dictate toolpath selection and affect heat input and material properties. If applicable, test samples are to be extracted from the actual demonstrator geometry.

FIGURE 3
Example of Facility Approval using DED Process (Straight Wall)

Build Platform: 1500 mm by 900 mm (60 inch by 36 inch)

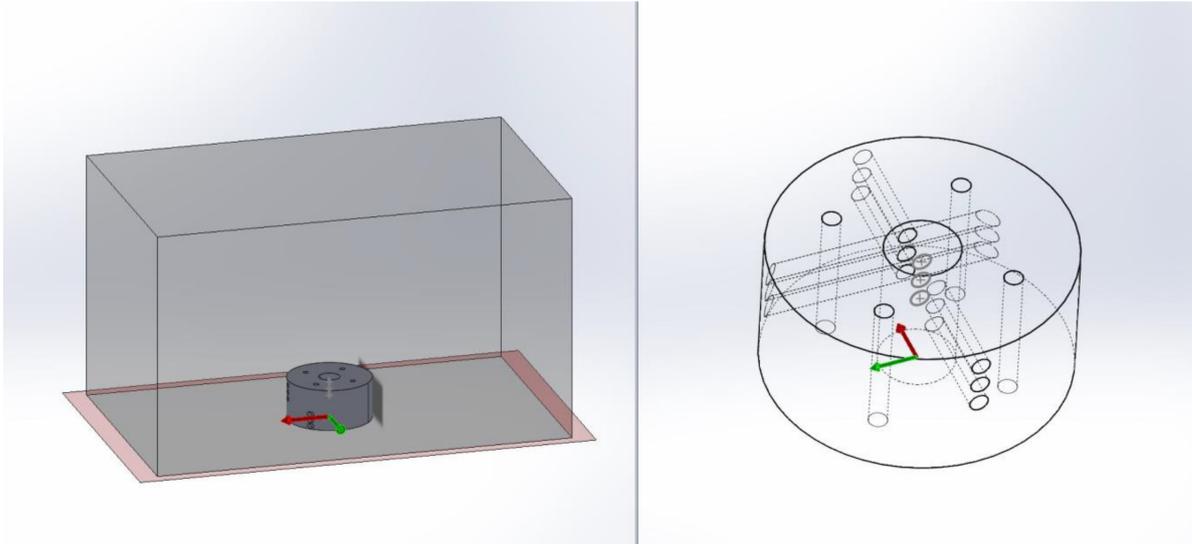


Notes:

- 1 This example represents a part having straight wall features with various thickness and represents the procedure qualification for facility approval. The features in the drawing provide the example to extract test samples from planned locations.
- 2 Unless otherwise agreed, for class applications, 3 tensile samples are to be tested in the Z direction, and 3 tensile samples are to be tested in the X direction from the thick wall section. An additional 3 tensile samples are to be tested in the Z direction from the thin wall section. A total of 9 tensile samples are to be tested. The definition of thin and thick wall is taken from traditional welding procedure qualification.
- 3 Unless otherwise agreed, for non-class material, 3 tensile samples are to be tested in the Z direction from the wall thickness that represents the intended part.
- 4 Unless otherwise agreed, for a part with extreme thickness (e.g., greater than 100 mm (4 in.)), 3 tensile samples are to be retrieved from the section attached to the build platform and 3 tensile samples are to be retrieved from the top section away from the build platform. A total of 6 tensile samples are to be tested.
- 5 Reduced test quantities may be specially considered and agreed upon depending on the target part dimensions and applications.

FIGURE 4
Example for Facility Approval using DED Process (Cylinder Wall)

Build Platform: 1500 mm by 900 mm (60 inch by 36 inch)

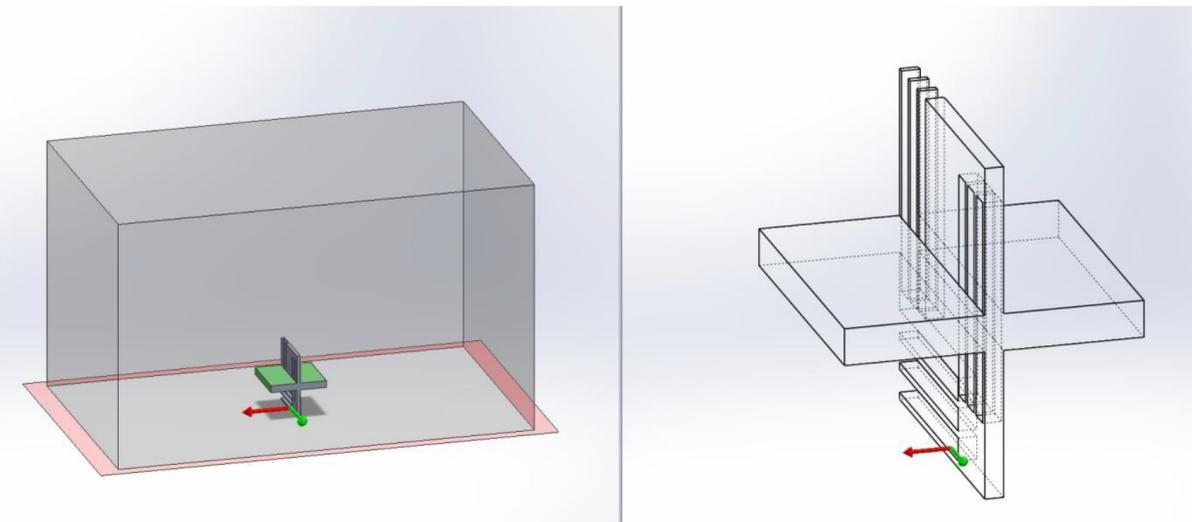


Notes:

- 1 This example represents a part having cylinder wall features and represents the procedure qualification for facility approval. The features in the drawing provide the example to extract test samples from planned locations.
- 2 Unless otherwise agreed, for class applications, 3 tensile samples are to be tested in the Z axis, 3 tensile samples are to be tested in the radial direction, and 3 tensile samples are to be tested in tangent direction.
- 3 Unless otherwise agreed, for non-class applications, 3 tensile samples are to be tested in the Z direction from the wall thickness that represents the intended part.
- 4 Reduced test quantities may be specially considered and agreed upon depending on the target part dimensions and applications.

FIGURE 5
Example for Facility Approval using DED Process (Integrated Build)

Build Platform: 1500 mm by 900 mm (60 inch by 36 inch)



Notes:

- 1 This example represents a part having an integrated build platform and represents the procedure qualification for facility approval considering (i) location, number of clamps, and clamping sequence of substrate clamping and (ii) distortion in the substrate which affects standoff. The features in the drawing provide the example to extract test samples from planned locations.
- 2 Unless otherwise agreed, for class applications, 3 tensile samples are to be tested in the Z direction, and 3 tensile samples are to be tested in X or Y direction from the AM build material. Additionally, 3 tensile samples are to be tested for the interface of the AM build material and build platform. The interface is to be characterized (refer to traditional welding procedure qualification).
- 3 Unless otherwise agreed, for non-class applications, 3 tensile samples are to be tested in the Z direction, and 3 tensile samples are to be tested for the interface of the AM build material and build platform. Additionally, the interface is to be characterized (refer to traditional welding procedure qualification).
- 4 Reduced tests may be specially considered and agreed upon depending on the target part dimensions for other applications.

9 Range of Approval

Range of approval for the AM facility is to be the combination of qualified specifications with revision (refer to Subsection 7/2 and Section 2).

- i) Machine
- ii) Feedstock material specification linked to feedstock supplier
- iii) AM procedure specification including pre-build, build, and post-build
- iv) Materials specification of final delivered condition
- v) The extent of approval tests, such as class application or non-class application

Supplementary tests can be carried out and recorded to expand the range of approval. Requalification is to be carried out if there is any quality concern for the delivered AM parts or materials.

Notes:

- 1 For class applications, yield and ultimate strength, the 95/95 one-side lower tolerance bound for the properties, calculated from the test data by valid and applicable statistical methods, are to meet the minimum design requirements. For non-class applications, all test results are to meet the minimum design requirements.
- 2 Unless otherwise agreed, wire feedstock is to be sourced from approved welding consumable suppliers and qualified in accordance with the approval tests in 7/7.2.
- 3 Unless otherwise agreed, powder feedstock is to be type approved or meet the approval tests in 7/7.2, which can also be linked with facility approval.
- 4 A family of materials may be qualified and approved, which is to be specially considered and agreed by ABS on a case-by-case basis.

SECTION 8 Approval of AM Parts

1 Scope

This Section provides approval requirements for AM parts in accordance with applicable ABS Rules and Guides, ABS recognized industry standards, or designer specifications. The approval process is to be in accordance with Subsection 1/3.

2 Submittals

The following documents are to be submitted for AM parts approval, to the satisfaction of ABS review and survey:

- i)* Documentation identifying the part as either a class part or non-class part (refer to Subsection 2/2)
- ii)* If applicable, CAD model or drawing for AM and engineering calculation or simulation for model (refer to Subsection 2/2)
- iii)* If applicable, digital build model of part and test coupons for building, including orientation, support structures, etc., for reference
- iv)* Material specification of final delivered condition including material grade, composition, properties requirements, and NDT test standard and acceptance criteria (refer to Subsection 2/2)
- v)* Feedstock material specification linked to feedstock supplier (refer to Subsection 3/2)
- vi)* AM procedure specification (refer to Subsection 4/2)
- vii)* Post-build procedure specification (refer to Subsection 5/2)
- viii)* Procedure Qualification Record for Part Approval including inspection and testing reports with traceability of applied parameters (refer to Subsection 4/2)
Note: One or separate qualification reports should include all controlled parameters and the corresponding test results. AWS D20.1/Annex A is to be referred to depending on the specific AM process. Any PQR format is acceptable if all applicable information is recorded with traceability.
- ix)* Functionality testing procedure and results of AM part (refer to Subsection 6/2)
- x)* AM part installation, operation, and maintenance instructions, mitigation plan, and survey plan with witness by ABS during service for class parts and non-class AM parts, evaluated by part designer/manufacturer, agreed by purchaser and ABS
- xi)* If applicable, fabrication and test plan for part certification and production (refer to Section 9)

3 Approval of AM Parts

3.1 General

Generic procedure qualification is required in accordance with Subsection 4/5.

AMPS and PQR for part approval are to be established by specification and documentation control and provide evidence that the technical/design requirements are achievable for application.

- i)* Test coupons and AM parts (sacrificial or reference) are to be built using the established digital build volume model including part location and orientation, support structure, machining stock, and test samples location and direction to meet the same specifications for production in the same build lot.
- ii)* Test coupons are to represent the actual part or the worst-case scenario, such as edge of build platform in Z direction for laser-based process.
- iii)* As applicable, the height/length of each separately built tensile sample in the Z direction is to be at least the maximum height of the intended part for the PBF process. If not applicable for the large part/component, the standardized tensile sample with 50 mm (2 in.) gage length is to be tested or multiple tensile samples are to be tested in the Z direction to cover the height of the large part/component.
- iv)* For separate coupons, the test samples are to represent the intended part and features.
- v)* As applicable, the samples are to be retrieved from the prolongation of the intended part for the DED process to replace the sacrificial part tests, considering prolongation to have similar dimensions (e.g., thickness of the part).
- vi)* The relationship between controlled/specified process parameters as input and test results as output in accordance with part model and materials specification is to be established for the specific combination of parameters by qualification record.
- vii)* The relationships of dimensions and material properties between test coupons and the intended AM part are to be established. The test coupons are applied to assist quality control continuity during fabrication or regular production.
- viii)* The test coupons and specific part are to achieve the required properties by approval tests in accordance with ABS Rules and Guides, industry standards, or designer/OEM specification.

3.2 Approval Tests

Alternative approval tests samples, methods, and quantities are acceptable if deemed as technically equivalent by ABS. Unless otherwise agreed, the test samples, methods, and test quantity denoted in Section 8/ Table 1 are to be followed.

TABLE 1
Approval Tests for AM Parts Approval

<i>Test Method⁽¹⁾</i>	<i>Powder Bed Fusion (PBF)</i>		<i>Directed Energy Deposition (DED)⁽¹⁰⁾</i>	
	<i>Class</i>	<i>Non-Class⁽¹¹⁾</i>	<i>Class</i>	<i>Non-Class⁽¹¹⁾</i>
Visual Inspection	Y	Y	Y	Y
Dimensional Inspection	Y	Y	Y	Y
Penetrant Inspection	Y	Y	Y	Y
Radiographic Inspection	Y	Y	Y	Y
Density Testing, if applicable	3	3	3	3

<i>Test Method⁽¹⁾</i>	<i>Powder Bed Fusion (PBF)</i>		<i>Directed Energy Deposition (DED)⁽¹⁰⁾</i>	
	<i>Class</i>	<i>Non-Class⁽¹¹⁾</i>	<i>Class</i>	<i>Non-Class⁽¹¹⁾</i>
Metallographic Examination ⁽⁸⁾	Y	Y	Y	Y
Chemical Analysis	Y	Y	Y	Y
Tensile Tests (Test Coupons)	3 ⁽²⁾	1 ⁽³⁾	NA ⁽⁴⁾	NA ⁽⁴⁾
Tensile Tests (AM Parts)	3 ⁽⁷⁾	3 ⁽⁷⁾	3	3
Charpy Tests (Test Coupons) ⁽⁵⁾	3 ⁽⁶⁾	1 ⁽⁶⁾	NA ⁽⁴⁾	NA ⁽⁴⁾
Charpy Tests (AM Parts) ⁽⁵⁾	3 ⁽⁷⁾	1 ⁽⁷⁾	3	3
Hardness Tests ⁽⁸⁾	Y	Y	Y	Y
Bend Tests	NA	NA	4 ⁽⁹⁾	4 ⁽⁹⁾
Function Tests	Y	Y	Y	Y

Notes:

- 1 Depending upon the intended parts and applications, other tests may be required, such as for fatigue, corrosion, wear, erosion, weldability, and residual stresses.
- 2 For PBF and class parts, at least 3 tensile samples are to be tested with 1 each in the X, Y and Z directions using coupons.
- 3 For PBF and non-class parts, at least 1 tensile sample is to be tested.
- 4 For parts approval by the DED process, reference or sacrificial parts are applicable to approval tests in lieu of the test coupons (refer to Section 8/ Figure 3 and Section 8/ Figure 4).
- 5 Alternative Charpy testing may be specially considered and agreed to by ABS, depending upon materials, design temperature, and build process.
- 6 For class parts, 3 sets are to be tested with 1 set each in the X, Y and Z directions. For non-class parts, 1 set is to be tested in Z direction. 1 set of Charpy contains 3 specimens.
- 7 If applicable, three tensile and three sets of Charpy are to be tested from the reference/sacrificial part for class parts, and three tensile and one set of Charpy are to be tested the reference/sacrificial part for non-class parts. If the size of the sacrificial/reference part is not applicable to tensile and Charpy tests, (i) Mini or reduced size samples are preferred to be tested from the sacrificial or reference part or (ii) in lieu of destructive testing of sacrificial or reference parts, 6 tensile and 6 sets of Charpy are to be tested with 2 in the X, Y and Z directions for class parts using test coupons (refer to Section 8/ Figure 1). 4 tensile and 2 sets of Charpy are to be tested in the Z direction for non-class parts using test coupons (refer to Section 8/ Figure 2).
- 8 Unless otherwise required, hardness and metallographic tests are to be carried out in accordance with the facility's practice, reported and specially considered by ABS on a case-by-case basis.
- 9 For both class parts and non-class parts, two bend tests in the Z and two bend tests in X or Y direction for wire/ powder arc DED process (refer to 6/3.4.4 for sample thickness and bend mandrel radius).
- 10 If the DED procedure is qualified for integrated build platform (refer to Section 7/ Figure 5), the AM part or material is not to be removed from the build platform for final delivered condition. As a minimum, six tensile samples are to be retrieved and tested for each integrated build platform materials. Three tensile samples are to represent the interface and heat affected zone (HAZ). The other three samples are to represent the AM build materials in the gage length. Charpy tests for integrated build qualification are to be specially considered and agreed to by ABS. The interface and HAZ are to be characterized, refer to traditional welding procedure qualification.
- 11 Non-class parts are not mandatory to be approved by ABS. However, if ABS approval is requested for non-class parts by clients, the AM facility/manufacturer is to submit the manufacturing process and procedures and part specific qualification/approval testing report with ABS witnessed qualification/approval tests.

4 Examples for Part Approval Test Builds

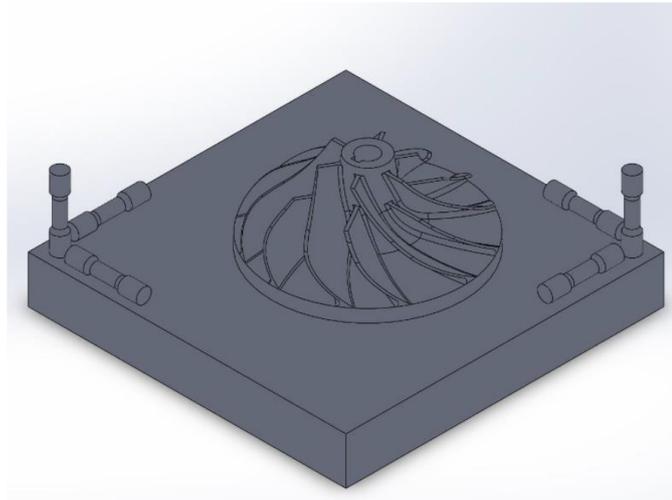
An alternative qualification build for part approval is acceptable if deemed to be technically equivalent by ABS. The below examples show the layout of tensile samples only. Approval test samples are to be in accordance with the facility's best practices.

4.1 PBF

Examples for part approval test builds using the PBF process are shown in Section 8/ Figure 1 for class parts and Section 8/ Figure 2 for non-class parts.

FIGURE 1
Example for Class Parts Approval using PBF Process

Build Platform: 250 mm by 250 mm (10 inch by 10 inch)

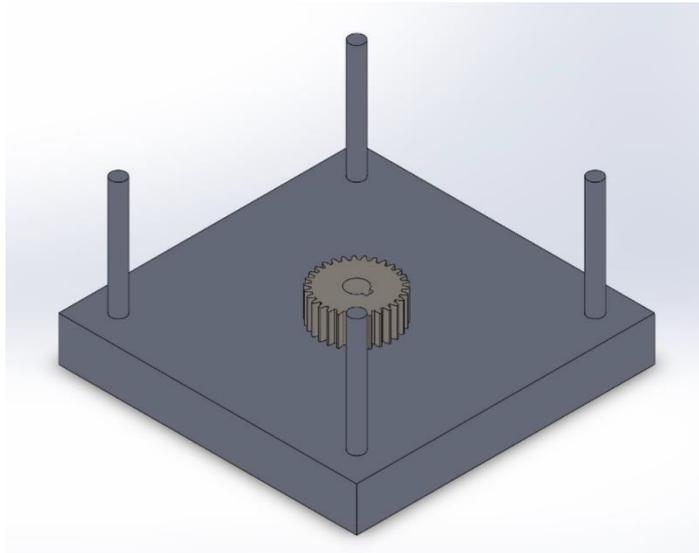


Notes:

- 1 This example represents a class part application. This example is for a small part where tensile samples are not practical to be retrieved from sacrificial parts as required in Section 8/ Table 1.
- 2 For PBF and class parts, a total of 6 tensile samples are to be produced and tested, with 2 each in the X, Y and Z directions.
- 3 Alternative test samples and quantities may be specially considered and agreed depending upon the target part dimension and applications.

FIGURE 2 Example for Non-Class Parts Approval using PBF Process

Build Platform: 250 mm by 250 mm (10 inch by 10 inch)



Notes:

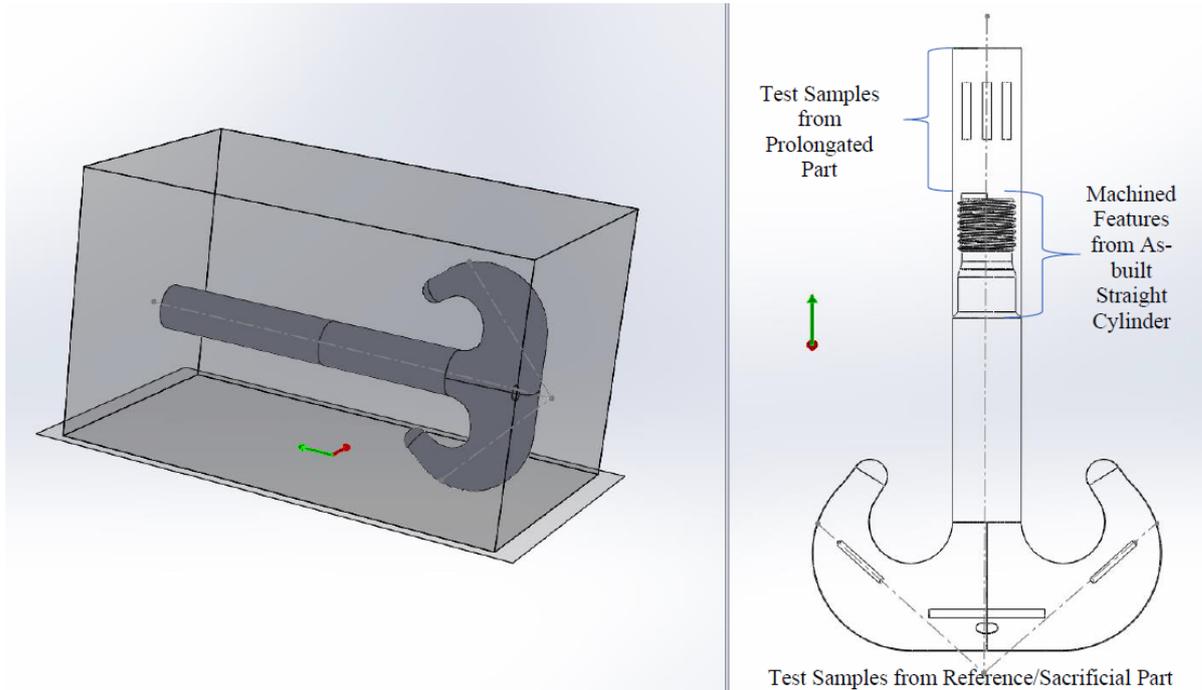
- 1 This example represents a non-class part application. This example is for a small part where tensile samples are not practical to be retrieved from sacrificial parts as required in Section 8/ Table 1.
- 2 For PBF and non-class parts, a total of 4 tensile samples are to be produced and tested in the Z direction.
- 3 Alternative test samples and quantities may be specially considered and agreed depending upon the target part dimension and applications.

4.2 DED

Examples for part approval test builds using the DED process are shown in Section 8/ Figure 3 for class parts and Section 8/ Figure 4 for non-class parts.

FIGURE 3
Example for Parts Approval using DED Process (Class Parts)

Build Platform: 1500 mm by 900 mm (60 inch by 36 inch)

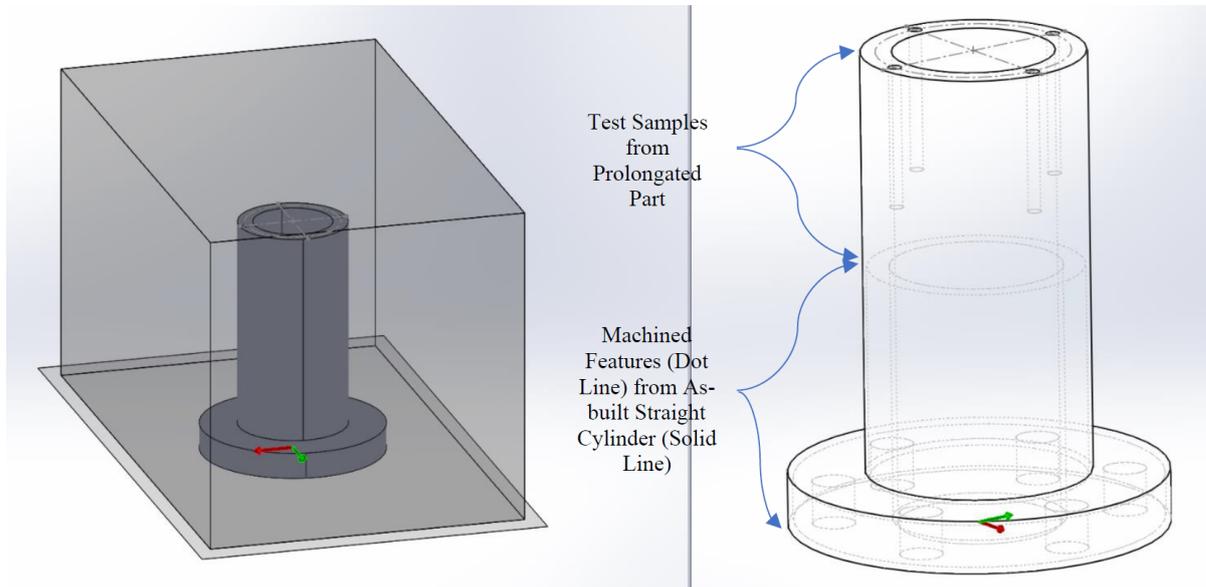


Notes:

- 1 The material stock for machining is to be added based on the final delivered dimensions and profile for the as-built part.
- 2 This example represents a class part. For DED and class parts, at least 3 tensile samples are to be tested.
- 3 For class parts approval by the DED process, reference or sacrificial parts are applicable to approval tests in lieu of the test coupons.
- 4 As applicable, the samples are to be retrieved from the prolongation of the intended part to replace the sacrificial part tests, considering prolongation to have similar dimensions (e.g., thickness of the part).
- 5 Tensile tests from separate test coupons for part approval are not preferred but may be specially considered and agreed to by ABS (e.g., reference/sacrificial parts or prolongation of parts are not feasible or practical for testing).
- 6 Alternative test samples and quantities may be specially considered and agreed upon depending on the target part dimensions and application.

FIGURE 4
Example for Parts Approval using DED Process (Non-Class Parts)

Build Platform: 1500 mm by 900 mm (60 inch by 36 inch)



Notes:

- 1 The material stock for machining is to be added based on the final delivered dimensions and profile for the as-built part.
- 2 This example represents a non-class part. For DED and non-class parts, at least 3 tensile samples are to be tested.
- 3 As applicable, the samples are to be retrieved from the prolongation of the intended part to replace the sacrificial part tests, considering prolongation to have similar dimensions (e.g., thickness of the part).
- 4 For non-class parts approval by the DED process, reference or sacrificial parts are also applicable to approval tests in lieu of the test coupons.
- 5 Tensile tests from separate test coupons for parts approval may be optional, which may be specially considered and agreed to by ABS (e.g., reference/sacrificial parts or prolongation of parts are not feasible or practical for testing).
- 6 Alternative test samples and quantities may be specially considered and agreed upon depending on the target part dimension and applications.

5 Range of Approval

The range of approval of AM parts is the combination of qualified model and specifications (refer to Section 2 and Subsection 8/2):

- i) Documentation identifying part as either a class or non-class part
- ii) CAD model or drawing with revision number
- iii) Materials specification of final delivered condition
- iv) Machine (refer to Subsection 8/2)
- v) Feedstock material specification linked to feedstock supplier
- vi) AM procedure specification including pre-build, build and post-build
- vii) Equipment/system to be installed

Supplementary tests can be carried out and recorded to expand the range of approval. Requalification is to be carried out if there is any quality concern for the delivered part.

Notes:

- 1 A family of parts may be qualified and approved, which is to be specially considered and agreed to by ABS on a case-by-case basis.
- 2 The in-service inspection is required for part approval of class parts and is optional for non-class parts, refer to 9/4.3.

SECTION 9 Certification of AM Parts

1 Scope

This Section provides certification requirements for AM parts in accordance with the applicable ABS Rules and Guides, ABS recognized industry standards or designer's specifications.

The certification process is to be in accordance with Subsection 1/3.

2 Fabrication and Testing Plan

Manufacturing and testing are to be witnessed by the attending ABS Surveyor for certification of class parts and are to be optionally witnessed for non-class parts.

Regular fabrication for approved and certified parts in Section 8 is to complete the following steps:

- i)* Qualified: CAD model or drawing or digital build model with revision number, defined in Subsection 2/1 and Subsection 2/4
- ii)* Qualified: Feedstock material specification linked to feedstock supplier, defined in Section 3
- iii)* Qualified: AM procedure specification, defined in Section 4
- iv)* Qualified: Post-build procedure specification, if applicable, defined in Section 5
- v)* Qualified: The sampling for production control including frequency and quantity are to be in accordance with the approved or agreed test plan (refer to Subsection 8/5) or specifically agreed, as a case-by-case basis.

3 Certification for AM Parts

Inspection and testing reports, defined in Section 6, are to be provided and accepted in accordance with ABS Rules and Guides, recognized industry standards, or OEM/designer specification.

The essential parameters are to be documented, traceable, and controlled by a quality management system, which is to be submitted to ABS upon request.

ABS certification for AM parts is to be issued for each part. The certificate is to state that the part has been produced in accordance with the fabrication and testing plan. Inspection and test results of parts/coupons are to meet the applicable design requirements. The certificate is to include the process control plan/specification and the revision of the agreed to or approved plan/specification.

Nonconformances are to be recorded, reported and may be specially considered by ABS on a case-by-case basis.

4 Survey

4.1 Marking

The manufacturer is to adopt a system for the identification of AM parts, which will enable the material of the final delivered condition to be traceable to the applied AM process chain, and the Surveyor is to be given full facilities for tracing the material when required.

Class parts are to be identified by Part No. and marked with the initial of **AB** and the applicable material grade in accordance with ABS Rules and the initial of **AM** for manufacturing process. (e.g., **Part No. AB EH36 AM**).

Non-class parts certified by ABS, are to be identified by Part No. and marked according to manufacturer's practice, with the initial **AB/S**, the applicable material grade in accordance with the material specification, and the initial **AM** for manufacturing process (e.g., Part No. **AB/S In625-ASTM F3056 AM**).

4.2 Retesting

For retesting of class parts, see 2-1-1/17.9 of the *ABS Rules for Materials and Welding (Part 2)*. For non-class parts, retesting may be specially considered by ABS on a case-by-case basis. Test results for the original test and retest are to be reported for class and non-class parts.

4.3 Surveys after Installation

Surveyor witness for functional testing is required for first article or prototype class parts and is optional for reproduced class parts or non-class parts. Functional testing may be carried out at OEM facility or on board the vessel.

Considering operation or service data of specific class or non-class AM part in marine and offshore industry, survey of the AM part in service is to be established by the manufacturer as required in accordance with 8/2x).

4.4 Weld Repair

If the AM part is designed, sustained, and maintained to be repairable, weld repair procedures and the method for repair are to be qualified, reported/documentated and be approved by ABS with additional established procedure for dimension loss to allow repair, nondestructive inspection before and after repair, etc.

1 AM Process Selection

An appropriate AM process should be selected after considering the value proposition and limitations.

1.1 Value Proposition

- i)* Generally, as an alternative to traditional manufacturing, AM is an integrated process of material manufacturing, machining, and fusion/joining to meet functional and system requirements. With appropriate design for AM, optimization for AM, materials, manufacturing, inspection, and testing, the AM process may add value over the traditional manufacturing process in the following cases:
- Manufacturing on demand with shorter lead time in supply chain
 - Change from management of physical parts to management of CAD models and manufacture on demand where and when it is needed
- ii)* Digital manufacturing with design for AM, optimization for AM and assembly:
- Increase design freedom and reduce cost for complex shapes
 - Integrate multi-parts as assembly and reduce time and installation cost for assembling
 - Optimize parts using the topology method or generative algorithm and efficiently reduce unnecessary weight and material usage
- iii)* Small batch production:
- Avoid the high tooling cost of traditional manufacturing
 - Reverse engineering for obsolete parts
- Note:* Reverse engineering needs to consider the technical requirements of the original properties, materials and configuration then apply this knowledge into developing the solid model and materials selection. IP issues will be specially considered and agreed to by ABS on a case-by-case basis.
- Self-sustain vessels in port or at sea
- iv)* Hybrid AM process with traditional manufacturing, such as casting or forging (refer to Section 7/ Figure 5):
- Apply AM process for repair or remanufacture
 - Add AM feature on traditionally manufactured part
 - Apply new materials for improved performance

1.2 Limitations

Potential limitations possibly affecting AM application should be identified and considered. A mitigation plan and effectiveness assessment should be implemented into design for AM, optimization for AM, material, manufacturing, inspection, and testing, which should be documented and submitted for ABS review if deemed necessary.

- i)* There may be manufacturing features and effects, such as islands, wall intersections, staircase effects, and accessibility issues. Thus, there may be limitations in achievable surface finish of as-built AM parts, which may affect functionality.
- ii)* Types/Grades of feedstock materials have limitations for the AM process, especially for powder feedstock. An additional challenge for powder is the accurate controlling of chemistry due to interstitial elements, powder quality, storage, handling, recycling, etc.
- iii)* Heating and cooling rates may be high due to fast, localized heat source exposure. As-built parts may have high thermal residual stress and local temperature differences, which may cause shrinkage, distortion, and cracking, as well as differences in microstructural grain growth.
- iv)* Process parameters may produce anisotropic materials characteristics resulting in material properties different from the expected values from forging or casting.
- v)* The inherent geometric complexity of AM components is a major challenge for traditional nondestructive testing (NDT). NDT procedures and methods may need to be developed or modified to account for the complex parts, such as lattice structures or optimized topology. Even for simple part geometries, traditional NDT may not possess the resolution needed to detect internal defects due to the signal decay through interlayer deposition. Advanced/Customized in-process monitoring, cross validated by x-ray computed tomography (CT) scan may be applied to identify the generation, location, and size of flaws and defects.
- vi)* Post-build processing to improve quality may be used such as blasting, tumbling, or machining for surface/feature finish. Post-build machining is required for the AM near-net shape build with extra machining stock/allowance. Post thermal treatments such as stress relief, hot isostatic pressing (HIP) for reduced internal pores and other methods of heat treatment may be used to improve the material properties.

APPENDIX 2 Reference Documents

References in this document are to various specifications from International Organization for Standardization (ISO), American Society for Testing and Materials (ASTM), American Welding Society (AWS), American Society of Mechanical Engineers (ASME) or other equivalent specification designations without year notations.

Unless otherwise noted, the latest issue of the specification is to be used.

1 ASME

ASME B46.1	Surface Texture, Surface Roughness, Waviness and Lay
ASME BPVC II C	Specifications for Welding Rods Electrodes and Filler Metals
ASME Y14.1000	Engineering Drawing Practices
ASME Y14.5	Dimension and Tolerancing
ASME Y14.36	Surface Texture Symbols
ASME Y14.41	Digital Product Definition Data Practices
ASME Y14.46	Product Design for Additive Manufacturing

2 ASTM

ASTM 52900	Additive manufacturing – General principles – Terminology
ASTM 52905	Additive manufacturing – General principles – Non-destructive testing of additive manufactured products
ASTM 52907	Additive manufacturing – Feedstock materials – Methods to characterize metallic powders
ASTM 52910	Additive manufacturing – Design – Requirements, guidelines and recommendations
ASTM 52911-1	Additive manufacturing – Technical design guideline for powder bed fusion - Part 1: Laser-based powder bed fusion of metals
ASTM 52911-3	Additive manufacturing – Technical design guideline for powder bed fusion - Part 3: Electron-based powder bed fusion of metals
ASTM 52921	Standard Terminology for Additive Manufacturing – Coordinate Systems and Test Methodologies
ASTM 52922	Guide for Additive Manufacturing– Design – Directed Energy Deposition
ASTM 52924-4	Additive manufacturing of metals – Qualification principles – Part 4: Qualification of machine operators for DED-LB

ASTM 52924-5	Additive manufacturing of metals – Qualification principles – Part 5: Qualification of machine operators for DED-Arc
ASTM 52926-1	Additive manufacturing of metals – Qualification principles – Part 1: General qualification of machine operators
ASTM 52926-2	Additive manufacturing of metals – Qualification principles – Part 2: Qualification of machine operators for PBF-LB
ASTM 52926-3	Additive manufacturing of metals – Qualification principles – Part 3: Qualification of machine operators for PBF-EB
ASTM 52935	Additive manufacturing – Qualification principles – Qualification of coordinators for metallic parts production
ASTM 52950	Additive Manufacturing – General principles – Overview of data processing
ASTM A20	Standard Specification for General Requirements for Steel Plates for Pressure Vessels
ASTM A370	Standard Test Methods and Definitions for Mechanical Testing of Steel Products
ASTM A751	Standard Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products
ASTM B213	Standard Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel
ASTM B214	Standard Test Method for Sieve Analysis of Metal Powders
ASTM B215	Standard Practices for Sampling Metal Powders
ASTM B311	Standard Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
ASTM B822	Standard Test Method for Particle Size Distribution of Metal Powders and Related Compounds by Light Scattering
ASTM B962	Standard Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes' Principle
ASTM E3	Standard Guide for Preparation of Metallographic Specimens
ASTM E8	Standard Test Methods for Tension Testing of Metallic Materials
ASTM E10	Standard Test Method for Brinell Hardness of Metallic Materials
ASTM E18	Standard Test Methods for Rockwell Hardness of Metallic Materials
ASTM E23	Standard Test Methods for Notched Bar Impact Testing of Metallic Materials
ASTM E92	Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials
ASTM E407	Standard Practice for Microetching Metals and Alloys
ASTM E1417	Standard Practice for Liquid Penetrant Testing
ASTM E1444	Standard Practice for Magnetic Particle Testing
ASTM E1570	Standard Practice for Fan Beam Computed Tomographic (CT) Examination
ASTM E1742	Standard Practice for Radiographic Examination
ASTM E2651	Standard Guide for Powder Particle Size Analysis
ASTM F3187	Standard Guide for Directed Energy Deposition of Metals
ASTM F3303	Standard for Additive Manufacturing – Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications

3 AWS

AWS A5.01	Welding Consumables – Procurement of Filler Metals and Fluxes
AWS A5.32	Welding Consumables – Gases and Gas Mixtures for Fusion Welding and Allied Processes
AWS D20.1	Specification for Fabrication of Metal Components using Additive Manufacturing

4 ISO

ISO 3452-1	Non-destructive testing – Penetrant testing – Part 1: General principles
ISO 3954	Powders for powder metallurgical purposes – Sampling
ISO 14175	Welding consumables – Gases and gas mixtures for fusion welding and allied processes
ISO 17296-1	Additive Manufacturing – General Principles – Part 1: Terminology
ISO 17296-2	Additive Manufacturing – General Principles – Part 2: Overview of Process Categories and Feedstock
ISO 17296-3	Additive Manufacturing – General Principles – Part 3: Main Characteristics and Corresponding Test Methods
ISO 17296-4	Additive Manufacturing – General Principles – Part 4: Main Characteristics and Corresponding Test Methods
ISO 17636-1	Non-Destructive Testing of Welds – Radiographic Testing – Part 1: X- and Gamma-Ray Techniques with Film
ISO 17638	Non-Destructive Testing of Welds – Magnetic Particle Testing
ISO 31000	Risk Management