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Criteria for Pressure Retaining Metallic Components Using Additive Manufacturing

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ASME PTB-13-2021

CRITERIA FOR PRESSURE RETAINING METALLIC COMPONENTS USING ADDITIVE MANUFACTURING

Prepared by:

The ASME BPTCS/BNCS Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment

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The American Society of Mechanical Engineers

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FOREWORD

This report provides specific criteria completed by the ASME Board on Pressure Technology Codes and Standards (BPTCS)/Board on Nuclear Codes and Standard (BNCS) Special Committee on Use of Additive Manufacturing. These first criteria address the Additive Manufacturing (AM) Powder Bed Fusion Process.

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EXECUTIVE SUMMARY

Recognizing a need to keep pace with rapid advancements in AM technology and AM's growing acceptance in industry the ASME BPTCS appointed a project team to evaluate the additive manufacturing technology as it applies to the construction of pressure equipment in 2015.

The first meeting of the ASME Project Team on Evaluation of Additive Manufacturing for Pressure Retaining Equipment was held in December 2015. The project team drafted and issued a gap analysis to the BPTCS in June 2016. The ASME NCS was also evaluating implementation of AM technology and was part of the membership of the ASME Project Team on AM. Following thorough review and discussion of the gap analysis, a recommendation was made to BPTCS to form a Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment. The formation of the committee was approved as a joint committee reporting to both the BPTCS and the BNCS.

The first meeting of the BPTCS/BNCS Special Committee on Use of Additive Manufacturing for Pressure Retaining Equipment was held in August 2017. The Special Committee began work on background information needed to support a technical baseline for the development of criteria for the AM Powder Bed Fusion Process. This report provides the specific criteria completed by the BPTCS/BNCS Special Committee on Use of Additive Manufacturing. These first criteria address the AM Powder Bed Fusion Process.

This additive manufacturing document provides criteria followed by commentary for the following areas:

- Scope
- Additive Manufacturing Specification
- Materials
- Thermal Treatment
- Powder Requirements
- Additive Manufacturing Design Requirements
- Additive Manufacturing Procedure
- Additive Manufacturing Procedure Qualification
- Qualification Testing of Additive Manufactured Components
- Production Build Cycles
- Chemical Composition Testing
- Mechanical Property Testing
- Metallographic Evaluation
- In-Process Monitoring
- Quality Program
- Records
- Definitions
- Referenced Standards

Description of the Powder Bed Fusion Additive Manufacturing Process

The build process begins by placing a baseplate into the machine. The printed component is constructed on this plate. The plate serves as a method of securing the component during printing, a method of preventing warping of the component, and a path for the removal of heat during the build process. The build chamber is sealed and is either purged and backfilled with an inert gas such as argon when using a laser energy source, or is left with a vacuum when using an electron-beam energy source. A thin layer of powder on the order of 100μm is deposited. Then, the energy source selectively melts specified areas of the powder in a prescribed geometry conforming to the component being manufactured.

At the completion of the layer, the fabricated portion of the component and the build plate are lowered, and another layer of powder is deposited. This process is repeated through the build until the full component height has been accomplished. At the end of the build, the component and build plate are extracted from the machine for thermal treatment and post processing.

1 SCOPE

(a) These criteria address the construction of pressure retaining component using the AM Powder Bed Fusion process using both Laser and Electron Beam energy sources.

(b) Additively Manufactured components shall meet the requirements of the applicable ASME Construction Code or Standard in addition to these criteria.

(c) Hybrid construction incorporating AM components joined (welded or brazed) to non-AM components is acceptable. Additive manufactured components joined to other AM components or non-AM components shall follow the requirements of the applicable ASME Construction Code or Standard.

(d) The maximum design temperature shall be at least 50°F (25°C) colder than the temperature where time-dependent material properties begin to govern for the equivalent wrought ASME material specification, as indicated in ASME Section II, Part D [1].

(e) The materials allowed for use in powder bed fusion under these criteria include:

(1) austenitic stainless-steel alloys; and

(2) nonferrous alloys

Commentary

The criteria provided in this Pressure Technology Book (PTB) address the construction of pressure retaining components by means of the AM Powder Bed Fusion process (PBF) using both Laser and Electron Beam energy sources.

When additively manufacturing components, these criteria are intended to be used with an existing ASME Construction Code or Standard. This PTB provides criteria to address the additional information necessary to supplement construction code requirements for materials, design, fabrication, examination, inspection, testing and quality control. These supplementary criteria are essential for any proposed standard or code action for the construction of metallic pressure retaining components using powder bed fusion.

The AM process is not intended for the manufacture of pressure components when traditional manufacturing methods will provide a cost and efficiency advantage. AM has advantage in the fabrication of complex components and applications with high-cost materials. AM provides a cost advantage when subtractive manufacturing processes result in large amounts of material waste. AM also provides schedule advantages and improved lead time compared to current forging and casting methods. A market for AM is developing for replacement components in the nuclear industry where the plant operating basis requires specific replacement parts. AM provides a manufacturing method to fabricate components to the design code of record when the original components are no longer available. These initial drivers for AM will require the installation of AM components into both existing systems and new construction. The criteria allow hybrid construction incorporating AM components joined (welded or brazed) to non-AM components.

The ASME AM Special Committee did not investigate data for AM components operating in the material creep regime. Creep data were discussed but sufficient material property data was not available to accept AM components operating at elevated temperature in the scope of the current AM criteria. The maximum design temperature is limited to at least 50°F (25°C) colder than the temperature where time-dependent material properties begin to govern for the equivalent wrought ASME material specification, as indicated by the T-Notes in ASME Section II, Part D [1].

The current criteria limit the materials that can be used for the AM Powder bed fusion process to austenitic stainless steels and nonferrous alloys. Current toughness requirements in ASME Codes allow many exemptions to toughness testing that are experienced based. The restriction on the materials addresses concerns with the lack of service experience with additively manufactured components by limiting materials to alloys that do not have a marked ductile-brittle transition behavior.

2 ADDITIVE MANUFACTURING SPECIFICATION

(a) The Additive Manufacturer shall prepare an Additive Manufacturing Specification that provides all requirements and references to all construction documents for a component build including, but not limited to:

(1) The governing Construction Code or Standard

(2) The Design Report

(3) File names with current revision for all model data describing the geometry of the component needed to build the physical component

(4) The applicable Material Specification

(5) The Powder Specification

(6) The applicable ASME Construction Code or Standard Nondestructive Evaluation and Testing Requirements

(7) Post-Processing Requirements

(8) Thermal Treatment Requirements

(9) All supplemental requirements identified by the Additive Manufacturer or the user.

(10) Any supplemental examination requirements identified by the Additive Manufacturer or the user in addition to the requirements of the ASME Construction Code or Standard.

(b) The Additive Manufacturing Specification shall be included in the Additive Manufacturer's Construction Records.

Commentary

The Additive Manufacturer is required to prepare an Additive Manufacturing Specification that provides all requirements and reference to all construction documents for a component. The AM Specification provides all the required information needed to start the AM procedure development and procedure and component qualification. At this point in the AM component development the component design is complete.

The AM process is dependent on the use and control of digital files. The revision and quality control requirements of all digital files are included within the AM Specification.

All required thermal treatment and post processing of the AM components are identified in the AM Specification. Since the final thermal treatment is required to meet the ASME identified material specification, thermal treatment is addressed separately in Section 4 of this criteria. Post processing in these AM criteria are limited to the manufacturing steps needed to achieve the final desired surface properties and surface finish, such as surface treatments, machining and grinding.

All supplemental requirements to these AM criteria are specified by the Additive Manufacturer, or by the AM component user, and identified in the AM Specification. ASME construction codes allow options for nondestructive examination (NDE) of a component. The NDE specific to the AM component build is identified in the Additive Manufacturing Specification. Any additional NDE required by the Additive Manufacturer or the user is identified in the AM Specification. ASME has updated ASME BPV Section V

Nondestructive Examination to include requirements for Computed Tomography (CT) to aid in the examination of AM components. CT examination should be considered when 100% volumetric examination is needed for an AM component. Any additional test specimens required for any specific material testing, such as corrosion coupons, are identified in the Additive Manufacturing Specification.

3 MATERIALS

(a) For the purpose of these criteria, Material is defined as an additively manufactured component meeting the requirements of the ASME material specification.

(b) The Additive Manufacturer shall select a listed wrought ASME material specification from ASME BPVC Section II for the component material. The selected ASME material specification shall be identified in the Additive Manufacturing Specification. In the remainder of this document, the selected material specification is identified as the ASME material specification.

(c) The requirements for chemical composition, grain size (where applicable), hardness, final heat treatment and mechanical properties shall be identical to the requirements of the ASME material specification.

(d) When a material does not meet a wrought material specification in ASME Section II, the Additive Manufacturer may request approval of a new material from ASME in accordance with the requirements of Appendix 5 of ASME BPVC Section II, Part D [1].

(e) All material processing and testing shall meet the requirements of the Additive Manufacturing Specification and these criteria.

Commentary

The material for the AM component is the additively manufactured component in its final heat-treated condition. The Additive Manufacturer shall select a listed wrought ASME material specification from ASME BPVC Section II for the AM component material. The selected ASME material specification shall be identified in the Additive Manufacturing Specification. The AM Committee reviewed data generated by several additive manufacturers and determined that AM component properties are appropriate to meet wrought specifications [2] when the additive manufacturer has achieved control of the AM process through rigorous qualification testing (see Section 8). Specifying the use of wrought material for AM component material follows the same direction used for the recent additions to ASME Code for components manufactured using powder metallurgy/hot isostatic pressing technology. The AM material shall meet the ASME material specification requirements for chemical composition, grain size, hardness, final heat treatment and mechanical properties. When a material for use in an AM build does not meet a wrought material specification in ASME Section II, the Additive Manufacturer may request approval of a new material from ASME in accordance with the requirements of ASME Section II, Part D, Appendix 5 [1]. As additive manufacturing becomes more common, the need will exist for new material with thermal treatments optimized for the powder bed fusion process, and thus, new materials will be needed for Code application.

4 THERMAL TREATMENT

(a) The final heat treatment of the AM material shall be that specified in the ASME material specification.

(b) Additional intermediate thermal treatment is acceptable. Intermediate thermal treatment may include stress relief, hot isostatic pressing or other thermal processing.

(c) When intermediate thermal treatment is performed, ASTM F3301 [3] may be used as guidance.

(d) When hot isostatic pressing is performed, recognized standards such ASTM A988 [4] or ASTM A1080 [5] may be used as guidance.

(e) All material testing shall be performed on material specimens in the final heat-treated condition of the ASME material specification.

Commentary

The AM component is required to have the identical final heat treatment requirements applied to the built component as specified for the ASME material specification. Additional intermediate thermal treatment such as hot isostatic pressing (HIP) is acceptable, but is not required by the criteria. The ASME AM Special Committee reviewed data that compared material properties for material receiving an intermediate HIP thermal treatment to material that had not received a HIP treatment. The data supports applying a HIP thermal treatment to improve the material properties by reducing defects through densification, but is not always necessary to meet the properties of the material specification. Depending upon the material, as-built microstructure, type and size of defect, HIP does not always improve material properties. The data also showed that applying a HIP thermal treatment will not account for a lack of rigorous AM process control prior to starting production builds. The emphasis in these AM criteria is achieving and maintaining process control during the AM builds. The criteria provide guidance for specifying the requirement for HIP and other intermediate thermal treatments in Section 4 when these processes are specified in the AM Specification (Section 2).

5 POWDER REQUIREMENTS

(a) The Additive Manufacturer shall provide a Powder Specification for each powder batch to the Powder Supplier. As a minimum, the Powder Specification shall specify all pertinent powder characteristics, properties, and processing steps necessary to ensure the final product meets the ASME material specification requirements.

(b) The test methods prescribed in ISO/ASTM 52907 [6] should be used for powder characterization.

(c) The Powder Specification shall include tolerance limits for all powder properties, powder manufacturing process conditions and acceptable values for test results.

(d) Powder particles shall be fabricated from source material which matches the alloy composition of the ASME material specification.

(e) The powder specification shall include, but is not limited to the following requirements:

  (1) Chemical composition

  (2) Density

  (3) Flowability

  (4) Particle size distribution

  (5) Particle morphology

  (6) Powder processing requirements

  (7) Storage and transport requirements

(f) The Powder Supplier shall provide a certified report to the Additive Manufacturer confirming that the powder conforms to the Additive Manufacturer’s Powder Specification. The report shall include all test data.

(g) The Powder Supplier test report shall be included in the Additive Manufacturer’s construction records.

(h) The Additive Manufacturer may blend multiple powder batches together to create a new batch.

(i) Each powder batch shall conform to the Powder Specification requirements prior to blending.

(j) The Additive Manufacturer may blend used powder conforming to the Powder Specification into any powder meeting the Powder Specification to form a new powder batch unless restricted by a supplementary requirement.

(k) Powder test reports and traceability recodes for used powder batches shall be included in the Additive Manufacturer’s construction records.

Commentary

The Additive Manufacturer is required to prepare a Powder Specification for all AM builds. The Powder Specification shall specify all pertinent powder properties data and powder processing requirements necessary to ensure the material meets the requirement of the ASME material specification following additive processing. The powder specification shall include acceptance criteria for all required testing. The test methods provided in ISO/ASTM 52907 [6] are recommended for all testing, but it is recognized that other testing criteria may be used. The criteria prescribe a minimum set of tests to be performed, but the Additive Manufacturer may require additional testing as deemed necessary for the specific AM component construction.

The criteria allow for reuse of powder when the blended batch of used powder meets all testing requirements in the powder specification identified in the AM Specification.

The AM criteria for powder do not allow the use of elemental powders to be blended to the composition proportions identified in the material specification. The powder particles are to individually represent the alloy composition of the ASME material specification to limit or eliminate the potential risk of an inhomogeneous composition that could be experienced when mixing elemental powders.

The Powder Supplier is required to provide a certified test report to the Additive Manufacturer which confirms that the powder conforms to the Powder Specification.

6 ADDITIVE MANUFACTURING DESIGN REQUIREMENTS

(a) In addition to the design requirements of the ASME Construction Code or Standard, the design requirements in 6(b) through 6(g) apply for components produced using the powder bed fusion AM process.

(b) Any material produced during the AM build that is specified as cosmetic material shall not be credited as load bearing material in the stress analysis.

(c) Fatigue-critical surfaces shall be designed to be accessible for liquid penetrant examination.

(d) Surfaces interfacing with sacrificial supports shall be fully accessible for removal of supports and for liquid penetrant examination.

(e) The effect of any support that will not be removed following the AM build shall be included in the stress analysis.

(f) Supports that are credited as load bearing in the stress analysis shall meet all relevant criteria identified in this document.

(g) A design report is required for all additively manufactured components.

6.1 Commentary

The design requirements for AM components follow the requirements in the applicable ASME Construction Code or Standard. The criteria require that each component has a design report. ASME BPV Code Section III and Section VIII, Division 2 have requirements for the content of a design report and can be applied for nuclear and non-nuclear applications, respectively. When the governing Construction Code or Standard applicable to the AM component does not have specific requirements for a design report the requirement in Section VIII, Division 2 are recommended for design. The Section VIII, Division 2 rules in Part 4 and Part 5 are acceptable for design as applicable. Since many of the AM components will have a significantly complex geometry, the rules of Section VIII Division 2, Part 5 are the most applicable for AM design for non-nuclear applications. The detailed stress analysis requirement in Section VIII, Division 2, Part 5 also allows for identification of the areas of high stress and fatigue critical areas in a component necessary for use in determining the location of required test specimens specified in Section 9 and direct NDE.

The AM build process requires that support structures be integrated into the build to provide support for overhanging sections of the component that occur above the build plate. The integral supports also serve to restrain the geometry against deflections caused by residual stresses that are generated during the build. These supports can be either sacrificial or permanent. Component surfaces interfacing with sacrificial supports need to be fully accessible for removal of supports and for liquid penetrant examination. The examination of these locations ensure that an unevaluated stress riser does not affect the structural integrity of the component. The effect of possible stress risers from any support that will not be removed following the AM build is required to be evaluated during the component stress analysis. Any material in a permanent support that is credited as load bearing in the stress analysis shall meet all relevant AM criteria provided in this report.

The surfaces of an AM component can be constructed with machine parameters to optimize dimensional tolerances and surface finish. These surfaces are defined as cosmetic material. Specifically, cosmetic material is material produced by process parameters that are not represented by qualification or witness specimen test results. When performing a stress analysis for an AM component, cosmetic material is not credited as load bearing material in the stress analysis. The cosmetic layer is addressed in the same manner as for material added for corrosion or mechanical allowance in the ASME construction code.

7 ADDITIVE MANUFACTURING PROCEDURE

(a) The Additive Manufacturer shall prepare an Additive Manufacturing Procedure.

(b) The AM Procedure shall address applicable process variables shown in Table 7-1 and include any required tolerance limits for process variables. The Additive Manufacturer may include additional process variables.

(c) The requirements for Full, Partial, and Design Procedure Qualification based on a change in a process variable are prescribed in Table 7-1.

(d) Criteria for Full, Partial, and Design procedure qualification are defined in Table 7-2.

(e) Full Qualification is required for any new Additive Manufacturing Procedure.

(f) Design requalification of the component is required when:

(1) a change in cosmetic material thickness results in a reduction of structural material in the component, and

(2) a change in support material credited as load bearing results in a reduction of structural material or an increased stress concentration.

(g) The Additive Manufacturing Procedure shall be included in the Additive Manufacturer's construction records.

Table 7-1: Process Variables for Laser and Electron Beam Powder Bed Fusion Processes

Process Variable	Energy Source	
	Laser Beam	**Electron Beam**
Powder (Feedstock)		
Powder Specification	P	P
Material Parameters		
Qualified Tensile Specimen Thickness Range	F	F
Machine		
Machine Location	P	P
Machine Manufacturer	F	F
Machine Model	F	F
Machine Serial Number	P	P
Machine Software Version	P	P
Machine Essential Components	P	P
Build Chamber		
Build Platform Preheat Temperature	P	F
Shielding Gas Composition	F	-
Shielding Gas Flow Rate	F	-
Vacuum Pressure	-	F
Build Chamber Essential Component	P	P
Heat Source Characteristics		
Heat Input/Power Input	F	F
Pulse Characteristics	F	F
Pulsing	F	F
Preheating by Beam Splitting	-	F
Focus Settings	F	F
Beam Diameter	F	F
Position of Beam Diameter Relative to Feedstock Layer	F	F
Deposition Characteristics		
Travel Speed	F	F
Scan Strategy (Applied Pattern, Rotation)	F	F
Adjacent Weld Vector Spacing (Hatch)	F	F
Maximum Length of Weld Vector (Stripe Width)	F	F
Programmed Process Layer Thickness	F	F
Cosmetic Parameter Thickness on Final Component Surface	D	D
Post-Build Thermal Treatment / Processing		
Post-Build Cooldown Procedure	-	F
Post-Build Thermal Treatment	F	F

General Notes:

D = design requalification

F = full procedure qualification

P = partial procedure qualification

Table 7-2: Procedure Qualification Criteria

Qualification Level	Criteria
Full (F)	Completion of all requirements of Section 8 and Section 9.
Partial (P)	Completion of 1 qualification build in accordance with Section 8 for 1 powder batch.
Design (D)	Completion of all requirements of Section 9.

Commentary

The ASME AM Committee evaluated existing standards when developing the requirements for the Additive Manufacturing Procedure. The recommendation from that review supported using NASA MSFC-SPEC-3717, the SAE-AMS7003, and AWS D20.1 [7] in the development of that AM manufacturing procedure. When determining the list of Process Variables provided in Table 7-1 the AM Special Committee relied heavily on the variables provided in AWS D20.1 [7]. American Welding Society standards are used extensively in ASME codes and standards for welding variables, and the list of variables in AWS D20.1 [7] was the most relevant list reviewed. The list of variables was modified to better integrate with this document. The AM Procedure shall address applicable process variables shown in Table 7-1 and include any required tolerance limits for process variables. It is recognized that because there is no standard for AM machine manufacturers to provide consistent names for process variables, a specific additive manufacturing procedure may specify process variables different from those identified in Table 7-1. The Additive Manufacturer is not required to address all of the process variables in Table 7-1. AM machines are built to provide different levels of control, and some machine variables are preset by the machine manufacturer depending on whether the machine is intended for production work or new material development. The intent is that the Additive Manufacturer specifies the variables required to achieve and maintain control process throughout a build cycle. Unlike the essential variables used in an ASME welding procedure, the AM build cycle relies on the results of the inspection and testing of the witness sample to provide the final measure of component quality control.

The Additive Manufacturing Procedure section of the criteria provides a graded approach to procedure qualification based on the maturity level of the procedure. The use of the graded approach requiring full or partial procedure qualification is utilized following the start of production builds.

8 ADDITIVE MANUFACTURING PROCEDURE QUALIFICATION

(a) The Additive Manufacturer shall complete sufficient qualification builds and produce sufficient material qualification specimens to support with 95% confidence that 99% of the produced material is in accordance with the ASME material specification. The statistical analysis shall be in accordance with ASTM E2586 [8].

(b) The qualification builds shall be used by the Additive Manufacturer to define the build envelope within the build chamber that produces acceptable material.

(c) The Additive Manufacturer shall identify the locations of limiting material conditions for each energy source as illustrated in Figure 8-1. Figure 8-1 is illustrative only, and is not intended to represent a specific AM machine, specimen geometry or layout. Multiple locations of limiting material conditions in the built volume may need to be defined depending on the material property of interest (i.e. the tensile strength and toughness may not be minimum at the same location). The limiting material locations shall address the maximum and minimum material cooling rates and the location of the energy sources.

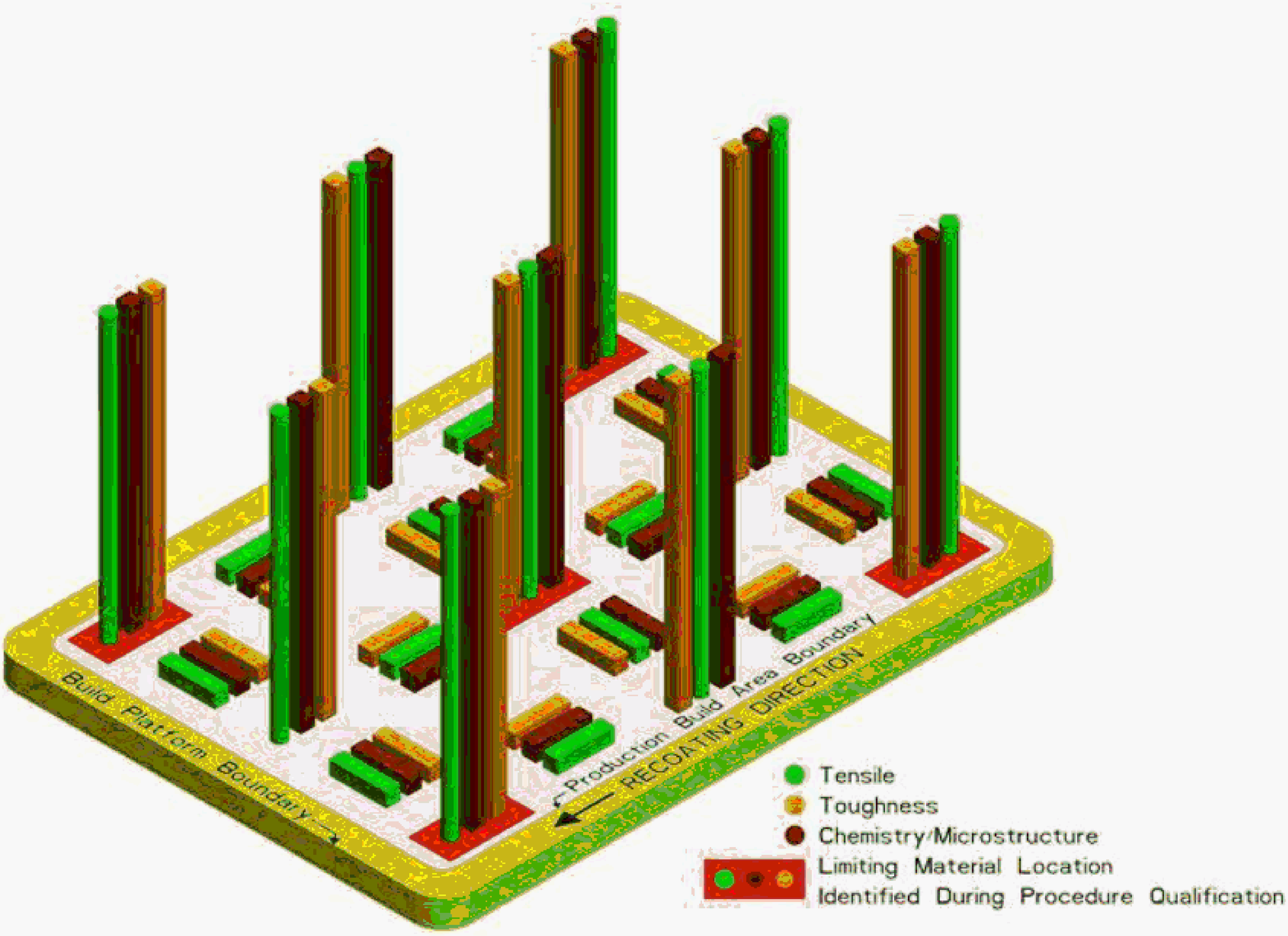

Figure 8-1: Material Qualification Specimens for Additive Manufacturing Procedure Qualification

(d) The horizontal and vertical material qualification specimens shall be constructed in both the X and Y coordinates that represent the range of the build volume.

(e) There shall be a minimum of 3 qualification builds, which represent a minimum of 3 powder batches.

(f) As a minimum, the locations in Table 8-1 shall include material qualification specimens for each procedure qualification build. The Additive Manufacturer shall add material qualification specimen locations as needed to determine the locations of limiting material conditions for the required material property.

Table 8-1: Locations for Material Qualification Specimens for Procedure Qualification (PQ) Builds

Location	Description	Minimum Samples
PQ1	Region at the beginning of the recoating path	1
PQ2	Region at the end of the recoating path	1
PQ3	Maximum radial distances each energy source may process for Electron Beam Powder Bed Fusion	2 per Energy Source
PQ4	Maximum radial distance that each energy source may process in the direction of the shielding gas flow inlet for Laser Beam Powder Bed Fusion	1 per Energy Source
PQ5	Maximum radial distance that each energy source may process in the direction of the shielding gas flow exhaust for Laser Beam Powder Bed Fusion	1 per Energy Source
PQ6	Maximum radial distance from each energy source where multiple energy sources work cooperatively to produce one qualification sample	1 per Overlap Zone
PQ7	Minimum radial distance from each energy source	1 per Energy Source
PQ8	Intermediate locations specified by the Additive Manufacturer	4 per Energy Source

(g) Vertical tensile specimens shall be designed to allow testing of the total height of the build volume to the maximum extent possible.

(h) The qualification builds shall provide material qualification specimens at the minimum thickness required for the components built to the specific Additive Manufacturing Procedure.

(i) The minimum wall thickness for any component built to a specific Additive Manufacturing Procedure shall not be less than the minimum vertical tensile specimen thickness constructed during the qualification builds.

(j) When toughness testing is required by the ASME construction code or standard, additional material qualification specimens located within 3/8” (10mm) of the tensile test specimens shall be provided for the toughness specimens.

(k) The required type of test specimens at each location for each qualification build shall comply with Table 8-2.

Table 8-2: Required Types of Material Qualification Test for Each Location

<table>
<tr><th>Location</th><th>Vertical Tension</th><th>Horizontal Tension</th><th>Vertical Toughness</th><th>Hardness</th><th>Microstructure</th><th>Chemical Composition</th></tr>
<tr><td>PQ1-PQ7</td><td>x</td><td></td><td>x</td><td rowspan="2">x 8(m)</td><td>x 8(l)</td><td rowspan="2">x 8(n)</td></tr>
<tr><td>PQ8</td><td></td><td>x</td><td></td><td></td></tr>
</table>

(l) Two metallographic evaluations shall be performed on material qualification specimens for locations PQ1-PQ7. One specimen shall be from a region near the bottom of the build volume and one specimen shall be from a region near the top of the build volume.

(m) One hardness test shall be performed on a material qualification specimen for each qualification build in the region having the highest measured tensile strength.

(n) One material qualification specimen shall be provided for chemical composition testing at a location determined by the Additive Manufacturer.

(o) When supplemental material testing is required as part of the Additive Manufacturing Specification, the material for the test specimens shall be produced as part of either the initial qualification builds or supplementary qualification builds.

(p) When additional material qualification specimens are required, the material for the specimens shall be located within 3/8 in. (10 mm) of tensile test specimens at locations of limiting material conditions.

(q) The results of the required testing shall be documented in a Procedure Qualification Test Report certified by the Additive Manufacturer. The Procedure Qualification Record and the Machine Qualification Record provided in AWS D20.1 [7] may be used as a guide in completing the Qualification Test Report for the qualification builds.

(r) The Procedure Qualification Test Report shall identify the locations of limiting material conditions for each energy source for use in Component Qualification and Production Testing.

(s) The Procedure Qualification Test Report shall identify the variation in material properties across the build volume.

(t) The Procedure Qualification Test Report shall be included in the Additive Manufacturer's construction records.

Commentary

The successful application of additive manufacturing requires rigorous qualification testing to achieve control of the AM Process. The AM Special Committee chose to specify performance-based criteria for acceptance of the AM procedure qualification. The Additive Manufacturer is required to complete sufficient qualification builds to produce sufficient material qualification specimens to support with 95% confidence that 99% of the produced material is in accordance the ASME material specification. The performance-based criteria were used instead of requiring a specific number of qualification samples. The performance basis criteria are intended to provide a graded approach to procedure qualification that will distinguish between the level of experience the additive manufacturer has with a specific AM machine and material. A new machine and first use of a material will require more testing than well-characterized AM machines and materials.

The AM Procedure Qualification section lays out specific requirements for sample size, location, and type of material testing. The criteria require that the minimum wall thickness of an AM component built to a specific Additive Manufacturing Specification shall not be thinner than the minimum thickness qualified by the process qualification. To meet the requirements for fracture toughness testing, thicker test specimens will be required to comply with most applications.

The Procedure Qualification is required to identify the locations of limiting material conditions for each energy source for use in Component Qualification and Production Testing. The limiting material location is a region defined by X, Y and Z coordinates within the build volume that produces the minimum material properties relative to the remainder of the processing space. The limiting material locations are required to be identified in the Procedure Qualification Test Report. Industry experience was the primary driver for specifying PQ1-PQ8.

Vertical is the prevalent orientation for material test samples used for testing both tensile properties and impact strength. Material test specimens built in the vertical orientation are the best indication of the entire build history because they capture information from the majority of build layers. Capturing the layer-by-layer data in qualification and production witness material test samples provide the opportunity to capture possible process upsets that occur during the build cycle. Data has also shown that the limiting toughness values occur when the failure surface is oriented parallel with the build layers.

The intent of Figure 8-1 is to provide an illustration of the layout and types of sample needed for procedure qualification. Figure 8-1 is illustrative only, not intended to invoke any requirements for how an Additive Manufacturer may conduct procedure qualification builds.

9 QUALIFICATION TESTING OF ADDITIVE MANUFACTURED COMPONENTS

(a) Fabricated components shall be subjected to qualification testing and shall be designated as Prototype Components.

(b) The Additive Manufacturer or its representative shall perform the qualification testing of the Prototype Components.

(c) Prototype Components that are used for qualification testing shall meet the requirements of the Additive Manufacturing Specification and the specified Additive Manufacturing Procedure.

(d) Prototype Components for qualification testing shall be fabricated and tested to the requirements of Table 9-1. Prototype Component toughness testing is only required when toughness testing is required by the construction code or standard.

Table 9-1: Prototype Testing Requirements

Prototype Test	Number of Prototypes	Test Criteria
Proof	1	Section 9(o)
Fatigue	2 to 5	Section 9(p)
Material Properties and Metallographic Evaluation	1	Sections 12-14
Toughness	1	When required, testing is in accordance with the Construction Code or Standard

(e) Prior to prototype testing, each Prototype Component shall be examined to verify compliance with requirements of the applicable ASME construction code or standard and the Manufacturing Specification.

(f) As a minimum, the location in Table 9-2 shall include material qualification specimens for each component qualification build.

Table 9-2: Locations for Material Qualification Specimens for Component Qualification (CQ) Build

Location	Description	Minimum Samples
CQ1	Locations of limiting material conditions identified during the procedure qualification	2 per Energy Source
CQ2	Thinnest pressure retaining feature in the component	1
CQ3	Highest stressed location in the component	1

(g) Material qualification specimens that represent the thinnest pressure retaining feature and highest stressed location in the component shall be collected from the prototype produced for material property testing, subject to the following:

(1) When the specimen cannot be collected for the prototype component, material qualification specimens may be located within 3/8" (10mm) of the prescribed feature.

(2) When the thinnest pressure retaining feature and highest stressed location are at the same location in the component, one material qualification specimen is required.

(h) The required type of test specimens at each location for each qualification build shall comply with Table 9-3.

Table 9-3: Required Types of Material Qualification Specimens for Each Location

<table>
<tr><th>Location</th><th>Vertical Tensile</th><th>Horizontal Tensile</th><th>Toughness</th><th>Hardness</th><th>Microstructure</th><th>Chemical Composition</th></tr>
<tr><td>CQ1</td><td>x</td><td></td><td rowspan="3">Sections 9(l) and 9(m)</td><td rowspan="3">x</td><td>x</td><td rowspan="3">x</td></tr>
<tr><td>CQ2</td><td>x</td><td></td><td>x</td></tr>
<tr><td>CQ3</td><td>x</td><td></td><td>x</td></tr>
</table>

(i) One metallographic evaluation shall be performed on material qualification specimens for locations CQ1-CQ3.

(j) One material qualification specimen shall be provided for hardness testing at a location determined by the Additive Manufacturer.

(k) One material qualification specimen shall be provided for chemical analysis at a location determined by the Additive Manufacturer.

(l) When required by the ASME construction code or standard, a prototype shall be fabricated for material qualification specimens required for toughness testing.

(m) Toughness test results shall conform to the requirements of the applicable ASME construction code or standard.

(n) The results of the required testing shall be documented in a Component Qualification Test Report which is certified by the Additive Manufacturer, and included in the Additive Manufacturer's construction records.

(o) Component Hydrostatic Proof Testing

The following are required for component hydrostatic proof testing:

(1) The component shall be hydrostatically tested by pressurizing at a maximum rate of 70 psi/s (5 bar/s). The test shall be carried out under room temperature conditions.

(2) The proof test pressure and the pressure rise as a function of time shall be recorded during the test.

(3) The proof test pressure or pressure at failure (burst test) shall be not less than the calculated value from equation (1):

$$P_{Proof\ Test} = P_{Design} \times \frac{4.0}{E_{AM}} \times \frac{S_{u,actual}}{S_u} \times \frac{S}{S_{DT}} \times \left[\frac{t}{(t - c)}\right]^n \qquad (1)$$

Where:

$P_{Proof\ Test}$ = test pressure to be achieved without leakage

P_{Design} = component design pressure at room temperature

E_{AM} = efficiency factor based on examination

E_{AM} =1 for Full Volumetric or CT Examination

E_{AM} =0.7 for No Volumetric Examination

$S_{u,actual}$ = the maximum actual value of tensile strength determined from the qualification specimens tested at room temperature from the component prototype builds

S_u = specified minimum tensile strength at room temperature

S = maximum allowable stress at room temperature

S_{DT} = maximum allowable stress at design temperature

t = thickness of the component at the weakest point

c = allowance added for corrosion, erosion, and cosmetic material

n = 1 for curved surfaces such as cylinders, spheres, or cones with ½ apex angle ≤ 60°

n = 2 for flat or nearly flat surfaces, flanges, or cones with ½ apex angle > 60°

(p) Component Fatigue Testing

The following are required for component fatigue testing:

(1) The component shall be subjected to a hydraulic pressure cycle test between a pressure no greater than 10% of design pressure to the design pressure for N pressure cycles as calculated using equation (2):

$$N = K_n \times SL \times C \qquad (2)$$

Where:

N = required test cycles

K_n = Fatigue design margin = max $[K_s^{4.3}, 2.6]$

K_s = max $[(K_{st} \times K_{ss}), 1.25]$

$K_{st} = E_{Test\ Temperature} / E_{Design\ Temperature}$ (Factor for the effect of test temperature)

$K_{ss} = \max [(1.470 - 0.044\ n),1.0)$ (Factor for the statistical variation in test results)

n = Number of replicate fatigue test (Minimum value = 2)

SL =Service Life (years)

C = required cycles per year

(2) The total number of required test cycles is a function of the number of fatigue tests.

(3) The frequency of reversals shall not exceed 0.25 Hz.

(4) The temperature on the outside surface of the component shall not exceed 100°F (38°C) during the test.

(5) The test component shall have the same surface finish and thermal treatment as the production component.

(6) The following parameters shall be recorded for each fatigue test:

(a) Number of cycles achieving upper cyclic pressure;

(b) Minimum and maximum cyclic pressures;

(c) Cycle frequency;

(d) Test medium used;

(e) Mode of failure if applicable

(7) The AM Component shall withstand N pressurization cycles without failure by burst or leakage.

(8) The test shall continue for an additional N pressurization cycles or until the component fails by leakage or burst.

(9) The fatigue test acceptance criteria are provided in Table 9-4.

Table 9-4: Fatigue Test Acceptance Criteria

Cycles	Component Condition Following Pressure Cycles		
	No Failure	**Leakage Failure**	**Burst Failure**
0-N	Complete Cycles N-2N	Not Acceptable	Not Acceptable
N-2N	Acceptable	Acceptable	Not Acceptable

Commentary

The component qualification section is the AM criteria which provides assurance that material properties in the components are comparable to the specimen testing performed for procedure qualification. A single AM procedure may be used for multiple components, but each component design requires qualification testing. The component's qualification criteria require the building of a series of prototype builds depending on the component service conditions and loading. As a minimum, two prototypes are required, one for proof testing and one for material property testing. Additional prototypes are required when the component will require impact testing for low temperature service and when the component is in fatigue service. The component qualification criteria also require the placement and testing of material test specimens to evaluate specific component properties and monitor the limiting material locations.

The hydrostatic proof testing section is adapted from ASME BPVC Section VIII Division 1, par. UG-101, and is included in this document because not all ASME construction codes and standards have requirements for hydrostatic proof testing. When geometrically similar components are being additively manufactured, the requirements for hydrostatic proof testing in UG-101 may be used to limit the required number of tests.

There is not sufficient available fatigue data to provide either a new fatigue curve for AM Material or a sufficient comparison to existing fatigue curves in ASME BPVC Section III or Section VIII, Division 2. Some of the data reviewed by the AM Special Committee indicates that AM material fatigue data may fall below the existing design fatigue data. Until additional AM fatigue data is available, and a fatigue curve can be established, the committee recommends cyclic testing for components in fatigue service. The fatigue testing methodology in the AM criteria was adapted from ASME Section VIII, Division 2.

The results of the required component qualification testing shall be documented in a Component Qualification Test Report.

10 PRODUCTION BUILD CYCLES

(a) All Production Build Cycles shall comply with the requirements of the Additive Manufacturing Specification and the qualified Additive Manufacturing Procedure.

(b) Witness specimens shall be constructed and tested with each production build cycle.

(c) One witness specimen from the first and final production build cycle for each production run shall be provided for chemical analysis at a location determined by the Additive Manufacturer.

(d) The criteria for testing production witness specimens based on the number of production build cycles and tension test results are provided in Table 10-1.

Table 10-1: Production Testing Requirements

Production Build Cycles	Tensile Test Results	Full Witness Sample Testing Table 10-2	Reduced Witness Sample Testing Table 10-3	Requalification
1-10	Conforming	X		
	Nonconforming	X		• Partial procedure qualification in accordance with Table 7-2 is required following a nonconforming tension test result. • Full witness sample testing shall resume for 10 production build cycles. • Reduced witness sample testing may begin following 10 production build cycles with full witness sample testing and all tension test results conforming to the material specification.
11-30	Conforming		X	
	Nonconforming	X		• Partial procedure qualification in accordance with Table 7-2 is required following a nonconforming tension test result. • Full witness sample testing shall resume for 3 production build cycles. • Reduced witness sample testing may begin following 3 production build cycles with full witness sample testing and all tension test results conforming to the material specification.
Greater Than 30	Conforming		X	
	Nonconforming	X		• Full witness sample testing shall resume for 1 production build cycle. • Reduced witness sample testing may begin following 1 production build cycle with full witness sample testing and all tension test results conforming to the material specification.

(e) The criteria for full production witness sample testing are provided in Table 10-2.

Table 10-2: Full Production Witness Sample Testing Criteria

Item	Criteria
1	A vertically oriented witness specimen shall be constructed over the total height of the build volume at a minimum of 2 locations of limiting material conditions determined during procedure qualification for each energy source.
2	Tension test specimens shall be constructed from all witness specimens.
3	Witness specimens shall be subdivided when required to meet the requirement of ASTM E8 [9], as illustrated in Figure 10-1.
4	All tension test specimens from each energy source shall be tested to the requirements of Section 13.

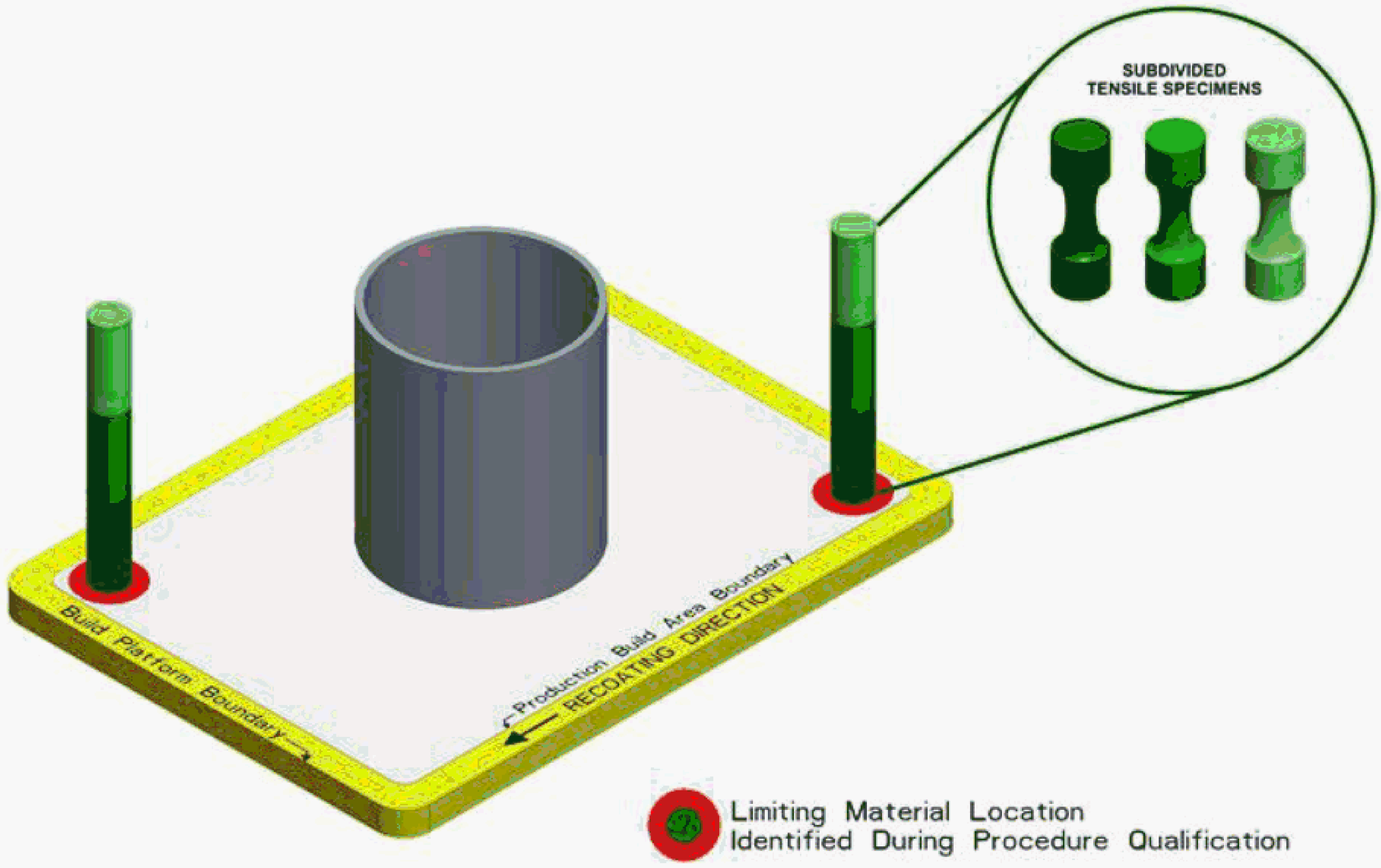

Figure 10-1: Full Production Witness Sample Testing

(f) The criteria for reduced production witness sample testing are provided in Table 10-3.

Table 10-3: Reduced Production Witness Sample Testing Criteria

Item	Criteria
1	One vertically oriented witness specimen for each energy source shall be constructed to the height required to capture the limiting material location determined from the data for the first 10 production build cycles for each energy source.
2	A single tension test specimen shall be constructed from each witness specimens as illustrated in Figure 10-1.
3	The location of the single tension test specimen shall be at the limiting location within the witness sample identified during the first 10 production build cycles.
4	The single tension test specimen from each energy source shall be tested to the requirements of Section 13.

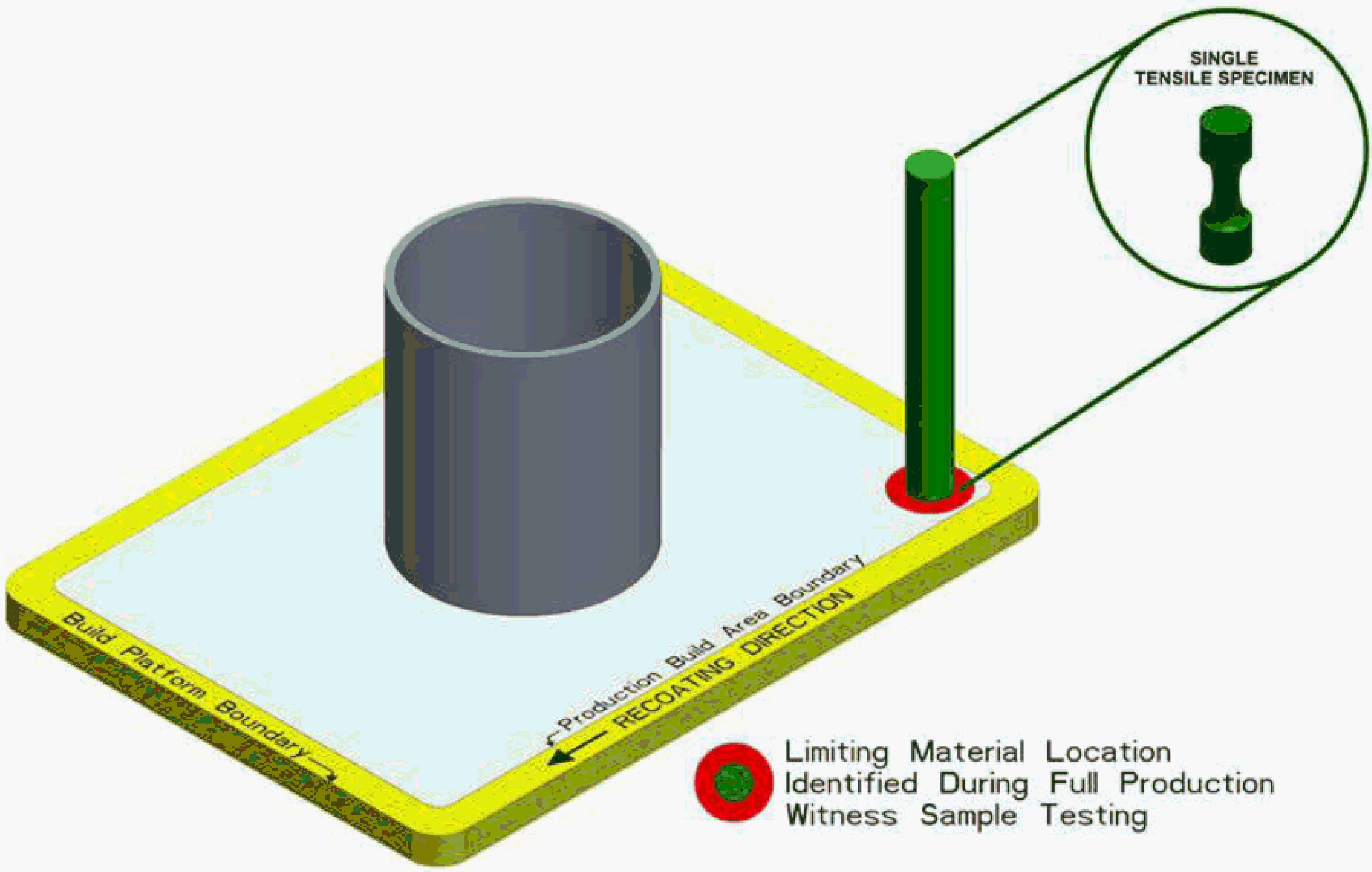

Figure 10-2: Reduced Production Witness Sample Testing

(g) The criteria for requalification and witness sample testing following a nonconforming tension test result are provided in Table 10-1.

(h) Following any production tension test failure, all components fabricated during the build cycle utilizing the energy source that produced the nonconforming test specimen shall be dispositioned using the Additive Manufacturers Quality Control nonconformance process.

(i) The tension test results for all tested witness samples shall be included in the Additive Manufacturer's construction records.

Commentary

The quality of component production builds is required to be monitored utilizing witness samples for each production build. The AM criteria provides a graded approach for witness sample testing based on the number of production builds completed with all witness sample testing conforming to the requirements of ASME material specification. During the first 10 production builds all material specified for witness samples is required to be tested. The Additive Manufacturer may evaluate the data from the first 10 build cycles and identify the single location of limiting material condition per energy source to utilize for reduced production testing. The criteria provide requirements for full and partial procedure requalification based on nonconforming tension test sample and the number of build cycles. Following the completion of 30 successful build cycles the process is mature and the nonconforming tests should only result from unscheduled maintenance issues.

11 CHEMICAL COMPOSITION TESTING

(a) Chemical composition testing shall be in accordance with the ASME material specification.

(b) The chemical composition of the specimens shall conform to the ASME material specification.

Commentary

Verification for material chemical composition is required as specified in Sections 8, 9, and 10. Chemical composition testing is required to comply with the ASME Material Specification.

12 MECHANICAL PROPERTY TESTING

(a) All room temperature tension testing shall be in accordance with ASTM E8 [9].

(b) Reporting of tension tests results shall be in accordance with Specification ASTM F2971 [10].

(c) The as-printed surface finish shall be used for testing all tension test specimens less than 0.25 in. (6 mm).

(d) A machined surface finish may be used for tension test specimens greater than or equal to 0.25 in. (6 mm).

(e) Any material specimens used for tension testing shall be in the final thermal treatment condition identified in the ASME material specification.

(f) The as-built length of the material qualification and witness specimens may require subdivision into multiple sections for testing.

  (1) Subdivided tensile specimens shall meet the requirements of ASTM E8 [9].

  (2) Subdivided toughness specimens shall meet the requirements of the construction code for Charpy specimens.

(g) Hardness testing shall comply with ASTM E10 [11], ASTM E18 [12] or ASTM E92 [13].

(h) The hardness testing shall be performed on the material qualification specimen in the region of the location of highest tensile strength. Hardness test may be performed on material qualification specimens generated for other testing. Material qualification specimens are not required solely for hardness testing.

(i) The room temperature mechanical properties of the AM material shall conform to the specified material specification.

(j) Requirements for elevated temperature testing shall be identified as a supplemental requirement in the Manufacturing Specification. All elevated temperature specimen testing shall be in accordance with ASTM E21 [14].

(k) When the AM Manufacturing Specification requires elevated temperature testing, test data is required at 100°F (50°C) above the specific design temperature for the production component or the maximum temperature allowed by the applicable ASME code or standard, whichever is lower.

(l) The acceptance criteria for elevated temperature mechanical properties shall be identified in the Additive Manufacturing Specification.

Commentary

Verification for mechanical property testing is required as specified in Sections 8, 9, and 10. Chemical Composition testing is required to comply with the ASME Material Specification, and the testing is required to be performed to the specified ASTM Standard listed in the AM criteria.

When elevated temperature testing is identified as a supplemental requirement in the Manufacturing Specification all elevated temperature specimen testing shall be in accordance with ASTM E21 [14]. Test data is required at 100°F (50°C) above the specific design temperature for the production component or the maximum temperature allowed by the applicable ASME code or Standard, whichever is lower. The acceptance criteria for elevated temperature mechanical properties shall be identified in the Additive Manufacturing Specification.

13 METALLOGRAPHIC EVALUATION

(a) Metallographic specimens shall be prepared using methods prescribed in ASTM E3 [15], Standard Guide for Preparation of Metallographic Specimens and ASTM E407 [16], Standard Practice for Microetching Metals and Alloys.

(b) The microstructure shall be examined at magnifications ranging from 50X to 200X.

(c) The microstructure shall be reasonably uniform and free of cracks and lack of fusion defects.

(d) Porosity in the microstructure shall comply with AWS D20.1 [7].

Commentary

Verification for AM material microstructure is required as specified in Sections 8 and 9. Metallographic evaluation is required and performed to the specified ASTM Standard using the magnifications levels specified in the AM criteria. The microstructure is required to be reasonably uniform and free of cracks and lack of fusion defects. The porosity level in the microstructure is required to comply with AWS D20.1 [7].

14 IN-PROCESS MONITORING

(a) In-process monitoring methods that control machine operation are not permitted by these criteria.

(b) In-process monitoring methods for data acquisition that do not control machine operation or do not automatically control any process qualification variable identified in Section 7 are permitted and are not required to be addressed in the Additive Manufacturing Procedure Qualification.

Commentary

In-process monitoring methods that control machine operation are not permitted to be used in the AM criteria. Process monitoring for data acquisition to track process qualification variables identified in the Additive Manufacturing Procedure is allowed by the criteria. Additional data is needed to support the use of data acquisition for real time defect monitoring during AM build. It is the opinion of the ASME Special Committee that in-process defect monitoring and control can become a viable method of quality control in the future. Until such time as this technique is validated, rigid process control remains the most practicable method for use with the current maturity of the technology.

15 QUALITY PROGRAM

(a) The Additive Manufacturer and the Powder Supplier shall maintain a quality program as defined by the ASME construction code or standard.

Commentary

The requirements for any code or standard actions implementing these AM Criteria should follow the quality program of the applicable ASME construction code or standard. Other quality programs are acceptable when approved by the Standards Committee implementing the AM Criteria.

16 RECORDS

(a) In addition to the requirements for the ASME Construction Code or Standard the Additive Manufacturer shall maintain the following records.

(1) Additive Manufacturing Specification

(2) Powder Supplier Test Reports.

(3) Additive Manufacturing Procedure

(4) Additive Manufacturing Procedure Qualification Test Report

(5) Additive Manufacturing Component Qualification Test Report

(6) Witness Sample Test Reports

Commentary

All documents identified as Construction Records are required to be maintained by the Additive Manufacture in accordance with the specified quality program.

17 DEFINITIONS

build chamber: enclosed location within the additive manufacturing system where the components are fabricated.

build chamber essential component: any component that controls the consistency of the applied feedstock layer or the position of the applied feedstock layer relative to the intended working plane of the process.

build cycle: single process cycle in which one or more components are built up in layers in the process chamber of the additive manufacturing system.

build volume: largest external dimensions of the x-, y-, and z-axes within the build space where components can be fabricated.

cosmetic material: material produced by process parameters that is included in the final component geometry but is not represented on qualification or witness specimen test results.

energy source: independently focused and directed thermal energy from a laser beam or an electron beam.

limiting material location: a region defined by *X*, *Y* and *Z* coordinates within the build volume that produces the minimum material properties relative to the remainder of the processing space.

machine essential component: any component that interacts directly with or facilitates the generation of the energy source.

material: an additively manufactured component meeting the requirements of the ASME material specification.

may: is used to denote permission, neither a requirement nor a recommendation.

powder batch: powder used as feedstock which could be used powder, virgin powder, or a blend of the two.

powder blend: quantity of powder made by thoroughly intermingling powders originating from one or more powder batches of the same nominal composition.

powder lot: quantity of powder produced under traceable controlled conditions, from a single powder manufacturing process cycle.

post-processing: process steps taken after the completion of an additive manufacturing build cycle in order to achieve the final desired properties in the final product. Thermal treatment, which is a post-processing activity, is treated separately in this document. In this document post-processing is limited to manufacturing steps such as surface treatments, machining and grinding.

production build cycle: a build cycle following the completion of the qualification process and that conforms to with the Additive Manufacturing Specification and the Additive Manufacturing Procedure.

production run: all components produced in one production build cycle or in a sequential series of production build cycles using the same feedstock batch and process conditions.

qualification specimens: material test specimens generated during the additive manufacturing Procedure Qualification and Component Qualification.

shall: is used to denote a requirement.

should: is used to denote a recommendation.

support material: structural material built in addition to the desired component geometry. The primary function of the support material is ensuring process cycle success through resisting residual stresses and providing distortion control during the build cycle. Support may remain in place or be removed, during post processing, following the build cycle.

used powder: powder that has been supplied as feedstock to an AM machine during at least one previous build cycle.

witness specimen: material test specimens, most often vertically oriented tensile specimens, generated during Production Build Cycles to measure and ensure on-going process stability.

Additional Terminology can be found in ISO/ASTM 52900 [17].

REFERENCES

The revision dates listed below are the latest document revision at publication of this report. The listed dates should be used unless otherwise specified in the construction code.

[1] ASME BPVC Section II Materials, Parts A, B, C and D; The American Society of Mechanical Engineers (ASME), 2 Park Avenue, New York, NY 10016

[2] Report Number 3002018273, ICME and In-Situ Process Monitoring for Rapid Qualification of Components Made by Laser-based Powder Bed Additive Manufacturing Processes for Nuclear Structural Applications, September 2020; Electric Power Research Institute (EPRI), 3420 Hillview Avenue, Palo Alto, California 94304-1338

[3] ASTM F3301, Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion; American Society for Testing and Materials (ASTM International), 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[4] ASTM A988-17, Standard Specification for Hot Isostatically-Pressed Stainless Steel Flanges, Fittings, Valves, and Parts for High Temperature Service; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[5] ASTM A1080-19, Standard Practice for Hot Isostatic Pressing of Steel, Stainless Steel, and Related Alloy Castings, ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[6] ISO/ASTM 52907-19, Additive Manufacturing – Feedstock Materials – Methods to Characterize Metallic Powders, International Organization for Standardization (ISO), Central Secretariat, Chemin de Blandonnet 8, Case Postale 401, 1214 Vernier, Geneva, Switzerland

[7] AWS D20.1-19 Specification for Fabrication of Metal Components Using Additive Manufacturing: 2019, American Welding Society (AWS), 8669 NW 36 Street, No. 130, Miami, FL 33166

[8] ASTM E2586-19, Standard Practice for Calculating and Using Basic Statistics, ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[9] ASTM E8-16, Standard Test Methods for Tension Testing of Metallic Materials; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[10] ASTM F2971-13, Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[11] ASTM E10-18, Standard Test Method for Brinell Hardness of Metallic Materials; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[12] ASTM E18-20, Standard Test Methods for Rockwell Hardness of Metallic Materials; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[13] ASTM E92-17, Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[14] ASTM E21-17, Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[15] ASTM E3-17, Standard Guide for Preparation of Metallographic Specimens; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[16] ASTM E407-15, Standard Practice for Microetching Metals and Alloys; ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959

[17] ISO/ASTM 52900-15, Additive manufacturing – General Principles – Terminology; ISO, Central Secretariat, Chemin de Blandonnet 8, Case Postale 401, 1214 Vernier, Geneva, Switzerland

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