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Report from BPTCS Project Team on Evaluation of Additive Manufacturing For Pressure Retaining Equipment

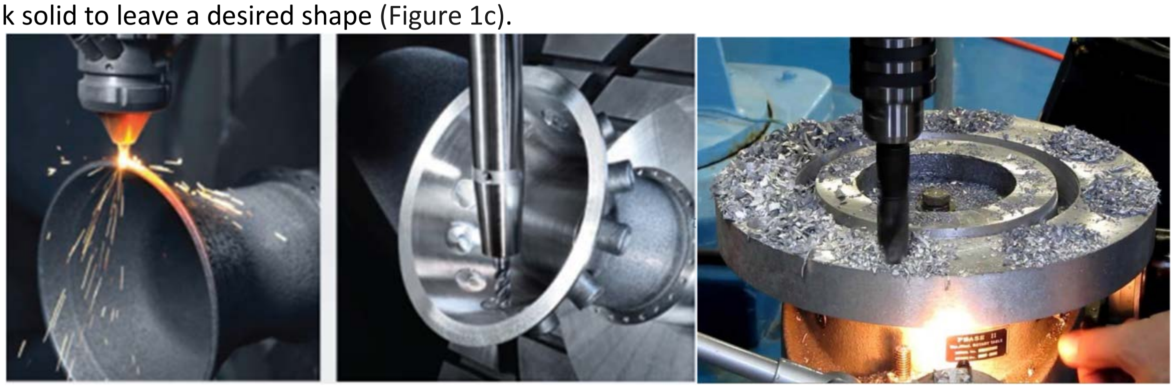
Introduction

ASME is evaluating the use of additive manufacturing (AM) for the construction of pressure equipment. The information in this report assesses available AM technologies for direct metal fabrication of pressure equipment. Background information is included in the report to provide context for those not experienced in AM technology. Only commercially available technologies for direct metal fabrication are addressed in the report because these AM methods are the only viable approaches for the construction of pressure equipment.

Metal AM technologies can produce near-net shape parts by using multiple layers of material from a three dimensional (3D) design model of the geometry. Additive manufacturing of metal components was developed from polymer based rapid prototyping or 3D printing. At the current maturity level, AM application for pressure equipment has the potential to reduce delivery times and costs for complex shapes. AM will also lead to a reduction in the use of high cost materials, since parts can be created with corrosion resistant layers of high alloy material and structural layers of lower cost materials.

Additive vs Subtractive Manufacturing

Additive manufacturing (Figure 1a) is defined by ASTM F2792 as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. In many cases the additive manufacturing process is combined with a machining process (subtractive manufacturing) to complete a part (Figure 1b). Subtractive Manufacturing is defined as the controlled removal of material by machining (e.g., milling, drilling, grinding, etc.) from a bulk solid to leave a desired shape (Figure 1c).



(a) (b) (c)

Figure (1)(a) Additive Manufacturing Process, (b) Hybrid - Additive + Subtractive Manufacturing Process, (c) Subtractive Manufacturing Process

Technologies Considered for Pressure Equipment

The review of AM technologies for direct metal fabrication of pressure equipment will evaluate two AM processes for the first evaluation. Metal AM processes can be characterized by two features, the type of raw material input and the energy source used to melt raw material and form the component. Two AM technologies are evaluated for the construction of pressure equipment using direct metal fabrication powder bed fusion and direct metal disposition. The main effort in the development of AM standards worldwide is focused on Powder Bed Fusion technology and powder and wire feed Direct Energy Deposition. Powder Bed Fusion processes include Selective Laser Melting (SLM), and Electron Beam Melting (EBM). Directed Energy Deposition processes include Laser Engineering Net Shape (LENS), Laser Metal Deposition (LMD) and Electron Beam Deposition (EBD). The Directed Energy Deposition processes can be either wire or powder fed machines.

Powder Bed Fusion AM Processes

Powder bed fusion is a process where energy is selectively applied to regions of metal powder. This energy is generally applied in the form of a laser or an electron beam. The energy causes a temperature rise, resulting in the local melting of the metal powder, with subsequent cooling to solidify the part. This process is repeated layer by layer until the desire part is printed.

The process begins by placing a baseplate into the machine. The part will be built from this plate. The plate serves as a method of securing the part during printing, a method of preventing warping of the part, 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, or is left with a vacuum. A thin layer of powder is deposited, on the order of 100µm. The energy source then selectively heats and melts the powder. The exterior surfaces are generally melted first, and done with machine parameters to optimize dimensional tolerances and surface finish. The interior volume is solidified next, with parameters optimized for reducing porosity and increasing build speed. On some machines, such as the Arcam Electron Beam printers, the entire powder bed is heated, loosely bonding the entire volume together, before fully solidifying the part. The unmelted powder is used to both extract heat and to support subsequent geometry.

At the completion of the layer, the build plate is lowered and another layer of powder is deposited. This process is repeated through the build until the full part height has been accomplished. At the end of the build, the part and build plate is extracted from the machine after a cooldown cycle. If the powder has not been solidified, the part and the build plate can be removed for post processing. If the powder has been loosely solidified, it can be removed through sandblasting or other mechanical removal methods.

The powder can be sieved and reused, but should be done with caution. Powder morphology can change. It shape, size, and size distribution can all be affected by the build process. It is also possible to pick up oxygen or water when the powder is exposed to the atmosphere, leading to potential chemistry changes.

Different machine manufacturers have different methods of controlling the heat of a build. Sometimes they will place small features in or on a part to facilitate conduction of heat. This is due to the raw powder and the solidified metal having different thermal conductivity. Often these features are automatically placed and the operator may not be fully aware that they exist.

Build orientation, part placement on the build plate, and other parts being printed at the same time, all can have an effect on the final part. A part build on its own, centered on the build plate, with the long dimension horizontal may have different properties than a part built with several other parts, built in a corner of the build plate, with the long axis vertical.

Powder bed systems are growing in build volume, but are generally limited to approximately a 12" cube.

Directed Energy Deposition AM Processes

Directed Energy Deposition is a process where an energy source, generally a laser, is used to create a melt pool on a base part, and then feedstock is blown into the pool, adding material to the part. This technique can be used to add material to an existing part, such as repairing damaged turbine blades, to clad a part with a different material for chemical or mechanical purposes, or to build a part starting from a base plate.

The feedstock for directed energy deposition can be in a powder form, or in a wire or rod form. The use of wire is beneficial when dealing with materials that may pose a hazard in powder form, such as aluminium which can be pyrophoric. Rod is used when the material is not ductile enough to be formed into a wire. Some machines have multiple material feed heads, allowing for blending of different feedstock seamlessly through the part, resulting in alloys that can be tailored to the requirements of the finished part at a specific area. For instance, a more corrosion resistant alloy could be on the interior of a pressure vessel, while a stronger alloy could make up the exterior of the vessel, and this can be accomplished in one step.

Directed energy deposition offers additional benefits of a fast build time, and the ability to produce large parts – well over 1x1x2 meters.

- Laser Deposition Technology (LDT) is a process in which metal powder is injected into the focused beam of a high-power laser under tightly controlled atmospheric conditions. The focused laser beam melts the surface of the target material and generates a small molten pool of base material. Powder delivered into this same spot is absorbed into the melt pool, thus generating a deposit that may range from 0.005 to 0.040 in. thick and 0.040 to 0.160 in. wide. The resulting deposits may then be used to build or repair metal parts for a variety of different applications.

ASME Pressure Equipment Methodology

The ASME Boiler and Pressure Vessel Code (BPV) and the B31 Code of Pressure Piping are both safety codes for pressure equipment. The intent of these Codes is to provide a system of requirements that include a design margin on the burst pressure of the equipment being constructed and protection of the public from the potential hazards of the contained fluid. These codes provide requirements for construction of pressure equipment, and are structured using the following elements:

- Scope
- Materials
- Design
- Fabrication
- Examination
- Testing
- Inspection

All the requirements must be met to ensure the design margin is achieved. A common error made by code users is focusing on one element and not following the entire Code. This is understandable for personnel that are not trained in code requirements. To evaluate the extent to which additional coverage is needed for using AM for the construction of pressure equipment, AM technologies are compared to the current coverage in ASME BPV and B31 codes, including an evaluation to incorporate AM.

Materials

Summary

- Sufficient powder and wire feedstock material specifications are available for to proceed with an ASME Standard for additive manufacturing.
- Sufficient material testing methods are available to evaluate AM materials.
- ASME Section II has approved Code Cases powdered metals. This model can be used to approve powdered metal for additive manufacturing.

ASME Material Specifications

The ASME BPV and B31 Codes incorporate requirements for structural integrity of components. Achieving a design margin (factor of safety) on structural integrity requires ensuring the material strength and quality are acceptable. The material requirements in ASME Code specify that construction materials must be provided with minimum strength and toughness properties. The minimum strength levels are addressed by requiring that material be supplied to nationally recognized specifications. The majority of Code material requirements incorporate ASME and ASTM material specifications. These material specifications require that the chemistry and minimum mechanical properties such as yield and tensile strength are controlled. Material toughness is important when the material is used near its ductile brittle transition temperature or in high-pressure systems where high energy levels are contained by the pressure boundary.

Materials for Additive Manufacturing

The materials used as feedstock in metal AM machines are either a powder metal or wire product form, depending on the AM technology used to fabricate the component. Powder Bed fusion technologies, such as, Selective Laser Melting (SLM) and Electron Beam Melting (EBM) utilize different heating techniques to consolidate powders into a solid part. Directed Energy Deposition, including both laser and electron beam heating, use either powder or wire feedstock.

Wire Feedstock

When using the Directed Energy Deposition with wire feedstock, the code basis for material qualification is well established. The wire feedstock for AM processes is common welding filler material. In ASME Section II, Part C, Specifications for Welding Rods, Electrodes, and Filler Metals (XX) provides the necessary requirements for specifying these types of filler material.

Powder Feedstock

The requirements for the metal powder for the EBM and SLM AM processes are specified by the component manufacturer. The specification includes the chemistry, size distribution, shape, and the tap density for the process being used. Powder metals consumed in additive manufacturing should have a spherical shape to ensure good flow and a high packing density. The particle size distribution is usually below 25 µm to 120 µm, but will vary based on the AM process and machine type. The particle size distribution is specified based on the application and the desired material properties. The specification of a particle size distribution is essential in achieving specific surface finish.

In metal AM processes the particle size distribution of powder is an important variable in achieving the specified density for fabricated components. The density obtained for the AM component has a direct correlation to the mechanical properties of the material. Although it's possible to attain high densities with a range of powder size distributions, the AM processing parameters must be tuned to the specific distribution. A few small residual porosities are common in parts below the surface. However, densities of 99.9% are commonly reached with additive manufacturing processes. To achieve full density, post processing by Hot Isostatic Pressing (HIP) can be done. A fine microstructure is obtained in AM parts due to the very rapid solidification process. A slight anisotropy in Z direction material properties is normal resulting in slightly lower mechanical properties because of the superposition of layers.

A significant issue in metal powder bed fusion processes is the degradation of the unconsumed metal powders during a build. This degradation is a result of the metal powder being exposed to contaminants during the recycling process. The powder can also be oxidized during the recycling process if controls are not in place to limit the atmospheric exposure.

ASTM Material Specification for Powder Feedstock

Currently there are four ASTM powder metal standards for use in Powder Bed Fusion AM processes. These to standards include:

- ASTM-F2924 - Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
- ASTM-F3001- Additive Manufacturing Titanium-6 Aluminum-4 Vanadium EKI (Extra Low Interstitial) with Powder Bed Fusion
- ASTM- F3055 –Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
- ASTM- F3056 - Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion

These ASTM standards are technical specifications for the identified materials and provide requirements for the manufacture of components. While these specifications address many of the requirements for additive manufacturing, the ASTM specifications are silent on design margins. Many of the requirements are to be addressed as commercial issues. The topics addressed by the ASTM Standards are listed in Table 1 below. The review of these ASTM documents is included in the materials section because material requirement are the most prescriptive in the specification. A review of the topics provided in Table 1 provides a framework for addressing material requirements in an ASME Standard. The topics provided in the ASTM specification are very similar to the recommendations for European AM Specifications.

Table 1 - ASTM Framework for an Additive Manufacturing Specification

Topic	Description
Scope	The scope identifies the material type covered by the standard and the allowed AM process. User requirements that are more stringent are noted to be included as a commercial issue.
Reference documents	References to specific and general applicable standards
Terminology	Defines specific AM and material related terms
Ordering Information	Provided minimum requirement User input for the procurement
Classification	Provides 6 Classes of thermal processing. Class E requires no thermal processing and has no requirement for mechanical properties
Manufacturing Plan	Requires a plan to control all aspects of the AM build. Most notably the manufacturing plan requires a qualification procedure to test mechanical properties of the specified material.
Feedstock	Requires chemical composition limits for the as-built component. Controls powder size distribution, shape, tap density, and flow rate for the specified AM process/ machine as determined by the component manufacturer. Places controls on blending powder and recycling powder.
Process	Required work to be performed within the manufacturing plan and states that all process changes and allowed external intervention are required to be specified in the manufacturing plan. Identified the need for additional material testing for fatigue strength. Specifies that post built machining may be needed to meet surface finish and definitional requirements.
Chemical Composition	Specifies chemical composition limits and required testing and test methods.
Microstructure	Requirements specific to the specified Titanium Alloy microstructure.
Mechanical Properties	Provides minimum mechanical properties for the specified Titanium Alloy and testing methods, including requirements for test specimen orientation based on the build volume coordinates.
Thermal Process	Specific references to thermal treatment standards specific to Titanium Alloys
Hot Isostatic Pressing	Specifies pressure, temperature, and hold time for HIP
Dimensions and Permissible Variations	Final tolerances are stated to be a commercial issue. Machining is allowed to achieve final dimensions. Welding repair is required to be approved by the User.
Cleanliness of products	Cleaning is specified as a commercial issue. This requirement is in the microstructure section of the ASTM specification
Retests	Provides requirements for retest of chemical and mechanical properties as a manufacturer's option.
Inspection	Inspection is a commercial issue between the user and the manufacturer. No requirements or methods for examination of the final part are provided.
Rejection	Components not meeting the specification are rejected.
Certification	The manufacturer is required to certify the component meets the specification.
Product Marking	Commercial issue only
Quality program	Manufacturer is required to maintain a quality program such as ISO 9001
Supplementary requirements	Listing of additional Supplementary Requirements to be specified by the User when required including: Furnace Anneal, Liquid Penetrant, Radiographic Examination, Hardness Test, Fracture Toughness, Fatigue Testing, Feedstock Flow Rate, Component Density, Contamination from Powder Distribution System, Surface Finish, Compression, Shear, Bearing, Crack Growth, Other Supplemental Requirements, and Quality Assurance

ASME has accepted powered metal for use in Section I components. Code Case 2770 addresses Grade 91 produced by powder metallurgy using a hot isostatic pressing thermal treatment. A task group reporting to ASMEBPV Committee on Materials has a scope to ensure that the current ASTM specifications for HIP component (ASTM A988, A989, and B834) and the additional code cases controls are adequate to ensure the integrity and quality of the HIP component. Since Mandatory Appendix 5 in Section II, Part D is silent on HIP components the task group has to determine whether HIP components are equivalent to their wrought specification. This code case and the task groups work provides a starting point to compare with the ASTM specification to provide direction for material requirements for additive manufacturing. Code Case 2770 is provided below for review.

ASME BPVC.CC.BPV-2015

CASE
2770

Approval Date: May 13, 2013

Code Cases will remain available for use until annulled by the applicable Standards Committee.

Case 2770
Grade 91 Steel, 9%Cr-1%Mo (UNS K90901)
Section I

Inquiry: May austenitized and tempered UNS K90901 material that meets the specification requirements of ASTM A989/A989M-11 for hot isostatically-pressed alloy steel powder metallurgy parts for high temperature service be used for Section I components for welded construction?

Reply: It is the opinion of the Committee that austenitized and tempered UNS K90901 material conforming to ASTM A989/A989M-11 for hot isostatically-pressed alloy steel powder metallurgy parts may be used for Section I welded construction, provided the following additional requirements are met:

(a) For purposes of welding procedure and performance qualification, this material shall be considered P-No. 15E.

(b) The material shall be austenitized within the temperature range of 1,900°F to 1,975°F (1040°C to 1080°C), followed by air or accelerated cooling, and tempered within the range of 1,350°F to 1,470°F (730°C to 800°C).

(c) The maximum allowable stress values for the material shall be those given in Tables 1 and 1M.

(d) The maximum use temperature is 1,200°F (649°C).

(e) The maximum allowable powder size is 0.019 in. (0.5 mm), and the powder shall be produced by the gas atomization process.

(f) Following atomization, powders shall be stored under a positive nitrogen or argon atmosphere to minimize potential oxidation or contamination.

(g) In addition to a chemical composition analysis of the final blend powder, an analysis of a sample (component or compact) from each lot of parts shall be required.

(h) The material shall be examined using either the magnetic particle or liquid penetrant inspection method per ASTM A989/A989 M-11, Supplementary Requirement S4 or S5.

(i) Weld repairs to the material shall be made with one of the following welding processes and consumables:

(1) SMAW, SFA-5.5/SFA-5.5M E90XX-B9

(2) SAW, SFA-5.23/SFA-5.23M EB9 + neutral flux

(3) GTAW, SFA-5.28/SFA-5.28M ER90S-B9

(4) FCAW, SFA-5.29/SFA-5.29M E91T1-B9

In addition, the Ni + Mn content of all welding consumables shall not exceed 1.0%.

(j) Weld repairs to the material as a part of manufacture shall be made with welding procedures and welders qualified in accordance with Section IX.

(k) Repair by welding shall not exceed 10% of the part surface area and $33^1/_3$% of wall thickness of the finished part or $^3/_4$ in. (19 mm), whichever is less, without prior approval of the purchaser.

(l) If during the manufacturing any portion of the component is heated to a temperature greater than 1,470°F (800°C), then the component shall be reaustenitized and retempered in its entirety in accordance with (b).

(m) Yield strength, tensile strength, external pressure, and physical properties used shall be the same as found in SA-335 for Grade 91.

(n) This Case number shall be shown on the Manufacturer's Data Report.

The Committee's function is to establish rules of safety, relating only to pressure integrity, governing the construction of boilers, pressure vessels, transport tanks and nuclear components, and inservice inspection for pressure integrity of nuclear components and transport tanks, and to interpret these rules when questions arise regarding their intent. This Code does not address other safety issues relating to the construction of boilers, pressure vessels, transport tanks and nuclear components, and the inservice inspection of nuclear components and transport tanks. The user of the Code should refer to other pertinent codes, standards, laws, regulations or other relevant documents.

1 *(2770)*

Many material suppliers produce powder metals using standard material specifications. For example, Sandvik Osprey Ltd. produces powdered metal using the gas atomization process, specializing in fine metal powder, less than 38 µm and can produce particle sizes up to 250 µm. A review of available powdered metal manufacturers indicates that obtaining the needed powder feedstock will not be an issue for AM. Examples of available material are provided in Table 2.

Table 2 - Examples of Available Powder Metals

Type	Alloy	Examples
Stainless steels	Austenitic, ferritic, duplex, martensitic & preciptitation hardening	304L, 316L, 430L, 440C, SAF2507 & 17-4PH
Tool steel	All types	M2, H13, D2, SKD-11
Low alloy steels	All types	4140, 4365, 8620
Copper alloys	Bronze, CuMnNi	Cu10Sn, Cu10Mn3Ni
Cobalt alloys	All types	F75, F90
Other types	Maraging steel, Ni-based	18Ni300, IN625, IN718

Material Testing

The current direction in ASME BPV Section II is to accept powdered metals by code case. Mechanical properties are being assigned based on the base metal properties. Section II has formed a task team on powdered materials. The current approach used by the three powdered metal code cases is to require hot isostatic pressing (HIP) as a final thermal processing step. The goal with HIP is to achieve full density of the material. Final density of the AM component is an essential variable that must be addressed if base metal material mechanical properties are to be specified. Porosity can lower an AM's components effective mechanical properties. The presence of porosity is a concern for both fracture toughness and fatigue strength. Density is influenced by the development of pores or entrapment of un-melted powders during the layering (XX). Porosity or partial de-lamination of the material can initiate cracks and result in component failure. For pressure equipment, toughness and fatigue resistance are critical requirements. Repeatedly obtaining additively manufactured materials with 100% of the full base material density is challenging. AM of metallic processes can achieve densities in excess of 99% (XX). Hot isostatic pressing is one option for insuring full density of an as-built AM component. The determination of mechanical properties will have to be addressed in any effort that provides code requirements for AM components. Determining the requirements for testing, including the methods to be used for sampling, are being address by other standards.

ASTM Material Testing Standards for AM

Standards for testing of mechanical properties for components using AM are being developed by Subcommittee F42.01 on Test Methods, as part of ASTM International Committee F42 on Additive Manufacturing Technologies. ASTM has issued the following standards for testing AM fabricated materials.

- ASTM - F2971 Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
- ASTM - F3049 Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes

- ASTM - F3122 Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes

These ASTM documents are written at a high level to provide available direction to the AM industry to help support its move forward. Additional, more specific standards for testing mechanical properties for AM processes are expected to follow as the industry matures. ASTM Specification F3049 is a guide to direct AM manufactures to existing standards for metal powder. The guide provides direction for test methods that can be used to characterize AM feedstock that is applicable to both the power bed fusion and the direct energy deposition for both new and recycled powders. ASTM 3049 addresses sampling, size determination, morphology characterization, chemical composition, flow characteristics, and density measurements for powder metals. ASTM standard F3122 is a guide to existing ASTM testing methods that may be applicable to determine specific mechanical properties of materials manufactured using the AM process. Methods to test tension, compression, bearing, bending, modulus, hardness, fatigue, and fracture are provided. ASTM F3122 addresses the issue of anisotropic behavior in AM components by specifying standard reporting criteria in ASTM F2971. ASTM F2071 requires that all material and processing information be reported for test specimens including a description of the feedstock material. The standard also provides criteria for placement and orientation of the test specimens in the build volume. An example for a reference frame for test specimen orientation is shown in Figure 2.

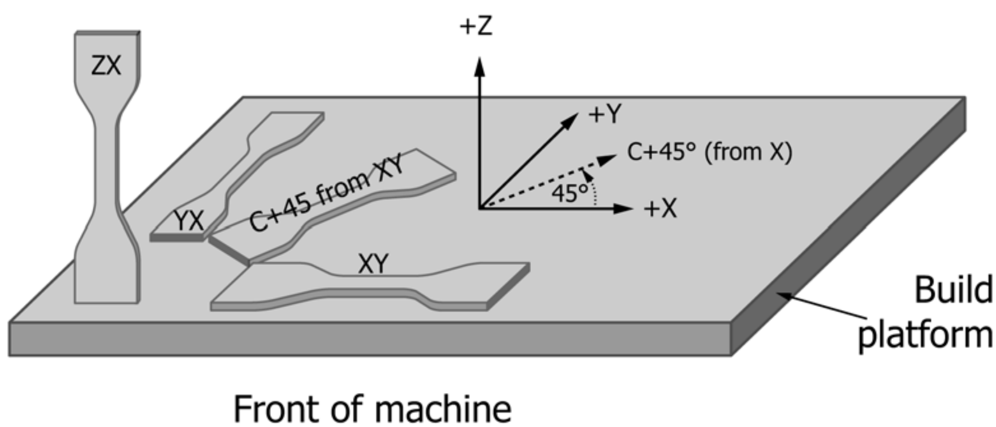


Figure 2 Example AM Test Specimen Orientation (From ASTM F2971)

Design

Summary

- There is a sufficient design and analysis approach to support an ASME additive manufacturing standard
- Requirements for qualification testing will be needed for AM pressurized equipment.
- The design by analysis rules in ASME Section VIII Div. 2 are the most appropriate requirements to evaluate the complex shapes for additive manufacturing.

ASME Design Margins

The design sections of ASME BPV VIII and B31 Codes provide requirements for pressure design and rating of components for pressure service. The design margin on a component's burst pressure varies between codes. In the codes of interest for the additive manufacturing, the design margin is in a range of 2.4 to 3.5 for the Section VIII Pressure Vessel Code and 3.0 to 3.5 for the B31 Pressure Piping Code. When the code specifies lower design margins, material quality, examination and testing requirements are increased to higher levels. These rules for most standard parts are commonly expressed by equations that address minimum required component wall thickness and procedures to prescribe component pressure ratings. When a simple geometry, like a cylinder (pipe or tube), is used under a static internal pressure load, there is a single equation to address the code minimum wall thickness requirement. As the geometry and loadings become more complex, the required calculations and design procedures are more involved. At the present level of the technology, AM components are most economical for complex geometries and high alloy materials. The most suitable code rules available today for complex shapes are in ASME Section VIII Division 2, Part 5. The specification of an appropriate design margin for an AM standard for pressurized equipment will require additional review and will depend on the level of confidence in the as-built material properties and the confidence that can obtained in control of the built process.

Design for Additive Manufacturing

There are unique design areas in additive manufacturing. The design strategies focus on using AM technologies as a production technique for final products. AM design strategies are used to make decisions about sequencing of design steps during a build. Examples for these features are shown in Figures 3 and 4. Figure 3 shows an exaggerated illustration of stair casing formed as part of the layering effect during the AM build. Figure 4 is an example of the supports (red sections) needed to hold the AM component in position during a build. There are other design features that are unique to AM such as techniques to achieve surface finish and specification of dimensional tolerances. While these AM design feature have to be addressed as part of the design process of a pressurized component, they are not a real factor in determining a methodology for design qualification.

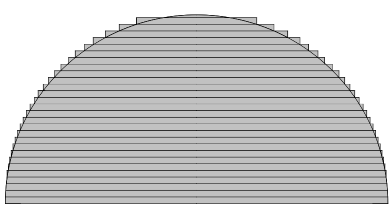


Figure 3 - Example of Stair Casing 0r Layering during the AM Component Build

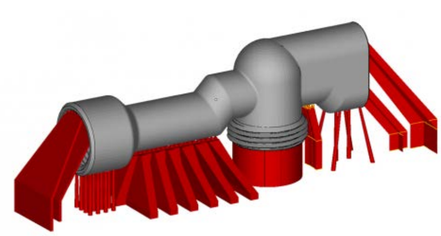


Figure 4 - Example of Supports Formed as Part of the Build Process to Support an AM Component

There are currently three methods that are used for design qualification in ASME pressure equipment qualification codes. These include design by rules, design by analysis, and design by qualification testing.

Performance Based Testing

The majority of the equipment, where the economics support the use of AM, will be complex shapes where design by rule equations and standard details will not support complete design qualification. The resent work for fiber reinforced hydrogen pressure vessels used a combination of design by analysis to demonstrate that a maximum stress level was not exceeded and a series of performance based qualification tests. The performance based testing was done on prototypic components. Testing prototypes provided qualification of the final design geometry and demonstrated control of manufacturing and material strength. The methodology applied to the composite pressure vessel effort is a path that will support qualification of an additively manufactured component. The Manufacturer would be responsible to qualify the AM design that is fabricated to the requirements of the Manufacturing Specification specific to the component and AM build process. New designs would have a sufficient number of prototype components fabricated to complete the qualification testing.

Fabrication

Summary

- Requirements for controlling fabrication need additional development to proceed with a standard for additive manufacturing
- The specification being developed AWS will provide the requirements for fabrication control when they are completed
- Control of fabrication at this point in time will require a performance based approach with the manufacturer developing and qualifying a Manufacturing Specification.

ASME Control of Fabrication

Fabrication requirements in pressure safety codes prescribe minimum workmanship requirements and control of fabrication processes such as welding, heat-treating, bending and forming, and machining. The qualification of welding procedures and welding operators defined in ASME B&PV Section IX and AWS Standards is applicable to developing controls for fabrication for additive manufacturing.

American Welding Society Specifications

The AWS D20 Committee has been working on the development of specification D20.1 “Specification for Fabrication of Metal Components using Additive Manufacturing” (xx). The current plan is to have a draft standard ready for ballot by the end of 2016. The design sections of the draft AWS specification is generic and addresses the requirements for the basic build geometry needed to determine inputs for the selection of an AM process. The specification does not address design margins. The standard also classifies parts based on consequence of failure. The classification supports a graded approach to procedure qualification and inspection requirements. The standard follows the current process to develop a Welding Procedure Specification (WPS) that is qualified using a Procedure Qualification Record (PQR) as being used for current welding processes. There is an increase in the level of difficulty with the procedure qualification when addressing AM, in that the number of essential variables increases dramatically to control the entire build process as opposed to a welded joint. The current draft addresses seven topical areas to control the AM build process including:

- Feedstock Material Specification

- AM Equipment Qualification
- Build Process Parameters (Essential Variables for the Part Recipe)
- Work Instructions for Each Job Run
- Qualification of the AM Process to Build & Inspect Each Part Number
- Lot Acceptance Testing for Production
- Reports/Certifications

Notable in the draft specification is the scheme to provide specimens for material properties. The specification utilizes a standard test array and witness specimens shown in Figure 5. The standard test array for powder bed fusion additive manufacturing processes shall consist of as-built tensile specimens. The as-built tensile specimens in each test array include different specimen orientations to quantify possible anisotropic material behavior that may be seen in the build process. The witness specimen is a solid vertical section built with test arrays from which a tensile specimen can be machined with the greatest height (Z-direction) of the build contained in its gage length. The witness test specimens shall have all post-build treatments performed as the manufactured component.

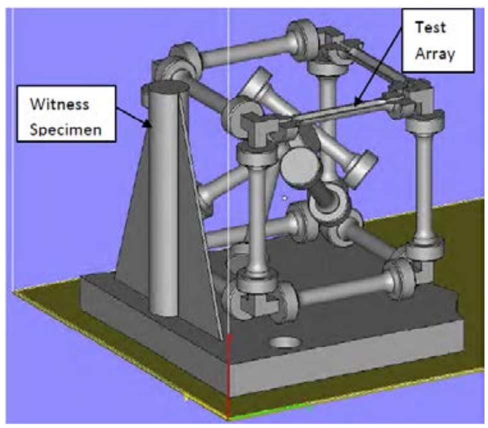


Figure 5 Example of Material Specimen Test Array

ASME has a precedent for adopting AWS specifications for use in control of welding processes and material. The body of work that AWS has prepared is well developed and expected to be balloted later this year. The review and adoption of the AWS additive manufacturing specification is one option to provide control of fabrication for an ASME AM pressurized equipment standard.

The control of manufacturing can also follow the model used for composite pressure vessels. The manufacturer would be required to provide a manufacturing specification. The Manufacturing Specification would specify as a minimum all pertinent material properties data, the essential variables for the AM process and the AM machine being used in the specific component fabrication, and all other significant process data associated with the component design. The Manufacturing Specification would include tolerance limits for all appropriate material properties, process conditions such as time and temperature, acceptable test results, and material testing records. The Manufacturing Specification would be a required Manufacturer’s Record. The use of the Manufacturing Specification model has some advantages because the AM process is still evolving, and there is more flexibility for accepting proprietary and unique techniques with this approach.

Examination

Summary

- Specification of examination criteria need addition development to ensure quality of AM components
- Existing NDE methods used today for metallic components are available for AM components
- Current NDE acceptance criteria will need to be reviewed for applicability to AM components
- Extent of examination will need to be integrated with qualification and production testing

ASME Examination Requirements

Examination for pressure equipment ensures quality control is maintained during fabrication process. Personnel involved with the mechanical and structural integrity are familiar with non-destructive examination of welded joints. Both welding and non-welding examinations are required by pressure equipment codes.

Examination of AM Components

The current techniques in ASME BPV Section V for nondestructive examination can be applied to AM pressurized equipment. The current acceptance criteria specified in the ASME construction Codes will need to be reviewed for applications to AM components. Current methods to be are listed in Table 3. Additive manufacturing will be used across ASME B&PV and B31 Codes. Common flaw acceptance criteria should be evaluated to support the implementation for AM if an ASME Standard is developed. The extent of examination required for AM component will need to be integrated with qualification and production testing to provide the most efficient means to ensure quality of AM components.

Acceptance of AM components will heavily depend on visual examination. Visual examination can be used to determine correct geometric features, correct dimensions, and absence of gross flaws, piece-to-piece consistency, and surface finish. Examination using in-situ equipment monitoring will be needed to ensure essential variables remain in specified tolerances.

Computed tomography needs to be investigated to ensure sufficient examination of components with complex geometries.

Table 3 Available Examination Methods for Additive Manufacturing

Examination Method	ASME Section V	ASTM Specification	Acceptance Criteria Section VIII Division 2	Acceptance Criteria B31.3
Visual	Article 9	-	7.5.2	341.3.2
Penetrant	Article 6	E1417	7.5.7	341.3.2
Magnetic Particle	Article 7	E1444	7.5.6	341.3.2
Radiographic	Article 2	E1742	7.5.3	341.3.2
Ultrasonic	Article 4 & 5	E213	7.5.4	344.6.2
Computed Tomography (CT)	-	E 1570	-	-

Testing

Summary

- There are sufficient hydrostatic and leak testing requirements to support an ASME additive manufacturing standard

ASME Hydrostatic Testing

ASME pressure equipment Codes require an elevated pressure test to prove leak tightness. The hydrostatic elevated pressure test level is in the range of 1.3 to 1.5 times the design pressure of the component. Based on the design margins for pressure components the test pressure level is well below a point that will challenge the structural integrity of the component unless a gross design or fabrication error is present. For this reason, it is important to acknowledge that the code pressure test is a leak test used to prove the component or system is leak tight. The code leak test is not a structural integrity test to prove pressure safety of a component. Qualification testing can be specified as part the design qualification process. The standard code hydrostatic test is needed for any pressurized AM component. The current hydrostatic and pneumatic testing methodology codified today is acceptable for AM components. No additional work is needed for this topic. Because of the potential for porosity in an AM component consideration for specifying a sensitive leak test should be considered when developing AM components leak testing requirements.

Inspection

Requirements for inspection by either an Authorized Inspector or owner's inspector will be reviewed for application of inspection of AM pressure components.

Conclusions

This report provides a**n** assessment of the extent to which additive manufacturing (AM) processes are covered under ASME BPV and B31 codes, and the next steps to be considered to provide adequate coverage for AM in those codes for the construction of pressure components.

Recommendations

1. The ASME Project Team on Additive Manufacturing recommends moving forward with development of requirements for AM pressurized equipment applications. Since AM is being investigated for use by several ASME standards linking this effort to a specific standard should be determined at a future date.
2. The ASME requirement should utilize current AM standards when possible. Specifically the work being performed by the AWS D20 Committee should be monitored with the intent of adopting the AM AWS specifications by reference for use in AM procedure specification and procedure qualification as is currently done in ASME Section IX for welding processes.
3. Data supporting a technical baseline should be developed to document an acceptable design margin for pressurized AM equipment considering the current level of variability in material properties for AM parts.
4. Current radiographic and ultrasonic examination methods are acceptable for the majority of current geometries being fabricate using AM today. Criteria that define acceptable geometrics

for examination using current examination method will need to be developed for the ASME AM requirements for pressurized equipment. Additional development work for examination techniques will be needed to accept the more complex AM parts that can be fabricated today.