Designation: F2924 – 14

Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion[1]

This standard is issued under the fixed designation F2924; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This specification covers additively manufactured titanium-6aluminum-4vanadium (Ti-6Al-4V) components using full-melt powder bed fusion such as electron beam melting and laser melting. The components produced by these processes are used typically in applications that require mechanical properties similar to machined forgings and wrought products. Components manufactured to this specification are often, but not necessarily, post processed via machining, grinding, electrical discharge machining (EDM), polishing, and so forth to achieve desired surface finish and critical dimensions.

1.2 This specification is intended for the use of purchasers or producers, or both, of additively manufactured Ti-6Al-4V components for defining the requirements and ensuring component properties.

1.3 Users are advised to use this specification as a basis for obtaining components that will meet the minimum acceptance requirements established and revised by consensus of the members of the committee.

1.4 User requirements considered more stringent may be met by the addition to the purchase order of one or more Supplementary Requirements, which may include, but are not limited to, those listed in S1-S16.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

B213 Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel
B214 Test Method for Sieve Analysis of Metal Powders
B243 Terminology of Powder Metallurgy
B311 Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
B600 Guide for Descaling and Cleaning Titanium and Titanium Alloy Surfaces
B769 Test Method for Shear Testing of Aluminum Alloys
B964 Test Methods for Flow Rate of Metal Powders Using the Carney Funnel
D3951 Practice for Commercial Packaging
E3 Guide for Preparation of Metallographic Specimens
E8/E8M Test Methods for Tension Testing of Metallic Materials
E9 Test Methods of Compression Testing of Metallic Materials at Room Temperature
E10 Test Method for Brinell Hardness of Metallic Materials
E11 Specification for Woven Wire Test Sieve Cloth and Test Sieves
E18 Test Methods for Rockwell Hardness of Metallic Materials
E21 Test Methods for Elevated Temperature Tension Tests of Metallic Materials
E23 Test Methods for Notched Bar Impact Testing of Metallic Materials
E29 Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications
E238 Test Method for Pin-Type Bearing Test of Metallic Materials
E384 Test Method for Knoop and Vickers Hardness of Materials
E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness K_{Ic} of Metallic Materials
E407 Practice for Microetching Metals and Alloys

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

E466 Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials
E539 Test Method for Analysis of Titanium Alloys by X-Ray Fluorescence Spectrometry
E606 Test Method for Strain-Controlled Fatigue Testing
E647 Test Method for Measurement of Fatigue Crack Growth Rates
E1409 Test Method for Determination of Oxygen and Nitrogen in Titanium and Titanium Alloys by Inert Gas Fusion
E1417 Practice for Liquid Penetrant Testing
E1447 Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by Inert Gas Fusion Thermal Conductivity/Infrared Detection Method
E1450 Test Method for Tension Testing of Structural Alloys in Liquid Helium
E1820 Test Method for Measurement of Fracture Toughness
E1941 Test Method for Determination of Carbon in Refractory and Reactive Metals and Their Alloys by Combustion Analysis
E2368 Practice for Strain Controlled Thermomechanical Fatigue Testing
E2371 Test Method for Analysis of Titanium and Titanium Alloys by Direct Current Plasma and Inductively Coupled Plasma Atomic Emission Spectrometry (Performance-Based Test Methodology)
F629 Practice for Radiography of Cast Metallic Surgical Implants
F1472 Specification for Wrought Titanium-6Aluminum-4Vanadium Alloy for Surgical Implant Applications (UNS R56400)
F2792 Terminology for Additive Manufacturing Technologies,

2.2 *ISO/ASTM Standards:*[2]

52915 Specification for Additive Manufacturing File Format (AMF) Version 1.1
52921 Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies

2.3 *ASQ Standard:*[3]

ASQ C1 Specifications of General Requirements for a Quality Program

2.4 *ISO Standards:*[4]

ISO 148-1 Metallic materials—Charpy pendulum impact test—Part 1: Test method
ISO 1099 Metallic materials—Fatigue testing—Axial force-controlled method
ISO 4545 Metallic materials—Knoop hardness test—Part 2: Verification and calibration of testing machines
ISO 5832-3 Implants for Surgery—Metallic Materials—Part 3: Wrought Titanium 6-Aluminum 4-Vanadium Alloy Third Edition
ISO 6506-1 Metallic materials—Brinell hardness test—Part 1: Test method
ISO 6507-1 Metallic materials—Vickers harness test—Part 1: Test method
ISO 6508 Metallic materials—Rockwell hardness test—Part 1: Test method (scales A, B, C, D, E, F, G, H, K, N, T)
ISO 6892-1 Metallic Materials—Tensile Testing at Ambient Temperature
ISO 6892-2 Metallic Materials—Tensile Testing—Part 2: Method of test at elevated temperature
ISO 9001 Quality Management System – Requirements
ISO 9044 Industrial Woven Wire Cloth – Technical Requirements and Testing
ISO 12108 Metallic materials—Fatigue testing—Fatigue crack growth method
ISO 12111 Metallic materials—Fatigue testing—Strain-controlled thermomechanical fatigue testing method
ISO 12135 Metallic materials—Unified method of test for the determination of quasistatic fracture toughness
ISO 12737 Metallic materials—Determination of plane-strain fracture toughness (withdrawn)
ISO 13485 Medical devices – Quality management systems – Requirements for regulatory Purposes
ISO 19819 Metallic materials—Tensile testing in liquid helium

2.5 *SAE Standards:*[5]

AMS2249 Chemical Check Analysis Limits Titanium and Titanium Alloys
AMS2801 Heat Treatment of Titanium Alloy Parts
AMSH81200 Heat Treatment of Titanium and Titanium Alloys
AS1814 Terminology for Titanium Microstructures
AS9100 Quality Systems – Aerospace – Model for Quality Assurance in Design, Development, Production, Installation and Servicing

2.6 *ASME Standards:*[6]

ASME B46.1 Surface Texture

2.7 *National Institute of Standards and Technology*[7]

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3. Terminology

3.1 *Definitions:*

3.1.1 *as built, n, adj*—refers to the state of components made by an additive process before any post processing except where removal from a build platform is necessary or powder removal or support removal is required.

3.1.2 *build cycle, n*—single cycle in which one or more components are built up in layers in the process chamber of the machine.

3.1.3 *heat, n*—powder lot.

3.1.4 *manufacturing lot, n*—manufactured components having commonality between powder, production run, machine, and post-processing steps (if required) as recorded on a single manufacturing work order.

[3] Available from American Society for Quality (ASQ), 600 N. Plankinton Ave., Milwaukee, WI 53203, http://www.asq.org.

[4] Available from American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036, http://www.ansi.org.

[5] Available from SAE International (SAE), 400 Commonwealth Dr., Warrendale, PA 15096-0001, http://www.sae.org.

[6] Available from American Society of Mechanical Engineers (ASME), ASME International Headquarters, Three Park Ave., New York, NY 10016-5990, http://www.asme.org.

[7] Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, http://www.nist.gov.

3.1.5 *machine, n*—a system including hardware, machine control software, required set-up software and peripheral accessories necessary to complete a build cycle for producing components.

3.1.6 *manufacturing plan, n*—plan including, but not limited to the items in Section 6, written by the component supplier that specifies the production sequence, machine parameters and manufacturing control system used in the production run.

3.1.6.1 *Discussion*—Manufacturing plans are typically required under a quality management system such as ISO 9001 and ASQ C1.

3.1.7 *near net shape, n*—components that meet dimensional tolerance as built with little post processing.

3.1.7.1 *Discussion*—Near net shape components are typically used for, but not limited to, Class 4 components.

3.1.8 *powder bed, n*—refers to the build area in an additive manufacturing process in which feedstock is deposited and selectively melted with a heat source to build up components.

3.1.8.1 *Discussion*—Powder bed processes are in contrast to other metal additive manufacturing processes in which powder or wire are fed simultaneously with the heat source. Powder bed processes include, but are not limited to, the processes know as selective laser melting, metal laser sintering, and electron beam melting.

3.1.9 *powder blend, n*—quantity of powder made by blending powders originating from more than one powder lot.

3.1.10 *powder lot, n*—a quantity of powder produced under traceable, controlled conditions, from a single unifying manufacturing process cycle and provided with source documentation.

3.1.10.1 *Discussion*—The size of a powder lot is defined by the powder supplier. It is common that the powder supplier distributes a portion of a powder lot to multiple powder bed fusion component suppliers.

3.1.11 *production run, n*—all components produced in one build cycle or sequential series of build cycles using the same process conditions and powder.

3.1.12 *used powder, n*—powder from a powder blend or powder lot that has been processed in at least one previous build cycle.

3.1.13 *virgin powder, n*—unused powder from a single powder lot.

3.2 Terminology relating to titanium microstructure in AS1814 shall apply.

3.3 Terminology relating to additive manufacturing in Terminology F2792 shall apply.

3.4 Terminology relating to coordinate systems in Terminology 52921 shall apply.

3.5 Terminology relating to powder metallurgy in Terminology B243 shall apply.

4. Classification

4.1 Unless otherwise specified herein, all classifications shall meet the requirements in each section of this specification.

4.1.1 Class A components shall be stress relieved or annealed per Section 12.

4.1.2 Class B components shall be annealed per Section 12.

4.1.3 Class C components shall be hot isostatically pressed per Section 13.

4.1.4 Class D components shall be solution heat treated and aged per Section 12.

4.1.5 For Class E components all thermal processing shall be optional.

4.1.6 Class F components shall be stress relieved or annealed per Section 12.

5. Ordering Information

5.1 Orders for components compliant with this specification shall include the following to describe the requirements adequately:

5.1.1 This specification designation,

5.1.2 Description or part number of product desired,

5.1.3 Quantity of product desired,

5.1.4 Classification,

5.1.5 SI or SAE units,

5.1.5.1 *Discussion*—The STL file format used by many powder bed fusion machines does not contain units of measurement as metadata. When only STL files are provided by the purchaser, ordering information should specify the units of the component along with the electronic data file. More information about data files can be found in ISO/ASTM 52915.

5.1.6 Dimensions and tolerances (Section 14),

5.1.7 Mechanical properties (Section 11),

5.1.8 Methods for chemical analysis (Section 9),

5.1.9 Sampling methods (S16),

5.1.10 Post-processing sequence of operations,

5.1.11 Thermal processing,

5.1.12 Allowable porosity (Section S8).

5.1.13 Component marking such as labeling the serial or lot number in the CAD file prior to the build cycle, or product tagging,

5.1.14 Packaging,

5.1.15 Certification,

5.1.16 Disposition of rejected material (Section 15), and

5.1.17 Supplementary requirements.

6. Manufacturing Plan

6.1 Class A, B, C, D, and F components manufactured to this specification shall have a manufacturing plan that includes, but is not limited to, the following:

6.1.1 A machine, and manufacturing control system, qualification procedure as agreed between component supplier and purchaser;

NOTE 1—Qualification procedures typically require qualification build cycles in which mechanical property test specimens are prepared and measured in accordance with Section 11 or other applicable standards. Location, orientation on the build platform, number of test specimens for each machine qualification build cycle, and relationship between specimen test results and component quality shall be agreed upon between component supplier and purchaser.

6.1.2 Feedstock that meets the requirements of Section 7;

6.1.3 The machine identification, including machine software version, manufacturing control system version (if

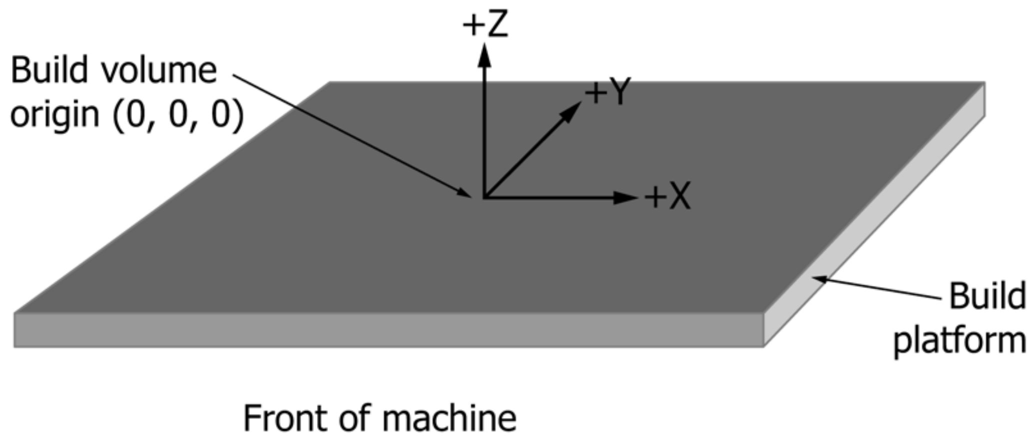

FIG. 1 Build Platform Coordinates for Test Specimens (for reference only)

automated), build chamber environment, machine conditioning, and calibration information of the qualified machine;

6.1.4 Predetermined process as substantiated by the qualification procedure;

6.1.5 Safeguards to ensure traceability of the digital files, including design history of the components;

6.1.6 All the steps necessary to start the build process, including build platform selection, machine cleaning, and powder handling;

6.1.7 The requirements for approving machine operators;

6.1.8 Logging of machine build data files, upper and lower limits of the parameters affecting component quality and other process validation controls;

6.1.9 The number of components per build cycle, their orientation and location on the build platform, and support structures, if required;

6.1.10 Process steps including, but not limited to, Section 8;

6.1.11 Post-processing procedure, including sequence of the post-processing steps and the specifications for each step;

6.1.12 Thermal processing including furnace anneal, hot isostatic pressing, heat treat, and aging; and

6.1.13 Inspection requirements as agreed between the purchaser and component supplier, including any supplementary requirements.

7. FeedStock

7.1 The feedstock for this specification shall be metal powder, as defined in Terminology B243, that has the powder type, size distribution, shape, tap density, and flow rate optimized for the process as determined by the component supplier.

7.2 The metal powder shall be free from detrimental amounts of inclusions and impurities and its chemical composition shall be adequate to yield, after processing, the final material chemistry listed in Table 1.

7.3 Powder blends are allowed unless otherwise specified between the component supplier and component purchaser, as long as all powder used to create the powder blend meet the requirements in Table 1 and lot numbers are documented and maintained.

TABLE 1 Composition

Element	min	max
Aluminum	5.50	6.75
Vanadium	3.50	4.50
Iron	—	0.30
Oxygen	—	0.20
Carbon	—	0.08
Nitrogen	—	0.05
Hydrogen	—	0.015
Yttrium	—	0.005
Other elements, each	—	0.10
Other elements, total	—	0.40
Titanium	remainder	

7.4 Used powder is allowed. The proportion of virgin powder to used powder shall be recorded and reported for each production run. The maximum number of times used powder can be used as well as the number of times any portion of a powder lot can be processed in the build chamber should be agreed upon between component supplier and purchaser for Class A, B, C, D, and F. There are no limits on the number of build cycles for used powder for Class E components. After a build cycle, any remaining used powder may be blended with virgin powder to maintain a powder quantity large enough for next build cycle. The chemical composition of used powders shall be analyzed regularly, as agreed upon between component supplier and purchaser. Powder not conforming to Table 1 or 7.7 shall not be further processed in the machine to manufacture Class A, B, C, D and F components.

7.4.1 All used powder shall be sieved with a sieve having a mesh size appropriate for removing any agglomerates or contaminants from the build cycle.

7.5 All powder sieves used to manufacture Class A, B, C, D and F components shall have a certificate of conformance that they were manufactured to ISO 9044 or all powder sieving shall be in conformance with Specification E11.

7.6 Sieve analysis of used powder or powder lots during incoming inspection or in-process inspection shall be made in accordance with Test Method B214 or as agreed between component supplier and purchaser.

7.7 The maximum percentage of aluminum in Table 1 may be increased for virgin powder, used powder and powder blends when agreed upon between component supplier and purchaser. When component supplier and purchaser agree to an increase in the maximum percentage of aluminum, 9.2 shall apply.

7.8 Any powder lot or powder blend containing any used powder shall be considered used powder.

8. Process

8.1 Processing shall be conducted per applicable standards or as agreed upon between component supplier and purchaser according to an approved manufacturing plan as described in Section 6.

8.1.1 Test specimens for quality assurance may be built and tested in accordance with Section 11 with each build cycle or before and after a production run as agreed upon between the component supplier and purchaser.

NOTE 2—In addition to tension test specimens, fatigue test specimens may be required by the purchaser to be built with the components at the beginning and end of each production run. Fatigue testing is described in Supplementary Requirement S6.

8.2 Permissible parameter, process changes and extent of external intervention during the build cycle shall be identified in the manufacturing plan. All process changes shall be continuously monitored and recorded. When agreed to by the purchaser, minor changes to the manufacturing plan are permissible without machine requalification.

8.3 Condition and finish of the components shall be agreed upon between the component supplier and purchaser.

8.4 Post-processing operations may be used to achieve the desired shape, size, surface finish, or other component properties. The post-processing operations shall be agreed upon between the component supplier and purchaser for Class A, B, C, D and F components.

9. Chemical Composition

9.1 Except for Class E, as-built components shall conform to the percentages by weight shown in Table 1. Carbon shall be determined in accordance with Test Method E1941. Hydrogen shall be determined in accordance with Test Method E1447. Oxygen and nitrogen shall be determined in accordance with Test Method E1409, and other elements in accordance with Test Methods E539 or E2371. Other analytical methods may be used if agreed upon by the component supplier and purchaser.

9.2 Chemical check analysis limits shall be in accordance with AMS2249 and Table 2. Chemical check analysis tolerances do not broaden the limits in Table 1, but cover variations between laboratories in the measurement of chemical content. The supplier shall not ship components that are outside the limits specified in Table 1.

TABLE 2 Check Analysis Tolerances

Element	Permissible Variation in Check Analysis
Aluminum	±0.40
Vanadium	±0.15
Iron	±0.10
Oxygen	±0.02
Carbon	±0.02
Nitrogen	±0.02
Hydrogen	±0.002
Yttrium	±0.0006
Other Elements, each	±0.02

9.3 The chemical composition requirements in this specification for powder bed fusion Ti 6A1 4V components is the same as Specification F1472 and ISO 5832-3 for wrought alloy.

10. Microstructure

10.1 Alpha case is not permitted on final, net components when examined on a metallurgical cross section at 100X magnification.

10.2 The alpha case requirement for near net shape components shall be agreed upon between component supplier and purchaser when subsequent post processing operations are adequate to remove all alpha case.

10.3 When agreed between component supplier and purchaser, components shall be descaled and cleaned in accordance with Guide B600.

10.4 The microstructural requirements and frequency of examinations shall be mutually agreed upon by the supplier and purchaser. Specimen preparation shall be in accordance with Guide E3 and Practice E407.

11. Mechanical Properties

11.1 Build platform coordinates and build platform location for test specimens shall be used in accordance with Terminology 52921.

11.2 Tension test specimens shall be prepared in accordance with Test Method E8/E8M either before or after thermal processing as agreed upon by component supplier and purchaser.

11.3 In accordance with Terminology 52921, specimens used for tension testing shall be machined from bulk deposition or near net shape bars and built in *X*, *Y*, *Z*, orientation.

NOTE 3—Mechanical properties of the test specimens may vary because of the location of the sample on the build platform and the test specimen orientation. Whether or not the test specimens are near net shape or machined from larger blocks is a matter of preference.

11.4 Tensile properties on test specimens shall conform to Table 3, as determined in accordance with Test Method E8/E8M at a strain rate of 0.003 to 0.007 mm/mm/min through yield and then the crosshead speed may be increased so as to produce failure in approximately one additional minute.

12. Thermal Processing

12.1 When required, Class A and F components shall be stress relieved or annealed as agreed between component supplier and purchaser. Stress relief is optional for all other classifications.

NOTE 4—Stress relief is typically performed while the components are attached to the build platform. AMS2801 and SAE H81200B provide stress relief guidance. some residual stress may remain depending on the stress relief processing. Components manufactured on some powder bed fusion machines may not require a stress relief procedure.

TABLE 3 Minimum Tensile Properties[A]

Room Temperature	Tensile Strength MPa *X* and *Y* Directions	Tensile Strength MPA Z Direction	Yield Strength at 0.2 % Offset MPa *X* and *Y* Directions	Yield Strength at 0.2 % Offset MPa *Z* Direction	Elongation in 5 cm or 4D (%) *X* and *Y* Direction	Elongation in 5 cm or 4D (%) *Z* Direction	Reduced Area *X* and *Y* Direction	Reduced Area Z Direction
Classification								
A, B, C, D	895	895	825	825	10	10	15	15
E	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement
F	895	895	825	825	6	6	15	15

[A] A gauge length corresponding to ISO 6892 may be used when agreed upon between supplier and purchaser (5.65 times the square root of S0, where S0 is the original cross-sectional area).

12.2 Class B components shall be annealed per AMS2801 or AMSH81200. Other classifications may be annealed as agreed between component supplier and purchaser.

12.3 Class D components shall be solution heat treated and aged per AMS2801, except that components shall be inert gas back-fill cooled or air cooled during the solution heat treat process.

13. Hot Isostatic Pressing

13.1 Hot Isostatic Pressing (HIP) is required for Class C components and optional for all other classifications.

13.1.1 Process components under inert atmosphere at not less than 100 MPa within the range 895 to 955°C; hold at the selected temperature within ±15°C for 180 ± 60 min, and cool under inert atmosphere to below 425°C.

14. Dimensions and Permissible Variations

14.1 Tolerances on as-built components shall be agreed upon by the component supplier and purchaser.

14.2 As-built components may be machined to meet dimensional requirements.

14.3 Component repair by welding shall be approved by the purchaser.

15. Retests

15.1 If the results of any chemical or mechanical property test or any inspection method, including Supplementary Requirements S1-S10, on a component are not in conformance with the requirements of this specification, the component may be retested at the option of the manufacturer.

15.1.1 The frequency of the retest will be double the initial number of tests. If the results of the retest conform to the requirement, then the retest values will become the test values for certification.

15.2 All test results including the original test results and the conforming retest results shall be reported to the purchaser.

15.3 If any of the results for the retest fail to conform to this specification, the material shall be rejected in accordance with Section 17.

16. Inspection

16.1 Inspection criteria shall be agreed upon by the component supplier and purchaser.

17. Rejection

17.1 Components not conforming to this specification, or modifications to this specification that are not authorized by purchaser, will be subject to rejection.

17.2 All rejected components shall be quarantined and reported to the component purchaser.

18. Certification

18.1 A certificate, including a complete test report, shall be provided by the component supplier at the time of shipment stating that the components were manufactured and tested in accordance with this specification.

18.2 If the component supplier and purchaser are one and the same, equivalent internal documentation shall be acceptable in lieu of certification.

19. Product Marking and Packaging

19.1 Each component shall be identified as agreed upon between the component supplier and purchaser.

19.2 Unless otherwise specified, components purchased under this specification shall be packaged in accordance with the manufacturer's standard practice or Practice D3951.

20. Quality Program Requirements

20.1 The component supplier and its metal powder supplier shall maintain a quality program as defined in ASQ C1 or other recognized quality management systems such as ISO 9001, AS9100, or ISO 13485 for Class A, B, C, D and F components.

NOTE 5—To ensure full component and feedstock traceability, the component purchaser should require the component supplier to use and maintain a comprehensive manufacturing control system except for Class E components. What constitutes a comprehensive manufacturing control system shall be agreed upon between component supplier and purchaser.

21. Significance of Numerical Limits

21.1 All observed or calculated values shall be rounded to the nearest unit in the last right hand digit used in expressing the specification limit, in accordance with the rounding method of Practice E29.

22. Keywords

22.1 additive manufacturing; electron beam melting; metal laser sintering; selective laser melting

SUPPLEMENTARY REQUIREMENTS

S1. Furnace Anneal

Furnace anneal shall be performed to specifications as agreed between the component supplier and purchaser.

S2. Liquid Penetrant

S2.1 Testing shall be performed on components surfaces after machining only.

S2.2 Fluorescent penetrant inspection in accordance with Practice E1417 with the sensitivity level agreed by the component supplier and purchaser shall be performed on all compnents.

S3. Radiographic Examination

Components shall be subject to radiographic examination in accordance with Practice F629. Acceptance criteria and sampling plan other than 100 % inspection shall be agreed upon between component supplier and purchaser.

S4. Hardness Test

Hardness tests shall be performed in accordance with the requirements of Test Method E10 or Test Methods E18 as agreed upon by component supplier and purchaser.

S5. Fracture Toughness

Static fracture toughness shall be tested in accordance with Test Method E399 or Test Method E1820. Dynamic fracture toughness shall be tested in accordance with Test Methods E23. Use of other relevant methods requires prior agreement between the component supplier and purchaser.

S6. Fatigue Testing

It is recommended that users evaluate fatigue properties for powder bed fusion components that experience dynamic load in service. Fatigue testing shall be in accordance with Practice E466, Practice E606, or other relevant methods and performed as agreed between the component supplier and purchaser.

S7. Feedstock Flow Rate

In powder bed fusion machines, the feedstock should have a flow rate that is optimized for each process. The powder flow rate shall be measured in accordance with Test Methods B964 or Test Method B213.

NOTE 6—Physical characteristics such as interparticle friction and particle size of Titanium-6 Aluminum-4 Vanadium powder can vary significantly depending upon the process used to produce the powder. These physical variations subsequently lead to variations in powder flow characteristics. These powder flow variations can be critical in additive manufacturing powder bed fusion machines, and if not addressed properly, may lead to defects such as porosity in the components. Thus, changes in feedstock vendors may require revalidation of the process.

S8. Component Density

Component density shall be measured in accordance with Test Method B311.

S9. Contamination from Powder Distribution System

The powder distribution system should be non-contaminating to the feedstock for Class A, B, C, D and F components. What constitutes non-contaminating shall be agreed upon between the component supplier and purchaser.

S10. Surface Finish

As built surface finish can vary significantly depending on process, machine, and material parameters and orientation. Surface finish should be agreed upon between component supplier and purchaser as measured in accordance with ASME B46.1 or other relevant methods.

S11. Compression

Compression shall be tested in accordance with Test Method E9.

S12. Shear

Shear shall be tested in accordance with Test Method B769.

S13. Bearing

Pin-Type bearing shall be tested in accordance with Test Method E238.

S14. Crack Growth

Crack growth shall be determined by Test Method E647 or as agreed between the component supplier and purchaser.

S15. Other Supplemental Requirements

Other tests may be performed on components as agreed upon between the component supplier and purchaser.

S16. Quality Assurance

S16.1 When specified in the purchase order or contract:

S16.1.1 The components as received by the purchaser shall meet engineering tolerances and notes and other requirements of the purchase order.

S16.1.2 Components shall be free from cracks, defects, discontinuities, foreign material, inclusions, imperfections, and porosity detrimental to the usage of the component.

S16.1.3 When agreed upon between the component supplier and purchaser, a first-article inspection shall be performed on one component for each part number.

S16.1.3.1 Multiple components may be included in a first-article production run.

S16.1.3.2 The first-article inspection shall include verification of the requirements of the engineering drawing and all test results.

S16.1.4 Manufacturing lot inspection shall be performed in accordance with the manufacturing plan. Inspection criteria shall be agreed upon between the component supplier and purchaser.

S16.1.5 The inspection and sequence of operations shall be carried out as listed in the manufacturing plan.

S16.1.6 Manufacturing lots rejected on the basis of a sampling plan, regardless of the inspection method, may be resubmitted for 100 % inspection and unacceptable components removed from the lot.

S16.1.7 Individual component rejection shall apply in those instances in which 100 % inspection is required in the manufacturing plan and any individual component fails an inspection method. Only unacceptable components need to be rejected when the balance of the components in the manufacturing lot meet inspection requirements.

APPENDIX

(Nonmandatory Information)

X1. ADDITIVE MANUFACTURING OF METALS WITH POWDER BED FUSION

X1.1 Commercially available full-melt, powder bed additive manufacturing systems have two main heat sources: laser and electron beam. Although both heat sources produce titanium-6 aluminum-4 vanadium (Ti-6Al-4V) components with nearly no porosity and good mechanical properties, the technologies differ significantly in their implementation, which upon examination can show differences in microstructure and the need for furnace annealing. The purchaser should be educated as to the differences in the processes and enforce supplemental requirements where appropriate.

X1.2 The commercially available powder bed fusion systems that fully melt metal powders to create components are machines that typically allow the operator much latitude in terms of process parameters. Adjustments by the operator or from other sources to the process parameters can have a dramatic effect on surface finish, internal porosity, mechanical properties, and chemistry. Therefore, the manufacturing control system will contain safeguards to prevent changes of the validated digital component files and of the process parameters and track the planned versus real process parameters. It is also a recommendation that Class A, B, C, D and F components have tension test specimens built and tested as part of the machine validation process. Components built with a robust manufacturing plan are likely to have similar properties to the test specimens. Additionally, this specification allows the purchaser to require tension test samples to be included with each component build cycle; however, this requirement should only be enforced when lot testing is not adequate or when each process cycle has significantly different components in terms of geometry.

X1.3 Suppliers of Ti-6Al-4V powder bed fusion components should use a validated, fixed process that takes into account and minimizes machine to machine and operator variability. The supplier and purchaser should agree upon what constitutes a validated process and ensure the manufacturing plan is accurate, comprehensive, adequate, monitored and continuously recorded for the components being procured.

X1.4 In order for this standard to be accepted internationally, ISO and ASTM reference standards were cited where applicable. In 2012, the National Institute of Standards and Technology (NIST) published an internal report, NISTIR 7847, called Mechanical Properties Testing for Metal Parts Made via Additive Manufacturing: A Review of the State of the Art of Mechanical Property Testing. In this internal report, the authors compared ISO and ASTM testing methods for determining properties of metal materials. The following chart shows the equivalent and significantly similar test methods between ISO and ASTM as determined by IR 7847. Care should be taken when substituting test methodology and there should be agreement between component supplier and purchaser on all test methods.

Comparison of Similar ASTM and ISO Test Methods for Metals

ASTM Specification	ISO Specification	Notes
E8/E8M	6892-1	tension test 10°C–38°C
E21	6892-2	tension test > 38°C
E1450	19819	tension test <(–196°C)
E10	6506-1	Brinell hardness 10°C–35°C
E18	6508	Rockwell B, C hardness
E384	4545-1	Knoop Hardness
E384	6507-1	Vickers Hardness
E606	1099	fatigue test 10°C–35°C, strain controlled
E647	12108	crack growth
E2368	12111	fatigue, thermomechanical, strain controlled
E399	12737	fracture toughness, plane-strain
E1820	12135	fracture toughness
E23	148-1	Charpy and Izod tests