**Designation: ~~F2924 − 12~~ F2924 − 12a**

# 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-S11.~~S1-S12.

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
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
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
E384 Test Method for Knoop and Vickers Hardness of Materials

[1] This specification is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.05 on Materials and Processes.

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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.

E399 Test Method for Linear-Elastic Plane-Strain Fracture Toughness $K_{Ic}$ of Metallic Materials
E407 Practice for Microetching Metals and Alloys
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 Practice for Strain-Controlled Fatigue Testing
E647 Test Method for Measurement of Fatigue Crack Growth Rates
E1304 Test Method for Plane-Strain (Chevron-Notch) Fracture Toughness of Metallic Materials
E1409 Test Method for Determination of Oxygen and Nitrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Technique
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 Atomic Emission Plasma Spectrometry
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
F2921 Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies

2.2 *ASQ Standard:*[3]
ASQ C1 Specifications of General Requirements for a Quality Program

2.3 *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~~Purposes
ISO 19819 Metallic materials—Tensile testing in liquid helium

2.4 *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

2.5 *ASME Standards:*[6]
ASME B46.1 Surface Texture



[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.

2.6 *National Institute of Standards and Technology*[7]
IR 7847 (March 2012) CODEN: NTNOEF

## 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 *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.

3.1.4 *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.

3.1.5 *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.

[7] SLM is a registered trademark of Realizer GmbH, SLM Solutions GmbH and Renishaw plc. DMLS is a trademark of EOS GmbH. EBM is a registered trademark of Arcam AB, Molndal, Sweden.Available from National Institute of Standards and Technology (NIST), 100 Bureau Dr., Stop 1070, Gaithersburg, MD 20899-1070, http://www.nist.gov.

3.1.5.1 *Discussion—*

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

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



3.1.6.1 *Discussion—*

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

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



3.1.7.1 *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 of know as selective laser melting (SLM®), direct melting, metal laser sintering (DMLS™), LaserCUSING, sintering, and electron beam melting (EBM®).melting.

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

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

3.1.9.1 *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.

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

3.1.11 *used powder, n*—powder from a powder blend or powder lot containing some portion of powder that has been processed in at least one previous build cycle.

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

3.2 Terminology relating to titanium microstructure in AS1814 shall applyapply.

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

3.4 Terminology relating to coordinate systems in Terminology F2921 shall apply.

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

## 4. Classification

4.1 ~~Components manufactured to Class 1 requirements are often used for, but not limited to, safety critical and structural components where hot isostatic press is not required.~~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.

~~4.2 Components manufactured to Class 2 requirements are often used for, but not limited to, safety critical and structural components.~~

~~4.3 Components manufactured to Class 3 requirements are often used for, but not limited to, performance critical components.~~

~~4.4 Components manufactured to Class 4 requirements are typically concept models and prototype parts.~~

## 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 ~~inch-pounds~~SAE units,

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 ~~(S12),~~(S11),

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 ~~1, Class 2 and Class 3~~ 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;

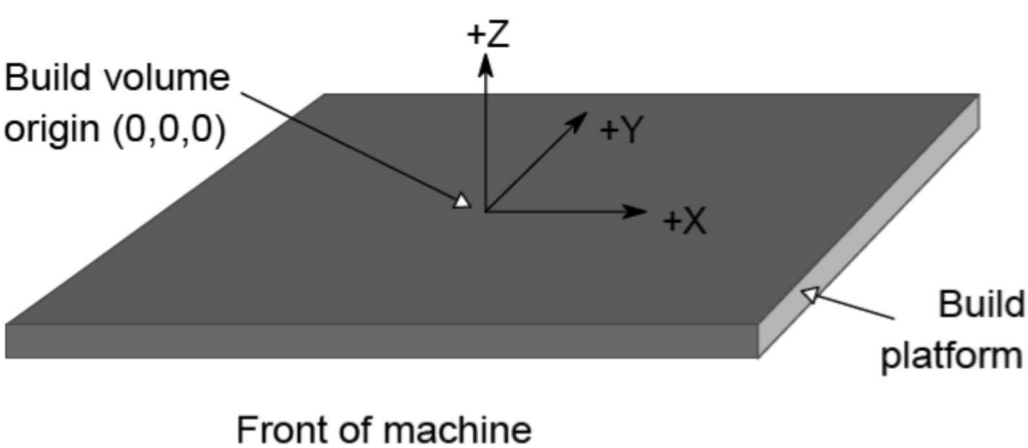


FIG. 1 Build Platform Coordinates for Test Specimens (for reference only)

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 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.

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 ~~1 and Class 2 components.~~ A, B, C, D, and F. There are no limits on the number of build cycles for used powder for Class ~~3 and Class 4~~ 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 ~~1, Class 2 or Class 3~~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 ~~Class1, Class 2 and Class 3~~ 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.

**TABLE 1 Composition**

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

7.7 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.

## 8. Process

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

8.1.1 ~~For components meeting Class 1 and Class 2 properties, test~~ Test specimens for quality assurance may be ~~required to 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.

~~8.1.2 For components meeting Class 3 properties, test specimens for quality assurance may be required to be built and tested in accordance with Section 11 before and after a production run or manufacturing lot as agreed upon between the component supplier and purchaser.~~

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 ~~1, Class 2 and Class 3~~ A, B, C, D and F components.

## 9. Chemical Composition

9.1 ~~As-built~~ 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.

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.

**TABLE 2 Check Analysis Tolerances**

| Element | Permissible Variation in Check Analysis |
|---|---|
| Aluminum | ±0.40 |
| Vanadium | ±0.15 |
| ~~Iron~~ | ~~±0.15~~ |
| Iron | ±0.10 |
| ~~Oxygen~~ | ~~±0.08~~ |
| Oxygen | ±0.02 |
| Carbon | ±0.02 |
| Nitrogen | ±0.02 |
| ~~Hydrogen~~ | ~~±0.003~~ |
| Hydrogen | ±0.002 |
| Yttrium | ±0.0006 |
| Other Elements, each | ±0.02 |