



# Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion<sup>1</sup>

This standard is issued under the fixed designation F3001; 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 ( $\epsilon$ ) indicates an editorial change since the last revision or reapproval.

## 1. Scope

1.1 This specification covers additively manufactured titanium-6aluminum-4vanadium with extra low interstitials (Ti-6Al-4V ELI) 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 ELI 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-S4 and S1-S16 in Specification F2924.

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

## 2. Referenced Documents

### 2.1 ASTM Standards:<sup>2</sup>

**B214** Test Method for Sieve Analysis of Metal Powders

<sup>1</sup> 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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<sup>2</sup> 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.

- B243** Terminology of Powder Metallurgy
- B600** Guide for Descaling and Cleaning Titanium and Titanium Alloy Surfaces
- B769** Test Method for Shear Testing of Aluminum Alloys
- 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
- E11** Specification for Woven Wire Test Sieve Cloth and Test Sieves
- 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
- E407** Practice for Microetching Metals and Alloys
- E539** Test Method for Analysis of Titanium Alloys by X-Ray Fluorescence Spectrometry
- E1409** Test Method for Determination of Oxygen and Nitrogen in Titanium and Titanium Alloys by Inert Gas Fusion
- E1447** Test Method for Determination of Hydrogen in Titanium and Titanium Alloys by Inert Gas Fusion Thermal Conductivity/Infrared Detection Method
- 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
- 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)
- F136** Specification for Wrought Titanium-6Aluminum-4Vanadium ELI (Extra Low Interstitial) Alloy for Surgical Implant Applications (UNS R56401)
- F2792** Terminology for Additive Manufacturing Technologies
- F2924** Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
- 2.2 *ISO/ASTM Standards:*<sup>2</sup>
- 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*:<sup>3</sup>

**ASQ C1 Specification of General Requirements for a Quality Program**

2.4 *ISO Standards*:<sup>4</sup>

**ISO 5832-3 Implants for Surgery—Metallic Materials—Part 3: Wrought Titanium 6-Aluminum 4-Vanadium Alloy Third Edition**

**ISO 6892 Metallic Materials—Tensile Testing at Ambient Temperature**

**ISO 9001 Quality Management System—Requirements**

**ISO 9044 Industrial Woven Wire Cloth – Technical Requirements and Testing**

**ISO 13485 Medical devices—Quality management systems—Requirements for regulatory purposes**

2.5 *SAE Standards*:<sup>5</sup>

**AMS 2249 Chemical Check Analysis Limits Titanium and Titanium Alloys**

**AMS 2801 Heat Treat of Titanium Alloys**

**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**

### 3. Terminology

3.1 Terminology relating to titanium microstructure in AS1814 shall apply.

3.2 Terminology relating to additive manufacturing in Terminology **F2792** shall apply.

3.3 Terminology relating to coordinate systems in Terminology **52921** shall apply.

3.4 Terminology relating to powder metallurgy in Terminology **B243** shall apply.

3.5 Terminology relating to powder bed fusion in Specification **F2924** shall apply.

### 4. Classification

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

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 post processing shall be optional.

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

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

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

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 (S11 in **F2924**),

5.1.10 Post-processing sequence of operations,

5.1.11 Thermal processing,

5.1.12 Allowable porosity (S8 in **F2924**),

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 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;

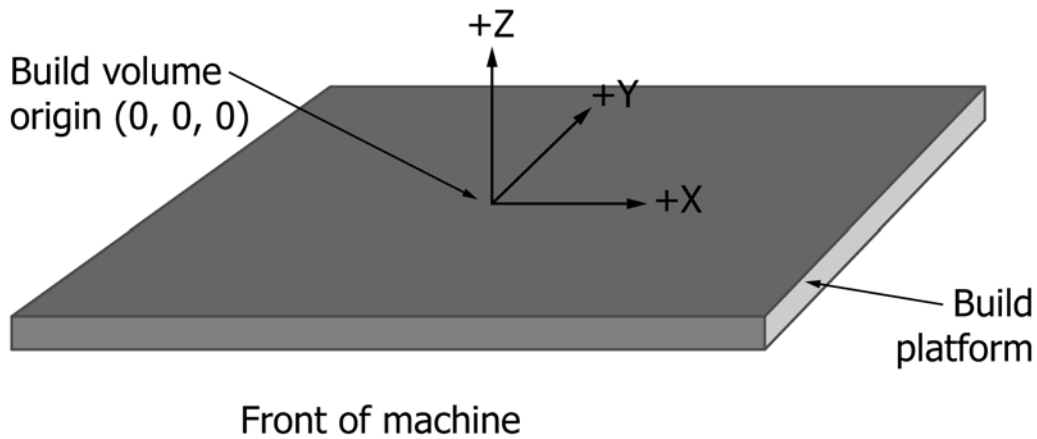


FIG. 1 Build Platform Coordinates for Test Specimens (for reference only)

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 acceptable 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 meets 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 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 the 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.

TABLE 1 Composition

Element	min	max
Aluminum	5.50	6.50
Vanadium	3.50	4.50
Iron	...	0.25
Oxygen	...	0.13
Carbon	...	0.08
Nitrogen	...	0.05
Hydrogen	...	0.012
Yttrium	...	0.005
Other elements, each	...	0.10
Other elements, total	...	0.40
Titanium	remainder	

## 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 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 of F2924.

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 re-qualification.

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 AMS 2249 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 227 6Al 4V ELI components

is the same as Specification F136 and ISO 5832-3 for wrought alloy except that the concentration of yttrium is controlled in this specification.

## 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 de-scaled 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 Methods E8/E8M either before or after thermal processing as agreed upon by component supplier and purchaser.

11.3 In accordance with ISO/ASTM 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 Methods E8/E8M at a strain rate of 0.003 to 0.007 mm/mm/min through yield and then the cross-head 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. AMS 2801 and SAE H81200 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.

12.2 Class B components shall be annealed per AMS 2801 or AMSH81200. Other classifications may be annealed as agreed between component supplier and purchaser.

**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

**TABLE 3 Minimum Tensile Properties<sup>A</sup>**

Room Temperature Classification	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
A, B, C, D	860	860	795	795	10	10	25	25
E	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement	no requirement
F	825	825	760	760	8	8	20	20

<sup>A</sup> A gauge length corresponding to ISO 6892 may be used when agreed upon between supplier and purchaser (5.65 times the square root of S<sub>0</sub>, where S<sub>0</sub> is the original cross-sectional area).

12.3 Class D components shall be solution heat treated and aged per AMS 2801, 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 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  $\pm 15^\circ\text{C}$  for  $180 \pm 60$  min, and cool under inert atmosphere to below 425°C.

### 14. Dimensions, Mass, 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 S1-S4 and S1-S10 of **F2924**, 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 the 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, AS 9100, 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. Supplementary requirements from **F2924** shall apply.

**S2. 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.

**S3. Other Supplemental Requirements—**Other tests may be performed on components as agreed upon between the component supplier and purchaser.

**S4. Quality Assurance**

S4.1 When specified in the purchase order or contract:

S4.1.1 The components as received by the purchaser shall meet engineering tolerances and notes and other requirements of the purchaser order.

S4.1.2 Components shall be free from cracks, defects, discontinuities, foreign material, inclusions, imperfections, and porosity detrimental to the usage of the component.

S4.1.3 When agreed upon between the component supplier and purchaser, a first-article inspection shall be performed on one component for each part number.

S4.1.3.1 Multiple components may be included in a first-article production run.

S4.1.3.2 The first-article inspection shall include verification of the requirements of the engineering drawing and all test results.

S4.1.4 Manufacturing lot inspection shall be performed in accordance with the manufacturing plan. Inspection criteria shall be agreed upon between the component supplier and purchaser.

S4.1.5 The inspection and sequence of operations shall be carried out as listed in the manufacturing plan.

S4.1.6 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.

S4.1.7 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.

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