SAE Aerospace
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AEROSPACE MATERIAL SPECIFICATION

SAE AMS4999 | REV. A

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Superseded by AMS4999

Titanium Alloy Direct Deposited Products 6Al - 4V Annealed

RATIONALE

AMS4999A is a Five Year Review and update of this specification and includes the addition of direct metal deposition.

1. SCOPE

1.1 Form

This specification covers metal products fabricated by direct metal deposition.

1.2 Application

This product has been used typically for machining and forging preforms in applications that require static mechanical properties similar to wrought mill and recrystallized annealed products, but usage is not limited to such applications.

2. APPLICABLE DOCUMENTS

The issue of the following documents in effect on the date of the purchase order forms a part of this specification to the extent specified herein. The vendor may work to a subsequent revision of a document unless a specific document issue is specified. When the referenced document has been cancelled and no superseding document has been specified, the last published issue of that document shall apply.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AMS2249 Chemical Check Analysis Limits, Titanium and Titanium Alloys

AMS2631 Titanium and Titanium Alloy Bar and Billet, Ultrasonic Inspection

AMS2750 Pyrometry

AMS4911 Titanium Alloy, Sheet, Strip, and Plate, 6Al 4V, Annealed

AMS4928 Titanium Alloy Bars, Wire, Forgings, Rings, and Drawn Shapes, 6Al - 4V, Annealed

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SAE values your input. To provide feedback on this Technical Report, please visit
http://www.sae.org/technical/standards/AMS4999A

AMS4992 Castings, Structural Investment, Titanium Alloy 6Al 4V Hot Isostatically Pressed

AMS4998 Titanium Alloy Powder, 6Al 4V

AMS6945 Titanium Alloy, Single Melt, Sheet, Strip, and Plate, 6Al - 4V, Annealed

2.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM E 8 / E8M Tension Testing of Metallic Materials

ASTM E 399 Plane-Strain Fracture Toughness of Metallic Materials

ASTM E 539 Linear-Elastic X-Ray Emission Spectrometric Analysis of 6Al-4V Titanium Alloy

ASTM E 606 Strain-Controlled Fatigue Testing

ASTM E 1304 Plane-Strain (Chevron-Notch) Fracture Toughness of Metallic Materials

ASTM E 1409 Determination of Oxygen and Nitrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Technique

ASTM E 1447 Determination of Hydrogen in Titanium and Titanium Alloys by the Inert Gas Fusion Thermal Conductivity/Infrared Detection Method

ASTM E 1742 Radiographic Examination

ASTM E 1941 Determination of Carbon in Refractory and Reactive Metals and Their Alloys by Combustion Analysis

ASTM E 2371 Analysis of Titanium and Titanium Alloys by Atomic Emission Plasma Spectrometry

2.3 AWS Publications

Available from American Welding Society, 550 N. W. LeJune Road, Miami, FL 33126, www.aws.org.

AWS A5.16 Titanium and Titanium-Alloy Welding Electrodes and Rods

3. TECHNICAL REQUIREMENTS

3.1 Composition

Shall conform to the percentages by weight shown in Table 1; carbon shall be determined in accordance with ASTM E 1941, hydrogen in accordance with ASTM E 1447, oxygen and nitrogen in accordance with ASTM E 1409, and other elements in accordance with ASTM E 539 or ASTM E 2371. Other analytical methods may be used if acceptable to the purchaser.

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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
Nitrogen	--	0.05 (500 ppm)
Hydrogen	--	0.015 (150 ppm)
Yttrium (3.1.1)	--	0.005 (50 ppm)
Other Elements, each (3.1.1)	--	0.10
Other Elements, total (3.1.1)	--	0.40
Titanium	remainder	

3.1.1 Determination not required for routine acceptance.

3.1.2 Check Analysis

Composition variations shall meet the applicable requirements of AMS2249.

3.2 Processing

3.2.1 Feedstock

The feedstock for the direct metal deposition process shall be either wire conforming to AWS A5.16 ERTi-5 (Al content up to 7.5% is allowed, and a minimum of 1400 ppm oxygen) or powder conforming to AMS4998 except that powder compaction and evaluation provisions do not apply, and the minimum oxygen content shall be 1400 ppm.

3.2.1.1 The feedstock shall be free from inclusions, impurities, and the chemistry of the feedstock shall be adequate to yield, after processing, the final material chemistry outlined in Table 1.

3.3 Deposition Practice

3.3.1 Deposition shall be conducted in an atmosphere of vacuum or in argon and/or helium. The oxygen content shall not exceed 1200 ppm (equivalent) at any time during the deposition operation. The oxygen content shall be dynamically monitored throughout the deposition operation. Sufficient energy shall be present to completely fuse the deposit with the substrate and/or previous and adjacent passes.

3.3.2 Feedstock shall be deposited on a target plate conforming to AMS4911, AMS4928, AMS4992, or AMS6945.

3.4 Condition

Annealed.

3.5 Thermal Processing

Direct metal deposited products shall be annealed using one or a combination of the following thermal cycles. Intermediate stress relief treatments shall be performed at temperatures below 1025 °F (550 °C) if further deposition is to be performed. Intermediate stress relief treatments shall be performed at temperatures below 1225 °F (663 °C) if no further deposition is to be performed. Pyrometry shall be in accordance with AMS2750.

3.5.1 Hot Isostatic Pressing

Process at not less than 14.5 ksi (100 MPa) within the range 1650 to 1750 °F (899 to 954 °C), hold at the selected temperature within ±25 °F (±14 °C) for 2 to 4 hours, and cool under inert atmosphere in the autoclave to below 800 °F (427 °C).

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3.5.2 Furnace Anneal

Process direct metal deposited products by heating under vacuum or in argon and/or helium to a temperature within the range of 1650 to 1700 °F (899 to 927 °C), holding at the selected temperature within ±25 °F (±14 °C) for 2 to 4 hours and gas cool to below 800 °F (427 °C) using argon and/or helium.

3.5.2.1 Heat treatment may be performed in air provided the oxygen and nitrogen contaminated region is fully removed chemically or by machining.

3.5.3 Following processing to 3.5.1 and/or 3.5.2, parts shall be aged by heating the product to 1000 °F ± 25 (538 °C ± 14) for 4 hours ± 0.25 in an inert, vacuum or air atmosphere followed by an air or furnace cool.

3.6 Properties

The product shall conform to the following requirements:

3.6.1 Tensile Properties

Shall be as specified in Table 2, determined in accordance with ASTM E 8 / E 8M on specimens as in 4.3.1.2 with the rate of strain set at 0.005 inch/inch/minute (0.005 mm/mm/minute) and maintained within a tolerance of ±0.002 inch/inch/minute (0.002 mm/mm/minute) through the 0.2% offset yield strain. Tensile property requirements must be met within the direct metal deposit and across the direct metal deposit/substrate interface.

TABLE 2A - MINIMUM TENSILE PROPERTIES, INCH/POUND UNITS

Nominal Diameter or Least Distance Between Parallel Sides Inches	Tensile Strength ksi X and Y Directions	Tensile Strength ksi Z Direction	Yield Strength At 0.2% Offset ksi X and Y Directions	Yield Strength At 0.2% Offset ksi Z Direction	Elongation in 2 Inches or 4D % X and Y Directions	Elongation in 2 Inches or 4D % Z Direction
Up to 6.000, incl	129	124	116	111	6	5

TABLE 2B - MINIMUM TENSILE PROPERTIES, SI UNITS

Nominal Diameter or Least Distance Between Parallel Sides Millimeters	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 2 Inches or 4D % X and Y Directions	Elongation in 2 Inches or 4D % Z Direction
Up to152.4, incl	889	855	799	765	6	5

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3.6.1.1 Specimen orientation is defined in Figure 1. When specified by purchaser, the tensile specimen oriented in the "Z" direction shall include the substrate-to-deposit interface.

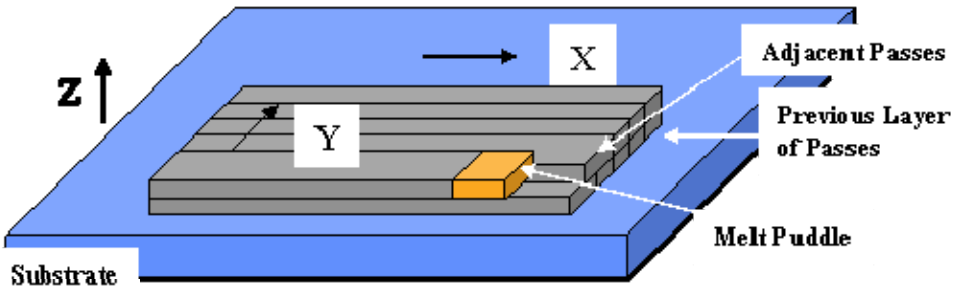

FIGURE 1 - SPECIMEN ORIENTATION

3.6.2 Microstructure

Shall be a transformed structure of acicular alpha in a beta matrix in the deposit and heat affected zone.

3.6.2.1 Columnar grain structure in the deposit area is acceptable if the mechanical properties in Table 2 are met.

3.6.3 Surface Contamination

Alpha case, or other surface contamination, is acceptable for preforms to be machined all over provided such layer is removable within the machining allowance on the preform.

3.6.4 Fracture Toughness

Shall be a minimum K_{IVM} of 75 ksi-in^{½} when tested in accordance with ASTM E 1304, or a minimum K_{Ic} of 60 ksi-in^{½} when tested in accordance with ASTM E 399.

3.7 Quality

The product, as received by purchaser, shall be uniform in quality and condition, sound, and free from foreign materials, imperfections, and porosity detrimental to usage of the product.

3.7.1 Deposits, including the substrate, 0.500 to 4.0 inches (6.25 to 102 mm), exclusive, in the Z direction, shall be ultrasonically inspected in accordance with AMS2631, shall meet Class A1 requirements to AMS2631.

3.7.2 Deposits 0.500 to 4.0 inches (6.25 to 102 mm), exclusive, in the Z direction, shall be ultrasonically inspected in accordance with AMS2631, shall meet Class A1 requirements to AMS2631.

3.7.3 Deposits 4.0 to 6.0 inches (102 to 152 mm), inclusive, in the Z direction, shall be ultrasonically inspected in accordance with AMS2631, shall meet Class A requirements to AMS2631.

3.7.4 Deposits, after intermediate or finish machining, shall be radiographically inspected in accordance with ASTM E 1742, shall be meet the requirements of Table 3.

TABLE 3 - RADIOGRAPHIC INSPECTION ACCEPTANCE CRITERIA

Imperfection	Acceptance Criteria
Subsurface Porosity and Inclusions Individual Size, Maximum	0.33T or 0.060 inch (1.52 mm), whichever is less
Subsurface Porosity and Inclusions Spacing, Maximum	4 times the size of the larger adjacent imperfection
Subsurface Porosity and Inclusions Accumulated Length in any 3 inches (76.2 mm) of Deposit	1.33T or 0.24 inch (6.10 mm), whichever is less.
Incomplete Fusion	None allowed
Cracks	None allowed

T is the thickness of the machined part detail

3.8 Tolerances

3.8.1 Machining Preforms

Machining and hybrid preforms shall have a minimum allowance of +0.030 inch (0.76 mm) for machining to the desired net shape. Forging preforms shall have an allowance agreed to by the vendor and purchaser.

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3.8.2 Net Shape Features

Shall have tolerances mutually agreed to by the vendor and purchaser.

4. QUALITY ASSURANCE PROVISIONS

4.1 Responsibility for Inspection

The vendor of the product shall supply all samples for vendor's test and shall be responsible for the performance of all required tests. Purchaser reserves the right to sample and to perform any confirmatory testing deemed necessary to ensure that the product conforms to specified requirements.

4.2 Classification of Tests

4.2.1 Acceptance Tests

The following requirements are acceptance tests and shall be performed on each direct metal deposition production run as applicable (See 8.3).

4.2.1.1 Composition (3.1) of each direct metal deposition production run.

4.2.1.2 Tensile properties (3.6.1), microstructure (3.6.2), and surface contamination (3.6.3) of each direct metal deposition production run.

4.2.1.3 Fracture toughness (3.6.4) of each preform, when specified by purchaser

4.2.1.4 Ultrasonic quality (3.7) of the deposit in each preform

4.2.1.5 Radiographic quality (3.7) of the deposit in each preform

4.2.1.6 Tolerances (3.8) of each preform.

4.3 Sampling and Testing

Shall be in accordance with the following (See 8.3.1 for production run definition):

4.3.1 For Acceptance Tests

4.3.1.1 Composition

One sample from each direct metal deposition production run, except that for hydrogen and oxygen determinations one sample from each run obtained after thermal and chemical processing is completed.

4.3.1.2 Mechanical Properties

Unless otherwise specified, at least one specimen in both the X and Z directions shall be tested from each run. When specified by purchaser, one fracture toughness specimen of orientation specified by the purchaser shall be tested

4.3.1.3 Microstructure and Surface Contamination

At least one sample from each direct metal deposition production run.

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4.3.1.4 Ultrasonic Quality

Complete inspection of deposit in the Z-direction on each perform. Note that this may be postponed until after machining when agreed to by vendor and purchaser. This shall be performed prior to any hot isostatic pressing.

4.3.1.5 Radiographic Quality

4.3.1.5.1 All preproduction and qualification articles after intermediate or final machining. This shall be performed prior to any hot isostatic pressing.

4.3.1.5.2 First five production lots after intermediate or final machining.

4.3.1.5.3 Five production lots after radiographic failure and corrective action.

4.3.1.5.4 Five production lots after any change in the fixed process

4.4 Reports

The vendor of direct metal deposited products shall furnish with each shipment a report showing the results of tests for composition for each direct metal deposition production run and for the hydrogen and oxygen content and mechanical properties of each direct metal deposition production run, and stating that the product conforms to all other technical requirements and has been fabricated to an approved schedule listing the parameters used in producing the parts. This report shall include the purchase order number, direct metal deposition production run number(s), AMS4999A size or part number, specific heat treatment used, and quantity.

4.5 Resampling and Retesting

If any specimen used in the above tests fails to meet the specified requirements, disposition of the product may be based on the results of testing three additional specimens for each original non-conforming specimen. Failure of any retest specimen to meet the specified requirements shall be cause for rejection of the product represented. Results of all tests shall be reported.

4.6 Approval of Processes and Vendors

All processes (energy source, energy range, feedstock, feed method, atmosphere, deposition path generation, powder supply) and vendors shall be approved by the purchaser prior to producing preproduction hardware. At least three different configurations agreed upon by purchaser and vendor fabricated by direct metal deposition from at least three different feedstock heats, with a minimum of fifty test results from each direction shall be submitted for source qualification. Each of the qualification parts shall meet all quality requirements of this specification. The submitted tensile results shall meet the requirements of Table 4. While multiple powder types (Rotating Electrode Process (REP), Gas Atomized, Hydride-DeHydride, etc.) may be used in a single approval; process approval shall be repeated if a new powder type is introduced.

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TABLE 4A - PROCESS APPROVAL TENSILE PROPERTIES, INCH/POUND UNITS

Property and Direction	Maximum Coefficient of Variation, Percent	Individual, Minimum, ksi
Ultimate Tensile Strength		
X and Y	3.3	130
Z	3.3	125
Tensile Yield Strength		
X and Y	3.1	116
Z	3.1	110
Total Elongation, Percent	-	
All Directions		6

TABLE 4B - PROCESS APPROVAL TENSILE PROPERTIES, SI UNITS

Property and Direction	Maximum Coefficient of Variation, Percent	Individual, Minimum, MPa
Ultimate Tensile Strength		
X and Y	3.3	896
Z	3.3	855
Tensile Yield Strength		
X and Y	3.1	800
Z	3.1	758
Total Elongation, Percent	-	
All Directions		6

4.7 Approval of Deposition and Deposition/Geometry Parameters

The deposition or deposition/geometry parameters and powder process and vendor for each process shall be approved by the purchaser prior to producing preproduction hardware. Each of the parameter or parameter/approval parts shall meet all quality requirements of this specification. The different procedures are provided below: The parameter approval plan shall be prepared by the vendor and approved by the purchaser.

4.7.1 Deposition Parameters

A parameter space shall be defined for each type of build path (single-width, multiple-width, cross-hatched), that consists of the following parameters:

- Power density
- Feedstock feed rate
- Melt puddle travel speed
- Minimum time between subsquent layers for any given location
- Powder type and vendor

Sufficient parts shall be fabricated, heat treated, and inspected such that all of the proposed process extremes, and the midpoint are included in these parts. One heat of feedstock shall be used, and all parts shall be heat treated together. A minimum of six (6) Z-tensile coupons shall be extracted from each part. The tensile tests shall meet the requirements of Table 4. A minimum of three fatigue coupons shall be extracted from each deposit. Strain-life fatigue testing per ASTM E 606, R = -1, ε_{max} = 0.005 for each deposit shall meet a minimum of 8000 cycles, and a mean result of all deposits shall meet a minimum life of 15 000 cycles.

4.7.2 Deposition/Geometry Parameters

A parameter space shall be defined for each process, which consists of the following deposition parameters and geometry features:

- Power density
- Feedstock feed rate
- Melt puddle travel speed
- Minimum time between subsquent layers for any given location

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- Substrate thickness
- Deposit length
- Deposit height
- Deposit width
- Deposit angle in relation to substrate
- Build path (single, multiple, cross-hatched)
- Intersection type and direction
- Intersection angle
- Intersection Individual length, height, and width
- Minimum arc radius

Sufficient parts shall be fabricated, heat treated, and inspected such that all of the proposed process extremes are included in these parts.

4.7.2.1 Bulk Deposits

A minimum of four (4) X-tensile, four (4) Y-tensile (where applicable), and four (4) Z-tensile coupons shall be extracted from each deposit. The tensile tests shall meet the requirements of Table 4. A minimum of four (4) X-fatigue, four (4) Y-fatigue (where applicable), and four (4) Z-fatigue coupons shall be extracted from each deposit. Strain-life fatigue testing per ASTM E606, R = -1, ε_{max} = 0.005 for each deposit shall meet a minimum of 8000 cycles, and a mean result of all deposits shall meet a minimum life of 15 000 cycles.

4.7.2.2 Intersections

A minimum of four (4) X-tensile coupons shall be extracted from each intersection. The tensile tests shall meet the requirements of Table 4. A minimum of four (4) X-fatigue coupons shall be extracted from each intersection. Strain-life fatigue testing per ASTM E606, R = -1, ε_{max} = 0.005 for each intersection shall meet a minimum of 8000 cycles, and a mean result of all deposits shall meet a minimum life of 15 000 cycles.

4.8 Approval of Production Hardware

Production hardware shall be approved by fabricating and testing of at least one qualification article. The article shall meet all of the requirements of this specification. Parts made using approved Deposition/Geometry Parameters are qualified upon successful completion of all acceptance tests, including radiography, in this specification. Parts made using approved Deposition Parameters only are qualified upon successful completion of first article destructive testing in accordance with a plan prepared by the vendor and approved by the purchaser. When identical mirror image (left hand/right hand) part numbers exist, the testing of one part number will be sufficient for qualification of both parts. Tensile test results shall meet the requirements of Table 5, with a mimimum of 12 data points taken in each applicable direction. If all of the required tensile tests cannot be extracted from one part, multiple parts shall be cut up and tested to meet the requirements of Table 5.

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