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Fusion Welding Titanium and Titanium Alloys

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1. SCOPE:

1.1 Purpose:

This specification defines the procedures and requirements for fusion welding titanium and titanium alloys and the properties of such weldments.

1.2 Application:

Primarily for high-quality, fusion welding of titanium and titanium alloy components for aerospace applications. The procedure covered by this specification uses gas-tungsten-arc-welding (GTAW), gas-metal-arc-welding (GMAW), and plasma-arc-welding (PAW).

2. APPLICABLE DOCUMENTS:

The following publications form a part of this specification to the extent specified herein. The latest issue of Aerospace Material Specifications (AMS) shall apply. The applicable issue of other documents shall be as specified in AMS 2350.

2.1 SAE Publications:

Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

2.1.1 Aerospace Material Specifications:

AMS 2350	Standards and Test Methods
AMS 2631	Ultrasonic Inspection of Titanium Alloys
AMS 2635	Radiographic Inspection
AMS 2645	Fluorescent Penetrant Inspection
AMS 4901	Titanium Sheet, Strip, and Plate, Annealed, 70,000 psi (483 MPa) Yield Strength

2.2 U.S. Government Publications:

Available from Commanding Officer, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120.

2.2.1 Military Specifications:

MIL-I-6866	Inspection, Penetrant Method of
MIL-A-18455	Argon, Technical
MIL-P-27407	Propellant Pressurizing Agent, Helium
MIL-H-81200	Heat Treatment of Titanium and Titanium Alloys

2.2.2 Military Standards:

MIL-STD-453	Inspection, Radiographic
MIL-STD-794	Parts and Equipment, Procedures for Packaging and Packing of
MIL-STD-1595	Qualification of Aircraft, Missile, and Aerospace Fusion Welders

2.3 ANSI Publications:

Available from American National Standards Institute, Inc., 1430 Broadway, New York, NY 10018.

ANSI B46.1 Surface Texture

2.4 AWS Publications:

Available from American Welding Society, 2510 North West Seventh Street, Miami, FL 33125.

AWS A2.0	Welding Symbols
AWS A3.0	Welding Terms and Definitions
AWS A5.12	Tungsten Arc-Welding Electrodes

3. TECHNICAL REQUIREMENTS:

3.1 Materials:

3.1.1 Parent Materials: Shall be those titanium and titanium alloys specified on the applicable part drawing.

3.1.2 Filler Metals: Shall be as specified on the applicable part drawing. When not specified, filler metal shall be compatible with the parent metal. If filler metal is not specified for joints consisting of two or more parent metal alloys, the filler metal shall be as agreed upon by purchaser and vendor.

3.1.3 Protective Atmospheres or Environments:

3.1.3.1 Environment: Helium conforming to MIL-P-27407 or equivalent, argon conforming to MIL-A-18455 or equivalent, or a mixture of the two shall be used for shielding during the welding operations, unless a specific gas requirement is specified herein or in the approved welding schedule.

3.1.3.2 Shielding: The root and face sides of the parent metal and the weld deposit shall be adequately shielded to prevent atmospheric contamination during and after welding until the weld zone has cooled below 900 °F (480 °C).

3.1.3.2.1 The weld bead and an area not less than 1/32 in. (0.8 mm) from each side of the weld bead shall be bright silver to light straw in color on completion of each welding pass.

3.2 Equipment:

3.2.1 Welding Environment: Manual welding shall be performed in an inert atmosphere. A weld made using no filler metal on a test piece of AMS 4901 titanium shall show no discoloration of the test piece or the weld metal. The weld deposit, if analyzed, shall have an oxygen content not more than 10 ppm higher than the parent metal of the test piece and the total interstitial content of the weld shall be not more than 25 ppm higher than the parent metal of the test piece.

3.2.2 Machine Welding (Automatic and Semi-Automatic): Assemblies may be welded without fixed chambers with automatic or semi-automatic welding machines using appropriate leading and trailing inert-gas shielding devices certified by the approved welding procedure. A test bead made with the equipment and procedures defined in the approved welding procedure shall meet the requirements of 3.2.1.

3.2.3 Tooling:

3.2.3.1 Only copper tooling, either solid or water-cooled, shall be used for chilling adjacent to the weld bead.

3.2.3.2 Other metallic materials may be used for weld joint alignment tooling, providing the distance from the edge of the molten weld metal is greater than 1/8 in. (3 mm) for weldment thickness 0.125 in. (3 mm) and under, and greater than 1/4 in. (6 mm) for weldment thicknesses over 0.125 in. (3 mm).

3.2.3.3 Cadmium-plated tools and tooling shall not be used.

3.3 Welding Operator Qualification:

All welding operations shall be performed by welders who are currently qualified to perform the same type of welding on the type of titanium used in the assembly. Qualification shall be in accordance with MIL-STD-1595.

3.4 Welding Procedure, Symbols, and Definitions:

Interpretation of welding symbols and definitions shall be in accordance with AWS A2.0 and AWS A3.0, respectively.

3.4.1 Welding Schedule: A schedule shall be established for processing of each welded assembly. This schedule shall cover all significant operations and shall include, but not be limited to, the following

Parent Metal(s) - Alloys and sizes of all parts including applicable material specifications
Filler Metal - Alloy and wire sizes including applicable material specifications
Tools and Fixtures
Cleaning Procedures - pre- and post-welding
Preheating Temperature Range
Interpass Temperature Controls
Minimum Parent Metal Temperature for Welding
Protective Environment - type, nozzle positions, flow rates
Tack Welds - location, permissible size, number
Welding Schedule - equipment control settings
Post Heating - temperature range, time at heat, environment
Stress-Relieving - temperature range, time at heat, environment
Inspection Procedures and Methods
Repair Procedures (when authorized)
Final Cleaning

3.4.2 Weld Joint Qualification: Unless otherwise specified, weld joints shall be qualified and the following process control requirements shall apply:

3.4.2.1 A weld joint simulating the production part, or the first part, shall be welded in accordance with 3.4.7 or 3.4.8 and inspected to verify conformance to the requirements of this specifiction and the part drawing prior to production welding.

3.4.2.2 Production parts, after approval of the weld joint qualification specimen, shall be welded with the welding procedures established in accordance with 3.4.7 or 3.4.8.

3.4.3 Edge Preparation: Weld joint and adjacent surface preparation, prior to welding, shall be as follows and shall be included as part of the approved procedure certification

3.4.3.1 Joint Preparation: Joints shall be prepared to conform to requirements of the part drawing. Unless otherwise specified, surfaces of joints shall have a surface texture of 32 - 125 microin. (0.8 - 3.2 µm), determined in accordance with ANSI B46.1.

3.4.4 Weld Start and Run-Off Tabs: Tabs, when used, shall be of the same alloy as the detail parts being welded and shall be cleaned in the same manner as the parts. Tabs shall be integral with the part, either being machined in, or welded to, the part pieces prior to assembly.

3.4.5 Preparation and Preweld Cleaning:

3.4.5.1 Cleaning of Detail: The weld joint, filler material, parent material, and all tooling adjacent to weld joints shall be free from all foreign substances. These include oxides, dirt, grease, oil, pencil marks, and sulfur-base compounds and low-melting metals or alloys, such as lead or proprietary forming dies.

3.4.5.1.1 The parent materials shall be cleaned with non-chlorinated solvents, such as acetone, alcohol, and methyl ethyl ketone (MEK). Trichloroethylene, methylene choloride, and other chlorinated solvents shall not be used on titanium.

3.4.5.1.2 Cleaning may also be accomplished by using an alkaline wash or dip.

3.4.5.1.3 Cleaning shall be followed by acid pickling in a solution containing 2 - 4% hydrofluoric acid (HF) and 30 - 50% nitric acid (HNO_3) at a bath temperature not exceeding 140 °F (60 °C), thoroughly rinsing in clean water, and drying.

3.4.5.2 Immediate Preweld Cleaning: Immediately before welding, the joint faces and sharp edges shall be draw filed, rotary burr filed, or polished with fine garnet paper, 100 grit (150 µm) or finer, or equivalent polishing cloths. These areas shall be brushed clean using a stainless steel brush, methyl ethyl ketone (MEK), acetone, or ethyl acetate and immediately wiped with a dry, clean cloth, or blown dry with dry nitrogen, oil- and water-free air, or argon. All tools and equipment shall be dry; if necessary, heat may be used to dry off moisture.

3.4.5.3 In-Process Cleaning: In multiple-pass welds, the surface of each weld deposit shall be visually examined and cleaned, as required, to ensure that the surface is free from imperfections that could cause weld-integrity problems. Cleaning shall be accomplished using a stainless steel brush, with remaining residue of loose particles removed with a dry, clean cloth or with dry nitrogen, oil- and water-free air, or argon. No solvents shall be applied.

3.4.6 Positioning and Set-up: The parts to be joined shall be positioned, in a locating fixture if desired, so that the finished assembly will conform to the dimensions of the applicable drawing. Parts may be tack welded providing all the controls applicable to the basic weld are met, unless tack welding is specifically prohibited by purchaser.

3.4.7 Gas-Tungsten-Arc Welding (GTAW) and Gas-Metal-Arc-Welding (GMAW):

3.4.7.1 Environment or shielding gas shall be as specified in 3.1.3.1.

3.4.7.2 Either 1% or 2% thoriated tungsten electrodes conforming to AWS A5.12 shall be used for all GTAW welding operations.

3.4.8 Plasma-Arc-Welding (PAW):

3.4.8.1 Plasma orifice gas shall be argon conforming to MIL-A-18455.

3.4.8.2 Secondary shielding of all welding operations shall be with helium conforming to MIL-P-27407, argon conforming to MIL-A-18455, or a mixture of the two.

3.4.8.3 2% thoriated tungsten electrodes conforming to AWS A5.12 shall be used for all PAW welding operations.

3.4.8.4 Prior to a keyhole weld pass in a square-groove joint, a line shall be scribed approximately 0.050 in. (1.25 mm) on each side of the weld joint on the root surface. The subsequent root bead shall leave no evidence of the scribed lines on the root face after completion of welding.

3.4.9 Other Welding Processes: The conditions and requirements for other fusion welding processes shall be as agreed upon by purchaser and welding processor.

3.4.10 Specific Alloy Requirements:

3.4.10.1 5A1 - 2.5Sn: Prior to welding 5A1 - 2.5Sn titanium alloy, all detail parts that have been cold-worked within a distance of 50 times the weld joint thickness or 2.0 in. (50 mm), whichever is less, from the weld location shall be stress-relieved in accordance with MIL-H-81200.

3.4.10.2 6A1 - 4V: Detail parts of a 6A1 - 4V titanium alloy weldment may be in different heat-treat conditions prior to welding, except that solution heat treated material shall not be welded to solution heat treated and aged material.

3.4.11 Postweld Processing:

3.4.11.1 Welds shall not be cleaned prior to inspection. Weldments shall not be pickled prior to stress relief or aging.

3.4.11.2 Welds shall be stress relieved or heat aged, as applicable.

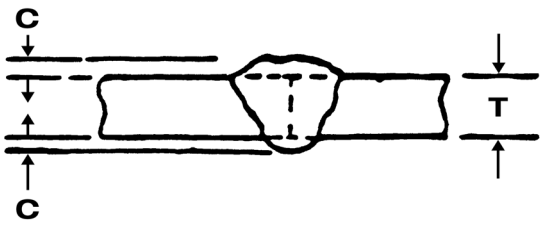
3.4.11.3 Weldments which require cleaning after heat aging or stress-relieving shall be cleaned in accordance with 3.4.5.1.

3.5 Weld-bead Requirements:

Welded joints shall fair evenly into the parent metal, shall be uniform in size and contour, and shall be free from incomplete fusion, cold-laps, cracks, and excessive splatter, drop-thru, or undercutting.

3.5.1 Butt Weld Dimensional Requirements: Weld deposits shall conform to the dimensions specified on the applicable drawing. If dimensions are not specified thereon, the following shall apply:

3.5.1.1 Maximum face height and root reinforcement shall be as specified in Fig. 1 and Table 1.



C = Nominal weld reinforcement or drop-thru
T = Nominal thickness of parent metal (thinnest member)

FIGURE 1

TABLE 1

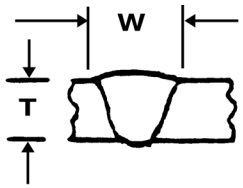
Nominal Thickness (T) inches	Height of Weld Reinforcement or Drop-Thru (C) inch, max
Up to 0.070, incl	1T or 0.020, whichever is greater
Over 0.070 to 0.180, incl	1/2T or 0.070, whichever is greater
Over 0.180 to 0.500, incl	1/4T or 0.090, whichever is greater
Over 0.500	0.130

TABLE 1 (SI)

Nominal Thickness (T) millimetres	Height of Weld Reinforcement or Drop-Thru (C) millimetres, max
Up to 1.75, incl	1T or 0.50, whichever is greater
Over 1.75 to 4.50, incl	1/2T or 1.75, whichever is greater
Over 4.50 to 12.50, incl	1/4T or 2.25, whichever is greater
Over 12.50	3.25

3.5.1.2 When a flush or machined surface is specified, the weld reinforcement shall be not less than flush after machining. Weld bead removal to obtain a flush surface shall be accomplished in a manner that will avoid overheating the surface as indicated by discoloration. Surface discoloration exceeding a light straw color is not acceptable.

3.5.1.3 Maximum allowable weld bead width for square-groove (square-butt) welds is a function of material thickness and shall be within the limits specified in Table 2 and Fig. 2.



T = Nominal thickness of parent metal (thinnest member)
W = Width of weld bead

FIGURE 2

TABLE 2

Nominal Thickness (T) Inches	Nominal Thickness (T) Millimetres	Bead Width (W) max
Up to 0.200, excl	Up to 5.00, excl	4T
0.200 to 0.400, excl	5.00 to 10.00, excl	2-1/2T
0.400 to 0.700, excl	10.00 to 17.50, excl	1-1/2T
0.700 to 1.000, incl	17.50 to 25.00, excl	1T

3.5.1.4 Maximum allowable weld bead width for prepared groove welds shall be equal to the prepared groove opening plus 0.130 in. (3.25 mm).

3.5.1.5 Cross-sectional misalignment between the parent metal surfaces of the joint components to be welded shall not exceed 0.100 in. (2.50 mm) or 10% of the nominal thickness of the thinnest joint member, whichever is less.

3.5.2 Fillet and Corner Fillet Weld Dimensional Requirements:

3.5.2.1 For single fillet welds, the leg size shall be 1 to 3 times the nominal thickness of the thinner member (T) and the weld throat shall be not less than 0.7T. For double fillet welds, the leg size shall be 0.5T to 2.5T and the weld throat shall be not less than 0.3T.

3.5.2.2 For single fillet welded corner joints the weld throat shall be at least equal to the thinnest member thickness. For double fillet welded corner joints the minimum thickness, face-to-face of the welds, shall be not less than the nominal thickness of the thinnest joint member.

3.5.3 Penetration:

3.5.3.1 Butt welds shall have complete joint penetration. The weld metal shall completely fuse all surfaces of the original joint.

3.5.3.2 Fillet and corner fillet welds shall completely fuse all surfaces of the original root face and/or prepared joint when full penetration welds are specified by the drawing. When partial penetration welds are specified, corner fusion must be accomplished.

3.5.4 Undercutting and Melt Back: Shall not exceed the following for all joint configurations. Limits of Class A shall apply, unless Class B is specified.

3.5.4.1 Class A Welds: At any location, the thickness of the member(s) joined shall not be decreased more than 5% of the nominal thickness and the total length of reduced thickness sections shall be not more than 10% of the weld length.

3.5.4.2 Class B Welds: At any location, the thickness of the member(s) joined shall not be decreased more than 15% of the nominal thickness and the total length of reduced thickness sections shall be not more than 15% of the weld length.

3.5.5 Marking and Identification: Each weld shall be traceable to the date of welding and identifiable to the welding operator, and shall be recorded, unless waived by purchaser.

3.6 Weld Quality:

Welds shall be nominally uniform in quality and condition, sound, and free from foreign materials and from internal and external imperfections detrimental to fabrication or to performance of the welded joints.

3.6.1 Face and Root Surfaces: The following requirements shall apply to the face and root surfaces of the weldment and shall be considered to apply both to as-welded surfaces either in process or on completion of welding and to welded surfaces exposed by machining:

3.6.1.1 Weld deposit surfaces shall be smooth in appearance or have an even repetitive ripple pattern and shall be fayed smoothly into the parent metal.

3.6.1.2 Weld deposit surfaces shall be free from surface voids, overlapping folds, sharp folds, lack of fusion, oxide folds, pitting, undercut, cracks, and porosity. Particular attention shall be directed to weld interruptions and terminations to ensure removal of crater cracks.

3.6.1.3 Discolorations of the weld bead surface is not acceptable except as noted in 3.5.1.2. Welding over a discolored surface shall not be permitted.

3.6.1.4 When more than one weld pass is required to fill a weld joint, each previous (intermediate) weld pass shall present a surface free from defects as noted in 3.6.1.1, 3.6.1.2, and 3.6.1.3 prior to deposition of subsequent weld passes.

3.6.2 Evaluation of Surface Defects:

3.6.2.1 Evaluation of surface defects shall be conducted using optical aids providing 10 - 25X magnification.

3.6.2.2 Weld surfaces shall be brushed clean and any remaining residue or loose particles removed in accordance with 3.4.5.3 prior to evaluation for defects.

3.6.2.3 All surface defects shall be removed using metal removal techniques that will avoid overheating (discoloration) and contamination of the surface by imbedding grinding particles. Remaining residue or loose particles shall be removed in accordance with 3.4.5.3.

3.6.2.4 There shall be no underfill of the finished weld deposit surface below the parent metal surface (concavity or suckback) or undercut.

3.6.3 Internal Weld Quality: The following requirements, determined in accordance with 3.7, shall apply to the interior of weldments both in-process and on completion of welding. The requirements shall also apply to weldments after completion of specified machining operations.

3.6.3.1 Weldment interiors shall be free from incomplete fusion, inadequate joint penetration, oxide folds, and cracks.

3.6.3.2 Porosity, voids, and inclusions having sharp tails are unacceptable.

3.6.3.3 Acceptance limits for total and lineal porosity or inclusions, or both, per inch (25 mm) of weld length are based on individual defect size, total defect area, and defect location relative to other defects and shall be as shown in Table 3.

TABLE 3 - Porosity and Inclusion Limits

Maximum Size Inch (Millimetre)	Maximum (1) Total Indication Area (sq. in/inch) (mm^2/mm)	Maximum (2) Lineal Indication Area (sq. in/inch) (mm^2/mm)	Minimum Spacing
Lesser of 1/3T (3) or 0.040 (1.00)	Lesser of 0.05T (3) or 0.006 (0.15)	Lesser of 0.025T (3) or 0.003 (0.08)	4 x smallest adjacent pore diameter

NOTES: (1) Total shall be interpreted to mean scattered plus lineal indications and scattered shall be interpreted to be all indications except those defined as lineal or those excluded (See 3.6.3.4).

(2) Lineal shall be interpreted to mean three or more indications whose radiographic images can be intersected by a straight line parallel to the longitudinal axis of the weld deposit.

(3) T = Joint thickness dimension (See 3.6.3.5).

3.6.3.4 Evaluation of porosity and inclusion indications shall be based on the following criteria:

3.6.3.4.1 Porosity and inclusions, either tungsten or nonmetallic, shall be subject to the same dimensional limitations. When both inclusions and porosity are present, the sum of the areas shall not exceed the limits defined in Table 3 (either total or lineal as applicable).

3.6.3.4.2 The diameter of any indication shall be defined as its largest dimension.

3.6.3.4.3 Interconnected indications shall be considered as a single defect. Indications spaced closer than shown in Table 3 shall be considered to be interconnected.

3.6.3.4.4 Indications having diameters equal to or less than 10% of the joint thickness (T) or 0.010 in. (0.25 mm), whichever is less, shall not be considered when determining total defect area and spacing.

3.6.3.5 Joint thickness dimension (T) as specified in Table 3 shall be interpreted as follows:

3.6.3.5.1 For butt welds between members specified by the drawing to be of equal thickness, joint thickness (T) shall be the nominal parent metal thickness.