Process Specification for Automatic and Machine Gas Tungsten Arc Welding of Titanium and Titanium Alloy Hardware

Engineering Directorate

Structural Engineering Division

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REVISIONS		
VERSION	**DESCRIPTION**	**DATE**
Baseline	Original version	03/20/16
A	Changed title. Removed and added text throughout for clarity. Sections 2.0, 3.0, 4.0 5.1 5.2, 6.1 and 6.2 revised for clarity. Sections 7.1 and 7.3 reversed locations. Sections 6.2.2, 6.3.1, 6.3.2, 6.3.2.1, 6.3.2.2, 6.3.2.3 were deleted in their entirety. In addition, Tables II, III & IV were deleted. A new Table II was added, and Table V became Table III. Definitions were added Section 10.0. Discoloration in Appendix A & B was changed. Appendix D was added.	05/15/2020

1.0 SCOPE

This process specification provides the minimum requirements that govern the automatic and machine gas tungsten arc welding of titanium and titanium alloy hardware. Procedural and quality assurance requirements are given. All Detailed Process Instructions (DPI) and Weld Procedure Specifications (WPS) used during welding shall satisfy the requirements of this process specification and its applicable documents.

2.0 APPLICABILITY

This process specification applies to arc welding of titanium and titanium alloy hardware that is fabricated under the authority of NASA/Johnson Space Center (JSC) by the following welding process: Orbital Tube Gas Tungsten Arc Welding (OTGTAW).

3.0 USAGE

This process specification shall be invoked by including a note on the applicable engineering drawing with the following example which specifies the PRC and weld class nomenclature:

WELD AND INSPECT PER NASA/JSC PRC-0015, CLASS A.

To minimize fabrication costs by avoiding over-inspection and unnecessary rework/repair, individual welds, or components on a weldment shall be classified separate where possible. This can be accomplished by including a note on the engineering drawing with the general format shown below which specifies only the PRC nomenclature. The weld class shall then be indicated by either: 1) calling out the specific weld class with the welding symbol at the individual weld joints or, 2) by using specific flag notes with the welding symbol at the individual weld joints. Refer to Figure 3.0a and 3.0b below for examples of these methods.

WELD AND INSPECT PER NASA/JSC PRC-0015. WELD CLASSES SHALL BE AS INDICATED AT WELD LOCATION CALLOUTS.

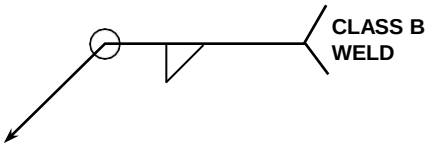


FIGURE 3.0a

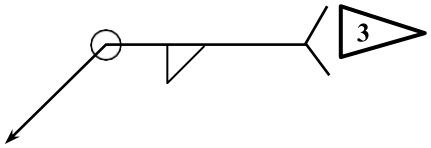


FIGURE 3.0b

3.1 WELD CLASSIFICATION

Welds made using this specification shall be primarily classified in accordance with the service conditions of the weldment. The "Class" governs the extent to which quality assurance provisions are applied to the weld joint.

Alternatively, individual welds, welded connections, or entire weldments (for simplicity, the terms weld, welded connection, and weldment will be used interchangeably) may be classified by relating the weld to the factor of safety used in the design. However, when classifying welds in this manner, regardless of the factor of safety, adequate consideration should be given to the severity of the service conditions (e.g., static loading vs. dynamic loading, cyclic, vibration, fatigue, corrosive, extreme temp, etc.), material characteristics (e.g., ductility, toughness, etc.), and the potential consequences of weld failure.

Where conditions exist that make it difficult to choose between 2 weld classes, then the more stringent of the 2 classes shall be applied.

Quality assurance provisions for all weld classes are detailed in Section 7.0. Weld classes shall be chosen on the basis of the following definitions:

a. Class A (Flight or non-flight) — Applies to welds in critical load bearing elements that are not fail-safe. Class A welds are typically used in primary load bearing connections. Failure of a Class A weld in service would be catastrophic and would result in the loss of life, system(s), control, or major components. Alternatively, if it is determined from appropriate engineering analyses that a weld has a Factor of Safety (FSuts) vs ultimate tensile strength of the calculated minimum weld throat cross section of <2.0, it shall be designated as a Class A weld.

b. Class B (Flight or non-flight) — Applies to welds in load bearing elements that are fail-safe. Class B welds are typically used in secondary load bearing (i.e., shared load) connections. Failure of a Class B weld in service would reduce the overall efficiency of the system, but the loss of the system(s) or endangerment to personnel would not be expected. Alternatively, if it is determined from appropriate engineering analyses that a weld will have a FSuts of ≥ 2.0 and <3.5, it may be designated as a Class B weld.

c. Class C (Flight or non-flight) — Applies to welds that are in minor load bearing elements that are fully contained where failure in service would have minor or no effect on the efficiency of a system and endangerment to personnel would not occur. Class C welds are typically used in secondary or tertiary load bearing (i.e., shared load) connections. Alternatively, if it is determined from appropriate engineering analyses that a weld will have a FSuts of ≥ 3.5, it may be designated as a Class C weld. Class C shall not be applied to welds in pressurized components.

In addition to the above definitions, the following requirements shall also apply to weld classifications:

- If any weld intersects or overlaps another weld of a higher classification, then the lower classed weld shall be automatically upgraded to the higher of the 2 weld classes and subjected to the appropriate quality assurance provisions.

- If any weld falls within ½" of any higher classed weld, then it shall be automatically upgraded to the higher of the 2 weld classes and subjected to the appropriate quality assurance provisions.

3.2 WORK INSTRUCTIONS

Work instructions shall be generated for implementing this process specification. The work instructions shall contain enough detail to ensure that the manufacturing process produces consistent, repeatable products that comply with this specification. At JSC, these work instructions are approved as Detailed Process Instructions (DPIs) that describe in a detailed, step-by-step format the required procedures, equipment, and materials to be used for conducting a given process.

If this manufacturing process is to be performed by an outside vendor, work instruction development shall be the responsibility of the vendor. The contractor shall ensure that the work instructions meet the requirements of this process specification.

3.3 DESIGN REQUIREMENTS

a. The design of welded joints (including weld sizes) shall utilize adequate engineering analysis methods (e.g., stress analysis, fracture mechanics/fracture control, finite element analysis, failure mode and effects analysis, etc.) to ensure that the resultant connection strength is capable of successfully transferring the maximum load expected to pass between the interconnecting members and meet the required factors of safety and design margins.

b. All engineering drawings shall depict welded joints using the applicable symbols described in AWS A2.4.

c. The engineering drawing shall specify any additional or alternate testing or inspection requirements. Where spot, intermittent, or other special inspection requirements are specified that deviate from those stated herein, it shall be detailed on the drawing as a note or by using the applicable symbology described in AWS A2.4.

d. Class A welds are expected to be welds requiring full strength of the weld joint therefore, these welds shall be a groove design and full penetration wherever possible. The ability to successfully perform radiographic examination on these weld joints shall be considered during design.

e. Class A welds which will be subjected to unusual or extreme service conditions (e.g., severe dynamic loading, cyclic, vibration, impact, corrosive, fatigue, extreme temp, etc.), shall be welded using a WPS qualified in accordance with AWS B2.1 "Special Test Weldments." This requirement shall be noted on the engineering drawing.

f. Unless otherwise specified on the engineering drawing or WPS, welded hardware will be delivered in the “as welded” condition. If required, any heat treatment processing required shall be detailed on the engineering drawing and shall include notation that will reference NASA/JSC PRC-2001 or PRC- 2003 as applicable.

g. When required weld insert material shall be noted on the drawing and parts list. Weld insert design/dimensions shall be either on the hardware drawing or a separate drawing.

4.0 REFERENCES

The standards and documents listed below shall be considered a part of this specification to the extent specified herein. Unless otherwise indicated, the revision that is in effect on the date of invitation for bids or the date of request for proposals shall apply.

a. Aerospace Industries Association of America (AIA) National Aerospace Standards (NAS)

NAS 410 *NAS Certification & Qualification of Nondestructive Test Personnel*

b. American Society of Nondestructive Testing (ASNT)

SNT-TC-1A *Personnel Qualification and Certification in Nondestructive Testing*

c. American Welding

ANSI/AWS A2.4 *Standard Symbols for Welding, Brazing and Nondestructive Testing*

ANSI/AWS A3.0 *Standard Welding Terms and Definitions*

ANSI/AWS A5.12 *Specification for Tungsten Arc Welding Electrodes*

ANSI/AWS B2.1 *Standard for Welding Procedure and Performance Qualification*

ANSI/AWS D1.9 *Structural Welding Code – Titanium*

ANSI/AWS D17.1 *Specification for Fusion Welding for Aerospace Applications*

ANSI/AWS G2.4 *Guide for the Fusion Welding of Titanium and Titanium Alloys (2007)*

ANSIAWS QC-1 *Standard for AWS Certification of Welding Inspectors*

d. Compressed Gas Association Inc. (CGA)

CGA G-11.1 *Argon, Commodity Specification for*

e. Federal Documents

BB-H-1168 Helium Federal Specification

f. Military Documents

MIL-A-18455 *Argon, Technical*

MIL-P-27407 *Propellant Pressurizing Agent, Helium*

g. NASA/JSC Documents

JPG 5322.1 *Contamination Control Requirements Manual*

JPG 8500.4 *Engineering Drawing System Manual Drawing Format, Requirements, and Procedures*

PRC-5010 *Process Specification for Pickling, Etching and Descaling of Metals*

PRC-6503 *Process Specification for Radiographic Inspection*

PRC-6506 *Process Specification for Liquid Penetrant Inspection*

PRC-6510 *Process Specification for Ultrasonic Inspection of Welds*

SOP-004.5 *Control of Weld and Braze Filler Materials, Electrodes, and Fluxing Materials*

SOP-007.1 *Preparation and Revision of Process Specifications*

h. NASA Headquarters

NASA-STD-5006 *General Fusion Welding Requirements for Aerospace Materials Used in Flight Hardware*

NASA-STD-5009 *Nondestructive Evaluation Requirements for Fracture Critical Metallic Components*

NASA-STD-6016 *Standard Materials and Processes Requirements for Spacecraft*

i. SAE – Aerospace Material Specifications (AMS)

SAE AMS-H-81200 *Heat Treatment of Titanium and Titanium Alloys*

5.0 MATERIAL REQUIREMENTS

All base materials used in the welding of hardware per this process specification, shall meet the requirements of an applicable commercial specification (e.g., AMS, ASTM, etc.). Alternatively, a manufacturer's specification may be used but it must be approved by the responsible M&P Engineering authority. Filler and electrode materials used shall conform to the applicable American Welding Society (AWS) specification. Filler metals shall be extra low interstitial (ELI) grade wherever possible. Interstitial elements include but are not limited to, oxygen, hydrogen, and nitrogen. Filler metals and electrodes purchased to alternate specifications shall be allowed provided they meet the minimum requirements of the specifications listed herein.

5.1 SHIELDING GASES

Allowable shielding gases (including purge gases) are listed in Table I.

Table I - Allowable Shielding Gases

GAS	DESCRIPTION	SPECIFICATION
Argon	Gas	MIL-A-18455
Argon	Type II, Grade B (Liquefied)	CGA G-11.1
Helium	Type I, Grade A	MIL-P-27407
Helium	Grade A	BB-H-1168

Gases purchased to alternate specifications shall be allowed provided they meet the minimum requirements of the specifications listed herein. Mixtures of these gases are allowed, and the nominal mixture used for the qualification welding shall be that used for production and shall be listed on the WPS. All shielding and purging gases and nominal gas mixtures shall be subject to the qualification variable requirements listed in AWS B2.1. In addition:

a. All gases used for welding shall be delivered through clean low-nonvolatile residue (NVR)/particulate tubing.

b. Nitrogen, hydrogen, carbon dioxide, and mixtures containing these gases shall not be used in welding titanium and its alloys. A great deal of care needs to be exercised to ensure complete inert gas (argon or helium) coverage during welding.

c. All gases used for shielding or purging shall have a dew point of -60°F (-51 °C) or better. All k-bottles shall be tested to meet the -60°F (-51 °C) or better dew point and certified.

5.1.1 Weld Atmosphere

A protective weld atmosphere shall be freely accessible to all portions of the joint. The weld atmosphere for inert gas chambers, and gas supplies for trailing shields shall be monitored for moisture or oxygen content. Dewpoints shall be -60°F (-51 °C) or better and O2 content shall not be greater than 50ppm. All gas shielding must be checked to ensure that a positive flow exists all times, so that a stagnant atmosphere does not exist during welding or when the base metal is at an elevated temperature. Shielding and purging flows shall not be disengaged until the substrate is below 600°F (~316°C).

5.1.2 Weld Atmosphere Purity Test

Atmospheric purity shall be verified by making an autogenous fusion pass on a commercially pure (CP) titanium strip, which has been properly cleaned. A fusion zone and heat affected zone with a bright silver or light straw color is acceptable (condition #1 or #2 below). No tacking or welding shall be performed on production hardware until an acceptable color has been obtained.

Weld discoloration condition in increasing order of contamination is:

1. bright silver - acceptable
2. light straw - acceptable
3. dark straw - unacceptable
4. purple - unacceptable
5. any shade of blue - unacceptable
6. yellow – unacceptable
7. grey - unacceptable
8. white (may have loose powder) – unacceptable
9. brushed – unacceptable (welds that have been brushed before inspection are rejectable regardless of color before brushing)

5.2 FILLER METALS AND ELECTRODES

All filler metals shall meet the requirements of the applicable AWS filler metal specification relative to the specific alloy and process being used. Filler metals shall be selected based on the specific base metals being welded, service conditions, design requirements (load conditions, etc.), and other design or service factors. The specific selection must be approved by the responsible Materials & Processes (M&P) Engineering organization prior to use. Tubular sleeve and filler insert materials shall have compositions similar to those indicated in the applicable AWS filler metal specification. In addition, the following shall apply:

a) Titanium and its alloys shall be welded with alloy-matching fillers or autogenously.

b) All filler metals shall be used in accordance with a qualified WPS.

c) Filler and electrode materials used shall conform to the applicable AWS specifications listed herein. Filler metals and electrodes purchased to alternate specifications shall be allowed provided they meet the minimum requirements of the specifications listed herein. Filler metal configurations which cannot be procured to an AWS or other applicable filler metal specification shall meet an applicable NASA/JSC or other industry material specification and shall be approved by the responsible M&P Engineering authority prior to use.

d) Filler metals shall be manufactured by a high-quality (HQ) method involving multiple melt cycles. In addition, the final melt cycle shall be made under vacuum.

e) Joints between all-alpha unalloyed titanium (i.e., Commercially Pure (CP)) and alpha-beta alloys such as Ti 3Al-2.5V shall be approved by the responsible M&P Engineering authority. Hydrogen content within raw materials shall be restricted to low levels – preferably below 80ppm. CP titanium filler shall not be used on Ti 6Al-4V/Ti 6Al-4V ELI – hydride formation can occur in the weld. Hydride formation can lead to severe embrittlement or delayed cracking, both of which can result in catastrophic failure.

f) Whenever possible, filler metals designated as extra-low interstitial (ELI), shall be used.

g) Where the end product will be used in a cryogenic application, then ELI filler metals shall be used.

h) Filler metals shall be listed on the engineering drawing.

i) Non-consumable tungsten and tungsten alloy electrodes for shall conform to the applicable AWS specification.

5.2.1 Control and Storage

Welding electrodes and filler metal shall be stored in a clean, dry, and controlled area that provides protection from contamination, physical damage, commingling of alloys, and loss of identification/traceability. Any form of electrodes or weld filler metal which is damaged, dirty, exhibits oxidation/corrosion or has been contaminated with water, oil, grease or any form of hydrocarbons shall not be used and shall be disposed of in accordance with an appropriate disposal procedure. Outside vendors shall provide control and storage according to the applicable material specification or manufacturer's recommendation, whichever is more rigid.

5.3 MECHANICAL PROPERTIES

Unless otherwise specified, the minimum mechanical properties that determine an acceptable weld qualification for titanium alloys shall be that as specified in AWS B2.1.

5.4 WELDING CHAMBERS AND TRAILING GAS SHIELDING

When an inert gas or vacuum chamber is used for welding or trailing torch shields and/or a trailing or fixed gas purge assemblies are used, the specific equipment and method shall be considered an essential variable during qualification of the WPS and personnel qualifications.

6.0 PROCESS REQUIREMENTS

a. All weldments shall be fabricated according to the requirements of this process specification and shall be performed using WPSs that have been qualified in accordance with the requirements of Section 8.0, in addition to that as detailed below. In addition, when qualifying a WPS for titanium welding, the welding setup shall be considered an essential variable. WPSs qualified outside of a weld chamber using trailing shields and gas purge assemblies may also be used for welding in a weld chamber, but not vice versa.

b. The requirements of the applicable codes and standards listed in Section 4.0, shall be met as specified by this PRC based on the design and intended function of the hardware. Certain paragraphs of this process specification are abbreviated re-statements taken from the applicable standards and are included here for the user's convenience. The remaining paragraphs of this process specification represent requirements imposed in addition to the basic requirements of the applicable codes and standards.

c. All arc welding shall be performed using WPSs that have been qualified in accordance with the requirements of Section 6.2. To accommodate any unique differences due to tooling, fixtures, grounding, etc. in the weld parameter settings between a test specimen welding condition and a production component welding condition, a one-time adjustment to the heat input specific parameters shall be allowed with no additional qualification testing required. This adjustment in setting(s) shall be allowed on the "first production component" only. The specific changes shall be documented on a revised WPS reflecting the statement "First Production Component Adjustment" to differentiate from the original WPS.

d. Prior to welding, all weld joint surfaces within a minimum of ½" of the weld line shall be cleaned in a manner shown to be adequate and repeatable in producing a surface cleanliness level conducive to producing sound welds by a given weld process. The specific process and procedural steps to carry out the process shall be part of the procedure qualification activities and shall be appropriately detailed on the qualification and procedure specification (Procedure Qualification Record (PQR) and WPS) documentation as well in the production work instructions. Personnel shall be trained in these same methods and process techniques.

e. Weldments shall be fixtured with appropriate tooling as deemed necessary by the fabricator. Tools and fixtures shall be constructed of materials that will not interfere with the welding process nor damage or contaminate the hardware.

f. Temporary (includes the term —tack welding) welding in areas of the hardware not planned for welding or where the temporary weld will not be totally consumed by the final weld, shall not be allowed. All temporary welds placed at or in a weld joint shall be ground or feathered by welding appropriately to accommodate the final welding process to achieve the expected deposit of sound weld metal. All temporary and tack welding shall only be performed by a welder(s) whose qualifications are current and applicable.

6.1. WELDING PRECISION CLEANED HARDWARE (including tube preparation for welding)

Operators must maintain cleanliness for precision-cleaned hardware during welding into an assembly. The welding operation shall be performed in a dedicated Class 100,000 clean work area. This may require temporary tents over the weld area and/or local monitors located in the area of welding to ensure the Class 100,000 environment is being met. Portable particle counters shall be located as close as possible to the work area, so as to monitor local contaminants during tube preparation and welding. All tools used in weld preparation shall be cleaned to the visibly clean (VC) level per JPG 5322.1 and maintained clean (e.g. bagged in VC clean bags when not in use).

Hardware that cannot be subsequently precision-cleaned shall implement an approved method for protecting against system contamination during tube preparation and welding. Consult the NASA/JSC M&P Engineering branch for approval prior to welding. The installation and removal of physical barriers (e.g., plugs, etc.) shall be tracked by a reliable method and independently verified. Exposed internal surfaces of the tube shall be cleaned using a swab wetted with an approved solvent. A positive backpressure shall be maintained as the plug is removed. Abrasives including sandpaper or abrasive pads inside tubes or on unprotected surfaces shall not be allowed.

Tube cutters shall use a sharp blade, changed frequently. Cutting shall be performed with minimal cutter pressure to aid in preventing particle generation. Tube facing operations shall use vacuum to remove particulate. Facing operations shall be performed away from the weld assembly area, to reduce particulate contamination of the welding work area. Tube facing shall be performed without the use of cutting oils, other fluids, lubricants or coolants. Abrasives, including sandpaper or abrasive pads, shall not be used inside tubes or when unprotected internal surfaces are exposed. After each tube preparation, and prior to welding, a high-velocity gas purge shall be performed. The purge gas velocity shall be the maximum attainable using a 90-psig (minimum) source. The purge gas used during facing and welding shall meet the hydrocarbon and particulate requirements for the system under assembly. The purge gas shall be supplied in accordance with Section 5.1.

6.2 PROCESS-SPECIFIC REQUIREMENTS

6.2.1 Gas Tungsten Arc Welding

Filler metal shall be used for tack welding with the GTAW process. This method of welding shall be specified on an approved WPS.

6.3 WELD QUALIFICATION

This specification provides specific allowances for components that are fabricated for pressure containing applications and non-pressure containing (i.e., structural only) applications.

6.3.1 WPS Qualification

A Welding Procedure Specification (WPS) shall be qualified for each unique weld type (as detailed in 6.3.2) to be produced, before the production welds are made. An existing qualified WPS for one unique weld type may be used for a different engineering drawing provided the requirements of 6.3.2 are met, and it is demonstrated that the essential weld variables listed in Table III will be met. Demonstration shall constitute all the requirements of Section 6.3 except that no additional documentation is required except, when a WPS(s) is written for a specific item(s) of hardware, it shall be revised/amended to show allowance for use on other than the initial specifically stated hardware. The actual welding variables, methods, practices, specific tooling requirements, and test results used during WPS qualification shall be recorded on a PQR.

6.3.2 WPS Test Requirements

At a minimum, the following are minimum requirements for the qualification of a welding procedure. This effort shall include the welding of a minimum of 9 weld samples that represent the weld type specified.

Table II – Required Testing

Heat Input	# of Weld Samples	**Required Testing**			
		VT(1) (2)	RT(2) (3)	Tensile(3)	Metallographic(4) (5)
Nominal (amps)	3 Each	3	3	2	1
-5% of Nominal	3 Each	3	3	2	1
+5% of Nominal	3 Each	3	3	2	1

(1) Visually test O.D. & I.D.

(2) Acceptance criteria is Class A

(3) If the weld procedure includes a PWHT, the radiographic testing shall, at a minimum, be performed after the PWHT cycle

(4) Evaluated to the requirements of AWS B2.1

(5) Photomicrographs shall be taken of the prepared samples and retained with the PQR

6.3.3 Essential Variables

The WPS shall specify all of the essential welding variables and the applicable allowable ranges qualified for each variable, as indicated in Table III. In addition, the WPS shall detail all methods, practices, specific tooling requirements that are determined necessary by the operating facility to successfully execute the weld in production.

Table III - Essential Welding Variables

Variable #	Variable / Weld Type	Range Allowed
1	Power Source Model #	None
2	Weld Head Model #	None
3	Joint Configuration	None
4	Groove Angle	+/- 5º
5	Nominal Tube Dia.	None
6	Nominal Wall Thickness	None
7	Material Type(s)	None
8	Electrode Start Position	+/- 60º
9	Pre-weld Cleaning Steps	None
10	Allowable Joint Gap	None
11	Pre-weld Purge Time	(1)
12	Post-weld Purge Time	(1)
13	Tube ID Pre-purge Flow Rate or Pressure	None
14	Weld Head Pre-purge Flow Rate	+/- 15%
15	Gas Composition/Spec.	None
16	Electrode Travel Speed & Machine Setting	None
17	Arc Travel Start Delay	None
18	Total Weld Current On Time	None
19	Weld Time @ Level or Circumference Interval	None
20	Current Pulse Width (%)	None
21	Current Pulse Rate	None
22	Consumable Insert Type and Specification	None
23	Background Welding Current	None
24	Pulse Welding Current	None
25	Electrode Type	None
26	Electrode Diameter	None
27	Electrode Tip Geometry	None
28	GTAW Electrode to Work Gap (nom. setting)	+/- 10%
29	Minimum Preheat Temp.	None
30	PWHT Procedure/Spec.	None

6.3.3 Requalification of WPS

Requalification of the WPS shall be required when any of the following conditions exist:

a) The weld system has been placed on a different external power source except when the power supply has a means for internal power regulation.

b) Major maintenance has been performed on the weld system. Major maintenance includes replacement of the power supply, major repair of the power supply requiring entrance into the controller welding power supply, or replacement of the weld head has occurred.

c) Preproduction weld samples do not meet requirements and no assignable cause for the failure can be determined.

Requalification may be performed with less total test sample requirements than that required for an initial qualification for a unique weld type. For requalification, only 2 weld samples shall be produced and submitted; one at the “high limit” setting and one at the “low limit” setting for that WPS. Requalification due to item a) or b) above only requires weld samples to be made from one WPS that is specified for use on that system.

The samples shall, at a minimum, be subjected to visual inspection and volumetric NDE and shall meet the applicable requirements specified herein. Requalification results shall be documented on a PQR with a specific notation made indicating “Requalification” and an explanation as to the cause. If the requalification activities result in any welding parameter(s) deviations that exceed the range specified in Table II or AWS B2.1 as applicable, for that parameter, then the level of testing in 6.3.3 shall be required.

6.4 POST WELD HEAT TREATMENT (PWHT)

Post-weld heat treatment, when required by the engineering drawing or WPS, shall be performed after completion of all welding in accordance with AMS-H-81200, as applicable. Vibratory techniques shall not be used in place of thermal treatments.
The following shall be considered for post-weld heat treatment:

a. NASA/JSC M&P shall be contacted when strengthening and/or stress relieving welded alpha, alpha-plus-beta, and beta alloys as AMS-H-81200 calls out wide ranges for both soak temperature and soak time – amount of strengthening and stress relieving are temperature and time dependent.

b. Stress relieving temperatures should not exceed aging temperatures for Ti 6Al-4V and Ti 6Al-4V ELI.

c. Welded alpha and alpha-plus-beta alloys shall be stress relieved in a vacuum or inert gas environment (Ar or He), unless otherwise noted by the responsible M&P Engineering authority.

d. Beta alloys that are welded shall be evaluated on a case-by-case basis with respect to stress relief.

6.5 WELD REPAIRS AND WELDED REPAIRS TO BASE METAL

All weld and welded repairs shall be performed using the WPS used for the original weld or a specific qualified WPS for that repair and shall meet all of the requirements of the original drawing and any additional requirements that are documented in the WPS. A weld repair may be applied manually in lieu of an automated or machine applied repair, provided the essential variables/parameters of the original WPS are duplicated and the heat input applied is less than the initial weld. Rework and repairs shall meet all of the requirements of the original drawing and any additional requirements documented in the WPS. Weld repair does not include the correction of dimensional or other deficiencies of weld joints groove/bevel preparation by “buttering” or build up provided the area corrected by welding is fully consumed in the final weld. Also, the following requirements shall be required in the weld repair activity:

a. Mechanical Repairs. Defects shall be repaired by routing or machining the weld metal to the extent needed to completely remove the defects. Thermal gouging and cutting shall not be used. For groove welds, the reinforcement shall not be machined past flush to the base metal. For fillet welds, the final machined weld profile shall meet the applicable profile and size requirements. In both cases, the repair shall be blended smoothly into the unrepaired weld metal. All repairs shall be subjected to the same visual, surface and subsurface inspections as the unrepaired weld. Repairs requiring liquid penetrant inspection shall be etched in accordance with PRC-5010 prior to inspection.

b. Weld Repairs. Defects shall be repaired by routing or machining the weld metal to the extent needed to completely remove the defects. Thermal gouging and cutting shall not be used. The final repair cavity shall be of a configuration suitable for welding. Prior to welding, the excavation shall be subjected to the same visual, surface and subsurface inspections as the unrepaired weld. Excavations requiring liquid penetrant inspection shall be etched in accordance with PRC-5010 prior to inspection, unless it’s determined that liquid penetrant method interferes with subsequent weld repair. Weld repairs shall be documented by the use of a weldment map or other record with sufficient detail to ensure identification of the weldment, identification of repair location(s), and type of defect. Repair welds shall be subjected to the same visual, surface and subsurface inspections as the unrepaired weld.

   No more than two weld attempts shall be made to successfully repair a rejected flaw. If a second attempt is unsuccessful, a discrepancy report requiring review and dispositioning by the responsible Material Review Board (MRB) shall be generated. The level of documentation of repair welds shall, at a minimum, be consistent with that required for the original production weld.

c. Straightening. Welds or adjacent base metal which have been deformed by the welding operation may be straightened using a fixture and at annealing temperatures. Prior to any straightening operation(s) taking place, responsible M&P Engineering authority shall be consulted. All straightening operations shall be performed prior to any final inspection.

d. Base Metal Repairs. Repairs to base metal anomalies shall be brought to the attention of the responsible M&P Engineering authority for consideration of cause, prior to repair activities.

6.6 SURFACE DEGRADATION FROM CONTAMINANTS

To prevent surface contaminants that can induce liquid and solid metal embrittlement, stress corrosion, hydrogen embrittlement, or reduce fracture toughness from coming in contact with the base material, the use of these substances on or with titanium is prohibited:

1. Mercury
2. Cadmium
3. Silver
4. Gold
5. Hydrochloric Acid
6. Chlorinated Cutting Oils and Solvents
7. Fluorinated Hydrocarbons
8. Methyl Alcohol
9. Methylene Chloride

7.0 PROCESS VERIFICATION

Process verification shall consist of the inspections described in sections 7.1 to 7.3. In addition, the manufacturer shall assure that fabrication activities are carried out in a manner that meets the requirements of this process specification and verify the following items at the appropriate time during fabrication activities.

a) The welding operator is certified for the specific welding operation prior to welding.

b) The fit-up is in accordance with the engineering drawing prior to welding for Class A and B Pressure Containing Components.

c) A WPS exists prior to welding.

d) Compliance with the WPS for essential variable ranges during welding.

e) The PWHT is in accordance with the assigned WPS after welding.

f) Weld one in-process control specimen at each of the following conditions:
   1. Prior to welding the first production joint during each shift.
   2. Upon changing from one certified machine setting to another.
   3. Upon discovery of unsatisfactory system performance.
   4. Specimens shall be visually inspected by an AWS CWI.

7.1 CERTIFICATION AND QUALIFICATION OF INSPECTION PERSONNEL

7.1.1 Visual Inspection

Personnel performing visual inspections of Class A, B and C welds shall be an AWS CWI. The CWI certification must be current.

7.1.2 Nondestructive Inspection

Personnel performing acceptance inspections of flight hardware (Class I, II, IIIW and GSE – see Appendix C) shall be qualified and certified, at a minimum, to Level 2 in accordance with NAS 410. Personnel performing acceptance inspections requiring Special Non-Destructive Evaluation (NDE) shall also be qualified and certified for Special NDE in accordance with NASA-STD-5009.

Personnel performing acceptance inspections of non-flight hardware (Class III, STE/D, mockup, and facility hardware – see Appendix C) shall be qualified and certified in accordance with either NAS 410 or SNT-TC-1A. Personnel making accept/reject decisions shall, at a minimum, be certified to Level 2. Level 3 personnel making accept/reject decisions shall have successfully completed a hands-on practical examination equivalent to the examination required for Level 2. Level 1 personnel may perform acceptance inspections under the direct supervision of a Level 2 but shall not make accept/reject decisions.

Formal qualification and certification is not required for personnel performing engineering evaluation inspections.

Unless otherwise specified, all welds in a structure shall be subjected to the required inspections for the applicable weld class or classes. All unconsumed temporary or tack welds shall be placed where consumed by final weld and subjected to the level of inspection required by the highest weld class specified in the design documentation.

7.2 INSPECTION METHODS AND ACCEPTANCE CRITERIA

7.2.1 General

Inspections shall be performed in accordance with a written procedure by personnel certified in accordance with section 7.3.

7.2.2 Visual

Welds shall be visually inspected for conformance to the drawing requirements and acceptance shall be in accordance with the applicable Class A, B or C acceptance criteria in Appendix A or B.

7.2.3 Liquid Penetrant

a) Non-Flight Hardware: Liquid penetrant inspections shall be performed per PRC-6506. Unless otherwise specified, a fluorescent (Type I) Sensitivity Level 3 or 4 penetrant shall be used for Class A welds and Class B welds in pressurized components. Visible (Type II) penetrant may be used for Class Welds in non-pressurized and structural components. Acceptance shall be in accordance with the applicable Class A or B acceptance criteria in Appendix A or B.

b) Flight Hardware: Liquid penetrant inspections shall be performed per PRC- 6506. Unless otherwise specified, a fluorescent (Type I) Sensitivity Level 3 or 4 penetrant shall be used. Acceptance shall be in accordance with the applicable Class A or B acceptance criteria in Appendix A or B.

7.2.4 Radiographic

a) Non-Flight Hardware: Radiographic inspections shall be performed per PRC-6503. Acceptance shall be in accordance with the applicable Class A or B acceptance criteria in Appendix A or B. Gamma radiation sources shall not be used unless approved by the responsible M&P Engineering authority. Approval of gamma radiation sources shall be based on demonstration of radiographic sensitivity equivalent to that obtainable with an X-ray source.

b) Flight Hardware: Radiographic inspections shall be performed per PRC-6503. Acceptance shall be in accordance with the applicable Class A or B acceptance criteria in Appendix A or B.

7.2.5 Ultrasonic

a) Non-Flight Hardware: Unless otherwise specified, ultrasonic inspections and acceptance shall be performed per PRC-6510, Class A.

b) Flight Hardware: Ultrasonic inspections and acceptance shall be performed per PRC-6510, Class A.

7.3 REQUIRED INSPECTIONS

Unless otherwise specified, all welds in a structure shall be subjected to the required inspections for the applicable weld class or classes. Unconsumed temporary or tack welds shall be subjected to the level of inspection required by the highest weld class specified in the design documentation.

7.3.1 Class A

Class A welds require visual, surface and subsurface inspections. Surface inspections shall be accomplished using the liquid penetrant method. Subsurface inspections shall be accomplished using the radiographic method. In cases where the weld configuration renders adequate radiographic inspection impractical, an alternate inspection method shall be utilized as approved by the responsible M&P Engineering authority. When ultrasonic inspection is selected and approved as an alternate to radiographic inspection, the ultrasonic inspection shall be performed as specified in section 7.2.5. When liquid penetrant is the only available option for inspection and is selected and approved as an alternate to radiographic inspection, the liquid penetrant inspection shall be performed as specified in section 7.2.3. For multi-pass welds, inspections shall be performed on every pass.

7.3.2 Class B

Class B welds require visual and surface inspections. Surface inspections shall be accomplished using the liquid penetrant method.

7.3.3 Class C

Class C welds only require visual inspection.

8.0 PROCESS VERIFICATION

The WPS, PQR, and Welding Operator Performance Qualification (WOPQ) shall be prepared and retained as a permanent record and made available upon request to the NASA/JSC M&P organization for review**.** These procedures must contain, at a minimum, all of the essential welding parameters, an identification of the welding equipment, the pre-weld cleaning procedure (refer to Section 6.1.1) and include any pertinent tooling information. One copy of the WPS shall be maintained in the vicinity of the welding station and shall be readily accessible by the welders, inspectors, supervision, and engineering.

8.1 DEVIATIONS AND WAIVERS

Any deviations or waivers regarding the use of this process specification shall be requested in writing. This request shall be directed to the responsible M&P Engineering authority with the appropriate justification and rationale. A written response will be provided upon such a request.

9.0 TRAINING AND CERTIFICATION OF PERSONNEL

9.1 WELDING OPERATOR QUALIFICATION

Welding shall be performed by a welding operator qualified and certified in accordance with AWS B2.1. Sufficiently detailed records shall be maintained to demonstrate continuity of operator performance on the welding system or system(s) on a semi-annual (6 month) basis. These records shall be made available to the responsible M&P Engineering authority upon request.

9.1.1 Additional Qualification Variables

When qualifying personnel for titanium welding, the welding setup shall be considered an essential variable. Personnel qualifying outside of a weld chamber using trailing shields and gas purge assemblies shall also be qualified for welding in a weld chamber but not vice versa. When qualifying personnel for titanium welding by the guided bend test method, titanium alloys not listed in AWS B2.1, Appendix C1 or C2, the plunger diameter (dimension —All in Annex II of AWS B2.1) shall not exceed 20T (10T radius). For the alloys listed in Appendix D, use the bend radiuses shown in the table.

10.0 DEFINITIONS

The following definitions (and associated acronyms) shall apply to this entire document:

1. **Ductility** – The ability of the material to be plastically deformed by elongation prior to fracture.
2. **Procedure Qualification Record (PQR)** – a detailed written record of the process that has been qualified. The record shall include all the applicable inspection and tests that were conducted and a record of the results of those tests. The PQR shall be signed (certified) by the responsible organization overseeing the welding operations.
3. **Repair** – an action taken to correct a production deficiency in the hardware that results in the hardware not meeting the original design but is fully functional and serviceable as intended by the design.
4. **Rework** – an action taken to correct a production deficiency in the hardware that results in the hardware meeting the original design and is fully functional and serviceable as intended by the design.
5. **Toughness** – A property of a material capable of absorbing energy by plastic deformation. Low energy absorption is considered brittle and high energy absorption is considered ductile.
6. **Welding Procedure Specification (WPS)** – a detailed written procedure that is used by a welder to ensure that the execution of the qualified process is carried out as intended.

Appendix A

WELD ACCEPTANCE CRITERIA FOR PRESSURIZED COMPONENTS

Table A1. Class A Visual and Surface Inspection Acceptance Criteria

Size and Appearance of Groove Welds	Minimum size as specified on drawing. If profile requirements are not specified on the drawing, the weld shall be convex with a maximum reinforcement as stated herein. Any profile is unacceptable where the weld to base metal transition forms a sharp notch or reduces the base metal thickness (T) beyond the minimum specified on the drawing.
Cracks	None allowed.
Undercut	Undercut shall not exceed 20% of the total weld length. The depth of any undercut indication where T < 0.035", undercut shall not exceed 5% of T. Where T is >/= 0.035" and </= 0.09", undercut shall not exceed 10% of T or 0.010", whichever is the lesser. Where T > 0.09", the depth of undercut shall not exceed 0.010". The minimum distance allowed between adjacent undercut or underbead concavity indications is 1/2 the length of the longest adjacent indication.
Pores or Voids	The maximum diameter shall not exceed 0.02" or ¼ of T, whichever is the lesser. Indications less than .010" in diameter shall not be considered.
Inadequate Penetration and Incomplete Fusion	The maximum length of any indication shall not exceed ¼ of T in any weld length of 6T or less. The minimum distance allowed between adjacent incomplete penetration or fusion indications, is ½ the length of the longest adjacent indication.
Weld Face or Root Concavity or WM Thinning	Concavity shall not exceed 10% of T or 0.01", whichever is the lesser.
Overlap	None allowed.
Misalignment	Misalignment shall not exceed 10% of T, or 0.020", whichever is the lesser.
Peaking	Weld joint peaking shall not exceed a total of 5 degrees.
Weld Face or Root Convexity	Reinforcement, or melt-thru, shall not exceed 20% T or 0.06", whichever is the lesser.
Surface Discoloration Refer to AWS G2.4, Figure 7, for weld color examples.	1. bright silver - acceptable 2. silver - acceptable 3. light straw - acceptable 4. dark straw - unacceptable 5. bronze - unacceptable 6. brown – unacceptable 7. violet - unacceptable 8. green - unacceptable 9. any shade of blue - unacceptable 10. grey - unacceptable 11. white (may have loose powder) – unacceptable Welds that have been brushed before inspection are rejectable regardless of color before brushing.
Surface Roughness	Surface finish of welds and adjacent material resulting from processes used to remove weld reinforcement and otherwise shall not exceed 63 microinches.

Table A2. Class B Visual and Surface Inspection Acceptance Criteria

Size and Appearance of Groove Welds	Minimum size as specified on drawing. If profile requirements are not specified on the drawing, the weld shall be convex with a maximum reinforcement as stated herein. Any profile is unacceptable where the weld to base metal transition forms a sharp notch or reduces the base metal thickness (T) beyond the minimum specified on the drawing.
Cracks	None allowed.
Undercut	Undercut shall not exceed 15% of the total weld length. The depth of any undercut indication where T < 0.035", undercut shall not exceed 10% of T. Where T is >/= 0.035" and </= 0.09", undercut shall not exceed 15% of T or 0.010", whichever is the lesser. Where T > 0.09", the depth of undercut shall not exceed 0.015".
Pores or Voids	The maximum diameter shall not exceed 0.02" or 1/3 of T, whichever is the lesser. Indications less than .010" in diameter shall not be considered.
Weld Face or Root Concavity or WM Thinning	Concavity shall not exceed 15% of T or 0.015", whichever is the lesser.
Overlap	None allowed.
Misalignment	Misalignment shall not exceed 15% of T or 0.025", whichever is the lesser.
Peaking	Weld joint peaking shall not exceed a total of 5 degrees.
Weld Face or Root Convexity	Reinforcement, or melt-thru, shall not exceed 20% T or 0.06", whichever is the lesser.
Surface Discoloration Refer to AWS G2.4, Figure 7, for weld color examples.	1. bright silver - acceptable 2. silver - acceptable 3. light straw - acceptable 4. dark straw - acceptable 5. bronze - unacceptable 6. brown – unacceptable 7. violet - unacceptable 8. green - unacceptable 9. any shade of blue - unacceptable 10. grey - unacceptable 11. white (may have loose powder) – unacceptable Welds that have been brushed <u>before</u> inspection are rejectable regardless of color before brushing.
Surface Roughness	Surface finish of welds and adjacent material resulting from processes used to remove weld reinforcement and otherwise shall not exceed 63 microinches.
General Workmanship	Weld deposits, face and root reinforcement and adjacent base metal shall display a smooth and uniform appearance. The weld toes shall blend smoothly into the base metal without unfused overlaps or undercut exceeding that specified.

Table A3. Class A Subsurface Inspection Acceptance Criteria

Cracks	None allowed.
Cold Shut and Laps	None allowed.
Porosity and Inclusions	The maximum diameter shall not exceed 0.02” or ¼ of T, whichever is the lesser. Indications less than .010” in diameter shall not be considered.
Inadequate Penetration and Incomplete Fusion	The maximum length of any indication shall not exceed ¼ of the base metal thickness in any weld length of 6T or less. The minimum distance allowed between adjacent incomplete penetration or fusion indications, is ½ the length of the longest adjacent indication.
Undercut and Underbead Concavity	The length of any undercut or underbead concavity indication shall not exceed 20% of the total weld length. The depth of any undercut indication where T < 0.035”, undercut shall not exceed 5% of T. Where T is >/= 0.035” and </= 0.09”, undercut shall not exceed 10% of T or 0.010”, whichever is the lesser. Where T > 0.09”, the depth of undercut shall not exceed 0.010”. The minimum distance allowed between adjacent undercut or underbead concavity indications is 1/2 the length of the longest adjacent indication.
Misalignment	Misalignment shall not exceed 10% of T, or 0.020”, whichever is the lesser.
Weld Face or Root Concavity or WM Thinning	Thinning shall not exceed 10% of T or 0.01”, whichever is the lesser.
Weld Face or Root Convexity	Reinforcement, or melt-thru, shall not exceed 20% of T or 0.06”, whichever is the lesser.

Table A4. Class B Subsurface Inspection Acceptance Criteria

Cracks	None allowed.
Cold Shut and Laps	None allowed.
Porosity and Inclusions	The maximum diameter shall not exceed 0.02” or 1/3 of T, whichever is the lesser. Indications less than .010” in diameter shall not be considered.
Inadequate Penetration and Incomplete Fusion	The maximum length of any indication shall not exceed 1/3 of the T in any weld length of 6T or less. The minimum distance allowed between adjacent incomplete penetration or fusion indications, is ½ the length of the longest adjacent indication.
Undercut and Underbead Concavity	The length of any undercut or underbead concavity indication shall not exceed 15% of the total weld length. The depth of any undercut indication where T < 0.035”, undercut shall not exceed 10% of T. Where T is >/= 0.035” and </= 0.09”, undercut shall not exceed 15% of T or 0.010”, whichever is the lesser. Where T > 0.09”, the depth of undercut shall not exceed 0.015”. The minimum distance allowed between adjacent undercut or underbead concavity indications is 1/2 the length of the longest adjacent indication.
Misalignment	Misalignment shall not exceed 15% of T, or 0.025”, whichever is the lesser.
Weld Face or Root Concavity or WM Thinning	Thinning shall not exceed 15% of T or 0.015”, whichever is the lesser.
Weld Face or Root Convexity	Reinforcement, or melt-thru, shall not exceed 20% of T or 0.06”, whichever is the lesser.

Appendix B

WELD ACCEPTANCE CRITERIA FOR NON-PRESSURIZED AND STRUCTURAL COMPONENTS

Table B1. Class A Visual and Surface Inspection Acceptance Criteria

Size and Appearance of Groove Welds	Minimum size as specified on drawing. If profile requirements are not specified on the drawing, the weld shall be convex with a maximum reinforcement as stated herein. Any profile is unacceptable where the weld to base metal transition forms a sharp notch or reduces the base metal thickness (T) beyond the minimum specified on the drawing.
Cracks	None allowed.
Undercut	Undercut shall not exceed 15% of the total weld length. The depth of any undercut indication where T < 0.035", undercut shall not exceed 10% of T. Where T is >/= 0.035" and </= 0.09", undercut shall not exceed 15% of T or 0.010", whichever is the lesser. Where T > 0.09", the depth of undercut shall not exceed 0.015".
Pores or Voids	The maximum diameter shall not exceed 0.02" or 1/3 of T, whichever is the lesser. Indications less than .010" in diameter shall not be considered.
Weld Face or Root Concavity or WM Thinning	Concavity shall not exceed 15% of T or 0.015", whichever is the lesser.
Overlap	None allowed.
Misalignment	Misalignment shall not exceed 15% of T or 0.025", whichever is the lesser.
Peaking	Weld joint peaking shall not exceed a total of 5 degrees.
Weld Face or Root Convexity	Reinforcement, or melt-thru, shall not exceed 20% T or 0.06", whichever is the lesser.
Surface Discoloration Refer to AWS G2.4, Figure 7, for weld color examples.	1. bright silver - acceptable 2. silver - acceptable 3. light straw - acceptable 4. dark straw - acceptable 5. bronze - unacceptable 6. brown – unacceptable 7. violet - unacceptable 8. green - unacceptable 9. any shade of blue - unacceptable 10. grey - unacceptable 11. white (may have loose powder) – unacceptable Welds that have been brushed <u>before</u> inspection are rejectable regardless of color before brushing.
Surface Roughness	Surface finish of welds and adjacent material resulting from processes used to remove weld reinforcement and otherwise shall not exceed 63 microinches.
General Workmanship	Weld deposits, face and root reinforcement and adjacent base metal shall display a smooth and uniform appearance. The weld toes shall blend smoothly into the base metal without unfused overlaps or undercut exceeding that specified.

Table B2. Class B and C Visual and Surface Inspection Acceptance Criteria

Size and Appearance of Groove Welds	Minimum size as specified on drawing. If profile requirements are not specified on the drawing, the weld shall be convex with a maximum reinforcement as stated herein. Any profile is unacceptable where the weld to base metal transition forms a sharp notch or reduces the base metal thickness (T) beyond the minimum specified on the drawing.
Cracks	None allowed.
Undercut	Undercut shall not exceed 15% of the total weld length. The depth of any undercut indication where T < 0.035", undercut shall not exceed 10% of T. Where T is >/= 0.035" and </= 0.09", undercut shall not exceed 15% of T or 0.010", whichever is the lesser. Where T > 0.09", the depth of undercut shall not exceed 0.015".
Pores or Voids	The maximum diameter shall not exceed 0.02" or 1/3 of T, whichever is the lesser. Indications less than .010" in diameter shall not be considered.
Weld Face or Root Concavity or WM Thinning	Concavity shall not exceed 15% of T or 0.015", whichever is the lesser.
Overlap	None allowed.
Misalignment	Misalignment shall not exceed 15% of T or 0.025", whichever is the lesser.
Peaking	Weld joint peaking shall not exceed a total of 5 degrees.
Weld Face or Root Convexity	Reinforcement, or melt-thru, shall not exceed 20% T or 0.06", whichever is the lesser.
Surface Discoloration Refer to AWS G2.4, Figure 7, for weld color examples.	1. bright silver - acceptable 2. silver - acceptable 3. light straw - acceptable 4. dark straw - acceptable 5. bronze - unacceptable 6. brown – unacceptable 7. violet - unacceptable 8. green - unacceptable 9. any shade of blue - unacceptable 10. grey - unacceptable 11. white (may have loose powder) – unacceptable Welds that have been brushed before inspection are rejectable regardless of color before brushing.
Surface Roughness	Surface finish of welds and adjacent material resulting from processes used to remove weld reinforcement and otherwise shall not exceed 63 microinches.
General Workmanship	Weld deposits, face and root reinforcement and adjacent base metal shall display a smooth and uniform appearance. The weld toes shall blend smoothly into the base metal without unfused overlaps or undercut exceeding that specified.

Table B3. Class A Subsurface Inspection Acceptance Criteria

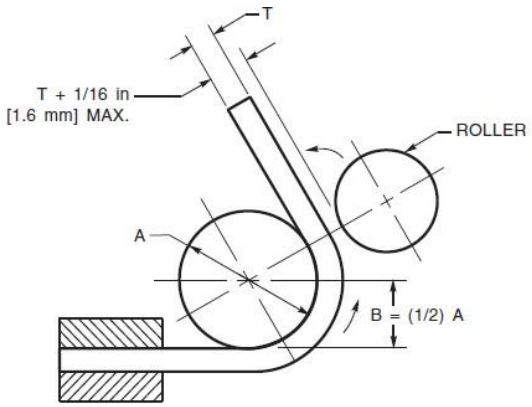
Cracks	None allowed.
Cold Shut and Laps	None allowed.
Porosity and Inclusions	The maximum diameter shall not exceed 0.02” or 1/3 of T, whichever is the lesser. Indications less than .010” in diameter shall not be considered.
Inadequate Penetration and Incomplete Fusion	The maximum length of any indication shall not exceed 1/3 of the T in any weld length of 6T or less. The minimum distance allowed between adjacent incomplete penetration or fusion indications, is ½ the length of the longest adjacent indication.
Undercut and Underbead Concavity	The length of any undercut or underbead concavity indication shall not exceed 15% of the total weld length. The depth of any undercut indication where T < 0.035”, undercut shall not exceed 10% of T. Where T is >/= 0.035” and </= 0.09”, undercut shall not exceed 15% of T or 0.010”, whichever is the lesser. Where T > 0.09”, the depth of undercut shall not exceed 0.015”. The minimum distance allowed between adjacent undercut or underbead concavity indications is 1/2 the length of the longest adjacent indication.
Misalignment	Misalignment shall not exceed 15% of T, or 0.025”, whichever is the lesser.
Weld Face or Root Concavity or WM Thinning	Thinning shall not exceed 15% of T or 0.015”, whichever is the lesser.
Weld Face or Root Convexity	Reinforcement, or melt-thru, shall not exceed 20% of T or 0.06”, whichever is the lesser.

Appendix C

Hardware Classification

Hardware Classification	
Class I	Flight hardware - refers to any hardware acceptable for space flight use
Class II	Ground tests or training in a hazardous environment
Class IIIW	Hardware used in water immersion training
GSE	Ground Support Equipment
Class III	“Non-Flight hardware” refers to any hardware acceptable for use in non-hazardous training or displays
STE/D	Special Test Equipment/Devices used in facilities (buildings and related accessories), mockup mission equipment and engineering prototype and development hardware.
1 E	Any combination of hardware and software that is developed and operated to answer a scientific or engineering question that cannot be addressed in a terrestrial environment. Operating this hardware does not provide mission critical functions, and hazards are eliminated or controlled such that the safety of the crew, the space vehicle, or launch vehicle are not compromised.

Appendix D



Material M Number (Grade)	Mandrel Diameter A	Bend Radius B
51 (Grade 1)	8 × test coupon thickness	4 × test coupon thickness
51 (Grade 2)	8 × test coupon thickness	4 × test coupon thickness
52 (Grade 3)	10 × test coupon thickness	5 × test coupon thickness
53 (Grade 9)	16 × test coupon thickness	8 × test coupon thickness
53 (Grade 5)	16 × test coupon thickness	8 × test coupon thickness
54 (Grade 23)	16 × test coupon thickness	8 × test coupon thickness
(Grade 38)	18 × test coupon thickness	9 × test coupon thickness

Notes:
1. Dimensions not shown are the option of the designer. The essential consideration is to have adequate rigidity so that the fixture parts will not spring.
2. The specimen shall be firmly clamped on one end so that there is no sliding of the specimen during the bending operation.
3. Test specimens shall be removed from the fixture when the outer roll has moved 120° from the starting point and the center of the weld is contained within an area that has been subjected to the maximum possible strain, typically between 60° and 90° from the start.
4. The test fixture mandrel shall be at least 0.25 in [6 mm] wider than the specimen being tested.

Figure 3.16—Wraparound Guided Bend Jig (see 3.11.2.1)

Grade 1 = CP Ti (min. 20 ksi YS)
Grade 2 = CP Ti (min. 40 ksi YS)
Grade 3 = CP Ti (min. 55 ksi YS)
*Grade 4 = CP Ti (min. 70 ksi YS)
Grade 5 = 6Al-4V Ti
Grade 9 = 3Al-2.5V Ti
Grade 23 = 6Al-4V ELI Ti
Grade 38 = 4Al-2.5V-1.5Fe Ti

***Use Mandrel Diameter A and Bend Radius B given for Grade 3.**