Process Specification for Friction Stir Welding

Engineering Directorate

Structural Engineering Division

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Process Specification for Friction Stir Welding

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REVISIONS		
VERSION	**DESCRIPTION**	**DATE**
Baseline	Original version	10/23/2002
A	Modified section 6.4 to remove “after completion of all welding” from the paragraph	10/29/2002
B	Comprehensive rewrite to combine PRC-0013 and PRC-0014 and make editorial and technical changes to accommodate non-flight hardware. PRC-0013 will be cancelled with this change. Make provision for Class D welds for ground based hardware.	1/5/2005
C	Comprehensive 2 year review. Added ES4 reviewer (Johannes).	3/21/2007
D	Excluded pressure vessels and pressurized components from the scope in 1.0; revised the definitions of flight and non-flight hardware in 2.0; clarified the term “tool diameter” in 3.4e; added NAS 410, AWS D1.1, AWS D1.6, AWS D17.3, NASA-STD-5009 and PRC-6510 to 4.0; deleted PRC-6504 from 4.0; revised 7.0 through 7.3 to add separate inspection requirements for flight hardware and require NAS 410 certification for NDE personnel inspecting flight hardware; deleted the table in A4.0; reduced the weld surface finish requirement to 125 µ-inch in A4.0; and added common FSW defect types to Table A3.0.	11/08/12

1.0 SCOPE

This process specification provides the minimum requirements that govern Friction Stir Welding (FSW) of flight and non-flight hardware, excluding pressure vessels and pressurized components. Procedural and quality assurance requirements are given. All work instructions and Weld Procedure Specifications (WPS) used during welding shall satisfy the requirements of this process specification and its applicable documents.

2.0 APPLICABILITY

This specification applies to FSW of all flight and non-flight hardware fabricated under the authority of the NASA/Johnson Space Center (JSC) by any of the following process modes and their process derivatives whereas the Friction Stir joining process is occurring in the solid state:

a. **Standard** - *(force from pin tool is reacted by a stationary anvil beneath the part)*
b. **Self Reacting** - *(pin tool employs opposing shoulders on either side of the threaded pin. Force is reacted only within the pin tool, between the 2 shoulders. Friction is generated at each shoulder interface)*
c. **Heat Source Assisted** - *(auxiliary heat source travels simultaneously and in front of [tandem arrangement] pin tool; LASER, gas torch, GTAW torch, induction coil, etc.)*

The term “flight hardware” refers to any hardware acceptable for space flight use (Class I), use in ground tests or training in a hazardous environment (Class II), use in water immersion training (Class IIIW) and Ground Support Equipment (GSE). The term “non-flight hardware” refers to any hardware acceptable for use in non-hazardous training or displays (Class III), Special Test Equipment/Devices (STE/D), use in facilities (buildings and related accessories), mockup mission equipment and engineering prototype and development hardware.

Future builds of hardware where the existing engineering documentation calls out NASA/JSC PRC-0013 for welding shall utilize this specification. Existing hardware fabricated to PRC-0013 requirements shall not be affected by this change.

3.0 USAGE

This process specification shall be called out on the engineering drawing by a drawing note with the following general format:

WELD AND INSPECT PER NASA/JSC PRC-0014, CLASS X

Note: It is intended that the above welding note be used for an entire weldment drawing, however, designers should give consideration to specifying a different “Class” to individual weld joints (see 3.1).

3.1 WELD CLASSES

The specific selected weld class (see 3.2) shall be invoked by including a note on the applicable engineering drawing with the above given general format shown in 3.0 which specifies the PRC and weld class nomenclature:

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 as shown below. 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-0014. WELD CLASSES SHALL BE AS INDICATED AT WELD LOCATION CALLOUTS.

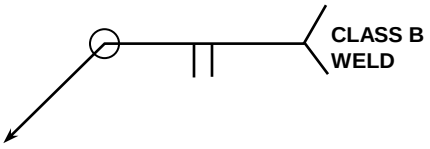


FIGURE 3.0a

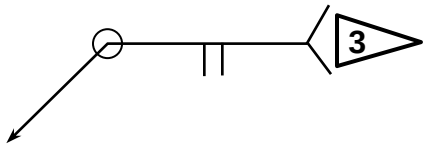


FIGURE 3.0b

3.2 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 (FS_{uts}) 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 FS_{uts} 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 affect 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 FS_{uts} of ≥ 3.5 and <5.0, it may be designated as a Class C weld.

d. **Class D** (Non-flight hardware only) — Applies to welds that are in non-critical elements and where failure would have no affect on the efficiency of a system and endangerment to personnel would not occur. Class D welds are typically used in connections where any expected load transfer at the weld would be negligible. Alternatively, if it is determined from appropriate engineering analyses that a weld will have a FSuts of ≥ 5.0, it may be designated as a Class D weld.

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.

3.3 WORK INSTRUCTIONS

Work instructions shall be generated for implementing this process specification. The work instructions shall contain sufficient detail to ensure that the manufacturing process

produces consistent, repeatable results 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.

3.4 DESIGN REQUIREMENTS

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

b) Groove welded joints are preferred and shall be full penetration where possible.

c) Class A and B weldments, which will be subjected to unusual or extreme service conditions, 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.

d) Unless otherwise specified on the engineering drawing, hardware will be delivered in the “as welded” condition. If required, the engineering drawing shall include notation that will specify the appropriate heat treatment process, referencing NASA/JSC PRC-2001, PRC-2002, or PRC-2003, as applicable.

e) Class A, B, and C welds shall be specified such that the weld termination point that is left with a depression is 1) removed from the hardware by cutting off an extension of the part (minimum 1.5 tool shoulder diameters), 2) filled by arc fusion welding or Friction Stir plug welding, or 3) shown by appropriate engineering analysis that the presence of such a depression will not affect structural integrity. Where welding is selected, the specific weld procedure shall be qualified by test per section 6.2 to prove the structural integrity meets the design requirements. Where engineering analysis is selected and a “no fill” condition is allowed, then appropriate NDE shall be required to show the absence of injurious flaws in this area.

f) Intermittent welding (skip welds) shall not be specified for Class A joints.

g) Weld joints that are specified for intermittent welding shall have the ends of the parts, or departure from a straight weld line (e.g., square corner, etc.), welded regardless of the interval of the weld.

h) Intermittent welds shall not be specified for butt welds (square or groove design) unless the unwelded portions of the joint are adequately supported to prevent one member from coming out plane with the adjoining member.

i) The engineering drawing shall specify any additional special testing or inspection requirements beyond what is required herein.

j) Class C and D welds shall not be specified for pressure-containing components. Class D welds shall not be allowed on flight hardware.

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 Society (AWS) Standards

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

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

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

ANSI/AWS B4.0 *Standard for Mechanical Testing of Welds*

ANSI/AWS D1.1 *Structural Welding Code - Steel*

ANSI/AWS D1.6 *Structural Welding Code - Stainless Steel*

ANSI/AWS D17.3 *Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications*

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

d. NASA/JSC Documents

PRC-2001 *Process Specification for the Heat Treatment of Steel Alloys*

PRC-2002 *Process Specification for the Heat Treatment of Aluminum Alloys*

PRC-2003 *Process Specification for the Heat Treatment of Nickel Alloys*

PRC-6503 *Process Specification for Radiographic Inspection*

PRC-6505 *Process Specification for Magnetic Particle 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 (PRCs)*

TI-0000-04 *Training For Welders and Welding Operators*

e. NASA Headquarters

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

5.0 MATERIAL REQUIREMENTS

All base materials welded by the FSW process for flight or non-flight hardware shall meet the requirements of an applicable JSC material specification unless otherwise specified. If a JSC material specification is not available, then an applicable commercial specification or a manufacturer's specification shall be used.

5.1 TOOLING AND FIXTURING

The design of fixture and tooling shall be such that the materials selected are appropriate to ensure that contamination or degradation of the weldment is prevented. Weldments shall be fixtured with appropriate tooling as deemed necessary by the fabricator.

5.2 PIN TOOLS

FSW pin tools shall be designed such that any expected erosion of the tool will be negligible and thus not be of concern to the final metallurgy of the finished weld zone.

Prior to production welding, newly fabricated pin tools shall be tested in a trial weld run in the same alloy, temper, and thickness and under the same weld conditions (WPS) as the production hardware will be subjected to so as to subject the tool to equivalent expected tool loads that will be seen in the production weld runs. Prior to allowing use in production, the pin tool shall perform as expected in the trial weld run with no sign of detrimental wear or damage to the tool.

Pin tools shall be permanently marked with unique identification numbers to ensure positive traceability to the tool configuration specified by a production WPS.

Production ready pin tools shall be stored in a clean, dry, and secure environment so as to avoid contamination and damage to the tools or commingling of the tools with other tools in development, testing or other non production approved operations.

6.0 PROCESS REQUIREMENTS

All weldments shall be fabricated according to the requirements of this process specification. 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.

All Friction Stir Welding shall be performed using WPSs that have been qualified in accordance with the requirements of Section 6.2.

6.1 PROCESS-SPECIFIC REQUIREMENTS

Intermittent or continuous arc fusion tack welding of weldment assemblies to facilitate fit up or otherwise shall be allowed, with or without filler metal. However, this allowance shall be made provided that the weld qualification tests include the very same tacking operation and metallurgical and mechanical test specimens that include lengths of the weld seam which contained the specified tack weld. Tack welding shall be considered an essential variable and shall be specified on an approved WPS.

Wherever possible, weld run-on and run-off tabs shall be used for starting and terminating welds. Alternatively, extra length may be designed into the workpiece to act as starting and terminating areas. Start and termination areas shall have a minimum length of 3 tool diameters (measured at the O.D. of the shoulder).

6.2 WELD QUALIFICATION

A Welding Procedure Specification shall be qualified for each unique weld type (as detailed in 6.2.2) 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 it is demonstrated that the essential weld variables listed in Table V and VI will be met. Demonstration shall constitute weld trial runs detailed in Section 6.2.4 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 Procedure Qualification Record (PQR).

6.2.1 Unique Weld Type

A "unique weld type" includes those weld joint configurations that differ from one another in any of the following respects:

1. Base metal type/alloy,
2. Base metal temper,
3. Base material thickness,
4. Specific type and shape of joint
5. Addition or deletion of filler material (via a tacking pass or otherwise),
6. Addition, deletion, or change in the preheat, interpass, or post weld heat treatment requirements.

6.2.2 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 1 weld sample with at least 20” in length of useable weld that represents the weld type specified. The full length of the weld shall be made in one continuous setup and machine cycle. The test weld shall be made in the actual production weld fixture. The beginning and ending length of weld equal to a minimum of 3 tool diameters, shall not be considered for examination or testing.
The sample(s) shall be visually inspected on the O.D. and I.D. to Class A criteria, dye penetrant inspected to Class A criteria, and radiographically inspected to Class A criteria. Prior to all inspections, any existing weld flash shall be removed. If the weld procedure includes a specific heat treatment (pre- or postweld heat treatment), the dye penetrant and radiographic inspections shall, at a minimum be performed after the final heat treat cycle.

A minimum of 5 samples from the test plate shall be mechanically tested in tension per AWS B4.0 and the results evaluated to the strength requirements of AWS B2.1 or evaluated to the strength requirements specified by the drawing or contract requirements. A minimum of 2 samples shall be sectioned and metallographically examined and the results evaluated to the requirements of AWS B2.1. Photomicrographs shall be taken of the prepared samples and retained with the PQR. A minimum of 2 face and 2 root bends shall be conducted to the testing requirements of AWS B2.1. Alternatively, 2 side bend specimens may be conducted in lieu of the face and root bend. All bend specimens shall not exceed 3/8” in thickness.

6.2.3 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 V. 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. If an essential variable is changed beyond the allowable range listed, requalification shall be required.

Table V

ESSENTIAL WELDING VARIABLES

No.	Variable / Weld Type	Range Allowed
1	Machine Tool Model #	None
2	Machine Tool Head Model #	None
3	Pin Tool Configuration	See Table VI
4	Joint Configuration (groove vs. lap, etc.)	None
5	Nominal Material Thickness	Drawing tolerances
6	Base Material Alloy Type(s) and Temper	None
7	Preweld Cleaning Steps	None
8	Allowable Joint Gap	≤0.015”
9	Tool or Shop Aid Identification	None
10	Tack welding filler metal	None
11	Heat assistance source	None

Table V ESSENTIAL WELDING VARIABLES		
No.	**Variable / Weld Type**	**Range Allowed**
12	Heat input from heat assistance source (e.g., LASER, GTA torch, etc.)	± 10%
13	Pin Tool Travel Angle	± ½ º
14	Pin Tool Plunge Depth (or Heel Plunge Depth)	± 0.010”
15	Travel Speed	± 10%
16	Travel Start Delay	± 10%
17	Spindle RPM	± 10%
18	Spindle Rotation Direction	See Note 1
19	Heat Treat Procedure/Spec.	None

Table VI ESSENTIAL VARIABLES FOR PIN TOOLS		
No.	**Variable – See Figure 1**	**Range Allowed**
1	Dimension A (dia., pitch, thread direction; LH or RH)	None
2	Dimension B (pin end radius)	± 0.03”
3	Dimension C (pin length from shoulder edge)	± 0.002”
4	Dimension D (shoulder O.D.)	± 0.06”
5	Dimension E (draft angle on shoulder face)	± ½ º
6	Dimension F (shoulder outer & inner radius)	± 0.03” See Note
7	Shoulder face surface configuration	None
8	LH pin thread direction & CW tool rotation	None (See Note 1)
9	RH pin thread direction & CCW tool rotation	None (See Note 1)
10	Pin tool base material	See Note 2
11	Pin tool base material temper	See Note 2
12	Pin tool wear coating	See Note 2

NOTE 1 *– Spindle rotation direction (CW or CCW) shall be fixed for a given specific pin tool thread direction (RH or LH). In addition, spindle rotation shall always be CW when the pin thread direction is LH and CCW when the pin thread direction is RH. For non-threaded pins, spindle rotation may be either direction.*

NOTE 2 *– A change in the base material, temper, or coating (or the addition or deletion of a coating) of a pin tool without changing any of the physical configurations shall not automatically require a weld schedule requalification provided that the tool proves to perform satisfactorily as demonstrated in a preweld test run not less than 20” in length.*

6.2.4 REQUALIFICATION OF WPS

Requalification of the WPS shall be required when preproduction weld samples do not meet requirements and no assignable cause for the failure can be determined.

The samples shall, at a minimum, be subjected to visual inspection and the same NDE as specified for the original WPS qualification 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 V or Table VI, as applicable for that parameter, then the level of testing in 6.2.2 shall be required.

6.3 PREHEATING AND HEAT ASSISTED WELDS

Preheat shall not exceed the temperature specified in the applicable WPS.

Where a heat assistance source is used simultaneously ahead of the FSW pin tool (tandem), parameter control of the heat assistance source to ensure absolute heat input control per linear inch of weld may be substituted for workpiece temperature control provided there are no conditions where the heat assistance source becomes stationary during the weld run. The specific parameters requiring control applicable to the selected heat assistance source shall be identified and specified by NASA/JSC M&P organization.

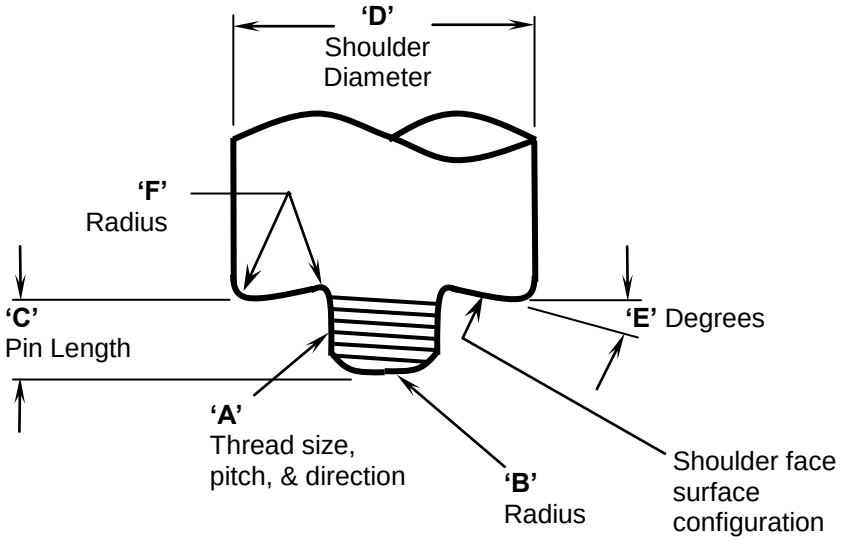


FIGURE 1 – FSW PIN TOOL ESSENTIAL VARIABLES

6.4 HEAT TREATMENT

Heat treatment, when required by the engineering drawing or WPS, shall be performed in accordance with NASA/JSC PRC-2001, PRC-2002, or PRC-2003, as applicable. Vibratory techniques shall not be used in place of thermal treatments.

6.5 WELD REPAIRS AND WELDED REPAIRS TO BASE METAL

All repairs to welds and base metal 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. Weld repair does not include the correction of dimensional or other deficiencies of weld joints 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) Defect Location. Weld repairs shall be adequately documented by the use of a weldment map or other manufacturing record with sufficient detail to ensure identification of the weldment, identification of repair location(s), and type of defect. All indicated defects shall be brought to the attention of the responsible manufacturing or materials engineer for consideration of cause, prior to repair activities.

b) Repair. No more than 1 weld repair attempt shall be made to successfully complete a repair. If this first attempt is unsuccessful, a discrepancy report shall be generated and shall require dispositioning by the responsible Material Review Board (MRB). 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 or heat treatment operation may be straightened. All straightening operations shall take place at temperatures not to exceed 65°C (150°F). All straightening operations must be validated by an appropriate method(s) to show that the process used for straightening does not degrade the joint or surrounding material below specified design requirements.

d) Base Metal Repairs. Repairs to base metal anomalies shall be brought to the attention of the NASA/JSC M&P organization for consideration of cause, prior to repair activities.

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.

7.1 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.

7.1.1 Class A

Class A welds require visual, surface and subsurface inspections. Surface inspections shall be accomplished using liquid penetrant or magnetic particle methods. 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 NASA/JSC M&P engineering organization. When ultrasonic inspection is selected and approved as an alternate to radiographic inspection, the ultrasonic inspection shall be performed as specified in section 7.2.6.

7.1.2 Class B

Class B welds require visual and surface inspections. Surface inspections shall be accomplished using the liquid penetrant or magnetic particle methods.

7.1.3 Class C

Class C welds only require visual inspection.

7.1.4 Class D

Class D welds only require inspection to verify the weld type, nominal size, length and location and to verify that the welds exhibit good workmanship practices. Good workmanship shall be defined as the presence of a uniform appearance and overall clean weld zones absent of flash, tool marks and other obvious discontinuities. Where a size is not specified, the nominal weld size shall be per best shop practice and at the discretion of the manufacturing organization with the intent to utilize single pass welds wherever possible so as to avoid over-welding. A CWI is not required for this inspection. This level of inspection may serve as a means of “in process” or “self verification” where design and/or manufacturing protocols permit.

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.

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. Acceptance shall be in accordance with the applicable Class A or B acceptance criteria in Appendix A.

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.

7.2.4 Magnetic Particle

a) Non-Flight Hardware: Magnetic particle inspections shall be performed per PRC-6505. Unless otherwise specified, the wet fluorescent continuous method shall be used. Acceptance shall be in accordance with the applicable Class A or B acceptance criteria in Appendix A.

b) Flight Hardware: Magnetic particle inspections shall be performed per PRC-6505. Unless otherwise specified, the wet fluorescent continuous method shall be used. Acceptance shall be in accordance with the applicable Class A or B acceptance criteria in Appendix A.

7.2.5 Radiographic

a) Non-Flight Hardware: Radiographic inspections shall be performed per PRC-6503. Acceptance shall be in accordance with the applicable Class A acceptance criteria in Appendix A. Gamma radiation sources shall not be used unless approved by the NASA/JSC M&P engineering organization. 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 acceptance criteria in Appendix A.

7.2.6 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 CERTIFICATION AND QUALIFICATION OF INSPECTION PERSONNEL

7.3.1 Visual Inspection

Personnel performing visual inspections of Class A, B and C welds shall be American Welding Society (AWS) Certified Welding Inspectors (CWI). The CWI certification must be current.

7.3.2 Nondestructive Inspection

Personnel performing acceptance inspections of flight hardware (Class I, II, IIIW and GSE) shall be qualified and certified, at a minimum, to Level 2 in accordance with NAS 410. Personnel performing acceptance inspections requiring Special 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) 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.

8.0 PROCESS DOCUMENTATION REQUIREMENTS

The WPS, PQR, and 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 (machine tool or specific machine), 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 welding operators, inspectors, supervision, and engineering.

8.1 WELDING PROCEDURE SPECIFICATION

A Welding Procedure Specification (WPS) is a qualified written working procedure that must be developed before beginning production for each unique weld type to be produced. Qualification support documentation in the form of a Procedure Qualification Record (PQR) shall be maintained on file to show proof of process/procedure capability using the WPS. The WPS shall be traceable by means of serialized nomenclature and shall show traceability to the applicable PQR(s). The WPS used for production welding shall meet the requirements stated herein and shall be certified by the responsible M&P organization at the operating facility, prior to use in production.

8.2 PROCEDURE QUALIFICATION RECORD

A Procedure Qualification Record (PQR) is documentation to support the welding procedure specification to show proof of process/procedure capability. A PQR shall be unique and traceable, by means of serialized nomenclature. The PQR shall be process-specific and specific to a unique weld type. Data required in the PQR shall include detailed descriptions of the test coupon configurations and joint designs, all pertinent material specifications, all pertinent essential process variables used, all destructive and nondestructive test results from the qualification sample set, and all required certifications from the approving organization. The PQR shall be approved by the responsible M&P organization at the operating facility.

8.3 WELDING OPERATOR PERFORMANCE QUALIFICATION RECORD

A Welding Operator Performance Qualification (WOPQ) is certified documentation that a welding operator has been tested in accordance with the requirements stated herein and shown competent to produce a sound weld for a specific welding process/base material/base metal thickness combination. WOPQ records shall show the limits of the operator's qualification.

9.0 TRAINING AND QUALIFICATION OF PERSONNEL

9.1 TRAINING

At JSC, if welding operator training is considered necessary prior to qualification/requalification of existing JSC welding personnel or the initial qualification of new hires, it shall be conducted in accordance with TI-0000-04. For an outside JSC vendor, welding operator training (when necessary) should consist of practice using the facility welding equipment and a specific WPS to demonstrate proficiency, under the supervision of a qualified/certified welding operator. Specific development of an appropriate training program shall be the responsibility of the vendor.

9.2 WELDING OPERATOR QUALIFICATION

Welding shall be performed by a welding operator qualified and certified in accordance with AMS-STD-1595 . Sufficiently detailed records shall be maintained to demonstrate continuity of operator performance on the welding system (machine tool) or system(s) on a semi-annual (6 month) basis. These records shall be made available to the NASA/JSC M&P organization upon request.

10.0 DEVIATIONS AND WAIVERS

Any deviations or waivers regarding the use of this process specification shall be requested in writing by the outside vendor. This request shall be directed to the NASA/JSC M&P organization with the appropriate justification and rationale. A written response will be provided upon such a request.

Appendix A

WELD ACCEPTANCE CRITERIA

GENERAL . Unless otherwise stated, the criteria in this Appendix shall apply to all weld classes except class D. Acceptance criteria for Class D welds are detailed only in Section 7.1 of this specification. Alternate and/or additional acceptance criteria may be used for any weld class however; it shall be specified in the design documentation. If any of the inspection conditions listed herein conflict with the requirements of the engineering drawing, then the more strict criteria shall govern. Pertinent to this Appendix, the designation 'T' shall mean the nominal base metal thickness of the thinnest component in the welded connection. In addition, the term "weld length" shall be the distance from end to end of the weld deposit or to a sharp change in direction of the weld where the angle of change in any direction is greater than 30 degrees at a radius of <1/2".

A1.0 SIZE AND APPEARANCE

All Classes - The minimum weld size shall be the size (i.e., size = effective weld throat) specified on the drawing. If profile requirements are not specified, the weld shall be flat or concave within the limits specified in A1.0. Where a weld size is not specified, the penetration requirement shall be 100%.

A2.0 WELD CONCAVITY (THINNING)

Weld concavity depth (face and root) shall not exceed that specified in Table A2.0. This requirement shall not apply where the weld is specified to be machined to the extent of being indistinguishable from the adjacent base metal.

TABLE A1.0 – Weld Concavity Depth Limits

Weld Class	Concavity Depth (apply whichever value is lesser)
Class A	0.02" or 10% of T
Class B	0.03" or 15% of T
Class C	0.045" or 20% of T

A3.0 MISALIGNMENT

Weld joint misalignment shall not exceed that specified in Table A2.0.

TABLE A2.0 – Weld Misalignment Limits

Weld Class	Misalignment (apply whichever value is lesser)
Class A	0.01" or 10% of T
Class B	0.02" or 15% of T
Class C	0.025" or 20% of T

A4.0 SURFACE ROUGHNESS

Weld surface finish shall not exceed 125 µ-inch. This requirement shall not apply where the weld is specified to be machined to the extent of being indistinguishable from the adjacent base metal.

A5.0 DISCONTINUITIES

All Classes - Weld discontinuities exceeding the maximum allowable sizes for the applicable Class in Table A3.0 shall not be allowed. Linear discontinuities shall be defined as having a length to width ratio of ≥ 3:1. Rounded discontinuities shall be defined as having a length to width ratio < 3:1. A crack shall be defined as a fracture type discontinuity characterized by a sharp tip and a high ratio of length to width.

For base metal thicknesses (T) ≥ 1/8", the following shall apply to Table A3.0:

Class A - Any discontinuity, except cracks and linear discontinuities, <0.01" at its greatest dimension, shall not be considered.
Class B - Any discontinuity, except cracks and linear discontinuities, <1/32" at its greatest dimension, shall not be considered.
Class C - Any discontinuity, except cracks and linear discontinuities, <1/16" at its greatest dimension, shall not be considered.

TABLE A3.0 - Maximum Allowable Discontinuity Sizes

LINE ITEM	DISCONTINUITY TYPE	Class A	Class B	Class C
1	**Cracks in the weld or base metal (1) (Includes surface tearing)**	None allowed	None allowed	None allowed
2	**Inadequate Penetration and Incomplete Fusion (1) (Includes wormholes, residual oxide defects, joint line remnant, and lack of adequate forging)**	None allowed	1/16" or 0.3T, whichever is the lesser	3/32" or 0.6T, whichever is the lesser
3	**Linear (1)**	None allowed	1/32" or 0.4T in length, whichever is less (3) Sum of all visible indications shall be ≤3/8" or T in length, whichever is less, in any 1" of weld length and ≤3/4" in any 12" of weld length (4)	1/16" or 0.6T in length, whichever is less (3) Sum of all visible indications shall be ≤1/2" in length, in any 1" of weld length and ≤1.75" in any 12" of weld length (4)
4	**Rounded (1)**	Surface: 1/16" or 0.3T diameter, whichever is less (2)	3/32" or 0.4T diameter whichever is less (2) Sum of all visible indications shall be ≤3/8" or 1.5T in length, whichever is less, in any 1" of weld length and ≤3/4" in any 12" of weld length (4)	1/8" or 0.6T diameter, whichever is less (2) Sum of all visible indications shall be ≤1/2" in any 1" of weld length and ≤1.75" in any 12" of weld length (4)

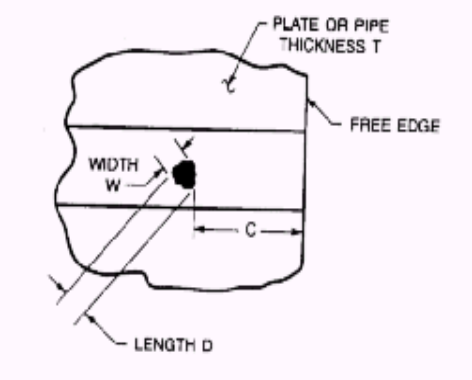
TABLE A3.0 Footnotes:

(1) For all discontinuities approaching a free edge (See Figure A6.0 below) that are being considered, the closest edge of the discontinuity shall have clearance from the free edge ≥ 3X the largest of its dimensions or, ≥ 2X the nominal weld throat, whichever is greater.

(2) Adjacent rounded discontinuities separated by ≤ 1X the length of the longest dimension of the larger discontinuity shall be considered a single discontinuity.

(3) Adjacent linear discontinuities separated by ≤ 3X the length of the longest dimension of the smaller discontinuity, shall be considered a single discontinuity.

(4) For weld lengths less than 12", the total sum of indications shall be an equivalent proportion of the weld length, to that given.



C = Clearance spacing between closest edge of discontinuity and free edge