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MSFC TECHNICAL STANDARD

PROCESS SPECIFICATION - WELDING AEROSPACE HARDWARE

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1.0 SCOPE

This process specification establishes uniform requirements for the design, fabrication, and inspection of welds in flight and ground support hardware. This process specification combines the lessons learned from extensive Agency-wide welding engineering experiences and combines the requirements of project, Center, other government, and industry documents used for the manufacture of historic spaceflight hardware such as Saturn, the Space Shuttle, and the International Space Station.

When this process specification is specified on contract documents, the contractor may submit an alternative, corporate, detailed weld process specification that meets the intent of this specification. Industry, government, and company specifications may be used for welding hardware in lieu of this specification if approved by the responsible National Aeronautics and Space Administration (NASA) Technical Authority. The content of this process specification meets the intent of NASA-STD-(I)-5006A.

1.1 Purpose

The purpose of this process specification is to establish the minimum process control requirements for the design, fabrication (including the qualification of welders, welding operators, and welding procedure specifications), and quality assurance of manual, semiautomatic, mechanized, and automatic welds in flight and ground support hardware used by or for Marshall Space Flight Center (MSFC).

1.2 Applicability

This process specification is approved for use by MSFC and may be cited in contract, program, and other documents as a technical requirement. This process specification may also apply to contractors and subcontractors to the extent specified or referenced in their contracts.

Requirements are numbered and indicated by the word "shall." Explanatory or guidance text is indicated in italics beginning in section 4.

1.2.1 Applicable Processes

This process specification is applicable to weld processes used for joining metallic materials. These include, but are not limited to, the following:

a. Arc Welding: Gas Tungsten Arc (GTAW), Gas Metal Arc (GMAW), Plasma Arc (PAW), Variable Polarity Plasma Arc (VPPA), Shielded Metal Arc (SMAW) Submerged Arc (SAW) Flux Core Arc Welding (FCAW) and the pulsed derivatives

b. Solid-State Welding: Friction, Friction Stir (FS), Inertia, Plug (FPW)

c. Resistance Welding

d. High-Energy Density Welding: Electron Beam (EB) and Laser Beam (LB).

1.2.2 Applicable Materials

This process specification covers all metallic materials used in the manufacture of flight hardware.

1.3 Tailoring

Tailoring of this process specification for application to a specific assembly or subassembly shall be formally documented on the engineering drawing and approved by the responsible NASA Technical Authority.

1.4 Safety

1.4.1 Industrial Safety

a. Appropriate personal protective equipment shall be used in all hazardous processes.

b. All hazardous materials and processes that are required in compliance with provisions of this process specification and that are located or performed at sites other than MSFC are subject to applicable federal, State, and local safety codes, standards, and regulations.

c. All hazardous materials and processes that are required in compliance with provisions of this process specification and that are located or performed at MSFC shall be subject to MPR 8715.1, Marshall Safety, Health, and Environmental (SHE) Program.

1.4.2 System Safety

a. System safety engineering (SSE) shall identify critical and catastrophic hazards and mitigations to eliminate and/or control the hazards of the welding operations.

b. SSE shall participate within the various program working groups, panel reviews, and procedures and drawing reviews of welding systems and processes.

c. SSE shall participate in welding process reviews and decisions to ensure that safety concerns are addressed and appropriate safety requirements and design criteria are implemented in accordance with applicable program Safety, Reliability, and Quality Plan.

1.5 Specific Process Weld Requirements

1.5.1 Resistance Welding

Resistance welding shall be in accordance with AWS D17.2/D17.2M, Specification for Resistance Welding for Aerospace Applications, or SAE AMS-W-6858A, Welding, Resistance: Spot and Seam.

1.5.2 Laser Beam Welding

LB welding shall be in accordance with AWS C7.4/C7.4M, Process Specification and Operator Qualification for Laser Beam Welding.

1.5.3 Friction or Inertia Welding

Direct drive friction or inertia welding shall be in accordance with AWS C6.1, Recommended Practices for Friction Welding.

2.0 APPLICABLE DOCUMENTS

The latest issues of the following documents form a part of this specification to the extent specified herein. In the event of a conflict between the documents referenced herein and the contents of this specification, the content of this specification shall take precedence. The contractor may pursue substituting equivalent specifications and documents to the ones identified herein as long as the substitution does not compromise the intent of the specifications and documents identified herein and is approved by NASA/MSFC before implementation.

2.1 Applicable Documents

STANDARDS

Military

MIL-A-18455	Argon, Technical
MIL-PRF-27401	Propellant Pressurizing Agent, Nitrogen
MIL-PRF-27407	Propellant Pressurizing Agent, Helium

NASA

NASA-STD-5009	Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware
NASA-STD- 6016	Standard Materials and Processes Requirements for Spacecraft

OTHER PUBLICATIONS

ASTM E 8/E 8M	Standard Test Methods for Tension Testing of Metallic Materials
AWS A2.4	Standard Symbols for Welding, Brazing, and Nondestructive Examination
AWS A3.0	Standard Welding Terms and Definitions Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying
AWS A5-ALL	Filler Metal Procurement Guidelines
AWS A5.01M/A5.01	Procurement Guidelines for Consumables – Welding and Allied Processes – Flux and Gas Shielded Electrical Welding Processes
AWS A5.12M/A5.12	Specification for Tungsten and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting
AWS B2.1/B2.1M	Specification for Welding Procedure and Performance Qualification
AWS B4.0	Standard Methods for Mechanical Testing of Welds
AWS C6.1	Recommended Practices for Friction Welding
AWS C7.4/C7.4 M	Process Specification and Operator Qualification for Laser Beam Welding
AWS D17.1	Specification for Fusion Welding for Aerospace Applications
AWS D17.2/D17.2 M	Specification for Resistance Welding for Aerospace Applications
AWS D17.3	Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications
AWS G2.4/G2.4 M	Guide for the Fusion Welding of Titanium and Titanium Alloys
AWS QC1	Standard for AWS Certification of Welding Inspectors
BB-C-101	Carbon Dioxide (CO_2): Technical and USP
BB-H-886	Hydrogen

BB-O-925	Oxygen, Technical, Gas and Liquid
CxP 70156	Constellation Program Fluid Procurement and Use Control Specification, Welding Precision Cleaned Hardware
MIL-HDBK-1823	Nondestructive Evaluation System Reliability Assessment
MPR 8715.1	Marshall Safety, Health, and Environmental (SHE) Program
NPR 1441.1	NASA Records Retention Schedules
NAS 410	NAS Certification & Qualification of Nondestructive Test Personnel
NAS 1514	Radiographic Standard for Classification of Fusion Weld Discontinuities
NASA-STD-(I)-5006A	Welding Requirements for Aerospace Materials Used in Flight Hardware
SAE AMS 2680	Electron-Beam Welding for Fatigue Critical Applications
SAE AMS 2770	Heat Treatment of Wrought Aluminum Alloy Parts
SAE AMS-W-6858A	Welding, Resistance: Spot and Seam

2.2 Reference Documents

The documents listed in Appendix H are provided as background information for users of this specification, defining the source of the requirements in sections 4 through 11 of this specification. The listing in this section does not levy any new or relieve any specific requirements that are imposed by this specification or other contractual documents associated with procurement of this specification end item.

2.3 Order of Precedence

Conflicts between this specification and other requirements documents shall be resolved by the responsible NASA Technical Authority.

3.0 ACRONYMS AND DEFINITIONS

3.1 Acronyms and Abbreviations

°C	degrees Celsius

°F	degrees Fahrenheit
≤	equal to or less than
>	greater than
<	less than
µ	micro
-	minus
%	percent
+	plus
±	plus or minus
AMS	Aerospace Material Specification
ASTM	ASTM, International
AWS	American Welding Society
Btu	British thermal unit
C-FSW	conventional friction stir welding
cm	centimeter
CO_2	carbon dioxide
CxP	Constellation Program
deg	degree
DOP	depth of penetration
EB	electron beam
ELI	extra low interstitial
FPW	friction plug weld
FS	friction stir
FSW	friction stir weld, friction stir welding
GTAW	gas tungsten arc welding
HDBK	handbook
hr	hour
in	inch
ipm	inches per minute
J	joule
ksi	thousand pounds per square inch
LB	laser beam
LH_2	liquid hydrogen
LO_2	liquid oxygen
LOP	lack of penetration
M	metric
M	mega
MAX	maximum
MIL	military
MIN	minimum
min	minute (angle)
min	minute (time)
mm	millimeter
MPa	megapascal

MPR	Marshall Procedural Requirements
MRB	Material Review Board
MSFC	Marshall Space Flight Center
MUA	Materials Usage Agreement
N/A	not applicable
NAS	National Aerospace Standards
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
NIST	National Institute of Standards and Technology
Pa	Pascal
POD	probability of detection
PQR	Procedure Qualification Record
PRF	performance (specification)
R	reinforcement (crown)
R'	reinforcement (root)
rpm	revolutions per minute
RPT	retractable pin tool
S	weld bead concavity
S&MA	Safety and Mission Assurance
SAE	Society of Automotive Engineers, International
sec	second
SHE	safety, health, and environmental
SI	Systeme Internationale or metric system of measurement
SMA	Safety and Mission Assurance
SPAW	soft plasma arc welding
SR-FS	self-reacting friction stir
SSE	system safety engineering
SSME	Space Shuttle Main Engine
STD	standard
t	thickness of thinner joint member
T	thickness of thicker joint member
USP	United States Pharmacopeia
VPPA	variable polarity plasma arc
W	Watt
W'	maximum weld width (crown)
W"	maximum weld width (root)
WPQ	Welder Performance Qualification
WPS	Weld Procedure Specification

3.2 Definitions

3.2.1 General Welding Definitions

Unless otherwise defined in this process specification, welding terms, definitions, and symbols shall conform to AWS A2.4, Standard Symbols for Welding, Brazing, and Nondestructive Examination, and AWS A3.0, Standard Welding Terms and Definitions Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying.

<u>2-for-1 Replacement</u>: The practice of replacing a procedure qualification panel that does not meet specification requirements with two panels welded with identical parameters; this practice is only used when the original panel failed the criteria because of a processing error not associated with the weld parameters.

<u>Anomaly</u>: A deviation or irregularity.

<u>Automatic Welding</u>: Welding with equipment that performs the welding operation without adjustment of the controls by a welding operator.

<u>Backing Button/Plate</u>: The anvil that reacts the load during friction plug push/pull welding.

<u>Certified</u>: Term describing a welder or inspector who passes qualification tests based on requirements established in this process specification or term describing a weld procedure that passes qualification tests based on requirements established in this process specification.

<u>Chill Bar</u>: A steel, aluminum, or copper bar that limits distortion by limiting the heat flow from a weld joint.

<u>Concave Root Surface</u>: A weld root with penetration not extending beyond the thickness of the base metal; sometimes referred to as “suckback.”

<u>Confidence Panel/Weld</u>: A full-scale, high-fidelity weld made in production tooling with procedures and parameters intended for flight hardware; can be nondestructively and destructively tested to validate the production weld procedure.

<u>Critical Defect</u>: A defect that adversely affects the weld properties, causing the weld not to perform as designed, resulting in failure of the weld joint.

<u>Cross-Slide</u>: Travel perpendicular to the weld direction along the surface of the hardware.

<u>Deburred</u>: Having had the thin ridge or area of roughness produced in cutting or shaping metal removed.

<u>Defect</u>: A discontinuity or discontinuities that by nature or accumulated effect render a

part or product unable to meet minimum standards or specifications; designates rejectability.

Degaussed: Made effectively nonmagnetic by means of electrical coils carrying currents that neutralize the magnetism of a metal object.

Essential Variables: Weld process parameters that influence directly the weld process and resulting weld properties; examples are heat input, travel speed, torch setup, pin tool configuration.

Fail Safe: A condition in which, after failure of a single individual structural member, the remaining structure can withstand the redistributed loads with an ultimate factor of safety of 1.0 on limit load. The failure is contained or constrained so that the failed part does not affect other flight elements or personnel.

Fixture: A device designed to hold and maintain parts in proper relation to each other.

Forge Load: A compressive load applied to the weld after the heating cycle in friction plug or friction welding.

Forge Time: The time during which the forge load is applied.

Heat Input: Quantity of energy introduced per unit length of weld from a traveling heat source, expressed in British thermal units per inch (Btu/in) (joules per millimeter (J/mm)). (Computed as the ratio of the total input power of the heat source in watts (W) (Btu/second (sec)) to the travel velocity in millimeters per second (mm/sec) (inches per minute (in/min)).

Heat-Sensitive Alloys: Alloys that require mechanical working, precipitation strengthening, or other metallurgical mechanisms to obtain their rated strength, if exposure to the heat input from the welding process reduces or eliminates this strengthening mechanism in proximity of the weld.

Heating Displacement/Burn Off: Terms used in friction plug pull welding, referring to the distance the plug is pulled through the material after initial contact with the part being welded.

Heating Load: The compressive load applied during the heating phase of friction plug welding.

In-Process Correction: Action taken by a welder to complete a process before submittal to inspection.

Incomplete Fusion: A weld discontinuity in which fusion did not occur between weld metal and fusion faces or adjoining weld beads.

Incomplete Joint Penetration: A weld depth (extending from its face into the joint, exclusive of reinforcement) that is less than the joint thickness.

Lack of Fill: A weld face surface not extending beyond the thickness of the base metal.

Machine Welding: Welding with equipment that performs the welding operation under the constant observation and control of a welding operator.

Manual Welding: A welding operation performed and controlled completely by hand.

Material Review Board (MRB): A cross-functional group that reviews production or purchased items on hold because of nonconformance or usability concerns and that determines their disposition, which may include rework, scrap, or return to the vendor.

Material Thickness: The minimum material thickness of a joint member in accordance with drawing tolerance; the thinner of the joint members with different thicknesses is designated "t."

Mismatch: The linear distortion of the components; calculated as the difference in the alignment of the center lines of the two parts; does not refer to the difference in center lines as a result of welding two different thickness components.

Nonstructural Weld: A non-load-bearing weld.

Pathfinder: High-fidelity demonstration weld before first production article; last item to be welded before first production article.

Peaking: The angular distortion of the components resulting from welding; calculated as the angle resulting from the intersection of tangents taken from the surface of the two components being welded.

Peening: The surface working of metal by means of mechanical, thermal, or acoustic methods. Most commonly accomplished through repeated blows of impelled shot or a round-nose tool.

Planishing: Mechanical working of weld metal by rolling in a mill or through a rapid succession of blows delivered by highly polished dies or hammers.

Procedure Qualification Record (PQR): A document providing the actual welding variables used to produce an acceptable test weld and the results of tests conducted on the weld for the purpose of demonstrating process and procedural capability and repeatability; demonstration of capability qualifies the welding procedure.

Proficiency Demonstration: Demonstration of a welder's or welding operator's ability to produce welds meeting prescribed standards.

Procedure Qualification: Demonstration that welds made by a specific procedure can meet prescribed standards.

Qualified: A term describing a welder (operator) who has demonstrated adequacy to meet prescribed requirements or describing a procedure that has demonstrated adequacy to meet prescribed requirements.

Qualified Inspector: A certified individual with the responsibility and ability to judge the quality of the welded specimens in relation to a written specification.

Quantitative Nondestructive Evaluation (NDE): A statistically grounded detection size, generally 90 percent detection level with 95 percent confidence probability of detection study.

Repair: A procedure that makes a nonconforming item acceptable for use. The purpose of the repair is to reduce the effect of the nonconformance. Repair is distinguished from rework in that the characteristics after repair still do not completely conform to the applicable drawings, specifications, or contract requirements. Nonstandard repair procedures are authorized by MRB action for use on a one-time basis only. All repairs require MRB approval before implementation.

Rework: A procedure applied to a nonconforming item that completely eliminates the nonconformance and results in a characteristic that conforms completely to the drawings, specifications, or contract requirements.

Root of Joint: That portion of a joint at which members are closest to each other. (Illustrated in Figure 4.)

Root of Weld: The point at which the weld intersects the base metal surfaces. (Illustrated in Figure 4.)

Semiautomatic Welding: Welding with equipment that controls only the filler metal feed; advance of welding is controlled manually.

Sound Metal: Weld metal that is free from defects or flaws.

Suckback: A condition in which the weld face or root surface extends below the adjacent surface of the base metal; also called “concave root surface” or “underfill”.

Superalloy: An alloy that resists oxidation and can withstand high temperatures and stresses

Tapered Welds: Weld joints that change in thickness along the length of the joint.

Technical Authority: A representative of the contracting agency or corporate organization who acts on behalf of the customer on technical matters. (AWS specifications use the term "engineering authority;" for this specification, "engineering authority" is to be interpreted to mean the NASA technical authority.

Tooling: Production machinery.

Total Porosity Index: The total amount of porosity in a single lineal inch of weld. The porosity index shall be determined by summing the sizes of all individual pores including individual pores contained in a cluster, in that portion of weld. Pores of size less than .001 inch shall be deemed to be .001 inch. For convenience, each 0.001 inch increment is assigned an index number of one (1). Thus a weld containing four pores, in a given lineal inch, with sizes of .030, .020, 0.001 and .0005, would have a total index of 30+20+1+1 = 52.

Undercut: In fusion welds, a groove melted into the base metal adjacent to the weld toe or weld root and left unfilled by weld metal.

Underthickness: A thickness less than nominal in friction stir welds.

Weld Land: Thickened base metal at the weld joint.

Weld Procedure Specification (WPS): A document providing in detail the required variables for a specific application to ensure repeatability by properly trained welders and welding operators.

Weld Zone: The weld metal fusion zone plus the heat-affected zone.

Welder: Individual who performs manual or semiautomatic welding.

Welder Certification: Written verification that a welder has produced welds meeting a prescribed standard of welder performance.

Welder Performance Qualification (WPQ): The demonstration of a welder's ability to produce welds meeting prescribed standards.

Welding Operator: Individual who performs mechanized or automatic welding.

3.2.2 Friction Stir Welding (FSW) Definitions

The following definitions apply specifically to the FSW process, illustrated in Figure 1, Conventional Friction Stir Welding Process, and Figure 2, Self-Reacting Friction Stir Welding Process:

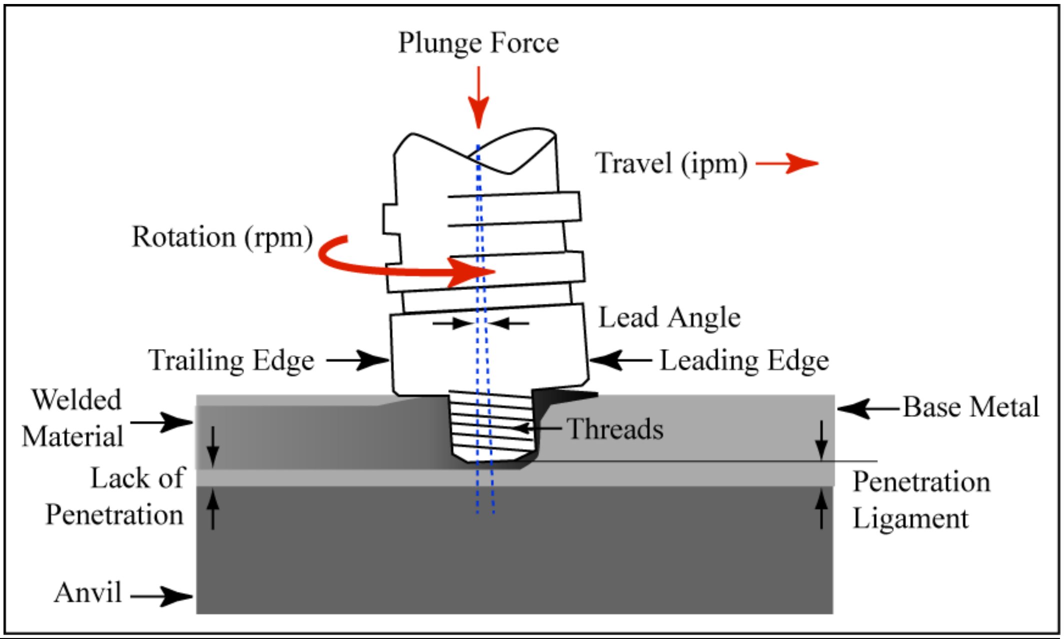


Figure 1. Conventional Friction Stir Welding Process

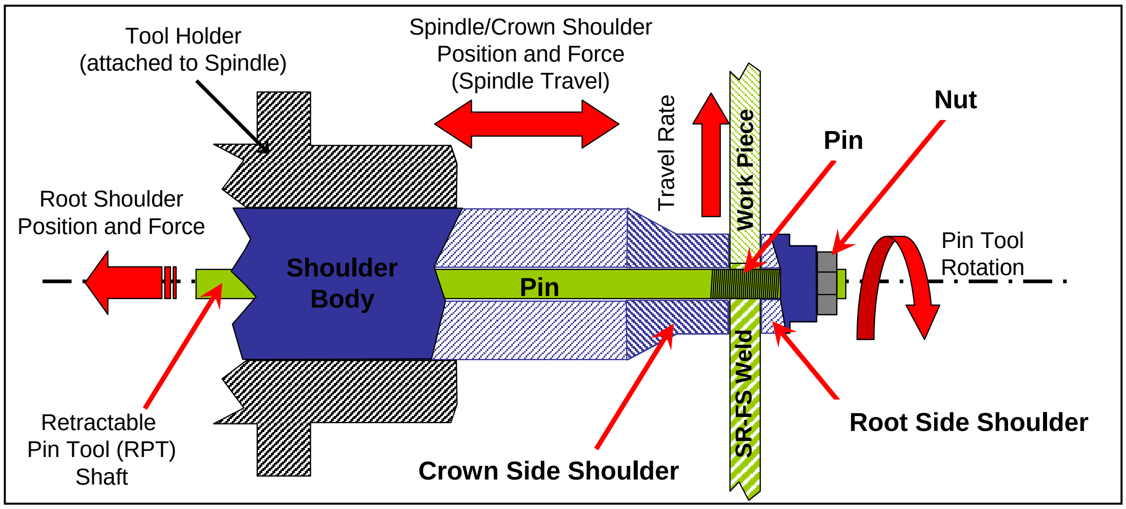


Figure 2. Self-Reacting Friction Stir Welding Process

Advancing Side: The side of the FS weld on which the local tangential velocity of the tool and the travel (translational) velocity of the tool are in the same direction; for dissimilar metal combinations, the joint designation follows the naming convention of advancing/retreating.

Anvil: A rigid surface used to keep the workpiece stationary and to react the plunge force in conventional FSW (C-FSW).

Centerline Offset: The distance from the theoretical center that the pin tool is offset toward either the advancing or retreating side.

Conventional FSW: FSW in which the load is reacted by an anvil.

Forge Load: A compressive load applied to the weld during friction stir welding.

Forge Time: The time during which the forge load is applied.

Gouge: A depression or groove on the surface of the metal in which some of the metal has been removed; similar to a scratch but usually larger and wider with a flat or concave bottom; may have a sharp burr or raised metal at the terminal end.

Heel Plunge: The greatest distance the shoulder plunges below the surface of the material being joined during a weld; typically measured at the trailing edge of the shoulder.

Joint Line Remnant: Discontinuity consisting of a semi-continuous layer of oxide in the weld.

Lack of Fill/Surface Lack of Fill: A condition in which the weld face surface extends below the surface of the adjacent base metal; a continuous or intermittent surface void caused by insufficient FSW pin tool heel plunge depth.

Leading Edge: The edge of the pin tool that is instantaneously located in the position farthest forward along the weld in the direction of travel.

Penetration Ligament: The shortest distance between the anvil and the pin tip during a weld.

Pin (Probe): The threaded part of the tool; embedded below the surface of the workpiece.

Plunge Force: The necessary force to maintain a consistent heel plunge or penetration ligament.

Retreating Side: The side of the FSW on which the local tangential velocity of the tool and the travel (translational) velocity of the tool are in the opposite direction.

Self-Reacting Friction Stir (SR-FS): FS welding process in which the anvil is replaced by a root side shoulder that reacts the crown shoulder load, squeezing the material between the crown and root side shoulders.

Scratch: A groove formed in the surface of the metal. Metal is not always removed, but raised metal may be present on either side of the impression.

Shoulder: The part of the tool that rests directly on the surface of the workpiece.

Surface Galling: Damage that removes particles from the surface; caused by excessive pin tool rotation.

Surface Tearing: Minute surface cracks caused by excessive pin tool rotation.

Thickness Offset: The difference in thickness of the two parts making up the weld joint.

Tool Mark: An impression or cut in the metal that generally occurs in a distinct pattern.

Trailing Edge: The edge of the pin tool that is instantaneously located in the position farthest back along the weld, in the direction of travel.

Traverse: To travel in the weld direction.

Traverse Load: The force necessary to push the tool along the workpiece joint during welding; depends on the weld pitch, pin tool geometry, workpiece thickness, and material alloy being welded.

Weld Flash: Material pushed outward by the tool shoulder along the edges of the shoulder contact area. (Also occurs in plug, inertia, and flash welding.)

4.0 JOINT CLASSES

a. Deviations from the following requirements shall be approved by the responsible NASA Technical Authority.

b. Welds performed using this process specification shall be classified in accordance with the consequences of joint failure as described in the following sections.

c. Welds shall be inspected per Figure 3.

Method of Inspection	**Weld Class**		
	A	**B**	**C**
Visual	**X**	**X**	**X**
Dimensional	**X**	**X**	**X**
Surface	**X**	**X**	**O**
Volumetric	**X**	**see note**	**O**
Additional Inspection When Required by Drawing	**X**	**X**	**X**

Note: Class B welds shall be subjected to volumetric inspection if required by engineering design and specified by drawing or special instruction.

Figure 3. Minimum Inspection Requirements

4.1 Class A Joints

4.1.1 A weld joint whose failure would result in loss of crew, loss of vehicle, or loss of mission shall be classified as a Class A joint.

4.1.2 Class A welds shall pass quantitative surface and volumetric NDE and visual inspection in accordance with Figure 3 and Section 11 of this specification.

4.1.3 Class A fillet welds shall require a Materials Usage Agreement (MUA) in accordance with NASA-STD -6016, Standard Materials and Processes Requirements for Spacecraft.

Based on consequences of failure, all fracture-critical welds are, by definition, Class A joints. If the quality of the Class A joint cannot be verified as required by this specification, e.g., inaccessible volume or root surfaces, then alternative rationale for acceptance is to be presented to the responsible NASA Fracture Control Board for approval as required by NASA-STD-5019, Fracture Control Requirements for Spaceflight Hardware

4.2 Class B Joints

4.2.1 A fail-safe weld joint shall be classified as a Class B joint.

4.2.2 Class B welds shall pass quantitative NDE and visual inspection in accordance with Figure 3 and Section 11 of this specification.

4.3 Class C Joints

4.3.1 A nonstructural weld joint shall be classified as a Class C joint.

4.3.2 Class C welds shall pass a visual inspection in accordance with Figure 3 and Section 11 of this specification.

4.3.3 Class C welds shall be contained fully so that failure in service would have minor or no effect on the efficiency of a system and so that endangerment to personnel would not occur.

5.0 EQUIPMENT

5.1 Welding Equipment

a. When operated by a qualified operator in accordance with a qualified WPS, in accordance with sections 7.1 and 7.2 of this process specification, all welding equipment shall be capable of producing welds that meet the weld quality requirements specified herein.

b. Welding equipment shall be procured in accordance with an approved specification.

c. Equipment parametric fluctuations, variations that occur in equipment without human intervention, shall be characterized by the equipment vendor.

d. Violations of tolerances related to equipment variations during the steady-state portion of the weld and that occur for less than 6 sec shall not be cause for rejection.

Variations caused by the number of times the data are sampled per second can cause the readings to be outside the certified range. As long as the number is random (hence, the 6-sec limit), it is not cause for rejection.

e. EB welding equipment shall be of a hard vacuum type for welding in $5x10^{-4}$ torr ($6.7x10^{-2}$ Pa) (or better) vacuum.

5.1.1 Acceptance Testing

a. New, repaired, relocated, or modified welding machines shall be acceptance tested under the cognizance of the responsible quality control organization before release to manufacturing departments for production welding.

b. Equipment shall meet the requirements of the applicable purchase specification, design specification, or modification order.

c. All equipment (electrical and mechanical) shall operate reliably within the range of parameters and duty cycle to be used for welding of production parts.

5.1.2 Calibration

a. Calibration shall be traceable to National Institute of Standards and Technology (NIST) standards.

b. Welding shall be accomplished using equipment containing calibrated data indicators within manufacturer-specified tolerance ranges that display and/or record welding parameters.

c. Measuring instruments, meters, gauges, or direct reading electrical control circuits to be used for welding operations shall be calibrated.

d. Calibration shall be verified periodically at intervals specified by the manufacturer of the welding equipment, not to exceed 1 year, or when any maintenance or repair is performed that may have changed calibration.

e. Current calibration status shall be posted with the equipment.

5.1.3 Maintenance and Maintenance Records

a. A preventive maintenance plan shall be implemented for welding equipment.

b. Welding machines shall be provided with adequate periodic preventive maintenance service.

c. A current record of each maintenance repair shall be maintained for each welding machine.

d. Location of maintenance records shall be identified on welding machines.

e. Maintenance records shall be maintained per section 11.3.1 of this weld specification.

f. Records shall include unique identification of equipment, date, and time of service/repair, description of work completed, and traceability to employee performing the maintenance.

5.1.4 Equipment Qualification

a. Welding equipment shall pass qualification testing to demonstrate capability to accomplish the intended work before use in production welding.

b. The qualification welds shall meet the strength requirements of section 7.3.3 and the Class A weld quality requirements of Appendix D.

c. Welds shall be made periodically, not to exceed 5 years, to verify that the equipment performance has not changed.

d. Equipment qualification documentation shall be retained as long-term temporary records by the developing organization per section 11.3.1 of this weld specification.

5.1.5 Weld Equipment Requalification

a. Weld equipment requalification shall be required when the welding equipment has failed to accomplish the intended function or when any major modification is made to the equipment.

Major modifications include any changes to sensor equipment, support hardware, software, or the weld system affecting process control.

b. When any modification or maintenance (outside the regular maintenance schedule) is made to the equipment, the responsible NASA Technical Authority shall be notified.

c. Equipment requalification documentation shall be retained as long- term temporary records by the developing organization

5.2 <u>Tooling and Fixtures</u>

5.2.1 General Requirements

a. Tooling and fixtures shall be identified in the WPS.

b. Tooling and fixtures used in the welding operation shall be constructed of materials that do not adversely affect the weld process and are not detrimental to the weld quality.

c. Tooling and fixtures shall not be a source of contamination of the weld or of the part being welded.

d. Fixtures within 2 in (5 centimeters (cm)) of the weld joint shall be visually free from rust, oxide scale, dirt, oil, grease, paint, low melting alloys, e.g., lead, tin, cadmium, and other contaminants detrimental to weld quality.

Paint may be within 1 in (2.5 cm) on FSW fixtures.

5.2.2 Clamping and Alignment

a. Tooling and fixtures shall maintain component alignment during welding and ensure compliance with dimensional requirements of section 10.3 of this process specification.

b. In plug welding, there shall be contact between the component and the backing anvil.

5.2.3 Magnetic Materials

a. When used with arc or EB welding, magnetic materials shall be degaussed before welding.

b. Degaussing of magnetic materials shall be controlled by the WPS when necessary for the successful completion of the weld.

c. <u>Degaussing</u> – Prior to welding, ferromagnetic parts or tooling which have been subjected to the influence of magnetic fields (e.g., GTAW tack welded, machined using magnetic chucks, or magnetic particle inspected) shall be degaussed prior to welding. (This is to prevent electron beam deflections while welding the joint).

5.2.4 Chill Bars

a. Chill bars shall not be used in such a manner that the weld joint location surfaces pick up chill bar material.

Chrome-plated copper chill bars may be used.

Copper or copper alloys have caused liquid metal embrittlement of austenitic alloys.

Electroless nickel plating introduces phosphorus, which is detrimental to the weld process.

b. Aluminum, aluminum alloys, or other low melting alloys shall not be used for chill bars for non-aluminum alloy weld joints.

5.3 EB Welding

5.3.1 EB welding shall be performed in a vacuum with absolute pressure of 0.133 Pa (0.001 torr) or lower”.

5.3.2 Back-up material used to deflect or absorb residual EB energy shall be of the same alloy as the part being welded, except when authorized by the NASA Technical Authority.

Alternate back-up materials may be used when specified by the WPS.

6.0 MATERIALS

6.1 Base Metals

6.1.1 Unless otherwise specified or approved by the procuring agency, the base metal alloy shall conform to applicable material specifications as defined on the engineering drawing.

6.1.2 The base metal type and condition, as well as the appropriate material specification shall be recorded as a part of the WPS.

6.1.3 Weld start and run-off tabs, when used, shall be of the same alloy as the material being joined and be welded with the same filler metal specified on the drawing or WPS.

Backing material may be used when authorized by the WPS.

6.2 Filler Metals

6.2.1 Weld filler materials shall be purchased according to AWS A5.01M/A5.01 Procurement Guidelines for Consumables – Welding and Allied Processes – Flux and Gas Shielded Electrical Welding Processes.

6.2.2 Unless otherwise specified or approved by the procuring agency, filler metal alloy shall conform to all AWS A5 filler metal material specifications (AWS A5-ALL, Filler Metal Procurement Guidelines).

6.2.3 Weld filler materials and the appropriate specifications shall be recorded on the WPS.

6.2.4 Weld filler materials shall be stored under conditions to maintain filler material cleanliness and quality.

6.2.5 Uncoated weld filler wires shall be identified with a unique identification placed at the lowest level of control, i.e., wire, package, tube, to ensure material traceability of all uncoated welding filler wires.

Recommended weld filler metals are listed in Appendix F.

6.2.6 Metal consumable inserts shall be qualified, their material traceability maintained, and both recorded as part of the WPS.

6.2.7 Material traceability for friction plugs shall be ensured.

6.2.8 Commercially pure titanium filler metal shall not be used for joining Ti-6Al-4V weld joints.

6.3 Shielding Gas

6.3.1 Welding-grade gases conforming to the applicable industry or military specifications shall be used for gas shielding when required.

a. Argon – Argon gas shall conform to the requirements of MIL-A-18455, Argon, Technical

b. Nitrogen – Nitrogen gas shall conform to the requirements of MIL-PRF-27401, Propellant Pressurizing Agent, Nitrogen

c. Oxygen – Oxygen gas shall conform to the requirements of BB-O-925, Oxygen, Technical, Gas and Liquid

d. Helium – Helium gas shall conform to the requirements of MIL-PRF-27407, Propellant Pressurizing Agent, Helium

e. Hydrogen – Hydrogen gas shall conform to the requirements of BB-H-886, Hydrogen

f. Carbon dioxide – Carbon dioxide gas shall conform to the requirements of BB-C-101, Carbon Dioxide (CO_2): Technical and USP

6.3.2 The shield gas type and flow rates shall be recorded as a part of the WPS.

6.3.3 Inert gas back-side shielding shall be used on joints requiring full or partial penetration on alloys susceptible to heavy oxide formation on the root side, the formation of which cannot be removed by wire brushing and will interfere with surface inspection.

6.3.4 Only helium or argon shielding gas shall be used for welding titanium and titanium alloys.

6.4 Tungsten Electrodes

6.4.1 Tungsten electrodes shall conform to AWS A5.12M/A5.12, Specification for Tungsten and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting.

6.4.2 The electrode diameter and tip shape and alloy composition shall be recorded as a part of the WPS.

6.5 FSW Pin Tools

6.5.1 FSW pin tools (shoulders and pins) and tack tools shall be made of materials that resist wear during welding.

6.5.2 Pin and shoulder service life shall be demonstrated to meet the intended use and the use of pins and shoulders limited to the demonstrated life.

a. Pins and shoulders that have reached the specified service life shall be marked and removed from service to preclude accidental future use in the FSW production process.

b. If used for more than one weld joint, pins and shoulders shall be cleaned and inspected as required before reuse on production hardware.

6.5.3 Pin tools shall be visually inspected after each production weld for unacceptable wear and damage. Cracks, pits, flakes, and missing or broken threads shall result in the rejection of the pin tool from use in production.

6.5.4 Findings of pin tool visual inspections shall be recorded and hardware welded with damaged pin tools dispositioned before acceptability for use.

6.5.5 Pin tool design and materials shall be recorded as part of the WPS.

6.6 Anvils and Plug Weld Backing Material

6.6.1 Unless otherwise specified or approved by the procuring agency, anvil materials shall conform to applicable government and/or industry specifications for each given alloy group.

6.6.2 Anvil material shall be resistant to deformation under the loads and temperatures experienced during C-FSW.

6.6.3 Anvil material shall not chemically react with the components to be joined.

6.6.4 Anvil and plug weld backing materials shall be recorded as part of the WPS.

6.7 Friction Plugs

6.7.1 Unless otherwise specified or approved by the procuring agency, friction plug materials shall conform to applicable government and/or industry specifications for each given alloy group and their material traceability be ensured.

6.7.2 Plugs shall be stored in an area that precludes their degradation by humidity, contamination, or chemical attack.

6.7.3 Plug weld design and material shall be recorded as part of the WPS.

7.0 WELDER PERFORMANCE AND WELD PROCEDURE QUALIFICATION

7.1 Welder Performance Qualification

7.1.1 Operators of welding equipment shall be certified by successful completion of a qualification test for the applicable process.

a. Each fusion welder or fusion welding operator shall be qualified in accordance with AWS D17.1, Specification for Fusion Welding for Aerospace Applications, Section 5, accepted to Class A requirements of this process specification.

Other requirements may be added but may not be substituted for the requirements in section 5.

(1) All qualification groove welds shall be radiographically inspected.

(2) All fillet welds with a base metal thickness more than 0.063 in (1.6 mm) shall be bend tested or, alternately, examined metallographically.

b. FS welding operators shall be qualified in accordance with AWS D17.3, Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications, section 7, accepted to Class A requirements of this process specification.

c. Friction plug welding operators shall be qualified in accordance with AWS D17.3, section 7, using a square groove test weld in sheet for making plug welds accepted to Class A requirements of this process specification.

7.1.2 Welder qualification testing shall be repeated at intervals not exceeding 5 years or when there is evidence to question the ability of the welder or welding operator to meet the requirements for qualification.

7.1.3 To maintain qualification, welders and welding operators shall have performed the weld process on the alloy groups for which they are certified within the previous 6 months.

7.1.4 Proficiency demonstration shall be required if a welder or welding operator has not performed the weld process on the alloy groups for which he/she is certified within the previous 6 months.

7.1.5 Records of operator certification documentation shall be maintained by the contractor's quality assurance organization as long-term temporary records and be provided to the procuring agency before welding of flight hardware.

7.2 Weld Procedure Specification

7.2.1 A WPS shall be qualified and maintained for each nominal thickness (t) weld (listed below) as welded on the specific equipment, before welding of the first production part of each thickness and material combination, unless approved by the responsible NASA Technical Authority.

a. t (±0.020 in (±0.51 mm)) for automatic, semiautomatic, and mechanized welds

b. t (±0.1t) for orbital tube welding

c. t (-0.5t/+2t) for manual welds

Appendix E lists information that should be included in a WPS.

7.2.2 All test and evaluation data shall be recorded in the PQR.

7.2.3 The WPS shall contain all the information necessary to produce welds that consistently meet the strength and quality requirements.

a. All essential variables shall be identified on the WPS.

b. For weld qualification tests, base metal and consumables shall be identified by lot or heat number, type, and condition.

c. This base metal and consumable identification shall be maintained through all evaluation processes.

d. The WPS shall document all other prewelding operations, setup conditions, welding equipment, and any other pertinent information about the welding system used that affects the welding operation.

e. Operator trim parameter tolerances used for automatic, semiautomatic, and mechanized welding shall be listed in the qualified WPS.

7.2.4 Test samples representing the minimum and maximum heat input bounded in the WPS for automatic, semiautomatic, and mechanized welds shall be tested in accordance with section 7.3 of this process specification to verify acceptable welds.

7.2.5 The procedure qualification welds shall be inspected visually and nondestructively as specified in section 10.0 of this process specification, in accordance with Class A requirements.

a. Following visual and nondestructive inspection, the qualification welds shall be subjected to the same processes as the production parts, including reinforcement removal, mechanical deformation, stress relief, and thermal treatments associated with artificial aging or any operation affecting mechanical properties.

Rejectable surface indications can be removed using mechanical means (sanding or polishing), not rewelding.

b. All visual and surface indications noted on the qualification welds that have been mechanically removed shall be recorded in accordance with section 7.3.1 and the records retained with the qualification weld documentation.

7.2.6 Operating ranges for current and voltage shall be established during the weld procedure specification qualification for the steady-state portion of manual welds.

7.2.7 Tapered thickness welds shall be qualified at the maximum and minimum thickness (specified in section 7.2.1 of this process specification) and with a full-length confidence weld (specified in section 7.3.2 of this process specification).

7.2.8 In recognition of the differences in welding conditions between a test panel fixture and a major weld tool, the weld schedule developed on the test panel fixture shall be adjusted to the degree necessary when welding on the major weld tool.

a. The variation shall be noted on the WPS.

b. The adjustment shall be allowed one time only on the first part welded on the major weld tool.

c. An adjustment approach that allows more than one adjustment shall be approved by the responsible NASA Technical Authority.

d. A confidence weld shall be completed before welding production hardware in accordance with the requirements of 7.3.2.

7.3 Procedure Qualification Records

7.3.1 All test results, including visual, dimensional, and NDE, shall be recorded on a PQR.

The provisions of AWS B2.1/B2.1M, Specification for Welding Procedure and Performance Qualification, can be followed for fusion welds.

7.3.2 A confidence weld for each of the following different weld configurations shall be made and tested in accordance with section 7.3.3 of this process specification to validate the weld procedure specification:

a. Tapered thickness welds made with automatic, semiautomatic, or mechanized weld processes.

b. Aluminum and heat-sensitive alloy welds.

c. All SR-FS welds.

d. All C-FS welds.

e. Cases in which the procedure qualification weld does not provide an appropriate representation of the product form, e.g., forging, casting, extrusion, or geometry of the components being welded, e.g., tubing, rolled shape.

f. Class A weld without root side access to verify full penetration.

7.3.2.1 The confidence weld shall replicate the production part with respect to section thickness, alloy, heat treat condition, joint preparation, preweld cleaning, and fitup and be made in the actual production weld fixture, using the actual production welding equipment.

7.3.2.2 The confidence weld shall replicate the production weld with respect to length, start up, and tail out.

The pathfinder article may be used for the confidence weld if the above criteria are met.

7.3.3 Welds shall be tested in accordance with AWS B4.0, Standard Methods for Mechanical Testing of Welds.

7.3.3.1 Tensile Tests

a. A minimum of five specimens shall be tested to qualify a weld procedure.

b. Tensile specimens and test procedures shall conform to ASTM E 8/E 8M, Standard Test Methods for Tension Testing of Metallic Materials.

c. Plug weld tensile test specimens gauge width shall be a minimum of 1.3 times the major diameter of the plug weld.

d. At a minimum, tensile specimens shall be tested to destruction at room temperature.

e. Percent elongation in 1.0-in (2.5-cm) and/or 2.0-in (5-cm) gauge lengths, 0.2 percent offset yield stress, and ultimate tensile strength shall be recorded.

f. Percent elongation for round samples shall be measured across a 4 x diameter.

g. Weld strength shall meet or exceed the values in Appendix A.

h. Qualification welds for aluminum alloys used in cryogenic applications

(1) Qualification welds for aluminum alloys used in cryogenic applications shall be tensile tested at the intended use cryogenic temperature and at room temperature.

(2) A minimum of four test specimens shall be tested to destruction.

i. A minimum of 15 total specimens shall be from the confidence welds**.**

(1) Five specimens shall be taken from the beginning, five specimens from the middle, and five specimens from the end of the confidence weld.

(2) For weldments of insufficient size or configuration, the NASA Technical Authority shall approve the test approach.

7.3.3.2 Shear Tests

a. A minimum of five specimens shall be shear tested for each corner, Tee, lap, and edge joint to qualify the weld procedure.

When it is not feasible to fabricate shear test specimens from qualification welds, shear tests may be implemented in accordance with AWS B4.0.

b. The shear ultimate strength shall meet 60 percent of the weld ultimate tensile strength requirement shown in Appendix A, unless otherwise approved by the responsible NASA Technical Authority.

7.3.3.3 Metallographic Sections

a. The welded joint shall be sectioned transverse to the direction of welding and the surface adequately prepared for visual examination in an unetched condition at a magnification of 10X for weld characteristics and defects.

b. The section shall be lightly etched to reveal microstructure and reexamined at a higher magnification (a minimum of 50X and not greater than 200X) for dimensional requirements and the following weld quality requirements:

(1) Overall fusion of the weld, root penetration, burn-through, and blowholes.
(2) Convexity, concavity, and size of bead or fillet.
(3) Undercutting and overlapping.
(4) Inclusions or voids.
(5) Cracks.

c. The weld cross section in titanium welds shall contain no titanium hydrides (TiH_2) or alpha case.

These two detrimental phenomena are indications of the hydrogen content exceeding the solubility limit and an oxygen-enriched alpha-stabilized surface resulting from air contamination at elevated temperatures, respectively.

7.3.3.4 Titanium Chemistry

a. Titanium weld qualification samples shall be analyzed for hydrogen, oxygen, and nitrogen content, in accordance with the requirements of the base metal specification, to assure conformance to the purity requirements.

b. The level of interstitial gases in the completed weld shall not exceed the worst-case maximum level permissible in the procurement specification for the base materials being welded.

7.3.4 A weld of length sufficient to provide the specimens described in section 7.3.3 of this process specification shall be produced and tested at a minimum interval of 5 years for Class A and Class B welds to verify PQR data.

Failed qualification welds that have anomalies with a clear definable cause may be repeated with a 2-for-1 replacement.

7.3.5 Special tests required by Engineering Authority shall be conducted as supportive evidence of meeting design requirements. Such tests may include fatigue, hardness, impact, etc.

7.3.6 Requalification shall be required if any of the essential variables of the WPS is modified.

7.4 Records

7.4.1 Records of test specimens that meet the acceptance requirements of this process specification shall be signed and dated by a Safety and Mission Assurance (S&MA) representative as an accurate record of the welding and testing of the procedure test weldment.

7.4.2 The WPS and PQR shall be prepared and retained as long-term temporary records in accordance with NPR 1441.1, with the current WPS being maintained at the welding station.

7.4.3 All WPSs and PQRs shall be maintained and made available for review by the responsible NASA Technical Authority before production of quality-sensitive or flight hardware.

8.0 PREWELD OPERATIONS

8.1 Weld Joint Design

8.1.1 Joint configurations shall be documented in the WPS and on the design drawing.

Acceptable joint designs are butt, lap, corner, Tee, and edge. Corner and Tee joint designs should be designed to minimize susceptibility to lamellar tearing.

8.1.2 Class A and Class B full-penetration weld joint configurations that will be inaccessible for root side inspection are subject to the requirements of section 7.3.2 and shall be identified on engineering drawings and require approval for use as a weld joint design by the responsible NASA Technical Authority.

8.1.3 LB and EB weld joint edges shall be machined parallel to ensure proper fitup and meet the preweld joint fitup requirements in Appendix B.

a. Weld joints for other than friction plug welds shall be deburred after machining, yielding joint preparation results that have no rounded edges.

b. For Class A welds, faying surfaces of joints shall have a surface roughness of 32 to 125 µin (0.81 to 3.2 µm) per ASME B46.1.

8.1.4 FSW joint design shall be butt joint configuration only.

8.2 Preweld Cleaning

8.2.1 Preweld cleaning of contaminants detrimental to weld quality or filler materials and surfaces to be welded shall be in accordance with Appendix G.

8.2.2 Preweld cleaning shall be accomplished in a controlled environment that does not degrade weld quality and that is maintained until the weld operation is complete.

8.2.3 After surface preparation, parts shall be covered or otherwise protected to prevent contamination until welding is completed.

8.2.4 Personnel performing the cleaning operation or any subsequent operation shall wear powder-free, non-vinyl, moisture barrier gloves.

8.2.5 Before use, tooling (including hold-down clamps, anvils, and parts of welding fixtures that contact or are placed in close proximity to the weld joint) shall be free of oil, moisture, and foreign materials.

8.2.6 Tools and instruments used for measurements or other devices that contact the surfaces to be welded shall be free of oil, grease, moisture, or other foreign materials before use.

8.2.7 Tools shall be cleaned initially and intermittently as necessary.

8.2.8 Preweld and interpass cleaning requirements shall be included in the WPS.

8.2.9 Stainless steel wire brushes shall be used in all instances where wire brushing is performed.

Low-current (10 ampere maximum), reverse–polarity, high-frequency arc cleaning (using manual, automatic, semiautomatic, or mechanized welding equipment) may be used to remove oxides from iron-, nickel-, and cobalt-base alloys.

8.2.10 Fusion welding shall be started within 24 hours (hr) of initiating preweld cleaning, unless otherwise permitted by the responsible NASA Technical Authority.

a. Time between initiation of pre-weld cleaning and welding shall be documented in production build records.

8.2.11 In aluminum alloys, C-FSW joints that will intersect fusion welds shall be cleaned by draw filing or scraping the abutting edges and scraping or wire brushing the crown and root surfaces of the weld land 0.5 in (12.7 mm) beyond the shoulder diameter.

8.2.12 All SR-FS weld joints in aluminum alloys shall be cleaned by draw filing or scraping the abutting edges and mechanically abrading the crown and root surfaces of the weld land 0.5 in (12.7 mm) beyond the shoulder diameter.

Following the mechanical cleaning operations described in sections 8.2.11 and 8.2.12 above, solvent cleaning by wiping with lint-free clean cloth is permitted.

8.2.13 The FSW full-penetration pass shall be started within 48 hr of initiating preweld joint cleaning.

Tack welding is not considered a full-penetration weld.

8.2.14 EB welding shall start within 40 hr after surface preparation has been completed, unless otherwise permitted by the responsible NASA Technical Authority, with the following exceptions:

a. EB welding of aluminum alloys shall be accomplished within 8 hr after cleaning.

b. If parts have been vacuum dried and stored in a sealed plastic film (other than polyethylene or nylon) bag purged with dry argon or gaseous nitrogen, the parts shall be welded together within 100 hr of cleaning.

8.2.15 Weld joints adjacent to brazed surfaces shall be cleaned in accordance with Appendix G to remove contamination from brazing operations.

8.2.16 All brazing alloy deposits shall be removed from the weld joint region that includes the joint and the area within 0.25 in (6.4 mm) of the joint, unless otherwise specified on the engineering drawing.

8.2.17 When welding precision-cleaned hardware, all welding of assemblies for precision-cleaned systems (including tube preparation) shall meet the requirements of CxP 70156, Constellation Program Fluid Procurement and Use Control Specification, Welding Precision Cleaned Hardware.

8.2.18 Plugs used for friction plug welding and the material to be plug welded shall be cleaned by abrasion to remove the oxide layer, followed by solvent cleaning within 8 hr of plug welding.

8.3 <u>Preweld Joint Fitup</u>

a. After the parts have been mated, positioned and tacked for the welding operation, the joint shall be verified for compliance with the preweld and postweld dimensional requirements of Appendix B of this process specification.

b. Preweld joint gap requirements for specific materials and processes shall meet the requirements listed in Appendix B.

c. The interrelationship of mismatch, joint gap, peaking, and pin tool offset shall be shown by engineering analysis or test to assure that positive margins of safety exist.

8.4 <u>Weld Start and Run-Off Tabs</u>

8.4.1 Weld start and run-off tabs (when used) shall be of the same alloy as the detail parts being welded.

8.4.2 Weld start and run-off tabs shall be cleaned in the same manner as the parts.

8.4.3 Tabs shall be integral with the part, being either machined in, welded with the same filler metal, or rigidly attached to the part pieces before assembly.

8.4.4 Length of weld start and run-off tabs shall be established, based on the confidence panel test results.

8.4.5 Use of weld start and run-off tabs shall be included in the WPS.

8.5 Laser and Electron Beam-to-Joint Alignment

8.5.1 Flat and Circular Welds

a. Before welding every weld joint of every production run, the entire length of the joint shall be leveled to within ±0.005 in (±0.127 mm) using a calibrated dial indicator.

b. The assumed centerline of the beam shall be aligned within 30 minutes of the gun angle defined in the approved weld parameter, as determined using a calibrated inclinometer in conjunction with a surface at a known reference angle to the joint faces.

8.5.2 Circumferential Welds

a. Before welding every weld joint of every production run, the axis of the assembly shall be leveled, using a calibrated dial indicator to within ±0.005 in (±0.127 mm) in relation to reference surfaces for weld joint faces perpendicular to the axis.

b. For off-axis joints, the assumed centerline of the beam shall be aligned within 30 min of the gun angle defined in the approved weld parameter, using a calibrated inclinometer in conjunction with a surface at a known reference angle to the joint faces.

9.0 PRODUCTION WELDING

9.1 Equipment Operational Readiness Check

A welding equipment operational readiness check shall be made immediately before a production weld to verify that the equipment is operating properly.

An equipment checklist can be used to ensure equipment performance. Items such as pin tool part and serial number (FS), torch setup (fusion), air pressure, water pressure, shield gas flow, and other factors affecting equipment performance may be verified before weld initiation.

9.2 Temperature Control

9.2.1 Preheat, interpass, and postheat temperatures shall be controlled so as not to degrade the properties of the material being welded.

9.2.2 These parameters shall be recorded in the applicable WPS.

9.3 <u>Tack Welding</u>

9.3.1 Tack welding shall be allowed, provided that the tack welds are completely consumed by the final weldment.

9.3.2 After the final weldment is completed, the tack areas shall be inspected to the requirements of the finished weld.

9.3.3 Tack welding parameters shall be included in the WPS.

Tack welding parameters are not essential variables.

9.3.4 Aluminum alloy joints to be FS welded shall be tacked using FS unless authorized by the responsible NASA Technical Authority.

9.3.5 For EB or LB welds, a tack weld made with EB or LB shall be made with a substantially reduced power density from the certified full-penetration pass, up to and including the full length of the weld.

A full-penetration tacking pass using certified parameters may be used.

a. If a full-penetration tacking pass using certified parameters is used, it shall not exceed 10 percent of the weld joint length for EB welds.

b. If a full-penetration tacking pass using certified parameters is used, it shall terminate in the weld start and run-off tabs when applicable.

9.4 <u>Welding Techniques</u>

9.4.1 Square groove welds shall be completely penetrated from one side (illustration A in Figure 4, Welding Techniques).

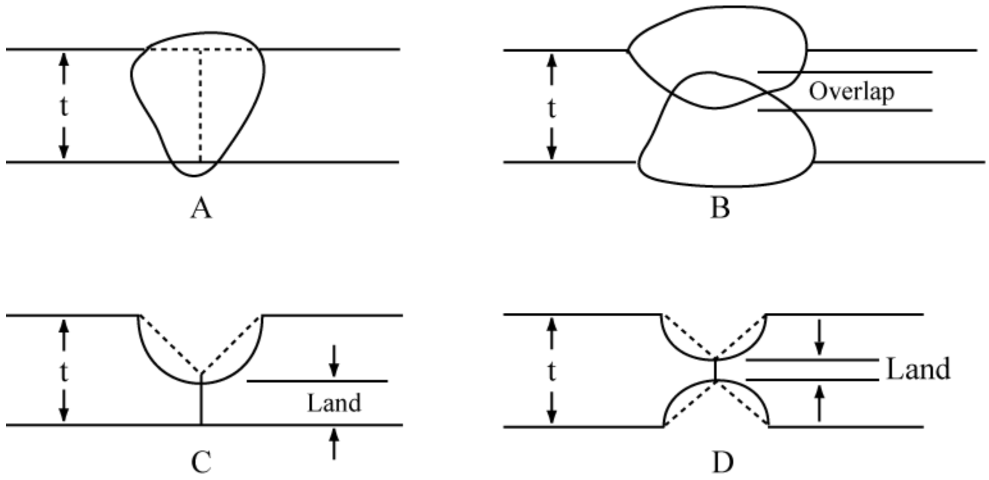


Figure 4. Welding Techniques

9.4.2 Partial-penetration groove welds shall be used only for Class C joints, unless approved by the responsible NASA Technical Authority.

9.4.3 Two-sided welding (Figure 4B) shall only be allowed under one of the following conditions:

a. The weld shall be performed in a prepared groove joint (Figure 4C and D), where it can be verified that the initial pass consumed the entire abutting edge.

b. Partial-penetration welds from one side shall be machined into the penetration root to sound metal before completing the next pass.

9.4.4 At a minimum, visual inspection shall be used to ensure penetration.

9.5 Welding Procedure

9.5.1 A specific WPS for each weld shall be required for all production welds in accordance with the requirements of section 7.2.1.

9.5.2 Weld parameters controlling the heat input for automatic and mechanized welds shall be recorded continuously using automatic recording devices during the weld operation.

a. As a minimum, parameter data shall be acquired at two times the speed of the control algorithm and stored electronically, in compliance with contractual requirements.

b. Equipment fluctuations or natural variations that occur in equipment without human intervention and change the readings of the qualified nominal parameter settings shall not be cause for rejection.

Section 5.1.d of this process specification provides additional information regarding equipment fluctuations or natural variations.

9.5.3 Procedure Departure

a. Any departure from the qualified WPS during production welding shall require withholding of the component for MRB disposition, except as noted in section 5.1.d.
b. MRB records shall be maintained as long term temporary records per NPR1441.1.

c. The cause for departure shall be determined and corrective action taken before further production welding.

9.5.4 Cosmetic passes shall only be allowed if included in a qualified WPS.

9.5.5 After welding, the EB vacuum chamber shall not be vented until the component has cooled to a temperature below its oxidizing temperature, which is specified in the qualified WPS.

9.5.6 SR-FS welds shall be welded with the pin tool offset toward the retreating side of the joint in accordance with Appendix B.

10.0 POSTWELD OPERATION

10.1 The Weldment

Each completed weldment (both face and root sides) and the adjacent base metal for a minimum 0.5 in (12.5 mm) on either side of the weld shall be inspected to ensure compliance with the requirements of sections 10.2, 10.3, and 10.6 and as dictated by the class of the weld, unless approved by the responsible NASA Technical Authority.

10.2 General Workmanship Requirements

Uniform appearance of weld deposits, buildup, and root reinforcement shall be verified by visual confirmation.

With the exception of titanium alloys, discoloration caused by vapor deposition during EB welding may be acceptable.

10.2.1 The face and root sides shall be free of surface cracks, crater cracks, other defects open to the surface, and oxide scale.

10.2.2 The weld deposits shall be free of open voids or unfused overlapping folds.

10.2.3 The edge of the weld deposit shall blend smoothly into the base metal without unfused overlaps or undercuts.

10.2.4 Titanium alloy welds and adjacent base metal shall meet the color requirements of AWS G2.4/G2.4M, Guide for the Fusion Welding of Titanium and Titanium Alloys.

10.2.5 The surface of FS welds shall be free of galling, tears, or blisters.

10.2.6 By-products of the welding process, such as weld-spatter, oxide scale, soot, flash, or other by-products, shall be removed from the welded component.

10.3 Dimensional Requirements

10.3.1 Welded Butt Joints

10.3.1.1 Welded butt joints shall have 100 percent penetration and meet the geometrical requirements of Appendix C.

10.3.1.2 The root bead width in fusion welds shall not exceed the maximum weld width specified in Appendix C.

10.3.1.3 FS welds shall meet the shoulder footprint minimum dimension specified in Appendix C.

10.3.1.4 Mismatch: The allowable postweld mismatch (Figure 5, Mismatch and Peaking) shall not exceed the values specified in Appendix B.

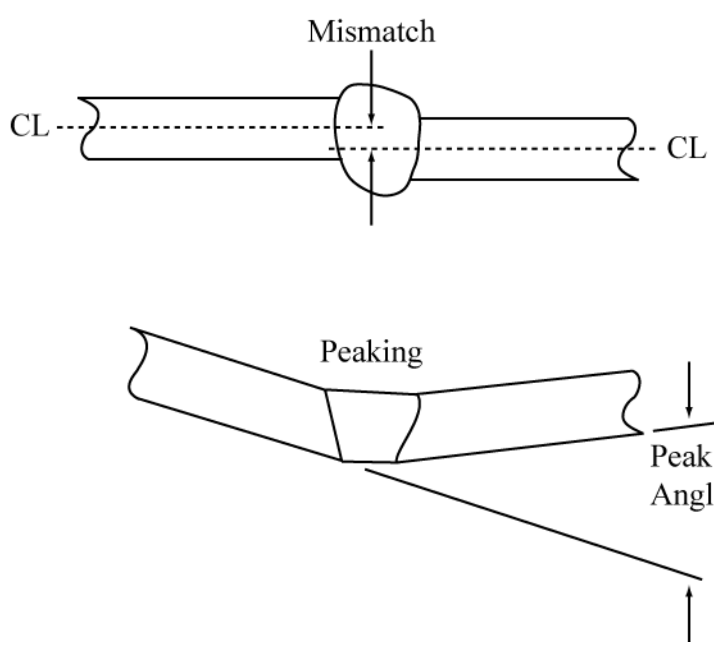


Figure 5. Mismatch and Peaking

10.3.1.5 Peaking: The allowable postweld peaking (Figure 5) of the welded joint and adjacent base metal shall not exceed the values in Appendix B.

10.3.1.6 A standard template or other calibrated electronic measurement device having specified reference points shall be used for determination of peaking.

The combined effect of mismatch and peaking on the efficiency of the weld joint is such that one can be increased if the other is decreased. A limited amount of mismatch and peaking greater than the values in Appendix B can be tolerated if it can be shown by engineering analysis or test that positive margins of safety exist.

10.3.1.7 Weld Reinforcement Removal

a. Weld reinforcement, both face side and root side, shall remain, unless specified by the engineering drawing.

The weld bead reinforcement may also be removed to eliminate defects occurring in the outer zones of the reinforcement unless otherwise specified on the engineering drawing.

b. Such removal shall not thin the weld or base metal below drawing dimensional requirements.

c. When flush contour is required by the welding symbol, weld reinforcement shall not exceed 0.015 in (0.4 mm).

d. Metal removal shall be such that the mechanically reworked area blends smoothly, e.g., 0.125-in (3.2-mm) radius, with adjacent material without abrupt sectional changes.

e. Surface roughness, after reinforcement removal, shall not exceed 250 µin (0.006 mm) or the specification on the drawing.

f. Grinding of base metal shall not be done when wall thickness cannot be verified after grinding.

g. Flash material in solid-state welds shall be removed.

(1) Techniques to remove flash, metal slivers, anvil marks on conventional welds, and other sharp or raised metal shall not interfere with postweld NDE inspections.

(2) Material thickness shall not be reduced below the minimum thickness specified on the design drawing.

h. Weldments that are machined, ground, or otherwise mechanically worked causing disruption or smearing of the material surface shall be etched to remove the masking material before penetrant application.

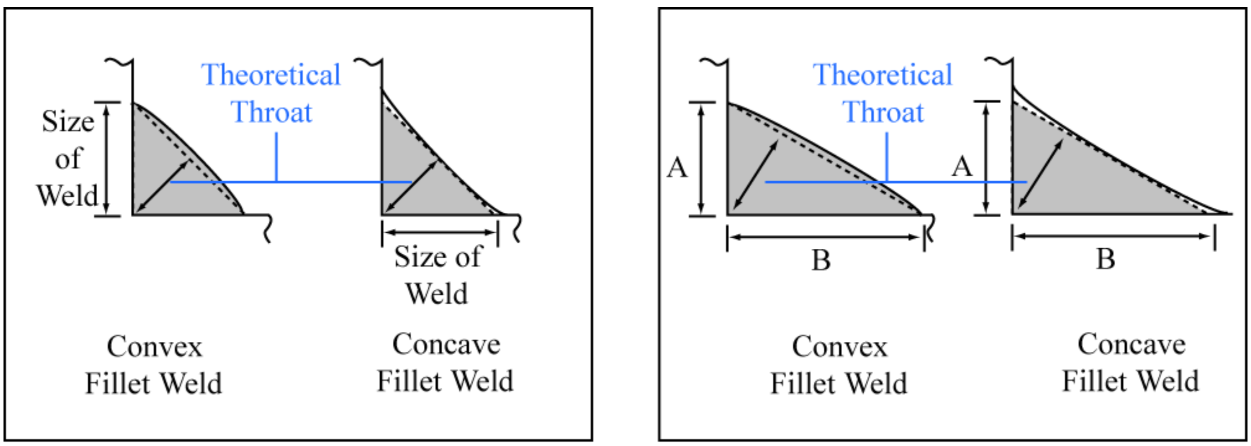
10.3.2 Fillet Welds

10.3.2.1 The minimum acceptable fillet size shall be that specified by the engineering drawing.

10.3.2.2 The maximum acceptable fillet size shall be the size specified plus 50 percent or 0.188 in (4.8 mm), whichever is less.

10.3.2.3 The minimum acceptable actual throat shall equal or exceed the theoretical throat (Figure 6, Fillet Weld Throats).

When not specified on a drawing, the fillet sizes for superalloys given in Appendix C can be used.



Equal Leg Fillet Weld **Unequal Leg Fillet Weld**

Figure 6. Fillet Weld Throats

For equal leg fillet welds, the fillet size is equal to the leg length of the largest inscribed right isosceles triangle.

For unequal leg fillet welds, the fillet size is the leg length of the largest right triangle that can be inscribed within the fillet weld cross section (A and B in Figure 6).

10.3.2.4 Fillet weld fusion of the root (Figure 7, Fillet Welds) shall have a minimum of 10 percent penetration of base metal thickness of the thinnest member of the root of the joint as determined by evaluation of transverse sections taken from the qualification welds.

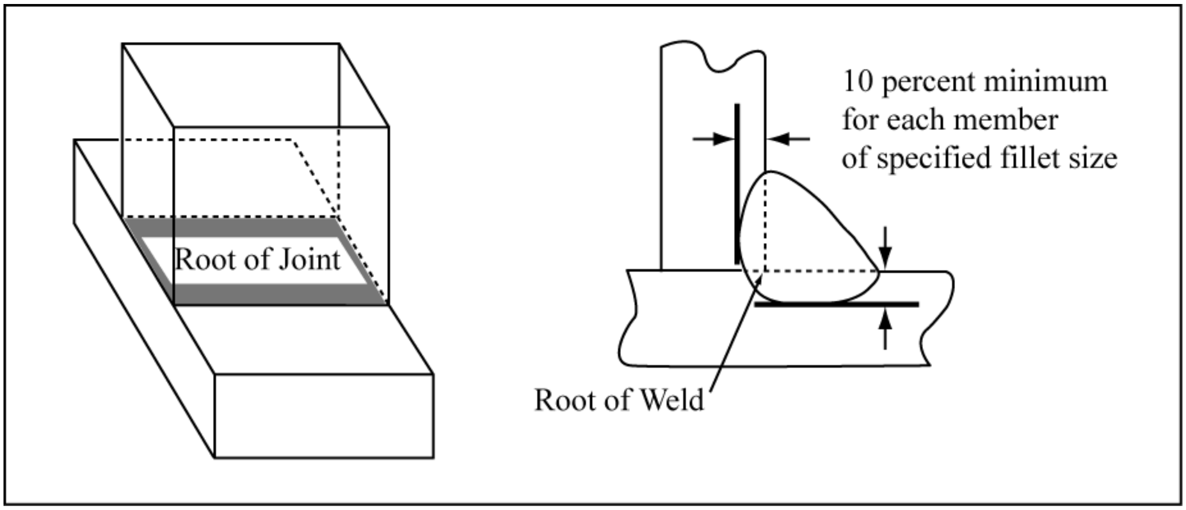


Figure 7. Fillet Welds

10.3.2.5 Fillet welds terminating at corners with unwelded joints shall have the fillet continued around the corner into the unwelded joint a minimum of 0.125 in (3.2 mm), and a maximum of 0.5 in (12.5 mm).

10.3.2.6 Toes of fillet welds shall blend smoothly with adjacent base metal.

10.3.2.7 The root of the weld shall penetrate to the extent that the actual throat dimension exceeds the theoretical throat dimension (Figure 6).

10.4 Weldment Straightening

a. Straightening of welds and adjacent base metal that have been deformed by the welding operation shall be allowed only in accordance with a procedure approved by the responsible NASA Technical Authority.

b. The straightening procedure shall be verified on test coupons using NDE, destructive testing, and metallurgical evaluation to verify that the process used for straightening does not degrade the weld and surrounding material below the specified design requirements.

c. The straightening procedure shall be documented on the WPS.

10.4.1 Weldment straightening shall not be performed on welds failing to meet the acceptance criteria described in section 10.6 of this process specification.

10.4.2 Following weldment straightening, the weld and adjacent base metal shall be inspected in accordance with section 10.1 of this process specification.

10.4.3 Weldments with defects revealed by straightening operations shall not be acceptable.

10.4.4 Peening

a. When specified on the engineering drawing, peening shall be performed in accordance with a qualified WPS that was established based on welded and peened qualification test samples that simulate the material type and joint configurations to be used on the production component in accordance with section 7.3.3 of this process specification.

b. Peening shall not be performed on cover passes or on welds less than 0.090 in (2.3 mm) in thickness.

c. When interpass inspections are required by the engineering drawing, they shall be performed before and after peening.

10.5 Postweld Heat Treatment Requirements

10.5.1 Weldments subject to heat treatment operations shall be inspected before and after heat treatment in accordance with the quality requirements listed in section 10.6 of this process specification.

10.5.2 Postweld heat treatment processing shall be as identified on the engineering drawing and the heat treatment included in the WPS.

10.6 Weldment Quality Requirements

It is recommended that a workmanship standard be developed for interpretation of acceptance criteria when needed.

10.6.1 Surface Requirements

Surface requirements shall apply to the final weld condition, to the crown side of all welds, and to the root side of full-penetration welds.

10.6.1.1 The surface acceptance requirements shall be as listed in Appendix D.

10.6.1.2. Deviations from the surface requirements of this process specification shall be supported by technical rationale and approved by the responsible NASA Technical Authority.

10.6.1.3 For penetrant inspection of unshaved VPPA weld root beads, transverse indications confined to the width of the weld bead are acceptable except at weld intersections. Transverse indications extending into the parent material or the toe radius are to be rejected regardless of length.

10.6.2 Volumetric Requirements

10.6.2.1 The volumetric acceptance requirements shall be as listed in Appendix D.

10.6.2.2 Deviations from the volumetric requirements of this process specification shall be supported by technical rationale and approved by the responsible NASA Technical Authority.

10.6.2.3 The radiographic linear indication at the root of the weld (Figure 7), which is inherent in the design of fillet welds, shall not be considered a crack.

Workmanship standards should be developed to facilitate interpretation of fillet weld radiographic linear indications.

10.7 <u>Repair Welding</u>

10.7.1 Additional welding operations shall be permitted to correct any unacceptable defect established in accordance with section 10.6 of this process specification, provided the repair or rework welding parameters and procedures are specified in a qualified repair WPS and that the repair or rework is contained within the original weld zone.

10.7.2 Complete records of the repair or rework welding operation, including identification of the repaired or reworked weldment, type of defect, and location of the repair or rework weld, shall be retained in accordance with NPR 1441.1.

10.7.3 Visual reinspection and NDE examination of all repair weld areas shall be performed using the same methods/requirements as used on the original weld.

10.7.4 All 2195 fusion weld repairs shall be planished to recover 70 percent of the shrinkage induced during heat repair operations using qualified planishing procedures.

10.8 <u>Material Review Board</u>

MRB disposition shall be required when any one of the following conditions exists:

a. When more than two weld repair attempts have been performed at the same location on materials that are heat sensitive.

b. When more than five weld repair attempts have been performed at the same location on materials that are not heat sensitive.

c. When the wrong filler metal has been used.

d. When a repair weld is required after the weldment has been postweld heat treated.

e. When a repair weld is required after final machining has been completed.

f. When the repair extends outside the original weld zone (fusion zone and heat affected zone).

g. When a weldment has been direct aged, i.e., aged only without intermediate solution heat treatment, unless authorized by the NASA Technical Authority.

h. When a weldment has been made with parameters outside the qualified WPS range.

i. All repairs of defective plug welds.

j. Weld repairs following proof or leak test.

11.0 VERIFICATION

11.1 General

11.1.1 The supplier shall be responsible for the performance and evaluation of all visual inspection requirements and nondestructive evaluations as required by this process specification.

11.1.2 The supplier shall use visual inspection and nondestructive examination facilities and services approved by the procuring agency or through a vendor selection process approved by the procuring agency unless otherwise specified.

The procuring agency or its designated representative reserves the right to perform any or all of the visual inspections and nondestructive examinations required to assure that the end item conforms to the prescribed requirements.

11.1.3 NDE procedures to be used in inspection for weldment volumetric and surface quality requirements shall be validated as being capable of detecting the acceptance criteria described in Appendix D of this process specification before inspection of the first production weld.

11.1.4 Personnel performing visual weld inspections shall be certified to AWS QC1, Standard for AWS Certification of Welding Inspectors, or equivalent.

11.1.5 Personnel performing NDE weld inspections shall be certified in accordance with NAS 410, NAS Certification & Qualification of Nondestructive Test Personnel.

11.1.6 For inspection of fracture-critical welds, personnel performing NDE shall be, at a minimum, certified Level II in accordance with NAS 410.

11.2 Postweld Inspection

11.2.1 The supplier shall certify that each semiautomatic, mechanized, and automatic production weld was made within the range of operating parameters established in the qualified WPS.

11.2.2 Visual Inspection

The weld metal and adjacent base metal for a minimum distance of 0.5 in (12.5 mm) on either side of the weld interface shall be visually inspected to ensure compliance for all weld classes with the general workmanship requirements of section 10.2.

11.2.2.1 The weld shall be in the as-welded condition for the initial visual inspection, except that surface smut and loose oxide have been removed in such a way that does not smear metal or change the quality of the weld.

11.2.2.2 Titanium weld deposit and heat-affected zone discoloration shall be in accordance with the accept/reject criteria requirements within AWS G2.4/G2.4M color chart.

11.2.2.3 FS Welds

a. Scratches and tooling marks shall not be cause for rejection, provided they meet surface finish requirements.

b. Indications that are attributed to anvil joint gaps or anvil gouges for C-FSW shall not be cause for rejection.

11.2.3 Dimensional Inspection

11.2.3.1 Dimensional inspection shall be performed on weldments of all weld classes to assure compliance with the requirements of the design drawing for all weld classes and requirements in section 10.3 of this process specification.

11.2.3.2 For FS welds, within 1.5 in (38.1 mm) of an intersection weld minimal thickness must be equal to or greater than the minimum drawing thickness.

11.2.4 Volumetric Quality NDE

NDE methods shall be performed, as required by engineering drawing, to assure that the weldment meets quality requirements for Class A and Class B welds, as applicable.

a. NDE procedures and techniques shall be qualified in accordance with NASA-STD-5009, Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components, and with guidelines from MIL-HDBK-1823, Nondestructive Evaluation System Reliability Assessment, for detectability of critical defect.

b. When reliability of inspection and critical flaw detection so dictate, redundant and/or complementing inspection techniques and procedures shall be used.

Volumetric inspections may be waived for non-fracture-critical fillet welds when the specified fillet size is increased 25 percent for Class A aluminum welds and 30 percent for Class A steel, corrosion- or heat-resistant alloys, or 20 percent for Class B aluminum welds and 25 percent for Class B steel, corrosion- and heat-resistant alloys, given prior approval by the responsible NASA Technical Authority.

11.2.5 Surface Quality NDE

NDE methods shall be performed to assure compliance with the surface quality requirements as required by engineering drawing and those in paragraph 10.6.1 and Appendix D of this process specification for Class A and Class B welds.

a. NDE procedures shall be qualified in accordance with NASA-STD-5009 and with guidelines from MIL-HDBK-1823 for detectability of critical defect.

b. When reliability of inspection and critical flaw detection so dictate, redundant and/or complementing inspection techniques and procedures shall be used.

c. The supplier shall verify that weldments that have been subjected to mechanical working have been etched to remove smeared metal before penetrant application.

11.3 Records

11.3.1 Records of a continuous audit of weldment production quality (including validation and qualification of NDE procedures and techniques) shall be submitted and maintained in accordance with contract requirements.

11.3.2 Resulting records shall include, but not be limited to, the location of repairs, type of defects repaired, procedures used, inches of repair per total inches of weld, and number of repair attempts in any one location.

11.3.3 The probability of detection (POD) capability documentation shall be retained as a long-term temporary record by the developing organization.

11.3.4 These records shall be accounted on a quarterly basis, with such accounting made available to the responsible NASA Technical Authority.

11.3.5 Production build records, including visual inspection and NDE test records, shall be maintained and made available upon request by the procuring agency or its designated representative.

11.3.6 Deviations from requirements stated here in shall be approved by the responsible NASA Technical Authority and maintained as long-term temporary records per 11.3.1 by the procuring agency or its designated representative.

11.3.7 The NASA Records Retention Schedules in NPR 1441.1 shall be flowed down through the contract.

12.0 PACKAGING

None

13.0 NOTES

None

APPENDIX A
PROCEDURE QUALIFICATION WELD STRENGTH REQUIREMENTS

A.1 PURPOSE AND/OR SCOPE

This appendix contains procedure qualification weld strength requirements, which are found in table 1, Butt Weld Ultimate Tensile Strength Requirements for Aluminum Alloys; table 2, Butt Weld Ultimate Tensile Strength Requirements for Superalloys; table 3, Butt Weld Ultimate Tensile Strength Requirements for Titanium; and table 4, Butt Weld Ultimate Tensile Strength Requirements for Stainless Steel.

A.2 BUTT WELD ULTIMATE TENSILE STRENGTH REQUIREMENTS (ALUMINUM ALLOYS)

The butt weld ultimate tensile strength requirements for aluminum alloys provided in table 1 shall be adjusted by the responsible NASA Technical Authority if product forms, temper, or the base metal plate gauge cross section, i.e., t/6, used to qualify the weld procedure is other than thin plate.

A.3 PROCEDURE QUALIFICATION TENSILE PROPERTIES

A.3.1 The values listed in this appendix for procedure qualification tensile properties are for qualification only and shall not be used for design purposes.

A.3.2 For alloy combinations not listed in table 1, table 2, table 3, or table 4, the responsible NASA Technical Authority shall be consulted.

A.4 ALTERNATE ULTIMATE TENSILE STRENGTH REQUIREMENTS

Alternate ultimate tensile strength requirements used for repair weld procedure qualification shall be approved by the responsible NASA Technical Authority.

A.5 PROCEDURE QUALIFICATION WELD STRENGTH REQUIREMENTS FOR ALUMINUM ALLOYS

Table 1. Butt Weld Ultimate Tensile Strength Requirements for Aluminum Alloys

Process	**Alloy**	**Temper of Base Material During Weld Operation**	**Postweld Age Cycle**	**Thickness of Thinner Member of Weld Joint**		**Ultimate Tensile Strength Values**							
						Room Temperature				**Cryogenic LO_2 Minimum**		**Cryogenic LH_2 Minimum**	
						Average		**Minimum Single Value**					
				(in)	(mm)	(ksi)	(MPa)	(ksi)	(MPa)	(ksi)	(MPa)	(ksi)	(MPa)
GTAW	2014	T6	As welded	<0.125	<3	45.5	314	43	297				
				0.125 - 0.25	3 - 6	42.5	293	40	276				
				>0.25	>6	40.5	279	38	262				
FSW	2014/2219	T6/T8X	As welded	≤0.25	≤6	48	331	46	317	57.6	397	62.4	430
FPW in FSW	2014/2219/2219	T6/T851/T8X	As welded	≤0.25	≤6	48	331	46	317	52.8	364	57.6	397
VPPA	2195	T8M4	As welded	≤0.25	≤6	42	299	40	276	48	331	52	359
				0.251 - 0.65	6.4-16.5	40	276	38	262	45.6	314	49.4	341
GTAW	2195	T8M4	As welded	≤0.25	≤6	42	299	40	276	48	331	52	359
				0.251 - 0.65	6.4-16.5	40	276	38	262	45.6	314	49.4	341
FSW	2195	T8M4	As welded	0.25 - 0.5	6.4-12.7	59	407	57	393	71	490	82.6	570
FSW	2219/2219	T87	As welded	.25-.50	6.4-12.7	50	345	48	331	55.2	381	60	414
FPW in FSW	2195/2195/2195	T8M4/T851/T8M4	As welded	0.25 - 0.320	6.4-8.1	56	386	54	372	62	427	67.5	465
FPW in FSW	2195/2195/2219	T8M4/T851 T8X or T6	As welded	0.32	8.1	47	324	45	310	52	358	56	386
	2219/2195/2195	T8X or T6/T851/T8X	As welded	0.32	8.1	49	338	47	324	54	372	59	408
GTAW	2219	T81	As welded	All	All	40	276	38	262				
		T87	As welded	All	All	40	276	38	262	45.6	314	49.4	341
		T3X*	350 °F (177 °C) for 18 hr	≤0.25	≤6	44	303	42	299				
				>0.25 - 0.5	>6 - 13	42	290	40	276				

Process	**Alloy**	**Temper of Base Material During Weld Operation**	**Postweld Age Cycle**	**Thickness of Thinner Member of Weld Joint**		**Ultimate Tensile Strength Values**							
						Room Temperature				**Cryogenic LO_2 Minimum**		**Cryogenic LH_2 Minimum**	
						Average		**Minimum Single Value**					
				(in)	(mm)	(ksi)	(MPa)	(ksi)	(MPa)	(ksi)	(MPa)	(ksi)	(MPa)
				>0.5 - 0.75	>13 - 19	44	303	42	290				
				>0.75 - 1	>19 - 25	45	310	43	297				
				>1 - 1.25	>25 - 32	46	317	44	303				
				>1.25 - 1.5	>32 - 38	47	324	45	310				
		O/T8X	As welded	0.125	3	21	145	19	131				
VPPA (Vertical Position)	2219	T87	As welded	≤0.4	≤10.2	40	276	38	262	45.6	314	49.4	341
				0.401 - 0.75	10.2 - 19.0	39	269	36	248	43.2	298	46.8	323
				0.751 - 1.1	19.1 - 27.9	38	262	35	241	42	290	45.5	314
VPPA (Flat and 45-deg Positions)	2219	T87	As welded	≤0.33	≤8.4	40	276	38	262	45.6	314	49.4	341
				0.331 - 0.360	8.4 - 9.1	38.5	265	37	255	43.2	298	46.5	321
VPPA	2195/2219	T8M4/T87	As welded	<0.25	<6	42	299	40	276	48	331	52	359
				0.251 - 0.650	6 – 16.5	40	276	38	262	45.6	314	49.4	341
FSW	2195/2219	T8M4/T87	As welded	0.320 - 0.65	8.1 – 16.5	48	331	46	317	55.2	380	64.4	444
	2219/2195	T87/T8M4	As welded	0.320 - 0.65	8.1 – 16.5	50	345	48	331	57.6	397	67.2	463
GTAW	5052	All	As welded	All	All	28	193	25	172				
GTAW	5456	All	As welded	All	All	44	303	42	290				
GTAW	6061	T4	As welded	All	All	27	186	24	166				
		T6	As welded	All	All	27	186	24	166				

* Applicable to tempers that require an aging cycle of 177 (±5) °C (350 (±10) °F) for 18 hr, in accordance with SAE AMS 2770, Heat Treatment of Wrought Aluminum Alloy Parts.

A.5.1 In relation to the GTAW process for 2219 (note accompanying above table), butt weld ultimate tensile strength requirements for tempers that require other postweld aging cycles shall be approved by the procuring agency.

A.5.2 Average shall be the arithmetic average of all values measured.

A.5.3 No single value shall be less than the minimum value specified.

A.6 PROCEDURE QUALIFICATION WELD STRENGTH REQUIREMENTS FOR SUPERALLOYS

Table 2. Butt Weld Ultimate Tensile Strength Requirements for Superalloys

Process	Alloy	Condition of Base Metal during Weld Operation	Postweld Age Cycle	Thickness of Thinner Member of Weld Joint		Ultimate Tensile Strength Room Temperature			
						Average*		Minimum Single Value**	
				(in)	(mm)	(ksi)	(MPa)	(ksi)	(MPa)
Fusion	Inconel 718	STA[1]	As-Welded	≤0.25	≤6	125	862	120	827
Fusion	Inconel 718	STA[1]	STA[1] or DA	≤0.25	≤6	175	1207	170	1172
Fusion	Inconel 718	Annealed[2]	As-Welded	≤0.25	≤6	105	724	100	689
Fusion	Inconel 625	Annealed[3]	As-Welded	≤0.5	≤12.5	110	758	105	724
Fusion	Haynes 188	Solution Treated	As-Welded	≤0.25	≤6	117	807	110	758

* No single qualification test value shall fall below the specified "Minimum Single Value."
** The mean value of all qualification tests shall equal or exceed the specified average value.

[1]Annealed and aged in accordance with either standard practice, 1750 °F (954 °C), or 1950 °F (1066 °C) anneal followed by aging.
[2]Annealed in accordance with either standard practice, 1750 °F (954 °C), or 1950 °F (1066 °C).
[3]Annealed 1750 °F (954 °C).

Table 3. Butt Weld Ultimate Tensile Strength Requirements for Titanium Alloys

Process	Alloy	Condition of Base Metal during Weld Operation	Postweld Age Cycle	Thickness of Thinner Member of Weld Joint		Ultimate Tensile Strength Room Temperature			
						Average*		Minimum Single Value**	
				(in)	(mm)	(ksi)	(MPa)	(ksi)	(MPa)
Fusion	Ti-6AL-4V ELI	Annealed	Stress relieved	≤0.25	≤6	138	951	130	896

*No single qualification test value shall fall below the specified "Minimum Single Value."

** The mean value of all qualification tests shall equal or exceed the specified average value.

Table 4. Butt Weld Ultimate Tensile Strength Requirements for Stainless Steel Alloys

Process	Alloy	Condition of Base Metal during Weld Operation	Postweld Age Cycle	Thickness of Thinner Member of Weld Joint		Ultimate Tensile Strength Room Temperature			
						Average*		Minimum Single Value**	
				(in)	(mm)	(ksi)	(MPa)	(ksi)	(MPa)
Fusion	304L	Annealed	As welded	≤0.5	≤12.5	68	469	65	448
Fusion	316L	Annealed	As welded	≤0.5	≤12.5	69	476	67	462
Fusion	321	Annealed	As welded	≤0.5	≤12.5	75	517	73	503
Fusion	347	Annealed	As welded	≤0.5	≤12.5	74	510	72	496
Fusion	21-6-9	Annealed	As welded	≤0.5	≤12.5	105	724	100	689

* No single qualification test value shall fall below the specified "Minimum Single Value."

** The mean value of all qualification tests shall equal or exceed the specified average value.

APPENDIX B
WELD JOINT DIMENSIONAL REQUIREMENTS

B.1 PURPOSE AND/OR SCOPE

The purpose of this appendix is to provide weld joint dimensional requirements.

B.2 TABLES

Table 5, Preweld Joint Fitup Requirements, and Table 6, Postweld Joint Fitup Requirements, present preweld and postweld joint fitup requirements for various welding processes.
Values in Tables 5 and 6 can be changed with approval by the responsible NASA Technical Authority if it can be shown by engineering analysis or test data that positive margins of safety exist.

Table 5. Preweld Joint Fitup Requirements

Process	Mismatch	Peaking	Joint Gap	Pin Tool Offset
Fusion	As required to meet postweld requirements	As required to meet postweld requirements	N/A	N/A
Electron Beam Laser Beam	10% of joint thickness or 0.01 in (0.25 mm), whichever is less, for thickness up to 0.25 in (6.25 mm) 10% of joint thickness or 0.03 in (0.75 mm), whichever is less, for thickness greater than 0.25 in (6.25 mm)	N/A	5% thickness up to 0.009 in (0.22 mm) 10% thickness over 0.009 in (0.22 mm) to 0.061 in (1.52 mm) Not to exceed 0.01 in (0.25 mm) thickness over 0.061 in (1.52 mm) to 1.49 in (37.2 mm) Not to exceed 0.005 in (0.12 mm) thickness over 1.49 in (37.2 mm)	N/A
Friction Stir – Self Reacting .200-.327 in 5.0-8.3 (mm)	0.040 in (1 mm)	2 deg	0.030 in (0.76 mm)	0.05 in (1.27 mm) (MIN) to 0.20 times pin diameter
Friction Stir – Conventional .250<t<.650 in (6.36<t<16.5) mm	0.02 in (0.508 mm)	3 deg	0.04 in (1 mm)	N/A

Table 6. Postweld Joint Fitup Requirements

Process	Base Metals	Mismatch	Peaking
Fusion	Steels, corrosion- and heat-resistant alloys	0.06 in (1.5 mm) or 20% of the thinnest member, whichever is less	5 deg MAX unless at weld intersection, then 2 deg for 6 in (15.2 cm) adjacent to intersection
	Aluminum alloys	0.02 in (0.508 mm) for thickness of 0.2 in (5.08 mm) or less For thickness greater than 0.2 in (5.08 mm), maximum 0.04 in (10.16 mm) or 10% of thinnest member, whichever is less	5 deg MAX unless at weld intersection, then 2 deg for 6 in (15.2 cm) adjacent to intersection
	Titanium alloys	0.06 in (1.5 mm) or 20% of the thinnest member, whichever is less for material thickness of 0.5 in (12.5 mm) or less 0.120 in (3.0 mm) or 10% of material thickness, whichever is less, for material thickness greater than 0.5 in (12.5 mm)	5 deg MAX unless at weld intersection, then 2 deg for 6 in (15.2 cm) adjacent to intersection
Friction Stir		N/A	N/A

APPENDIX C
WELD NUGGET DIMENSIONAL REQUIREMENTS

C.1 PURPOSE AND/OR SCOPE

The purpose of this appendix is to provide weld nugget dimensional requirements for various welding techniques and materials.

C.2 FUSION

Table 7, Dimensional Requirements for Butt Welds – Fusion, and Figure 8, Aluminum Fusion Butt Weld, provide fusion weld nugget dimensional requirements.

Table 7. Dimensional Requirements for Butt Welds – Fusion*

Base Metal	**Thickness** (in (mm))	**d-Minimum** (in (mm))	**As-Welded Reinforcement (R and R´) Minimum**		**Weld Width (W' and W'') Maximum**	
			R (in (mm))	**R´** (in (mm))	**Multipass, Beveled Joint, and Torch Oscillated**	**Single Pass, Square Butt**
Aluminum Alloys	<0.125 (3)	0.02 (0.508)	0.005 (0.127)	0.015 (0.381)	5t	0.375 in (9.5 mm) or 5t, whichever is smaller
	0.125 - 0.25 (3 - 6)	0.05 (1.27)	0.005 (0.127)	0.015 (0.381)	1t + 0.4 in (10.2 mm)	1t + 0.25 in (6 mm)
	>0.25 (6)	0.06 (1.524)	0.005 (0.127)	0.015 (0.381)	As required by design	As required by joint design
2195	0.125 - 0.25 (3 - 6)	0.05 (1.27)	0.04 (1)	0.04 (1)	1t + 0.4 in (10.2 mm)	1t + 0.25 in (6 mm)
	>0.25 (6)	0.06 (1.524)	0.04 (1)	0.04 (1)	0.75t + 0.45 in (11.4 mm)	0.5t + 0.45 in (11.4 mm)

*Reference Figure 8

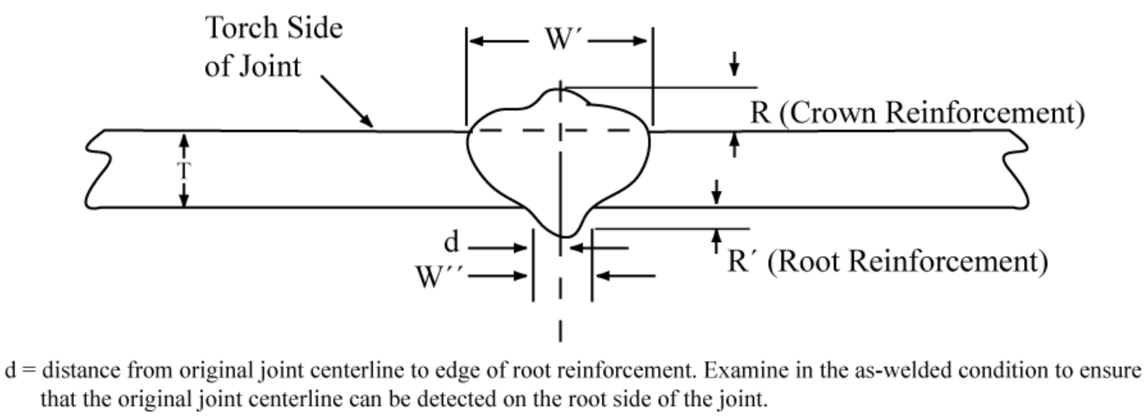


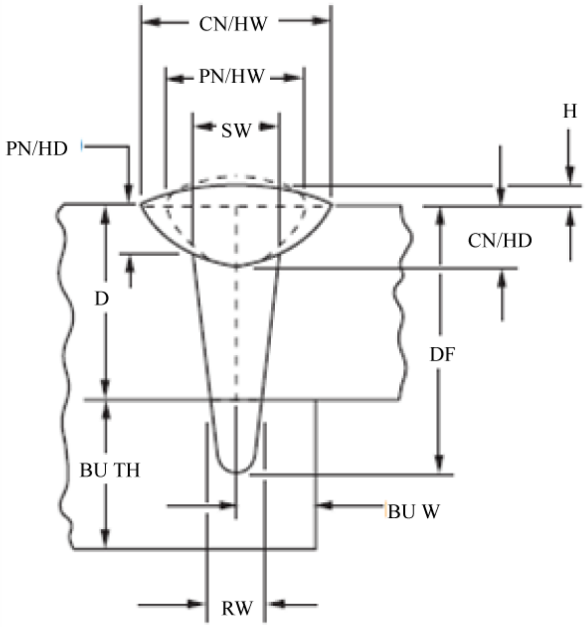
Figure 8. Aluminum Fusion Butt Weld

C.3 ELECTRON BEAM

Figure 9, EB Butt Weld; Figure 10, EB Maximum Weld Crown and Root Widths for Penetration Depths up to 1.6 in (41 mm); Figure 11, Minimum EB Weld Root Width for Penetration Depths up to 0.2 in (5 mm); and Figure 12, Minimum EB Weld Root Width for Penetration Depths of 0.2 to 1.6 in (5 to 41 mm), provide EB weld nugget dimensional requirements.

C.3.1 The weld offset shall not exceed 0.2D or 0.06 in (1.5 mm), whichever is less, where D is the minimum required depth of fusion.

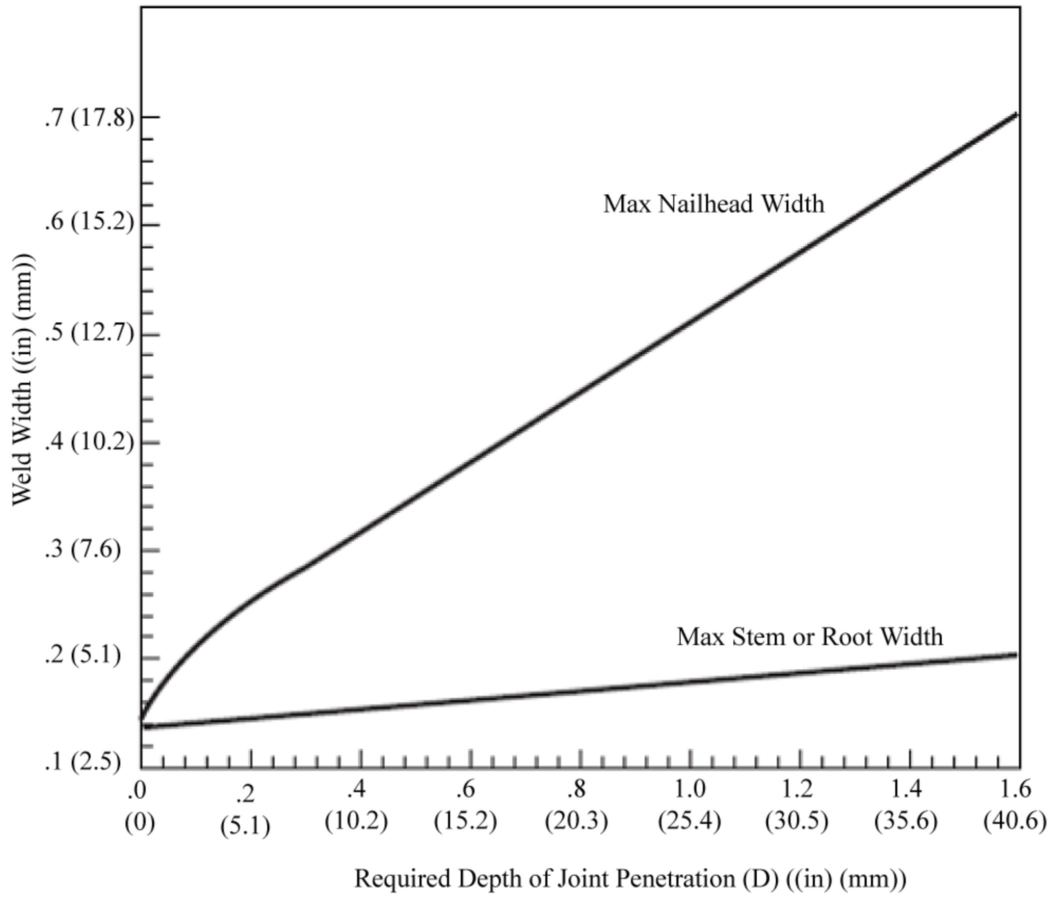
C.3.2 Offset shall be measured on the face side (beam impinging side) of the joint at a distance of 0.15 in (3.8 mm) ±0.06 in (±1.5 mm) from the edge of the fusion zone on either side of the weld.



(1) D = actual joint depth
CN/HW = cosmetic nailhead width
PN/HW = penetration nailhead width
CN/HD = cosmetic nailhead depth
PN/HD = penetration nailhead depth
SW = stem width
(2) RW = root width
BU W = backup width
BU TH = backup thickness
H = reinforcement height (0.090 in (0.228 cm) max)
DF = depth of fusion

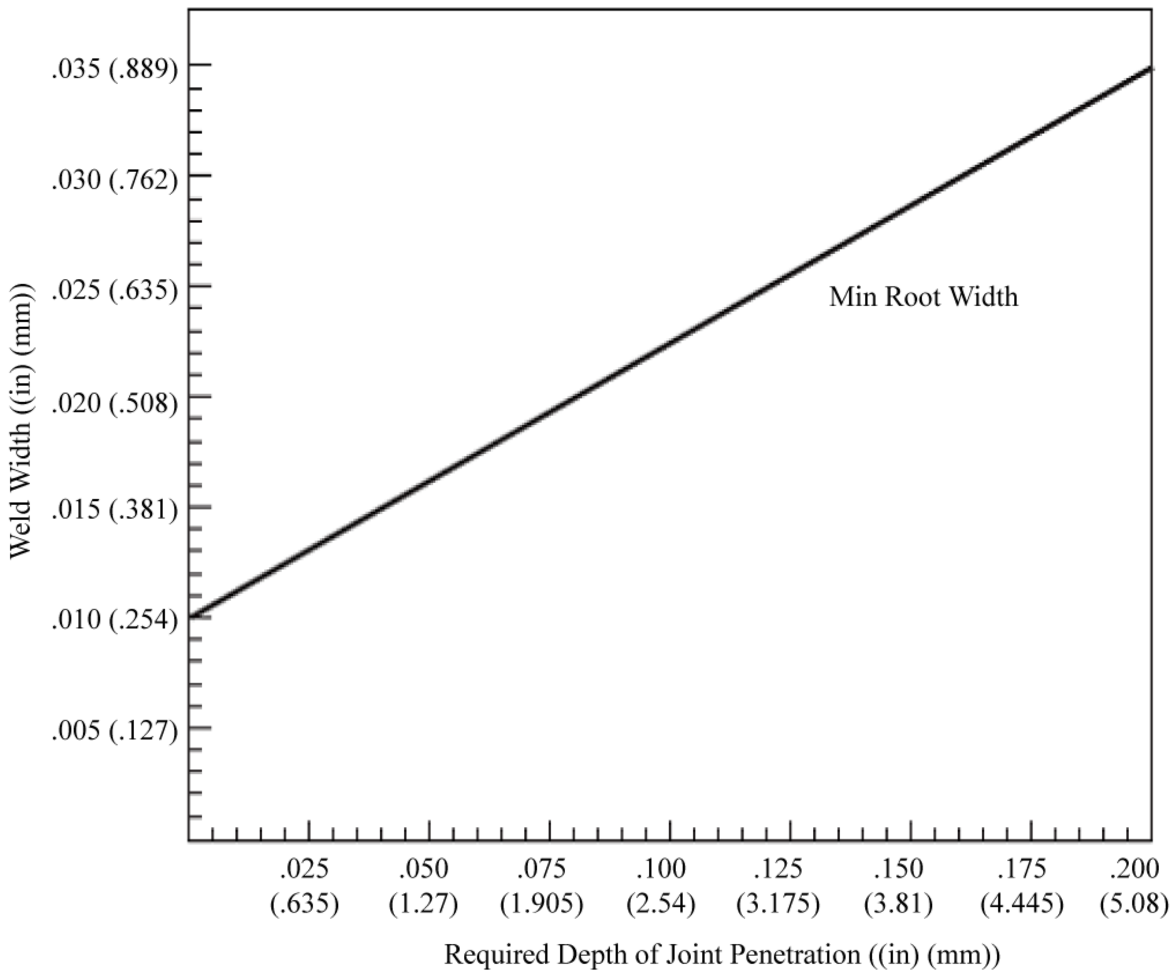
(1) = depth of joint or required depth of joint penetration, as applicable
(2) = root width, measured at a depth corresponding to the depth of the joint or the required depth of joint penetration, whichever is applicable

Figure 9. EB Butt Weld



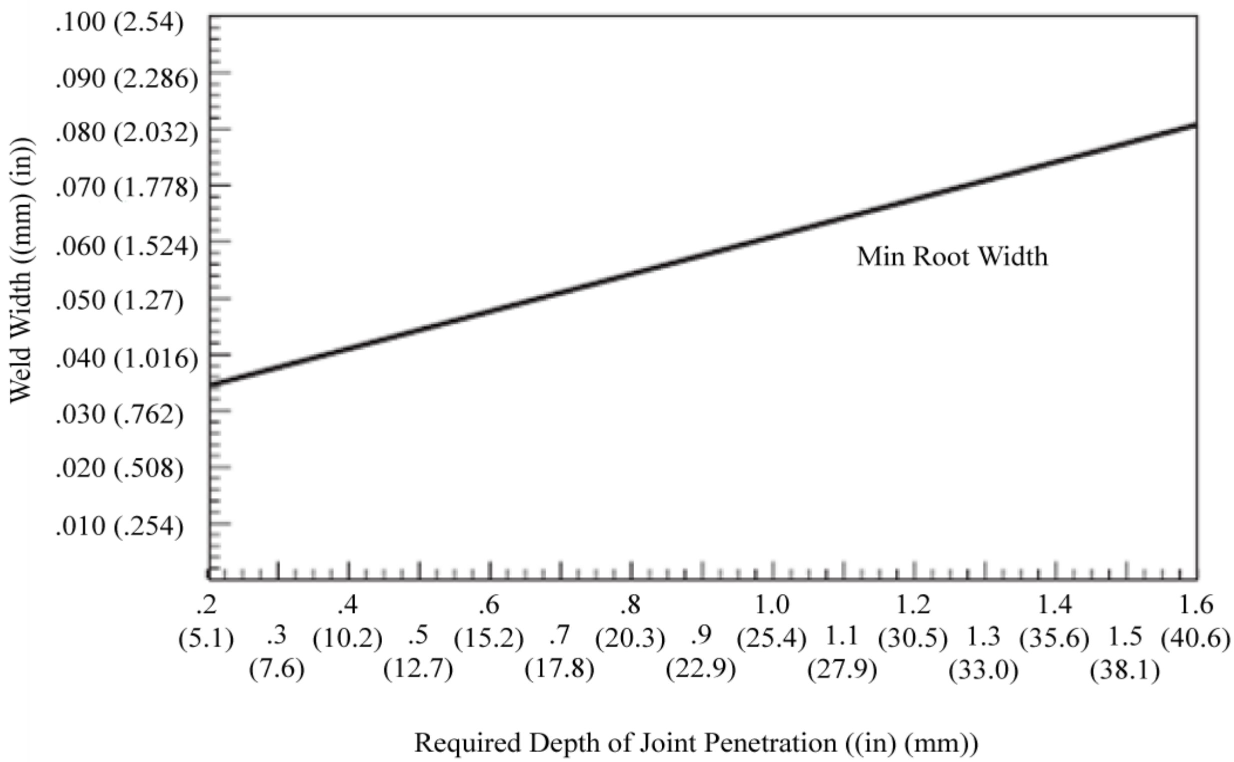
Note: For D >1.6 in (>41 mm): (a) Max stem width shall be 0.2 in (5 mm)
(b) Max root width shall be 0.2 in (5 mm)
(c) Max nailhead width shall be 0.7 in (18 mm)

Figure 10. EB Maximum Weld Crown and Root Widths for Penetration Depths (D) up to 1.6 in (41 mm)



For accurate calculations, use the following formula: $ROOT_{min} = 0.010 + 0.125D$

Figure 11. Minimum EB Weld Root Width for Penetration Depths (D) up to 0.2 in (5 mm)



Note: For D >1.6 in (>41 mm), the min root width shall be 0.080 in (2 mm).

For accurate calculations, use the following formula: $ROOT_{min} = 0.029 + 0.032D$

Figure 12. Minimum EB Weld Root Width for Penetration Depths (D) of 0.2 to 1.6 in (5 to 41 mm)

C.4 FRICTION STIR

Table 8, Dimensional Requirements for Butt Welds; figure 13, C-FSW Zone; and figure 14, S-R FSW Zone, provide FS weld nugget dimensional requirements.

Table 8. Dimensional Requirements for Butt Welds

Process	Base Metal	Thickness (in (mm))	Underthickness Maximum	Nugget Width Minimum*	
				W'	W''
C-FSW	Aluminum Alloys	.250<t<.650 in (6.4<t,<16.5) mm	0.01 in (0.25 mm) below as-built minimum weld joint thickness	92% of shoulder diameter**	0.5 x pin diameter**
S-R FSW	Aluminum Alloys	.200-.327 in 5.0-8.3 (mm)	0.015 in (0.38 mm) below as-built minimum weld joint thickness	80% of shoulder diameter**	80% of shoulder diameter**

*Weld root nugget width measurement can be eliminated in C-FSW if NDE technique can reliably find critical lack of penetration (LOP).
**Shoulder and pin diameters are nominal values listed on WPS.

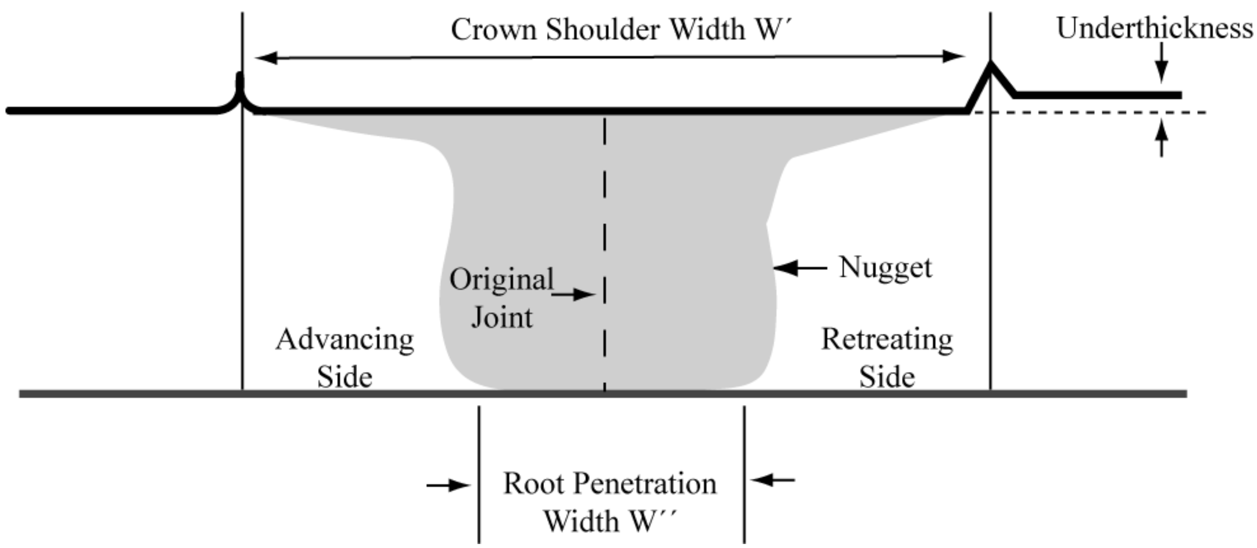


Figure 13. C-FSW Zone

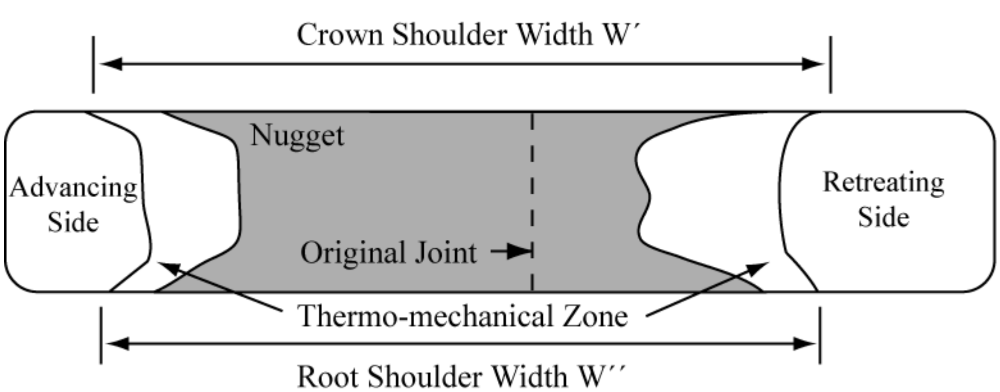
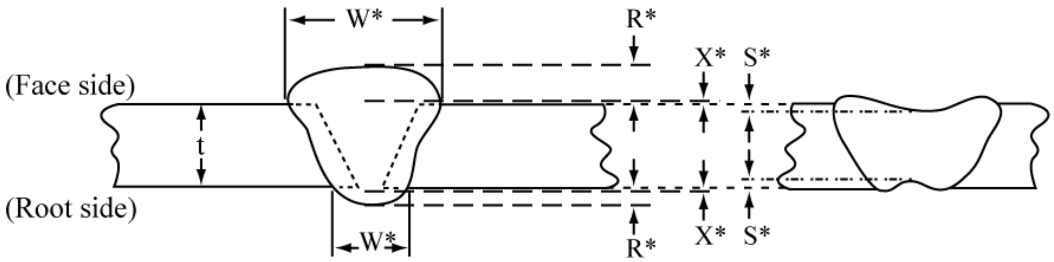


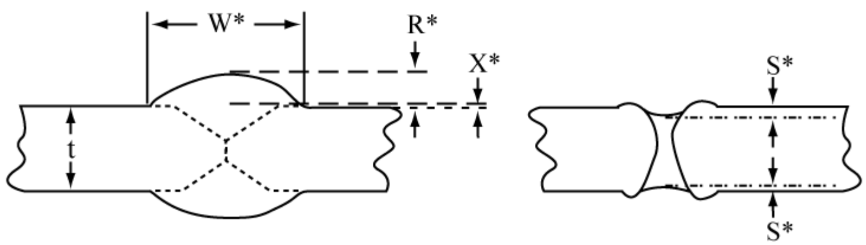
Figure14. S-R FSW Zone

C.5 TITANIUM

Figure 15, Titanium Full-Penetration Joint Welds; table 9, Dimensional Requirements (Titanium); figure 16, Titanium Butt Joint Maximum Allowable Weld Width versus Thickness; figure 16, Titanium Fillet Joint Maximum Allowable Weld Width versus Thickness; and figure 17, Titanium Maximum Fillet Weld Size, provide titanium weld nugget dimensional requirements.



A. Full-Penetration Joint Welded from One Side



B. Full-Penetration Joint Welded from Both Sides (R,S,W, and X limitations are the same for both sides of the weld.)

R* = R(max); maximum reinforcement of weld, based on joint thickness
S* = S(max); maximum weld bead concavity
W* = W(max); maximum width of weld, based on joint thickness
X* = X(min); minimum reinforcement of weld, based on joint thickness
The weld material contained within the minimum and maximum reinforcement limits (R-X) may be removed without rewelding.

Figure15. Titanium Full-Penetration Joint Welds

Table 9. Dimensional Requirements (Titanium)

Thickness Nominal (in (mm))		**Class A Weld**	**Class B Weld**
0 through 0.01 (0 through 0.254)	S(MAX) X(MIN) R(MAX) W(MAX)	0 0 0.5t + 0.02 0.09	.05t 0 0.5t + 0.02 0.09
0.01 to 0.02 (0.254 to 0.51)	S X R W	0 0 0.5t + .02 0.18	0.05t 0 0.5t + 0.02 0.18
0.02 to 0.03 (0.51 to 0.76)	S	0	.05t
	X	0	0
	R	0.3t + 0.02	0.3t + 0.02
	W	0.18	0.18
0.03 to 0.05 (0.76 to 1.27)	S	0	0.05t
	X	0	0
	R	0.3t + 0.02	0.3t + 0.02
	W	5.0t	5.0t
0.05 to 0.10 (1.27 to 2.54)	S	0	0.05t
	X	0	0
	R	0.4t + 0.02	0.4t + 0.02
	W	4.0t	4.0t
0.10 (2.54) and over	S	0	0.05t or 0.03*
	X	0.05t or 0.03*	0
	R	0.6t or 0.09*	0.6t or 0.12
	W	In accordance with figure 15	In accordance with figure 15

*whichever is less

Figure 15 contains definitions.

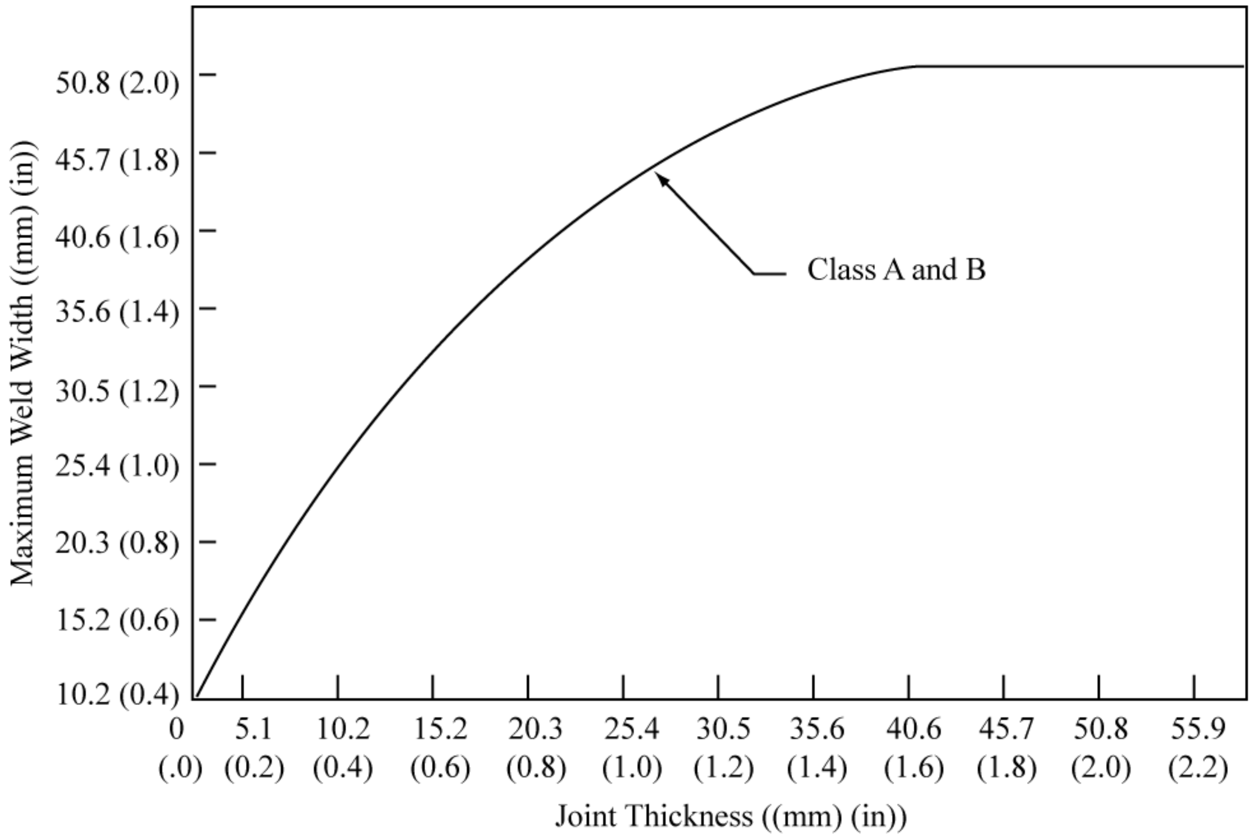
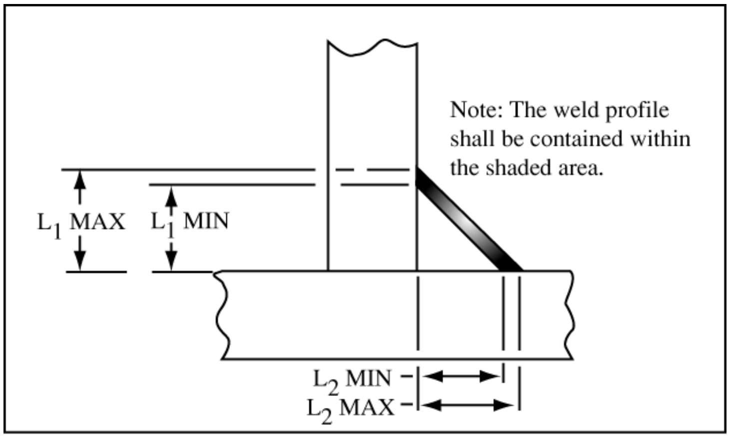
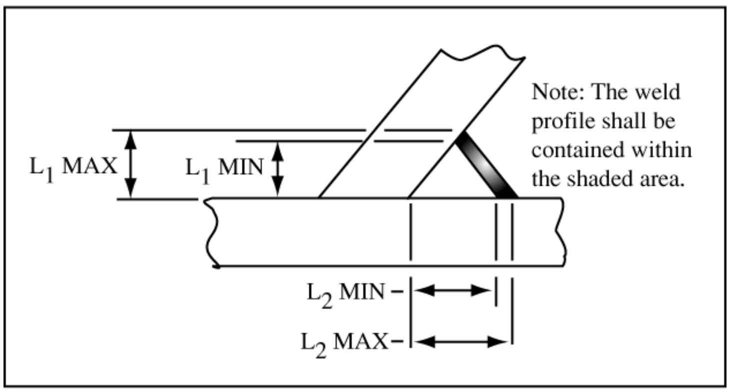


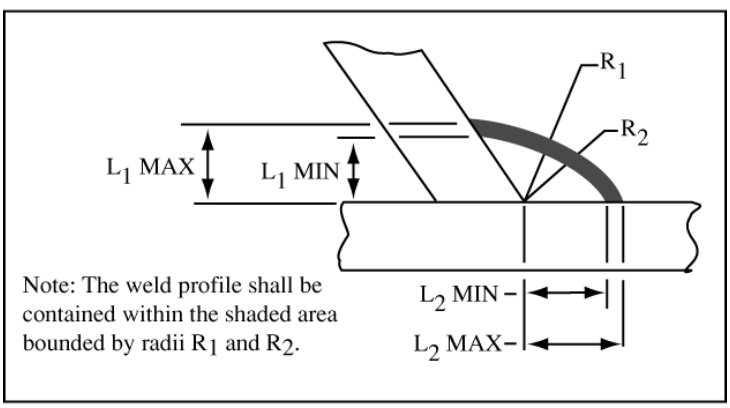
Figure 16. Titanium Butt Joint Maximum Allowable Weld Width (W) versus Thickness (t)



A. Right angle fillet weld

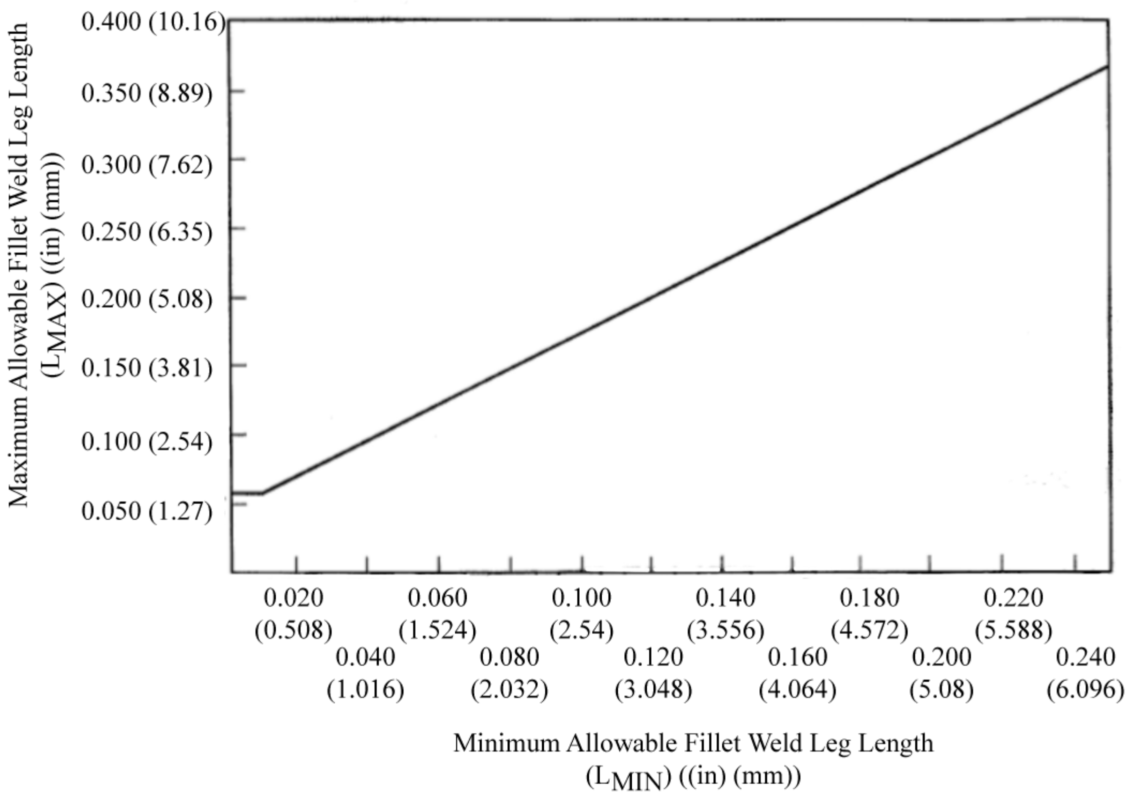


B. Acute angle fillet weld



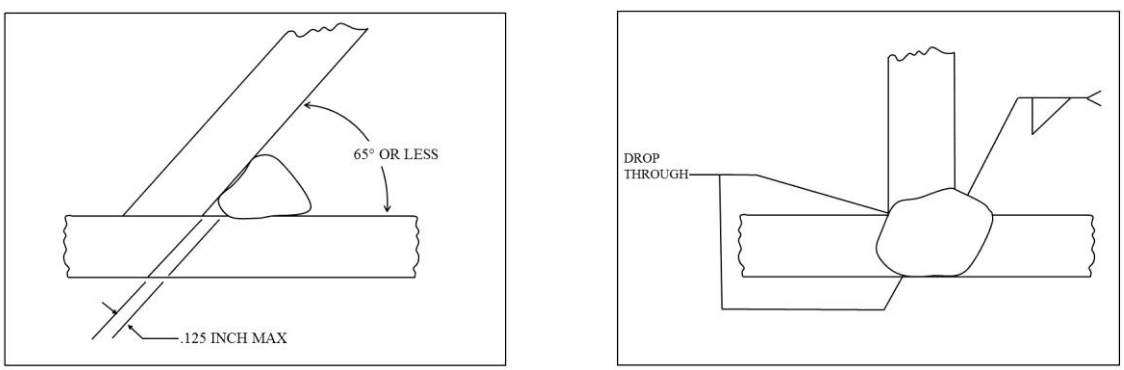
C. Obtuse angle fillet weld

Figure17. Titanium Fillet Joint Maximum Allowable Weld Width versus Thickness



Note: The maximum leg length in welds of 0.251 in (6.375 mm) or greater designated size (L) shall be L+0.12 in (+3.048 mm).

Figure 18. Titanium Maximum Fillet Weld Size (where L_{MIN} is equal to the thickness of the thinnest member)



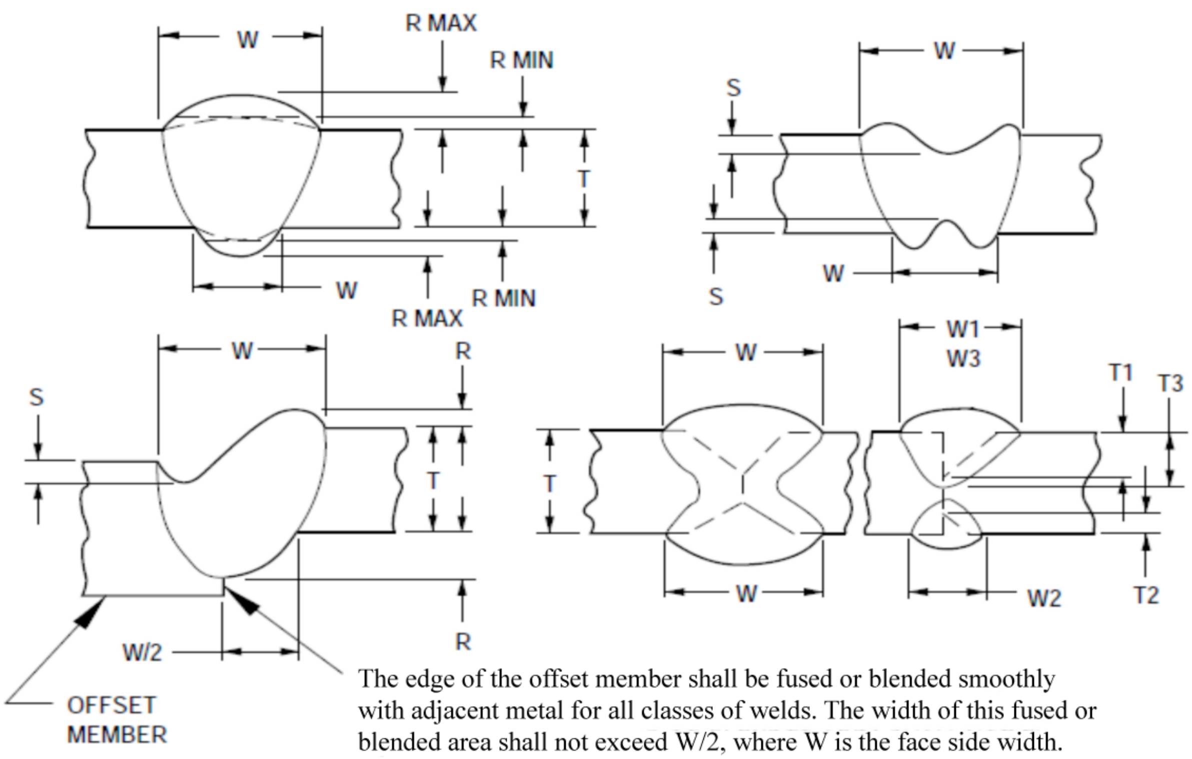
A. Acute angle fillet weld-unfused root

B. Fillet weld drop through

Figure 19. Titanium Fillet Weld Dimensions For Acute Angle and Drop Through

C.6 SUPERALLOYS

Figure 20, Weld Size Requirements for Butt Welds (Superalloys); figure 19, Class A Butt Weld Fusion Zone Weld Size Limits; figure 21, Class B Butt Weld Fusion Zone Weld Size Limits; figure 23, Class C Butt Weld Fusion Zone Weld Size Limits; figure 24, Weld Size Requirements for T and Corner Welds; figure 24, Class A Tee and Corner Weld Fusion Zone Weld Size Limits; figure 24, Class B Tee and Corner Weld Fusion Zone Weld Size Limits; and figure 27, Class C Tee and Corner Weld Fusion Zone Weld Size Limits, provide superalloy weld nugget dimensional requirements.



W = Maximum weld width. This dimenson shall apply to the entire fusion zone, regardless of the number of weld passes.

T = Designated nominal material thickness of thicker member of full-penetraion welds or specified groove depth (ref: T1, T2) of partial-penetration welds or specified penetration depth (ref: T3) of partial-penetration welds.

S = Maximum depth of weld concavity or suckback*.

R = Reinforcement. When flush contouring is required, R MAX shall not exceed 0.015 in (0.381 mm) after reinforcement removal.

*Note: Concavity or suckback that is contained entirely within the face or root reinforcement is acceptable.

Figure 20. Weld Size Requirements for Butt Welds (Superalloys)

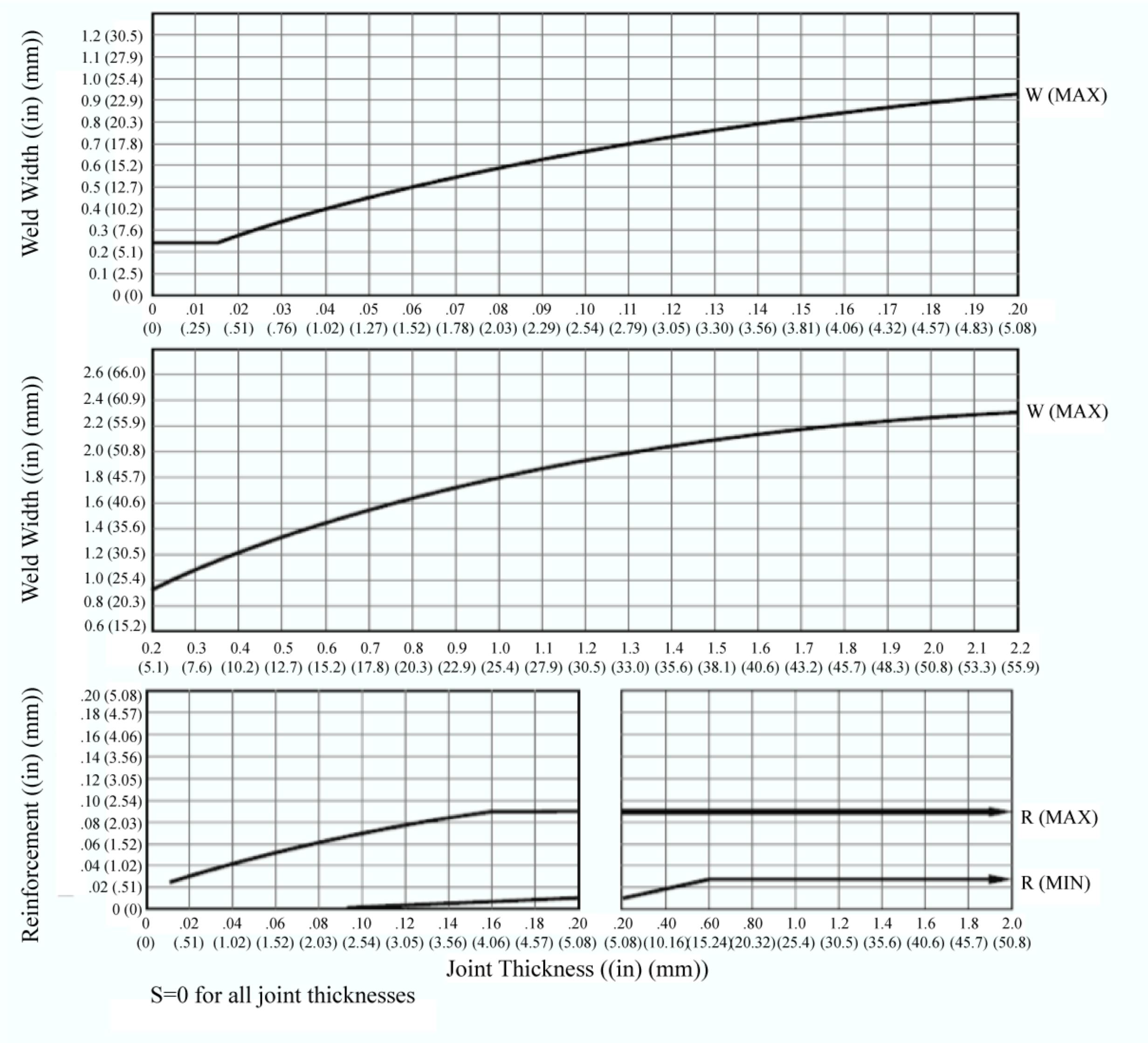
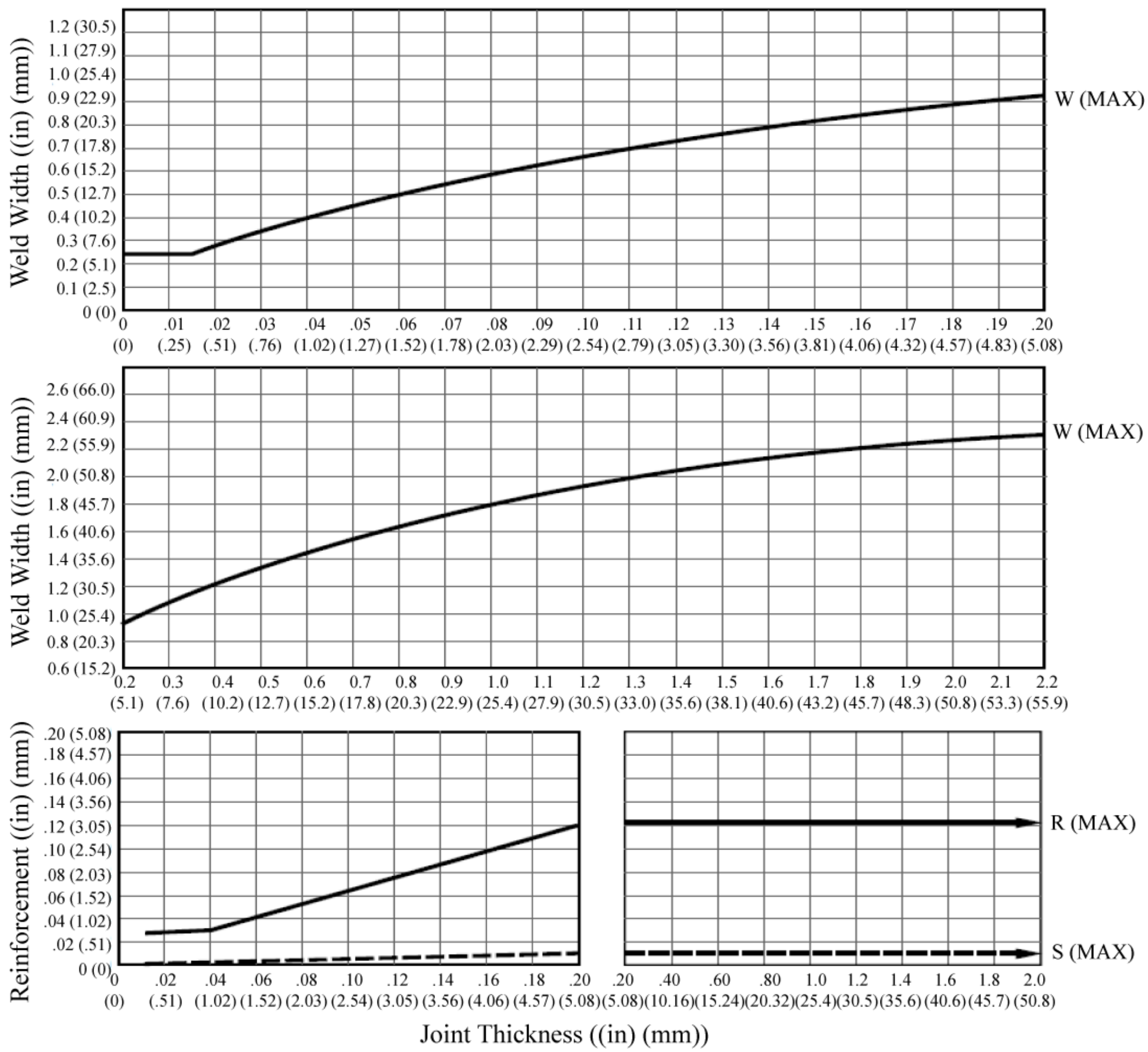
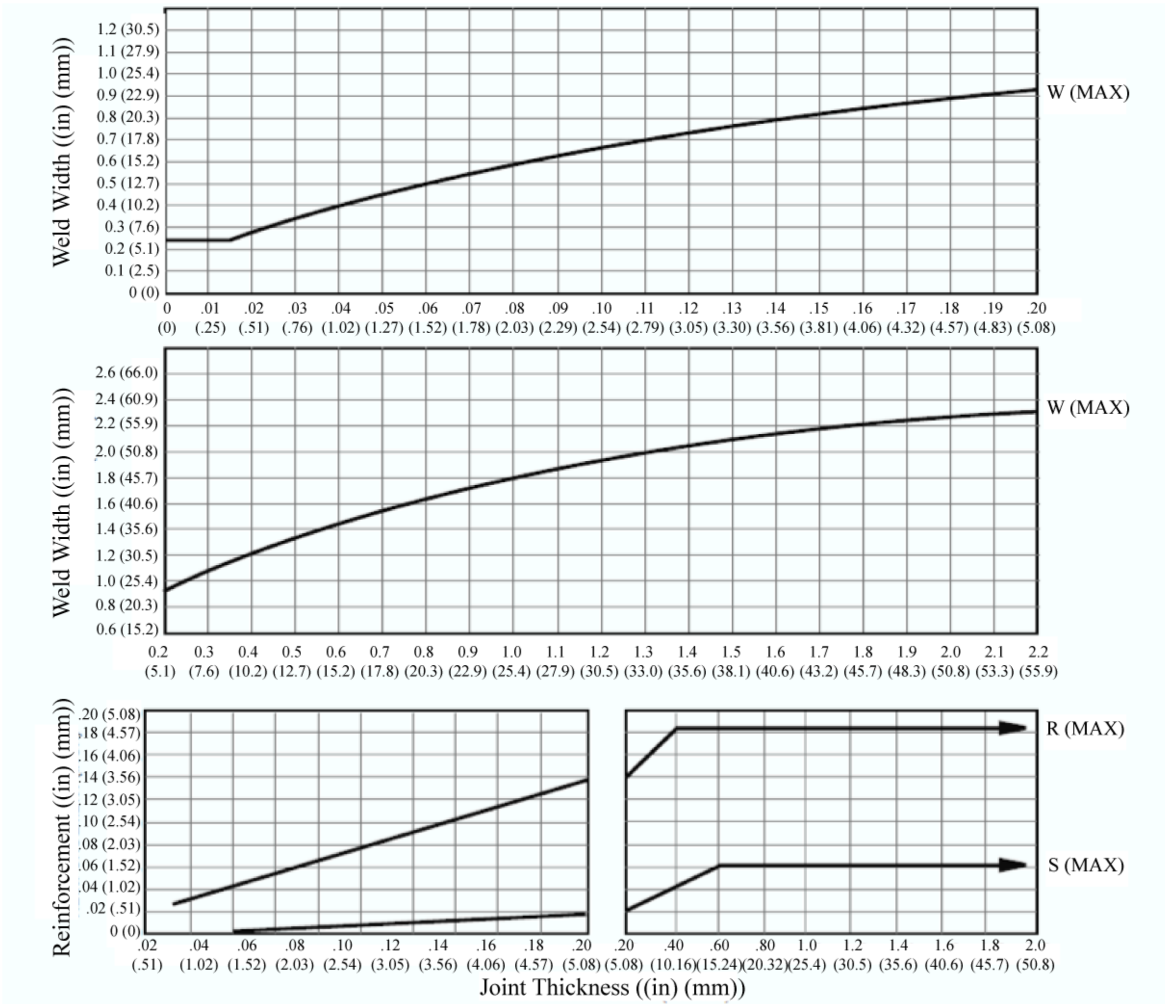


Figure 21. Class A Butt Weld Fusion Zone Weld Size Limits (Superalloys)



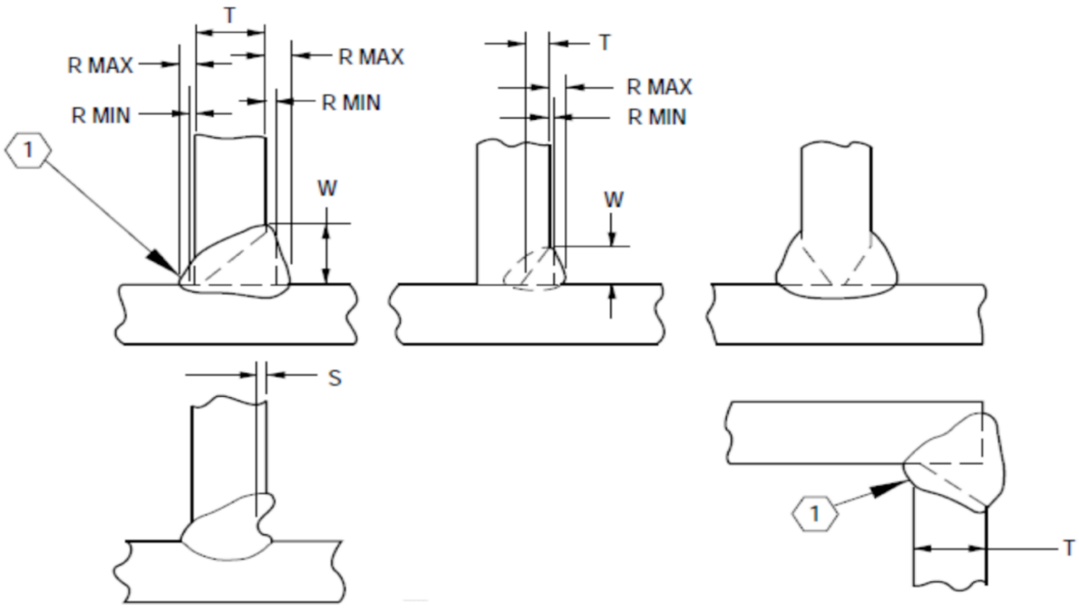
R (MIN)=0 for all joint thicknesses

Figure 22. Class B Butt Weld Fusion Zone Weld Size Limits (Superalloys)



R (MIN)=0 for all joint thicknesses

Figure 23. Class C Butt Weld Fusion Zone Weld Size Limits (Superalloys)



1 Fillet weld may be added on root side within reinforcement dimensions. S, X, R, and W requirements are the same for both sides.

W = Maximum weld width. This dimenson shall apply to the entire fusion zone, regardless of the number of weld passes.

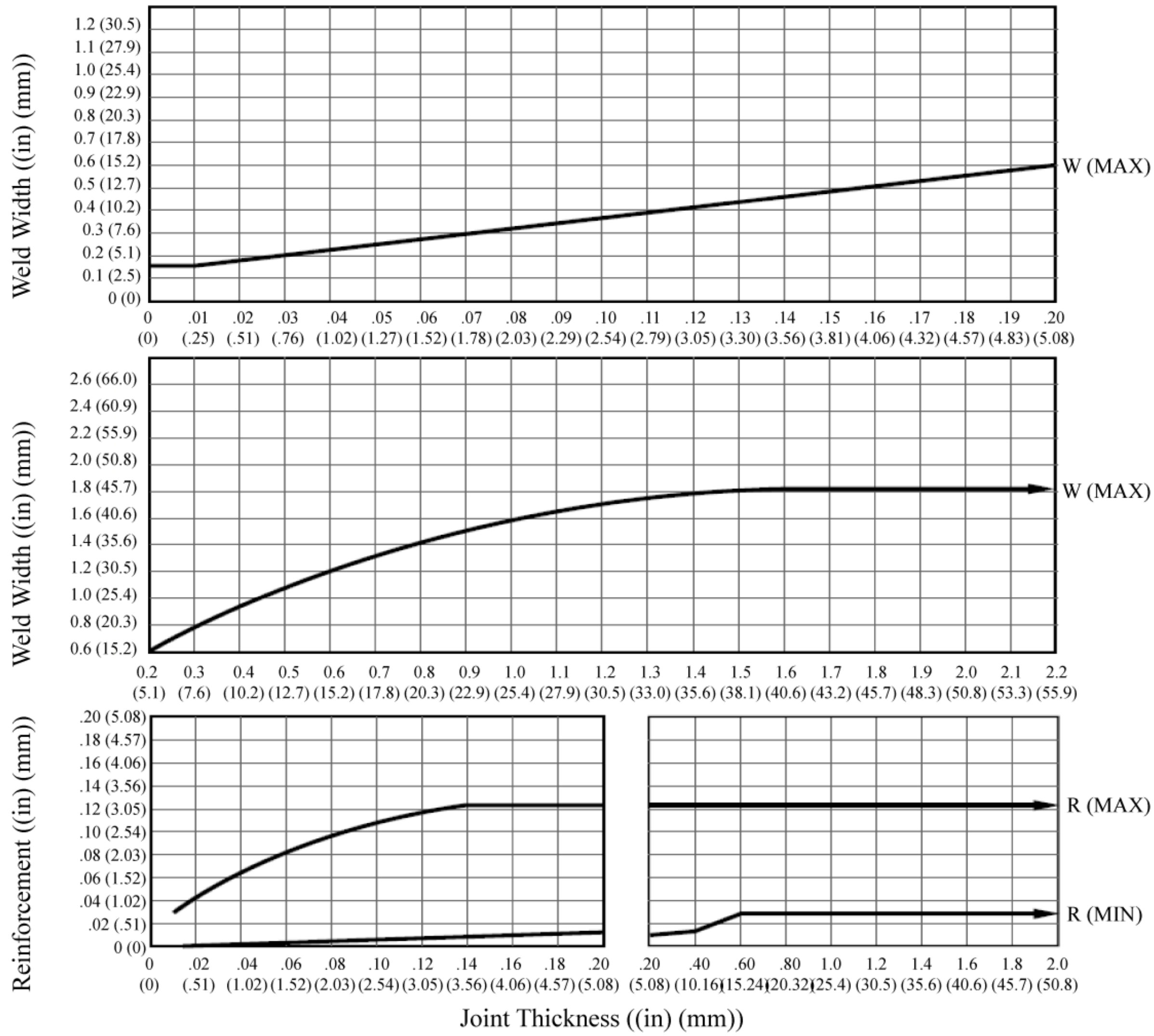
T = Designated nominal material thickness of the grooved member of full-penetraion welds or specified groove depth of partial-penetration welds or specified penetration depth of partial-penetration welds.

S = Maximum depth of weld concavity or suckback*.

R = Reinforcement. Mechanical removal of excess face buildup or (root) dropthrough is permissible. Full-penetration welds may have a fillet weld added on the root side within the maximum reinforcement dimensions.

*Note: Concavity or suckback that is contained entirely within the face or root reinforcement is acceptable.

Figure 24. Weld Size Requirements for Tee and Corner Welds (Superalloys)



S=0 for all joint thicknesses

Figure 25. Class A Tee and Corner Weld Fusion Zone Weld Size Limits (Superalloys)

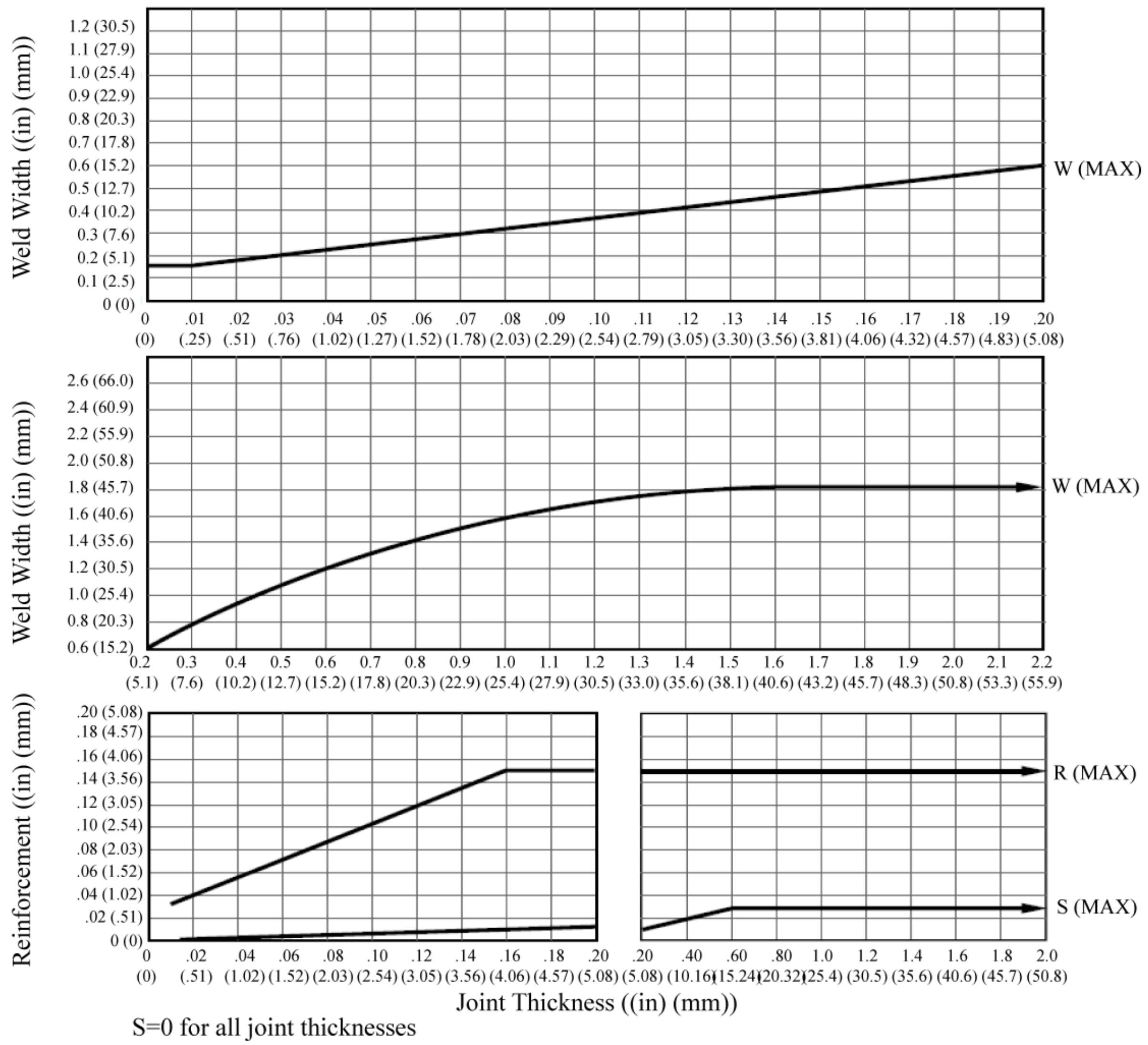
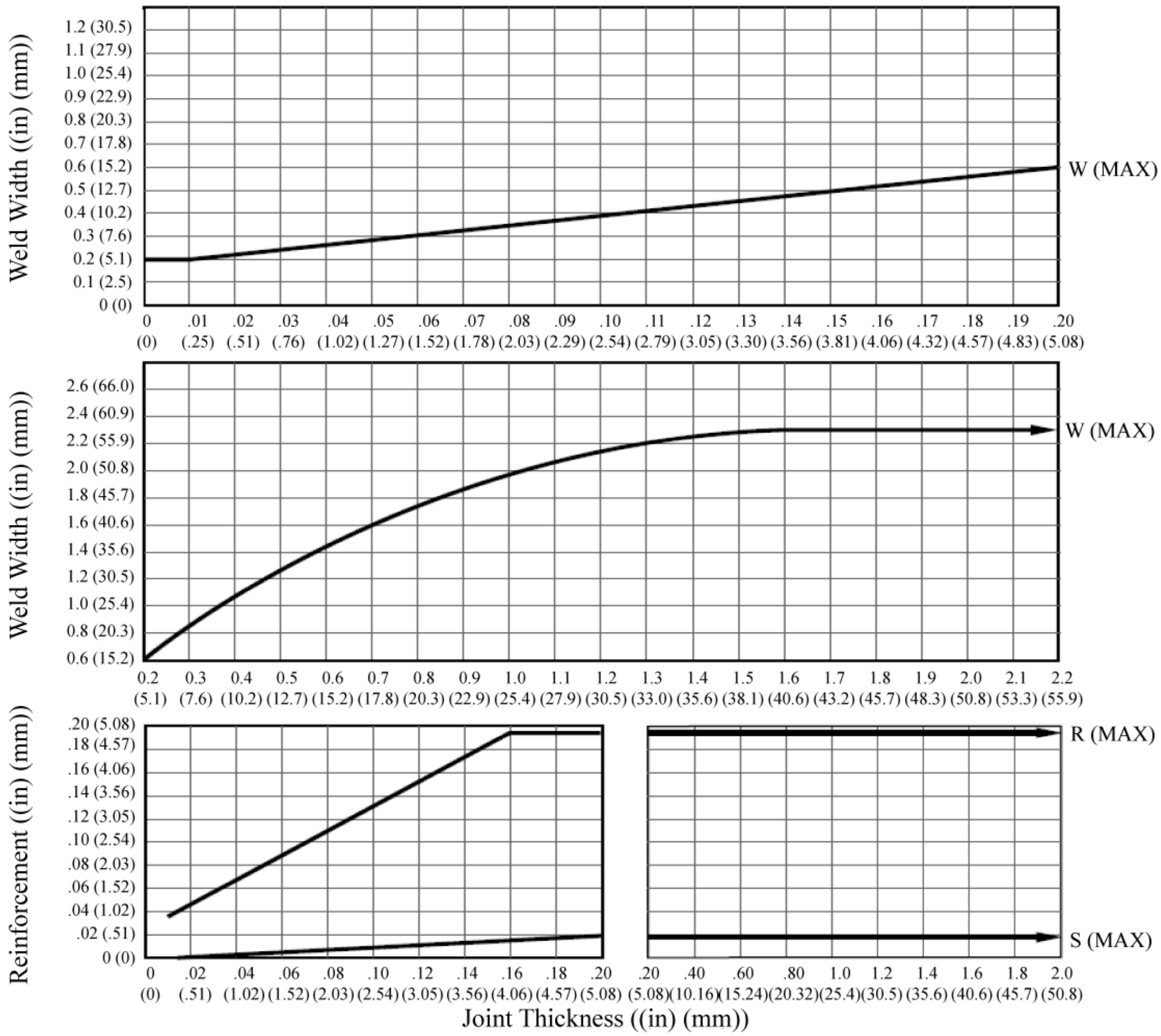


Figure 26. Class B Tee and Corner Weld Fusion Zone Weld Size Limits (Superalloys)



R (MIN)=0 for all joint thicknesses

Figure 27. Class C Tee and Corner Weld Fusion Zone Weld Size Limits (Superalloys)

APPENDIX D
WELD QUALITY REQUIREMENTS

D.1 PURPOSE AND/OR SCOPE

The purpose of this appendix is to provide weld accept/reject criteria requirements.

D.2 TABLES

Table 10, Weld Surface and Volumetric Acceptance Criteria – Aluminum Alloys; figure 28, External Discontinuities for Aluminium Alloys; figure 29, Internal Defects for Aluminum Alloys; table 11, Surface and Volumetric Weld Acceptance Criteria – Steels, Heat Resistant; figure 30, EB Weld Porosity Acceptance Criteria for Steels, Heat Resistant; and Table 12, Weld Surface and Volumetric Acceptance Criteria – Titanium Alloys, present weld surface acceptance criteria for various metals.

Table 10. Weld Surface and Volumetric Acceptance Criteria – Aluminum Alloys Process

Process	Discontinuity	Class A	Class B	Class C
All	Cracks	None allowed	None allowed	None allowed
	Overlap (cold lap)	None allowed	None allowed	None allowed
	Incomplete Fusion	None allowed	None allowed	None allowed
	Incomplete Penetration	None allowed	None allowed	None allowed for full-penetration welds
	Undercut, concavity, lack of fill, suckback	None allowed where it occurs as a sharp notch or where the depth reduces the material thickness below drawing requirements	None allowed where it occurs as a sharp notch or where the depth reduces the material thickness below drawing requirements	None allowed where it occurs as a sharp notch or where the depth reduces the material thickness below drawing requirements
Fusion				
	Surface porosity, oxides			
	Butt Joints	t/3 or 0.065 in (1.65 mm), whichever is smaller	t/2 or 0.100 in (2.54 mm), whichever is smaller	N/A
	Fillet Weld	S/3 or 0.050 in (1.27 mm), whichever is smaller	S/3 or 0.075 in (1.9 mm), whichever is smaller	N/A
	Scattered	Sum of the areas of all individual	Sum of the areas of all individual	N/A

Process	Discontinuity	Class A	Class B	Class C
		surface discontinuities within any 1 in (2.5 cm) of weld shall be less than 1/2 the maximum discontinuity area in Figure 28.	surface discontinuities within any 1 in (2.5 cm) of weld shall be less than 1/2 the maximum discontinuity area in Figure 28.	
	Scattered	No more than 15 individual surface discontinuities in any 1 in (2.5 cm) regardless of size are allowed.	14.0 N/A	N/A
	Linear	Three or more in a line are rejectable if the line extends more than 0.25 in (6 mm) and the discontinuities occupy more than 50% of the length of line.	Three or more in a line are rejectable if the line extends more than 0.50 in (12.5 mm) and the discontinuities occupy more than 50% of the length of line.	N/A
	Sharp	Rejectable if maximum dimension exceeds 0.100 in (2.54 mm).	Rejectable if maximum dimension exceeds 0.100 in (2.54 mm).	N/A
	Cluster	Three or more discontinuities each measuring 0.01 in (0.254 mm) or more, touching or falling within a 0.25-in (6-mm) diameter circle, shall be classified as a cluster when the sum of their maximum dimension exceeds t/3 or 0.065 in (1.65 mm) for butt welds and S/3 or 0.05 in (1.27 mm) for fillet, whichever is smaller. Two clusters are rejectable if separated by less than butt weld thickness (t) or less than specified fillet size (S).	Three or more discontinuities each measuring 0.02 in (0.508 mm) or more, touching or falling within a 0.25-in (10-mm) diameter circle, shall be classified as a cluster when the sum of their dimensions exceeds t/3 or 0.065 in (1.65 mm) for butt welds, and S/3 or 0.050 in (1.27 mm) for fillet welds, whichever is smaller for each weld. Two clusters are rejectable if separated by less than half the butt weld thickness (t/2) or less than half the specified fillet size (S/2).	N/A
	Volumetric voids, inclusions			
	Close Spacing	Discontinuities that appear overlapping, touching, or connected viewed normal to the weld surface for butt welds and at an optimum angle for fillet welds shall be treated as a single discontinuity. The spacing requirement is not	Discontinuities that appear overlapping, touching, or connected viewed normal to the weld surface for butt welds and at an optimum angle for fillet welds shall be treated as a single discontinuity. The spacing requirement is not applicable to	N/A

Process	Discontinuity	Class A	Class B	Class C
		applicable to discontinuities connected to the root of the weld for fillet welds.	discontinuities connected to the root of the weld for fillet welds.	
	Maximum Size	The maximum dimension of an individual internal discontinuity as viewed normal to the weld surface for butt welds and at an optimum angle for fillet welds shall not exceed the values obtained from Figure 29.	The maximum dimension of an individual internal discontinuity as viewed normal to the weld surface for butt welds and at an optimum angle for fillet welds shall not exceed the value obtained in Figure 29.	N/A
	Scattered	Scattered internal discontinuities not exceeding individual discontinuity limitations shall be evaluated for accumulative area per 1 in (2.5 cm) of weld. Area calculations shall be based on best fit circle or rectangle. Butt and fillet welds, including discontinuities connected to the root of fillet welds, shall conform to the requirements of figure 29.	Scattered internal discontinuities not exceeding the individual discontinuity limitations shall be evaluated for accumulative area per 1 in (2.5 cm) of weld. In addition, all discontinuities connected to the root of a fillet weld shall be included in the accumulative area. Area calculations shall be based on the best fit circle or rectangle. The area in any 1 in (2.5 cm) of weld shall not exceed the value obtained from Figure 27.	N/A
	Scattered - butt welds	Any 1 in (2.5 cm) of weld with maximum allowable area of figure 27 shall have no more than one-half the maximum allowable area in each adjacent 1 in (2.5 cm) of weld.		N/A
	Scattered - butt weld intersections	That 6 in (15.2 cm), i.e., 3 in (7.6 cm) to each side of the intersection, of weld intersection by another weld shall have the maximum allowable area of Figure 27 reduced by one-		N/A

Process	Discontinuity	Class A	Class B	Class C
		third.		
	Scattered	There shall be no more than 15 discontinuities in any 1 in (2.5 cm) of weld regardless of size or cumulative area loss.		N/A
	Linear	Three or more discontinuities, which are in line, are unacceptable if the line extends more than 0.25 in (6 mm) and the discontinuities occupy more than 50% of the length of the line. This requirement is not applicable to discontinuities connected to the root of fillet welds.	Three or more discontinuities, which are in a line, are unacceptable if the line extends more than 0.5 in (12.5 mm) and the discontinuities occupy more than 50% of the length of the line. This requirement is not applicable to discontinuities connected to the root of fillet welds.	N/A
	Sharp	Any discontinuity that appears to have a crack-like extension shall be cause for rejection. If the longest accumulative dimension is more than 5 times the width at the smallest dimension, the indication shall be cause for rejection. This requirement is not applicable to discontinuities connected to the root of fillet welds.	Any discontinuity that appears to have a crack-like extension shall be cause for rejection. If the longest accumulative dimension is more than 7 times the width at the smallest dimension, the discontinuity shall be cause for rejection. This requirement is not applicable to discontinuities connected to the root of fillet welds.	N/A

Process	Discontinuity	Class A	Class B	Class C
	Cluster	Three or more discontinuities, each measuring 0.010 in (0.254 mm) or more, touching or falling within a 0.25-in (6-mm) diameter circle, shall be classified as a cluster when the sum of their dimensions exceeds the allowable maximum dimension of an individual discontinuity in figure 29. For butt welds, two clusters are unacceptable if separated by less than t. For filet welds, two clusters are unacceptable if separated by less than the specified fillet size. This requirement is not applicable to discontinuities connected to the root of the fillet welds.	Three or more discontinuities, each measuring 0.02 in (0.508 mm) or more, touching or falling within a 0.25-in (6-mm) diameter circle, shall be classified as a cluster when the sum of their maximum dimensions exceeds the allowable maximum dimension of an individual discontinuity in figure 29. For butt welds, two clusters are unacceptable if separated by less than half the material thickness (t/2). For fillet welds, two clusters are unacceptable if separated by less than half the specified fillet size (S/2). This requirement is not applicable to discontinuities connected to the root of fillet welds.	N/A
Friction				
	Surface	Galling or tears on the surface of the weld visually indicated by open surface features or blisters shall be cause for rejection.	Galling or tears on the surface of the weld visually indicated by open surface features or blisters shall be cause for rejection.	N/A
	Volumetric voids, inclusions	Wormholes/voids/lack of adequate forgings shall be cause for rejection.	Wormholes/voids/lack of adequate shall be cause for rejection.	N/A
Electron Beam				
	Undercut and concavity	Sharp crevice at root		
		Thin weldment below minimum drawing requirements - rejectable		
		Exceed a depth of 0.05t or 0.040 in (1 mm), whichever is less - rejectable		
		Exceed a width of 0.25t or 0.08 in (2 mm), whichever is less - rejectable		
		Exceed a length of 0.5 in (1.3 mm) for any single indication or a total of 1.5 in (3.8 cm) in any 6-in (15-cm) length - rejectable		
	Volumetric porosity/inclusions	Accept per SAE AMS 2680, Electron-Beam Welding for Fatigue Critical Applications		

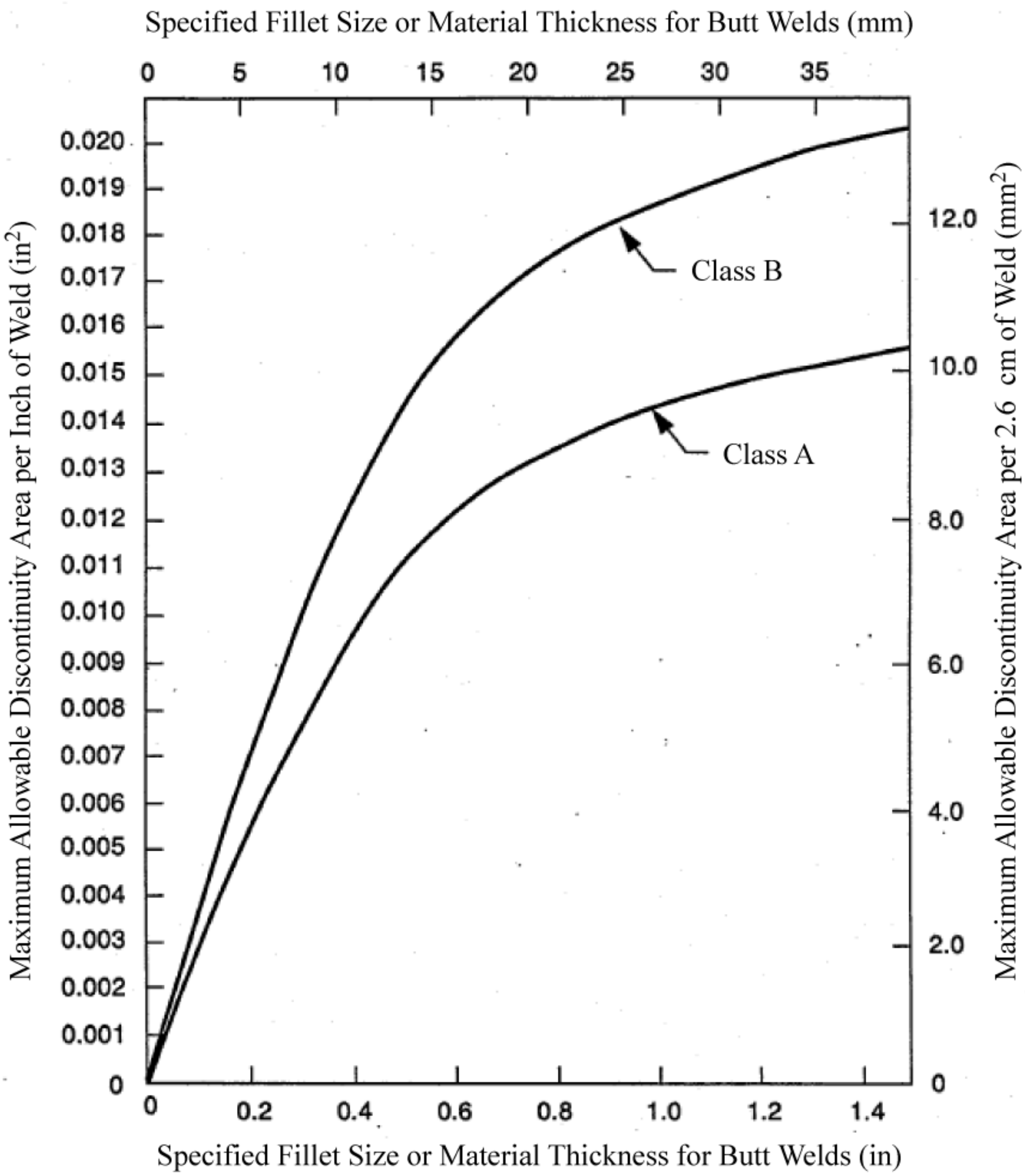


Figure 28. External Discontinuities for Aluminum Alloys

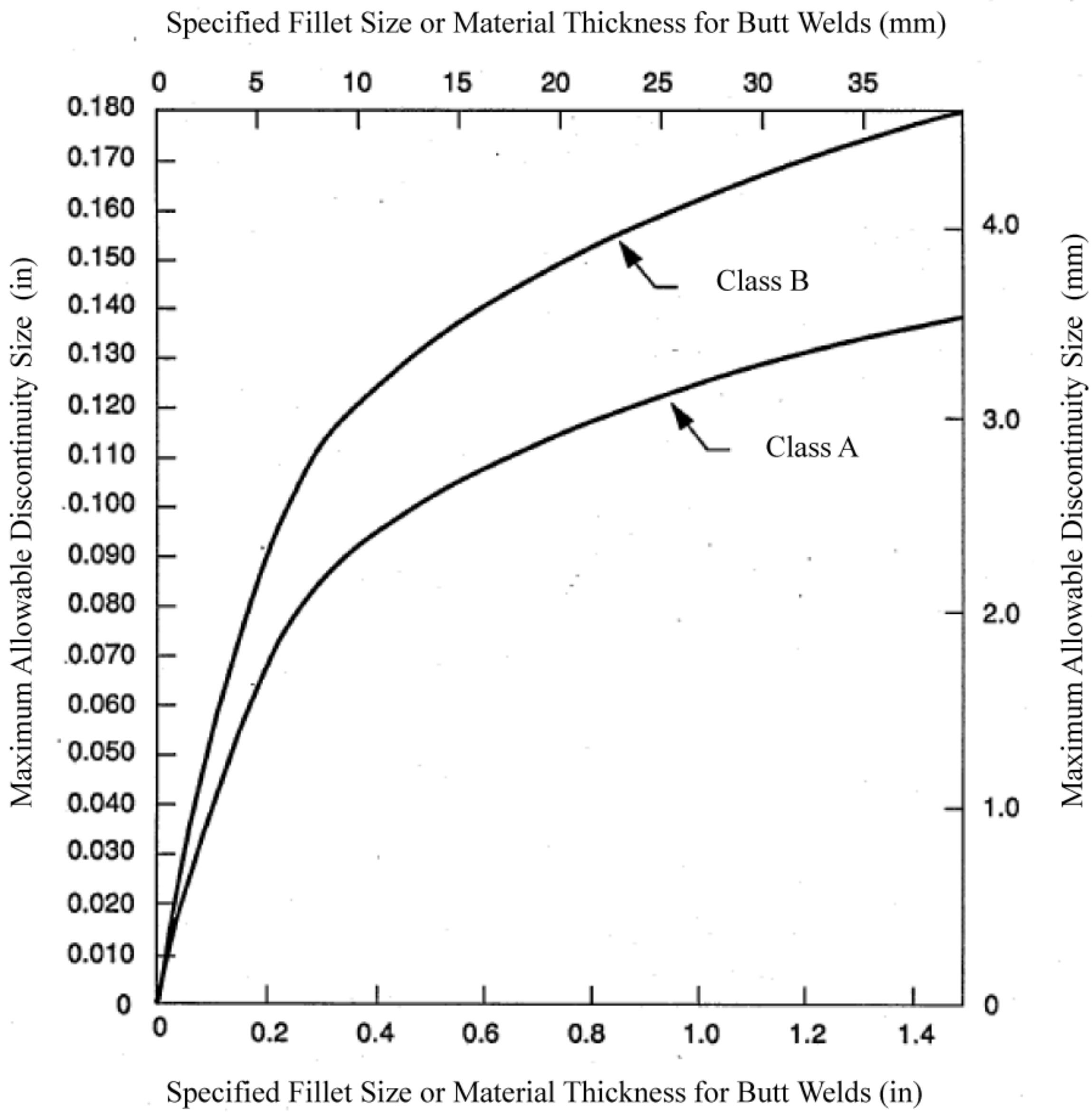
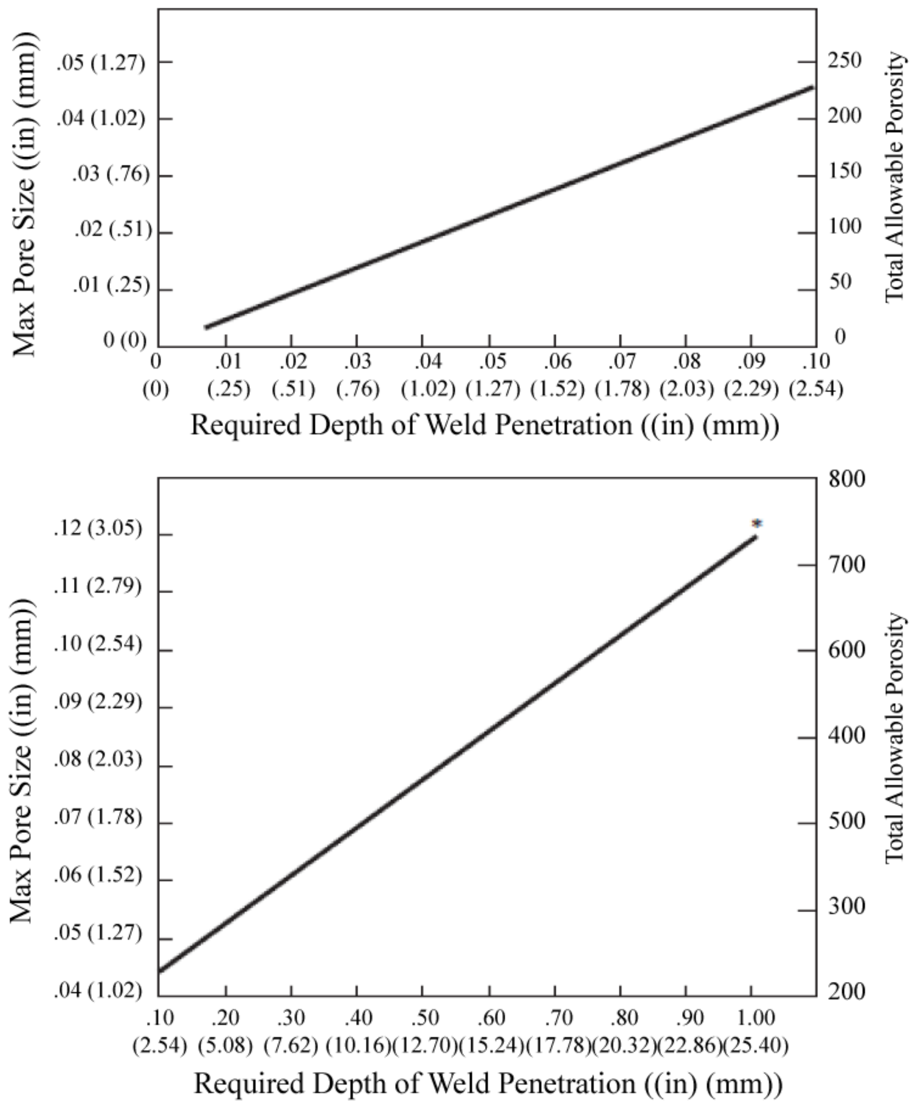


Figure 29. Internal Defects for Aluminum Alloys

Table 11. Surface and Volumetric Weld Acceptance Criteria – Steels, Heat Resistant

Process	Discontinuity	Class A	Class B	Class C
All	Cracks	None allowed	None allowed	None allowed
	Overlap (cold lap)	None allowed	None allowed	None allowed
	Incomplete fusion	None allowed	None allowed	None allowed
	Incomplete penetration	None allowed	None allowed	None allowed for full-penetration welds
	Undercut, concavity, lack of fill, suckback	None allowed where it occurs as a sharp notch or where the depth reduces the material thickness below drawing requirements	None allowed where it occurs as a sharp notch or where the depth reduces the material thickness below drawing requirements	None allowed where it occurs as a sharp notch or where the depth reduces the material thickness below drawing requirements
Fusion				
	Surface porosity and inclusions	NAS* 1514 Class I	NAS 1514 Class II	NAS 1514 Class III
	Internal quality	NAS 1514 Class I	NAS 1514 Class II	NAS 1514 Class III
Electron Beam				
	Undercut and concavity	Sharp crevice at root - reject		
		Thin weldment below minimum drawing requirements - reject		
		Exceed a depth of 0.05t or 0.040 in (1 mm), whichever is less - reject		
		Exceed a width of 0.25t or 0.080 in (2 mm), whichever is less - reject		
		Exceed a length of 0.5 in (1.3 mm) for any single indication or a total of 1.5 in (3.8 cm) in any 6-in (15-cm) length - reject		
	Porosity	See figure 28.		
	Pore clusters	Clusters of two or more pores are acceptable, provided the clusters can be enclosed within a circle of diameter equal to or less than the maximum pore size allowed.	Clusters of two or more pores are acceptable, provided the clusters can be enclosed within a circle of diameter equal to or less than the maximum pore size allowed.	

*NAS 1514, Radiographic Standard for Classification of Fusion Weld Discontinuities



*For depth of penetration (DOP) greater than 1.00 in (25.4 mm):
- max pore size is .12 in (3.05 mm)
- total porosity index is 750 x DOP

Figure 30. EB Weld Porosity Acceptance Criteria for Steels, Heat Resistant

Table 12. Weld Surface and Volumetric Acceptance Criteria – Titanium Alloys

Discontinuity	Class A	Class B	Class C
Cracks	None allowed	None allowed	None allowed
Overlap (cold lap)	None allowed	None allowed	None allowed
Incomplete fusion	None allowed	None allowed	None allowed
Incomplete penetration	None allowed	None allowed	None allowed
Porosity	NAS 1514 Class I	NAS 1514 Class II	NAS 1514 Class III

APPENDIX E
WELD PROCEDURE SPECIFICATION INFORMATION

E.1 PURPOSE AND/OR SCOPE

The purpose of this appendix is to provide guidance. It contains information of a general or explanatory nature but does not contain requirements.

E.2 RECOMMENDED PARAMETERS TO BE RECORDED IN WPS

Table 13, Recommended Parameters to be Recorded in WPS, contains information of a general or explanatory nature but does not contain requirements.

Table 13. Recommended Parameters to be Recorded in WPS

Electron Beam	Fusion (Automatic and Mechanized)	Fusion (Manual, Semiautomatic)	Friction Stir	Plug
Base metal alloys	Base metal alloys	Base metal alloys	Base metal alloys	Base metal alloys
Base metal thickness(es)	Base metal thickness(es)	Base metal thickness(es)	Base metal thickness	Base metal thickness(es)
Base metal heat treat condition(s)	Base metal heat treat condition(s)	Base metal heat treat condition(s)	Base metal heat treat condition(s)	Base metal heat treat condition(s)
Filler metal type and specification	Wire alloy and size	Weld filler metal type and diameter		
Filler wire feed speed (±10%)	Wire speed (ipm)	Wire speed (ipm)		
Joint configuration	Joint configuration	Joint configuration	Joint configuration	Joint configuration
Preweld cleaning procedure or specification or both	Preweld cleaning procedure or specification or both	Preweld cleaning procedure or specification or both	Preweld cleaning procedure or specification or both	Preweld cleaning procedure or specification or both
Surface preparation at weld joint	Joint preparation method	Joint preparation method	Joint preparation method	Joint preparation method
Tacking passes and parameters	Tacking passes and parameters	Tacking passes and parameters	Tacking passes and parameters	Plug alloy
	Weld type	Weld process	Plunge Load	Plug design
Welding Speed mm/sec (ipm) (±5%)	Travel speed		Travel speed	Travel speed
Beam current (±5%)	Tungsten size, type, configuration, and tolerances	Tungsten type, size, and configuration	Spindle speed	Spindle speed
High voltage (±5%)	Tungsten extension	Tungsten extension	Joint designation	Forge time
Number of passes and sequence	Number of passes and sequence	Number of passes and sequence	Torque range	Forge load
Focusing current (±5%)	Welding current	Target values for amps, volts, and travel speed	Pin tool part number, material, or drawing number	Heating load

Electron Beam	Fusion (Automatic and Mechanized)	Fusion (Manual, Semiautomatic)	Friction Stir	Plug
Welding vacuum pressure (torr)	Welding current type	Current polarity	Shoulder part number, material, or drawing number	Heating displacement
Sketch of setup, including all angles (±0.5 deg), MAX gap, Deliverable Date 1st Interim Report January 2012 Delivery of USW System/Develop DOE for weld trials April 2013 Begin Welding Development May 2013 2nd Interim Report July 2013 End of Year Report October 2013 ROI Report Annually for 3 years mismatch	Times for straight and reverse current	Range on power supply	Indicate force or position control	Backing plate/button drawing number
Procedure qualification number	Arc voltage	Power supply	Heel plunge	
EB certification number	Power supply ampere range	Maximum gap allowance	Pin length	
Operator and ID stamp	Power supply		Weld schedule	
Distance of gun to work (±0.125 in (±3 mm))	Power supply mode selection		Centerline offset	
Cathode to anode spacer	Shield gas type and flow rate	Shield gas type and flow rate	Traverse load	
Beam deflection ____on_____off	Backside shielding gas type and flow rate	Backside shielding gas type and flow rate	Lead angle	
	Shield cup/nozzle size	Shield cup/nozzle size	Axial load	
Weld position	Weld position	Weld position	Penetration ligament	Weld position
Procedure qualification number	Procedure qualification number	Procedure qualification number	MAX plunge force	Procedure qualification number
Computer program name/number	Computer program name/number	Torch	MAX plunge speed	Computer program name/number
	Torch lead angle	Torch lead angle		
Start-up parameters	Start-up parameters	Start-up parameters	Start-up parameters	Start-up parameters

Electron Beam	Fusion (Automatic and Mechanized)	Fusion (Manual, Semiautomatic)	Friction Stir	Plug
Nugget dimensions in accordance with figure 8	Start slope current and time		Dwell time	
	Tail slope current and time			
	Oscillation dwell, width, and speed			
	Torch			
			Specific tapered thicknesses, if a tapered thickness is being welded	
			Grain direction	
			Root face or surface coating	
Dimensions of starting weld tab and run off tab plates			Machine model and serial numbers	
			Root opening (or gap)	
			Weld fixture drawing number	
			Anvil material	
			Direction of tool rotation	
			Clamp pressure	
Termination parameters	Termination parameters		Termination parameters	

APPENDIX F
RECOMMENDED WELD FILLER METALS

F.1 PURPOSE AND/OR SCOPE

This purpose of this appendix is to provide guidance. It contains information of a general or explanatory nature but does not contain requirements.

F.2 TABLES

Table 14, Filler Alloys Recommended for Welding Aluminum Alloys and Combinations; table 15, Filler Alloys Recommended for Welding Carbon and Low Alloy Steels and Combinations; table 16, Filler Alloys Recommended for Welding Stainless Steels and Combinations**;** table 17, Filler Alloys Recommended for Welding Nickel- and Cobalt-Base Alloys and Combinations; table 18, Filler Alloys Recommended for Welding Copper Alloys and Combinations; and table 19, Filler Alloys Recommended for Welding Titanium Alloys and Combinations, present recommended filler alloys for various metals.

Table 14. Filler Alloys Recommended for Welding Aluminum Alloys and Combinations

Base Alloy	2014	2219	2195	5052	6061*	5456
2014	4043, 2319				4043	
2219	2319, 4043	2319	4043, 2319		4043	
2195		4043, 2319	4043			
5052				5356	4043	
6061*	4043	4043		4043	4043	
5456	4043, 5356	4043, 5356		5356, 5556	4043, 5356	5356, 5556

* Unless specified otherwise, filler metal is to be used when fusion welding 6061.

Table 15. Filler Alloys Recommended for Welding Carbon and Low Alloy Steels and Combinations

Base Alloy	Mild Steels	Construction Steels	4130	4135, 4140	4335, 4340	T1	9Ni 4Co	18-7 Maraging Steel (250)
Mild Steels	GA65	NAX 9115	Vac Melt 17-22AS	Vac Melt 17-22AS	Vac Melt 17-22AS, GA65	Vac Melt 17-22AS, GA65		
Construction Steels		NAX 9115	Vac Melt 17-22AS	Vac Melt 17-22AS	Vac Melt 17-22AS, GA65	Vac Melt 17-22AS, GA65		
4130			Vac Melt 17-22AS	Vac Melt 17-22AS	Vac Melt 17-22AS	Vac Melt 17-22AS		
4135, 4140				Vac Melt 17-22AS	Vac Melt 17-22AS	Vac Melt 17-22AS		
4335, 4340					Vac Melt 17-22AS	Vac Melt 17-22AS		
9Ni 4Co							HP 9-4-.2	
18-7 Maraging Steel (250)								18-7 Maraging Steel
Hastelloy C						Hastelloy W		
304, 310, 321, 347	Inconel 82	Inconel 82				Inconel 92		

Table 16. Filler Alloys Recommended for Welding Stainless Steels and Combinations

Base Alloy	304, 304L	310	316, 316L	321, 347	410	430	19-9DL,19-9DX	17-4 PH	17-7 PH
304 , 304L	308L	308L	316L	308L			349	Hastelloy W	Hastelloy W
310		310	310	310			349	Hastelloy W	Hastelloy W
316, 316L			316L	347			Inconel 92	Hastelloy W	Hastelloy W
321, 347				321, 347		Hastelloy W	349	Hastelloy W	Hastelloy W
410					410	430			
430						430			
19-9DL, 19-9DX							349	Hastelloy W	Hastelloy W
17-4 PH								17-4 PH	17-7 PH
17-7 PH									17-7 PH
16-25-6									
21-6-9									
29-20 Cb									
29-9									
AM350									
AM355									
A-286									
Haynes 21									
Haynes 188	308L, Haynes 188	308L, Haynes 188							
Incoloy 903 Cartech CTX-1									
Invar 36									

Table 16. Filler Alloys Recommended for Welding Stainless Steels and Combinations (continued)

Base Alloy	16-25-6	21-6-9	29-20 Cb	29-9	AM350	AM355	A-286	Incoloy 903 Cartech CTX-1	Invar 36
304, 304L	Hastelloy W	308L 36% Nickel	29.20 Cb		AM350	AM355			Hastelloy W
310	Hastelloy W	308L	29.20 Cb		AM350	AM355			Hastelloy W
316, 316L	Hastelloy W	308L	29.20 Cb		Inconel 92	Inconel 92			Hastelloy W
321, 347	Hastelloy W	308L 36% Nickel	29.20 Cb		AM350	AM355	Hastelloy W		Hastelloy W
410									
430									
19-9DL, 19-9DX									
17-4 PH									
17-7 PH									
16-25-6	349			312					
21-6-9		ARMCO 21-6-9					Hastelloy W		
29-20 Cb			29.20 Cb		AM355	AM355			
29-9				312					
AM350					AM350	AM350			
AM355						AM355			
A-286							A-286		
Haynes 21	Hastelloy W								
Haynes 188		Haynes 188							
Incoloy 903 Cartech CTX-1								Incoloy 903	
Invar 36									36% Nickel Hastelloy W

Table 17. Filler Alloys Recommended for Welding Nickel- and Cobalt-Base Alloys and Combinations

Base Alloy	Ni200 Ni270	ED Nickel	Monel 400	K-Monel 500	Inconel 600	Inconel X 750	Inconel 718	Inconel 625	Hastelloy B	Hastelloy C	Hastelloy X
Ni200 Ni270	Nickel 61	Nickel 61	Nickel 61	Nickel 61					Hastelloy W	Hastelloy W	Hastelloy W
ED Nickel	Nickel 61	Nickel 61	Nickel 61		Nickel 61	Nickel 61	Nickel 61	Nickel 61	Nickel 61	Nickel 61	Nickel 61
Monel 400			Monel 60	Monel 60							
Inconel 600					Inconel 82	Hastelloy W	Hastelloy W	Hastelloy W	Hastelloy W	Hastelloy W	Hastelloy W
Inconel X 750						Inconel 69	Inconel 718, Hastelloy W	Hastelloy W	Hastelloy W	Hastelloy W	Hastelloy W
Inconel 718							Inconel 718	Inconel 625	Hastelloy W	Hastelloy W	Hastelloy W
Inconel 625								Inconel 625	Inconel 625	Inconel 625	Inconel 625
Hastelloy B									Hastelloy B	Hastelloy W	Hastelloy W
Hastelloy C										Hastelloy C	Hastelloy W
Hastelloy X											Hastelloy X
Haynes 21											
Haynes 25 L-605											
Haynes 188											
Haynes 230											
Rene' 41											
Incoloy 800											
Incoloy 88											
4130, 4140					Inconel 92		Hastelloy W			Hastelloy W	
4340							Inconel 92				
304L, 347, 321, 316L , 310	Inconel 92				Inconel 625, Hastelloy W	Hastelloy W	Inconel 625, Hastelloy W	Inconel 625	Hastelloy W	Hastelloy W	Hastelloy W

Table 17. Filler Alloys Recommended for Welding Nickel- and Cobalt-Base Alloys and Combinations (continued)

Base Alloy	Haynes 21	Haynes 25 L-605	Haynes 188	Haynes 230	Rene' 41	Incoloy 800	Incoloy 88	Incoloy 903 Cartech CTX-1	21-6-9
Ni200. Ni270	Hastelloy W	Hastelloy W	Hastelloy W						
ED Nickel	Nickel 61	Nickel 61	Nickel 61		Nickel 61				
Monel 400									
Inconel 600	Hastelloy W	Hastelloy W	Hastelloy W		Hastelloy W				
Inconel X 750	Hastelloy W	Hastelloy W			Hastelloy W				
Inconel 718	Hastelloy W	Hastelloy W	Haynes 188			Incoloy 88	Incoloy 88	Incoloy 903	Inconel 625, Incoloy 88
Inconel 625	Inconel 625	Inconel 625	Inconel 625		Inconel 625		Inconel 625, Incoloy 88	Inconel 625	Inconel 625, Incoloy 88
Hastelloy B	Hastelloy W	Hastelloy W	Haynes 188						
Hastelloy C	Hastelloy C	Hastelloy W	Haynes 188						
Hastelloy X	Hastelloy W	Hastelloy W	Hastelloy W						
Haynes 21	Haynes 25	Haynes 25	Haynes 188						
Haynes 25 L-605		Haynes 25	Haynes 188						
Haynes 188			Haynes 188		Haynes 188		Haynes 188		Haynes 188
Haynes 230				Haynes 230					
Rene' 41					Hastelloy W, Rene' 41				
Incoloy 800						Incoloy 88			
Incoloy 88							Incoloy 88, Incoloy 903, Haynes 188		
4130, 4140									
4340									
304L, 347, 321, 316L, 310	Hastelloy W	Hastelloy W	Haynes 188				Hastelloy W		

Table 18. Filler Alloys Recommended for Welding Copper Alloys and Combinations

Base Alloy	OFCH Copper	Deoxidized Copper	Amzirc	Narloy A	Narloy Z
OFCH Copper	Deoxidized Copper	Deoxidized Copper Silicon Bronze	Deoxidized Copper	Deoxidized Copper	Deoxidized Copper
Deoxidized Copper		Deoxidized Copper	Deoxidized Copper	Deoxidized Copper	Deoxidized Copper
Amzirc			Deoxidized Copper	Deoxidized Copper	Deoxidized Copper
Narloy A				Deoxidized Copper	Deoxidized Copper
Narloy Z					Deoxidized Copper

Note: Deoxidized copper is used for maximum thermal conductivity. It has low strength.

Table 19. Filler Alloys Recommended for Welding Titanium Alloys and Combinations

Base Alloy	CP Titanium	5Al-2.5Sn	5Al-2.5Sn ELI	6Al-4V	6Al-4V ELI	3Al-2.5V
CP Titanium	CP Titanium					
5Al-2.5Sn	CP Titanium	Ti 5Al-2.5Sn, Ti 5Al-2.5Sn ELI				
5Al-2.5Sn ELI	CP Titanium	Ti 5Al-2.5Sn, Ti 5AL-2.5Sn ELI	Ti 5Al-2.5Sn ELI			
6Al-4V	Ti 6Al-4V, Ti 6Al-4V ELI	Ti 6Al-4V, Ti 6Al-4V ELI	Ti 5Al-2.5Sn ELI Ti6 Al-4V, Ti 6Al-4V ELI	Ti 6Al-4V, Ti 6Al-4V ELI	Ti 6Al-4V, Ti 6Al-4V ELI	
6Al-4V ELI		Ti 6Al-4V ELI	Ti 6Al-4V ELI	Ti 6Al-4V, Ti 6Al-4V ELI	Ti 6Al-4V ELI	
3Al-2.5V				Ti 6Al-4V, Ti 6Al-4V ELI, Ti 3Al- 2.5V	Ti 6Al-4V, Ti 6Al-4V ELI, Ti 3Al-2.5V	Ti 3Al-2.5V

APPENDIX G
PREWELD AND POSTWELD CLEANING METHODS

G.1 PURPOSE AND/OR SCOPE

The purpose of this appendix is to provide preweld and postweld requirements.

G.2 PREWELD AND POSTWELD CLEANING METHODS

Table 20, Acceptable Preweld and Postweld Cleaning Methods, lists preweld and postweld cleaning methods for various alloys.

Table 20. Acceptable Preweld and Postweld Cleaning Methods

	Method							
Alloy	**Degrease by Alkaline Wash**	**Chemical Descale**	**Chemical Deoxidize**	**Hand Scrape**	**Hand Grind/Sand**	**Hand Wire Brush[1]**	**Scotch-Brite™ Abrasion[2]**	**Hand Solvent Wipe**
Aluminum Alloys	X	X	X	X		X	X	X
Copper Alloys	X		X		X		X	X
Nickel- Based Alloys	X				X	X	X	X
Chromium-Based Alloys[3] Stainless Steels	X	X	X		X		X	X
Titanium Alloys[4]	X		X				X	X
Carbon Steels	X	X			X	X	X	X

1. Stainless steel wire brushes only.
2. Use only coated abrasive and Scotch-Brite™ Roloc™ products.
3. Do not use chlorinated solvents.
4. Do not use chlorinated or halogenated solvents.

APPENDIX H
REFERENCE DOCUMENTS

H.1 PURPOSE AND/OR SCOPE

This purpose of this appendix is to list the specifications used in the development of this process specification. This appendix contains information of a general or explanatory nature but does not contain requirements.

H.2 GOVERNMENT DOCUMENTS

Department of Defense

MIL-STD-2219A Fusion Welding For Aerospace Applications

NASA George C. Marshall Space Flight Center

MSFC-SPEC-504C Specification: Welding, Aluminum Alloys

MSFC-SPEC-560A The Fusion Welding of Steels, Corrosion and Heat Resistant Alloys

MSFC-SPEC-766 Fusion Welding Titanium and Titanium Alloys

NASA Lyndon B. Johnson Space Center

PRC-0001 G Process Specification for the Manual Arc Welding of Aluminum Alloy Hardware

PRD-0002 B Process Specification for the Manual Arc Welding of Titanium Alloy Hardware

PRC-0005 F Process Specification for the Manual Arc Welding of Carbon Steel and Nickel Alloy Hardware

PRC-0008 C Process Specification for the Qualification of Manual Arc Welders

PRC-0009 D Process Specification for the Resistance Spot Welding of Battery and Electronic Assemblies

PRC-0010 C Process Specification for Automatic and Machine Arc Welding of Steel and Nickel Alloy Hardware

PRC-0014 C	Process Specification for Friction Stir Welding

H.3 NON-GOVERNMENT DOCUMENTS

AWS

AWS C6.1	Recommended Practices for Friction Welding
AWS D17.1	Specification for Fusion Welding for Aerospace Applications
AWS D17.2	Specification for Resistance Welding for Aerospace Applications

NAS

NAS 976	Electron Beam Welding Machine – High Vacuum

SAE/AMS

AMS 2680	Electron-Beam Welding for Fatigue Critical Applications
AMS 2681	Electron-Beam Welding
ASME B46.1	Surface Texture Roughness, Waviness and Lay