**PREFERRED
RELIABILITY
PRACTICES**

WELDING PRACTICES FOR 2219 ALUMINUM AND INCONEL 718

Practice:

Gas Tungsten Arc Welding and Variable Polarity Plasma Arc Welding are preferred for joining 2219 Aluminum, and Electron Beam Welding is preferred for joining Inconel 718 in critical aerospace flight applications.

Benefit:

Adhering to proven design practices and processing techniques for 2219 Aluminum and Inconel 718 will result in high performance joints, reduced weld defects, reduced weld repair costs, and reduced inspection costs. These practices, if conscientiously applied, will reduce the potential for galvanic corrosion, hot cracking, imperfect bead shape, inclusions, lack of fusion, lack of penetration, microfissuring, mismatch, peaking, porosity, residual stresses, start/stop defects, and stress corrosion cracking.

Programs That Certified Usage:

Saturn I, Saturn V, Space Shuttle External Tank, and Space Shuttle Main Engine.

Center to Contact for More Information:

Marshall Space Flight Center (MSFC)

Implementation Method:

Three types of welding for two commonly used materials have been used predominantly at NASA/MSFC for the welding of aerospace hardware: (1) Gas Tungsten Arc Welding (GTAW) for 2219 aluminum; (2) Variable Polarity Plasma Arc Welding (VPPAW) for 2219 aluminum; and (3) Electron Beam Welding (EBW) for Inconel 718. In Gas Tungsten Arc Welding for 2219 aluminum, heat required to join the aluminum is generated through an electrical arc applied at the joint. An inert atmosphere of helium surrounds the arc to prevent oxidation during the welding process. The type of GTAW covered in this practice is direct current, straight polarity (DCSP) in which the torch serves as the negative electrode (cathode) and the work piece as the positive electrode (anode). In Variable Polarity Plasma Arc Welding for 2219 aluminum, an arc gas (argon) is constricted by an orifice in the torch so that it forms a narrow column of high density gas that carries the arc current. Current is reversed up to 20 percent of the time in a 20 to 25 microsecond cycle to provide a cleaning action to the work piece. Electron Beam Welding is performed in a vacuum and generates heat for fusing adjoining metals by impacting high kinetic energy electrons upon the work piece surface. [Definitions of selected welding terms applicable to the three types of welding are provided on the last page of this practice.]

The three types of welding, along with distinguishing recommended practices for each, are shown in Table 1. Among the important practices that will aid in ensuring high reliability welds are *welding in the proper position*, use of *high purity shield and plasma gasses*, *proper cleaning of the joint* prior to welding, *operator certification*, and *computer control* of the welding process. The use of 2-percent thoriated tungsten electrodes for GTAW and VPPAW provides arc stability and increases electrode service life over that of standard tungsten electrodes. Important additional precautions for all three types of welding are use of *rigid tooling* to reduce weld joint deformation, *nonmagnetic tooling* to prevent skewing of the arc due to magnetic deflection, and *correct and properly marked weld rod and wire*. Automation is highly desirable for all three methods to maintain weld uniformity. If *tack welds* are used to temporarily hold adjoining parts in place, they *should be consumed* during the welding process. Specific characteristics, parameters, precautions, and criteria for each type of welding are described in the following three paragraphs:

1. Gas Tungsten Arc Welding (GTAW) (DCSP) for 2219 Aluminum

As shown in Table 1, the flat (downhand) position is preferred for the best weld uniformity and penetration. Welding in the direct current, straight polarity (DCSP) mode while using high purity helium shield gas provides deep penetration without oxidation or contamination. (Welding in the alternating current mode is particularly suitable for welding thin aluminum as it produces less heat and provides good cathodic cleaning.) Pulsing of the weld current can be used to provide better control for some out-of-position welds. *Minimizing the number of weld passes* will decrease the tendency for distortion. A pointed tip electrode is used in GTAW. A positive torch "lead angle" is desirable for GTAW (DCSP) to provide preheating and more uniform melting.

Lower energy inputs generally increase weld strength. GTAW (DCSP) is a preferred process for tack welding of aluminum. GTAW (DCSP) also can be used for welding steels (including stainless steel), titanium, magnesium (with care), and refractory metals. The 2219 aluminum is an excellent alloy for maximum strength in cryogenic applications with good weldability.

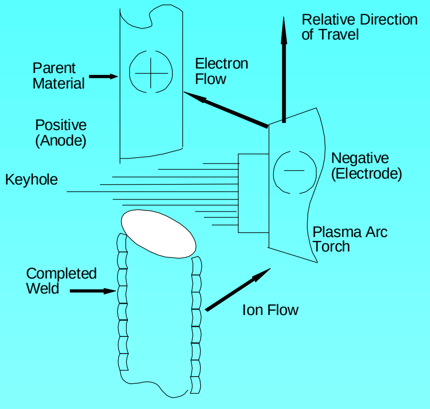
Table 1. Weld Characteristics/Parameters/Criteria for Three Types of Welding

CHARACTERISTIC OR PARAMETER	RECOMMENDED OR STANDARD PRACTICES		
	GAS TUNGSTEN ARC WELDING (2219 Al)	VARIABLE POLARITY PLASMA ARC WELDING (2219 Al)	ELECTRON BEAM WELDING (INCONEL 718)
Preferred Position	Flat	Vertical (UP)	Flat
Shield Gas	Helium (99.999% Purity)	Helium (99.999% Purity)	Vacuum
Plasma Gas	N/A	Argon (99.999% Purity)	N/A
Backing Required	No	No	In Some Instances (1)
Preferred Electrode	2% Thoriated Tungsten	2% Thoriated Tungsten	(Tungsten Filament)
Appropriate for Repair	Yes	Not Usually (2)	Yes
Cleaning Requirements	Mechanical Removal of Oxide, Free of Hydrocarbons	Mechanical Cleaning Not Required, Degrease Only	Special Cleaning for Vacuum Requirements
Used for Tack Welding	Yes	No	Yes
Computer Control	Desirable	Essential	Desirable
Most Prominent Potential Defects	Oxide and Tungsten Porosity, Lack of Penetration or Fusion	Undercut, Lack of Fusion	Improper Seam Tracking, Microfissuring

N/A: Not Applicable

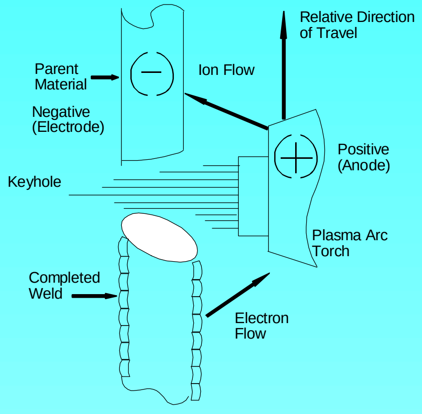
Notes:
(1) Backing bars are used for EBW in some instances to ensure full penetration without overshooting or to eliminate excessive spatter.
(2) VPPAW usually is employed in an initial manufacturing process since it is the most sophisticated method and the most adaptable to automation. Repair of larger seam welds may be appropriate for jobs of sufficient size warranting setup.

WELDING PRACTICES FOR 2219 ALUMINUM AND INCONEL 718



STRAIGHT POLARITY

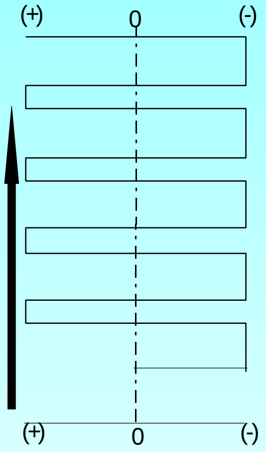
ADVANTAGES:
- Maximum Heat to Work Piece
- Minimum Deterioration of Electrode

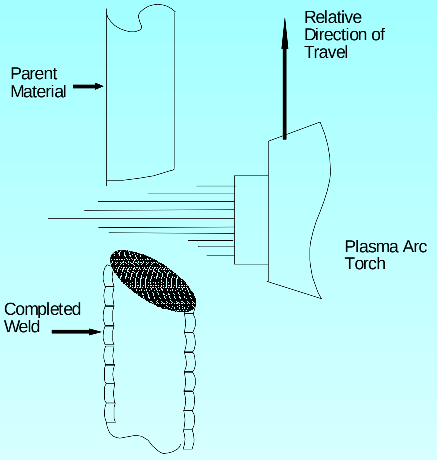


REVERSE POLARITY

ADVANTAGES:
- Cathode Cleaning of the Work
- Metal Flows Easily and Controllably Under the Arc

WELDING CURRENT PROFILE





VARIABLE POLARITY

ADVANTAGES:
- High Heating Capability of Straight Polarity
- Cleaning Feature of Reverse Polarity
- Proven in Thicknesses of 0.125 inches to 1.000 inches

OTHER BENEFITS
- Porosity-Free Welds
- Reduced Weld Repair Costs
- Reduced Joint Preparation Costs
- Digital Displays for Operator
- Adaptable to Automatic Seam Tracking and Bead Profiling
- Potential for Reducing Inspection

PRECAUTIONS
- EMI Reduction
- Shield Gas Purity
- Torch Rotation
- Self Centering Electrodes

Figure 1. The Plasma Arc Welding Process

2. Variable Polarity Plasma Arc Welding (VPPAW) for 2219 Aluminum

Figure 1 shows three variations of plasma arc welding: (1) Straight Polarity; (2) Reverse Polarity; and (3) Variable Polarity. Variable Polarity Plasma Arc Welding retains the high heating capacity of the straight polarity process while offering the part cleaning feature of reverse polarity. A flat-tipped electrode is used in VPPAW. A minimum of reverse cycle time is required to keep electrode erosion low. As in the case of GTAW (DCSP), lower energy inputs generally increase weld strength and minimize distortion. *Axial torch rotation* to align the arc with the weld joint, and torch designs incorporating *self-centering electrodes* will compensate for electrode tip erosion and will provide greater accuracy in seam tracking and weld bead uniformity. A positive torch "lead angle" of 0 to 3 degrees is desirable for automated welding with VPPAW. *Electromagnetic interference* caused by the welding process *will require shielding or distance separation* of computer monitoring and control devices. High purity grades of both the plasma gas and the shield gas are required. VPPAW also can be used for welding steels, Inconel, and other metals.

3. Electron Beam Welding (EBW) of Inconel 718

EBW produces deep, narrow welds with parallel sides and a narrow heat-affected zone. It is performed in a vacuum in most aerospace applications, and a near-zero joint gap is required to ensure fusion of the parts. EBW provides minimum distortion because of low total heat input whether used on thick or thin sections; however, full penetration welds may result in excessive spatter. *The vacuum environment requires special cleaning*. The size of work to be welded is limited by the size of the vacuum chamber and configuration of the manipulator. While EBW can be used to weld almost any metal, it often is used on high melting point metals including the refractory metals requiring stringent control of oxides. EBW is suitable for welding dissimilar metals and parts of dissimilar mass.

DESIGN CONSIDERATIONS FOR WELDED COMPONENTS

As will be seen in "Impact of Nonpractice," the concepts of a workable welded part design and a producible and inspectable weld joint configuration are very important to successful welding using any of the three processes described. The design of weld joints and of the special processes, tooling, and equipment needed to weld each configuration is best accomplished through use of a team approach in which the designer consults with materials, stress analysis, weld engineering, manufacturing, and inspection personnel as the welded design evolves. The process to be used to create the weld; the weld's fracture mechanics and fatigue properties in its planned environment; compatibility of the materials to be welded; the desired strength of the completed weld joint; and the method to be used to inspect the weld are among the many important factors that must be considered in weld joint design. Manufacturing, quality assurance, and design engineering personnel working hand-in-hand in this team approach will ensure reliable weld configurations. *The need for this team approach cannot be overemphasized*.

Among the design practices for welding aerospace hardware are: (1) detailed consideration of fracture mechanics and fatigue effects, particularly in welding very thick materials to very thin materials; (2) designing, testing, and qualifying coupons of new weld configurations; (3) locating welds to avoid bending forces that concentrate stresses in the weld bead area; and (4) the design of joints that accommodate adequate visibility, tool access, and inspectability. Conscientious adherence to the team approach to weld configuration and process design will account for these and many other factors that will result in defect-free, inspectable, and reliable welds.

NONDESTRUCTIVE EVALUATION OF WELDS

In addition to visual inspection, there are a number of methods to inspect welds. These include x-radiography, ultrasonics, eddy current, dye penetrant, and magnetic particle inspection. Real-time inspection can be performed while the welding is being performed in automated systems that incorporate weld bead profiling, infrared detection, and x-ray image display graphics. Although x-radiography is suitable for detecting voids or discontinuities in the weld or the parent material, fine surface cracks often go undetected. Double-walled inspections by this method should be avoided. This method is limited by the welded part configuration because the film used to record the x-ray image must be placed to provide a suitable angle of incidence. Ultrasonics has some physical limitations due to thickness and angle of assembly of parts (angles less than 45 degrees cannot be effectively inspected using ultrasonics). Eddy current inspection, which measures induced current in the weld and parent material in the presence of a magnetic field, requires highly skilled technicians, but is a favored method of weld inspection for many weld NDE situations. Both the ultrasonic and eddy current methods are sensitive to most weld and parent material flaws. Real-time inspection and recording of NDE results, as is done with automated weld bead profiling, provides a permanent record of weld parameters as the weld bead is generated. Automated NDE techniques offer the advantage of on-site correction of welding operations before detrimental effects of inaccurate welding become excessively costly.

Technical Rationale:

The design and processing recommendations in this practice have evolved over several decades of fabricating large aerospace vehicles and related ground support equipment. Rationale is documented in greater detail in the standards, specifications, technical memoranda, and reports listed as references. General processes are included in References 1, 2, and 7 through 9. Specific experience on VPPAW is described in References 5 and 6. The effect of impurities in plasma arc welding gasses was explored in an in-depth contracted effort by the University of Texas at El Paso (Reference 4). The causes of and remedies for microfissuring of welded Inconel 718 are described in Reference 3. Work is continuing to further explore and document effective practices for welding automation and nondestructive testing procedures. This continuing work will be the basis for additional practices that may be submitted for publication at a later date.

Impact of Nonpractice:

Impact of nonpractice is depicted in abbreviated form in Table 2, which shows various defects and other conditions that can occur in welds of all three types included in this practice along with a few of the most prominent potential causes of these conditions. The impact of nonpractice can be seen by viewing each column to determine the conditions brought about by improper or inadequate adherence to approved and appropriate practices and procedures. Each row can be scanned to determine some of the likely potential causes of a given condition or defect. Greater detailed guidance on the causes and effects of improper practices can be obtained from the references, from welding manuals published by the American Society for Metals or American Welding Society, or by contact with NASA/MSFC engineers and technicians who have had experience with the given processes.

Related Practices:

Related practices pertaining to specific weld design, processing and inspection characteristics, conditions, defects, and procedures are planned for future editions of this manual.

References:

Publications that contain additional information related to the practice are:

1. Nunes, Jr., A. C., "A Comparison of the Physics of Gas Tungsten Arc Welding (GTAW), Electron Beam Welding (EBW), and Laser Beam Welding (LBW)," NASA TM 86503, NASA/MSFC, August 1985.

2. Yang, H. Q. and Przekwas, A. J., "A Mathematical Model to Investigate Undercutting and to Optimize Weld Quality," CFRDC Report 4095/2, CFD Research Corporation, June 1990.

3. Nunes, Jr., A. C., "Interim Report on Microfissuring of Inconel 718." NASA TM-82531, NASA/MSFC, June 1983.

4. McClure, John C., "The Effect of Impurity Gasses on Plasma Arc Welded 2219 Aluminum," NAS-8-37425, The University of Texas at El Paso, August 1989.

5. Nunes, Jr., A. C., "The Variable Polarity Plasma Arc Welding Process: Its Application to the Space Shuttle External Tank - First Interim Report," NASA TM-82532, NASA/MSFC, June 1983.

6. Nunes, Jr., A. C., "The Variable Polarity Plasma Arc Welding Process: Its Application to the Space Shuttle External Tank - Second Interim Report," NASA TM-86482, NASA/MSFC, November 1984.

7. Schuerer, Paul H., "Welding Aluminum Alloys," MSFC-SPEC-504C, NASA/ MSFC, November 1990.

8. Schwinghamer, R. J., "Welding: The Fusion Welding of Steels, Corrosion and Heat Resistant Alloys," MSFC-SPEC-560A, NASA/MSFC, June 1988.

9. "Welding, Electron Beam, Process for," MIL-W-46132, Department of the Army, February 1989.

Table 2. Welding: Conditions and Potential Causes

Condition	**MOST PROMINENT POTENTIAL CAUSES (GTAW and VPPA on 2219 and EBW on Inconel 718)**					
	Improper Joint Design and Preparation	**Improper Atmosphere Control**	**Improper Postheat**	**Improper Heat Input**	**Improper Tooling**	**Improper Welding Procedure**
GALVANIC CORROSION			X			
HOT CRACKING	X			X		
IMPERFECT BEAD SHAPE		X		X	X	X
INCLUSIONS	X	X				X
LACK OF FUSION	X	X		X		X
LACK OF PENETRATION	X			X		X
MICRO-FISSURING	X			X		X
MISMATCH (OFFSET)					X	
PEAKING	X		X	X	X	X
POROSITY	X	X				
RESIDUAL STRESSES	X		X	X	X	
START/STOP DEFECTS						X
STRESS CORROSION CRACKING	X		X	X		

WELDING PRACTICES FOR 2219 ALUMINUM AND INCONEL 718

Definitions of Selected Welding Terms*

arc welding (AW). A group of welding processes that produces coalescence of metals by heating them with an arc, with or without the application of pressure, and with or without the use of filler material.

arc welding electrode. A component of the welding circuit through which current is conducted and which terminates at the arc.

backing. A material or device placed against the back side of the joint to support and retain molten weld metal. The material may be partially fused or remain unfused during welding and may be either metal or nonmetal.

defect. A discontinuity or discontinuities that by nature or accumulated effect (for example, total crack length) render a part or product unable to meet minimum applicable acceptance standards or specifications.

downhand. A nonstandard term for **flat position**.

flat position. The welding position used to weld from the upper side of the joint. The face of the weld is approximately horizontal.

fusion. The melting together of filler metal and base metal (substrate), or of base metal only which results in coalescence.

galvanic corrosion. Galvanic corrosion manifests itself in the accelerated corrosion of the more active metal (anode) of a dissimilar metal couple in an electrolyte solution or medium, and decreased corrosive effects on the less active metal (cathode), as compared to the corrosion of the individual metals, when not connected, in the same electrolyte environment. (MIL-STD-889B: 7 July 1976)

hot cracking. Cracking that develops during solidification.

inclusions. Particles or fibers of foreign materials and substances in the completed weld.

lead angle. Alignment of the welding device perpendicular (90 degrees) to the weld joint in the direction of travel would represent a <u>zero lead angle</u>. An increase of up to 3 degrees above 90 degrees in the direction of travel represents the recommended positive lead angle.

microfissuring. The formation of small cracks in the weld metal or weld heat-affected zone within the grain boundaries or low melting constituent regions resulting from weld thermal stresses.

mismatch (offset). An unintended nonplanar match of parallel work pieces resulting from the welding process.

peaking. An unintended angular displacement of the weld joint that can occur during welding.

penetration. The depth a weld extends from its face into a joint, exclusive of reinforcement.

porosity. Cavity-type discontinuities formed by gas entrapment during solidification.

postheating. The application of heat to an assembly after welding.

seam tracking. Alignment with respect to the joint of the welding device as it progresses along the interface between the two materials being joined.

stress corrosion cracking. Failure of metals by cracking under combined action of corrosion and stress, residual or applied.

tack weld. A weld made to hold parts of a weldment in proper alignment until the final welds are made.

undercut. A groove melted into the base metal adjacent to the weld and left unfilled by weld metal.

vertical position. The position of welding in which the weld axis is approximately vertical.

weldability. The capacity of material to be welded under the imposed fabrication conditions into a specific, suitably designed structure and to perform satisfactorily in the intended service.

weld axis. A line through the length of a weld, perpendicular to and at the geometric center of its cross-section.

weld bead. A weld resulting from a pass.

welder certification. Certification in writing that a welder has produced welds meeting prescribed standards.

weld pass. A single progression of welding or surfacing along a joint or substrate. The result of a pass is a weld bead.

*Adapted from American Welding Society, Inc.; <u>Standard Welding Terms and Definitions</u>; ANSI/AWS A3.0-85