

## Zircadyne® Zirconium Welding

### INTRODUCTION

Zirconium (Zr) is widely used in many industries for process equipment. Major applications include pressure vessels, heat exchangers, piping, tanks, shafts, mixers and other mechanical equipment, valves and pumps, spargers, trays, demisters, and tower packing. Zirconium is chosen because it provides excellent corrosion resistance to a wide range of media including most organic and inorganic acids, salt solutions, strong alkalis, and some molten salts. Zirconium is especially suitable in many acids, such as sulfuric, nitric, formic, hydrochloric, acetic, and in urea applications.

Discoverer	Klaproth, 1789
Abundance in Earth's Crust	19th Most Abundant Element
Color	Silver Gray
Atomic Number	40
Standard Atomic Weight (1989)	91.224
Density	6.50 gm/cm <sup>3</sup> (0.235 lbs/in <sup>3</sup> )
Hardness	Rockwell B82
Elastic Modulus in Tension	E = 14.4 x 10 <sup>6</sup> psi RT
Elastic Modulus in Torsion	G = 5.25 x 10 <sup>6</sup> psi RT
Poisson's Ratio	0.35
Thermal Expansion Coefficient 25°C (75°F)	5.7 x 10 <sup>-6</sup> cm/cm/°C (3.17 x 10 <sup>-6</sup> in/in/°F)
Thermal Conductivity (λ) at 27°C	19.53 Kcal <sub>th</sub> /h·m·°C (13.12 BTU <sub>th</sub> /ft·h·ft <sup>2</sup> ·°F)
Melting Point, T <sub>m</sub> , 1 Atm.	1852 ± 2 °C (3334°F)
Specific Electrical Resistivity	38.8 micro-ohms/cm/cm <sup>2</sup> at 0 and 20°C
Room Temperature Structure	Hexagonal Close Packed (alpha)

Nearly 85% of zirconium applications are in the nuclear industry. Separate specifications and grades are used for the nuclear applications. Except for composition differences, the welding requirements are much the same.

Zirconium is readily welded utilizing practical inert gas fusion welding techniques such as gas tungsten arc and plasma arc welding, as well as specialized processes like electron beam and laser welding.

Zirconium process equipment size is essentially unlimited because of practical welding techniques. The availability of qualified fabricators who specialize in zirconium, reactive metals, or explosively clad zirconium provides a wide range of options to end users.

In pressure equipment under the ASME Code, zirconium is limited to a maximum design temperature of 370°C (700°F) and the use of clad construction makes large equipment designed for high pressure and temperature economical.

This datasheet is intended to provide a basic knowledge of zirconium welding. It is written for welders, engineers, and those in the welding trades.

To be successful at welding zirconium, the fundamental characteristics of zirconium must be understood and respected throughout the organization, including not only the welders, but supervisors, management, and inspection and quality assurance personnel as well.

## PHYSICAL PROPERTIES

Zirconium is a silver grey metal with a density of about 81% that of stainless steel and 144% that of titanium. Its elastic modulus is about half of stainless steel, similar to titanium, and its thermal conductivity about 30% higher than stainless steel. Some useful physical properties are listed in Table 1.

## GRADES AND SPECIFICATIONS

Zirconium ores normally contain hafnium which is difficult and costly to separate from zirconium. Production of grades intended for nuclear applications require removal of hafnium. Recognition that hafnium did not significantly alter the mechanical properties or corrosion resistance of zirconium in most corrosion applications led to the introduction of specifications where cost was substantially reduced by allowing the hafnium to remain at natural levels. Thus, chemistry specifications intended for corrosion applications all contain a maximum of 4.5% hafnium.

Tables 2 and 3 list the common zirconium grades intended for corrosion applications. Unalloyed zirconium UNS R60702 (Zr 702), and UNS R60705 (Zr 705), alloyed with 2 to 3% niobium are the most common grades used in corrosion applications.

Zr 702 is the workhorse grade and is most commonly used. UNS R60700, or Zr 700, is a low oxygen, higher ductility version of Zr 702 with a maximum yield strength of 40 ksi (275 MPa) that is intended primarily for explosion cladding, but may find other applications where improved ductility is required.

Alloying with 2 to 3% niobium increases strength and ductility in Zr 705 and 706 as seen in Table 2. UNS R60706 is a low oxygen version of Zr 705 which was initially developed for high formability applications. The higher strength grade Zr 705 is primarily used in mechanical applications like fasteners, shafts, and tower trays.

Only Zr 702 and 705 are accepted for ASME Boiler Code construction, although Zr 702 is the dominant grade. Zr 705 use is limited in pressure equipment in part because of the requirement for stress relief within 14 days of welding. Without this stress relief of Zr 705 welds, delayed cracking resulting from hydride formation can occur in areas of high-residual stress.

ASTM publishes specifications for common zirconium mill products. Table 4 lists the specifications that are applied in corrosion applications. Most of these are adopted by ASME as SB Specifications and are used for boiler and pressure vessel applications.

There are separate but comparable specifications without hafnium that are intended for nuclear applications. The American Welding Society (AWS) publishes specifications for zirconium filler metal under A 5.24, "Zirconium and Zirconium Alloy Bare Welding Rods Electrodes". Standard 36" or 1 meter cut lengths in 1/16" (1.5 mm), 3/32" (2 mm) and 1/8" (3 mm) diameters meet most requirements. Spooled wire in common 0.030", 0.045", 0.062" (0.76 mm, 1.14 mm, 1.57 mm) sizes also meet most requirements for automated or semi-automated use. Table 5 lists the composition of the AWS recognized filler metals. These are usually applied to material with the corresponding UNS number or mill product grade.

**Table 2. ASTM Standard Grades of Zirconium**

		Mechanical Properties					
		Min. UTS	Max. UTS	Min. YS	Max. YS	Min. Elongation	Min. Bend Radius
Alloy	UNS #	ksi (MPa)	ksi (MPa)	ksi (MPa)	ksi (MPa)	%	Multiple of Thickness (T)
700	R60700	N/A	55 (380)	N/A	40 (305)	20	5T
702	R60702	55 (380)	N/A	30 (205)	N/A	16	5T
704	R60704	60 (415)	N/A	35 (240)	N/A	14	5T
705	R60705	80 (550)	N/A	55 (380)	N/A	16	3T
706	R60706	74 (510)	N/A	50 (345)	N/A	20	2.5T

**Table 3. ASTM Standard Grades of Zirconium**

		Chemical Composition, wt. Percent								
Alloy	UNS #	Zirconium + Hafnium Min.	Hafnium Max.	Niobium	Tin	Iron + Chromium	Oxygen Max.	Nitrogen Max.	Carbon Max.	Hydrogen Max.
700	R60700	99.2	4.5			0.2 max	0.10	0.025	0.05	0.005
702	R60702	99.2	4.5			0.2 max	0.16	0.025	0.05	0.005
704	R60704	97.5	4.5		1 to 2	0.2 to 0.4	0.18	0.025	0.05	0.005
705	R60705	95.5	4.5	2 to 3		0.2 max	0.18	0.025	0.05	0.005
706	R60706	95.5	4.5	2 to 3		0.2 max	0.16	0.025	0.05	0.005

**Table 4. Specifications for Zirconium for Industrial Corrosion Applications under ASTM**

B495	Standard Specification for Zirconium and Zirconium Alloy Ingots
(S)B551/B551M	Standard Specification for Zirconium and Zirconium Alloy Strip, Sheet, and Plate
(S)B493	Standard Specification for Zirconium and Zirconium Alloy Forgings
(S)B550/B550M	Standard Specification for Zirconium and Zirconium Alloy Bar and Wire
(S)B658/B658M	Standard Specification for Seamless and Welded Zirconium and Zirconium Alloy Pipe
B653/B653M	Standard Specification for Seamless and Welded Zirconium and Zirconium Alloy Welding Fittings
(S)B523/B523M	Standard Specification for Seamless and Welded Zirconium and Zirconium Alloy Tubes
B752	Standard Specification for Castings, Zirconium-Base, Corrosion Resistant, for General Application
B898	Standard Specification for Reactive and Refractory Metal Clad Plate
NOTE: (S) prefix indicates ASME has adopted this specification, e.g. SB551	

**Table 5. AWS A 5.24/A5.24:2005 Zirconium Filler Metal Chemical Requirements (Weight Percent)**

AWS	UNS #	Zirconium + Hafnium Min.	Hafnium Max.	Iron + Chromium	Tin	Oxygen	Hydrogen Max.	Nitrogen Max.	Carbon Max.	Niobium (Columbium)
ERZr2	R60702	99.9 min	4.5	0.20 max		0.11 - 0.15	0.005	0.015	0.03	
ERZr3	R60704	97.5 min	4.5	0.20 - 0.40	1.0 - 2.0	0.11 - 0.16	0.005	0.015	0.03	
ERZr4	R60705	95.5 min	4.5	0.20 max		0.11 - 0.16	0.005	0.015	0.03	2.0 - 3.0

## WELDING

Zirconium is readily welded, but requires extra attention to cleanliness and inert gas shielding to protect the weld zone from foreign materials and atmospheric contamination. Cleaning and shielding are the most important and critical factors affecting final weld quality. These will be discussed later in detail.

Practical “open air” welding of reactive metals, developed 40 years ago, utilized oversize welding torches with gas lenses to provide primary coverage of the molten weld metal. Trailing and back-up shielding devices were used to provide secondary coverage to protect the weld root and hot metal until it cools below temperatures where excessive surface oxidation occurs. Gas tungsten arc welding (GTAW) and Plasma Arc Welding (PAW) are the most practical and commonly used processes for fusion welding zirconium.



Open air manual GTA welding of zirconium pipe

Courtesy Titanium Fabrication Corporation

## METALLURGICAL FUNDAMENTALS THAT AFFECT WELDING

The strength of zirconium is determined by the amount of oxygen, nitrogen, carbon, hydrogen, and iron present. The more of these elements present, the higher the strength and lower the ductility.

Zirconium gains its corrosion resistance from a thin, tightly adherent, transparent  $ZrO_2$  surface oxide film. The oxide forms instantaneously at ambient temperatures and thickens as the zirconium is heated in air. Light refraction in the transparent film causes a spectrum of interference colors. The interference color spectrum repeats at least once as oxide thickness builds.

Molten zirconium reacts with and is embrittled by most materials including organic and inorganic compounds, iron and most other metals (see discussion of dissimilar metal welding), air, and other gases (except inert gases). Exposure to air of molten zirconium in a weld pool, aided by convection of the hot metal, results in a near instantaneous increase in oxygen and nitrogen throughout the molten metal. At the high temperatures adjacent to the molten weld metal, oxygen also diffuses fairly rapidly into the metal beneath.

Under the influence of welding heat, surface contaminants left by inadequate cleaning of the metal surface are volatilized and absorbed by the weld pool. This is evident by visual inspection as a bright silver line immediately adjacent to the weld toe with a dark brown or grey fringe just beyond it. In Figure 1, the brighter band adjacent to the weld is evident and there is essentially no discoloration beyond that, indicating that very good cleaning practice was employed.

The adverse effects of contaminants require that the weld joint and weld wire be carefully and completely cleaned and remain free of all foreign material during the welding processes. This also requires that the weld surface, weld root, and adjacent hot metal be protected during welding using inert gas shielding (usually using welding grade argon) until the weld metal cools from its  $1835^{\circ}C$  ( $3,334^{\circ}F$ ) melting point to below  $315^{\circ}C$  ( $600^{\circ}F$ ).

Color and surface appearance alone are not evidence of a good weld. Re-melting a contaminated zirconium weld under a protective argon blanket will result in surface appearance that is indistinguishable from an uncontaminated weld. In this case the contamination (i.e., oxide) on the surface of the weld will dissolve into the molten metal. The resulting weld metal may be significantly embrittled and likely unfit for service.

Figure 1. Bright band along weld toe is caused by welding heat



## DESIGN FOR WELDING

Minimizing the welding required is the first rule when considering weld design for any metal. This starts with eliminating welds wherever possible. Using formed, adequately radiused corners, for example, may not only eliminate a weld, but may also eliminate a vulnerable stress point. Machining details that present a smaller section for welding can also lower stresses in the weld.

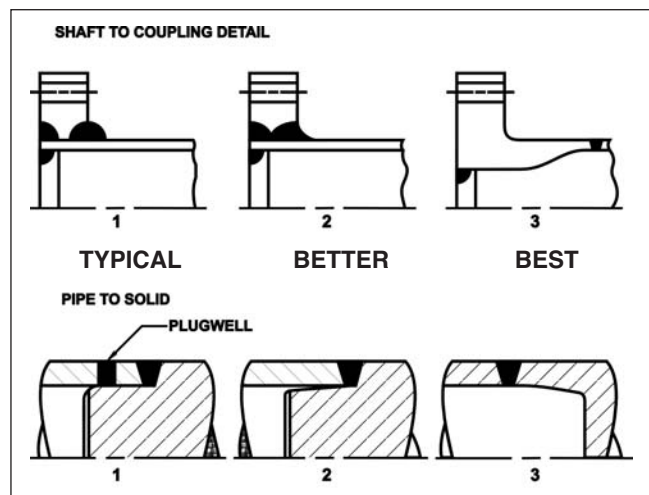
Selection of weld joint (preparation) details that minimize required weld metal is also important. Weld size should be minimized for reasons of economy, but also to minimize distortion. Accurate machined weld preparations and accurate fit-up also reduce weld metal volume and distortion.

The primary objective of a weld preparation is to allow the welding arc access to the root of the joint. To reduce the size of the weld preparation, it is acceptable to let the electrode extend more than 1" (25 mm) beyond the torch cup when welding in a deep groove. While straight single or double bevel joints are typically the least expensive to produce, J grooves with compound angles can often reduce the volume of weld metal required to fill a joint and should be considered for any section over about 3/4" (19 mm). For thick sections it may be beneficial to use a full size drawing and welding torch to help visualize access of the tungsten to the root as well as to encourage the welder to buy-in to an unusual joint design.

Attention to weld location by keeping the welds away from points of high stress and abrupt changes in section is desirable, particularly in equipment subject to fatigue. For example, in Figure 2, if a flange or a solid section of billet is to be welded to a pipe shaft, consider a full butt weld (3) rather than extending the shaft through the flange or the solid section into the pipe (1, 2).

Design to eliminate the need for back grinding by using J-Groove preparations or carefully controlled root gaps wherever possible. Back grinding, while common for steel, is often unnecessary as long as full fusion can be achieved by the welder. Back grinding is inherently dirty, adding significant cost for the re-cleaning of the component and weld area, and posing additional performance risks.

Figure 2. Designing so that welds are located in areas of low stress can reduce the amount of welding required as well as improve weld reliability as shown in these shaft-to-coupling and pipe-to-solid joints.



Access for gas shielding on front and back surfaces must always be considered. The welder should consider how weld roots can be visually inspected. If the root cannot be visually inspected, no matter how much care is applied in shielding or purging, it creates some risk that contamination can occur and remain undetected. Sequence of assembly, for example in pipe spools, may be modified to allow more weld roots to be inspected.

Provision for repair after time in service should be considered at the design stage. If a piece of equipment is subject to fatigue loading and cracking, partial penetration welds that allow process contaminants to spread widely can present a serious challenge at repair. Full penetration welds solve this problem and reduce susceptibility to fatigue failure, but may add cost and increase distortion.



Zr 702 extraction column

Courtesy Titanium Fabrication Corporation

## CUTTING AND WELD PREPARATIONS

Zirconium can be cut by machining, cold sawing, hack sawing, friction sawing, shearing, abrasive cutting, plasma processes, oxygen methods, laser, and waterjet cutting. Machining, sawing, and shearing processes are excellent as they will leave a surface free of thermal contamination.

While oxygen or plasma cutting can be used for rough cutting, both methods require removal of at least 1/16" (1.5 mm) material from the lowest point of the cut surface by machining or grinding to ensure removal of all metal contaminated in the cutting process. This means the total cutting allowance could be 3/8" (9.5 mm) for cuts in metal 1/2" to 1" (12.7 mm to 25.4 mm) in thickness, for example. The cost of the metal lost in the extra kerf should be calculated to gain an accurate cost comparison with other cutting methods. Plasma or oxygen cut surfaces should never be welded or placed in service without removal of all contaminated metal.

Laser cutting is used for thin sections, but the process leaves a narrow air contaminated zone unless special argon shielding is employed around the laser and cut during the cutting process. Friction sawing also leaves a slightly contaminated edge that should be dressed by filing before welding.

Abrasive grinding using dedicated aluminum oxide or silicon carbide wheels is commonly employed with zirconium. When abrasive grinding is used, adjacent zirconium surfaces and surroundings must be protected from the hot grinding sparks. Sparks are hot enough to perforate gas hoses and can start fires if directed into flammable debris. When either abrasive grinding or sanding is used, the ground surfaces

should be rotary or draw filed to eliminate possible abrasive particles on the joint surface. Similarly, abrasive cut surfaces should be filed or machined to remove areas of minor contamination due to local heating. Electric grinding motors or rear exhaust air tools equipped with an exhaust overhose can reduce oil spray onto the work and simplify post-grind cleaning operations.

Use caution if sanding processes produce incompletely oxidized metallic fine particles which can constitute a serious fire or explosion hazard.

Sheared surfaces are usually suitable in weld joint preparations on material under 3/16" (5 mm), but heavier material should be checked at least visually for any evidence of cracking, particularly where shear knife clearances can not be changed to suit the material thickness. Machine finishing or filing may be required to remove cracking.

Abrasive waterjet cutting can provide economical production of parts or configurations that would be expensive to produce by machining methods. Lower cutting speeds that produce a smooth surface maximize the benefit of the process by reducing post processing. Abrasives may be trapped on excessively rough surfaces and possibly even on smooth cut surfaces so it is recommended that surfaces to be welded are further processed, at a minimum by rotary or draw filing.

Whenever practical, machining is the preferred method of producing joints for precision of fit-up, minimum joint volume, and for ease of cleaning.

Finished weld joint surfaces should be smooth and contain no crevices, roughness or overlaps that can trap dirt or cleaning fluids.

## WELDING PROCESSES

The most common process used for zirconium welding is Gas Tungsten Arc Welding (GTAW). Manual GTAW allows all-position welding of any configuration the torch can access. Automation of GTAW usually limits welding to flat or horizontal positions, but increases in welding productivity generally overcome any disadvantage positioning the part requires. Automatic welding may also provide quality advantages over manual processes. Seam welding machines with copper back-up bars and continuous hold down using copper bars are common for straight joints. Tube to tubesheet and small pipe butt welds using automatic orbital GTAW equipment are also very common.

Plasma Arc Welding (PAW) is often used for single pass welds up to about 1/2" (13 mm) thick using automated equipment, copper backing bars, and square butt weld preparations. Typically, a GTAW cover

pass is used to correct under fill and the root side may require a cosmetic fusion pass or mechanical removal of excessive drop through.

High current GTAW welding processes like buried arc and keyhole GTAW should be considered for repetitive welding of heavy sections. Other fusion welding processes such as electron beam and laser welding are also readily applied. The general considerations in this discussion are equally applicable to these processes.

### POWER SUPPLY, TORCH, AND TUNGSTEN ELECTRODES

A direct current drooping characteristic power supply connected for straight polarity (negative to torch), equipped with high frequency arc starting, manual current control, and a contactor for making and breaking the arc is used for either GTAW or PAW of zirconium.

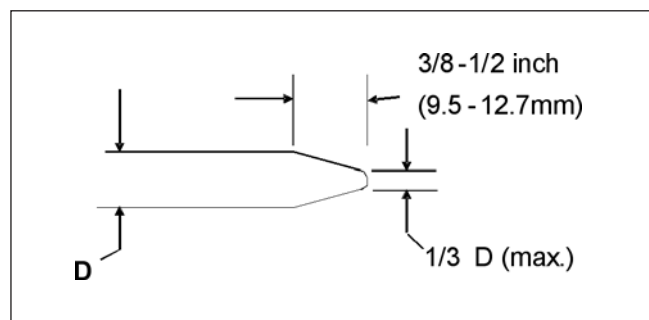
A water cooled torch equipped with a 3/4" (19 mm) ceramic gas cup and gas lens using 3/32" (2.4 mm) diameter or larger 2% thoriated tungsten electrodes (AWS EWTh-2) are recommended for most applications. For higher current applications, 2% ceriated (AWS EWCe-2), 1.0/1.5/2.0% lanthanated (AWS EWLa-1, EWLa-1.5, or EWLa-2) or 0.25% zirconiated (AWS EWZr-1) tungsten electrodes are sometimes used. Tungsten is usually ground with a 20 to 30 degree taper with the end blunted slightly (Figure 3). Larger tungsten allows the use of greater extension, minimizing overheating and risk of tungsten inclusions.

The large gas cup and gas lens are the most important elements of weld protection. The large gas cup and gas lens minimize turbulence and provide a uniform blanket of gas protection, even when the tungsten electrode is extended well beyond the cup for visibility or access. Smaller torches, still equipped with oversize ceramic cups and a gas lens are sometimes used for fine work or where access is restricted.

Torches with transparent gas cups are also available. Special surrounding shields are also employed for unusual geometries as shown in Figure 4.

Automatic equipment for either GTAW or PAW utilizes similar large gas cups and gas lenses.

Figure 3. Typical tungsten electrode shape



## FILLER METAL

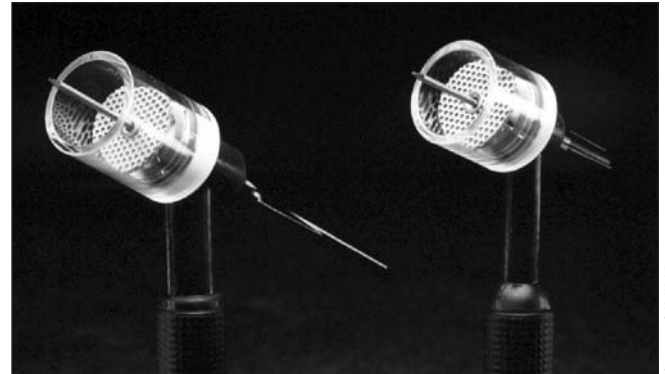
Filler metal supplied today is usually clean when it comes from the supplier as long as the filler metal container remains sealed. Obviously storage of filler metal requires attention. The storage area should be clean and dry and packages of zirconium filler metals should be stored in a tightly closed cabinet. Packages should remain sealed after receipt, and once opened, be re-closed and sealed with tape for storage.

Clean filler metal should produce no more than a very light gray residue when 10" to 20" (250 to 500 mm) is drawn through a clean white cloth. Filler metal cleanliness should be checked this way each time a new container is opened. Filler metal that fails this simple test can be cleaned adequately for most applications by wiping with a clean lint free cloth dampened with acetone or methyl ethyl ketone (MEK).

Once filler metal is issued for production, it should be kept in a closed container and separated from any other zirconium grade or other metal. For cut lengths, the best practice is to remove the filler metal from the container and use it immediately. Taking several lengths out and placing them on an open work surface is likely to cause contamination problems. There are no time limitations between issue and use for bare zirconium filler metal other than what may be necessary for wire control and cleanliness.

In the case of spooled wire, the spool should be protected with a closed cover. A plastic bag taped in place will work if commercial equipment is not available. Wire feed tubes should be clean and be dedicated to only zirconium and potentially other reactive metals. Apply the same tests for wire cleanliness described for cut lengths.

Figure 4. Oversize gas cups or surrounding shields



Courtesy C.K. Welding

## CLEANING

Overall shop floor organization and housekeeping are generally good indicators of management and worker attitude toward cleanliness and quality.

Maintaining cleanliness for zirconium welding is a continuous process that involves:

- Material handling
- Housekeeping in storage and work areas
- Processing procedures during preparation
- Cleaning of the overall components to be welded
- Careful cleaning of the local area where the weld is to be made
- Covering and protection of the work pieces during periods of inactivity

It is possible to weld zirconium in environments that are dirty, drafty, and where the component is also dirty, or in situations encountered in a field repair, however, the cost to do so while maintaining quality can be very high. The potential cost of producing poor quality welds can be even higher.

Care should be taken during storage and handling of zirconium materials. As an example, storage racks can be lined with wood or coated with plastic and wood blocks placed under the zirconium before it is placed on a concrete floor or graveled area. Wood or plastic fork protectors can be used to help prevent damage of the material surface. Equipment such as forming rolls or forming dies should be cleaned prior to use with zirconium. Cleaning of rolls must include removing steel burrs or roughness that can cause iron contamination or local deformation of zirconium surfaces. The use of self adhesive plastic films to protect surfaces of plate and sheet during forming and handling should be considered, particularly where forming equipment is normally utilized for other metals.

A clean shop environment with positive air pressure maintained with filtered air, heated in winter and air conditioned in summer is optimum. At the same time, heating and ventilation equipment must be designed to avoid drafts that can interfere with weld shielding. Equipment such as air compressors, machine tools, and waterjet cutting equipment generate airborne contaminants that can interfere with the welding process. Isolation of such equipment including separate heating, ventilating, and air conditioning equipment may be the best way to deal with this problem.

Keeping the welding shop and weld work area clean is very helpful in maintaining cleanliness throughout the welding operation.

Immediately prior to welding, all joint surfaces plus the first 1" to 2" (25 mm to 50 mm) of all surfaces

adjacent to the weld area should be wire brushed with a dedicated austenitic stainless steel brush and then wiped with a clean lint free cloth dampened with acetone, MEK, IPA, or similar non-chlorinated solvent. Electronic-grade acetone is usually most effective for final cleaning.

Small (and even fairly large) parts can be effectively cleaned using typical non-chlorinated household abrasive cleansers and hot water, followed by thorough hot water rinsing and air drying. Parts cleaned should be kept clean and ready for welding with no further local cleaning.

Wherever possible, clean, fit up, tack, and weld a joint right away. If welding must be delayed, even later in the same work shift, cover the joint with paper or plastic sheet to minimize dust or dirt accumulation. If extended times are necessary prior to welding, even if the welding shop area is clean, sealing the edges of the paper or plastic to the zirconium with masking tape is good practice (avoid putting tape directly on surfaces to be welded). Bagging using readily available self sealing plastic food storage bags is useful for keeping small parts clean.

## SHIELDING

Zirconium requires inert gas protection using argon, helium, or argon/helium mixtures of the molten weld to prevent oxygen, nitrogen, and moisture from normal atmospheres from contaminating the weld metal. Zirconium also requires inert gas protection of the solidified weld and adjacent metal surfaces heated during welding to prevent surface oxidation and related degradation. Practical “open air” welding of reactive metals, developed 40 years ago, utilized the same oversize welding torches with gas lenses recommended today to provide primary coverage of the molten weld metal and trailing and back-up shielding devices to provide secondary coverage to protect the weld root and hot metal.

The following shielding recommendations should be used on zirconium welds, including tack welds.

### Primary Shielding

Primary (torch) shielding must protect the weld metal until it solidifies. Air contact with the molten weld pool will contaminate the entire volume of molten metal and result in embrittlement of the weld bead. This is why large ceramic gas cups and gas lens are among the most important elements of successful zirconium welding. Use recommended gas flow rates. Excessive flow can cause turbulence and will waste argon.

### Secondary Shielding

Secondary (trailing) shielding blankets the solidified weld and adjacent hot metal with inert gas until the surface temperature reaches 315°C to 427°C (600°F to 800°F) or lower.

### Back-up Shielding

Back-up shielding protects the molten root of the weld on the first pass but is also necessary to blanket the solidified weld during subsequent passes until the root surface temperature cools to 315°C to 427°C (600°F to 800°F), usually after about 1/4" (6 mm) of metal is deposited. To avoid oxidation, back-up shielding should also be used on the back surface of sheet or plate under about 1/4" (6 mm) thickness, on the inner diameter of tubular structures, and on process-wetted surfaces of fillet welds.

### Gas Requirements

Welding grade argon (99.998% purity) is usually chosen for torch (primary), trailing (secondary), and back-up shielding. Argon provides excellent arc stability. Argon is less expensive than helium and its higher density makes it less sensitive to drafts. Helium or argon-helium mixtures are sometimes used for torch shielding where additional penetration is desired. Argon and helium mixtures are also occasionally employed in back-up shielding and purging where the low density of helium provides added assurance of purging blind spaces where heavier argon may not effectively displace the air.

Gas can be provided from a central liquid system, liquid cylinders, or high pressure gas cylinders. The liquid options are better from a gas purity point of view. Liquid cylinders (typically 4300 scf capacity) reduce the handling required with high pressure cylinders (typically 330 scf capacity) and reduce cost. Liquid systems rely on evaporative cooling to maintain cryogenic temperatures. If gas is not drawn from the insulated argon tank for several days, pressure increases and significant losses to the atmosphere can occur. For occasional use, pressurized gas cylinders may be better.

If a central system is used, periodic monitoring of the system is desirable, including checks for system leaks and at least daily checking of the purity of the gas at the point of use. For critical work, more frequent scheduled checks of gas purity and checks every time a cylinder is changed should be made. Gas purity should be checked as close to the torch or shielding device as practical (see weld quality checks).

### Gas Purity

Argon is usually purchased to 99.998% purity with a guarantee of less than 5 ppm oxygen, moisture, or total hydrocarbons. The dew point at the gas supply should be not more than -51°C (-60°F). A dew point meter should be used to check gas purity, which should be close to the expected purity -51°C (-60°F) at the point of supply. Do not, however, rely on just the gas purity at the point of supply. A dew point above these levels suggests a need for maintenance of the gas distribution system.

It is sometimes very difficult to know when minor levels of air or other impurities have entered the system. Welders should be trained to stop their work and investigate the cause of any noticeable disruption or abnormality in the welding arc.

### Flowmeters and Timers

Each gas flow, including purge flows, must be supplied through a separate flowmeter. On-off valves or pre-purge and post-purge timers can reduce gas consumption by automatically shutting or reducing gas flow between welding cycles. Interlocking gas flows with welding current is desirable so welding cannot be started unless all gas flows have been functioning for at least a few seconds.

Sufficient time must be allowed to fully clear the lines between the solenoid valve and the shield where automatic pre-purge and post-purge timers are used. A method to reduce this time is to provide a small bypass flow around the solenoid using either a separate bypass or flowmeter or by providing a small orifice in the solenoid valve itself.

### Gas Hoses

Clean, clear, plastic gas hoses (e.g., PVC, Teflon, polypropylene, high density polyethylene) should be used to eliminate the air diffusion that occurs with rubber. Gas connections must be tight, but barbed connectors without clamps are often adequate. Hoses should be kept off the floor as much as possible to keep them clean and protected to minimize the risk of puncture or leaks, e.g. due to a person stepping on the hose.

### Trailing and Back-up Shielding Devices

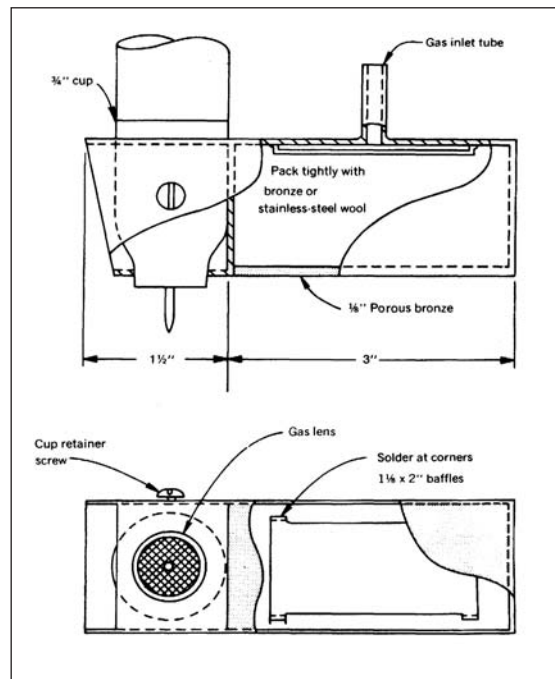
The art of shield design is two fold; to avoid velocities at the gas inlet that can entrain air, and to use two or three stage reduction of gas pressure and flow from the inlet tube to provide a gentle, uniform blanket at the shield surface. A well proven trailing shielding design is shown in Figure 5. The shield can be made of copper or stainless steel soldered or welded to form a light, compact body. It is attached directly to the welding torch and fits closely around the torch cup, with a flat baffle filling the space between them (a gap between the torch and shield surface causes problems). The gas inlet is above an internal baffle to eliminate velocities that can entrain air into the device. An alternate method is to bring the tube through the end or side of the device and provide gas inlets through a series of holes directed toward the back of the device. Never use a gas inlet tube that ends at the back or side of the device as it will entrain air from below the shield.

Packing at least an inch thick with coarse stainless or bronze wool provides a gradual reduction of pressure and creates a more uniform blanket of gas. Adding a porous metal surface diffuser achieves even gas flow over the shield surface and provides a soft uniform gas blanket with no turbulence or high velocities. The final diffuser can be porous (sintered) bronze, stainless steel "felt metal", or even a copper plate with a uniform grid of small perforated or drilled holes, or both.

A typical shield may use about 7 to 10 cfh (0.20 to 0.28 cu.m./hr) per square inch of surface, so the 1-1/2" x 3" (38 mm x 76 mm) shield in Figure 5 would be expected to use 30 to 40 cfh (0.84 to 1.12 cu.m/hr). As with the welding torch, excessive flow rates can cause turbulence or air entrainment. Shield performance can be checked by holding it 1/4" to 1/2" (6.4 mm to 12.7 mm) above a zirconium surface which is then heated from the opposite side and cooled with the shield in position. No oxide color should form.

High current applications, particularly with automatic equipment may require a shield of 3 in. to 4" (76 mm to 102 mm) in width and 12" (305 mm) or more in length. While the use of skirts (typically high temperature tape) around the shield is common, they should not be necessary with a properly designed shield.

Figure 5. Typical trailing shield design



Courtesy Titanium Fabrication Corporation

Manually positioned back-up shielding devices follow the same design principles as trailing shields. They are often contoured to match inside diameters or surfaces. Some typical examples are shown in Figure 6.

Sometimes simple flat baffles (Figure 7) that restrict the flow of gas from the torch are useful to properly shield a weld. Locating a baffle below the torch on an outside corner weld, for example, can eliminate problems with inadequate gas coverage.

Figure 6. Back-up shielding devices



Courtesy Hi-Tech Welding

channel inside the bar and along its full length is used to provide uniform pressure and gas distribution along the length. The distribution channel is connected to the gas groove with a series of small orifice holes 4" to 6" (102 mm to 152 mm) apart along the full length. The material to be welded must be clamped tightly to the gas groove, preferably with a full length hold-down. It is common practice to use tape to temporarily seal the weld groove while initial purge is established, but the tape can usually be removed a longer distance ahead of the torch because the full length gas distribution eliminates the problems encountered when a space is purged from just the weld start end.

The use of a glove box, as shown in Figure 8, is one solution for very complex configurations, but presents its own set of problems. Jigs and fixtures may be necessary to position parts. Parts to be welded and consumable materials must be thoroughly cleaned before placing them in the box, which is then purged with argon gas. A vacuum pump to reduce initial air pressure can be used to reduce the argon requirement if the box is designed for it. Welders must use care when removing their hands from the gloves themselves to avoid creating a temporary vacuum which can draw air through minor leaks in the chamber seals.

It is recommended that a continuous argon flow be maintained to sweep away any material released from the zirconium surface by the welding heat as well as to maintain a slight positive pressure. Argon is a poor heat conductor, so welded parts can become quite hot and may discolor slightly as the zirconium adsorbs the minor oxygen remaining in the argon atmosphere.

### Oxygen Meters and Dew Point Indicators

Shops welding zirconium or other reactive metals with any frequency should have a high quality dew point instrument. In recent years, improved sensing devices have resulted in electronic instruments to measure dew point. Gas purity is usually guaranteed to a dew point standard, providing a basic reference value. When a space is purged, it is logical that air will be displaced before all moisture evaporates, particularly if it is trapped in tight crevices or in foreign materials.

Figure 7. A baffle restricts argon from falling away from the weld in an outside corner weld

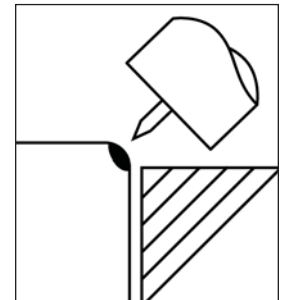


Figure 8. Chamber welding is ideal for small complex work



Courtesy Hi-Tech Welding

## PURGING

In many instances back-up shielding devices cannot be utilized due to restricted access. This requires the space on the root side of a weld to be purged. Unfortunately, most cases that require purging are also difficult or impossible to inspect visually after welding to confirm that shielding was effective in preventing oxidation. Examples are complex small diameter pipe systems, fillet welds associated with batten strips used in the welding of zirconium clad pressure vessels, and coil and dimple jacketed pressure vessels. Quality assurance for the root of the weld must often rely on the certainty of creating completely inert atmospheres in the purge space.

While monitoring the purity of the purging gas, the purging time is sometimes used when the risk of a problem is judged to be minimal or equipment is not available. A commonly used rule of thumb has been to purge at least six times the volume of the purge volume for spherical or tubular structures and twelve times the volume of the space for irregular shapes but baseline data for this practice has been lost.

### Factors Affecting Gas Volume Required for Purging

A purge space that is not clean often precludes achieving an adequate purge. Moisture trapped in foreign materials can take a very long time to diffuse and be swept from the space. When an adequate purge cannot be achieved in a reasonable time, it may be best to stop and reclean the purge space surfaces and then try again. Preheating is often proposed to minimize problems with any initial moisture and may be a good first step when initial purge quality cannot be achieved. This is often encountered in small diameter pipe or in-service repairs where interior surface cleaning is insufficient.

The general shape of the purge space is an important consideration. Under perfect plug flow (where there is no mixing of the argon and air), one purge space volume of argon would be all that is required. Under more realistic mixed conditions (argon and air mix in the space), getting adequate purity will require many times the volume of the purge space. However, all spaces are not equivalent. A long pipe, for example, tends to promote plug (unmixed) flow of the gas compared to the more mixed conditions in a short cylinder. For example, a 12" (305 mm) diameter pipe has an internal volume of about 0.75 cu. ft./ft (697 cu. cm/cm). A 10' (3.1 m) length is thus about 7.5 cu. ft (212 L). A 1" (25.4 mm) diameter tube has an internal volume of only .006 cu. ft/ft (5.6 cu. cm/cm). A 1200' (366 m) length has about the same 7.5 cu. ft. (212 L) volume. The 1" (25.4 mm) diameter tube will require fewer gas volumes than the 12" (305 mm) diameter pipe because the argon tends to mix with air more in the larger diameter, short space while the argon in the small pipe tends to push the air ahead of it with minimum mixing.

The way gas is introduced into the purge space also affects the volume of gas required to achieve adequate displacement of the air in the space. It is intuitively obvious that a high velocity argon flow from

a single inlet tube will mix with the air in the purge space more than a slow gas flow achieved either using a baffle or a diffuser (like a back-up shielding device, for example). Considering the same 10' (3.1 m) length of 12" (305 mm) diameter pipe, if argon is introduced via a straight inlet tube, more argon will be required than if the gas is introduced with a diffuser.

Because argon is heavier than air, it will displace the air from the bottom of the space being purged. For example, if our 12" (305 mm) diameter pipe is in the vertical position, introducing the argon from the bottom using a diffuser will gently lift the air above it with minimal mixing, while introducing it from the top causes the argon to cascade through and continually mix with the air. Clearly, it will take many times more argon to achieve a clean purge if it is introduced from the top.

If a water glass is inverted and a basin filled around it with water, it will retain a pocket of air. Argon acts in a similar manner. Any inverted pocket will trap air above the heavier argon. Such pockets must either be vented to allow the air to escape from the top, or lighter helium must be added to the purge gas. Obviously, using just helium results in the opposite problem.

Applying these basic principles can significantly reduce gas required for purging.

### Purging Technique

Interior surfaces in spaces to be purged must be free of dirt that can entrap air or moisture. This requires cleaning the entire surface space to be purged almost as carefully as the weld preparation itself.

Openings in the purge space, the ends of the pipe, or openings in a structure must be covered with metal or plastic sheet sealed with masking tape. Do not use cardboard or paper as air diffuses through them too rapidly. Be aware of blind spaces that can trap air. Either provide secondary gas escape or consider the use of argon-helium gas mixtures to be certain traps will be purged. Weld preparations must be sealed with masking tape until the purge quality is verified. Pin holes in the tape are effective in allowing minor gas escape where the weld space can act as a trap.

Gas should be fed continuously from the lowest end of the pipe or low point in the structure using a baffle or diffuser and be vented through a tube near the top.

Typical purge rates of 20 to 50 cfh (10 to 25 lpm) are used to start, and can be reduced to 5 to 20 cfh (2.5 to 10 lpm) once an inert atmosphere is achieved. Gas flow should be maintained at these lower rates to maintain slight positive pressure and sweep any volatilized contaminants from the purge space until the weld is complete or enough thickness is deposited. Ideally, no color forms on the root during welding. A

good rule of thumb where root inspection is not possible is to require at least 1/4" (6.3 mm) of base or weld metal thickness before removing purge gas.

Purge spaces must always be kept sealed except in the area where welding is being done. In practice, for the root pass 4" to 6" (102 mm to 152 mm) of tape should be removed and the root pass completed to within about 1" to 2" (25 mm to 50 mm) of the tape. Repeat this process until the root is sealed.

When welding long joints (either vertical or horizontal) using a purge space, the welding direction should be away from the purge entry and toward the purge exit. On the root pass, this allows the deposited weld to positively seal the space behind the welding torch where protection of the cooling metal is critical. In addition, welding heat causes surface adsorbed materials to volatilize. To some extent these will be absorbed into the weld or be adsorbed by the cooling metal surface. However, if the gas flow sweeps the contaminants ahead of the weld, this risk is reduced.

If tape used in sealing is heated by welding, materials in the adhesive will be volatilized and can contaminate the weld. During welding of a root pass in particular, it may be necessary to reduce heat input (usually by welding a short distance, then stopping to allow cooling before continuing). For this reason, manual welding of the root pass may be necessary in joints that otherwise might be fully automatically welded. Higher temperature tapes with special adhesives are used to minimize (not eliminate) this problem, but their higher cost suggests they be used only where necessary.

### **Limitations of Tight Fitted Joints Substituted for Back-up Shielding**

It is generally prudent to avoid use of lap joints. If they must be used, however, normal fit-up of lap joints on plates and other fabricated components is not enough to exclude air. Where there is a deep gap between two parts, for example when a loosely fitted flange is placed over a pipe or a lap joint of one plate on another, purging the space may be more effective than local shielding devices since it is more certain to sweep air from the gap.

However, there are some cases where a tightly fitted joint eliminates the need for back-up shielding. Where two parts are very tightly fitted, essentially an interference fit, back-up shielding may not be required or even be effective. For example, in a tube to tubesheet weld, provided the tube is first rolled to contact, back up shielding between the tube wall and the hole ID is not required. Welding before expanding to contact would require back-up gas between each tube and tube hole, something very difficult to achieve or monitor.

### Argon and Welder Safety

Drowning accidents in argon filled tanks and spaces are not common, but do occur every year. They are preventable.

Argon is heavier than air and will displace air in a closed tank in the same manner as filling it with water. If welding or shielding are to be done in a confined space, not only must confined space entry procedures be rigorously followed, but constant vigilance during welding operations is also required. Extra precautions must be taken to provide adequate forced ventilation and a means for “draining” the argon. Obviously the use of forced ventilation must avoid drafts that adversely affect shielding. Do not depend on vacuum driven gas lifts to pull argon up and out of a closed space. Argon will not lift as easily as air. A large diameter vent line connected to a fan positively pulling argon and air from the bottom nozzle of a tank is ideal.

## WELDING TECHNIQUE

### Electrical Characteristics

Typical parameters for manual GTAW with argon are shown in Table 6.

Start gas flow to clear air from gas hoses, back-up shields, and purge spaces several seconds or even minutes before welding. Position the torch and trailing shield over the weld start point for a few seconds to establish a gas blanket prior to arc initiation.

Initiate the arc with the high frequency start feature to avoid tungsten inclusions. If high frequency arc starting is not available consider running on tabs or strike pads. Special care should be taken to minimize the risk of tungsten inclusions (tungsten can be carried along in the weld pool) and to ensure shielding is maintained. Rapid movement of the torch and shield from a strike pad can disrupt the gas blanket.

The welder must be attentive to the stability of the arc. Instability is likely the result of interruption of the critical protective torch gas by a breeze,

<b>Table 6. Typical Parameters for Manual GTA Welding of Zirconium</b>			
<b>Wire Diameter</b>	<b>1/16 in. (1.6 mm)</b>	<b>3/32 in. (2.4 mm)</b>	<b>1/8 in. (3.2 mm)</b>
Current-Amps	100-150 a	125-175 a	150-175 a
Voltage	14-16 v	13-15 v	13-15 v
Speed	4-8 ipm (1.7-3.4 mm/s)	4-8 ipm (1.7-3.4 mm/s)	4-8 ipm (1.7-3.4 mm/s)
Torch Gas	15 cfh (7.1 lpm)	15 cfh (7.1 lpm)	15 cfh (7.1 lpm)
Trailing Gas	25-40 cfh (12-19 lpm)	25-40 cfh (12-19 lpm)	25-40 cfh (12-19 lpm)
Back-up Gas	as required	as required	as required

contaminants on the wire or metal, or even insects that are attracted to the light and vaporized on contact with the 6093°C (11,000°F) arc temperatures. When arc instability is observed, welding should be stopped, the area repaired, and the source of the problem identified and corrected.

The arc should be extinguished by current downslope and a contactor, usually controlled by a single foot pedal, to minimize the size of the crater. Keep the wire end under the torch. After the welding current stops, the torch must be kept in place and shielding maintained until the metal cools. The weld surface will be straw or light blue in color if shielding is not held long enough.



Courtesy Tricon Industrial

20 in. (0.5 m) diameter Zr 702 pipe spool

### Wire Feeding

Feed filler metal continuously into the weld puddle. The “dip-and-dab method”, common for stainless steel, may result in contamination of the hot wire end if it is removed from the protective inert gas shielding. If the wire is inadvertently removed from the inert atmosphere, welding should be stopped and the wire end clipped back 1/4" to 1/2" (6.4 mm to 12.7 mm) or as required to remove contaminated metal (indicated by surface color).

### Interpass Cleaning

Interpass cleaning is not required if the weld deposit is bright and silvery. Light oxide colors (straw or light blue) should be removed by brushing with a clean austenitic stainless steel wire brush followed by solvent cleaning with a lint free cloth moistened with acetone, MEK or similar non-chlorinated solvent.

### Repairs

Contamination that results from inadequate primary (torch) shielding causes the entire weld deposit to become contaminated. Because the weld pool is mixed, contaminants are instantly carried by convection within the molten weld metal throughout the weld deposit. In addition, some base material may be contaminated near the fusion line by diffusion of contaminants. Contaminated weld metal, which is usually indicated by a dark blue oxide or matte blue or gray surface, must be completely removed by mechanical means followed by careful cleaning before welding is continued.

Back side contamination on the root pass should be treated the same as a primary shield failure, and on subsequent passes, like secondary shield failure.

When making a repair, it is important to recognize the source of the contamination. Contamination that results from inadequate secondary (trailing) shielding results in surface contamination and repair may be limited only to removal of a shallow layer of hardened metal.

Contaminated weld metal does not always appear as surface oxide color. Slightly contaminated primary shielding with adequate trailing shielding can disguise the weld metal contamination by producing an oxide free surface. A heavily contaminated weld which is rewelded with adequate shielding may appear to be of excellent quality on the surface, but may conceal dangerous loss of ductility or embrittlement of the metal itself. Remember, color can always reject a weld, but alone can not accept it.

The welder himself is probably the best, and certainly the first, line of defense against contaminated welds. There is no substitute for training and an understanding of what causes contamination and what surface color and appearance means.

### Pre-heating

Pre-heating is not normally necessary for zirconium welding. However, where shop temperatures are below 10 to 15°C (50 to 60°F), under conditions of high humidity where material is brought into a warm shop from a cold area, under field conditions, or where surface moisture from other sources is possible, preheating to 40 to 60°C (100 to 140°F) is a good precaution. Preheating can be accomplished using ordinary gas torches set with a slightly oxidizing flame. The torch should be moved continuously and in such a manner that no oxide color forms on the metal surface. Quartz lamps, electric heaters, and similar methods that do not use a flame may also be effective, though less practical under many conditions. Non-contact surface pyrometers can be used for control, although just holding a hand above the surface to gauge temperature may be acceptable. Never use temperature-indicating crayons, such as Tempilstiks, which themselves become a source of contamination.

### Heat Input and Interpass Temperatures

Heat input must be kept low enough that shielding is sufficient; otherwise, employ wider or longer shielding devices. Interpass temperatures must be kept low enough that no surface color forms during interpass dwell time. Control of heat input and interpass temperatures, which affect cooling rates, have no significant effect on weld mechanical or corrosion properties except through contamination.

## WELDING PROCEDURES

Because the effects of cleaning and shielding have such an important influence on the final weld properties, it is not enough to specify just the welding parameters and the grade of filler metal. Welding procedures also need sufficient detail to describe the cleaning and shielding precautions that will be used in production. These procedures must be comparable to those used in developing the Welding Procedure Specification and the specimens used to prove mechanical properties. Unfortunately, many fabricators provide only the required essential variables using the ASME QW-483 format for their procedures. This leaves many critical details to the imagination of the person reviewing the procedure and provides a poor basis for evaluation or for quality control.

## WELD QUALITY TESTS AND CHECKS

Some simple tests allow the welder to monitor his own weld quality. These are not a substitute for normally required nondestructive tests such as liquid penetrant, ultrasonic, and radiographic inspection, but play an equally important role in maintaining overall quality.

### Poor Cleaning

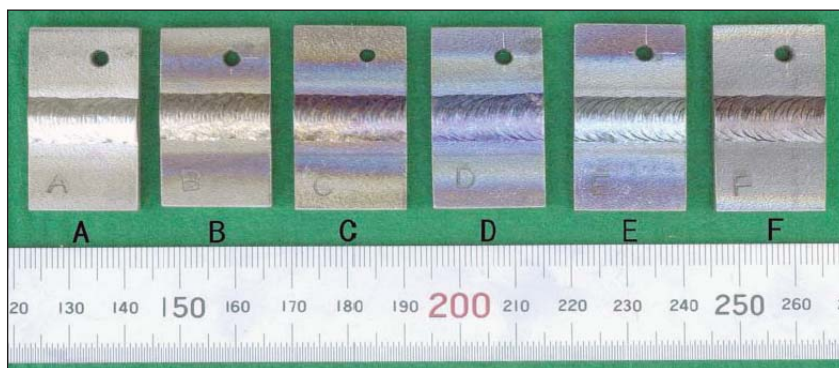
The bright silver band immediately adjacent to the weld toe (Figure 9, sample A) indicates base metal that has been heated to a temperature sufficient to cause minor surface contaminants to be volatilized and likely absorbed into the zirconium. This is characteristic even though a very good cleaning was used to prepare this sample. Poor cleaning is indicated by discoloration seen as a dark brown or black band just beyond the bright band along the weld toe. A lighter brown color band will be present even with typical shop cleaning and is acceptable for most work.

For very critical applications, this color condition can be completely eliminated by vigorous scrubbing with abrasive cleanser or acid pickling and clean water rinsing just prior to welding.

### Surface Color

Surface color is caused by light refracted in the transparent surface oxide. Color indicates the thickness of surface oxide only. A

Figure 9. Color and iridescence on as-welded surface indicates surface oxide or deeper contamination



shiny metallic silver color on the face of the weld is an indication of the effectiveness of the trailing shield only and does not necessarily guarantee that primary shielding was adequate or underlying metal is ductile. For example, welding over a contaminated weld can eliminate the color, but the contamination remains. However, color remains a primary tool for verifying weld quality.

Normal weld surfaces should be smooth, silver, and iridescent as seen in Figure 9, sample A. A light straw (Figure 9, sample B) iridescent surface generally indicates that the weld was exposed to air at a temperature below approximately 538°C (1000°F). This surface oxide (color) should be removed by wire brushing before welding is continued. Because zirconium oxide is dissolved by the metal at high temperatures (over 649°C or 1200°F), a dark straw or blue color (Figure 9, sample C and D) generally indicates sufficient contamination to warrant removal of 0.010" (0.25 mm) of surface material to eliminate the oxygen enriched surface. A loss of iridescence and darker blue color fringe or a matte gray surface (Figure 9, sample E and F) usually requires complete removal of the weld. A white/buff loose oxide results from total failure of primary or secondary shielding. The entire weld and about 0.020" (0.5 mm) of the base metal below the just deposited weld must be removed and re-prepped.

Table 7 is a guide to surface oxide color and appearance that can be used to help determine the extent of weld repair required. In any case, repair must include removing contaminated metal before welding is continued.

**Primary Shielding**

Primary Shielding can be checked by striking an arc on a piece of clean scrap zirconium using only the torch gas, holding it stationary until a small puddle, < 1/2" (<12 mm) diameter, forms under the torch cup. The arc is extinguished by downslope or contactor and the torch is held in position until the puddle cools. Impurities in the torch gas from air or water leaks, or impure or interrupted shielding gas will result in discoloration of the weld.

**Bend Test**

Welds with satisfactory ductility should bend over the radii listed in Table 2 without cracking. These tests should be conducted using standard guided weld bend test coupons or simple bead on plate samples.

<b>Table 7. Oxide Colors Indicate Temperature of Exposure of Solidified Metal</b>	
Silver	Good weld, no treatment required
Light Straw	Remove by wire brushing
Dark Straw	Remove by wire brushing
Light Blue	Remove by wire brushing
Dark Blue	Weld metal contamination, remove by grinding
Blue-Gray	Weld metal contamination, remove by grinding
Gray, White, Loose Deposit	Failure of primary and secondary shielding Remove weld metal and some base metal

## Hardness

An increase in hardness of over 30 points Brinnell (5 points Rockwell B) above base metal hardness indicates excessive contamination regardless of the color of the face or root of the weld. Welders may be able to distinguish between hardened and normal metal based on the way the zirconium is cut using a carbide burr or rotary file.

## DISSIMILAR METAL WELDING

While unusual, welds between zirconium alloys like Zr 702 and Zr 705 are sometimes needed. For this case, normally select the stronger Zr 705 filler metal. There are not significant differences in welding characteristics. However, stress relief heat treatment will be required because of the risk of delayed hydride formation and cracking in the Zr 705. Even if Zr 702 filler metal were used, stress relief would still be required.

In general, zirconium cannot be fusion welded to other metals because of the formation of brittle intermetallic compounds. The exceptions are other reactive metals including titanium, tantalum, niobium, vanadium, and hafnium which can be welded following the requirements outlined in this paper with some provision for differences in melting temperature, e.g., welding technique, different section thickness, etc. Differences in melting point and other thermal properties may limit the configurations that can be considered.

Applications for dissimilar metal welds are sufficiently specialized that they cannot be treated in this document, but it is clear that testing of actual sample welds for required mechanical and corrosion properties should be considered for any application.

## HEAT TREATMENT

Zirconium should be cleaned of all dirt, oils, solvents, or machining oil residues, especially those containing chlorides, prior to heat treatment. Cleaning comparable to that used for welding is ideal. Parts should be supported on firebrick or similar materials that are inert with respect to the zirconium itself. A sufficient number of thermocouples should be placed in contact with the metal surface to account for variations in the uniformity of the furnace environment as well as varying material thicknesses.

Vacuum or argon purged electric furnaces are preferred, but gas fired furnaces are also suitable. With gas fired heating, a slightly oxidizing atmosphere is recommended. Avoid other furnace fuels. Direct flame impingement must be avoided.

Zr 702 weldments generally do not require stress relieving, but a stress relief heat treatment at 565°C (1050°F) for 1/2 to 1 hour at temperature can be utilized to relieve residual stresses for machining stability, for improved fatigue performance. Stress relief heat treatment can restore ductility after severe forming. An intermediate heat treatment may permit tighter bends or deeper draws than are possible in a single step forming operation.



Courtesy Titanium Fabrication Corporation

Stress relief heat treatment of Zr 705 prevents delayed cracking

Zr 705 requires a stress relief heat treatment within 14 days after welding to prevent delayed hydrogen cracking. The ASME Code specifies a temperature of 538°C (1000°F) for a minimum of 1 hour plus 1/2 hour for each additional inch of thickness, with maximum cooling rate of 260°C/hour (500°F/hour) or 260°C (500°F) divided by the maximum section thickness in the shell or head, e.g. 1-1/2" (38 mm) thick plate would require 167°C/hour (333°F/hour) maximum cooling rate.

Typical stress relief for zirconium explosively clad to SA516-70 or similar carbon steel is 607°C/hour +/- 4°C/hour (1125°F +/- 25°F/hour) for 1 hour minimum, 15 min/inch (0.6 min/mm) up to a 2 hour maximum. For zirconium clad stainless steel, 538°C +/- 4°C (1000°F +/- 25°F), for 1 hour minimum, 15 min/inch up to a 2 hour maximum is typical.

## FIELD REPAIR CONSIDERATIONS

Wherever possible, remove equipment and send it to an experienced zirconium fabricator shop for repair. Repair of equipment that has been in service always presents the most difficult situation under which to produce welds of satisfactory quality. The equipment is usually dirty and may have adsorbed process material on the surface. Repairs must often be done in place under conditions with high humidity, or outdoors in the wind, or at too low or too high an ambient temperature.

There is always pressure from the production personnel to get the job done fast. However, there is little merit in speeding the job by cutting corners such as welding over poorly prepared areas. The resulting weld contamination will result in a premature failure and a repeat of the costly repair.

Expect to spend more time in preparing to weld than in welding. First, clean the equipment superficially to get rid of process material or debris that can be a continuing source of water or dirt. Then remove cracked or damaged material by cutting or grinding. Once this is done, the entire work area should be cleaned. Next, the work area should be enclosed sufficiently to eliminate drafts, dirt, water, etc. Plastic sheets draped over (or under) the work area or fastened to a temporary support are quite effective. Any metal surface to be welded or within about 0.25" (4.5 mm) of the weld that has been exposed to the process should be rotary filed to remove adsorbed surface contaminants. Finally the weld area itself and adjacent metal should be very carefully re-cleaned and dried. Use mild preheat under low temperature or high humidity conditions.

Repairs that are required for partial penetration welds or in areas where there are crevices are a special problem due to the potential for the presence of contamination in the crevices. Use of preheating to dry the restricted area and volatilize potential contaminants can minimize, but not completely eliminate, the problem during a repair.

Excellent and serviceable repairs can be made under seemingly adverse conditions if care is taken to meet the fundamental requirement described in this datasheet.