WELDING OF TITANIUM ALLOYS

1. INTRODUCTION

The high strength, low weight and outstanding corrosion resistance possessed by titanium and titanium alloys have led to a wide and diversified range of successful applications in aerospace, chemical plant, power generation, oil and gas extraction, medical, sports, and other industries. Welding of titanium by various arc welding processes is widely practiced, and good service performance of welds is proven. Newer joining methods, such as laser welding, have been successfully adapted for titanium. Application of appropriate welding technology to the design, manufacture and application of titanium products is as important a step in design as the specification of the alloy. Titanium is a unique material; as strong as steel but half its weight, with excellent corrosion resistance. Traditional applications are in the aerospace and chemical industries. More recently, specific alloys are finding use in the manufacture of implantable medical devices and sensors.

2. MATERIAL TYPES

2.1 Alloy Groupings

There are basically four types of alloys distinguished by their microstructure:

? **Titanium** - Commercially pure (98 to 99.5% Ti) or strengthened by small additions of oxygen, nitrogen, carbon and iron. The alloys are readily fusion weldable;

? **Alpha alloys** - These are largely single-phase alloys containing up to 7% aluminium and a small amount (< 0.3%) of oxygen, nitrogen and carbon. The alloys are fusion welded in the annealed condition;

? **Alpha-beta alloys** - These have a characteristic two-phase microstructure formed by the addition of up to 6% aluminium and varying amounts of beta forming constituents - vanadium, chromium and molybdenum. The alloys are readily welded in the annealed condition;

? **Ni-Ti** alloys.

Alloys which contain a large amount of the beta phase, stabilised by elements such as chromium, are not easily welded. Commonly used alloys are listed in Table 1 with the appropriate ASTM grade, the internationally recognised designation. In industry, the most widely welded titanium alloys are the commercially pure grades and variants of the 6%Al and 4%V alloy.

Table 1: Commonly used titanium alloys and the recommended filler material

ASTM Grade	Composition	UTS (min) MPa	Filler	Comments
1	Ti-0.15O_2	240	ERTi-1	Commercially pure
2	Ti-0.20O_2	340	ERTi-2	,,
4	Ti-0.35O_2	550	ERTi-4	,,
7	Ti-0.20 O_2-0.2Pd	340	ERTi-7	,,
9	Ti-3Al-2.5V	615	ERTi-9	Tube components
5	Ti-6Al-4V	900	ERTi-5	'Workhorse' alloy
23	Ti-6Al-4V ELI	900	ERTi-5ELI	Low interstitials
25	Ti-6Al-4V-0.06Pd	900	ERTi-25	Corrosion resistant grade

2.2 Ni-Ti Alloys

A wide variety of products use the Ni-Ti alloys including bend-resistant cell phone antennas, eyewear frames, orthodontic arch wires, and vascular stents used to prop open blocked arteries.

2.3 Filler Alloys

Titanium and its alloys can be welded using matching filler composition; compositions are given in AWS A5.16-2004. Recommended filler wires for the commonly used titanium alloys are also given in Table 1. When welding higher strength titanium alloys, fillers of a lower strength are sometimes used to achieve adequate weld metal ductility. For example, an unalloyed filler ERTi-2 can be used to weld Ti-6Al-4V and Ti-5Al-2.5Sn alloys in order to balance weldability, strength and formability requirements.

3. WELD IMPERFECTIONS

Titanium and its alloys are readily fusion welded providing suitable precautions are taken. TIG and plasma processes, with argon or argon-helium shielding gas, are used for welding thin section components, typically < 10 mm. Autogenous welding can be used for a section thickness of < 3 mm with TIG, or < 6 mm with plasma welding. Pulsed MIG is preferred to dip transfer MIG because of the lower spatter level. The most likely imperfections in fusion welds are:

- Weld metal porosity;
- Embrittlement;
- Contamination cracking.

Normally, there is no issue with solidification cracking or hydrogen cracking.

3.1 Weld Metal Porosity

Weld metal porosity is the most frequent weld defect. Porosity arises when gas bubbles are trapped between dendrites during solidification. In titanium, hydrogen from moisture in the arc environment or contamination on the filler and parent metal surface is the most likely cause of porosity. It is essential that the joint and surrounding surface areas are cleaned by first degreasing either by steam, solvent, alkaline or vapour degreasing. Any surface oxide should then be removed by pickling (HF-HNO3 solution), light grinding or scratch brushing with a clean, stainless steel wire brush. After wiping with a lint-free cloth, care should be taken not to touch the surface before welding. When TIG welding thin section components, the joint area should be dry-machined to produce a smooth surface finish.

3.2 Embrittlement

Embrittlement can be caused by weld metal contamination by either gas absorption or by dissolving contaminants such as dust (iron particles) on the surface. At temperatures above 500°C, titanium has a very high affinity for oxygen, nitrogen and hydrogen. The weld pool, heat affected zone and cooling weld bead must be protected from oxidation by an inert gas shield (argon or helium). An example pf trailing gas shields is shown in Figure 1.

When oxidation occurs, the thin layer of surface oxide generates an interference colour. The colour can indicate whether the shielding was adequate or an unacceptable degree of contamination has occurred. A silver or straw colour shows satisfactory gas shielding was achieved but for certain service conditions, dark blue may be acceptable. Light blue, grey and white show a higher, usually unacceptable, level of oxygen contamination as described in Table 2.

Table 2: Assessment of weld surface contamination level

Weld Surface Appearance	Probable Effect On Mechanical Properties	Recommended Actions
Bright silver Light straw	None Not measureable	Accept
Brown/purple	Very slight	Remove by emery, brush etc then check hardness
Blue Second order colours Mother of pearl	Slight except for possible hard surface layer	Check hardness, remove surface layers if necessary, then re-weld
Dull leaden grey Flaky white oxide Fluffy yellow oxide	Moderate to very severe. Welds will be hard and brittle	Remove weld and effected weld area

For small components, an efficient gas shield can be achieved by welding in a totally enclosed chamber, filled with the inert shielding gas. It is recommended that before welding, the arc is struck on a separate piece of titanium to remove oxygen from the atmosphere; the oxygen level should be reduced to approximately 40ppm before striking the arc on the scrap titanium and < 20ppm before welding the actual component. In tube welding, a fully enclosed head is equally effective in shielding the weld area and is be preferable to orbital welding equipment in which the gas nozzle must be rotated around the tube. When welding out in the open, the torch should be fitted fitted with a trailing shield to protect the hot weld bead whilst cooling. The size and shape of the shield is determined by the joint profile whilst its length is influenced by welding current and travel speed. It is essential in 'open air' welding that the underside of the joint is protected from oxidation. For straight runs, a grooved backing bar can be used with argon gas being fed into the groove. In tube and pipe welding, normal gas purging techniques are appropriate. Checks can be carried out on how effective the gas shielding is using a purge monitor, which measures the amount of oxygen that may be present in the gas purge. It is normal for the torch diameter to be as large as possible to obtain the maximum effect of gas shielding. In addition, a diffuser should be fitted inside the gas nozzle to ensure a laminar gas flow is achieved.

Figure 1: Typical trailing gas shields for avoidance of weld metal oxidation

3.3 Contamination Cracking

If iron particles are present on the component surface, they dissolve in the weld metal reducing corrosion resistance and, at a sufficiently high iron content, cause embrittlement. Iron particles are equally detrimental in the HAZ where local melting of the particles form pockets of titanium - iron eutectic. Microcracking may occur but it is more likely that the iron-rich pockets will become preferential sites for corrosion. Particular attention should be paid to separating titanium from steel fabrications, preferably by designating a dedicated clean area. Embedding of steel particles into the surface of the material can be minimised by:

- Avoiding steel fabrication operations near titanium components;
- Covering components to avoid airborne dust and ferritic particles settling on the surface;

- Not using tools, including wire brushes, previously used for steel;
- Scratch brushing the joint area immediately before welding;
- Not handling the cleaned component with dirty gloves.

To avoid corrosion cracking, and minimise the risk of embrittlement through iron contamination, it is best practice to fabricate titanium in a specially dedicated clean condition area. For welding to medical grade standards, checks can be made to determine whether ferritic contamination is likely to occur.

3.3 Test for Ferritic Contamination on Titanium Surfaces

3.3.1 Ferroxyl Test

The test solution is made up by dissolving 7 g of potassium ferricyanide and 4.5 ml of nitric acid (65% concentration) in 214 ml of distilled water. The solution deteriorates in a few days, becoming cloudy and should therefore be used shortly after it is made up. The test may be carried out in two ways:

a). Soak a filter paper in the solution and apply to the surface under examination, ensuring a good contact over the whole surface. The presence of iron is revealed by a blue colouration almost immediately after application of the paper in those areas which contain ferrite contamination.

b). Swab or spray the surface to be tested using the solution. Ferrite contamination is again exposed by blue discolouration. It may be helpful to increase the viscosity of the solution by the addition of an iron-free gelatine or similar agent, providing the gelatine or similar agent does not interfere with the sensitivity of the test.

3.3.2 Phenanthroline test

a). Dissolve 272 g of hydrated sodium acetate in about 500 ml of hot distilled water, add 240 ml of glacial acetic acid and dilute to 1litre with distilled water.

b). Dissolve 3.5 g of hydroxylamine hydrochloride in 350 ml of distilled water.

c). Dissolve 2.5 g of 1:10 phenanthroline monohydrate in about 200 ml of hot distilled water and dilute to 300 ml.

d). Mix solutions (1), (2), and (3) together to make 1650 ml. The mixed solution is reasonably stable provided that it is kept in a stoppered bottle. It will have a shelf life of about two to three months.

The procedure for application is the same as (1) for the ferroxyl test, i.e. the filter paper soaked in the solution is laid over the surface to be tested. Again ensuring good contact between the paper and the metal surface. Ferrite contamination is shown by an orange colouration in the contaminated region.

Note: Because the phenanthroline solution is more stable, it is more convenient than the ferroxyl test where only a limited amount of testing is to be done. After the test, the reagent should be removed from the titanium surface by washing followed by rinsing in an appropriate solvent.

WARNING
The chemicals referenced above may pose a health hazard and should therefore be handled by trained and competent personnel using appropriate personal protection equipment. Job Safety Analysis should be used when mixing and applying the chemicals. Similarly any waste should be disposed of by an authorised and handled by trained and competent personnel using appropriate personal protection equipment.