WELDING OF TITANIUM AND ITS ALLOYS

By Gene Mathers

Titanium is a reactive metal; it will burn in pure oxygen at 600°C and in nitrogen at around 800°C. Oxygen and nitrogen will also diffuse into titanium at temperatures above 400°C raising the tensile strength but embrittling the metal. In the form of a powder or metal shavings titanium also constitutes a fire hazard.

Despite this reactivity titanium is used extensively in chemical processing, offshore and aerospace applications. This is due to:

- The tenacious protective oxide film that forms, giving the alloys very good corrosion resistance, particularly in chloride containing environments.
- No loss of toughness at temperatures down to -196°C
- Good creep and oxidation resistance at temperatures up to almost 600°C.
- Similar strength to steel but at approximately half the weight.

Because of the affinity of titanium and its alloys for oxygen, nitrogen and hydrogen and the subsequent embrittlement, fluxed welding processes are not recommended although they have been used, primarily in the former USSR. Arc welding is therefore restricted to the gas shielded processes (TIG, MIG and plasma-TIG) although power beams, the solid phase processes and resistance welding are also used.

Titanium is allotropic; it has two different crystallographic forms depending on the temperature and chemical composition. Below 880°C it forms the hexagonal close packed alpha phase, above 880°C it exists as body centered cubic beta phase.

A range of elements may be used to improve the mechanical properties, some stabilize the alpha phase and others promote the formation of beta. Oxygen, carbon, nitrogen and aluminum promote the formation of the alpha phase; chromium, molybdenum, niobium, tin and vanadium promote the formation of beta. By suitable additions of these elements it is possible to produce four families of titanium alloys, divided on the basis of microstructure, into commercially pure titanium, alpha or near alpha alloys, alpha-beta alloys and beta alloys. ASTM designations, a simple numbering system, are a
commonly used shorthand way of identifying the various alloys and both these and the alloy composition eg Ti-6Al-4V, will be used within this article.

Commercially pure, unalloyed ASTM 1 - 4 and 7 grades contain small amounts of contaminants such as oxygen, nitrogen and carbon, typically less than 0.2%, and have mechanical properties matching those of a good quality low carbon steel. The fewer contaminants, the lower is the tensile strength. The majority of these alloys are used for their corrosion resistance. Welding is straightforward and has little effect on the mechanical properties in the HAZ and they are generally welded in the annealed condition.

The alpha and near alpha alloys, typified by the Ti-5Al-2.5Sn alloy, have ultimate tensile strengths (UTSs) of 500-900MPa, 0.2% proof (PS) of 600-800MPa and elongations (El%) of around 18%. As with the commercially pure alloys the mechanical properties of this group are insensitive to heat treatment. Weldability is good, the alloys being welded in the annealed condition.

The alpha-beta alloys are sensitive to heat treatment, solution treatment and ageing, increasing the strength by 50% compared with the annealed condition. The very high strength alpha-beta alloys such as Ti-5Al-2Sn-2Zr-4Mo-4Cr may have a UTS of 1200MPa, PS of 1150MPa and an El% of 10. Weldability of the alloys within this group, however, is dependent on the amount of beta present, the most strongly beta stabilized alloys being embrittled during welding and, although it is possible to restore some of the ductility by a post-weld heat treatment, this is often impractical. These very high strength, high beta content alloys are therefore rarely welded. Contrast this with possibly the most frequently used alpha-beta alloy, Ti-6Al-4V (ASTM Grade 5) with a UTS of 950MPa, a PS of 850MPa and El% of 15. This alloy has good formability, is readily workable, has good castability, excellent weldability and could be regarded as the alloy against which to benchmark all others.

The fully beta alloys, eg Ti-13V-11Cr-3Al, have similar strengths but with slightly improved ductility, typically around 15% elongation. The beta phase is termed metastable - cold work or heating to elevated temperatures may cause partial transformation to alpha. The alloys have high hardenability, very good forgeability and are very ductile. Weldability is good, taking place with the alloy in the annealed or solution treated condition although to obtain the full strength it is generally necessary to weld in the annealed condition, cold work, solution treat and then carry out an ageing treatment.

Filler metals, all solid wires and matching the composition of the commoner of the alloys, are available, the relevant specifications being AWS A5.16/A5.16M:2007 Specification for titanium and titanium-alloy welding electrodes and rods and BS EN ISO 24034.2010 Welding consumables, solid wires and rods for fusion welding of titanium and titanium alloys. Although readily available, the range of consumables is somewhat restricted with only fourteen or fifteen compositions being produced in accordance with these specifications.
Weldability, as mentioned above, is in general very good. The exception is the high beta alpha-beta alloys. The fundamental problem in welding titanium alloys is the elimination of atmospheric contamination. Contamination of the weld metal and the adjacent HAZs will increase tensile strength and hardness but may reduce ductility to an unacceptably low value such that cracks may occur even in conditions of only moderate restraint. The most likely contaminants are oxygen and nitrogen, picked up due to air entrained in the gas shield or from impure shield gas, and hydrogen from moisture or surface contamination.

The maximum tolerable limits in weld metal have been estimated as 0.3% oxygen, 0.15% nitrogen and 150ppm hydrogen so scrupulous cleanliness is essential for both parent metals and filler wires. Degreasing the weld preparation followed by stainless steel wire brushing and a further degrease is generally sufficient. Heavily oxidized components may need to be pickled in a nitric/hydrofluoric acid mixture to remove the oxide layer. Degreasing of the filler wire for TIG welding should be done as a matter of course and the cleaned wire handled with clean cotton gloves; grease and perspiration from the fingers can cause local contamination and/or porosity. MIG wire should be ordered in a degreased condition, stored in clean dry conditions and not left unprotected on the shop floor.
During welding those parts of the weldment exposed to temperatures above 520°C will absorb oxygen and nitrogen and must therefore be protected until they have cooled below this critical temperature. Fortunately heat conduction in titanium is low so the area affected is limited in size and chill blocks can be used to reduce this heated zone even further. The molten weld pool is protected by the normal gas shroud but the cooling weld and its HAZ will need additional protection by the use of a trailing shield with its own protective gas supply following along behind the welding torch. The back face of the weld also needs similar protection by the provision of an efficient gas purge.

Surface discoloration will give a good indication of the degree of atmospheric contamination as shown in the color chart. Under perfect shielding conditions the weld will be bright and silvery in appearance. Discoloration at the outer edges of the HAZ is not generally significant and may be ignored. As contamination increases the color changes from silver to a light straw color, then dark straw, dark blue, light blue, grey and finally a powdery white.

The light and dark straw colors indicate light contamination that is normally acceptable. Dark blue indicates heavier contamination that may be acceptable depending on the service conditions. Light blue, grey and white indicate such a high level of contamination that they are regarded as unacceptable. In multi-pass welds the contamination will obviously affect any subsequent weld runs so that surface appearance alone is not a reliable guide to whether or not unacceptable contamination has occurred. A simple bend test is a reliable but destructive method of checking if the weld is unacceptably embrittled but note that the bend radius varies depending on the particular alloy. For example, a 3t bend radius is used for testing a Grade 2 weld but a 10t bend radius is used when testing Ti-6Al-4V. Portable hardness checks may also be carried out on production items; this requires knowledge of the hardness expected in the specific alloy weld metal.

Titanium and its alloys are remarkably resistant to the cracking problems experienced by many of the other alloy systems. Solidification and liquation cracking are virtually
unknown and what could perhaps be called cold cracking, occurs generally only because of embrittlement arising from contamination, as discussed in Part 1.

Porosity is the commonest problem, particularly when close square butt joints are used. It is generally attributed to hydrogen and cleanliness is therefore crucial in eliminating porosity. The porosity may be of one or a mixture of two types: firstly, micro-porosity formed within the arms of the dendrites during solidification and secondly, larger pores that often align themselves along the weld center line.

As discussed in Part 1, cleanliness is the key to defect free welds and this means that not only must the component be thoroughly degreased but so should the filler wires; weld preparation edges must be deburred and the highest purity shielding gas must be used. Ideally the gas should have a dew point of less than -50°C (39ppm H₂O) and to maintain this low level the gas supply system should be free of leaks. Regular and frequent maintenance of the system is therefore essential, checking the joints for leaks and for damaged hoses. Ideally the gas supply should be from a bulk gas tank, not cylinders, and delivered to the work stations via welded or brazed steel or copper tubing. Plastic hoses should be kept as short as possible; most plastics used are porous and will allow moisture to permeate through the hose wall; neoprene and PVC are the worst, Teflon one of the least porous. It is worth remembering that moisture can collect in the hose over a period of time so a porosity problem, say after a weekend shut down, may be an indication that this is occurring.

TIG filler wires should be cleaned with a lint free cloth and an efficient degreasing immediately before use. Following cleaning, the wire should not be handled with bare hands but whilst wearing clean, grease-free gloves. MIG wire presents more of a problem but devices to clean the wire as it passes through the wire feeder are available. For the best results wire that has been shaved to remove any embedded contaminants can be obtained.

A further potential source of contamination that is frequently overlooked is the use of air powered tools for wire brushing or dressing weld preparations and welds. Most compressed air contains moisture and oil so that, even when oil and moisture traps are fitted, it is possible to leave a thin film of moisture and/or oil on the surface to be welded. It is recommended that electrically powered tools are used at all times once the item has been degreased prior to welding.

Although regarded as a very minor problem, ductility dip cracking (where alloys experience a severe loss of ductility at a temperature below the solidification temperature) has been noted in some of the titanium alloys; the alpha-beta alloys containing niobium being the most susceptible with Ti-6Al-2Nb-1Ta-0.8Mo the most sensitive. The temperature range in which this loss of ductility occurs is between 750°C and 850°C.
The cracking is intergranular and is thought to be partly the result of volume changes during the beta to alpha phase change coupled with the reduction in ductility.

A significant amount of welding of titanium alloys is carried out without the use of filler metals. When filler wire is used, generally a composition matching that of the parent metal is selected. There are, however, some exceptions. The welding of high strength but low ductility commercial purity titanium is generally performed with a low strength filler metal in order to achieve the desired weld quality. Similarly, unalloyed filler metal is sometimes used to weld alloys such as Ti-6Al-4V, thereby improving weld metal ductility by lowering the amount of beta phase that is formed. Extra low interstitial (ELI) filler metals are also available and may be used to improve weld metal ductility and toughness.

Most of the titanium alloys can be successfully fusion welded using the gas shielded welding processes and power beams; all can be welded using solid phase processes, friction and resistance welding. Welding parameters and weld preparations are similar to those that would be used to weld a carbon steel. From the welder's point of view, titanium is easier to weld than steel, having good fluidity and high surface tension, easing the task of depositing sound full penetration root beads.

TIG welding is probably the most commonly used process in both manual and mechanized applications. The current is DC-ve, generally with high purity argon as the shielding gas, although helium or Ar/He mixtures may be used to improve penetration. Torch nozzles should be fitted with gas lenses to improve gas shielding and the ceramic shroud should be as large a diameter as possible. A 1.5mm diameter tungsten, for example, should be used with a 16mm diameter ceramic. Arc lengths need to be as short as possible to reduce the risk of contamination; 1 to 1.5 times the electrode diameter is regarded as a good rule of thumb. Arc initiation should be achieved by the use of HF current or Lift Arc to prevent tungsten contamination. The equipment must also be capable of continuing the shield gas flow after the arc is extinguished so that the weld can cool within the protective gas shield. It is also advisable to keep the tip of the filler wire within the gas shield until such times as it has cooled to a sufficiently low temperature.

A supplementary trailing gas shield will also need to be attached to the torch to provide protection to the cooling weld metal as the welder moves along the joint line. This makes manipulation of the welding torch more difficult. Most welders manufacture their own supplementary shields, shaped to closely fit the component; several shields would therefore be required to weld a range of pipe diameters. A backing gas is also necessary and back purging should be maintained for at least the first three or four passes in a weld. Backing gas purity should be better than 20ppm maximum oxygen.

MIG welding using argon or argon/helium mixtures may be used but this process will not provide the same high-quality weld metal as the TIG process and it can be difficult to achieve the stringent quality levels required by aerospace applications. Dip transfer can lead to lack of fusion defects and spray transfer requires both leading and trailing
supplementary gas shields, the leading gas shield to prevent oxidation of any spatter that may be remelted into the weld pool. The improvements in pulsed MIG power sources by the use of inverter technology and micro-processor control have obviated some of these problems and substantially narrowed the gap between MIG and TIG. MIG is, however, still difficult for the manual welder because of the difficulty of manipulating the MIG torch with a supplementary gas shroud. Because of these difficulties MIG welding is often mechanized or automated.

Plasma-TIG may be used for welding titanium, being capable of keyholing a weld up to 12.5mm thick. The same requirements for gas purity and weld pool protection required for TIG are also needed for plasma-TIG. Plasma-TIG is rarely used in a manual application and never in the keyhole mode.

Atmospheric contamination is best avoided by the use of a welding chamber or glove box that can be filled with argon. Purpose built glove boxes can be purchased but it is a simple matter to fabricate a chamber of an appropriate size using slotted angle i.e. Dexion™ angle, to form the frame and covering this with a clear plastic or acetate sheet. The size of the component that can be welded within a glove box is necessarily restricted.

Electron beam, laser, friction, resistance spot and seam and flash welding are all used to weld titanium and its alloys. Electron beam welding, being carried out in a vacuum, needs no protective gas shield. Conventional friction welding may also be carried out without a protective shield although a gas shield should be used when friction stir welding. Similarly, no gas shield is required when resistance welding, although for the most critical applications a gas shield is recommended. Laser and flash welding both require gas shielding for the best results and least atmospheric contamination.

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