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Titanium joining - a brief review of the processes used on this material

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Abstract. In a few decades, titanium has gone from being used almost exclusively in top-secret aerospace projects to being used in the construction of custom car parts. Thanks to its incredibly high strength-to-weight ratio and excellent corrosion resistance, titanium will be used even more extensively in the future. There are various ways of joining titanium, one of the most used being welding. Titanium generally has good weldability, but welding it poses problems in terms of the danger of atmospheric contamination of the joint, as titanium, along with zirconium, beryllium, hafnium, and several other metals, has a high affinity for atmospheric gases. In this paper, the characteristics of titanium and its alloys will be presented, as well as the main processes for joining them by welding and a brief review of some examples.

Keywords: *welding, production, titanium, construction of custom car parts*

Introduction

Titanium represents about 0.6% of the Earth's surface, making it the fourth most abundant element after iron, aluminium, and magnesium. It is estimated that there is more titanium in the earth's crust than the sum of chromium, copper, nickel, zinc, and lead.

Although titanium is abundant in the earth's crust, its use only began around the 1950’s due to the difficulties of mining, processing, and refining.

However, its unique properties have made it a key player in the aerospace, aeronautics, nuclear, chemical, and medical (implants) industries.

Depending on how it is processed, titanium is used in two ways:

- technical titanium, which contains about 0.5% impurities (about 0.3% nitrogen, 0.15% oxygen, 0.15% iron, 0.1% magnesium, 0.05% silicon).
- pure titanium, containing a maximum of 0.04% impurities.

Titanium has two allotropic forms: up to 882°C titanium α with a hexagonal lattice, and at temperatures above 882°C titanium β with a cubic lattice with centred volume. Because of the value of the hexagonal cell c/a ratio (c/a = 1.587) titanium exhibits sufficient slip systems so that it is a ductile metal and without ductile-fragile transition point. As the density is relatively low (ρ= 4540 kg/m3) the mechanical strength/density ratio is superior to all other metals. Therefore, at the same level of stress the titanium/titanium alloy part is lighter [1-5].

The corrosion resistance of titanium is excellent and superior to stainless steels. Titanium is resistant to dilute sulphuric and hydrochloric acids, chlorine gas, chlorine-based solutions, and most organic acids, but is soluble in strong acids. The very good resistance in chlorine-containing environments is due to a thin (approx. 100 nm) protective film of titanium dioxide that forms on the surface of the metal. Titanium burns in air at around 1200°C and in pure oxygen at 600°C or more, forming titanium dioxide. The melting temperature of titanium is about 1725°C. Therefore, the metal cannot be melted in open air because it burns before it reaches the melting point; for this reason, the melting process can only be carried out in an inert gas atmosphere or vacuum. Titanium is, also, one of the few elements that burns in pure nitrogen gas (above 800°C and forms titanium nitride, which causes loss of ductility).

Titanium is a paramagnetic metal and has relatively low electrical and thermal conductivity.

The metal retains its toughness at very low temperatures (-196°C) and has good fatigue strength. Titanium alloys exhibit good mechanical strength at high temperatures.

Titanium is sensitive to impurities such as nitrogen, carbon, oxygen, and hydrogen. It forms with them the solid α-insert solution, as well as a series of intermetallic compounds (hydrides, carbides, nitrides) which lead to reduced ductility, workability, and weldability.

The automotive applications using titanium follow logically from high strength, low density, and low modulus, and they have excellent resistance to corrosion and oxidation. Titanium is primarily used in internal combustion engine components, such as valves, valve springs, retainers, and connecting rods.

In the last few years, titanium has been adopted to fracture-split connecting rods, fuel tanks, and fuel cell separators of mass produced vehicles because of not only the development of titanium alloys in which low-cost alloying elements are added and low-cost processing methods are carried out by material producers, but also the cooperative development of material producers, part makers, and car manufacturers.

2. Welding behaviour of titanium and its alloys

The welding behaviour of technical titanium is mainly determined by:

- its particular chemical affinity to oxygen, nitrogen and hydrogen, both in liquid and solid state at temperatures above 650°C;
- its tendency towards overheating and growth of β-phase grains.
- formation of brittle α' phase on cooling.

The influence of hydrogen on the properties of the base metal and welded joints is mainly manifested by a decrease in resilience at both normal and negative temperatures. It has been experimentally shown that by increasing the hydrogen content in the technical titanium from 0.01% to 0.05%, the Charpy V strength at +20°C decreases from 6 daN·m/cm^2 to 1.5 daN·m/cm^2, practically without any change in the tensile strength and elongation. In addition, hydrogen is the main source of pore formation in titanium welding.

The nitrogen, oxygen, and carbon content acts primarily to decrease the plasticity of welded joints. Experimental researches have shown that increasing the oxygen content of technical titanium from 0.15% to 0.38% (at 0.02% nitrogen content) decreases the bending angle of specimens taken from 1.5 mm thick sheet metal welded joints from 180° to 100°. The same phenomenon occurs when the carbon content increases from 0.05% to 0.28% [6-11].

The alloying elements of titanium, which greatly decrease the plasticity of the joint (in order of effectiveness: Cr, Fe, Mn, W, Mo and V) result in the formation of the α' phase in the seam and in the thermally influenced zone, with disordered orientation and particular brittleness.

Like technical titanium, titanium alloys containing nitrogen, oxygen, hydrogen, and carbon in small amounts have good welding behaviour. Depending on the alloying elements contained in the alloys, the influence of these damaging factors is felt. For example, in titanium alloys containing aluminium, tin, copper or manganese up to 5%, the presence of 0.05% hydrogen in the seam practically does not change the strength value; at the same time, titanium alloys with a similar molybdenum or iron content, with the same amount of hydrogen, show a marked increase in seam strength.

Preparation for welding surfaces

Regardless of the welding process applied, measures must be taken to prepare the surface of the joining sheets before welding.

In general, the surfaces of the sheets are covered with complex particles consisting of oxides resulting from the rolling process at relatively high temperatures and in an open atmosphere, grease, moisture, and dust, deposited or absorbed subsequently.

Removal of all impurities to achieve a welded joint free of pores and other defects can be done:

- mechanically by cleaning with a stainless-steel brush.
- chemically by pickling with a solution of 4% hydrofluoric acid, 40% nitric acid, 56% distilled water for 1...15 min.

If, however, the titanium sheets have been produced in a protective atmosphere, it is sufficient to clean the surface with a solvent such as methanol, ethanol, acetone, or any other substance that evaporates without leaving residues.

The surface of the sheet must be prepared to 25...30 mm from the edges that meet.

Both conventional and unconventional processes are used for welding titanium and its alloys. Conventional welding processes include WIG welding with or without filler material and MIG welding. The remainder are laser welding, plasma welding, electron beam welding and friction stir welding (FSW).

3. Welding processes used in titanium joining

3.1. WIG welding with or without filler material

WIG welding of titanium and its alloys is recommended for sheet thicknesses from 0.5 to 12...13 mm. Pure argon is used as a shielding gas, which is sometimes mixed with helium (maximum 25% He) for automatic welding. Pure argon means argon of at least 99.95% purity.

Welding in direct current, direct polarity, the arc is more stable than in reverse polarity welding; also, the electrode life and melting rate are longer.

WIG welding without filler material is used for joining 0.5...3 mm thick sheets. The joint is made in a single pass, without the need for edge machining and with zero joint width.

When access from both sides is possible, sheets up to 6 mm thick can be welded in this way.

Manual WIG welding with filler metal is used to join titanium sheets with a thickness of 0.8...6 mm.

Robotic or half-machined welding using the WIG process with filler metal is used to join 3...10 mm thick sheets with machined joints. Joining of sheets up to 6 mm thickness is carried out in one pass, and for greater thicknesses in 2...4 passes.

As filler materials for WIG welding of titanium and its alloys, rods with a chemical composition like that of the base metal are used.

According to ASTM, there are 31 classes of titanium with different plasticity, corrosion resistance and weldability. Therefore, special attention should be paid to the choice of filler material if it is to be used.

Before welding, both the wolfram electrode and the filler material must be cleaned to remove oxides, dust, moisture, and grease from their surfaces. This can be done with acetone or methyl ethyl ketone.

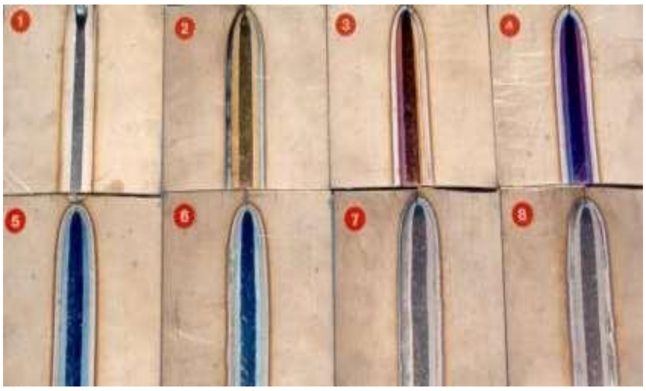

Figure 1. WIG welds in titanium sheet made successively by progressive contamination of shielding gas with air

Also, to prevent contamination of the weld joint, the end of the welding rod is cut off before welding.

Table 1. *Correlation between current intensity and wolfram electrode diameter*

Welding current	Diameter of Wolfram Electrode
< 125 A	≤ 1,6 mm
125 – 200 A	1,6...2,4 mm
> 200 A	2,4 mm; 3,2 mm

A particular case is the welding of pipes and tubes made from titanium or other reactive metals such as stainless steel and zirconium.

To prevent corrosion and blockage, pipes must be joined by good quality welds, which is not easy to achieve with conventional devices.

It is often not cost-effective to fill whole pipes with inert gas before welding and to maintain the gas supply both during and after the process. Also, in many of today's industries the welding area must be purged of oxygen down to 100 ppm (mg/l) or even less in the case of the food industry.

To overcome these challenges, Huntingdon Fusion Techniques (HFT) has introduced PurgElite, a range of affordable, inflatable tube and pipe purging systems ("purge dams") designed to drastically reduce the purge area, thereby reducing inert gas costs and welding time.

Each purge system features an IntaCal purge gas supply and a RootGlo positioning indicator light that allows the operator to ensure the system is accurately positioned, centrally within the tube or pipe.

HFT's innovative PurgeGate valve is available as an accessory and is suitable for all types of inflatable purge systems. The PurgeGate is a one-way valve designed to regulate gas flow and pressure during purging to prevent overfilling and bursting of purge dams.

Quick connect/disconnect fittings and o-rings to seal against gas leaks, fitted with an anti-release ring, are fitted to all systems to prevent accidental separation of component parts within the welded pipes.

Temperature resistant caps up to 300ºC are available as accessories to protect the inflatable 'booms'.

Interpretation of the colouring of a WIG weld in titanium

The following figure shows eight welds made in pure titanium by the WIG process, each with a different colour, and *Table 2* shows how to interpret the colour of each of these welds. It should be noted that the welds were made successively by progressively contaminating the shielding gas with air [8-13].

Table 2. *Colour interpretation of a WIG weld in titanium*

Nr. crt.	Colour	Interpretation
1	silver	Adequate, satisfactory protection
2	straw-yellow	Slight but acceptable contamination
3	open	Slight but acceptable contamination
4	dark straw-yellow	More pronounced contamination, but can be
5	dark blue	acceptable depending on application
6	light blue	Severe contamination unlikely to
7	blue grey	be accepted
8	grey	Very severe contamination, not acceptable

Some of the causes that lead to the colour change of a WIG weld in titanium are the following: - Insufficient gas protection at the root of the weld; - use of a filler material that does not contain titanium; - use of a gas nozzle of too small a size; - not using a weld shield.

3.2. MIG titanium welding

The MIG process for titanium is used to weld titanium and titanium alloy sheets with a thickness of 3...20 mm.

Helium (80%) mixed with argon (20%) is used as a shielding gas to increase the arc voltage and productivity of the process.

Helium has a higher ionisation potential than argon (24.5 V compared to 15.7 V) and therefore its introduction as a shielding gas lead to an increase in the calorific value of the arc and therefore to increased melting of the filler metal and base material.

The quality of the joint depends on the transfer of molten metal through the arc gap. Higher quality joints can be obtained by performing a very small droplet transfer of the type "spray droplets. For this reason, welding with thin wires (1.2...2 mm diameter) at high welding currents (160...220 A) is recommended.

MIG welding is carried out in direct current, both with direct and reverse polarity.

Welding of 8...10 mm thick sheets can be carried out in a single pass. Sheets thicker than 10 mm should be welded in several layers. For butt joining of 3...6 mm thick sheets it is recommended to use a V-shaped joint.

Table 3. *MIG welding parameters for different titanium thicknesses*

Thicknesses [mm]	I [A]	U [V]	Vs [m/h]	Gas flow (burner) [l/min]
3	200-220	20-25	22	35-40
6	300-330	22-27	20	35-40
16	400-420	25-30	25	40-45

3.3. Joining of titanium alloys by Friction Stir Welding technology

Although most common titanium alloys are generally weldable by conventional methods, problems can occur with distortion of the workpiece and poor weld quality. In addition, some of the more advanced titanium alloys (such as Ti-6246 and Ti-17) can be difficult to weld using fusion processes. The development of FSW offers the possibility of a new, cost-effective method of welding in high quality, low-deformation sheet and plate.

The first studies on FSW in Ti were carried out as early as 1995 as part of TWI's in-house research programme.

These initial welds were carried out in pure commercial titanium (grade 2) and demonstrated the potential of applying FSW to Ti alloys. A section through one of these initial samples is shown in the following figure.

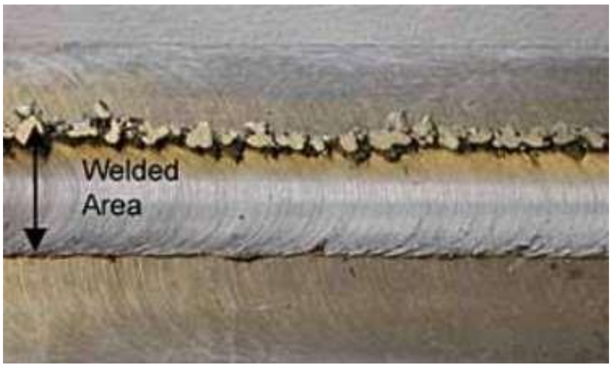

Figure 2. Section of an FSW weld in titanium produced at TWI in 1995

The darker areas in this section show where the material was heated above the β-transition line (approximately 900°C in this material). The lighter coloured areas of the weld were found to be untransformed but with significantly lower grain size.

Examples of FSW welding of Ti-6Al-4V alloy at TWI

Most of the work during the project sponsored by TWI Group on FSW of Ti alloys was carried out on 6.35 mm (¼ inch) thick Ti-6Al-4V plates. After identifying a suitable tooling material, an extensive program of weld testing was conducted to develop effective tooling designs and optimal process parameters for the 6.35 mm thick Ti-6Al-4V FSW plate. This ultimately led to the production of complete, high-quality FSW welds in Ti-6Al-4V, as shown in *Figures 3 and 4[9,10,11]*.

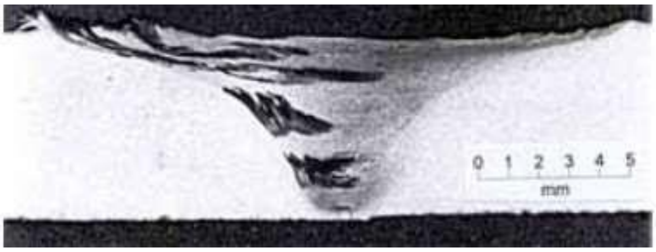

Figure 3. A quality FSW joint in 6.35 mm thick Ti-6Al-4V (photo taken from IWI)[11]

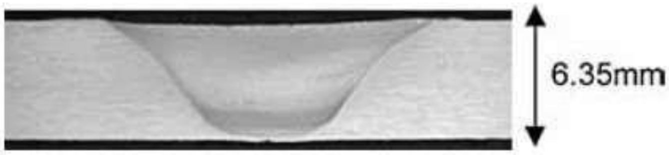

Figure 4. Cross-section of a 6.35 mm thick Ti-6Al-4V titanium FSW weld (photo taken from TWI).

3.4 Laser beam welding of titanium alloys
The industrial use of lasers for materials processing is increasing. Much of this growth is in conventional and thin materials.

However, high-power lasers, which could penetrate deeper, have paved the way for the use of lasers for welding unconventional materials and thicker plates. One such use is welding titanium alloys.

Titanium alloys are notable for being difficult to weld by conventional processes, and when electron beam welded there is the inconvenience of using a vacuum system. The high energy density and low amount of heat introduced into the base metal are characteristics of laser beam welding.

However, the rapid solidification and quenching associated with these characteristics affect the microstructure and properties of the weld, while atmospheric welding and specimen preparation influence the chemical composition of the fusion zone and its mechanical properties.

A case study on laser beam welding of titanium alloys will be presented below, highlighting the variation of mechanical properties of some welds made in Ti-6Al-4V as a function of plate thickness and the influence of the weld preparation mode of pure commercial titanium specimens on their hardness.

The titanium alloys that were used in this study are Ti-6Al-4V and pure industrial titanium, also known as ASTM B265-58T, mark 5 and B265-58T, mark 2 respectively. The titanium plates were 12.5 mm (0.5 in.) thick, and butt welded using unmachined joints [10-11].

The preparation for welding of the plate surface was the same for all plates except those referred to as "uncured" plates and/or welds. Preparation consisted of wiping the surfaces with acetone to remove dirt and grease, followed by immersion in 3% hydrofluoric-nitric acid pickling solution. This was done to remove contaminants in the form of titanium oxide and hydrocarbons embedded in the surface.

The pickling time was about 15 minutes, after which the plates were rinsed with distilled water and alcohol and then dried in nitrogen gas. This was done five minutes before welding to minimize the amount of oxide deposited on the welded surfaces.

A continuous wave (CW) CO2 laser with a power of 15 kW was used for welding.

Welds were made using an output power of 13 kW, with a welding speed of 11 mm/s (25 ipm).

Plasma suppression was provided by a tangential flow of helium, which was accompanied at the bottom and top by a gaseous shield also based on helium.

Weld alignment was achieved using a helium-neon (He-Ne) laser, coincident with the CO2 laser.

3.5. Electron beam welding joining of titanium alloys

Electron Beam Welding (EBM) is a process that uses a high-speed electron beam to join two metals. Electron beams are more precise than laser beams, generate more heat and allow the metal density to remain constant in the joint. The welded seam looks like a string of beads, but its internal structure is homogeneous.

Electron beam welding allows the joining of general and stainless steels in a delivered, annealed, or hardened condition. This process uses an electron beam to create a low-temperature arc between the parts to be joined. This process does not require the use of special joining fixtures or a large amount of heat and pressure to form high quality welds with a small number of contaminants, making it an ideal process for welding plates up to 76 mm thick and up to 1081x1551 mm in size.

A major aerospace company recently dropped an electron beam weld from a height of 14630.4 mm (48 ft) as part of an internal quality test, with the result that the joint was completely unaffected by the impact.

Electron beam welding is a natural choice when it comes to joining materials susceptible to oxidation, such as titanium, because the welding process must take place in a vacuum.

An electron beam can provide penetrations in titanium of up to 1.5" (40 mm), which is far beyond what any other process can provide.

Electron beam welding requires computer control of both the electron beam, the welding environment, and the positioning of the parts to be welded, resulting in high reliability and easy reproducibility.

Titanium parts can generally be welded without prior machining, as long as they are properly cleaned, and the electron beam welding process can be very cost-effective due to automation.

Weld preparation and decontamination

Before welding titanium, the joining areas must be thoroughly cleaned of all oxides and any hydrocarbon contaminants to ensure superior weld quality. This can be done mechanically, by sanding, grinding, scraping or, most commonly, using stainless steel wire brushes to remove oxides[16-19].

There are also chemical cleaning methods, such as immersion in caustic solutions and water, which can be effective. The chosen cleaning method is largely determined by the configuration of the part and the position(s) of the weld(s). Residues in the form of hydrocarbons on titanium are removed using acetone or alcohol-based solvents. Chlorinated solvents can form toxic gases when heated and should not be used around the weld area.

It is preferable that freshly cleaned titanium parts are welded immediately. If this is not possible, cleaned parts should be stored in airtight plastic bags that are filled with a neutral gas, such as argon or nitrogen.

Rules for preparing parts for welding:

- Do not use shop rags that may be contaminated with oil residue to clean parts. Use a clean cloth such as a cheese cloth or paper towels when you want to clean titanium surfaces with solvents.
- If residue needs to be removed from a part, use a bottled gas such as nitrogen or argon. Compressed shop air contains moisture and oil residue that can contaminate the weld area.
- First clean parts and joints using solvents, then clean them with a stainless-steel wire brush. Wire brushing before solvent cleaning usually leads to the embedding of hydrocarbons and other contaminants in the part, making solvents much less effective.

- Always use new or freshly cleaned stainless steel brushes to clean joint surfaces. Older, dirty brushes may contain oils and other contaminants. Brushes used to clean titanium should not be used with other materials, as metal shavings can be carried on the brush.
- Be sure to clean stainless steel wire brushes and etched metal surfaces thoroughly. Residual contaminants and by-products from the etching process can change the chemical composition of the weld pool.
- Frequently clean all wire brushes and scraping/spinning/cutting tools.

An example of a circular weld in a Ti-6Al-4V plate is shown in the next figure -13,14,15,16].

Figure 5. *Circular weld -Ti-6Al-4V*

4. Conclusion

As a conclusion, although titanium is a difficult material to weld, there are various methods of joining it, even other than those presented in this paper. The quality of a titanium joint is ultimately dependent on a lot of factors, from the properties of the material being welded to the skill of the welding operator or the welding parameters set, but if certain basic rules and principles are followed, obtaining a quality joint is not difficult.

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