

- Guide to best practice -

**WELDING TITANIUM**  
A DESIGNERS AND USERS HANDBOOK



WORLD CENTRE FOR  
MATERIALS JOINING  
TECHNOLOGY

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# TITANIUM INFORMATION GROUP

The TITANIUM INFORMATION GROUP, (TIG) is an association of European suppliers, design engineers, and fabricators of titanium formed with the intention of promoting the use of titanium.

The aim of the Group is to influence the initial selection of materials so that titanium is given the consideration merited by its unique combination of physical and mechanical properties, outstanding resistance to corrosion and cost effectiveness in a wide range of demanding applications.

Regular publications and literature available from the Group present detailed and up-to-date technical and commercial information to materials engineers, plant and equipment designers and buyers, and provide the answers to everyday questions about cost, availability, fabrication and use of titanium and its alloys.

Members of the Group are available to give presentations about titanium on either general or specific topics to companies or at seminars. A list of member companies of TIG appears on pages 32 and 33. Copies of the TIG video, 'Titanium Today' and the data diskette 'Titanium and Its Alloys' are available for use in educational and training establishments to provide an introduction to the metal its applications and properties.

Further information on TIG publications can be found on the web: [www.titaniuminfogroup.co.uk](http://www.titaniuminfogroup.co.uk)

## TWI

TWI is based at Abington, near Cambridge, UK and is one of Europe's largest independent contract research and technology organisations. Over 400 staff, with a unique blend of technical backgrounds, international experience and language skills, work with industry world-wide to apply joining technology effectively. Some 2500 member companies in over 50 countries benefit from TWI services.

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Surfacing - arc cladding, friction, high velocity oxyfuel, laser, arc spraying.

Cutting - flame, plasma, water jet, laser.

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Data available in literature available from TWI, TIMET and other members of TIG and TWI is incorporated in this publication.

May 1999



# 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. There is a common question which links all of these applications, and that is how best to join titanium parts together, or to other materials to produce the final component or structure. The variety of titanium alloys, and the vastly greater number of engineering metals and materials requires that there should be a versatile selection of joining processes for titanium if the metal is to be capable of use in the widest range of applications. Although mechanical fastening, adhesives, and other techniques have their place, welding continues to be the most important process for joining titanium. Welding of titanium by various processes is widely practised, and service performance of welds is proven with an extensive and continuously extending record of achievements. Newer methods adaptable for titanium are further advancing the science, technology and economics of welding. Application of this technology to the design, manufacture and application of titanium is as relevant to first time users as to committed customers. For many applications, choosing the welding process is as important a step in design as the specification of the alloy.

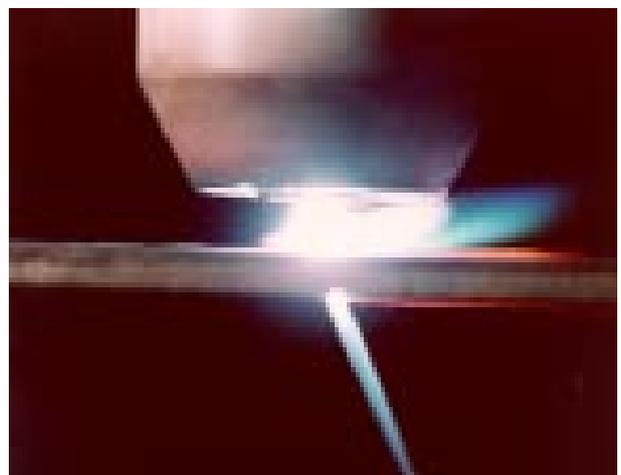
This handbook, the sixth in a series, is produced jointly by the Titanium Information Group and TWI World Centre for Materials Joining Technology. The aim of this edition remains as with its predecessors, to bring together key elements of widely dispersed data into a single source book. Use of this handbook will enable those responsible to select welding processes that will be appropriate to the titanium alloy, the component, and the application. In this way the most demanding goals for reliability, maintainability and safety can be achieved, together with the lowest overall cost for components and systems of the highest performance and integrity.

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*Titanium alloy (grade 5) fabricated structure for high specification military application*



*Keyhole plasma welding*

## WHY USE TITANIUM

*Light, strong titanium should be considered for applications wherever weight or space are factors or corrosion/erosion is a problem.*

In all fields of engineering, designers, fabricators and end users are ready to consider titanium for an ever widening range of applications. The metal and its alloys are no longer seen as 'exotic'. Outdated and misguided notions about cost, availability, and fabrication are less likely than ever to prejudice engineers who can see for themselves all the excellent benefits which titanium offers. This brochure has been compiled to show how the metal's reputation for being difficult to weld, is both misleading and inappropriate. Titanium alloys joined by any one of a wide range of welding processes are routinely at work in applications as widely differing as aero engines, offshore platform pipework, implants for the human body and ultra lightweight roofing. Practical and competitive welding processes ensure there are today few other materials that can approach, economically or technically, the performance provided by titanium.

Titanium is as strong as steel, yet 45% lighter. Titanium alloys will work continuously at temperatures up to 600°C, resisting creep and oxidation, and down to liquid nitrogen temperatures without loss of toughness. Titanium will survive indefinitely without corrosion in seawater, and most chloride environments. The metallurgical characteristics which give titanium its favourable properties can be reproduced, by selection of an appropriate practice, in welded joints for most titanium alloys. The oxide film, which is the basis of the metal's corrosion resistance forms equally over welds and heat affected zones as over parent metal, and other than in a few very harsh environments, weldments perform identically to parent metal in corrosion resistant service.

The wide range of available titanium alloys enables designers to select materials and forms closely tailored to the needs of the application. The versatility of two basic compositions is such however that they continue to satisfy the majority of applications, and this level of common use remains a major factor in the cost effective production, procurement and application of titanium. The two compositions are commercially pure titanium, (ASTM Grade 2), selected for basic corrosion resistance with strength in the range 350 - 450MPa, and high strength titanium alloy Ti-6Al-4V, (900 - 1100MPa). Welding consumables are readily available for these grades. Although there are other weldable alloys, consumables for these may need to be obtained from specialist sources. The full range of titanium alloys reaches from high ductility commercially pure titanium used where extreme formability is essential, in

applications such as plate heat exchangers and architectural cladding and roofing, to fully heat treatable alloys with strength above 1500MPa. Corrosion resistant alloys are capable of withstanding attack in the most aggressive sour oil and gas environments or geothermal brines at temperatures above 250°C. High strength oxidation and creep resistant alloys see service in aero engines at temperatures up to 600°C. Suitable welding processes are essential for the application and performance of titanium to be optimised in most of these uses.

Improving the understanding of welding titanium and the preservation of its properties after joining are design steps towards increased flexibility in materials selection and use, resulting in improved quality and performance of products and processes. In this way, the technical superiority of titanium will be confirmed for even more engineering applications than at present, to the mutual benefit of the titanium industry and its customers.

**What is the cost?** This question frequently comes first. The price per kilo of titanium is no guide to the cost of a properly designed component, or piece of equipment. First cost is in any event only one part of the full cost equation. Maintenance, downtime and replacement costs which may be a very significant element in plant designed for long and reliable service life are another. In this area, welding plays a significant role, ensuring that the performance of a titanium fabrication matches that of the metal overall. Additional costs of energy associated with operating unnecessarily heavy or thermally inefficient equipment may be a third penalty on life cycle costs. Titanium is frequently specified for its ability to cut costs through reliable and efficient performance. Titanium welded tube is for example installed in steam turbine condensers and welded pipe in nuclear power plant service water applications with 40 year performance guarantees against corrosion failure. One manufacturer offers a 100 year warranty on its metal supplied for architectural applications.

It is not possible in this guide to give an absolute cost or an accurate comparison of cost for the different welding processes described. The equipment capabilities and cost structures of equally competent welding contractors frequently results in a range of prices being offered for the same basic job. Some processes are, however, intrinsically more expensive than others. Always seek advice from an appropriate welding specialist or contractor before attempting to develop a budget or notional cost for a welding project.

## PROPERTIES OF TITANIUM AND ITS ALLOYS

A convenient and widely used system for specific identification of the various grades of commercially pure titanium and titanium alloys used for engineering and corrosion resisting applications is provided by ASTM which cover all the forms supplied in titanium and its alloys:-

- B 265 - Strip Sheet and Plate
- B 337 - Seamless and Welded Pipe
- B 338 - Seamless and Welded Tube
- B 348 - Bars and Billets
- B 363 - Seamless and Welded Fittings
- B 367 - Castings
- B 381 - Forgings
- B 861 - Seamless Pipe (to replace B337)
- B 862 - Welded Pipe
- B 863 -Wire
- F 67 - Unalloyed Titanium for Surgical Applications
- F 136 - Ti-6Al-4V for Surgical Applications

Grades 1,2,3,4 are commercially pure (alpha) titanium, used primarily for corrosion resistance. Strength and hardness increase, and ductility reduces with grade number. Grade 2 is the most widely used specification in all product forms. Grade 1 is specified when superior formability is required. Grades 3 and 4 are used where higher levels of strength are necessary.

Grades 7, 11, 16, 17, also alpha alloys, contain palladium (Pd) and provide superior corrosion resistance in particular to reducing acid chlorides. Grades 26 and 27 are similarly also alpha alloys, and contain .1% ruthenium (Ru) to provide enhanced corrosion resistance in reducing environments. The mechanical properties of grades 7, 16 and 26 are identical to those of Grade 2. The mechanical properties of grades 11, 17 and 27 are similarly identical to those of Grade 1.

Grade 12 (alpha) also offers superior corrosion resistance to commercially pure titanium, but is stronger and retains useful levels of strength up to 300°C.

Grade 5 is the 'workhorse' alpha-beta alloy of the titanium range. It is also specified with reduced oxygen content (ELI) for enhanced toughness (Grade 23), and with addition of .05% palladium for added corrosion resistance, (Grade 24) and with palladium and nickel (Grade 25). Current interest in this alloy for marine applications is focused upon Grade 23 with .05% palladium or Grade 29 with .1% ruthenium. Restrictions on fabricability may limit availability in certain products.

Grade 9, (near alpha) has good fabricability and medium levels of strength. Grade 18 (Grade 9 + .05% Pd) and Grade 28, (Grade 9 + .1% Ru) offer enhanced corrosion resistance.

Beta-C and TIMETAL®21S are high strength highly corrosion resistant beta alloys in the ASTM range. They are respectively Grade 19, and Grade 21. (The counterpart of Grade 19 with .05% Pd is Grade 20). Grade 32 (Navy alloy) has good weldability together with high toughness and resistance to stress corrosion cracking in marine environments. Grade 21, (TIMETAL®21S) and Grade 32, (TIMETAL®5111) are also available with the addition of .05% palladium.

Weldments in ASTM grade 2 are normally characterised by increased strength, accompanied by a reduction of ductility and fracture toughness. Any strengthening induced by cold work will be lost in the joint region. Weldments in Ti-6Al-4V typically exhibit near-matching strengths to the base metal, but have lower ductility. The toughness of the weld zone is superior to alpha-beta processed material, showing similar values to alpha-beta processed parent alloys. Some examples of actual weld properties are given for processes described in the text, but you are strongly advised to consult with your welding specialist in cases where weld performance is critical in your design.

*Typical mechanical properties and physical properties of titanium and titanium alloys (100MPa = approx. 15 ksi)*

Designation	Commerically Pure Titanium	Medium Strength Alloys	High Strength Alloys	Highest Strength
Alloy Type	Alpha	Alpha-Beta	Alpha-Beta	Beta
0.2% Proof Stress MPa	345 - 480	480 - 550	725 - 1000	1100 - 1400
Tensile Strength MPa	480 - 620	600 - 650	830 - 1100	1200 - 1500
Elongation %	20 - 25	15 - 20	8 - 15	6 - 12
Tensile Modulus GPa	103	104	110 - 120	69 - 110
Torosion Modulus GPa	45	43	40 - 48	38 - 45
Hardness HV	160 - 220	200 - 280	300 - 400	360 - 450
Density kg/l	4.51	4.48 - 4.51	4.43 - 4.60	4.81 - 4.93
Thermal Expansion 10 <sup>-6</sup> /°C	8.9	8.3	8.9	7.2 - 9.5
Conductivity W/mK	22	8.0	6.7	6.3 - 7.6
Specific Heat J/kg/°C	525	544	565	490 - 524

# JOINING TITANIUM AND ITS ALLOYS

## WELDABILITY

Most titanium alloys can be fusion welded and all alloys can be joined by solid state processes (see table). Indeed, Welds in titanium are substantially immune to many of the weld cracking problems that cause trouble with ferrous alloy fabrications. Despite this and other beneficial characteristics, some engineers still believe that titanium is difficult to weld, possibly due to its particular requirements with regard to gas shielding, or because it has normally been handled only by specialist fabricators. Titanium is actually easy to weld by most processes, as are most of its more common alloys. Embrittlement through contamination with air and carbonaceous materials poses the biggest threat to successful fusion welding titanium, so the area to be welded must be clean and protected by inert gas while hot. The means to protect the weldment with inert gas are commercially available and easy to implement.

Welding consumables are readily available for the common titanium grades and specifications for welding wire are provided in AWS Specification A5.16. Permissible filler metal, normally identical to the parent metal, may be specified as in ASTM B 862.

The weldability of titanium alloys is usually assessed on the basis of the toughness and ductility of the weld metal. Commercially pure grades are considered very easy to fabricate and are ordinarily used in the as-welded condition. Titanium alloys show reduced weld metal ductility and toughness. The table below highlights the weldability of the common ASTM titanium grades and other alloys. Technical consultation should be sought prior to designing or fabricating any of the titanium alloys, if there is any likelihood of problems arising from unfamiliarity with the materials concerned.

*Weldability of the common ASTM grades*

ASTM Grades	Weldability	Comments
1,2,3,4,7,11,12,13 14,15,16,17,26,27 9,18,28 5,23,24,29 21 6,6ELI	Excellent Excellent Fair-good Excellent Good-excellent	Commercially pure and low alloy grades with minor additions of Pd, Ru, Mo etc Ti-3A1-2.5V grades Ti-6A1-4V grades Beta alloy Ti-5A1-2.5Sn

*Weldability of selected non-ASTM Ti alloys*

Alloy	Weldability	Comments
Ti-6A1-2Sn-4Zr-2Mo	Fair-good	Common aerospace alpha & beta grade
Ti-6A1-2Sn-4Zr-6Mo	Limited	Aerospace alpha & beta grade
Beta III	Excellent	Beta alloy
Ti-15V-3A1-3Sn-3Cr	Excellent	Beta alloy

*Welding of a titanium fuel tank for the record breaking Breitling Orbiter III balloon (Bunting Titanium)*



*Fabrication of a large titanium pressure vessel (Bunting Titanium)*



# ARC WELDING PROCESSES

## TUNGSTEN INERT GAS (TIG) WELDING

Tungsten inert gas welding is also known as tungsten arc welding and gas-tungsten arc welding (GTAW) and is currently the most commonly applied joining process for titanium and its alloys. Titanium is one of the easiest of metals to weld by the TIG process; the weld pool is fluid and its combination of low density and high surface tension enables good control of the weld surface profile and penetration, even when unsupported. An arc between the tungsten alloy electrode and workpiece obtains fusion of the joint region, while an inert gas (the torch gas) sustains the arc and protects the tungsten electrode and molten metal from atmospheric contamination. The inert gas is typically argon, but a mixture of helium and argon can be used to increase penetration or speed. Welds can be made autogenously (i.e. without filler addition) or with addition of a consumable wire into the arc. The TIG process is fully capable of operating in all welding positions and is the only process that is routinely used for orbital welding. Specialist orbital welding equipment is commercially available for a wide range of component diameters and often has the added advantage of incorporating the inert gas trailing shield necessary for titanium fabrication.

### TIG (GTAW)

#### Advantages

- Manual or mechanised process
- All position capability
- Capable of producing high quality welds
- Significant industrial experience
- No weld spatter

#### Disadvantages

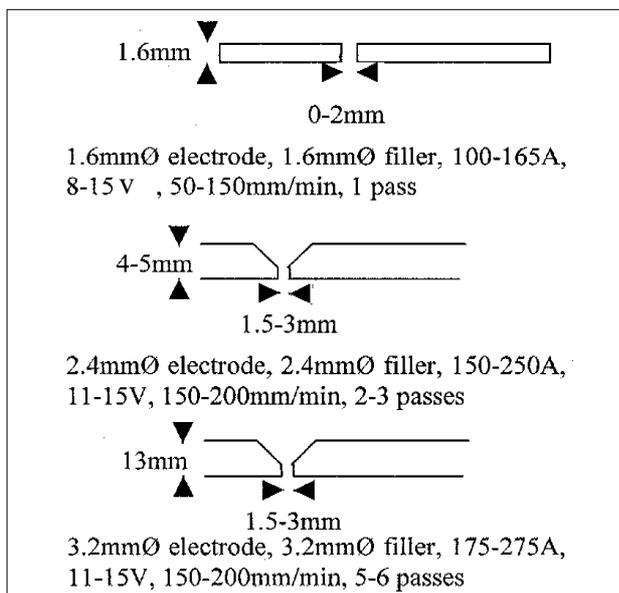
- Low productivity
- Tungsten inclusions if electrode touches weld pool

Higher productivity variants of the TIG process have been applied to titanium. Hot wire TIG enables a greater fill rate to be achieved, improving productivity on multipass welds required for heavier section thicknesses. Activated TIG (A-TIG) achieves deeper penetration through the use of a special flux sprayed onto the joint surfaces prior to welding. The latter process has had particular success for welding stainless steels, but its potential application to titanium joints has yet to be fully exploited.

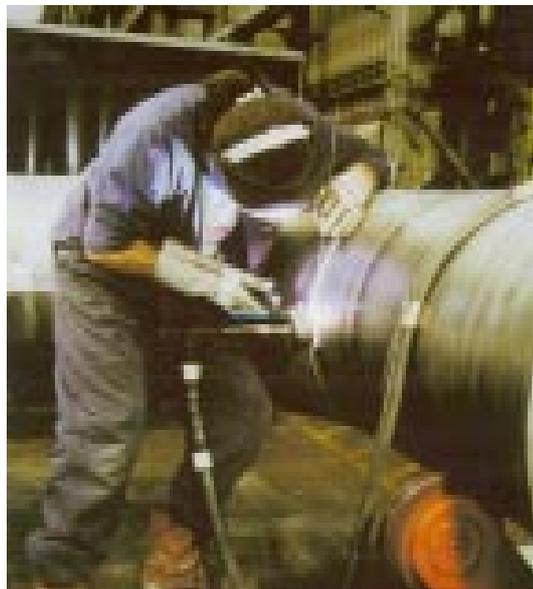
Typical tensile properties of TIG weldments

Alloy	Tensile Strength (MPa)		Proof Stress (MPa)		Elongation (%)	
	Parent	Weld	Parent	Weld	Parent	Weld
Grade 2	460	510	325	380	26	18
Ti-6Al-4V	1000	1020	900	880	14	8
Ti-3Al-2.5V	705	745	670	625	15	12

Example welding parameters (1mm = .04inch)



Manual TIG welding of a titanium vessel (Bunting Titanium)

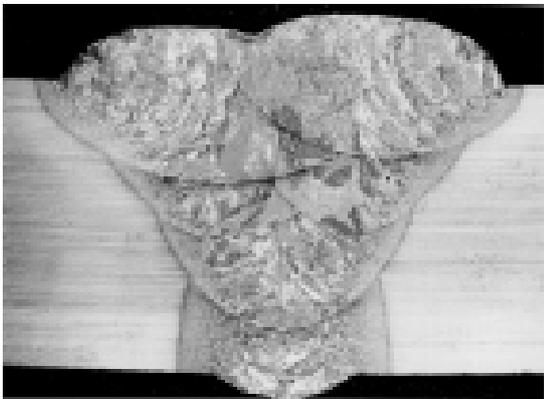


## METAL INERT GAS (MIG) WELDING

The MIG process has not been applied as widely to titanium as it has been to ferrous and other non-ferrous alloys. Many of the historical reasons why MIG welding has not been favoured for titanium no longer apply. High currents are required for stable metal transfer and the poor surfaces originally produced on titanium wire caused rapid contact tip wear. More recently, the combination of modern inverter power sources with pulsed currents gives more stable metal transfer, whilst the improved surface finish of titanium wire has reduced contact tip wear such that the problem is barely apparent in development work.

In MIG welding, an arc is generated between a continuously fed consumable electrode (a wire of matching composition to the base material) and the workpiece. Spray transfer occurs above a critical welding current density and requires the use of direct current with the electrode positive. This method demands high currents and therefore high welding speeds, which in turn require long trailing shields, and effectively restricts the process to mechanised welding. Dip transfer, whereby the electrode comes into contact with the weld pool, can be used for semi-mechanised welding, typically for sheet material, but defects, caused by lack of fusion, can be a problem. Pulsed MIG appears to be the most satisfactory process, especially when used in

MIG weld in 20mm thick Ti-6Al-4V



Properties of a keyhole plasma arc weld in 14mm (.55") thick Ti-6Al-4V

Property	Base Metal	Weld Metal
Tensile Strength (MPa)	987	979
Proof Stress (MPa)	934	848
Elongation (%)	17	8
CTOD <sub>m</sub> (mm)	0.017	0.044
K <sub>max</sub> (MPa)	50.8	71.4

### MIG (GGAW)

#### Advantages

- Manual or mechanised process
- All position capability
- Better productivity than TIG welding

#### Disadvantages

- Weld Spatter

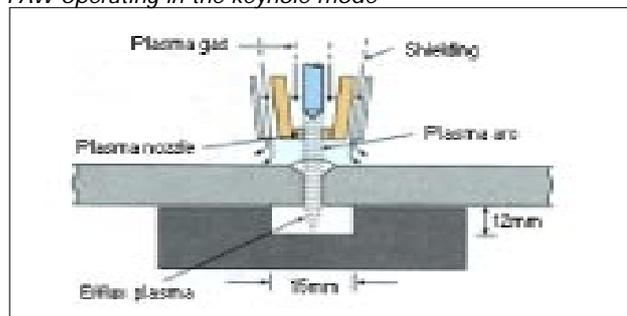
combination with argon-helium (Ar-He) shielding gas.

MIG welding offers greater productivity than TIG welding, especially for completing thicker section joints. As yet the process has been typically applied to joints for which exceptional weld quality is not critical, e.g. appliqué armour plate, but with development the process may be capable of satisfying higher quality welding requirements. A disadvantage of the process is that some degree of weld spatter appears to be unavoidable. Spatter can be reduced by employing Ar-He torch shielding gas mixtures: the addition of helium acting to stabilise the arc. Even so, in most instances spatter removal poses no problem.

Properties of a MIG weld in 6mm thick Ti-6Al-4V

Region	Tensile Strength (MPa)	Proof Stress (MPa)	Elongation (%)
Base Metal	987	934	17
Weld Metal	979	848	8

PAW operating in the keyhole mode



## PLASMA ARC (PAW) WELDING

Plasma arc welding retains the high quality associated with TIG welding whilst having significant penetration and speed advantages. Similar to TIG, heat is transferred by an arc generated between a tungsten electrode and the workpiece; but, in the PAW process the arc is constricted by a copper alloy orifice to form a highly collimated arc column (see figure). In addition to a surrounding shielding gas, a 'plasma gas' flows through the copper orifice and a portion of this is ionised producing the characteristic plasma jet. In the conduction-limited mode a weld pool similar to that produced during TIG welding is generated, whilst in the keyhole mode, the plasma jet fully penetrates the joint. Molten metal flows around the keyhole and solidifies behind the plasma jet as the torch traverses along the joint line. In many ways the keyhole plasma arc process is akin to a slower version of one of the power beam processes (electron beam and laser welding). A third process variation exists, referred to as microplasma arc welding. This is simply a low current variant (typically 0.1-15A) of the conduction-limited mode, suitable for producing small controlled weld beads. Welding is generally performed with continuous direct current with the electrode negative (DCEN), but a pulsed current can be used to broaden the tolerance window of welding parameters which produce acceptable welds.

Plasma arc welding offers significant productivity gains over both TIG and MIG, especially when operated in the keyhole mode. Although welds are only typically made in the 1G or 2G positions, single pass welds can be made in material up to 18mm thick. Furthermore, the keyhole PAW process appears to offer greater immunity to weld metal porosity than any other fusion welding process. Because introduction of filler into the arc can cause instabilities in the gas plasma, keyhole PAW is normally performed autogenously, thus a small amount of underfill is typical. Completing a second pass, adding filler with the same torch operated in the conduction-limited mode, or alternatively using TIG welding, can correct this. Pipe circumferential welding (e.g. pipe joints) is

*Keyhole PAW is used extensively in the fabrication of the Ti-6Al-4V VSEL lightweight field gun.*



## PAW

### Advantages

- Faster than TIG
- Single pass welds possible in material up to 18mm thick
- Greater immunity to weld metal porosity than any other fusion process

### Disadvantages

- Limited positional capability

certainly possible, but requires a controlled slope-down of the plasma gas flow rate and arc power to avoid any porosity defects at the stop position.

## FLUXED WELDING PROCESSES

The application of fluxed welding processes such as submerged arc, electroslag and flux cored arc welding have been investigated and reportedly used in the former Soviet Union for welding thick section titanium alloy. The main difficulty is the selection of an appropriate flux; oxides cannot be used these would contaminate the weld metal and, for similar reasons, fluxes should not be hygroscopic (i.e. adsorb moisture). Most of the fluxes have been rare earth and/or alkaline metal-based halogens and have been reported to produce contaminant-free welds. Some tests carried out in the UK on commercially pure titanium showed mechanical properties in conformance with ANSI standards. Work performed at the Paton Institute, Kiev has shown that joints can be produced in titanium alloys with performance comparable to those of TIG welds. In practice, however, the quality of welds made using fluxes is suspect, since the opportunities for contamination and slag inclusions are significant. Due to these intrinsic risks, fluxed welding processes cannot currently be recommended for joining titanium. Further research into these welding methods is needed but the improvements to be gained, over conventional arc welding, are considerable and could present major cost savings for thick section titanium alloy fabrication.

*MIG welding has found application for appliqué armour plate such as for the General Dynamics M1 Abrams tank.*



# POWER BEAM WELDING PROCESSES

## LASER WELDING

Laser welding is finding increasing application for titanium, for example in the production of welded tube and pipe. The process, which offers low distortion and good productivity, is potentially more flexible than TIG or electron beam for automated welding. Application is

### Laser Welding

#### Advantages

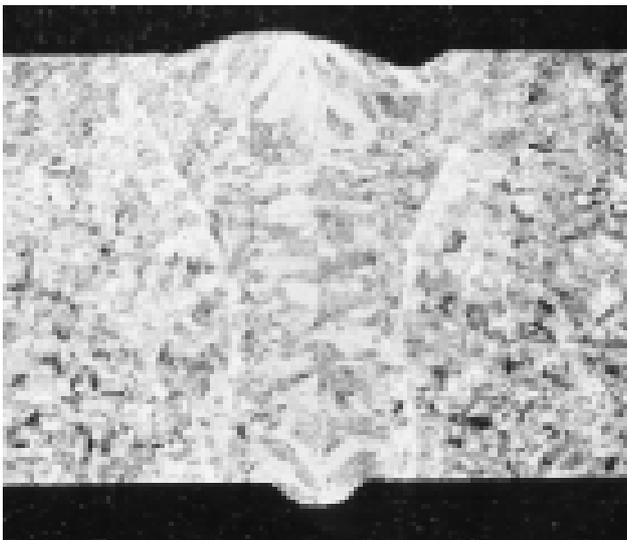
- Automated process
- High welding speed
- Fibre optic beam delivery with Nd-YAG

#### Disadvantages

- Expensive equipment
- Thickness limited with Nd-YAG
- Weld Spatter

not restricted by a requirement to evacuate the joint region. Furthermore, laser beams can be directed, enabling a large range of component configurations to be joined using different welding positions. CO<sub>2</sub> lasers offer the greatest power range, with single pass welds possible in 20mm thick titanium using 25kW systems. Nd-YAG laser welding offers superior flexibility due to the possibility of fibre optic beam delivery systems, but penetration is restricted by a lower power capability. Laser welds can suffer from weld spatter, which may pose a problem on the root surface, particularly if postweld access is restricted.

RPEB weld in 13mm thick Ti-6Al-4V



## ELECTRON BEAM WELDING

Electron beam (EB) welding has traditionally been the preferred process for making critical joints in titanium alloys. High quality welds can be produced with low distortion and with high reliability. Productivity can also be good, especially for thick sections which can be welded readily in a single pass. Conventional electron beam welding is performed in a vacuum of about 10<sup>-4</sup>

### Electron Beam Welding

#### Advantages

- Automated process
- Single pass welding of thick sections
- No filler or gas shield required
- Significant industrial experience

#### Disadvantages

- Expensive equipment
- Component size limited by vacuum chamber (not applicable for RPEB)

mbar, requiring a sealed chamber and pumping system. This adds to the capital cost of the equipment, especially for large components. A further drawback for large components is the extended time it takes to achieve a vacuum in the chamber, decreasing productivity. However, electron beam guns have been designed which can operate at lower vacuum or near atmospheric pressure. So called 'reduced pressure' electron beam (RPEB) welding shows great promise for decreasing costs and increasing productivity beyond that achievable using conventional EB welding. Simple seals can be used to isolate the joint region of a large component, which is evacuated to a pressure of around 10<sup>-1</sup>mbar (achievable using inexpensive mechanical vacuum pumps). An RPEB steel pipe J-laying system is currently under development at TWI. High quality welds have also been produced in titanium alloy pipe and plate.

Laser weld 10mm (.4") thick Gr 2 joined to Ti-6Al-4V



# RESISTANCE WELDING

## INTRODUCTION

Resistance welding of titanium is quite straightforward and is aided by the metal's high resistivity and low thermal conductivity. The associated processes rely on the heat generated by the resistance to electrical current flowing through the workpiece to fuse the metal with the joint. Shaped electrodes apply the current and pressure required to make a localised weld. As with other joining processes, cleanliness of the abutting joint faces is essential for a successful weld. Experience gained with stainless steels is relevant for resistance welding commercially pure titanium grades, since the resistivity and thermal conductivity of the two metals are similar. Titanium alloys, however, have quite different thermal and electrical characteristics and should not be welded using parameters established for stainless steel.

### Resistance Welding

#### Advantages

- Automated process
- Low distortion
- Spot welds do not require gas shielding

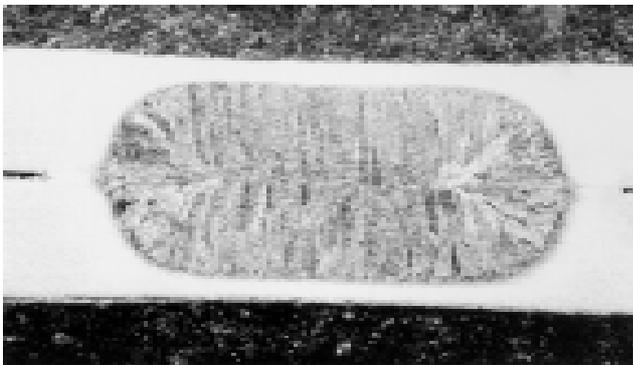
#### Disadvantages

- Poor fatigue strength
- Limited to sheet material

## SPOT WELDING

Spot welding is performed using copper alloy electrodes with a spherical face, a current of 5-10kA (increasing with sheet thickness) and an electrode force of several kiloNewtons. Inert gas shielding is not required for spot welding since the thermal cycle resulting from the brief electrical pulse is extremely rapid, minimising local oxidation.

A spot weld in ASTM grade 2 sheet



## SEAM WELDING

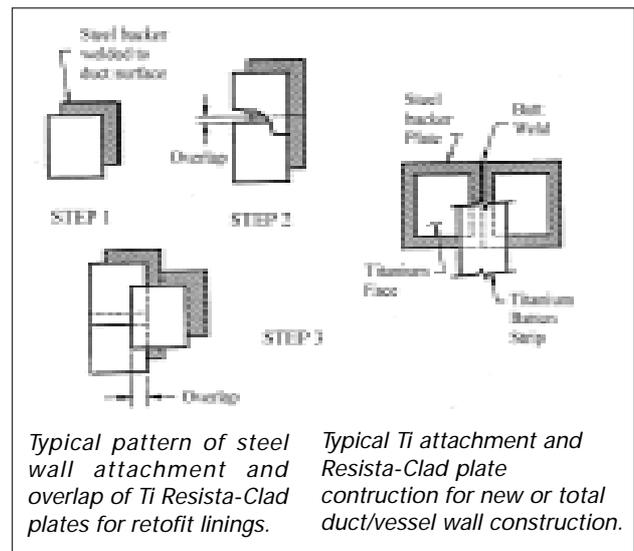
Continuous or intermittent seam welds are made using rotating disc electrodes, again with a spherical contact profile, and the repeated application of brief electrical pulses. During welding, the electrode is rotated, traversing the contact position along the joint line. Inert gas shielding or flood water cooling may be desirable for seam welds since the repeated thermal cycles can result in the accumulation of heat and subsequent oxidation.

## TITANIUM RESISTA-CLAD™ PLATE

This patented process is principally used to supply requirements for vessel cladding and flue gas desulphurisation (FGD) duct and flue linings. Electrical resistance heating is used to bond titanium to a less expensive steel backing, using an intermediate stainless steel mesh. The bond is a seam 12.7mm (0.5 inch) wide, having typical shear and peel strengths of 303MPa and 15kg/m respectively. The seams can be spaced to meet the application requirements of stresses imposed in service by gravity, vibration, thermal expansion and pressure cycling.

Pre-bonded sheets are supplied for installation with the titanium offset on two sides to permit overlap and fillet seal welding of adjoining sheets. For retrofit installations, the thicknesses of titanium and the backing steel would each be 1.6mm, (1/16 inch). For new build, the titanium sheet can be recessed on all sides to allow butt welding of the steel backer, followed by seal welding of a titanium batten strip. Here, the thickness of the titanium is 1.6mm, but the steel backer may be heavier up to 25.4mm (1 inch), or as required by the operating conditions of the vessel or structure.

Resista-Clad™ plate. Methods of application



# FRICION WELDING PROCESSES

## INTRODUCTION

There are approximately 20 variants of friction welding, most of which could be applied to titanium and its alloys. In practice only a few of these are used industrially to join titanium. An important feature of friction welding is its ability to join titanium to other materials, which, although often requiring an intermediate material, is virtually impossible to do by any process involving fusion. The advantages of friction welding include no need for shielding gases for most processes, very rapid completion rates, and good mechanical properties. Most welds result in flash formation, which typically must be removed. The main process variants are described below:

### Friction Welding - general comments

#### Advantages

- Rapid one shot processes
- Fully automated
- Can join dissimilar Ti alloys
- Potential to join Ti to some other materials

#### Disadvantages

- Equipment may be expensive
- Inspection can be difficult

## ROTARY FRICTION WELDING

There are two main variants of rotary friction welding; the continuous drive and inertia processes. In the continuous drive rotary friction welding process, a component in bar or tube form is rotated under pressure against a similar component, or one of larger dimensions,

### Rotary Friction Welding

#### Advantages

- Extensive industrial experience
- No shielding gas or filler

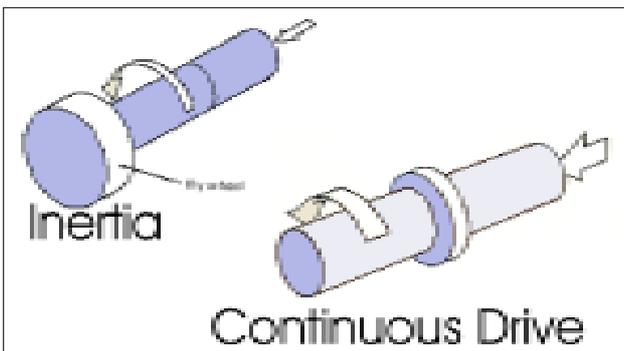
#### Disadvantages

- Rotational symmetry required

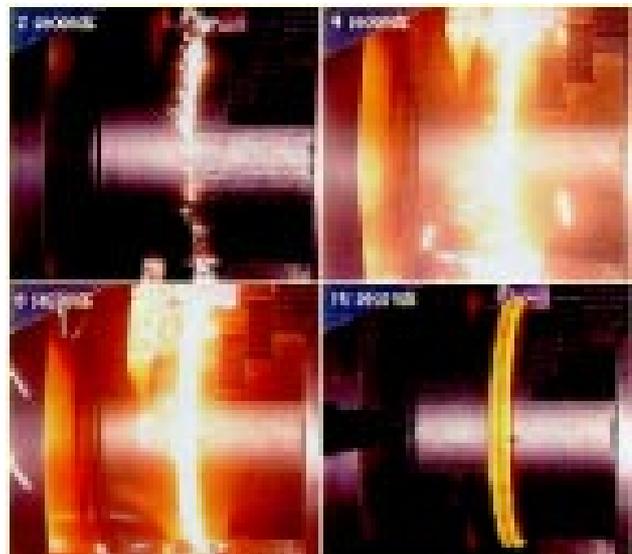
under an applied pressure. Frictional heat develops, causing the material close to the rubbing surfaces to soften and flow. After a certain displacement distance (called burn-off) has been reached, the rotation is stopped rapidly, and the contact force increased to provide a forging action to consolidate the joint. Any interfacial contamination is expelled with the flash that is extruded from the joint.

Inertia friction welding has one component attached to a flywheel, and spun to a predetermined rotation speed before being pushed against the other component under pressure. The braking action results in the generation of frictional heating, and the formation of a weld. Inertia friction welding delivers energy at a decreasing rate through the weld cycle, whereas continuous drive friction welding delivers energy at a constant rate. Inertia welding is more commonly used in the USA, and less so in Europe, where continuous drive welding is predominant.

Schematic diagrams of the two rotary friction welding variants



Rotary friction weld in 13mm thick Ti-6Al-4V pipe



Properties of a rotary friction weld in Ti-6Al-4V

Region	Tensile Strength (MPa)	Proof Stress (MPa)	Elongation (%)
Base Metal	949	834	15
Weld Zone	994	854	11

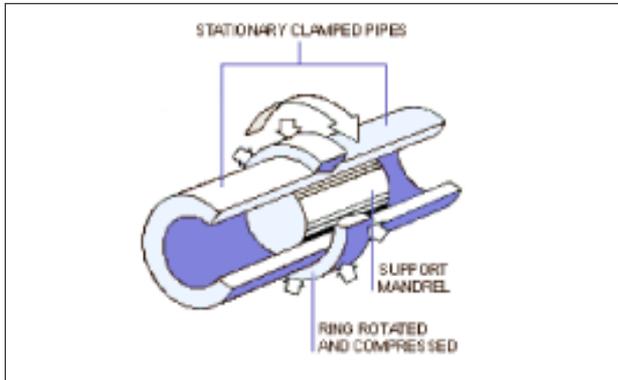
## FRICION STUD WELDING

Friction stud welding equipment is portable and can be used in-situ in remote and adverse environments. Like other friction welding processes the added advantages of friction stud welding are its rapidity at completing the joint and its ability to join to dissimilar metals. Current applications include stud attachment to architectural titanium panels.

## RADIAL FRICTION WELDING

One drawback of rotary friction welding is the necessity to rotate one of the components. With small parts this is not normally a problem, but for example with long lengths of pipe there are obvious potential difficulties. One solution to this is to use radial friction welding, in which the pipes are held stationary, and a V section ring of narrower angle than the edge preparation in the pipe is rotated between them using a continuous drive mechanism, and simultaneously compressed radially to force the ring into the joint. The equipment required for this process is more complex than that required for rotary friction welding, as it requires a radial compression unit, and also an internal mandrel to resist the high radial loads. One advantage of the internal mandrel is that the internal flash is eliminated, although there is generally a small reduction of internal diameter which may need to be removed.

Schematic diagram of radial friction welding process



Stolt Comex's radial friction welding pipe laying barge



### Radial Friction Welding

#### Advantages

- No shielding gas required
- Neither component is rotated during welding
- No bore flash

#### Disadvantages

- Expensive equipment
- Internal bore support required

Properties of radial friction weld in Ti-6Al-4V-0.1Ru

Region	Tensile Strength (MPa)	Proof Stress (MPa)	Elongation (%)
Base Metal	910	840	14
Ring (as-received)	885	795	11
Ring (as-welded)	1055	925	9
Cross-weld	900	820	9

## LINEAR FRICTION WELDING

This process variant was designed to eliminate the need for rotational symmetry in one or both of the parts being joined, and as a result the process can successfully join parts of differing section. As its name implies, linear friction welding uses a reciprocating linear motion to provide the friction. The frequency is typically 25 to 100Hz, with an amplitude of +/- 2mm.

The process will be used extensively in the aero-engine industry, in particular for joining compressor blades to disks, but has not been taken up by other industrial sectors for joining any metal. However, a close variant of the process, vibration welding, is used extensively in several industries for joining thermoplastics.

### Linear Friction Welding

#### Advantages

- Shielding gas not required
- Very good positional accuracy
- Rotational symmetry not required

#### Disadvantages

- Expensive equipment

## ORBITAL FRICTION WELDING

In this process, one component is moved against the other in an orbital motion. This removes the requirement for symmetry in both of the components.

## FRICTION STIR WELDING

This novel process has been well developed for aluminium alloys. Progress is being made for its application to titanium alloys, although it will be some time before it can be considered a competitive process. A number of advantages have already been demonstrated for aluminium that may also apply to titanium. Friction stir welding involves moving a small rotating tool between close butted components. Frictional heating causes the material to soften, and the forward motion of the tool forces material from the front of the tool to the back, where it consolidates to form a solid state weld. The process combines the flexibility of mechanised arc welding with the excellent characteristics of a friction weld. Progress has been swift in developing the technology for titanium and development welds have been completed successfully at TWI.

## THIRD BODY FRICTION WELDING

Third body friction welding is a useful technique for joining dissimilar materials which cannot normally be joined by conventional friction welding. In this process, one component is rotated and plunged into a hole in the second component, into which a third material has

been placed. This third material can be a metal which softens at a lower temperature than either of the two components being joined, or it can be a brazing alloy.

## FRICTION TAPER PLUG WELDING

In this process a tapered plug is rotated and plunged into a pre-machined hole. It was developed for weld repair of alloys that are difficult to fusion weld or are in a hazardous environment. By placing overlapping friction taper plugs into the material, linear features (such as cracks) can also be repaired. This is known as Friction Taper Stitch welding.

### Friction Stir Welding

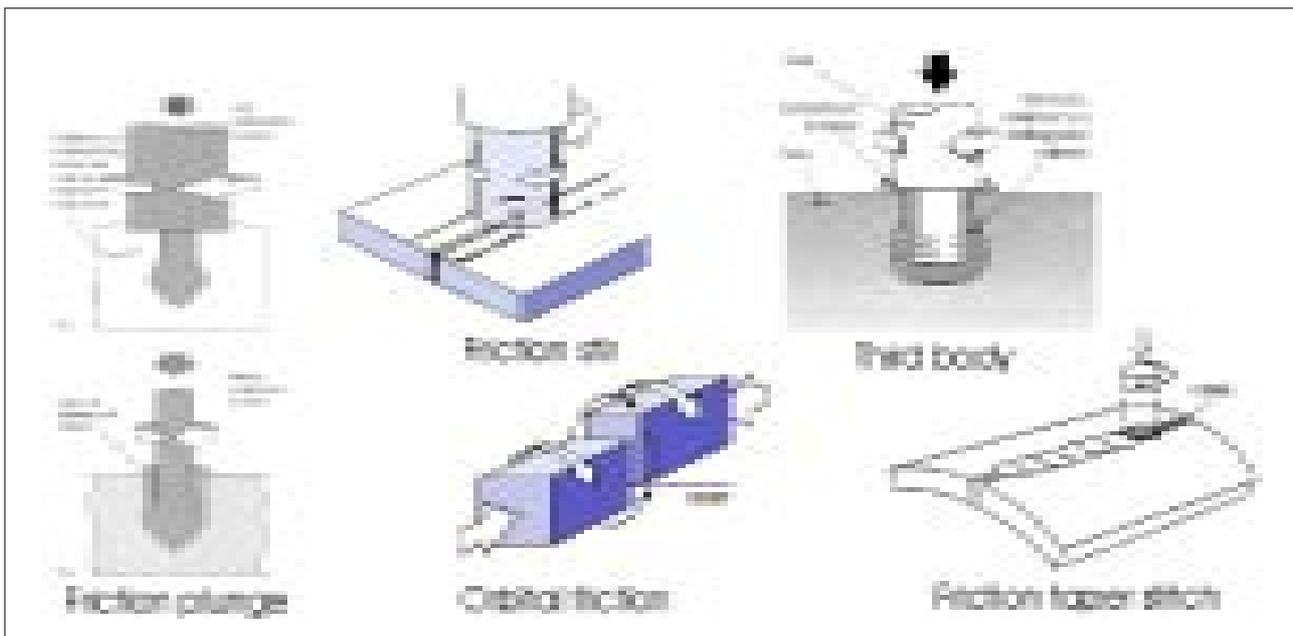
#### Advantages

- No filler
- Low distortion
- Fully mechanised
- Increasing industrial usage for non-ferrous alloys

#### Disadvantages

- Still under development for titanium
- Gas shield required

*Schematic diagrams of the above welding processes*



# DIFFUSION BONDING

## CONVENTIONAL DIFFUSION BONDING

Titanium is the easiest of all common engineering materials to join by diffusion bonding, due to its ability to dissolve its own oxide at bonding temperatures. Conventional diffusion bonding is a slow process, and requires careful control of temperature, and joint face alignment. The process also needs to be undertaken in a vacuum. Under ideal conditions a bond of very high quality can be made with no flash formation. However, the process is slow, and requires considerable precision, making it unattractive for field use, although it has been widely used in the aerospace industry, in particular in conjunction with superplastic forming. The process, including superplastic forming, is also used in the

successful development of titanium compact heat exchangers.

### Diffusion Bonding

#### Advantages

- Limited microstructural changes
- Can join dissimilar Ti alloys
- No filler required
- Can fabricate very complex shapes, especially using superplastic forming

#### Disadvantages

- Slow
- High vacuum required
- Expensive equipment

*Rolls Laval's diffusion bonded compact heat exchanger*



*Rolls Royce's SPFDB front fan blade for the Trent 800*



## ELECTRON BEAM DIFFUSION BONDING

This process is a variant of diffusion bonding in which only the interface region is heated, resulting in a considerable energy saving. The heating source is an electron beam which is swept over the area of the joint at such a speed that fusion of the titanium alloy is prevented. A force is applied across the joint. As the heated area is very limited, higher forces can be used

without the risk of plastic collapse of the components being welded, resulting in a significant reduction of welding time, typically by an order of magnitude. The process has been investigated for joining several titanium aluminide alloys to themselves and other titanium alloys, and for joining titanium alloys. Very good results have been reported from these trials, but to date the process has not been used commercially.

# FORGE WELDING PROCESSES

## FLASH BUTT WELDING

Flash welding is a forge welding process in which heat is generated by resistance when a large current is passed across the surfaces to be joined. During the initial flashing stage points of contact resistance heat, melt and blow out of the joint as the faces are progressively moved together at a predetermined rate. When a critical metal displacement has been reached the faces are forged together rapidly to consolidate the weld.

The process has been used for many years for the

### Flash Butt Welding

#### Advantages

- Very rapid weld time
- Single shot process

#### Disadvantages

- Flash removal required
- Inspection may be difficult

production of aeroengine stator rings, and with suitable equipment is capable of joining pipe and other extruded sections of any configuration. Properties close to those of the parent metal are obtained from substantially defect free joints.

## HOMOPOLAR WELDING

Homopolar welding is a new method currently under development in the USA, where it has been developed primarily for welding pipes. Kinetic energy stored in a flywheel is rapidly converted to a high direct current low voltage electrical pulse using a homopolar generator, and

*The explosive bonding process*



this high current pulse is passed across a closely butted weld joint, causing a resistance weld to be made. A high axial load is also applied, causing softened material to be expelled. Neither of the components has to be rotated, and no shielding gas is required. Trials have been undertaken on titanium, apparently successfully, but results have yet to be published.

## EXPLOSIVE BONDING

Explosive bonding should be considered for applications when a thin uniform lining of titanium is required on a base metal. The technique is regularly used for the production of high pressure tubeplates for tube and shell heat exchangers, reaction vessels, chlorine generators, and for lined plant and ductwork subject to negative pressure. In the process, thin titanium sheet is placed at a closely controlled distance on top of a backing plate. Explosive spread uniformly on top of the titanium is detonated from a single point, the explosion driving the titanium down across the air gap to impact on the backing metal. A jet of surface oxides is expressed from the apex of the collapse angle formed, and this removes any residual contamination from the mating surfaces, producing a metallurgical bond of wave-like form and guaranteed shear strength. The continuity of the bond can be confirmed ultrasonically. All low to medium strength titanium grades, (ASTM 1, 2, 7, 11, 12, 16, 17, 26, 27), can be bonded typically down to 2mm (.08 inch) thick onto a variety of ferrous or non ferrous backing plates, nominally 12.7mm (.5 inch) or thicker. Plates have been produced up to 3.5 metres (137 inch) diameter or 15 sq. metres area (160 sq. ft.).

*Cross-section of an explosively bonded steel to titanium joint.*



# BRAZING

## CONVENTIONAL BRAZING

Titanium alloys have been brazed successfully using silver, aluminium and titanium alloy braze metals. Although there are many variants, only vacuum brazing has significant application for titanium due to the requirement to protect the base metal from oxidation. However, development work has been performed in the use of silver chloride-lithium fluoride fluxes and TIG brazing has proven successful in some applications. Silver alloy brazes were the first to be applied to titanium and commercially pure silver, silver alloys with copper and manganese, and silver-copper alloys with zinc and tin have all shown some success. Although joints tend to have good ductility, strength is poor at elevated temperatures and corrosion resistance is poor in chloride-containing environments. However, the silver alloy braze metals have liquidus temperatures below the beta transus of alloys such as Ti-6Al-4V, thus the brazing cycle will have little or no effect on the base metal microstructure and properties. The use of aluminium-silicon fillers also enables low temperature brazing to be performed, with the added benefit of decreased weight. It is crucial, however, to maintain as short a braze cycle as possible to minimise the formation of brittle intermetallics.

### Brazing

#### Advantages

- Complex geometry's can be joined
- Dissimilar metal joints are possible

#### Disadvantages

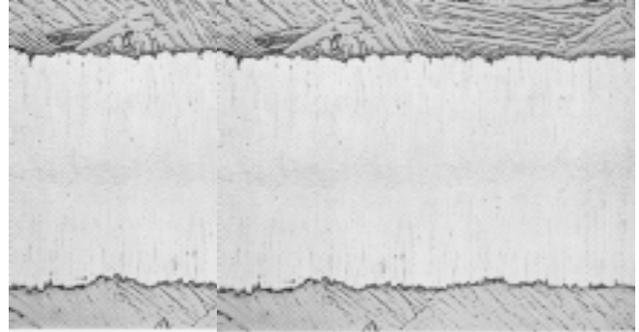
- Slow, unless batch processing is possible
- Must be performed in a vacuum
- Galvanic corrosion may limit application

Titanium alloy brazing alloys are by far the most common for joining titanium, the most available commercial alloys being titanium-copper-nickel alloys. These offer high strength and good corrosion resistance, but the most readily available alloy (Ti-15Cu-15Ni) requires brazing at temperatures over 1000°C (1830°F). A Ti-20Cu-20Ni alloy and amorphous Ti-Zr-Cu-Ni braze foil have been developed for brazing at lower temperatures (850 and 950°C, (1560 - 1740°F) respectively). These have advantages for application with Ti-6Al-4V. For the highest temperature joint applications, palladium based alloys have been used although brazing must also be performed at high temperatures.

The brazing process offers the capability of dissimilar metal joining, using a silver alloy braze metal. Dissimilar titanium alloy and titanium to ferrous, nickel and

refractory metal joints are possible. Complex configurations can be joined, limited only by the necessity to maintain closely abutting joint faces.

*Titanium brazed with a silver braze metal.*



## TRANSIENT LIQUID PHASE BONDING

This process has been described as a diffusion bonding process, but transient liquid phase (TLP) bonding has more in common with brazing than diffusion bonding. An interlayer, or melting point suppressant, is placed between the joint faces prior to heating in a vacuum. The interlayer material is chosen to react with the base metal, forming a eutectic liquid at the joining temperature. The reaction progresses until the liquid metal resolidifies isothermally, leaving a joint microstructurally similar to the base metal. Pure nickel and copper, and copper-nickel alloy interlayers have shown good performance for joining titanium alloys. A further benefit of the process over conventional brazing is the reduced weight of the structures, since only a very thin interlayer is required. However, a significant perpendicular load must be applied to the components to maintain good surface contact during the bonding process.

## SOLDERING

Titanium is extremely difficult to solder because of the same properties that confer its superb corrosion resistance - the tenacity and stability of its surface oxide. Conventional soldering methods depend on aggressive fluxes to allow the solder alloy to wet the surface of the base metal. None of the conventional fluxes is effective for titanium and so the surface is typically precoated with a more compatible metal, such as copper, by PVD or sputter coating. It is also possible to 'tin' the surface of the titanium by extended immersion in a molten tin bath at 600°C (1110°F); the titanium oxide is adsorbed by the base metal, allowing the tin to wet a non-oxidised surface. Some success has also been reported in the use of molten silver or tin halides, which react with the oxide surface to produce a tin or silver coating; and in the use of conventional fluxes whilst disrupting the surface oxide with an ultrasonic soldering iron.

## ADHESIVE BONDING

Adhesive bonding provides an alternative to welding, particularly for joining sheet material and for joints between titanium and non-metals such as polymer composites. The use of adhesives is often a viable alternative or companion process (i.e. hybrid bonding) to resistance spot welding in joints designed to experience predominantly shear stresses in service. Factors such as the service environment dominate the selection of adhesive, but this subject is too complex to discuss in detail in this publication. The high strength of modern structural adhesives is entirely appropriate to the use of bonded titanium in structural applications, although careful pre-treatment of the bond surfaces is critical for achieving maximum properties. It is strongly

*Adhesively bonded carbon fibre composite/ titanium wishbone of a Williams formula one racing car.*



### Adhesive Bonding

#### Advantages

- Rapid
- Titanium to polymer/composite joints are possible

#### Disadvantages

- Poor performance in peel
- Application is limited for most corrosive environment

recommended that technical consultation is sought for advice on all aspects of the bonding process.

*Close up of joint*



## MECHANICAL FASTENING

Mechanical joining processes for titanium include all types of fastener, many of which are routinely manufactured in titanium and widely used in the aerospace industry. Non-titanium fasteners in materials of lower corrosion resistance compared to titanium may be used where no danger of galvanic corrosion is present, or where the fastening is totally isolated from the corrosive environment. In environments which pose a risk alloys.

*Selection of titanium bolts, fasteners and captive nuts*



of galvanic corrosion, non titanium fasteners can be used provided they are insulated from the titanium using suitable gaskets.

Other mechanical joining methods such as lock seaming (e.g. in automotive exhaust box manufacture) and overlap joints, (used for architectural panels) are limited to the more ductile grades of the metal and its

*Both lock seaming and welding are used in the manufacture of titanium exhaust systems*



## JOINING TITANIUM TO OTHER MATERIALS

Titanium is incompatible with most other metals and will form brittle compounds if fusion welded directly to them. Indeed the only commercial alloys that can be directly fusion welded to titanium are those based on zirconium, niobium and certain other refractory alloys. More common structural materials, such as all ferrous and aluminium alloys, are invariably unsuitable for direct fusion welding to titanium. Several novel joining techniques have been adopted for making dissimilar joints, but the range of possibilities is too vast to address here in any detail. Many of the welding processes discussed in the preceding sections can be applied to dissimilar material joints between titanium and other metals. Indeed, explosively bonded titanium clad steel and Resista-Clad™ plate are prime examples of

successful dissimilar bonding technologies. Explosive bonding has also been used to form transition joints between titanium and ferrous alloys, for example titanium pipe to stainless steel flange joints.

The following table is intended to highlight generic processes that may be capable of fabricating joints between titanium and other materials. These will normally require particular practices to be adopted to achieve a satisfactory joint. The suitability of the various processes will depend on the components to be joined and the properties required and it is strongly recommended that technical consultation be sought prior to finalising a component design incorporating dissimilar joints.

*Joining processes that may be capable of forming sound joints between titanium and other materials.*

	EB	Laser	Friction <sup>1</sup>	Adhesives	Explosive bonding	Resistance welding	Brazing
Steel	X	X	✓	✓	✓	✓	✓
Stainless Steel	X	X	✓	✓	✓	✓	✓
Nickel alloy	X	X	✓	✓	✓	X	✓
Refractory metals	✓	✓	✓	✓	✓	X	✓
Copper	X	X	✓	✓	✓	✓	✓
Aluminium	X	X	✓	✓	✓	✓	✓
Cobalt alloy	X	X	✓	✓	✓	X	✓
Ceramics	X	X	X	✓	X	X	✓
Polymer composites	X	X	X	✓	X	X	X

Notes <sup>1</sup> Does not indicate that all friction processes are appropriate for a given dissimilar joint.

**CAUTION: GALVANIC CORROSION** Titanium is highly corrosion resistant, and can accelerate the corrosion of dissimilar metals when coupled to a less noble metal. In addition to accelerated corrosion, when such a galvanic couple exists, hydrogen can be taken up by the titanium, leading in some circumstances to hydride cracking and failure. Alloys which occupy a similar position in the galvanic series as titanium may be safely coupled to titanium in environments which would not ordinarily lead to corrosion of the uncoupled base metal. For example duplex and super-austenitic stainless steel, and Ni-Cr-Mo alloys can often be safely coupled to titanium. However, it is recommended that specific technical advice is sought for any given operating environment and dissimilar joint. Further details on simple mechanical couplings can be found in TIG Data Sheet No 6.

## SELECTION OF A WELDING PROCESS

The foregoing sections have provided a brief summary of the characteristics of the various joining processes that can be used to weld titanium structures. Most fabrication is performed by TIG welding and this is unlikely to change, however it is crucial to the production of low cost titanium components that higher productivity, more cost effective processes be considered where possible. For example, PAW often

enables significant productivity gains for a low capital investment, while achieving similar or greater quality to that achievable using TIG welding. More 'exotic' processes such as power beam and friction welding should also be considered, since even if no in-house capability exists, work can often be subcontracted to experienced fabricators.

## WORKSHOP PRACTICE

This section concentrates mainly on the practical skills and workshop methods that are required to manufacture welds of the highest quality. Most of these guidelines apply to all processes, while others are more appropriate to either fusion or solid state welding. Greatest attention is paid to the arc welding processes, since those having to weld titanium for the first time are most likely to use these techniques.

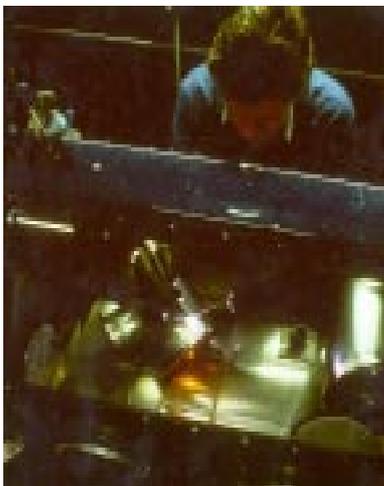
## WORKSHOP LAYOUT

It is preferable for a separate area to be set aside for titanium fabrication, provided that there is sufficient work to justify the additional expense. If this is not possible, extreme care should be taken to segregate materials. Titanium is similar in appearance to stainless steel and the consequences of using a ferrous filler wire in a titanium joint could be very costly. The entire working area should be kept clean to avoid any contamination during welding. Likewise, the working space should be absolutely dry. Water is a potential source of oxygen and hydrogen and all equipment, jigs, fixtures etc. should be free from moisture. If equipment is found to be wet, the safest means of drying out is to use a hot air blast or a volatile solvent such as acetone. The fume produced when titanium is welded is not harmful to health. Consequently, extraction systems should be designed to keep the general area clean without producing noticeable draughts at the point of welding. Screens or curtains should be used to reduce draughts locally.

## INERT GAS PROTECTION

The affinity of hot titanium for gases such as oxygen, nitrogen and hydrogen, and its embrittlement by these gases when absorbed, means that inert gas protection (or vacuum) is essential during welding. Conventionally, protection is afforded to the weld bead and heat affected region whilst hot, enough to cause oxidation.

*In-chamber welding (Vickers Aerospace Components)*



## IN-CHAMBER WELDING

Welding chambers are typically restricted to the fabrication of smaller components. Although the use of a chamber can be quite cumbersome and requires significant operator skill, complete protection of the weld root and cap is provided regardless of joint geometry or component complexity. Rigid chambers are typically either box section or domed and either constructed mostly from clear plastic, or incorporate several clear viewing panels. Flexible enclosures can also be employed and, due to their reduced cost, are particularly suitable for the occasional welding of titanium. It is essential that the air content within the chamber is reduced to a very low level, prior to commencing welding. Fabricators who frequently weld in chambers are advised to use an oxygen meter to continuously sample the chamber environment (this should be <20-30ppm). For occasional use, where the cost of an oxygen meter may not be justified, the chamber environment can be tested by placing a weld bead on a scrap piece of titanium; if the weld is not discoloured then a low enough air content in the chamber has been achieved.

*Flexible enclosure (Huntingdon Fusion Techniques)*

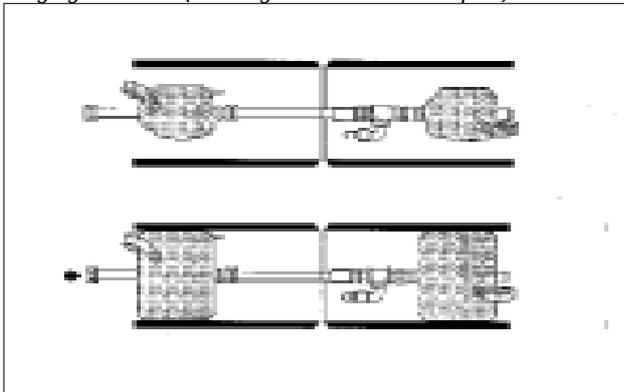


## OPEN AIR WELDING

The requirement for additional gas shielding of both the back-face and cap regions during open-air welding is the only significant factor which differentiates titanium from most stainless steel fabrications. There are, however, many commercial solutions for the protection of titanium weldments, making both linear and circumferential welds quite straightforward. Greater experience is necessary for more difficult configurations, but many commercial fabricators weld more or less complex shapes on a regular basis.

Conventional back purging techniques, as used for high quality stainless steel welding, are commonly adopted for titanium. Straight runs employ a grooved backing bar which is purged with a moderate gas flow. For more complex configurations aluminium or copper foil can be taped to the underside forming the necessary channel for the gas purge. In this instance, care must be taken to prevent the foil coming into contact with the hot titanium. Purging dams or bladders are used to protect the underside of circumferential welds, or difficult to access regions. It is important that sufficient time is allowed during back purging to reduce the air content in the purged region to very low levels. No hard and fast rule exists for purge time, since this depends largely on the purged volume, its complexity and the flow rate of

*Purging bladders (Huntingdon Fusion Techniques)*



argon. Use of an oxygen meter is advised in most instances to ensure that oxygen content of the purge gas is lower than approximately 20ppm prior to commencing welding. The cost of solid state oxygen meters capable of reading to these low levels has dropped in recent years and the capital investment can be quickly recouped by a reduced use of argon, rework and scrapped components. If possible welding should be performed with touching root faces, since a root gap makes purging of the underside significantly more difficult. If a root gap is unavoidable then, where there is access to the underside, a root side gas shield' similar to that used for protecting the weld cap (discussed below), is the best solution. If access is limited, then aluminium or copper foil can be taped over the top face and removed ahead of the torch during the completion of the root weld pass.

Protection of the weld cap is routinely achieved by the use of a trailing shield, however in certain circumstances, such as a TIG root pass in a deep groove, the use of an appropriate gas lens on the welding torch can achieve satisfactory results. Whilst no hard and fast rule can be stated, the ceramic nozzle is suitable for TIG welding currents up to about 35 amps and the annular gas lens for currents up to about 90 amps. It is stressed that this depends on a favourable joint geometry, allowing the torch shielding gas to flood the joint and provide gas protection away from the torch. Welding at higher currents or anything other than slow traverse speeds, should be carried out with a trailing shield attached to the torch. The argon supply to this shield is via a separate supply rather than by diverting a proportion of the torch argon. The body of the shield can be made from copper or aluminium if lightness is important and should incorporate a stainless steel woven mesh gauze for diffusing the gas stream. The design of a successful trailing shield requires experience, but proven commercial products are available for circumferential, fillet and straight welding. Their length and width depends on the welding process: MIG and automatic TIG welding require longer trailing shields than for manual TIG since traverse speeds are greater. Heat resistant glass may be employed instead of metal for shields where better visibility is required.

*Trailing shields (Huntingdon Fusion Techniques)*



Despite the high reactivity of titanium, shielding gases are not normally required for friction welding. Material contaminated by exposure to air is pushed into the flash, and can be removed. There will be some surface discoloration close to the weld, but the depth of contamination is very small. If the application is critical, it may be advisable to remove this material after welding. An exception to the lack of requirement for shielding gases occurs when processes are used which develop little or no flash. Friction stir welding of titanium requires a high quality gas shield.

## PREPARATION OF THE JOINT FOR WELDING

The need for care and planning at the materials preparation stage cannot be over emphasised. Frequently, where problems have been reported with titanium fabrications, all or part of the cause can be traced to this stage. The correct preparation of the weld joints is essential for arc welding, diffusion bonding, resistance welding and brazing, although friction welds are typically more forgiving.

### GEOMETRY OF WELD PREPARATIONS:

For TIG welding, a square-cut edge can be used for all butt or corner welds in thin gauge sheet and tube where the thickness does not exceed 1mm. Rough edges with burrs are difficult to set up and can result in high levels of weld porosity. Thicker sheet and tube should be provided with a V-preparation with the 90° included angle V terminating in a 0.6mm root face. By this means it is possible to achieve consistent penetration during the first weld run. Experience has shown that commercially pure titanium gives lower weld penetration than Ti-6Al-4V alloy. Thus, although the difference is not as extreme as is commonly found between different casts of stainless steels, joint designs should be qualified for the titanium grade to be welded. For plate welding at more than 6mm thickness, a simple open V can give rise to unacceptable distortion due to thermal stresses. In this case a machined J-preparation is used in which the angle of the sides is as steep as possible consistent with achieving complete side-wall fusion. As a guide, the total included angle should be not greater than 65° and not less than 45°. A double V-preparation is an acceptable alternative to the J-preparation when there is access to both sides of the weld.

Preparations that are suitable for TIG welding are also generally appropriate for MIG and plasma when operated in the conduction-limited mode. Keyhole plasma welding requires only a simple square butt penetration for thicknesses up to approximately 18mm (.7"). Thicker material can be prepared as for TIG welding, but with a root face up to 15mm, and filled by PAW or TIG. Electron beam, laser and most friction welds require simple butt geometry.

### CUTTING

Any thickness of titanium can be cut with conventional flame cutting equipment. However, it must be remembered that contamination of the metal with oxygen will result in hardening of the metal adjacent of the cut edges. Thus a size tolerance of +6mm, (.25") should be allowed for subsequent cleaning up. Plasma arc cutting or the use of lasers are possible alternative techniques to the oxyacetylene process. As-cut surfaces should not be welded before the joint faces are finished using a machining technique capable of giving a non-contaminated good quality surface. As-guillotined joint

faces should not be welded. Experience has shown that this cutting technique which produces a smeared edge leads to excessive weld metal porosity.

### MACHINING

The following techniques are suitable for the preparation of titanium joints:

- (a) Turning, milling and planing: The surface obtained by conventional machining processes such as lathe-turning, milling and planing are suitable for welding with no additional cleaning other than degreasing to remove cutting lubricants. Care is needed to ensure that the metal is not overheated during the machining operation and that other (non machined) surfaces to be welded are not oxidised.
- (b) Grinding: This technique is widely used for preparing the edges of medium and thick material for welding. The aim should be to produce the smoothest, most regular profile possible with the scratch lines running along the line of the weld and never across it. If overheating of the material occurs it will be evident from discoloration. Whenever practicable, grinding should be followed by draw filing, or any other technique which improves the smoothness and profile of the weld and ensures that any grinding particles are removed.
- (c) Linishing: Belt or disc finishers are suitable for edge preparation of medium gauge components. A 100 grit grade of paper can be used for most purposes. Linishing is a relatively slow operation which produces fine dust and is expensive on consumables. However, it is very flexible and can give excellent results.
- (d) Draw filing: Preparations made by grinding can be improved by draw filing. A fine toothed flat file is drawn repeatedly along the metal surface, an operation which removes minor irregularities. Filing requires skill and the use of a clean file or it can worsen rather than improve the surface
- (e) Scratch brushing: Surfaces can be scratch brushed to remove any residual contamination. With stainless steel brushes there is a slight risk of iron pick up and titanium brushes should be used for critical applications.

It is usual to machine the abutting surface of a friction weld before welding. It is not necessary to have great accuracy in the finish, although a good square set up is usually needed. Since there is always a loss of length due to burn-off into the flash, there is little point in machining overall lengths to any precision. This should be done after welding, when the flash must also be removed. Much greater precision is required for diffusion bonding and, to a lesser extent, brazing since good fit-up of the joint faces is essential to the success of these joining methods.

Machined joint faces and material likely to be fused (i.e. nearby material on the joint underside and top face), should be cleaned and degreased prior to welding to remove any cutting fluids or grease.

## PICKLING

Acid pickling can be used to remove oxygen contaminated metal from the surface of titanium. It is also useful for removing any surface iron contamination that may be present from machining. Pickling solutions are typically aqueous solutions of hydrofluoric (48% concentration) and nitric acid (70% concentration). The acid ratio should always be maintained between 1:5 and 1:9 (5%HF/35%HNO<sub>3</sub> has been found to be an effective solution). Pickling should be carried out at room temperature, for 1-5 minutes depending on the activity of the bath. If the surface of the metal is dirty or oily, degreasing or aquablasting must precede pickling or the acid dissolution will be non-uniform producing a pitted effect.

## PREWELD CLEANING

The surface of the weld preparation and adjoining metal is critical to the quality of the joint and should be scrupulously clean prior to welding. The surface should be inspected to see whether a final hand finishing operation is necessary, e.g. to smooth out rough machining marks and remove slivers of metal. The smoothness of abutting edges is particularly important for reduced porosity in arc welds and diffusion bonds. Vapour and liquid degreasing methods are applicable for titanium alloys.

(a) Vapour: Immersion tanks based on trichlorethylene vapour are effective in removing grease, oil,

fingermarks and general dirt from the surface of titanium components. It should be ensured that the tanks are not located too near to the welding area nor that components are transferred immediately from the tank to the welding booth because of the risk of phosgene formation. Trichlorethylene should regularly be checked for HCl acidity.

(b) Liquid: Small components can be degreased by immersion in, for example, acetone or isopropyl alcohol. Larger items can be cleaned by wiping with lint free cloths or tissues soaked in the solvent. *Under no circumstances should methanol be employed as a degreasing agent.*

Once components have been degreased, the surfaces must be handled only with clean gloves and preferably not at all: bare hands, even ostensibly clean ones, deposit a surprising amount of grease and salt.

## CLAMPING AND FIXTURES

Clamps and fixtures for arc welding should be designed to minimise distortion and, where necessary, incorporate the purging system required to protect the underside of the weldment.

For conventional rotary friction welds, the rotating part is normally held in a three jaw chuck, although special tooling may be required for the non-rotating part if it is not axially symmetrical. For linear friction welding, special tooling specific to the component is always required. The tooling for the reciprocating component must be designed with care in order to minimise the weight and hence inertia of the system, which will have to change direction typically 100 times every second.

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# ARC WELDING TECHNIQUE

## POWER SOURCES AND TORCHES

Titanium and its alloys can be welded with most conventional welding power sources and torches. For TIG welding a power source equipped with a non-contact arc strike facility is essential to prevent tungsten contamination of the weld, which occurs if a touch down technique is employed. The power source must also be capable of breaking the arc on completion of a weld run, without stopping the inert gas flow, or weld metal contamination by air may occur at the weld stop position.

## TUNGSTEN ELECTRODE

The choice of electrode composition and diameter is no different than for TIG welding stainless steels and is influenced by the requirements for electrode longevity, ease of arc initiation and stability. A simple 60° cone gives satisfactory results for most manual TIG welding. With angles less than 40° there is a greater risk of

tungsten loss while above 80° arc initiation is difficult and the arc has a tendency to wander. Should the electrode touch the weld both must be carefully examined before restarting. Any tungsten in the weld, no matter how small must be excavated.

## SELECTION OF WELDING PARAMETERS

TIG, PAW and MIG welds can be made using a variety of current/speed combinations, the differences being the result of operator preference. However, it is worth remembering that the aim should be to achieve a good bead shape with minimum heat input. In that way, distortion and argon shielding problems will be minimised. TIG and plasma welding are best achieved with direct current electrode negative (DCEN) polarity and, for MIG welding, pulsed operation is generally preferred. Suggested welding parameters are given in the table, although these should be used as a guideline only.

## SHIELDING GASES

For most purposes, the commercial grade of argon may be used for welding titanium, although productivity can be enhanced through the use of argon-helium mixtures or pure helium. The use of helium-containing gases has particular advantages for MIG welding since spatter can be reduced considerably. Commercially available cylinders of welding grade argon and helium are of sufficient purity for all welding operations, however care should be taken to ensure that non-permeable hoses are used for all attachments to ensure that moisture is not incorporated into the shielding gas. If cylinders are used it is inevitable that they will contain a small amount of moisture. This level is extremely low when the gas cylinder is full, but as the pressure in the cylinder drops, so the moisture content rises. There is some justification for using gas from a cylinder for welding titanium only until the pressure has fallen to ~25bar, after which it

should be used to supply gas for welding less sensitive metals. Bulk supplies of argon have much lower moisture contents. Where an on-site gas tank is used to supply several welding stations gas purifiers, moisture and oxygen meters can be connected to the main feed line to provide overall quality assurance.

Inadequate shielding of the weld cap can occur when argon flow from the torch is either too low so that all the air is not displaced, or too high so that turbulence occurs. Some experimentation on off-cuts of material may be needed to establish the most suitable conditions. Keeping a record of values used on previous work eventually helps to reduce the time spent in setting up. It is advised that a gas lens be used to maintain a lamellar gas flow. This applies equally to the gas flow rate for trailing shields, although the minimum flow rate will depend on the size of the shield.

*Suggested welding parameters for automatic TIG and MIG welding titanium (1/16" = 1.6mm)*

	TIG (GTA) without filler			TIG (GTA) with filler			MIG (GMA)				
	0.030	0.060	0.090	0.060	0.090	0.125	0.125	0.250	0.500	0.625	
Gauge, in	0.030	0.060	0.090	0.060	0.090	0.125	0.125	0.250	0.500	0.625	
Electrode diameter, in	1/16	1/16	1/16-3/32	1/16	1/16-3/32	3/32-1/8	1/16	1/16	1/16	1/16	
Filler wire diameter, in	-	-	-	1/16	1/16	1/16	-	-	-	-	
Wire feed rate, ipm	-	-	-	22	22	20	200-225	300-320	375-400	400-425	
Voltage, V	10	10	12	10	12	12	20	30	40	45	
Amps, A	25-30	90-100	190-200	120-130	200-210	220-230	250-260	300-320	340-360	350-370	
Nozzle ID, in	3/4	3/4	3/4	3/4	3/4	3/4	3/4-1	3/4-1	3/4-1	3/4-1	
Torch shield, cfh	15Ar	15Ar	20Ar	15Ar	20Ar	20Ar	50Ar+	50Ar+	50Ar+	50Ar+	
							15He	15He	15He	15He	
Trailing shield, cfh	20Ar	30Ar	50Ar	40Ar	50Ar	50Ar	50Ar	50Ar	60Ar	60Ar	
Backing gas, cfh	4Ar	4Ar	5Ar	5Ar	6Ar	6Ar	30Ar	50Ar	60Ar	60Ar	
Travel speed, ipm	10	10	10	12	12	10	15	15	15	15	
Power supply	DCEN	DCEN	DCEN	DCEN	DCEN	DCEN	DCEP	DCEP	DCEP	DCEP	

*Suggested Welding parameters for PAW welding titanium*

Thickness		Welding technique	Nozzle Orifice				Orifice and shielding gas	Welding current, A*	Arc voltage, V	Travel speed		Filler wire feed**	
in.	mm		Diameter		Flow					ipm	mm/s	ipm	mm/s
			in.	mm	cfh	l/min							
0.008	0.20	Melt-in	0.030	0.76	0.5	2.3	Ar	5	-	5	2.1	-	-
0.015	0.38	Melt-in	0.030	0.76	0.5	2.3	Ar	6	-	5	2.1	-	-
0.125	3.18	Keyhole	0.136	3.45	9	42	Ar	150	24	15	6.3	40	16.9
0.188	4.78	Keyhole	0.136	3.45	10-12	47-57	Ar	175	30	15	6.3	42	17.8
0.250	6.35	Keyhole	0.136	3.45	16	76	Ar	160	30	12	5.1	45	19
0.313	7.95	Keyhole	0.136	3.45	15	71	Ar	172	30	12	5.1	48	20.3
0.390	9.92	Keyhole	0.136	3.45	32	151	He+25Ar	225	38	10	4.2	-	-
0.500	12.7	Keyhole	0.136	3.45	27	127	He+50Ar	270	36	10	4.2	-	-

Notes: \* Direct current electrode negative  
 \*\*0.062inch (1.6mm) diameter wire

Backing gas flow rates depend largely on the volume being filled. Flow rates for backing bars will normally be lower than those for the torch. Similarly, backing gas flow rates for a dammed pipe are limited by the magnitude of the positive pressure maintained inside the pipe. The pressure must not be too great or the weld root may be 'pushed' in, giving a concave profile. Sufficient time must be allowed for the argon to sweep all air out of the backing volume, and this will vary according to the exact volume and flow rates used. Typically, a greater flow rate is used when purging a dammed area. Where a backing bar is used, localised oxidation can result from either an inadequate purge time or excessive argon flow rate. A similar effect can be caused by a badly fitting jig or by impure argon.

Strong air currents can reduce the efficiency of even well designed argon shields and should thus be avoided. Screens may be used indoors to minimise the effect of draughts while for on-site work, a polythene sheet tent or other draught proof enclosure may be necessary.

### SELECTION OF FILLER WIRE

Filler wires are produced for a wide range of titanium alloys, and those for grades 2 (CP) and 5 (Ti-6Al-4V) are readily available to AWS specifications in straight lengths and spools. The expedient of cutting strips from sheet to provide filler material is one which may prove far from satisfactory. Wire for welding is made to a specification which includes composition, dimensions, surface quality and cleanliness. Edge slittings are unlikely to conform in all these aspects and their use without great care may prove troublesome.

Under normal circumstances, the grade of filler wire will be identical with that of the parent material. Thus, when two grade 2 components are to be welded, a grade 2 filler wire should be used. Where some atmospheric contamination can be anticipated, for example on positional welds in pipework, or where specifications impose low hardness differences between weld bead and parent metal, a softer grade of wire such as grade 1 can be employed. However, on no account should the use of a softer filler be used as a substitute for good shielding practice. Welds between different grades of commercially pure titanium can be made using filler of either composition. The choice will depend on which is the most important property of the weld, strength or ductility.

For welds in Ti-6Al-4V, TIG welding with a matching filler metal can lead to a reduction in ductility in the weld because of metallurgical changes within the structure. This can be overcome to some extent by the use of Ti-6Al-4V ELI, extra low interstitial grade wire. Joints between low and higher alloy titanium grades (e.g. Ti-6Al-4V to CP) should be considered carefully, particularly where postweld heat treatment is employed, as hydrogen embrittlement can be more likely.

When the arc is extinguished the tip of the filler wire should remain, with the weld, in the argon stream from the torch until both are sufficiently cool not to oxidise. If filler wire does accidentally become oxidised, the contaminated end must be removed before welding is recommenced.

Titanium welding electrode compositions

AWS Wire Classification	ASTM Grade	Composition, wt.%								
		C	O	H	N	Al	V	Fe	Other	Ti
ERTi-1*	1	0.03	0.10	0.008	0.012	-	-	0.10	-	Rem.
ERTi-2	1	0.05	0.10	0.008	0.020	-	-	0.20	-	Rem
ERTi-3	2	0.05	0.10-0.15	0.008	0.020	-	-	0.20	-	Rem
ERTi-4	2,3,4	0.05	0.15-0.25	0.008	0.020	-	-	0.30	-	Rem
ERTi-0.2Pd	7,16,17,11	0.05	0.15	0.008	0.020	-	-	0.20	Pd 0.12-0.25	Rem
ERTi-3Al-2.5V	9	0.05	0.12	0.008	0.020	2.5-3.5	2.0-3.0	0.25	-	Rem
ERTi-3Al-2.5V-ELI*	9	0.04	0.10	0.005	0.012	2.5-3.5	2.0-3.0	0.15	-	Rem
ERTi-6Al-4V	5	0.05	0.15	0.008	0.020	5.5-6.75	3.5-4.5	0.25	-	Rem
ERTi-6Al-4V-ELI*	5,23	0.04	0.10	0.005	0.012	5.5-6.75	3.5-4.5	0.15	-	Rem
ERTi-12	12	0.03	0.25	0.008	0.020	-	-	0.30	Mo 0.2-0.4 Ni 0.6-0.9	Rem

Notes: \* This classification of filler metal restricts the allowable interstitial content to a low level so that the high toughness required for cryogenic applications and other special uses can be obtained in the deposited weld metal.

## TACK WELDING

Tack welds are used to fix parts into the correct relative position before welding. Since the tack is eventually incorporated into the weld, it must be shielded to the same high standard as the weld itself. Tacks may be used in conjunction with a root gap i.e. where the edges of the weld are deliberately set slightly apart to assist in achieving uniform penetration. A tapering root gap, wider at the finish end, can be set to counteract the scissor effect caused by weld contraction.

## MULTIPASS WELDING

The initial pass of a multipass weld will generally be autogenous with only minor filler additions to correct for small variations. It is advisable to X-ray the weld at this stage if work is being carried out to radiographic standards since porosity and lack of fusion defects are more often associated with this first pass than with subsequent runs.

Bright silvery coloured welds which have been correctly shielded do not require any attention before laying subsequent passes onto them.

Heat build up from previous weld runs can lead to surface contamination on subsequent passes. In extreme cases, the only solution may be to leave the work to cool before further welding is carried out. Another approach is to make any long welds in shorter sections. In addition to helping with cooling, sequence welding can also be effective in reducing distortion. Interpass temperatures up to 500°C, depending on circumstances, can be used for commercial purity titanium and Ti-6Al-4V. This ensures that heat build up of the work piece does not reduce the effectiveness of the shielding arrangements, which are typically based on single pass welds.

## RESISTANCE WELDING TECHNIQUE

Equipment and technique are very similar to those required for austenitic stainless steels. As with fusion welding techniques, the quality of the joints depends largely on the cleanliness of the joint surfaces, which should be free of grease oil and other contaminants. Similarly, an oxidised surface, even one which is only lightly discoloured, should be ground or scratch brushed with a titanium or stainless steel brush, prior to welding. Pickling achieves the lowest contact resistance, but mechanical cleaning methods are more than adequate for the production of sound joints. Gas shielding is not typically necessary, since contamination is minor as a result of the very rapid thermal cycle. However, metallographic and mechanical testing should always be used to determine if shielding is required for a given combination of parameters, materials, requirements and machine.

The face of resistance welding electrodes should have a domed profile, rather than the truncated cone profile favoured for some other materials, to prevent excessive indentation of the titanium.

Guideline spot welding parameters are given in the Table for Ti-6Al-4V, although the required parameters for a given job depends on many factors and the values in the table should only be regarded as a starting point when establishing procedures. For seam welding, an appreciably greater welding load should be applied than is necessary for spot welding (3 times the spot welding load is typically a good starting point for welding trials). Current and on/off cycle ratios should be determined by trial and error. Care must be taken when evaluating the welds to ensure that good overlap is achieved between successive weld nuggets. Weld penetration is normally high but the grain coarsened HAZ can easily be mistaken for the nugget zone.

*Guideline parameters for spot welding Ti-6Al-4V*

Parameters for spot welding (1 inch = 25.4mm; 1lb = 0.454 kg)

Sheet thickness (inches)	0.035	0.062	0.070	0.093
Joint overlap (inches)	1/2	5/8	5/8	3/4
Squeeze time (ms)	60	60	60	60
Weld time, cycles	7	10	12	16
Hold time (ms)	60	60	60	60
Electrode force (lbs)	600	1500	1700	2400
Weld current (A)	5500	10600	11500	12500
Cross tensile strength (lbs)	600	1000	1850	2100
Tensile shear strength (lbs)	1720	5000	6350	8400
Ratio C-T/T-S	0.35	0.20	0.29	0.25
Weld diameter (inches)	0.255	0.359	0.391	0.431
Nugget diameter (inches)	-	0.331	-	-
Weld penetration (%)	-	87.3	-	-
Electrode indentation (%)	-	3.1	-	-
Sheet separation (inches)	0.0047	0.0087	0.0079	0.0091

*Notes: Electrode type : 3" (75mm) spherical radius, 5/8" (15.9mm) dia, class 2 copper*

# EVALUATION OF WELD QUALITY

## LIKELY DEFECTS

Titanium, like all metals, is susceptible to certain welding defects. However, the range of possible defects is much less extensive than, say, for ferrous fabrications. Solidification cracking, a common defect in stainless steel and aluminium weldments, is not found in Ti-6Al-4V or CP. Likewise, liquation and reheat cracking are not encountered in titanium fabrications. Contamination due to inadequate gas shielding is one of the more common defects responsible for rework or scrap and applies to all welding processes with the exception of friction welding. Tiny pores, irrelevant to many applications, can be formed in titanium weld metal but careful surface preparation will substantially reduce their presence.

Most of the defects commonly encountered in titanium TIG weldments can be traced to a deviation from ideal welding parameters. Molten titanium metal is fluid and its combination of low density and high surface tension enables good control of the weld surface profile and penetration. Thus, titanium is more forgiving in this respect than many other metals, but defects such as lack of fusion, incomplete penetration and underfill are still possible. Porosity can also be encountered in titanium weld metal, typically at the fusion boundary. Pores are spherical and between 50-300µm in diameter. MIG welds are susceptible to similar defects, but are also prone to spatter. For critical applications, it is important that the parent material be protected using metal foil or heat resistant fabric. Hydrogen contamination in the weld or parent material can lead to hydride cracking (typically in positions of maximum residual stress), but this is typically encountered only when Ar-H shielding gases, used commonly for stainless steels, are used for titanium fabrication.

Plasma arc welds are susceptible to the same range of defects as TIG welds. Incomplete penetration when operated in the keyhole mode typically results in gross tunnel porosity. Autogenous keyhole plasma welds in thick material typically exhibit a minor amount of underfill, but this can be readily addressed by applying a PAW or TIG final pass. One of the major benefits of keyhole plasma welds is their seeming immunity to weld metal porosity. Electron beam and laser welds are susceptible to porosity, voids, underfill, incomplete penetration and missed seams. Again, the likelihood of these defects is no greater than for most other metals. A lack of bonding is the most common defect in diffusion bonds, brazed joints, adhesive bonds and resistance welds.

The most likely defect in a friction weld, and the most difficult to detect non-destructively, is the so called "kissing bond", which is a region where intimate contact is made between the two parts of the weld, but where either the joint is weak or no metallurgical bond exists. If insufficient flash is generated during welding, the joint can be seriously embrittled, but this can typically be assessed visually. Porosity is not encountered in friction welds.

## RADIOGRAPHY.

Radiography is one of the more useful weld inspection techniques for titanium and its application does not differ substantially from the radiography of other metals, either in execution or interpretation. Allowance must be made for the lower absorption of X-rays than is found with iron or copper. One minor difficulty is that a titanium image quality indicator (IQI) is not available: the aluminium IQI is probably the best choice rather than iron or copper.

Radiography will reveal:-

- tungsten inclusions as sharp white spots
- porosity which shows up as dark spots that usually appear circular
- lack of root or sidewall fusion indicated as a dark line or area, often with associated porosity
- cracking, which is evident as a dark line, sometimes angular and sharp

## DESTRUCTIVE TESTS

The principles used in approval and qualification testing of other metals apply equally to titanium but some provision is necessary for assessing contamination. Colour should certainly be noted, but is an inadequate indicator on its own. Transverse tensile tests normally will not show contamination, since the weld is usually stronger than the parent metal. For plates that are sufficiently thick, results of side bend tests will give a guide. For thinner plate or sheet, the longitudinal bend test is preferable to the transverse, since this gives a direct comparison with base metal performance. Some care is needed, because the weld zone will usually be less ductile even in the absence of contamination, particularly with some alloys. Comparison should be made between the weld and HAZ (rather than parent), so as to account for hardening that occurs during the weld thermal cycle. Finally, the oxygen and nitrogen content of the welds may be analysed to provide a direct measure of any contamination.

Typical bend radii for as-welded titanium

ASTM Grades	Alloy type	Minimum bend radius
1, (11, 17, 27)	CP (+Pd/Ru)	2t
2, (16, 7 26)	CP (+Pd/Ru)	3t
3, 4	CP	4t
5, (24)	Ti-6Al1-4V (+Pd)	10-12t
23, (29)	Ti-6Al1-4V ELI (+Ru)	8-10t
12	Ti-0.7Ni-0.3Mo	5t
-	Ti-6Al1-6V-6Sn	16-18t

## VISUAL INSPECTION

Most elements of visual inspection are not unique to titanium welding: weld bead location, size, shape, uniformity and penetration. Visual inspection is also critical for assessing if sufficient flash has been generated in a friction weld. However, the major application of visual inspection for titanium weldments is the assessment of the success or otherwise of the gas shielding arrangements. This approach makes use of the interference colours generated by thin layers of surface oxide in the weld zone. The observed colour changes with oxide thickness and this effect is utilized to give an indication of the oxidizing potential of the shielding arrangements.

Colour	Intepretation
Silver	Correct shielding, satisfactory
Light straw	Slight contamination, but acceptable
Dark straw	Slight contamination, but acceptable
Dark blue	Heavier contamination, but may be acceptable depending on service
Light blue	Heavy contamination, unlikely to be acceptable
Grey blue	Very heavy contamination, unacceptable
Grey	Very heavy contamination, unacceptable
White	Very heavy contamination, unacceptable

Despite the precautions taken to avoid contamination it is inevitable that shielding arrangements will occasionally fail to fully protect the weld. The easiest and almost universally adopted inspection method is the monitoring of the colour of the weld surface. This technique, although appearing straightforward may give misleading results since the most detrimental form of contamination, i.e. entrainment of air into the torch shielding gas, could still give a silver weld if the trailing shield were to provide good protection. However, if welds are inspected during welding then contamination of the electrodes will be noticeable if air has been entrained into the torch shielding gas. A rule of thumb guide to interpreting weld zone colour is given in the table below.

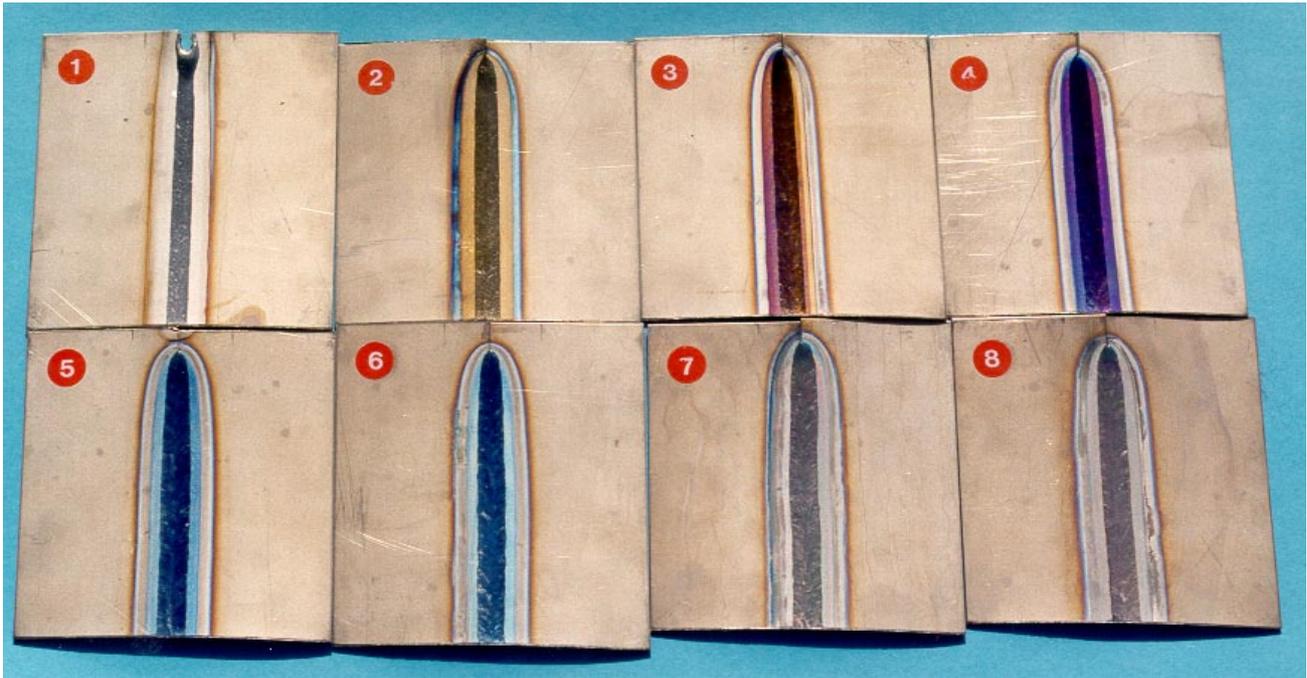
The full sequence of colours is rather complicated, progressing through first and second order colours, separated by a dull "silvery hiatus" which itself could readily be misinterpreted as a contamination-free weld. The interpretation of weld colour requires extensive operator training and experienced inspectors are needed to maintain confidence in the technique.

It should be noted that discoloration away from the weld bead does not necessarily indicate poor shielding. Indeed dark straw to blue 'tramlines' parallel to the weld bead are commonly encountered in fusion welds.

Work performed at TWI has established the origin of these features, which are believed to be non-harmful and are not related to the shielding integrity.



*A piece of titanium sheet 10mm wide, the lower edge of which has been heated (in air) showing the effect of progressive oxidation and increasing oxide thickness.*

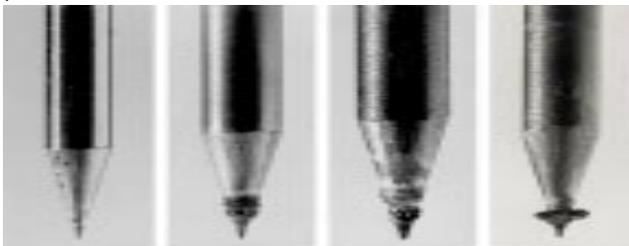


TIG welds in commercially pure titanium sheet made with successively greater air contamination of the shielding gas.

### ALTERNATIVES TO THE COLOUR CRITERIA

Hardness testing and eddy current inspection can be used to provide supporting evidence for contamination in commercially pure grades of titanium, since contaminated welds will exhibit greater hardness and resistivity. Portable hardness testing procedures that can be applied in-situ are currently being developed at TWI for grade 2 and 5 titanium. The successful application of these techniques will allow rejects to be minimised and the highest quality to be achieved.

Contamination of TIG electrodes from air entrainment (from left to right 0%, 0.5%, 1%, 1.5% air in the Ar torch shielding gas)



### DYE PENETRANT INSPECTION

Under normal circumstances, weld cracking is very rare with titanium. However, problems can sometimes arise where several weld seams intersect or where contamination has occurred. In these cases, the defects can be detected by dye penetrant inspection, the technique also being suitable for locating porosity in partly machined welds. It should be noted, however, that the dye penetrant must be completely removed prior to attempting weld repair.

### NOTES FOR FRICTION WELDS

Friction welded components are by definition very difficult to inspect. As the process is only economic for mass produced items, individual inspection of each component can seldom be justified. Experience has shown that, as the process is fully mechanised, and therefore repeatable, reliance on statistical process control is normally satisfactory. In this approach, the tolerance of the process to key welding parameters is first determined, and much tighter tolerances are then imposed on the production process. Providing the process is kept within these tolerance levels, the probability of getting a poor weld should be very small indeed. If a parameter is recorded to be just outside the tolerance range, the weld should still be acceptable, but this issues a warning that some intervention is required to return the parameter to its intended setting, and to investigate the cause for the change.

## REPAIR OF DEFECTS

### LOCALISED MINOR REPAIRS

Defects in titanium welds such as isolated tungsten inclusions and porosity are quite easy to repair. The affected area is removed by drilling or grinding and cleaned prior to filling the hole or depression with the appropriate filler material, taking care that any metal added is properly fused into the existing weld metal.

### SEAM REPLACEMENT

Where a line of pores is found by radiography, the weld can be re-melted up to a maximum of, say, 3 times subject to a satisfactory contamination check after each stage. This re-melt will require a higher current than that used on the original weld but can potentially remove all or most of the porosity. Should this fail, however, or if the defect is of a more serious nature, the entire weld bead must be removed by machining or grinding and then rewelded. These types of major weld repairs are usually slow and costly and consideration should be given to patching or even complete replacement of the items.

### REPAIR OF LARGE AREAS

Any substantial areas can be repaired by cutting out and replacing with new material or by welding a patch over the entire area. Generally, replacement is preferable to patching except for the repair of thick sheet with access to only one side, and for the repair of titanium/steel explosively clad plate. Electron beam welding has

proven particularly successful for replacement repair welding, allowing sections to be welded into components with minimal distortion and high accuracy. For example, flap tracks for the Tornado fighter/bomber aircraft have been repaired using this technique.

*TIG weld repair and HVOF surfacing was used to repair slat tracks on the Tristar aircraft*



### REPAIR OF DETAILS

Details on components that are damaged either in service or during fabrication are routinely repaired by the build up of weld beads using, for example, TIG welding. Fine details can be repaired using microplasma welding, allowing the precise positioning of small weld beads prior to machining to the required geometry.

## FURTHER NOTES ON POROSITY

Weld metal porosity occurs commonly in most materials, including for example nickel alloys and stainless steel. Titanium fusion weldments can also exhibit pores, but under most circumstances they do not have any particular detrimental effects. For example, pores are typically isolated and less than 0.3mm (.012") diameter, and have no discernible consequence for tensile properties or toughness. Similarly, if the weld cap and root profile are left intact (i.e. not ground flush with the parent metal), fatigue life is typically determined by the severity of the stress concentration at the weld toe and will not be influenced by the presence or otherwise of small pores.

For some applications, however, all geometry-specific stress-raisers, such as weld toes, are removed in order to maximise the fatigue performance of the joints. Under these circumstances fatigue strength can be lowered significantly by the presence of weld metal pores, especially those near the surface. This is true of most materials, but the degradation in fatigue life is typically greater for titanium, than, say, steel. Unduly restrictive maximum specified pore sizes in welding codes may not have any profound effect on fatigue performance.

Indeed, the removal of such defects and subsequent weld repair may be more detrimental to fatigue performance than the original defect. It is stressed, however, that if the weld cap and root are left intact, then weld metal porosity becomes irrelevant, and allowable stresses can be calculated solely on the basis of the severity of the profile of the weld toe.

Porosity in titanium fusion welds can be formed for a variety of reasons, but the most profound influence is the condition of the joint surfaces. In principle, final machining of the joint surfaces without aqueous lubricants and welding in the same 24h period is advised, although acid pickling may be used successfully on 'old' joint surfaces, provided welding is performed shortly after the pickling treatment. The joint surfaces should always be carefully degreased.

The presence of a hydrated scale and/or surface contaminants can be identified during tack welding. If a discoloured ring has formed within the protection of the gas shielded area and surrounds silver weld metal then, if porosity is to be minimised, the joint surfaces should be re-prepared. Not all welding processes show the same susceptibility to weld metal porosity. Although TIG, MIG, EB and laser welds often exhibit weld metal

pores, keyhole plasma welds are typically pore-free, showing that this latter process has significantly greater tolerance to the condition of the joint surfaces. Weld metal porosity can of course be completely avoided by using a solid state welding process.

## **DISTORTION**

Because welding involves highly localised heating of joint edges to fuse the material, non-uniform stresses are set up in the component. Initially, compressive stresses are created in the surrounding cold parent metal when the weld pool is formed due to the thermal expansion of the hot metal (heat affected zone) adjacent to the weld pool. However, tensile stresses arise on cooling when the contraction of the weld metal and the immediate heat affected zone is resisted by the bulk of the cold parent metal. If the stresses generated from thermal expansion/contraction exceeded the yield strength of the parent metal, localised plastic deformation of the metal occurs. Plastic deformation causes a permanent distortion in the structure.

The main factors affecting the type and degree of distortion, are parent material properties, amount of restraint, joint design, part fit-up and welding procedure.

## **PARENT MATERIAL PROPERTIES**

Parent material properties which influence distortion are coefficient of thermal expansion (greater values increase distortion) and specific heat per unit volume (lower values increase distortion). As distortion is determined by expansion and contraction of the material, the coefficient of thermal expansion of the material plays a significant role in determining the stresses generated during welding and, hence, the degree of distortion. Simple calculations and practical experience shows that the level of distortion expected in a titanium component lies between those observed for steel and stainless steel (i.e. distortion will be greater than for steel, but lower than observed in many austenitic stainless steels).

## **RESTRAINT**

If a component is welded without any external restraint, it distorts to relieve the welding stresses. So methods of restraint such as 'strong backs' in butt welds can prevent movement and reduce distortion. It should be noted, however, that restraint produces higher levels of residual stress in the material.

## **JOINT DESIGN**

Both butt and fillet joints are prone to distortion. It can be minimised in butt joints by adopting a joint type which balances the thermal stresses through the plate thickness. For example, a double-sided in preference to a single-sided weld. Double-sided fillet welds should eliminate angular distortion of the upstanding member,

especially if the two welds are deposited at the same time.

## **PART FIT-UP**

Fit-up should be uniform to produce predictable and consistent shrinkage. Excessive joint gap can also increase the degree of distortion by increasing the amount of weld metal needed to fill the joint. The joints should be adequately tacked to prevent relative movement between the parts during welding.

## **WELDING PROCEDURE**

This influences the degree of distortion mainly through its effect on the heat input. As welding procedure is usually selected for reasons of quality and productivity, the welder has limited scope for reducing distortion. As a general rule, weld volume should be kept to a minimum. Also the welding sequence and technique should aim to balance the thermally induced stresses around the neutral axis of the component.

## **STRESS RELIEF**

As for welds in any other metal, postweld heat-treatments are performed to reduce the residual stresses encountered in the weld zone and improve fatigue performance. Residual stresses in ferrous fabrications can equal the yield stress of the alloy, but residual stresses in titanium are typically lower. For example a maximum residual stress of approximately 85% of yield can be encountered in Ti-6Al-4V in highly restrained metal, such as typical for repair welds. Postweld heat treatments of different durations are required for stress relief of the various titanium alloy grades. Heat-treatment schedules for weldable higher strength alloys are commonly combined so that postweld heat-treatment relieves residual stresses and ages the parent material.

Postweld heat-treatment may be performed in a vacuum or argon atmosphere to prevent the formation of contaminated layers. Adsorbed oxygen forms a brittle surface, or 'alpha case', and is best avoided. Heat treatment in air is possible provided that the oxidised surface is removed by pickling, grinding or blasting and descaling.

Welded fabrications in commercially pure titanium, including pipe and fittings, will not normally require stress relief. Alloy fabrications, however, typically do require stress relief. One to two hours at 600°C (1110°F) max is usually adequate for both CP and Ti-6Al-4V, to reduce residual stress to manageable levels whilst avoiding excessive thermal oxidation. Indeed, higher temperatures should be avoided, since microstructural ageing can reduce toughness and ductility. Suppliers should be consulted for a suitable heat treatment cycle for welded alloys requiring postweld solution treatment and ageing.

## PRACTICAL POINTS..... THE DO'S AND DON'TS OF TITANIUM

**Design Cost Control:** *The practical points of successful design cost control are principally those of value engineering using a light, strong, corrosion-resistant material.*

**Do:** Check available standard products and specifications to obtain best availability and lowest cost.

Use design strategies based on using minimum material thickness.

Exploit corrosion resistant characteristics to the full.

Consider the use of liners and cladders in preference to solid design where heavy sections are unavoidable.

Consult suppliers and fabricators at the earliest stage of design.

**Do not:** Simply substitute titanium into existing designs.

Budget for titanium project costs by weight, especially not by the weight of steel or other alloys.

Specify little-used alloys or forms.

**Machining:** *The practical points of successful machining are principally those of observing the different mechanical and surface characteristics of titanium. Fire safety procedures must be applied for handling and control of titanium fines and turnings.*

**Do:** Use rigid set ups, correct speeds, feeds and tooling. Use flood lubrication.

Use roller steadies and running centres.

Regularly remove turnings from machines.

Employ special closeable containers for titanium turnings.

**Do not:** Allow titanium to rub on blunt tooling or smear on the other metals.

Mix combustible rubbish with titanium fines or turnings.

Allow open flames or welding near titanium fines.

**Fabrication:** *The practical points of successful fabrication are principally those of good housekeeping and clean practice in the workshop.*

**Do:** Use the correct weld preparation and remove all burrs.

Remove all grease, oil, paint and dirt before welding or heat treatment.

Clean weld areas with acetone on a lint-free cloth or use stainless steel or titanium wire brushes.

Dry titanium surfaces before welding.

Use clean dry titanium filler wire of the correct grade.

Ensure that the top and back face of the weld and weld areas are adequately shielded with argon gas.

**Do not:** Heat treat titanium in a reducing atmosphere, it will absorb hydrogen and become embrittled.

Use methyl alcohol (methanol) as a cleaning fluid, dry methanol can cause stress cracking.

Use sulpho-chlorinated or sulphurised cleaning fluids.

Apply cleaning fluid with tissue paper, wool or rags.

Wire brush with mild steel brushes.

Use hydrogen containing shielding gases.

**Surface Treatment:** *The practical points of successful surface treatments are the those of knowing the problem to be solved and deciding the appropriate treatment.*

**Do:** Confirm that any side effects are accounted for in the design and application.

Ensure that surface preparation is appropriate to the coating selected.

Provide the specified grade of lubrication.

**Do not:** Attempt to apply coatings to soiled or contaminated surfaces.

Exceed recommended inspection and maintenance intervals.

Re-use components showing excessive wear or surface damage.

**Installation:** *The practical points of successful installation are principally those of observing the different mechanical properties, corrosion resistance and surface characteristics of titanium.*

**Do:** Allow for the lower modulus of titanium in struts and support spans.

Provide surface treatment for titanium parts in sliding contact, or on bearing surfaces.

Coat external surfaces of exposed titanium structures in areas where dynamically induced sparking is a defined hazard.

**Do not:** Connect titanium without isolation to immediately adjoining less corrosion resistant metals, (to reduce the likelihood of galvanic corrosion).

## STANDARDS AND SPECIFICATIONS

ASME provides the only international non-aerospace standard for weldment qualification in titanium. For pressure vessel construction, the ASME Boiler and Pressure Vessel Code details procedure and performance tests which must be met for coded grades 1, 2, 3, 7, 9, and 12. Tensile and bend tests on trial welds made under conditions intended for production are the acceptance criteria. Impact or notch tensile tests may also be required, particularly for low temperature applications. Once good procedures are established, as evidenced by tensile and bend tests, they should be strictly followed in subsequent production welding. Although weld colour should certainly be included in any welding qualification

testing, ASME Code suggests that, if titanium weld metal hardness is more than 40 BHN (50VHN) greater than base metal hardness, excessive contamination is possible. A substantially greater hardness differential necessitates removal of the affected weld-metal area. The Code further specifies that all titanium welds be examined by liquid penetrant. In addition, full radiography of many titanium joints is required by the Code.

A European standard is currently being discussed for welder approval for titanium fabrication, but as yet (May '99) the final content of this document has not been ratified.

## HEALTH AND SAFETY

Welding fume generation from the common titanium alloys during TIG welding is minimal and there are no extraction requirements beyond those necessary for TIG welding other structural materials. Titanium will not

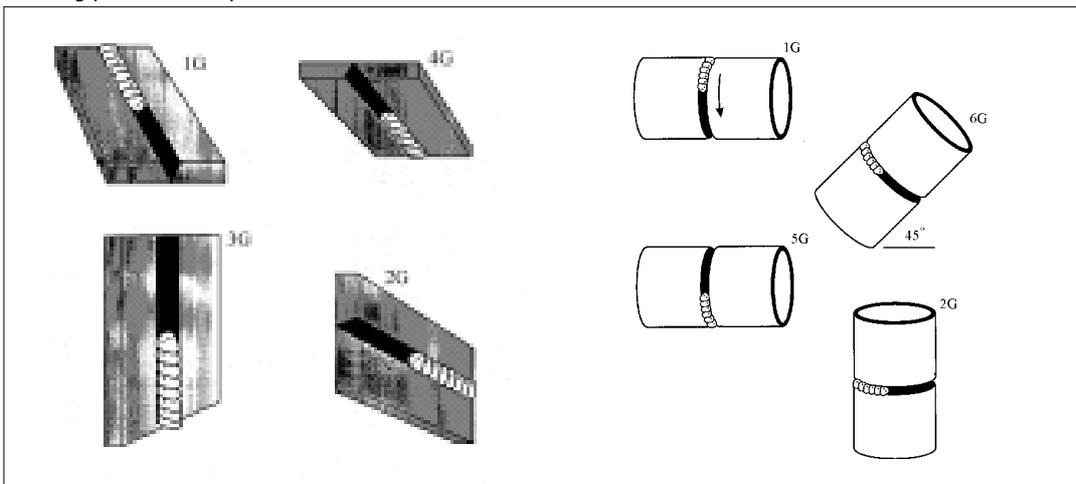
combust during welding. Instances in which titanium has caught fire are associated with finely divided material and ignition from combustible fluids or materials.

## GLOSSARY

**TIG:** tungsten inert gas or gas tungsten arc welding (GTAW)  
**MIG:** metal inert gas or gas metal arc welding (GMAW)  
**PAW:** plasma arc welding  
**DCEN:** Direct current electrode negative  
**DCEP:** Direct current electrode positive

**EB:** electron beam  
**RPEB:** reduced pressure electron beam  
**Nd-YAG** (laser) Neodymium-yttrium-aluminate-garnet  
**ASME** American Society of Mechanical Engineers

Welding positions for plate and circumferential welds.



## FOR FURTHER INFORMATION

The list of TIG Members over includes fabricators who will be pleased to assist with further information and advice. In addition, there are many industrial members of TWI that have considerable experience in fabricating titanium. Information on these companies can be obtained from TWI. Those looking for US fabricators should visit the following web sites: <http://www.welding-services.com>. The membership of TIG and the international Titanium Association includes many international specialist fabricators and these can be found on <http://www.titanium.net>.

## FOR HELP FROM TWI

**TWI**, Granta Park, Great Abington, Cambridge, CB1 6AL  
Tel: +44(0)1223 891162  
Fax: +44(0)1223 892588  
Email: [twi@twi.co.uk](mailto:twi@twi.co.uk)

## FOR WELDING CONSUMABLES

**Titanium International Ltd**  
Keys House  
Granby Avenue  
Garretts Green  
Birmingham B33 0SP, UK  
Tel: +44(0)121 789 8030  
Fax: +44(0)121 784 7694

**TIMET UK LTD**  
P.O. Box 704,  
Witton,  
Birmingham B6 7UR UK  
Tel : +44(0)121-356-1155  
Fax: +44(0)121-356-5413

**RMI Titanium Company**  
Riverside Estate  
Fazeley Tamworth  
Staffordshire S78 3RW  
Tel : +44(0)1827 262266  
Fax: +44(0)1827 262267

## FOR SHIELDING AND WELDING EQUIPMENT

**Huntingdon Fusion Techniques Ltd**  
Stukeley Meadows  
Huntingdon  
Cambridgeshire PE18 6EJ, UK  
Tel: +44(0)1480 412432  
Fax: : +44(0)1480 412841

## FOR BRAZING CONSUMABLES

**WESGO**  
GTE Products Corporation  
477 Harbor Boulevard  
Belmont, CA 94002, USA  
Tel: +01 (415) 592 9440

**Vacuum Brazing Consultants Ltd**  
The Hob Hill, Chapel Road  
Steeton  
Keighley BD20 6NU  
Tel: +44(0)1535 653598  
Fax: +44(0)1535 656707

## FOR FURTHER READING

There is a vast body of literature covering the joining of titanium and its alloys, far more than can be highlighted in this brochure. Request for information on specific welding issues should be directed to TWI.

L S Smith and M F Gittos: "High productivity pipe welding of Ti-6Al-4V alloys". TWI members report 660, November 1998.

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"AWS Welding Handbook, Materials and Applications Part 2", 8th edition, American Welding Society, Miami.

M J Hussion: "Practical use of a collapsible purge chamber for titanium welding". Welding Journal 66, July 1997.

Titanium: Design and Fabrication Handbook for Industrial Applications, TIMET, Titanium Metals Corporation 1997

B.Hanson, "The Selection and Use of Titanium - Designers Guide", Institute of Materials, 1995

## MEMBER COMPANIES OF TIG

Timet UK Limited  
PO Box 704  
Witton  
Birmingham B6 7UR  
Tel: 0121 356 1155  
Fax: 0121 356 5413

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Fax: 01332 864888

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Wyman Gordon Ltd  
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Livingston  
West Lothian EH54 5BZ  
Tel: 01506 446200  
Fax: 01506 446330

**Manufacturer of large titanium forgings including large diameter extruded tube**

Bunting Titanium Ltd  
34 Middlemore Industrial Estate  
Smethwick Warley  
West Midlands B66 2EE  
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Fax: 0121 558 8072

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Aerospace Forgings Ltd  
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Oldbury  
Warley  
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Fax: 0121 544 5731

**Manufacturer of closed die and hand forged titanium forgings**

TWI  
Abington Hall  
Abington  
Cambridge CB1 6AL  
Tel: 01223 891162  
Fax: 01223 892588

**Research, development and consultancy on joining techniques for materials including titanium**

Metal Improvement Co Inc  
Navigation House  
Hambridge Lane  
Newbury  
Berks RG14 5TU  
Tel: 01635 31071  
Fax: 01635 31474

**Surface treatment of titanium components to improve mechanical properties and to prolong service life**

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Riverside Estate  
Fazeley Tamworth  
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Fax: 0121 447 7493

**Stockist of titanium ingot, bar, plate, sheet, profile, tube and wire products**

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Super Alloys International Ltd  
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Fax: 01908 260494

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Woodville Swadlincote  
Derbyshire DE11 7JF  
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Fax: 01283 226468

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DERA  
Griffith Building A7  
Structural Materials Centre  
DERA Farnborough  
Hampshire GU14 0LX  
Tel: 01252 392540  
Fax: 01252 394135

**Research and development on materials including titanium**

Tecvac Limited  
Buckingway Business Park  
Swavesey  
Cambridge CB4 5UG  
Tel: 01954 233700  
Fax: 01954 233733

**Surface treatment of titanium particularly nitriding**

Titanium Mill Products Ltd  
Löwe House  
1 Ranmoor Crescent  
Sheffield S10 3GU  
Tel: 01142 308 855  
Fax: 01142 302 832

**Stockists of titanium wrought products**

Alba AS  
Lilleakerveien 23  
N-0283 Oslo  
Norway  
Tel: 47 22 50 00 20  
Fax: 47 22 50 01 11

**Titanium castings**

Deutsche Titan GmbH  
Altendorfer Strasse 104  
45143 Essen  
Germany  
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**Titanium fabricators**

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Katternberger Strasse 155-159  
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