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WELDABILITY OF TITANIUM AND TITANIUM ALLOYS

by

K. Winterton*

ABSTRACT

The literature on the welding of titanium and its alloys is reviewed.

Titanium is very reactive and is easily contaminated by carbon, hydrogen, oxygen or nitrogen. During welding, the hot metal must be protected at all times from the atmosphere, and it may be necessary to pay special attention to the purity of inert gases used for shielding.

Commercially pure titanium and the alpha alloys are the most readily weldable, and have been considered as a group. The alpha-beta and beta alloys can be joined, but the welds tend to be brittle, and vary in their response to heat-treatment. These alloys often need individual techniques and treatment to obtain optimum properties in the welded joints.

The most useful fabrication methods are tungsten inert-gas welding, metal inert-gas welding, and resistance spot and seam welding, and these have all been used extensively in aerospace applications. Good brazing methods have been developed and may be useful for "honeycomb" structures. Other specialized methods, such as electron-beam welding and explosive welding, have been tried successfully. In the U.S.S.R., submerged-arc welding and electro-slag welding are the most popular methods.

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SOUDABILITÉ DU TITANE ET DES ALLIAGES TITANÉS

par

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RÉSUMÉ

L'auteur passe en revue la documentation sur le soudage du titane et de ses alliages.

Le titane est chimiquement très actif: le carbone, l'hydrogène, l'oxygène ou l'azote le contaminent aisément. Au cours du soudage, le métal à température élevée doit être protégé à tout moment du contact avec l'atmosphère et il peut même être nécessaire d'accorder une attention particulière à la pureté des gaz inertes servant à le protéger.

Le titane de pureté commerciale et les alliages alpha sont le plus facilement soudables et sont étudiés ensemble. Les alliages alpha-bêta et bêta peuvent être soudés, mais les soudures tendent à être fragiles et réagissent différemment au traitement thermique. Il est souvent nécessaire d'utiliser des techniques et des traitements spéciaux dans le cas de chaque alliage pour que les soudures jouissent de qualités optimales.

Les méthodes de soudage les plus utiles sont le soudage à l'arc en atmosphère inerte avec électrodes de tungstène (TIG) ou fusibles (MIG), les soudages électriques par points et à la molette; toutes ces méthodes ont été employées couramment dans la construction d'engins aériens et spatiaux. De bonnes méthodes de brasage ont été mises au point et peuvent servir aux constructions en nid d'abeille. D'autres méthodes spécialisées ont été utilisées, telles le soudage par bombardement électronique et le soudage par explosions. En URSS, les méthodes les plus répandues sont le soudage à l'arc sous flux électroconducteur et le soudage électrique sous laitier.

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CONTENTS

PREFACE

A review is presented of the current state of technology in the welding of titanium and its alloys. For the most part, reliance has been placed on several excellent reviews and articles published in 1959 and 1960, and the subject has been brought up to date by reference to some of the work that has been done since that time.

Most emphasis has been placed on welding techniques, and on the modifications made necessary by the metallurgical characteristics of titanium in general and titanium alloys in particular. Mechanical properties have only been considered in qualitative terms. Quantitative values for these properties, together with details of weld settings, are readily available in the earlier reports, to which reference is made at the end of this bulletin.

GENERAL CONSIDERATIONS

Welded titanium and titanium alloy assemblies are used in aeroplanes, jet engines, missiles, and chemical equipment. These assemblies are fabricated from sheet, bar, plate and forgings, using a variety of welding processes that offer good atmospheric protection. The subject of welding titanium and its alloys has been reviewed previously(1-6).

(a) Protection

Titanium is a highly reactive metal, and, at the elevated temperatures necessary for most welding processes, will react with oxygen and nitrogen in the air, and indeed with most elements and compounds with which it is in contact, including all known refractories. The mechanical properties of titanium and its alloys are deleteriously affected by minute amounts of impurities, especially nitrogen, oxygen, carbon and hydrogen.

It is therefore essential that during welding the metal shall be carefully shielded, and sometimes this may require special precautions. Not surprisingly, the most successful welding processes include inert-gas welding in a vacuum-purged chamber, inert-gas welding in open air (provided that gas-backing and sometimes trailing shields are used), diffusion-bonding, and brazing. However, good success has been achieved with resistance welding, and in the U.S.S.R. the slag-shielded processes, i.e. submerged-arc welding and electro-slag welding, have apparently yielded satisfactory results.

Because of the danger of adding to the impurity content during welding, even under good control, it is important that the base material be purchased to specification requirements having maximum limits for nitrogen, oxygen, carbon and hydrogen.

(b) Inert Gas Purity

Argon is usually employed for shielding with tungsten inert-gas welding, but mixtures with helium are used for primary shielding with metal inert-gas welding, and, in general, to obtain good penetration and high welding speeds. Helium alone, although it promotes good wetting action, is inclined to give an unstable arc. It is sometimes used for back shielding.

For processes shielded by inert gas, contamination of the latter by air or water-vapour must be avoided, because of the undesirable effects on weld properties. Faulty valves, leaking transmission lines, or moist dirt in the equipment, may give trouble. The dew-point of the gas delivered for shielding should be measured and should not be higher than -20°F. In one series of tests(1), it was found that an increase in hydrogen level from 45 ppm to 100 ppm, together with a change in minimum bend radius from 13T to 19T, was associated with a change in dew-point from -20°F to -50°F.

It has been suggested(1) that it is better to use an argon system that changes the argon from liquid to vapour near the point of welding, rather than to use the argon from portable bottles that may become contaminated through improper handling.

Surface colouration is sometimes taken as an indication of contamination. However, this can be misleading. A bright finish can be obtained by a good trailing shield, although the results of poor primary shielding remain invisible.

One recommendation is to weld and bend test strips of titanium before and after the welding operation, as a check on the gas purity(1).

(c) Effect of Alloying

Commercially pure titanium (99.0 and 99.5% titanium) and the alpha titanium alloys may be treated as a group and are reasonably weldable. The alpha-beta alloys generally have unsatisfactory welding characteristics; despite the difficulties, some welding work has been done on certain of these alloys, because of the obvious advantages of having joining methods available for these high-strength materials. It is better to consider these alpha-beta alloys individually.

(d) Preparation for Welding

Various cutting methods are available for titanium, though oxy-acetylene cutting may be preferred for reasons of economy. With all thermal cutting processes, including those that normally provide good protection such as inert-gas tungsten-arc cutting, further removal of material by machining or grinding is necessary to provide clean, uncontaminated surfaces for welding.

Mill products are normally supplied free from heavy scale or even visible oxide. Forging or heat-treatment scale must be removed by molten-salt baths containing sodium hydroxide, or by vapour blasting or grit blasting followed by pickling. Light oxide scale may be removed by pickling in an acid solution, consisting of 30-40% nitric acid and 2-4% hydrofluoric acid, at temperatures below 140°F, followed by rinsing and drying. Bath composition is important, and a fall in the nitric acid content to 15% will be accompanied by a sharp rise in hydrogen absorption, depending on the titanium alloy composition. (It may also be noted that fuming nitric acid should not be allowed to come into contact with titanium, for an explosive reaction may result.)

Degreasing should be done with a spray application, followed by air drying. Chlorinated solvents are not recommended, for it has been found that trichlorethylene may cause stress-corrosion cracking. Acetone is satisfactory. Cleaning may also be done with a dilute solution of sodium hydroxide.

For fusion welding, the metal must at least be degreased, but abrasive cleaning followed by filing or wire-brushing, or pickling, is recommended. Pickling treatment may cause surface variations in electrical resistance and is not recommended for resistance welding. For manual welding, the filler wire may need a light sanding, followed by cleaning with a suitable solvent such as acetone.

(e) Stress Relief

After welding, stress-relief may be desirable. This is usually carried out in the range 1000-1200°F. It may be necessary to clean the assemblies before treatment if there has been any opportunity for contamination. The alpha-beta and beta alloys must be considered individually from the point of view of stress-relief; some of these alloys may be stress-relieved without difficulty; some may require special treatment, e.g., a short-term treatment within a closely controlled temperature range; and some may not be stress-relieved at all without serious embrittlement of the welded joints.

WELDING OF TITANIUM AND ALPHA TITANIUM ALLOYS

(a) Inert-gas Arc Welding

Mechanized equipment is recommended for welding in the open air, because the greater control makes it possible to provide better shielding. Tungsten inert-gas welding is preferred to metal inert-gas welding because the high heat input, characteristic of the latter, compounds the shielding problem. Longitudinal seams may be made by automatic tungsten inert-gas welding, using a jig with a backing mandrel. The latter incorporates a grooved copper backing insert through which inert gas flows to shield the root. A large shielding hood should be used, and trailing and lead shields may also be necessary. Supplementary shielding of the top surface by means of porous copper compacts incorporated in the hold-down bars has also been tried successfully. The metal should always be protected from the atmosphere at temperatures above 1000°F. For circumferential seams, an expansible fixture with segmented copper sections should be used to maintain close alignment with the inside diameter of the part. Chill rings should be securely fastened to the external surface, spaced 1/4 in. from the edge of the seam.

Manual welding is best done in a chamber, because the lower speed of welding and the lack of chill tooling make good shielding more necessary. Flow-purged chambers may be fixed or collapsible. Fixed chambers are purged by a volume of gas equivalent to 5 or 10 times the chamber volume, or, better still, they may be purged by alternate evacuation and filling with inert gas. Collapsible chambers are plastic bags that are repeatedly collapsed during purging. Vacuum-purged chambers provide the purest inert-gas atmosphere and are therefore recommended.

The weld settings for inert-gas arc welding may vary extensively, but for open-air welding the heat input should be low and the arc short, with a small molten pool. Better shielding permits more latitude in heat input and joint design. It is recommended that any coloured films, even though superficial, should be removed from the weld and heat-affected zone. This may be done by chemical or mechanical cleaning methods.

Cracking is usually only encountered in welds of the alpha alloy if gross contamination, by oxygen, nitrogen, hydrogen or carbon, has occurred. However, instances have been observed(7) of delayed cracking in unalloyed titanium weldments. This seems to be partly due to the formation of high residual welding stresses on welding under restraint. Hydrogen, even at concentrations of less than 100 ppm, is also thought to play a part, because hydrides have been identified in the vicinity of fracture. It is possible that stress can cause orientation of the hydride platelets, leading to planes of weakness(7).

Porosity is more common, and the causes are not fully known, although hydrogen is often suspected. It may sometimes be prevented and usually can be alleviated by improved cleaning and preparation of base metal and filler wire, or by allowing the gas to escape through the molten pool using somewhat increased heat input or reduced chill. A useful discussion on the factors affecting porosity has been prepared(8) together with some data on the influence of porosity on the properties of welded joints.

The alpha alloy Ti-5Al-2.5 Sn has been selected, partly because of its excellent weldability, for applications such as the frame of the Mercury capsule, pressure vessels for missiles, compressor cases and turbine inlet cases for jet engines, engine cowls, tail cones, and many other aircraft applications, and for cryogenic service (in slightly modified alloy form), all of which have required extensive inert-gas arc welding.

A fairly detailed description of the fabrication of small pressure vessels with 0.015 in. wall thickness, in commercially pure titanium, has been provided(9). The welding was done manually in a fixed enclosure. This application involved the use of copper chill straps and expandable aluminum fixtures.

An interesting use of commercial-purity titanium for a chemical plant has recently been described(10). Special shielding devices were built for the open-air tungsten inert-gas welding of tubing in all positions.

Laboratory work(11) to investigate the effect of various factors on the metal inert-gas welding of commercially pure titanium, especially downhand welding of 1/4 in. thick plate, was undertaken as a preliminary to providing procedures for remote welding of a reactor test core tank.

(b) Inert-gas Arc-Spot Welding

The inert gas arc-spot welding methods may be useful as a substitute for resistance spot welding when access from only one side is available(12). Tungsten arc-spot welding can be used for light gauge sheet, and metal inert gas arc-spot welding for thicknesses in excess of 1/8 in. The latter process involves a lower heat input, but precise control over wire straightness and contact-tube/weld-puddle distance is required.

(c) Electron Beam Welding

Electron beam welds have been made on titanium alloys in the thickness range 0.005 in. to 0.625 in.

Some experimental work has been carried out on several alpha alloys with sheet thickness approximately 0.1 in.(13). Welding was done at 14,000 volts with a current of 250 milliamp. and the welding speed was 8-10 in./min. In this case, the impact resistance of electron beam welds was equal to or better than that of the base metal, and considerably better than that of tungsten inert-gas welds. Some porosity was found, however, particularly in narrow welds. The alloy Ti-5Al-2.5Sn was considered to be commercially weldable.

Electron beam welding has been used for repair welding after machining errors, for welding on bosses and plugs, etc.

(d) Resistance Welding

Titanium and the alpha alloys may be successfully spot and seam welded. The high resistivity of the metal is an advantage. Weld variables are not unduly critical, and preheat and postheat are not required. Titanium resembles stainless steel in process requirements and in response of the metal to resistance welding. For flash welding, a short flashing time and high platen acceleration are recommended, to minimize exposure of the hot metal to the atmosphere. Low to intermediate upset pressures, 7,000-20,000 psi, are used. Inert-gas shielding has sometimes been used for flash welding, using external shielding (with a fibreglass enclosure) and internal shielding (for tubes and hollow parts).

Spot welding has been used in aircraft manufacture, and for the all-titanium cabin of the Gemini space capsule. Extensive spot and seam welding were required in the fabrication of the Mercury capsules. Spot welding, possibly regulated by numerically controlled programming, may be used for joining skins to stringers, and for window frames, in future supersonic transport planes(12). Flash welding is used almost exclusively to weld titanium rings for jet engines.

(e) Solid-State Bonding

Diffusion bonding of the titanium alloy, Ti-5Al-2.5Sn, to itself has been accomplished in a vacuum at 1850°F for 1 hour. Good fit-up is essential. Unit shear strengths equivalent to that of the base metal have been obtained. Diffusion bonding to other metals, such as stainless steel, involves the formation of a liquid eutectic. Fit-up need not be so precise, but time and temperature must be more carefully controlled. Some brittleness may result, so that for joining tubing, conical or cylindrical lap joints have been recommended.

(f) Brazing

Most of the brazing methods have been tried at least in the laboratory, including induction, furnace, resistance, torch and dip brazing. Production experience is limited, though no major obstacles are anticipated. Good reviews are available on the subject of brazing titanium and its alloys(1, 14).

Silver-lithium alloys (1-3% lithium in silver) and two silver-aluminum alloys (Ag-12½% Al and Ag-5 Al) are recommended for brazing titanium alloys, with brazing temperatures of 1400-1450°F, 1450°F and 1600°F respectively. It was found that the silver-lithium alloys had poor oxidation and corrosion resistance, and this led to the development of the silver-aluminum alloys with good resistance both to salt-spray corrosion and to prolonged exposure at 800°F. Other materials, such as the nickel-titanium alloys, have been used with a short cycle to minimize eutectic formation.

Special fluxes have been developed for torch brazing, usually mixed chlorides and fluorides, but because of the reactivity of titanium they must be carefully removed after brazing. A successful proprietary filler and flux have been developed by the Curtiss-Wright Corporation(14).

Usually, it is best to protect the metal by means of inert-gas or vacuum. A vacuum of 10^{-5} mm (Hg) or, alternatively, pure argon with a dew-point in the range -40°F to -70°F, may be necessary to prevent discolouration during brazing.

(g) Slag-shielded Welding Processes in the U.S.S.R.

In the U.S.S.R., since about 1956, submerged-arc welding has been used for joining titanium in the thickness range 0.08 in. to 2 in. Electro-slag welding is used for thicker plate. The analysis of the flux used for submerged-arc welding has never been published, although it is stated to consist of an oxygen-free mixture of chlorides and fluorides. A report(15) is available on the subject of welding titanium and its alloys in the U.S.S.R.

Submerged-arc welding is accomplished with a powdered slag back-up. A special hand gun has been developed for semi-automatic submerged-arc welding of titanium. A shorter electrode stick-out is recommended than that used for steel. With proper control, gas content is not increased in the weld metal over that present in the base metal. It has been claimed that the ductility of a single-pass submerged-arc weld is superior to that of a multi-run, argon-shielded, tungsten inert-gas weld, though the comparison has been clouded, on occasion, because of the use of impure argon.

An alloy development program, for which weldability was a prime consideration, showed that heat-affected zone cracking was apt to occur with a total content of beta-stabilizing elements in excess of about 3-3½%. The alpha-stabilizing elements had little effect. The high heat input of submerged-arc welding results in grain growth. This may be minimized in the weld metal by an addition of 0.2% rhenium to the filler metal, though without benefit to any grain growth that may occur in the heat-affected zone.

Submerged-arc welding is much faster than tungsten inert-gas welding, but there are no data on a similar comparison with metal inert-gas welding. It has been used for 18 in. diameter cylindrical pressure vessels.

Electro-slag welding is used for joining thick titanium alloy plate. The flux is dried by baking at 600°F for 2 hours. Its composition is similar to that used for submerged-arc welding, but with higher melting and boiling points. The molten slag is protected from the atmosphere with an argon shield. Ductility and impact strength are better with the heat input kept low.

Applications for electro-slag welding include the joining of large rings and forgings.

WELDING OF ALPHA-BETA AND BETA TITANIUM ALLOYS

As mentioned before, the welding characteristics of the alpha-beta titanium alloys as a group are generally not satisfactory, especially by fusion welding. The joints tend to be brittle as measured by bend tests. Exceptions are Ti-6Al-4V and Ti-16V-25Al, both of which contain only small amounts of beta phase.

The beta alloys do not necessarily respond to welding as do the alpha-beta alloys. The alloy Ti-13-V-11Cr-3Al has a metastable beta structure responding sluggishly to heat-treatment. It can be welded, in the solution-treated or the age-hardened condition, with the same facility as the alpha alloys. However, ageing in service may result in a brittle weld. Recently, treatment of the welded base metal by cold rolling, followed by ageing or duplex ageing, was recommended.

Unlike the alpha alloys, the alpha-beta and the beta alloys rely for their properties on heat-treatment. Welding the heat-treated alloy is likely to cause softening. A better solution is to heat-treat after welding, although some difficulty may arise in connection with the response of the weld metal to heat-treatment. These are problems associated with the welding of all heat-treatable alloys.

(a) Inert-gas Arc Welding

The same procedures are followed as given previously for the alpha alloys. However, welded joints in alpha-beta alloys sometimes tend to be brittle, and heat treatment may or may not be desirable to develop optimum properties.

The alloy Ti-5Al-2.7Cr-1.25Fe gives good ductility in the as-deposited condition, and the rather low joint strength cannot be much improved by heat-treatment. Similarly, the Ti-4Al-3Mo-1V alloy(16) gives 85% joint efficiency and reasonable ductility in the as-welded condition on heat-treated base metal, but elevated temperatures in post-weld heat-treatment or in service may lead to brittleness.

Studies have been made by the Boeing Airplane Co. aimed at improving the tensile strength and ductility of joints in the Ti-6Al-4V alloy(17) by heat treatment. It was found that the strength of the as-deposited weld could be improved by heat-treatment, but only annealing, which resulted in relatively low joint strength, was successful in improving weld ductility.

The Ti-6Al-6V-2Sn alloy(18) also requires annealing after welding, to obtain reasonable ductility. For example, the Titanium Metals Corporation recommend a Ti-3Al alloy filler for use in the welding of Ti-6Al-4V, and claims that joint efficiencies of 90-105% can be obtained with good results.

The beta alloy, Ti-13V-11Cr-3Al, is readily weldable by tungsten inert-gas welding, with 100% joint efficiency and good ductility in the as-deposited condition(19, 21). The weld metal suffers loss of ductility on annealing, accompanied by the appearance of a grain-boundary precipitate, which may be alpha phase; and a loss of ductility also occurs in the weld metal on ageing. Considerable work has been done to determine the best treatment after welding, to develop optimum properties. The variables investigated include magnetic stirring of the weld metal to induce grain refinement, single and duplex ageing treatments, sometimes preceded by cold-working by roll planishing, ageing followed by flash-annealing, etc. It appears, however, that with maximum strength in the base material, at least a slight loss of either strength or ductility must be sustained in the welded joint.

Various alpha-beta and beta alloys have been used for pressure vessels. Missile fuel and oxidizer tanks, for example, are fabricated in high-strength titanium alloys with up to $\frac{1}{2}$ in. wall thickness. Welding has been done by open-air techniques, usually by metal inert-gas welding. Filler wire of matching composition is usually preferred, but sometimes commercially pure titanium filler metal has been used, and in this case the weld section must be increased to compensate for lower strength. Burst tests on finished vessels show that the fractures are usually perpendicular to the welded joints.

Prototype work to develop procedures for the fabrication of cupolas for light-weight armoured vehicles has been described(22). The alloy Ti-4Al-4V was selected on the basis of strength and ballistic impact resistance. Commercially pure titanium filler wire was used because of its greater tolerance for contamination and lower sensitivity to cracking. Welding in the open air with trailing shields was abandoned because of inconsistent bend test results and surface contamination. All welding was done in fixed enclosures of varying size.

A program(23) aimed at developing procedures for the superstructures of armoured vehicles showed that annealed hot-rolled Ti-6Al-4V plate in thicknesses of up to 2 in. could be welded in all positions, using metal inert-gas welding. Filler of the same composition provided better strength and ballistic shock resistance than did commercially pure titanium filler metal, though some preheat was necessary to prevent transverse crack formation. Preheating was carried out at 125°F with an interpass temperature in the range 125-175°F. A mechanical problem described as "wire whip", apparently associated with wire stiffness and bending of the wire on passing through the equipment, was alleviated by the provision of an overhead roller support for the wire-carrying cable. The effect of post heat-treatment was apparently not investigated.

Work is in progress on the use of titanium alloys for deep submersible vehicles(24). Metal inert-gas welding is preferred because of the considerable thickness involved (2-3 in.), though submerged-arc welding may prove to be a practical alternative method.

(b) Electron-Beam Welding

Some work(13) has been done on three alpha-beta alloys, i.e., Ti-6Al-4V, Ti-16V-2.5Al and Ti-4Al-3Mo-1V, with sheet thickness in the range of 0.085 to 0.125 in. Welds were made at 14,000 volt, 250 ma, and 8-10 ipm welding speed. As a result, the Ti-6Al-4V alloy is considered to be commercially weldable by electron-beam welding. One of the above alloys, Ti-16V-2.5Al, and a beta alloy, Ti-13V-11Cr-3Al, included in the same program, were found to be weldable but did not respond satisfactorily to post-weld heat treatment. It has been stated that joints with greatly improved ductility and notch-toughness have been made in the Ti-13V-11Cr-3Al beta alloy by electron-beam welding, as compared with normal welding techniques (presumably inert-gas welding).

(c) Resistance Welding

Most of the alpha-beta alloys, including some not considered weldable by fusion processes, can be spot and seam welded, e.g., Ti-6Al-4V, Ti-4Al-3Mo-1V, Ti-5Al-2.7Cr-1.25Fe, Ti-16V-2.5Al, and Ti-8Mn. The shear strength of spot welds is satisfactory and comparable with that of welds in stainless steel, but the normal tensile strength is much lower, indicating poor ductility. Post-weld treatment generally causes embrittlement, so that it is preferable to age the material before welding and put it into service without further heat-treatment. Elevated temperature service may cause embrittlement, particularly with the Ti-16V-2.5Al alloys. The Ti-6Al-4V alloy seems to behave best from this point of view for service at temperatures up to 800°F.

The beta alloy, Ti-13V-11Cr-3Al, has been satisfactorily spot-welded and compares with the best of the alpha-beta alloys. However, exposure to temperatures above 400°F after welding is likely to cause some embrittlement.

Flash welding seems to be a more suitable process for the alpha-beta alloys than are fusion welding or spot welding, because of the elimination of fused weld metal. The resultant joint responds to heat-treatment as does the parent metal. Static and fatigue properties of flash-welded alpha-beta joints are satisfactory.

(d) Solid-State Bonding

Pressure welding is used successfully for joining the alpha-beta alloys, with cross-sectional areas in the range 4-50 sq. in. The process is applied for the production of spherical and cylindrical pressure vessels used in missiles, mostly using the Ti-6Al-4V alloy, but also with the Ti-7Al-4Mo alloy which gives a little greater ductility. Bar products and extruded shapes have also been joined by pressure welding. Pressure welds may be used in service in the annealed and also the age-hardened condition.

Diffusion welding may be useful in producing satisfactory joints without melting. Ultrasonic welding, however, has not been entirely satisfactory, because high temperatures (1400-1800°F) produced at the interface can result in undesirable phase transformations and age-hardening reactions. Intermittent weld cracking and variable weld strength are problems with this method. Similarly, the use of ultrasonic welding to join titanium alloys to other metals may not prevent the formation of brittle compounds characteristic of fusion welds.

(e) Explosive Welding

Successful explosive welds were made on the Ti-6Al-4V alloy in sheet of 0.020 in. thickness. A hard white film, probably martensitic, 0.00025 in. thick, formed at the interface. Bending did not cause separation. Satisfactory tensile strength was observed on lapped specimens(25).

Attempts were made to weld the beta alloy Ti-13V-11Cr-3Al, without success, though the possibility of successful welding was not discounted(25).

(f) Brazing

The same methods are used as previously discussed for the alpha alloys. It is desirable, in brazing the wrought alpha-beta alloys, to keep the brazing temperature below the beta transus for the alloy, in order not to affect the fine-grained equiaxed alpha-beta microstructure. If the alloy is to be used in the annealed condition, brazing may be carried out at the annealing temperature. If higher temperatures are necessary for brazing, step-cooling may be used to obtain an annealed structure or, alternatively, annealing is carried out after brazing. If the alloy is to be used in the solution-treated and aged condition, it may be possible to braze at the solution-treatment temperature and age after brazing. If higher temperatures are necessary for brazing, then solution-treatment and ageing must be done after completion of the brazing operation. Alloys such as Ti-6Al-4V may not be too satisfactory, as they require rapid cooling after solution-treatment.

The beta Ti-13V-11Cr-3Al may be brazed in the annealed condition. It is considered promising for applications requiring heat treatment. Transformation is sluggish, and the alloy can be furnace-cooled after brazing, and aged subsequently, without loss of strength.

One of the most important potential applications for brazing the high-strength titanium alloys is in the fabrication of titanium sandwich structures. Filler metal must not attack the thin foil core sections. Precautions to prevent contamination may include up to six cycles of evacuation and argon-purging of the furnace chamber, the use of welded seals, heated titanium to getter the argon, etc.

Brazing has been used to fabricate prototype components for airframes, jet engines, missiles, and electron tubes, but production experience is somewhat limited.

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