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REVIEW OF TITANIUM AND STEEL WELDING METHODS

ABSTRACT

The paper presents review of methods of titanium and steel welding. On basis of professional literature it was stated that titanium can be joined with steel by means of explosive welding or brazing. Joining titanium with steel by TIG welding and friction welding methods is possible with the use of copper and tantalum or vanadium interlayer.

Key words: *titanium, stainless steel, TIG welding, explosive welding, friction welding, brazing*

INTRODUCTION

Titanium and its alloys are characterized by high strength at relatively low specific gravity as well as by high corrosion resistance in the air, in sea water and in many corrosive environments. In consideration of its properties titanium is used in chemical industry, aircraft industry and nuclear power engineering [1,2]. Disadvantage of titanium is its high price. Commercial pure titanium is about 10 times more expensive than stainless steels and about 100 times more expensive than plain steels.

High price is the cause that generally elements are made not of the titanium but of cheaper constructional materials cladded with a layer of titanium. This is the way of producing e.g. tanks for municipal wastes containing significant quantities of chlorine [3]. In practice these is also a necessity of joining elements made of titanium with steel elements. An example may be a connection of titanium exhausted pipes with steel ship hull.

It is not possible to make a joint of high mechanical properties by direct titanium with steel using arc, laser beam, electron beam or friction welding methods [4-7].

Joining of titanium with steel is effected with the use of suitable interlayers or special welding methods. The aim of this paper is to present joining methods titanium with steel and pointing out advantages and disadvantages of each method.

TIG WELDING

Arc welding of titanium with steel produces in the joint cracks caused by occurrence of brittle intermetallic phases generated in result of incomplete solubility of iron in titanium. From literature [5] it follows that in titanium – iron solution containing over 0,1% Fe occurs generation of very hard intermetallic phase TiFe or Ti_2Fe (Fig. 1).

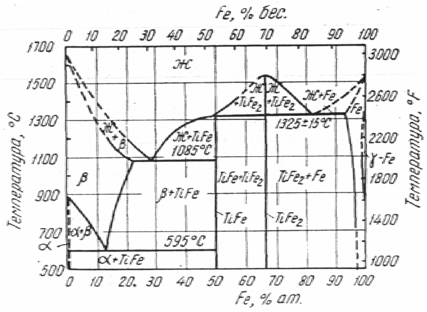

Fig. 1. The equilibrium iron - titanium diagram [5]

Joining of titanium with steel should be made with the use of properly choiced material. Welded joint of titanium alloy OT4 with 1X18H9T steel made by TIG method were produced with application of a plate of technical tantalum on the titanium side and bronze plate on the steel side. Application of such technology for welding 1,5 mm thick sheets allowed to make welds without any defects. Also mechanical properties of these welded joints were satisfactory. In case of joining technical titanium with steel tantalum sheet may be replaced by a vanadium one [5]. A disadvantage of TIG welding of titanium with steel is the necessity of using very expensive sheets of tantalum or vanadium and a multi – step process of making the joints. An advantage is the possibility of using general purpose welding units.

EXPLOSIVE WELDING

Explosive welding it is a joining method in which the joint is obtained in result of dynamic pressure on joined surface, generated by energy released by explosive materials detonation [8]. This method may be applied for production of titanium cladded sheets and forged disks [9]. First trials of explosive welding titanium with steel were carried out in Poland already in the seventies of the last century [10]. During explosive welding titanium with steel on the joint surface forms a layer of intermetallic phases, but its thickness is significantly lower than in other joining methods. Moreover, process of waves formation on boundary of the joint disturbs continuity and coherence of this layer (Fig. 2), so its strength grows [3]. Explosive welding ensures achieving very high strength properties of joined sheets. For example, at welding of 6000 mm long and 1250 mm wide plates achieved shear strength was up to R_s = 430 MPa [9].

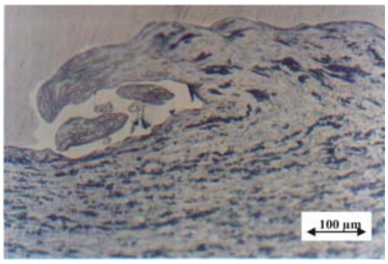

Fig 2. Microstructure of titanium – steel joint. In the area of created wave white intermetallic phase is visible [11, 12]

Advantages of explosive welding titanium with steel are as follows:
- possibility of welding both large and small elements,
- very good mechanical and technological properties of joints,
- low cost of joining.

Disadvantage of explosive welding titanium with steel is before all the necessity to have a special place, where the joining can be carried out (firing grounds, quarries) and a correct choice of explosive welding parameters [11,12]. At present, on the home market explosive welding elements are supplied for commercial purposes by Explomet [13].

FRICTION WELDING

Trials of direct friction welding of titanium with Armco iron have also shown that it is not possible to avoid creation of intermetallic phases in the whole joint. Amount of heat released in particular points of surface, which is a composite function of distances from axis of rotation, leads to generation of areas with intermetallic phases, especially at a distance of ca 2/3 of radius from the centre of specimen. Application of shorter joining times does not ensure obtaining correct joins along the whole cross – section of specimen [14].

Fig. 3 shows microstructure of titanium – Armco iron joint. In the place of intermetallic phases occurrence the microhardness reaches the value of 700 HV 0,015 and there appear microcracks. Linear distribution of chemical composition of titanium and iron (Fig. 3) drawn across such joint shows occurrence of phases from the equilibrium Fe – Ti diagram.

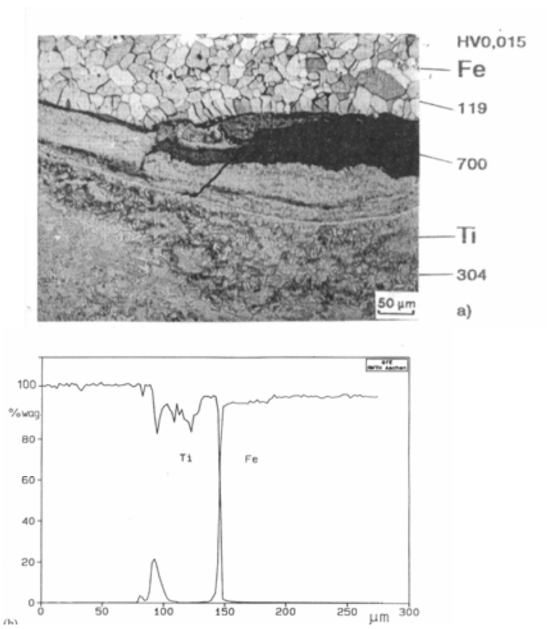

Fig. 3. Microstructure and linear distribution of titanium and iron in titanium – Armco iron joint [14, 15]

Since direct joining of titanium with iron proved unsuccessful it was decided to apply interlayers of vanadium and copper in titanium - X10CrNiTi189 steel joints often met in practice. Macrostructure of such a joint is shown in Fig. 4.

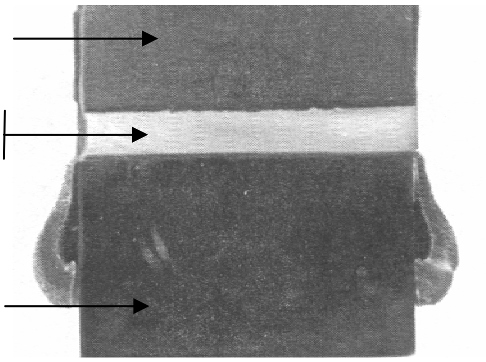

Fig. 4. Microstructure of titanium - X10CrNiTi189 austenitic steel joints welded by friction method [14]

Joining titanium with X10CrNiTi189 steel was done in three stages:
1) joining of X10CrNiTi189 steel with copper,
2) joining of titanium with vanadium,
3) joining of titanium – vanadium elements with elements composed of copper - austenitic steel.

Obtained joint had ca 3,5 mm thick layer of vanadium and ca 0,3 mm thick layer of copper. Its average tensile strength was 404 MPa and specimens broke in copper interlayer. Calculated temperature distribution in friction welded copper/ X10CrNiTi189 steel joints were used in designing interlayer of 18/9 type austenitic steel for St575 steel – TiAl6V4 titanium alloy joints.

As stated before titanium – steel joints of satisfactory strength properties may be done using interlayers of copper and vanadium. However, during joining St575 carbon steel and copper the termal cycle causes on steel side, at the joint surface, hardening structures of ca 700 HV 0,025 microhardness, which do not disappear in the process of welding next elements (Fig. 5).

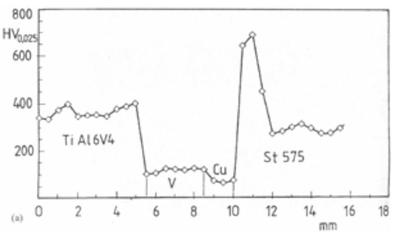

Fig. 5. Microhardness distribution in friction welded joint St575 steel - TiAl6V4 titanium alloy (joint with vanadium – copper interlayers) [14]

Heat treatment, which could remove changes occurring in the steel would cause soft annealing of copper interlayer what would significantly decrease strength of the whole joint. To avoid such situation it was decided to apply a second interlayer of 18/9 austenitic steel. It's aim to protect St575 steel against heating up to austenitizing temperatures (850°C) during joining with copper and later during joining with vanadium – titanium alloy joint. Minimum thickness of X10CrNiTi189 steel layer was 3,5 mm.

The joints were made in such a way that in the first place there was welded the joint St575 - X10CrNiTi189 steel, which was subjected to soft annealing (680°C, 1 h) then, leaving out the 3,5 mm thick layer of austenitic steel, first joints with copper then with vanadium – titanium alloy specimen were made. These joints didn't show dangerous increase of microhardness on St575 steel side (Fig. 6) and tensile strength of the whole joint was 454 MPa [14, 15].

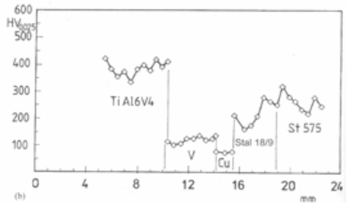

Fig. 6. Microhardness distribution in friction welded St575 - TiAl6V4 titanium alloy joint (joint with vanadium – copper - X10CrNiTi189 steel [14, 16]

Disadvantages of friction welding titanium with steel:
- necessity of applying interlayers what prolongs the time of joints preparation,
- application of vanadium increases significantly costs of joints preparation due to its high price and limited availability on Polish market,
- high labour consumption.

Advantage of friction welding is possibility of joining bar shaped elements.

SOLDERING OF STAINLESS STEEL AND TITANIUM

Components of titanium and stainless steel are generally joined by furnace brazing or more rarely by induction in vacuum of at least 10^{-1} – 10^{-2} Pa or in a pure neutral atmosphere [17, 18].
To this purpose silver – copper braze fillers (most often braze filler of eutectic Ag72Cu28 composition and 779°C melting temperature) are used. However, application of this braze filler may cause occurrence in the joints of brittle intermetallic phases of copper and titanium and of somewhat more plastic phases of silver and titanium. Laboratory research on modification of chemical composition of above mentioned silver braze filler joints in order to improve the strength of stainless steel – titanium joints showed a positive result for AgCu24In14Ti filler metal. There are also known cases of subject brazeing of materials system with silver filler metals with copper content limited to 10 % [18]. However, these filler metals, while reducing number of brittle phases of titanium with copper, show low wettability of stainless steel and unfavorable brazeing temperature exceeding 900°C.
From other specialistic braze fillers for joining titanium, for stainless steel – titanium system in particular cases filler metals such as Ti-Zr-Be, Ti-Ni-Cu, Ni-Cr-Fe-Si-B, Au-Ni and Pd-Ag-Si may be used.
Titanium filler metals (the first of them contains toxic beryllium) and nickel filler metals are rather brittle and they are produced only in the form of the powder or amorphous strips, golden and palladium filler metals are very expensive, so they are not recommended for common use. Moreover, except palladium braze fillers, they are conductive to occurrence of brittle phases with titanium in brazed joints (they contain copper and nickel) and considering relatively high melting temperature they require very short brazing time, what in furnace brazing processes is pretty difficult [18].
To prevent development of brittle intermetallic phases while brazing titanium and stainless steel it is sometimes recommended to cover the jointed surface of titanium

with a layer of metal or alloy which would form a protective barrier against diffusion of braze filler components. Also interesting is the form of application by PDV method of three - layer coat of Cr-Ni-Cu type which is also a filler metal in brazing process (brazing temperature 990°C). However, application of two- and three - layer coats in brazing stainless steel and titanium makes this process much more difficult and raises costs.

In order to determine the influence of conditions and parameters of brazing on kinetics of formation, structure and mechanical properties of stainless steel (X8CrNiTi18-10) – titanium (Grade2) joints, in Welding Institute at Gliwice some joints with the use of silver braze filler B-Ag72Cu-780 were made acc. to PN-EN 1044 [18].

Test joints for strength and structural tests (rolled specimens) were made in vacuum furnace (S-16 type from TORVAC) in vacuum over $1{,}33 \times 10^{-1}$ Pa. Brazing temperatures and time of holding the joints in these temperatures, conditioned by brazingability of stainless steel and titanium with silver braze fillers as well as allowing to observe changes of mechanical and structural properties of joints, were contained in the range 820÷900°C/ 540 min.

Shearing tests showed the best properties of brazed joints at temperatures: 900°C – at hold time 5-15 min (160-162 MPa) and 860°C at hold time 15 min.

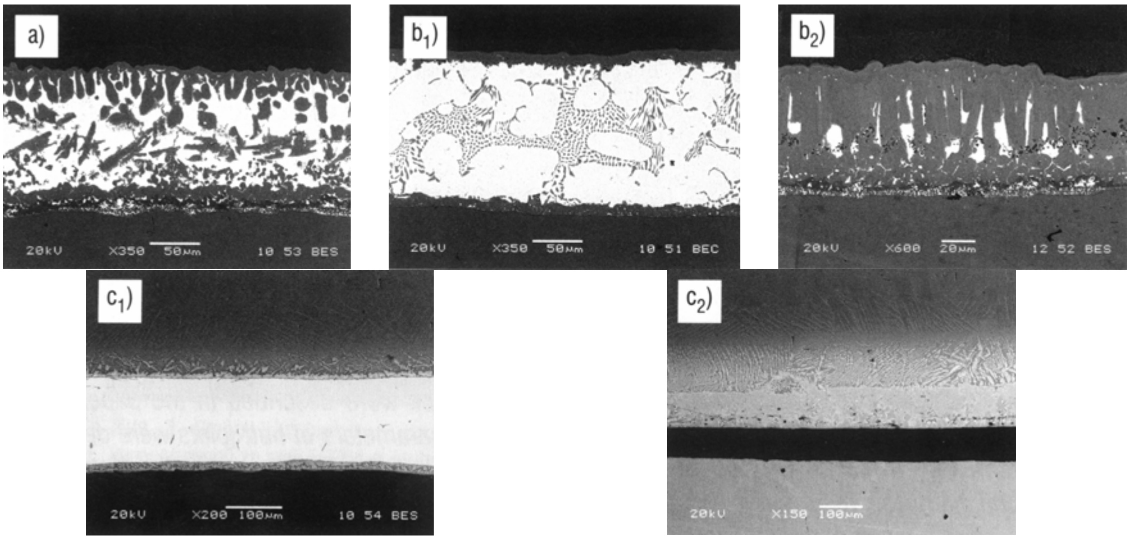

Fig. 7. Structure of stainless steel (bottom) – titanium (top) joint furnace soldered in vacuum with silver braze filler B-Ag73Cu-780 at temperature 820°C (a), 860°C (b), 900 °C (c); b_1, c_1 and b_2, c_2 - respectively „silver enriched" and „copper enriched" structures; in structures c_1 i c_2 a crack on soldered joint – stainless steel boundary [18]

Joints structures at temperatures of 820, 860, 900°C differed between themselves (Fig. 7). On titanium side the brazed specimens showed occurrence of eutectoid lamellar structure composed of solid solutions with copper and with silver. Below this layer in structures of specimens brazed at temperature 820°C and 860°C a layer of Ti – Cu phase composed of sublayers of increasing Cu (from 26 to 50% at) and Ag (from 1 to 7% at) content occurred. Diffraction electron analyses showed that this layer, ending with a corrugated columnar surface, is composed of solid solution on the matrix of Cu_3Ti_2 phase with precipitates of Cu_4Ti, Cu_2Ti phases and with small precipitates of titanium and of solid solutions on the matrix of silver and $Ag_{17}Cu_{17}Ti_{66}$ phase.

Solid solution on the matrix of Cu_3Ti_2 phase occurs also in the form of inclusions in eutectic structure of Cu – Ag in central part of soldered joints made at temperature

820°C. In soldered joints made at higher temperatures, i.e. 860°C and 900°C two kinds of structures were found.

In described joints of stainless steel and titanium these occurs also a part of brazed joint copper enriched (dark) and silver enriched (light) (Fig. 7 b,c). With the rise of temperature and longer soldering time a part of structure silver enriched, occurring at first in the form of interrupted segments on the joint cross – section, becomes concentration in its central part. In matrix of this structure is a solid solution based on silver and containing (% at): 90-97% Ag, 2-9% Cu, the rest Ti and Fe. The base of copper enriched structure is solid solution on the base of intermetallic phase Cu_3Ti_2 (45+64% Ti, 23+49% Cu, the rest Ag, Fe, Cr, Ni). In described brazed joints structures on the steel side these occur layers of phases of homogeneous and heterogeneous structure and of the contents (% at.): 24-80% Ti, 24-40% Cu, 20-30% Fe (the rest Cr, Ni, Ag). They are composed of multicomponent solid solutions on the base of intermetallic phases such Cu_3Ti_2, CuTi, Cu_3Ti, Cu_4Ti_3, Ti_2Cu, $Ag_{17}Cu_{17}Ti_{66}$, NiTi, $FeTi_2$ and of inclusions of solid solutions on silver base and $Ag_{17}Cu_{17}Ni_3Ti_7$ phase. In narrow (1-3 μm) layers containing: 58-69% Fe, 19-28% Cr, 1,5-8% Ti the rest NI, Cu, Ag, adjacent directly to the steel surface, occurrence of solid solutions on the base of the intermetallic $CuTiCu_{13}Fe_35Ti_7$ phases was observed. Phase layers on the steel side of relatively high steel composed (Fe, Cr, Ni) contents and microhardness in the range 300-400 HV 0,05 are decisive as regards mechanical properties of joints (here occurred fracture of specimen during tensile tests).

The best properties of titanium/stainless steel joints soldered with the use of silver solder B-Ag72Cu-780 is achieved at process temperature 860°C and hold time ca 15 min. [18, 19].

Disadvantages of hard titanium – stainless steel soldering are as follows:

- necessity to maintain relatively narrow range of soldering temperature (850-900°C), limited on one side by pretty high temperature of stainless steel wettability by braze fillers in controlled atmospheres and in vacuum and on the other side by the temperature of 900°C which should not be exceeded for titanium because of possible structure changes,
- requirement on one side to apply short brazing times because of reactivity and adverse structural changes of titanium as well as generation of brittle intermetalic phases in the joints and on the other hand necessity to apply prolonged times for the full wetting of stainless steel with braze fillers (especially silver braze fillers),
- limited size of brazed elements due to limitations connected with the size of vacuum furnace chamber.

Advantage of soldering is a possibility to connect pipes.

CONCLUSION

1. The best method of production of titanium clad steel sheets seems to be the method of explosive welding.
2. TIG welding and friction welding requires using expensive vanadium interlayers and is highly labor - consuming.
3. Soldering in vacuum furnace enables to join titanium and steel in the form of sheets and pipes.

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