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ARGON-ARC WELDING OF TITANIUM AND ITS ALLOYS USING FLUXES (REVIEW)

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In 1950–1980 PWI laid the scientific foundations of development of fluxes for welding and melting titanium and its alloys. Technology of automatic consumable electrode welding of titanium with application of oxygen-free fluxes was developed. Processes of tungsten electrode argon-arc welding over a layer of flux (TIG-F) and tungsten electrode welding with application of titanium flux-cored wire (TIG-FW) were developed. These methods expand the technological capabilities of tungsten electrode arc welding, provide high quality of titanium welded joints and guarantee absence of pores in welds. 17 Ref., 4 Tables, 9 Figures.

Keywords: *automatic arc welding, argon-arc welding,titanium alloys, consumable electrode, nonconsumable electrode, oxygen-free fluxes, flux-cored wire*

Complexity of technological processes of titanium welding is due, primarily, to its high reactivity. In welding, titanium actively absorbs gases from the environment leading to an essential lowering of ductile characteristics of the weld. In addition, pores can form in the weld that abruptly lowers fatigue characteristics of welded joints.

One of the founders of studies conducted at PWI to solve the problems of welding titanium, as well as reactive, refractory and non-ferrous metals, was Prof. S.M. Gurevich. Many years of work of the research team led by him, allowed solving for our country the problem of producing sound welds of titanium and its alloys. Owing to detailed investigations, performed under the leadership of Prof. S.M. Gurevich, scientific fundamentals for development of oxygen-free fluxes were laid, and fluxes for titanium welding were developed. As a result, application of practically all the known methods of fusion welding became possible at present to produce titanium welded joints, including consumable electrode submerged-arc welding, tungsten electrode welding, electroslag and electron beam welding, as well as solid-phase welding.

Automatic consumable electrode welding of titanium with application of oxygen-free fluxes. Consumable electrode submerged-arc welding taking one of the leading positions in modern industry by the scope and scale of commercial application, has a number of significant features, compared to other processes. First of all, this is the presence of a shell of molten flux, covering the welding zone and protecting it from harmful effect of atmospheric gases. Here interaction of metal and flux-slag takes places, and metallurgical reactions are running which may lead to weld enrichment in impurities.

It is known that fluxes applied for welding steels, have different oxidizing properties with respect to iron. Investigations conducted in 1950s in our country and abroad showed that in welding titanium even with low-silicon fluxes, conditionally called basic, which are characterized by the lowest oxidation ability, the metal is intensively saturated with oxygen, leading to a brittle joint [1].

As a result, in the initial period of industrial application of titanium as a structural material, some foreign researchers even denied the principal possibility of submerged-arc welding application for titanium, as at that time metallurgists failed to select a material that would not react with it or contaminate it with oxygen [2].

Theoretical studies, confirmed by experimental work conducted at PWI under the leadership of Prof. S.M. Gurevich, allowed refuting this erroneous opinion. Possibility of welding titanium using special refractory fluxes was proved, principles of construction were established and new systems of halogene oxygen-free fluxes were created [3].

Analysis of metallurgical and technological features of welding titanium allowed defining special requirements, which should be met by the developed flux systems. The main of them is complete absence of oxides. It was established that presence of even such stable oxides as Al_2O_3, ZrO_2 and TiO_2 in the flux does not prevent weld metal oxidation (Figure 1). Only complete removal of oxides from the flux ensures oxygen content below 0.1 % in the deposited metal.

Investigations, led by Prof. S.M. Gurevich, showed that oxygen-free fluxes for welding titanium and its alloys, meeting the above requirements, can be created by applying fluorides and chlorides of alkali and alkali-earth metals as their components [4]. Interaction of weld pool metal with the flux should be considered primarily as one of the most important metallurgical features of submerged-arc welding of titanium. Thermodynamic calculations, as well as results of some direct studies showed that two types of reactions can run: titanium reaction

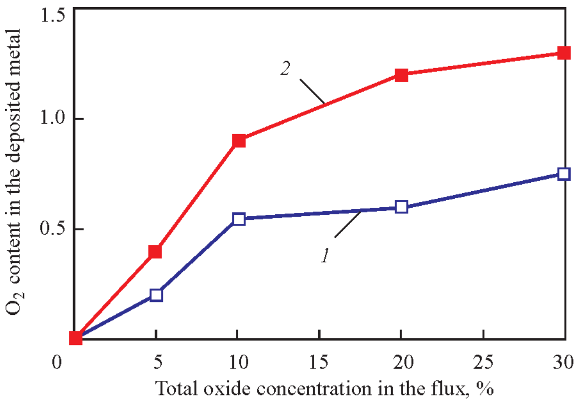

Figure 1. Oxygen content in the deposited layer, depending on concentration of some oxides in the flux: *1* — Al_2O_3; *2* — SiO_2

with flux components and titanium oxide reaction with the flux. Thermodynamic calculations, studies of the slag crust and deposited metal allowed formulating requirements to fluxes for welding titanium alloys:

- for a more complete interaction of flux with titanium and its oxides it is desirable for the flux composition to contain maximum amount of fluorides and minimum amount of chlorides;
- the most suitable components for the flux are fluorides, characterized by the greatest ability to react with titanium oxides.

The best results were obtained when CaF_2 was used as the flux base. An important property of this refractory fluoride is its ability to intensively interact with water vapour with formation of hydrogen fluoride, presence of which in the arc zone was established experimentally. Thermodynamic calculations show the possibility of running of a reaction between CaF_2 and water vapour at temperatures above 2000 °C. Ability to remove absorbed moisture from the welding zone and owing to that, protection of weld metal from saturation with hydrogen and oxygen, is an important feature of welding titanium using CaF_2-based flux, that is one of the causes of complete absence of porosity in welds made with consumable electrode using fluoride fluxes.

Selection of optimum composition of CaF_2 based fluxes is a complex task in connection with the fact that numerous eutectics form with lower-melting fluorides, while regions of melt concentrations characterized by sufficiently high melting temperature, are extremely limited. PWI studies were the basis to develop oxygen-free halogenide fluxes of ANT series, such as ANT-1, ANT-3, and ANT-7, designed for consumable electrode welding of titanium and its alloys [3, 5]. During welding, the developed fluxes reliably isolate the molten metal pool and cooling sections of the weld and HAZ from harmful contact with atmospheric gases, that is indicated by the results of analysis of gas content in the metal of commercial titanium weld (Table 1). To ensure impurity content in the weld metal on the level of their concentration in BM, it is necessary to apply flux with moisture content of not more than 0.05 %. Particle size distribution in the flux is from 0.3 up to 1.5 mm. Investigations showed that welds made with flux application, have no pores, slag inclusions, cracks or other defects.

Technological properties of fluxes of ANT series, designed for automatic consumable electrode welding of titanium (process stability, good weld formation, etc.), largely depend on CaF_2 purity. It is established that the cause for flux properties deterioration is CaO content in the flux, the amount of which should not be higher than 0.5 %. To ensure maximum purity of the fluxes, primarily, for oxide content, chemically pure reagents are used in their manufacture, application of minerals and components of commercial purity is not allowed.

Development of welding consumables for submerged-arc welding of titanium was also the basis for development of fluxes and technology for electroslag welding and melting of titanium [6].

Technology of automatic consumable electrode welding of titanium using oxygen-free fluxes was developed at PWI under the leadership of Prof. S.M. Gurevich [7]. This method allows making all the main types of welds on titanium, namely butt, fillet, tee and overlap welds at 3 to 40 mm thickness of the elements being joined.

A quite essential feature of automatic submerged-arc welding of titanium is the need to perform the process at minimum admissible distance between the surface of metal being welded and lower point of the nozzle — dry extension of electrode wire. This is due to the fact that titanium has very high specific electric resistance and increase of dry extension leads to excess heating of electrode wire, its saturation by harmful gas impurities, violation of welding process stability, and, consequently, deterioration of mechanical properties and quality of weld formation. Welding is performed at reverse polarity direct current. Welding at straight polarity and alternating current markedly impairs weld formation. Welding wires of 2.5; 3.0; 4.0 and 5.0 mm can be applied. Application of larger diameter wires is difficult, because of their higher rigidity. Welding wire of VT1-00sv grades is used for welding commercial titanium VT 1-00 and VT 1-0 and low alloys OT4, OT4-0, OT4-1, VT-5, VT5-1, and 4200. Wires of SPT2, VT20sv and other

Table 1. Content of main impurities in the metal of welds in VT1-00 titanium welded joints made with ANT-1 flux

Metal thickness *b*, mm	Content, % (BM/weld metal)			
	N_2	O_2	H_2	C
2.0	0.029/0.025	0.085/0.085	0.008/0.007	0.07/0.05
4.5	0.037/0.030	0.078/0.077	0.004/0.005	0.06/0.04

grades are applied for welding medium and high alloys. It is recommended to perform welding of PT-3V, PT-7M type alloys with 2V wire.

It is recommended to perform welding of longitudinal welds on thin metal (3–6 mm), as well as multilayer welds on metal of medium thickness at small current using ANT-1 flux. ANT-3 flux is applied for making circumferential welds on titanium of small thickness and all single-pass welds on titanium of medium thickness. ANT-5 and ANT-7 fluxes are designed for joining thick metal in welding at currents exceeding 700 A.

Comparison of the results of testing the metal of welds made by automatic submerged-arc welding and nonconsumable tungsten electrode welding in a chamber with argon atmosphere showed that the strength and ductility characteristics are almost equal in both the cases. However, toughness of welds made by submerged-arc welding, even though it is at a sufficiently high level, is inferior to the respective indices of welds, made with tungsten electrode in argon. Thus, impact toughness *KCU* of the metal of weld on VT5-1 alloy made by automatic submerged-arc welding, is equal to 48 J/cm^2, here impact toughness of the metal of weld made by tungsten electrode in argon, has the value of *KCU* = 62 J/cm^2.

A combined flux-gas method of weld pool shielding during automatic consumable electrode welding was developed for welding special-duty structures [8]. Its essence consists in that flux blowing with argon is performed in a hopper of special design during flux feeding into the welding zone. Nitrogen and oxygen penetration into the weld pool is completely eliminated as a result of argon ousting the air present between the flux granules. Mechanical properties of the metal of weld, produced with consumable electrode flux-gas shielding, and of the weld, made with tungsten electrode in a chamber with inert atmosphere of argon, were similar (Table 2). Flow rate of argon required for blowing the flux in the hopper, is equal to 3–4 l/min.

Butt joints up to 10 mm thick can be welded with success from one side. It is rational to perform butt joints of 10–16 mm thickness by welding from two sides on a copper water-cooled backing with inert gas shielding of the butt reverse side. For better penetration of the butt and quality of weld formation, it is rational to apply X-shaped groove preparation of the edges to be welded. Here, groove preparation with 90 deg bevel offers the greatest advantages from the technological point of view. This provides a high stability of the welding process, good separability of the slag crust, and improves the penetration depth. Experimental data enables establishing the dependence of welding current on electrode wire feed rate (Figure 2).

Table 2. Mechanical properties of welded joints (VT1-0) made with flux-gas shielding and with shielding in a chamber with controlled atmosphere

Weld pool shielding method	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	$a_?$, J/cm^2
Flux-gas	315	407	28.6	61.3	83
Inert gas	310	402	30.2	62.8	81

Automatic submerged-arc welding of titanium items of more than 16–18 mm thickness was performed with edge preparation by deposition of several layers. The surface of the previous weld should be thoroughly scraped before welding of each next layer. Number of weld scraping operations can be reduced by application of welding by two arcs, positioned one behind the other and shifted to a certain distance across the weld axis. This method allows producing welds with greater coefficient of groove filling, smooth transition from BM to weld reinforcement and high values of strength and ductility (Table 3). This method is also effective in welding fillet, tee and overlap joints [1].

Tungsten electrode argon-arc welding of titanium with application of oxygen-free fluxes. As shown by experience of application of automatic consumable electrode welding with oxygen-free fluoride-chloride fluxes, the produced welds are characterized by high density and absence of porosity. This was noted by the authors of works [9, 10], who studied the measures to prevent porosity, forming in nonconsumable electrode argon-arc welding of titanium. They showed experimentally that positive influence of fluorides on weld density is also preserved in welding in inert atmosphere. So, a radical method of prevention of weld porosity by metallurgical measures, namely welding with activating CaF$_2$ reagent, was proposed for the first time for argon-arc welding of titanium. Later on, more effective and adaptable-to-fabrication fluxes for tungsten electrode welding of titanium and its alloys were developed. More over, it turned out that halogenides of alkali and alkali-earth metals, when penetrating into the arc zone, constrict the arc and change the nature of metal penetration and weld formation. At arc movement along the butt at the moment of its transition from the surface of metal not coated by flux,

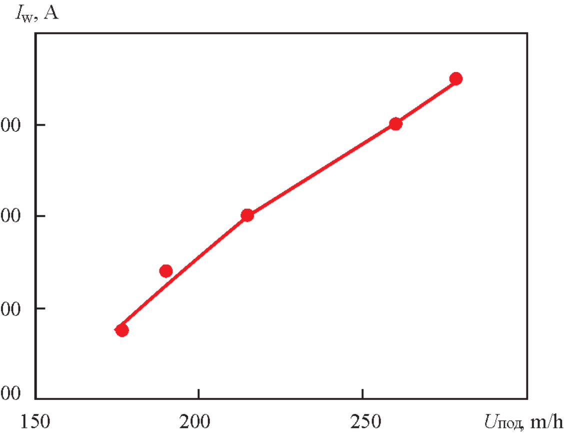

Figure 2. Dependence of welding current value on electrode wire feed rate in submerged-arc welding of titanium

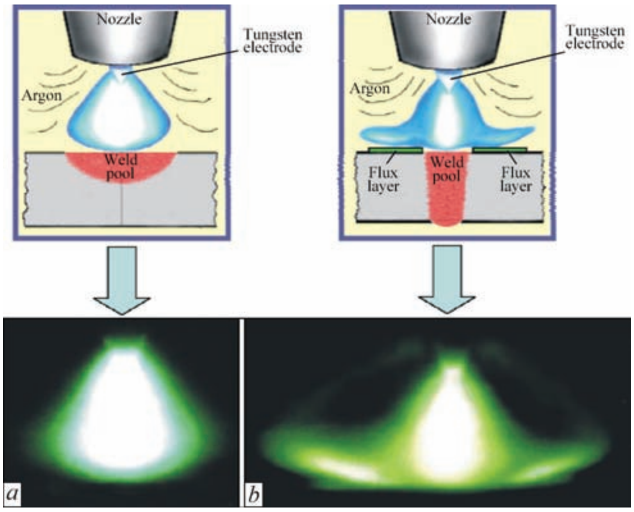

Figure 3. Schematic and photo of an arc without flux (*a*) and with flux (*b*)

to a layer of halogenide, arc constriction and change of its colour is visually observed, the arc moves deeper into the metal and the weld becomes narrower.

PWI studied the influence of fluorides of alkali and alkali-earth metals on the process of tungsten electrode welding, such as, for instance, LiF, CaF_2, SrF_2, BaF_2, KF, RbF, CsF, NaF, MgF_2, etc., investigated binary and ternary fluoride systems and as a result, developed ANT-17, ANT-32 and ANT-25 fluxes, designed for automatic tungsten electrode argon-arc welding of titanium. A method of argon-arc welding by tungsten electrode over a layer of flux (TIG-F) [1, 11] and with titanium flux-cored filler wire (TIG-FW) was developed [11, 12]. In both cases, the shielding role of the flux is secondary. Its main function is enhancement of technological capabilities of the arc. Deep penetration of metal, narrow welds, short extent of the HAZ, relatively low heat-input, and, consequently, reduction of residual welding deformations are some of the advantages of TIG-F welding process (Figure 3).

Flux addition to the arcing zone in argon-arc welding leads to a change of spatial characteristics and electric parameters of the arc, in particular, to compression of the arc column and increase of anode current density (Figure 4), and consequently, it allows controlling the parameters of welds, and, primarily, increasing penetration depth [12, 13].

The observed physical phenomena in the arc, dependent, primarily, on flux composition, determine also the technological advantages of TIG-F and TIG-FW welding, compared to TIG process. At unchanged value of welding current and welding speed flux application significantly increases penetration depth,

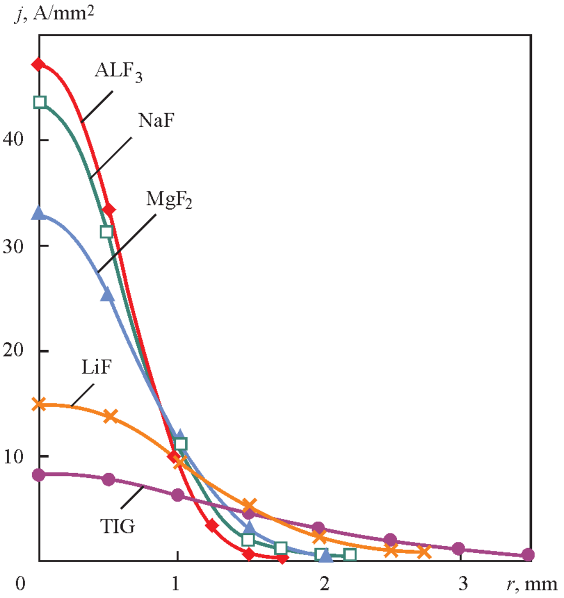

Figure 4. Radial distribution of current density in the anode spot in welding of titanium with different fluorides (I_w = 100 A; v_w = = 10 m/h)

reduces weld width, as well as lowers heat input (Figure 5). However, at current increase above 200 A, the applied quantity of flux is no longer sufficient and flux effectiveness drops markedly. Considering such a feature of TIG-F welding, this welding process is recommended to perform welds on metal of 0.8 to 6.0 mm thickness [14, 15]. ANT-23 flux is designed for welding sheets of 0.8–3.0 mm thickness, and ANT-25 flux is used for square edge welding of 3 to 6 mm thick sheets in a single pass. A small volume of the weld pool allows application of single-pass automatic welding over a layer of ANT-25 flux to join metal up to 6 mm thick on vertical plane.

Argon-arc tungsten electrode welding of titanium with application of flux-cored wires. As was already mentioned, at current increase above 200 A, the quantity of flux preapplied on the edges being welded is no longer sufficient and flux effectiveness decreases. The quantity of flux, added to the arc, i.e. the applied layer thickness, has the strongest effect on penetration depth, as greater penetration depth corresponds to greater thickness of the flux layer. Therefore, a welding consumable, principally new for titanium applications, namely flux-cored filler wire (Figure 6), and technology of tungsten electrode welding of titanium with application of flux-cored wire (TIG-FW), were developed for welding titanium of more than 6 mm thickness. Flux-cored wire basically is a titanium foil sheath, containing flux filler [14, 15]. Two types of

Table 3. Mechanical properties of welded joints made by automatic two-arc welding with ANT-7 flux*

Alloy grade	*b*, mm	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	ψ, %	$a_?$, J/cm^2
PT-3V	25	676/617	727/677	20.2/19.5	39.6/36.2	68/62
OT4	32	694/661	769/739	23.2/22.3	38.1/35.3	96/88

*VT1-0 electrode wire.

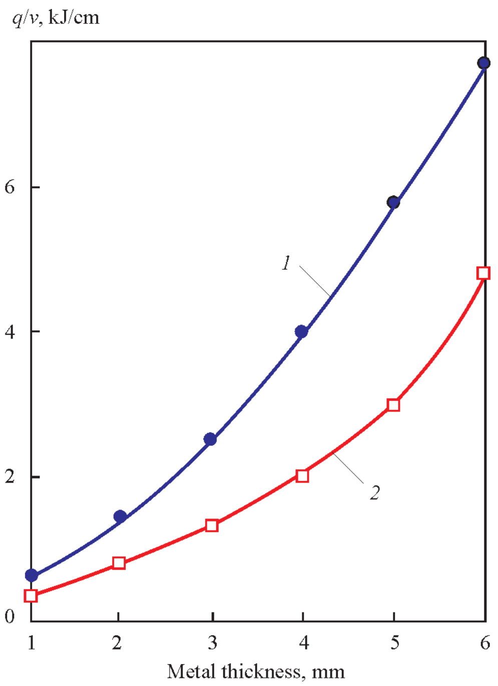

Figure 5. Dependence of heat input on metal thickness in welding without flux (*1*) and over a layer of flux (*2*) (ANT-23 and ANT-25A fluxes)

flux-cored wire were developed, namely PPT-1 and PPT-2, differing both by chemical composition of the filler, and by their design. Wire of PPT-1 grade is used in those cases, when no weld reinforcement is required by service conditions. Wire of PPT-2 grade with solid titanium wire inside it, allows producing welds with reinforcement.

Application of flux-cored filler wire allows increasing the quantity of flux in the welding zone. Due to that TIG-FW method (Figure 7) allows welding titanium alloys 6.0–16.0 mm thick in a single pass without edge reparation. Flux-cored wire can be applied with success for making not only butt, but also tee joints. As an illustration, Figure 8 gives the macrosections of welded joints of different types, made by TIG-F and TIG-FW processes.

After welding, a layer of solidified slag remains on the surface, which provides additional shielding of solidifying metal. Its removal is performed as after welding over a layer of flux. In addition to technological advantages, application of fluxes and flux-cored wires in argon-arc welding of titanium has an essential influence on metallurgical processes in the weld pool, in particular, it prevents formation of pores in welds. Porosity is known to be the main type of metallurgical defects in titanium alloy welded joints, made both by arc and beam welding processes. Presence of pores in welds only slightly affects the properties of welded joints at static loads, but significantly lowers their performance under dynamic loads, markedly decreasing the fatigue limit.

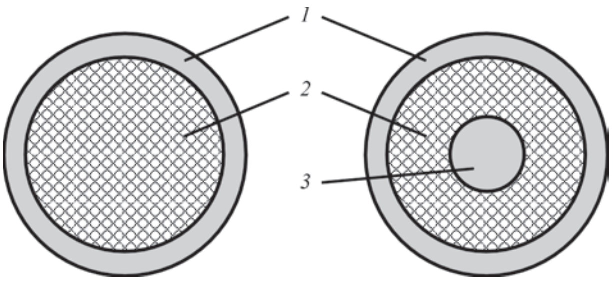

Figure 6. Flux-cored wire cross-section: *1* — sheath; *2* — flux filler; *3* — core

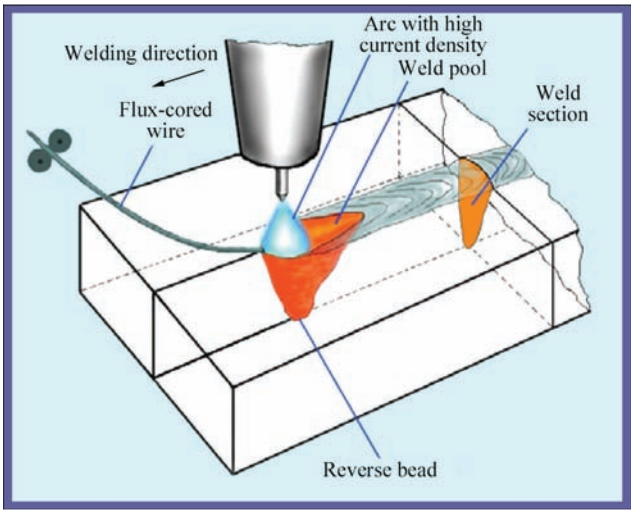

Figure 7. Schematic of TIG welding with flux-cored wire

Defects developing in the weld in the form of pores significantly lower welded joint fatigue resistance. Now, application of halogenide fluxes and flux-cored wires, allows prevention of pore formation in welds (Table 4).

As is seen from the above data, volume fraction of pores in the metal of welds made on commercial titanium by different fusion welding processes differs essentially by its value. Maximum number of pores is found in EBW welds and minimum number of pores is present in welds made by ESW and TIG with application of flux that is attributable to active metallurgical interaction of flux with molten metal of the weld pool [16].

Investigations showed that application of fluxes and flux-cored wires in welding leads to hydrogen binding by fluorine in the weld pool into hydrofluorides of TiF_xH_y type, which remain in weld metal as microscopic slag inclusions, that, as shown by testing, have no es-

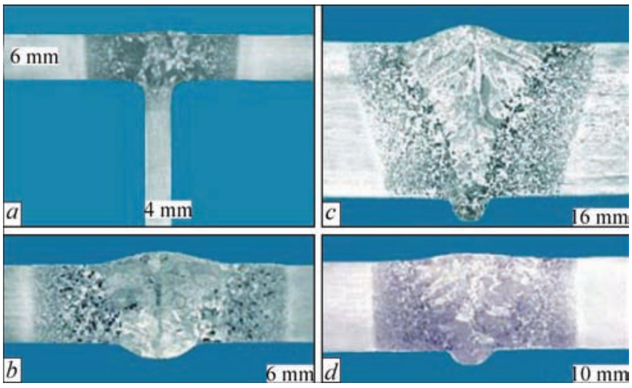

Figure 8. Macrosections of welded joints made over a layer of flux ANT-25A (*a*, *b*); PPT-2 (*c*); PPT-1 (*d*)

Table 4. Volume fraction of pores in titanium joints made by different welding processes

Welding process	Metal	Volume fraction of pores m_2, %
Argon-arc welding (TIG)	Base metal	0
	Weld made with through penetration of the plate	0.82
	Weld made over a layer of ANT-17A flux	0.65
	Weld made over a layer of ANT-25A flux	0.43
Electron beam welding (EBW)	Base metal	0
	Weld made with through penetration of the plate	1.40
	Butt weld	1.34
Electroslag welding (ESW)	Base metal	0
	Weld	0.46

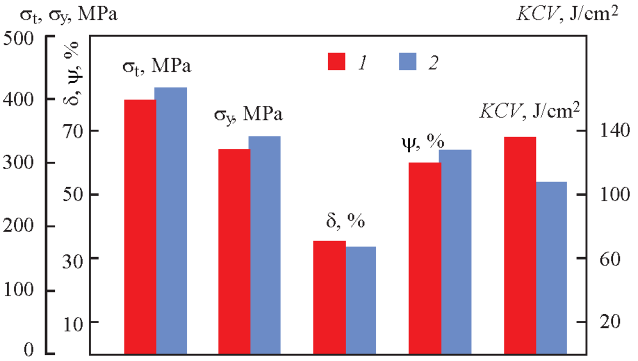

Figure 9. Mechanical characteristics of welded joint of unalloyed titanium of Grade 2 (6 mm thickness): *1* — base metal; *2* — weld metal

sential influence on mechanical properties of welded joints (Figure 9), made with flux application.

Application of welding over a layer of flux allows a significant improvement of technico-economic indices of welding [17]. So, for instance, in welding 5 mm titanium sheet welding time, wire consumption and argon flow rate are reduced by more than 60 %, and power consumption decreases by more than 50 %. Here, the cost of 1 m of weld (including additional cost of flux), decreases almost two times.

Conclusions

1. PWI developed a series of oxygen-free fluxes and technology of consumable electrode welding of titanium with application of the developed fluxes for welding titanium and alloys on its base.

2. Developed fluxes and method of tungsten electrode welding of titanium over a layer of flux (TIG-F) widen the technological capabilities of tungsten electrode welding of titanium, provide greater penetrability of the arc, absence of pores in welds, and high quality of the produced joints.

3. Application of flux-cored wire and TIG-FW method of tungsten electrode welding of titanium allows performing single-pass welding of up to 16 mm thick metal with complete penetration and guarantees absence of pores in welds and high quality of the produced joints.

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