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IMPACT OF TIG WELDING ON THE STRUCTURE AND MECHANICAL PROPERTIES OF JOINTS OF PSEUDO-β-TITANIUM ALLOY

S.V. Akhonin, V.Yu. Bilous, R.V. Selin and **I.K. Petrychenko**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

Structural pseudo-β-titanium alloys attract a lot of interest in fabrication of complex constructions for critical purposes. This alloy class includes alloys with the structure represented by one β-phase after hardening or normalizing from the β-region. The alloy weldability is an important factor at application of pseudo-β-titanium alloys in aircraft and rocket engineering. By their mechanical characteristics, the welded joints of modern pseudo-β titanium alloys should match the level of base metal mechanical properties. In this work, the impact of argon arc welding, as well as further heat treatment on the phase composition, structure and mechanical properties of welded joints of pseudo-β-titanium alloy was studied. It was established that as a result of the impact of thermal cycle of welding predominantly β-phase in the quantity of 77 % is recorded in the weld metal of joints of pseudo-β alloy VT19. Application of VT1-00sv filler wire enhances the quantity of dispersed α-phase particles and reduces the quantity of β-phase in the weld metal to 60 %, respectively. Annealing results in formation of a uniform, homogeneous finely-dispersed two-phase (α+β)-structure with tensile strength values of welded joints on the level of σ_t = 1010 MPa, that exceed the respective base metal values by 12 %. 16 Ref., 5 Tables, 8 Figures.

Keywords: *pseudo-β titanium alloys, TIG welding, mechanical properties*

Structural pseudo-β titanium alloys attract a lot of interest in manufacture of complex constructions for critical purposes. This class covers alloys with the structure, presented by one β-phase after hardening or normalizing from β-area. As-annealed structure of these alloys is presented by α-phase and a large amount of β-phase. The coefficient of β-stabilization of such alloys K_β = 1.4–2.4. They undergo β-phase transformation by β→(β+α) scheme. In the stable state they have (β+α)-structure [1−4].

An important factor at application of pseudo-β titanium alloys in aviation and rocket engineering is their weldability. By their mechanical characteristics, welded joints of modern pseudo-β titanium alloys should correspond to the level of those of base metal [5, 6].

Tungsten electrode argon-arc welding (TIG welding) became the most widely accepted for titanium alloy welding. Welding can be performed with and without filler metal application. Welding wires or rods from titanium alloys are used as filler metal [7, 8]. In order to increase the efficiency of arc heat utilization and arc penetrability in TIG welding of titanium, a number of variants of this process have been developed, such as submerged-arc welding, through-penetration welding, and semisubmerged-arc welding. The latter allows producing tight welds without pores [9]. Application of fluxes leads to reduction of weld pool dimensions, shortening of the time of metal being in the molten state and provides cracking resistance of welded joints, close to base metal values [10, 11].

The objective of this work is investigation of the impact of TIG welding with and without filler wire application, TIG welding over a layer of flux, as well as further heat treatment on phase composition, structure and mechanical properties of welded joints of pseudo-β titanium alloy.

Material and equipment. Pseudo-β titanium alloy, studied in the work, was developed by complex alloying theory, and contains, wt.%: Ti as base; 2.5–3.5 Al; 5–6 Mo; 3−4 Y; 4−5 Cr; 0.5–1.5 Zr; not more than 0.15 Si, 0.10 C, 0.15 O_2, 0.05 N_2, 0.015 H_2 [12]. The alloy contains β-stabilizers with coefficient of distribution greater and smaller than a unity, as well as with coefficient of distribution that is equal to a unity. Content of β-stabilizing elements is equivalent to 13.7–17.0 % Mo at average content equivalent to 15.3 % Mo. The ratio of isomorphous (equivalent to 7.8 % Mo) and eutectic-forming β-stabilizers (equivalent to 7.5 % Mo), expressed in molybdenum equivalent values, is equal to 1:1. The alloy is produced by cold-hearth electron beam remelting.

The impact of argon-arc welding on the properties and structure of joints of pseudo-β titanium alloy was

S.V. Akhonin — https: //orcid.org/0000-0002-7746-2946, V.Yu. Bilous — https: //orcid.org/0000-0002-0082-8030,
R.V. Selin — https: //orcid.org/0000-0002-2990-1131, I.K. Petrychenko — https: //orcid.org/0000-0002-0476-3983

Table 1. Modes of TIG welding of pseudo-β titanium alloy VT19

Mode number	Welding current I_w, A	Arc voltage U_a, V	Welding speed v_w, m/h	Arc length L_a, mm	Wire feed rate $v_{w.f}$, m/h	Quantity of filler wire in weld metal, %
1	310	12	10	1	−	0
2	380	12	8	1	30	10−12
3	420	12	8	1	60	22−24
4	240	11	10	2	−	0

studied. In particular, through-penetration TIG welding without filler wire, with filler wire and over a layer of flux was performed. Also studied was further heat treatment of the produced welded joints: annealing at the temperature of 760 °C for 1 hour and cooling in the furnace.

Unalloyed titanium welding wire VT1-00sv of 2 mm diameter was used as filler metal. This allowed variation of weld metal alloying in a narrow range. The quantity of filler metal was determined by examination of the macrostructure of transverse macrosections of the welds.

ANT-25 flux developed at PWI was used. It is designed for single-pass welding of 3–6 mm thick metal [13].

Samples of 200×100×6 mm size were welded. The mode of TIG welding of pseudo-β titanium alloy VT19 is given in Table 1. An example of transverse macrosection of the welded joint is shown in Figure 1.

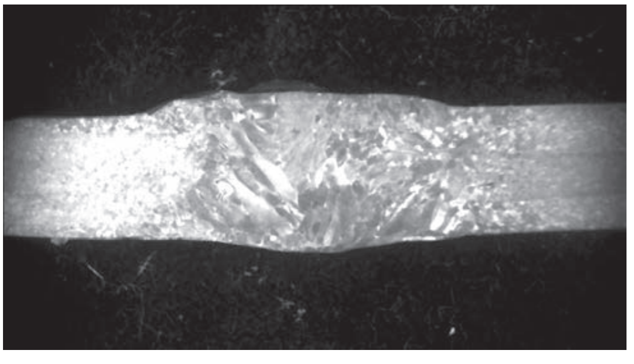

Figure 1. Transverse macrosection of the welded joint of pseudo-β titanium alloy VT19 produced by TIG welding with filler wire application

Calculation of the quantity of filler metal in the weld metal was performed by the results of studying the obtained transverse macrosections. It is found that in welding in mode 2 the quantity of wire in the weld metal is 10–12 %. In welding in mode 3 the quantity of filler metal VT1-00 in the weld metal is equal to 22–24 %, respectively [14]. The structures in the middle of a 6 mm thick sample are given. The quantity of β-phase in the weld metal, HAZ and base metal was determined on microsections and is based on the fact that different phases are etched and coloured differently. So, β-phase is of a light colour on microsections, α- and α′-phases are dark-coloured. Etching results allow revealing the shape and dimensions of individual grains, and quantity of β-phase, depending on the location of the region and thermal conditions of their formation.

Results. *Through-penetration argon-arc welding without filler wire.* Weld metal of the joints produced by TIG welding without filler wire in mode 1 (see Table 1), consists of β-phase grains, equiaxed and elongated in the direction of heat removal. Their hairlike borders are manifested against the background of the dendritic structure (Figure 2, *a*). Quantity of β-phase in this area is equal to 77 %. Fusion zone (Figure 2, *b*) is located at 5.4 mm distance from weld axis, on the right are weld grains against the background of the dendritic structure, on the left are equiaxed β-grains of HAZ area in the fusion zone. The quantity of β-phase in this area is equal to 81 %. Directly in the fusion zone one can see partially melted grains that belong simultaneously both to HAZ and to weld metal.

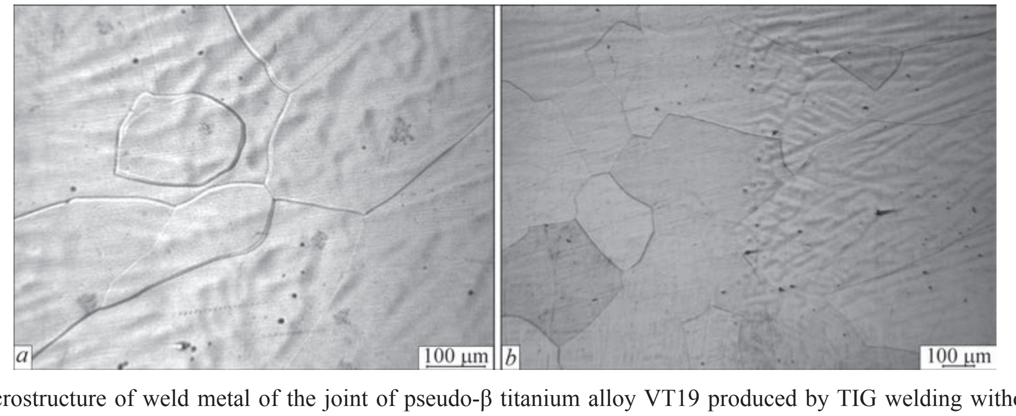

Figure 2. Microstructure of weld metal of the joint of pseudo-β titanium alloy VT19 produced by TIG welding without filler wire application in mode 1: *a* — weld center; *b* — fusion zone

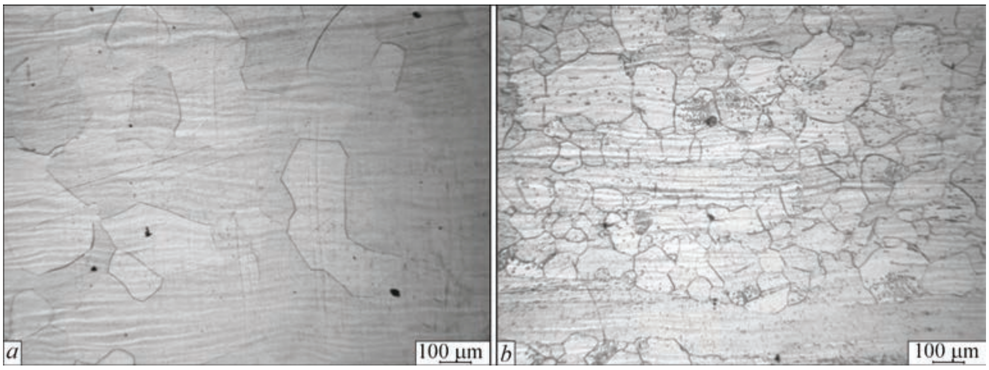

Figure 3. Microstructure of metal of the HAZ of welded joint of pseudo-β titanium alloy VT19, produced by TIG welding without filler wire application in mode 1: *a* — area of complete polymorphous transformation; *b* — zone of incomplete polymorphous transformation

HAZ area, where complete polymorphous transformation has occurred, consists of equiaxed β-grains (Figure 3, *a*), and its width is 4.75 mm. Quantity of β-phase is on the level of 80 %. HAZ area, where incomplete polymorphous transformation is observed, has a width of 2.5 mm (Figure 3, *b*), β-grains contain just the particles of other phases, which occur in the base metal, in particular β-phase. Quantity of β-phase is 75 %.

On the boundary of transition from the area of incomplete polymorphous transformation to base metal the quantity of β-phase is equal to 57 %. In the base metal the quantity of β-phase is 31 %.

Thus, microstructural investigations showed that predominantly β-phase in the quantity of 77 % is found in the metal of welded joint, produced without the filler wire, and in different HAZ areas it varies from 75 % to 80 %. In order to ensure decomposition of the formed metastable phases and provide equal strength, the welded joints produced without filler wire, should be further subjected to heat treatment — annealing.

Through penetration argon-arc welding with application of filler wire VT1-00sv. Microstructure of weld metal in welded joint of pseudo-β titanium alloy VT19, produced by TIG welding in mode 2 (see Table 1), is presented in Figure 4, *a*. Weld metal has a dendritic structure, against the background of which β-phase grains formed, which are elongated in the direction of heat removal. Dispersed particles of α-phase of approximately 1 μm size and smaller, are observed in β-grains. These particles are nonuniformly distributed in the grain volume. Quantity of β-phase in the weld metal is equal to 69.1 %.

Microstructure of weld metal in welded joint of pseudo-β titanium alloy VT19, made in mode 3 (see Table 1), is shown in as-welded condition in Figure 4, *b*. Weld metal consists predominantly of β-phase, the boundaries of which are manifested against the background of the dendritic structure. In weld metal structure dispersed precipitates of α-phase of approximately 1 μm size are also observed. The highest density of such precipitates is found in the weld upper part near the alloy zone. Here, the size of some particles is equal to 2–3 μm. The quantity of β-phase in the weld metal is equal to 60.3 %.

Microstructure of HAZ metal of welded joints of VT19 alloy, produced using filler wire VT1-00 in modes 2 and 3 is similar to that of this zone in joints made without application of filler wire VT1-00 in mode 1.

Thus, in welded joints produced with filler wire application, the quantity of dispersed particles of α-phase becomes greater and their size increases up to 2–3 μm in welds with 20 % of VT1-00sv wire. Temperature mode during welding and cooling promoted increase of the density and size of dispersed phase particles. Quantity of β-phase in the weld metal decreased to 60 % due to disalloying of weld metal and HAZ [15].

Argon-arc welding over a layer of flux. Microstructure of metal of the weld and near-weld zone of

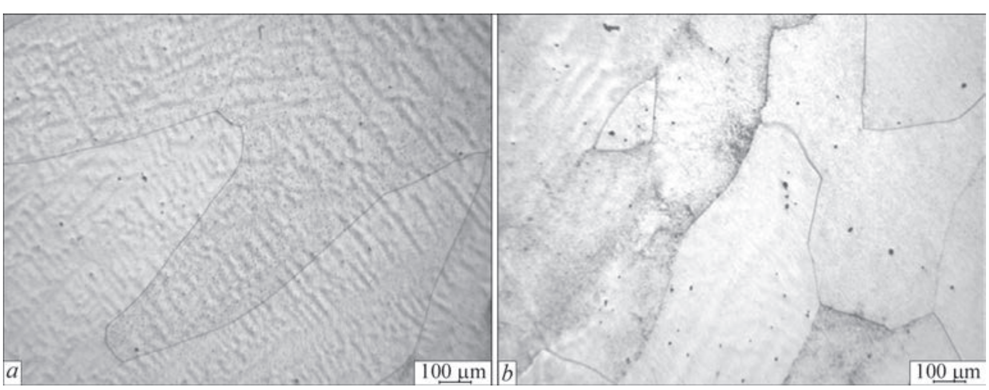

Figure 4. Microstructure of weld metal in welded joint of pseudo-β titanium alloy VT19, produced by TIG welding with filler wire VT1-00: *a* — in mode 2; *b* — in mode 3

Table 2. Quantity of β-phase in base metal and weld metal of TIG-welded joints of titanium alloy VT19

Sample number	Sample type, welding speed, filler material	Quantity of β-phase, %
Base metal		55.7
1	Welded joint, 10 m/h, without filler	77.1
2	Welded joint, 8 m/h, quantity of filler is 10 %	69.1
3	Welded joints, 8 m/h, quantity of filler is 22 %	60.3
4	Welded joint over a layer of flux, 10 m/h, without filler	97.2

welded joint produced at welding speed of 10 m/h (mode 4, Table 1) is given in Figure 5. Weld metal consists of equiaxed and nonequiaxed grains of β-phase with thin boundaries against the background of the dendritic structure; metal of the near-weld zone consists of equiaxed grains of β-phase.

Metal of the weld and near-weld zone of the HAZ of samples 1, 2, 3 and 4, while differing by the parameters and configuration of the zones, and direction of crystallite growth, has an identical microstructure, which consists of β-phase grains. Quantity of β-phase in the weld metal is equal to 60–70 % for samples 2 and 3, 77 % for sample 1, and 97 % for sample 4 (Table 2).

Analysis of mechanical properties of welded joints (Table 3) shows that the lowest strength and impact toughness is demonstrated by welded joints, made by TIG welding without filler wire over a layer of flux, in modes 1 and 4, where σ_t = 860 MPa, and σ_t = = 857 MPa, respectively. Thus, application of fluxes in TIG welding does not have any particular impact on the strength and impact toughness of welded joints, and promotes an increase of β-phase content in the weld metal due to reduction of energy input and increase of weld metal cooling rate.

Joints produced with application of filler wire VT1-00sv in modes ensuring VT1-00 metal quantity on the level of 22–24 % in the weld metal (mode 3, Table 1), have the highest strength.

Joints produced with application of filler wire VT1-00sv, in which the content of VT1-00 metal in the weld is on the level of 10–12 %, have intermediate strength values. This is attributable to a large content of β-phase in the weld metal of joints made without filler wire application. Metastable β-phase has a low strength that is why welded joints have low strength values.

Impact toughness *KCV* of samples with a sharp notch of weld metal in welded joints produced with application of filler wire VT1-00sv with feed rate in the mode, ensuring the content of VT1-00 metal in the weld on the level of 22–24 %, is also maximum and is equal to 32 J/cm^2.

Thus, the properties of welded joints of pseudo-β alloy VT19, produced by tungsten electrode argon-arc welding, both without filler wire and with application of filler wire VT1-00sv were studied, and it was established that the joints made with application of filler wire VT1-00sv in the quantity of 22 % have the strength equal to that of base metal, and the quantity of β-phase in the weld metal decreases from 77 % to 60 %. To ensure the uniform structure, decomposition of metastable phases and produce equal strength

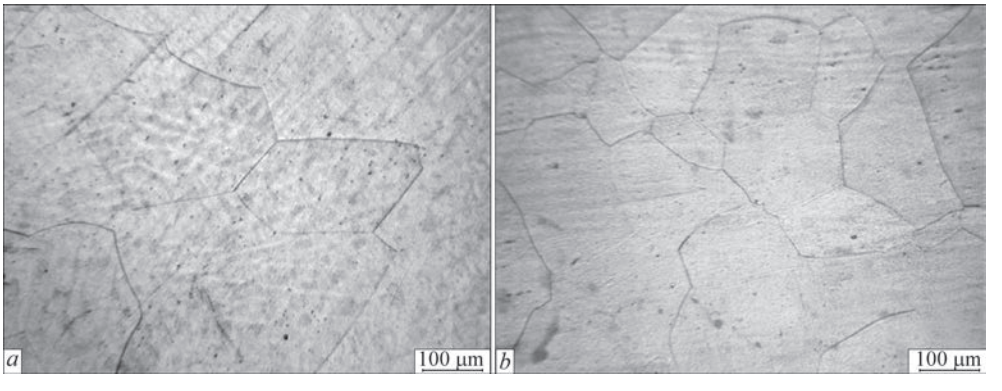

Figure 5. Microstructure of the metal of weld (*a*) and near-weld zone (*b*) of welded joint of pseudo-β titanium alloy VT19, produced by TIG welding (mode 4) with tungsten electrode over a layer of flux

Table 3. Mechanical properties of welded joints of pseudo-β titanium alloy VT19

Mode number	Sample type	Tensile strength σ_t, MPa	Yield limit σ_y, MPa	Relative elongation δ, %	Reduction in area ψ, %	Impact toughness *KCV*, J/cm^2	
						weld	HAZ
BM		887	958	12	42	22	
1	As-welded	860	839	13.3	60	19	22
2		895	868	7.3	23.4	28	26
3		963	942	6	24.5	32	24
4		857	815	13.3	55	14	26

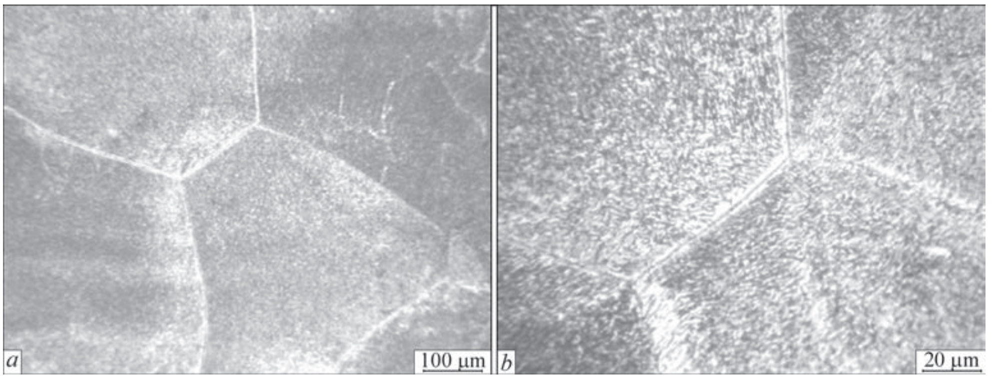

Figure 6. Microstructure of HAZ metal (*a*) of welded joint of pseudo-β titanium alloy VT19, produced by tungsten electrode argon-arc welding with through penetration after annealing at 760 °C; *b* — intragranular structure

joints, made without application of commercial titanium VT1-00 as filler material, and because of weld metal disalloying, the joints should be subjected to further heat treatment [16].

Selected as heat treatment was annealing which envisages heating up to the temperature of 750–760 °C, soaking and further cooling in the furnace.

Microstructure of HAZ metal of welded joint, made in mode 1 (without application of flux or filler wire) is shown in Figure 6.

HAZ metal consists of equiaxed polyhedral grains with homogeneous two-phase (α+β)-structure inside the grain. The intragranular structure of the HAZ metal consists of lamellar α-phase 2–5 μm long and up to 1 μm thick. Located between the plates are dispersed particles of α- and β-phase, the size of which is below 1 μm. In some grains, dispersed globular particles of up to 1μm size precipitate in β-matrix. Microstructure of weld metal of this welded joint is shown in Figure 7. Weld metal of the joint consists predominantly of nonequiaxed, elongated in the direction of heat removal primary β-grains (Figure 7, *a*) with highly refined intragranular structure that formed after decomposition of metastable phases (mainly β-phase), as a result of annealing of this welded joint at the temperature of 760 °C for 1 h (Figure 7, *b*).

After stabilization of weld metal structure finely-dispersed two-phase (α+β)-structure formed, which was uniform and homogeneous for the entire weld. The α-phase plates have the length of 2–4 μm, and thickness close to 0.5 μm, dispersed globular particles are of 0.5–1.0 μm size and smaller. A continuous or intermittent α-fringe 1.0–1.5 μm wide was observed along the grain boundaries. Finely-dispersed structure of the weld metal can provide its high strength.

For comparison, Figure 8 shows the microstructure of weld metal in welded joint of pseudo-β titanium alloy VT19, produced by through penetration argon-arc welding with filler wire VT1-00sv in modes that ensure VT1-00 metal content on the level of 22–24 % in the weld. The weld metal consists of elongated in the direction of heat removal primary β-grains (Figure 8, *a*) with two-phase intragranular structure, which consists of dispersed α- and β-phases (Figure 8, *b*). Thickness of α-phase particles is less than 1 μm at the length of 0.7–5.0 μm. An α-fringe up to 2 μm width is present on the boundaries of β-grains.

Application of filler wire at argon-arc welding of VT19 alloy allows reducing the content of β-phase in the weld metal and in as-annealed condition. So, after annealing the metal of welds, made with application of VT1-00 in the quantity of 22 %, contains β-phase on the level of 30 % (Table 4). In welds without filler wire application, the quantity of β-phase after annealing is fixed on the level of 43 %.

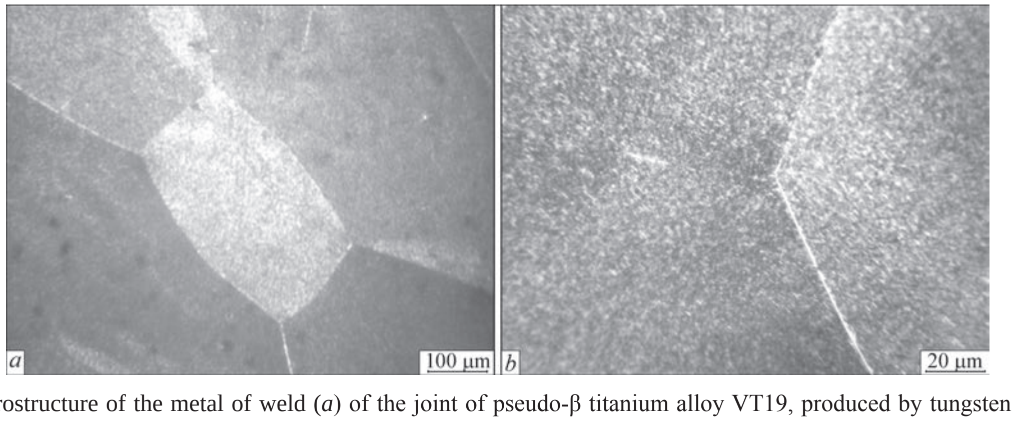

Figure 7. Microstructure of the metal of weld (*a*) of the joint of pseudo-β titanium alloy VT19, produced by tungsten electrode argon-arc welding with through penetration after annealing at 760 °C; *b* — intragranular structure

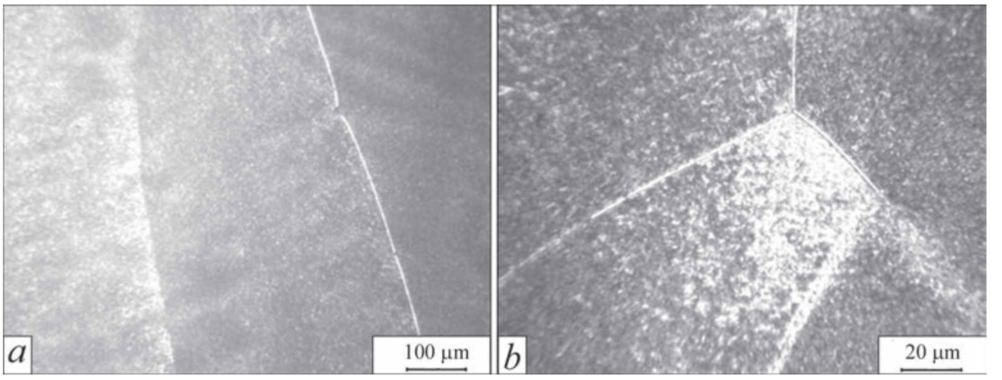

Figure 8. Microstructure of the metal of weld (*a*) of welded joint of pseudo-β titanium alloy VT19, produced by tungsten electrode argon-arc welding with through penetration with application of filler wire VT1-00 (22–24 % content in the weld) after annealing at 760 °C; *b* — intragranular structure

Table 4. Quantity of β-phase in the base metal and metal of welded joints of VT19 alloy

Sample type	Sample condition	Quantity of β-phase, %
Base metal	After annealing at 760 °C, 1 h, cooling with the furnace	22.98
Weld metal without filler, after annealing	After annealing at 760 °C, 1 h, cooling with furnace	43.72
Weld metal with VT1-00sv filler, 22–24 % content in the weld		29.87

Table 5. Mechanical properties of welded joints of pseudo-β titanium alloy VT19, produced by argon-arc welding (AAW) after annealing at 760 °C, 1 h, cooling with furnace

Sample type	Tensile strength σ_t, MPa	Yield limit σ_y, MPa	Relative elongation δ, %	Reduction in area ψ, %	Impact toughness *KCV*, J/cm^2
AAW without filler	981	946	9.7	15.3	29.4
AAW with filler wire VT1-00sv, in the quantity of 22–24 %	1011	989	9.1	15.1	25.9

Thus after annealing, the weld metal demonstrated a uniform, homogeneous for the entire weld finely-dispersed two-phase (α+β)-structure with plates of β-phase 2–4 µm long and 0.5 µm thick, and a 1.0–1.5 µm wide α-fringe formed along the grain boundaries. Finely-dispersed structure of the weld metal ensures its high strength. In the metal of the weld produced with application of filler wire VT1-00sv in the quantity of 20 %, the size of α-phase particles is larger: thickness of α-phase particles is close to 1 µm at the length of 0.7–5.0 µm. In the HAZ metal the thickness of α-phase increased to 1.5–2.0 µm as a result of annealing.

Studying the mechanical properties of welded joints of pseudo-β titanium alloy VT19, produced by tungsten electrode argon-arc welding, both without filler wire, and with application of filler VT1-00sv showed that both in as-welded condition and in the condition after annealing at 760 °C the joints produced without filler wire (Table 5) have the lowest strength values (Table 5).

However, the degree of strengthening as a result of annealing is different in different joints. So, joints produced by argon-arc welding with through penetration became stronger by 120 MPa after annealing, and joints made with filler wire application, became stronger by 48 MPa. During further investigations, it will be rational to study the impact of strengthening heat treatment on the structure and properties of welded joints of pseudo-β titanium alloy VT19.

Conclusions

1. As a result of the impact of welding thermal cycle, predominantly β-phase is found in the weld metal of joints of pseudo-β alloy VT19 produced by TIG welding without filler wire application; dispersed particles of α-phase of approximately 1 µm size, are observed in β-grains, and the quantity of β-phase in welded joint metal is maximum and equal to 77 %.

2. In welds of pseudo-β alloy VT19, made by TIG welding with application of filler wire VT1-00sv in the quantity of 10 and 20 %, the number of dispersed particles of α-phase becomes greater and their size increases up to 2–3 µm in welds with 20 % of VT1-00sv wire, and the quantity of β-phase in the weld metal decreases to 60 %.

3. Joints of VT19 alloy, made by TIG welding with application of filler wire VT1-00sv in the quantity

of 22 %, have tensile strength values on the level of σ_t = 965 MPa and equal strength to that of the base metal. Joints of VT19 alloy, produced by argon-arc welding without filler material application, have tensile strength values on the level of σ_t = 860 MPa. In order to ensure decomposition of metastable phases and equal strength of these joints, they should be subjected to further heat treatment by annealing.

4. As a result of the impact of annealing at the temperature of 760 °C, the metal of TIG-welded joints of VT19 alloy forms a uniform, homogeneous, finely-dispersed two-phase (α+β)-structure with α-phase plates, 2–4 μm long and 0.5 μm thick, and with tensile strength values on the level of σ_t = 980 MPa. Joints of VT19 alloy made by argon-arc welding with application of filler wire VT1-00sv in the modes, which provide filler metal content of 22–24 % in the weld after annealing at 760 °C have tensile strength values on the level of σ_t = 1010 MPa.

1. Iliin, A.A., Kolachev, B.A., Polkin, I.S. (2009) *Titanium alloys. Composition, structure, properties*: Refer. Book. Moscow, VILS-MATI [in Russian].
2. Khorev, A.I. (2012) Development of titanium β-alloy VT19 on the base of complex alloying. *Vestnik Mashinostroeniya*, **7**, 69−71 [in Russian].
3. Khorev, A.I. (2012) Titanium superalloy VT 19. *Tekhnologiya Mashinostroeniya*, **6**, 2−5 [in Russian].
4. Moiseev, V.N. (1998) β-titanium alloys and prospects of their development. *Metal Science and Heat Treatment*, **12**, 11–14 [in Russian].
5. Khorev, A.I. (2002) Titanium is a high-speed aviation and cosmonautics. *Tekhnologiya Lyogkikh Splavov*, **4**, 92−97 [in Russian].
6. Cui, C., Hu, B., Zhao, L., Liu, S. (2011) Titanium alloy production technology, market prospects and industry development. *Materials & Design*, 32(**3**), 1684–1691.
7. Blashchuk, V.E., Shelenkov, G.M. (2005) Fusion welding of titanium and its alloys (Review). *The Paton Welding J.*, **2**, 35−42.
8. Patel, N.S., Patel R.B. (2014) A review on parametric optimization of TIG welding. *Int. J. of Computational Engineering Research*, 4(**1**), 27–31.
9. Huang, J.L., Warnken, N., Gebelin, J.C. (2012) On the mechanism of porosity formation during welding of titanium alloys. *Acta Materialia*, 60(**6−7**), 3215–3225.
10. Zamkov, V.N., Prilutsky, V.P. (2004) Theory and practice of TIG-F (A-TIG) welding (Review). *The Paton Welding J.*, **9**, 11−14.
11. Dey, H.C., Albert, S.K., Bhaduri, A.K., Mudali, U.K. (2013) Activated flux TIG welding of titanium. *Welding in the World*, 57(**6**), 903–912.
12. Kostin, K.V. et al. (2016) Influence of complex alloying on improvement of mechanical properties and strength of titanium alloys. *Omsky Nauchny Vestnik*, 148(**4**), 45–47.
13. Gurevich, S.M., Zamkov, V.N., Prilutsky, V.P. et al. *Welding flux*. USSR author's cert. 439363 [in Russian].
14. Akhonin, S.V., Belous, V.Yu., Petrichenko, I.K., Selin, R.V. (2016) Influence of filler metal on structure and properties of welded joints of high-strength two-phase titanium alloys produced using argon arc welding. *The Paton Welding J.*, **1**, 39–43.
15. Akhonin, S.V., Belous, V.Y., Berezos, V.A., Selin, R. V. (2018) Effect of TIG welding on the structure and mechanical properties of the pseudo-β-titanium alloy VT19 welded joints. *Mat. Sci. Forum*, **927**, 112−118.
16. Hryhorenko, S.G., Achonin, S.W., Belous, W.J., Selin, R.W. (2016) Heat treatment effect on the structure and properties of electron beam welded joints made of high-alloy titanium. *Biuletyn Instytutu Spawalnictwa*, 60(**5**), 90−95.

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