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STRUCTURE AND PROPERTIES OF WELDED JOINTS OF PT-3V TITANIUM ALLOY PRODUCED BY NARROW-GAP WELDING

S.V. Akhonin, V.Yu. Bilous, R.V. Selin

E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine

ABSTRACT

Narrow-gap gas tungsten arc welding is an efficient and economical method for producing joints in thick titanium alloys. A key feature of the developed technology is the stable chemical composition of the weld metal, with the proportion of base metal in the weld reaching 89–91%. This work examines the influence of filler material on the structure and properties of welded joints in PT-3V titanium alloy produced by narrow-gap welding with a tungsten electrode and magnetically controlled arc. Filler wires of grades 2V and SPT2 provide high-quality formation of a concave weld bead surface during narrow-gap welding of PT-3V titanium alloy. The tensile strength of welded joints produced using 2V filler wire reaches 643 MPa, corresponding to 86 % of the strength of the base metal. The use of SPT2 filler wire for narrow-gap welding of PT-3V titanium alloy made it possible to obtain a weld metal structure similar to that of the base metal and to achieve weld strength equivalent to that of the base metal in the as-welded condition.

KEYWORDS: titanium, titanium alloy, pseudo-α alloys, gas tungsten arc welding, narrow-gap welding, controlling magnetic field, filler wire, microstructure, mechanical properties

INTRODUCTION

Narrow-gap gas tungsten arc welding is an efficient and economical method for producing joints in thick titanium alloys [1, 2]. For welded joints of titanium alloys, it is particularly important to reduce the consumption of filler wire and simplify the joint edge preparation [3, 4].

At the E.O. Paton Electric Welding Institute, a method for narrow-gap welding (NGW) with a tungsten electrode and magnetically controlled arc has been developed [5]. This welding method offers advantages such as a narrow weld width and a small volume of deposited filler metal [6, 7]. Another important feature of the technology is the simple joint edge design [8]. In addition, welding is performed under constant parameters. The weld metal has a stable chemical composition [9, 10], and the proportion of base metal in the weld metal reaches 89–91 %.

For welding PT-3V alloy joints by both manual and automatic arc welding, filler materials of grades VT1-00sv and 2V according to TUU 05416923.041–98 or GOST 27265–87 are recommended. VT1-00sv is an unalloyed titanium wire with a tensile strength of σ_t = 295–470 MPa. Since tungsten arc NGW with magnetically controlled arc results in a high proportion of filler metal in the weld formation, the mechanical properties of welded joints produced by NGW are primarily determined by the properties of the filler wire material [11]. Therefore, to ensure high strength of the weld metal and the welded joint, the use of 2V filler wire (Ti–Al–V system) is necessary.

However, the 2V filler wire is less alloyed compared to the base PT-3V titanium alloy, which results in lower weld metal strength compared to the base metal. To achieve equal-strength weld joints using NGW, it would be desirable to use filler wire with a chemical composition equivalent to PT-3V alloy. Unfortunately, such filler wire is not specified in TUU 05416923.041–98 or GOST 27265–87, therefore it is reasonable to investigate the possibility of using alternative filler wires.

Thus, it is important to study the influence of the chemical composition of various filler wires on the properties of welded joints of PT-3V titanium alloy produced by NGW with a magnetically controlled arc.

OBJECTIVE OF THE WORK

To investigate the influence of filler material on the structure and properties of welded joints of PT-3V titanium alloy produced by NGW with a tungsten electrode under a controlling magnetic field.

MATERIALS AND METHODS

To achieve this objective, multipass NGW with a magnetically controlled arc was performed on 45-mm-thick specimens made of PT-3V titanium alloy (Ti–Al–V system), GOST 19807–91. The chemical composition of PT-3V alloy is given in Table 1, and the mechanical properties for 12–60 mm thickness are listed in Table 2. The length of the test samples for welding was 600 mm.

Table 1. Chemical composition of PT-3V titanium alloy (GOST 19807–91), wt.%

Main components			Impurities, not more than							
Ti	Al	V	Zr	Si	Fe	C	O_2	N_2	H_2	Total other impurities
Base	3.5–5.0	1.2–2.5	0.3	0.12	0.25	0.1	0.15	0.04	0.015	0.30

Table 2. Mechanical properties of PT-3V titanium alloy sheets (GOST 19807–91)

Sheet thickness, mm	Ultimate tensile strength (σ_t), MPa	Elongation (δ), %	Reduction of area (φ), %	Impact toughness (*KCU*), kJ/m^2
		No less than		
12–19	638–834	11	25	687
20–60	638–814	10	15	

Table 3. Chemical composition of filler wires 2V and SPT2 (GOST 27265–87), wt.%

Grade	Main components				Impurities, not more than						
	Ti	Al	V	Zr	Si	Fe	C	O_2	N_2	H_2	Total other impurities
2V	Balance	1.5–2.5	1.0–2.0	–	0.10	0.20	0.07	0.12	0.04	0.003	0.30
SPT2		3.0–5.5	2.5–3.5	1.0–2.0		0,15	0,05				

Mechanical properties of the welded joints were determined at room temperature using specimens cut out from the base metal and the weld metal. Static tensile tests were carried out on cylindrical specimens of type MI-12, while impact toughness (*KCV*) was evaluated using sharp-notch specimens of type MI-50.

For welding the PT-3V titanium alloy, it is recommended to use filler wires made of commercially pure titanium grade VT1-00sv or the alloyed filler wire grade 2V (Ti–Al–V system) (Table 3). The mechanical properties of the 2V filler wire are presented in Table 4. To achieve strength matching in the welded joints, the filler wire grade SPT2 (Ti–Al–V–Zr system) (Table 3) was used as the filler material. The PT-3V titanium alloy and the filler wires SPT2 and 2V belong to the group of pseudo-α alloys. The chemical compositions of the SPT2 filler wire and the PT-3V titanium alloy are similar. It should be noted that a distinctive feature of the SPT2 wire is the presence of zirconium as an alloying element in its chemical composition. In titanium alloys, zirconium does not act as either an α-stabilizer or a β-stabilizer.

Table 4. Mechanical properties of welding filler wires 2V and SPT2 (GOST 27265–87)

Grade	Wire diameter, mm	Ultimate tensile strength (σ_t), MPa	Elongation (δ), %, not less than
2V	From 1.6 to 7.0	490–635	20.0
SPT2		645–845	13.0

Assembly of the components prior to welding was performed using a backing, which was manually tack-welded to the reverse side of the parts being joined. This backing forms the lower wall of the groove during the first pass [12, 13]. Welding of PT-3V titanium alloy specimens 45 mm thick in a narrow gap using a tungsten electrode with a magnetically controlled arc was carried out under the welding conditions given in Table 5. Macrosections of the welded joints are shown in Figure 1.

The macrostructure of welds produced by NGW using 2V and SPT2 filler wires is similar. The height of the deposited layer per single pass is 5 mm, and the weld width for the first and subsequent passes is 11.2–11.6 mm. Based on these geometric parameters of the weld macrostructure, the contribution of filler metal to the weld metal is 89–91 %.

The applied filler wires, under the selected NGW parameters for the PT-3V titanium alloy, ensure high-quality formation of a concave weld bead surface. No porosity or lack of fusion was detected in the weld metal.

Table 5. Welding parameters for NGW of PT-3V titanium alloy using a tungsten electrode with an externally controlled magnetic field

Welding speed (V_w), m/h	Arc voltage, V	Welding current (I_w), A	Filler wire feed rate, m/h	Shielding gas flow rate, l/min
8	12–13	420–440	55–65	30

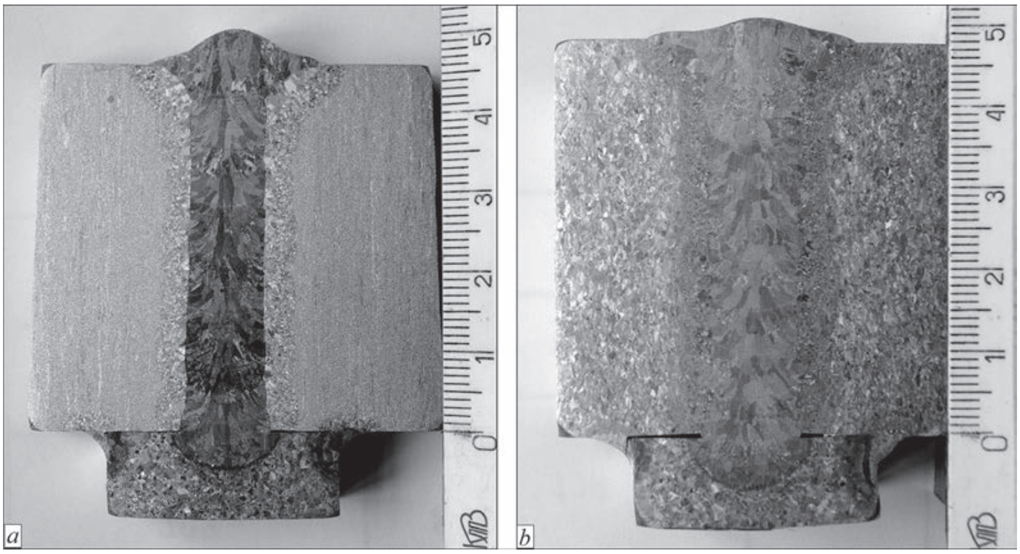

Figure 1. Transverse macrosections of welded joints of 45-mm-thick PT-3V titanium alloy produced by NGW: *a* — using SPT2 filler wire; *b* — using 2V filler wire

During NGW, no more than 11 % of the base metal enters the weld pool. Determining the chemical composition of the base metal and the weld metal produced by NGW using 2V and SPT2 filler wires showed that the weld metal made with filler wire 2V contains the lowest amount of alloying elements (Table 6). When using SPT2 filler wire, the aluminium content in the weld metal is lower compared with the base metal.

INVESTIGATION OF THE MICROSTRUCTURE OF PT-3V TITANIUM ALLOY WELDED JOINTS PRODUCED BY NGW

The microstructure of the base metal of the PT-3V alloy is shown in Figure 2. The base metal structure consists of equiaxed primary β-grains of various sizes, bordered by a continuous or discontinuous α-phase fringe (Figure 2, *a*) up to 15 μm thick. The intragranular structure consists of lamellar α-phase plates up to 1.5 μm thick. The lamellar α-phase structure contains fine parallel boundaries (Figure 2, *b*). Small amounts of β-phase may be present between the α-lamellae, although it is not always detectable by optical microscope.

Thus, the base metal contains predominantly α-phase with residual β-phase stabilized by vanadium. The relatively high density of intersecting lamellar structures indicates good plasticity and deformation capability of the alloy.

The microstructure of the weld metal of the PT-3V alloy produced by NGW using SPT2 filler wire — shown in the middle section of the weld in Figure 3 — consists of equiaxed primary β-grains formed at temperatures in the β-region (Figure 3, *a*, *b*). The boundaries of the primary grains are bordered by a continuous or discontinuous α-fringe up to 15 μm thick. The microstructure inside the primary grains is of the lamellar type. The α-phase plates are grouped into colonies, and within each colony the α-lamellae are parallel (Figure 3, *c*, *d*).

The microstructure of the weld reinforcement area (upper part of the weld) of the PT-3V alloy welded by NGW with SPT2 filler wire does not differ from the microstructure of the rest of the weld (Figure 4, *a*, *b*). The weld metal microstructure also consists of equiaxed primary β-grains. Inside the primary grains, the microstructure is lamellar, with α-phase plates forming colonies in which the lamellae are parallel.

The microstructure of the weld metal of the PT-3V alloy produced by NGW using the 2V filler wire in its central region is shown in Figure 5. The weld metal contains equiaxed and elongated primary grains of various sizes, within which thin packets of lamellar α-phase are located, with clearly defined grain boundaries. Despite the differences in configuration and size of the primary grains, the intragranular microstructure of the weld metal produced by NGW with the 2V filler wire, which is lamellar in nature, is very similar

Table 6. Chemical composition of the base metal and weld metal of PT-3V alloy produced by NGW using 2V and SPT2 filler wires, wt.%

Specimen type	Ti	Al	V	Zr	Cr	Si	Mo	Fe
Base metal		3.95	2.14	0.05			–	0.08
Weld metal, SPT2 filler	Balance	3.87	3.0	1.5	0.01	0.01	0.07	0.04
Weld metal, 2V filler		2.58	1.70	0.03			–	

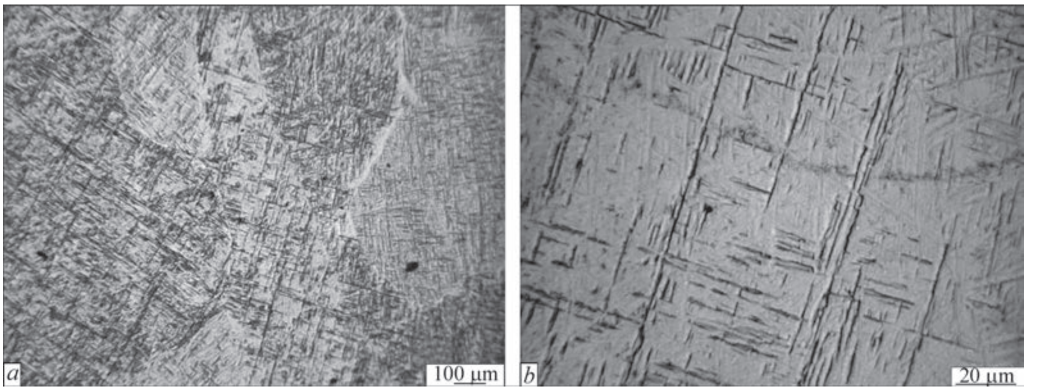

Figure 2. Microstructure of the base metal of PT-3V titanium alloy: *a* — ×50; *b* — ×100

to the microstructure of the base metal (Figure 5, *a*, *b*). The weld metal also contains α-lamellae with different growth orientations, indicating complex orientation relationships and heterogeneity in the formation of the α-phase. In certain regions, fine-dispersed α-structures are observed, which may have formed as a result of additional undercooling.

The microstructure of the metal in the fusion zone of the PT-3V alloy welded joint, produced by NGW using SPT2 filler wire, is shown in Figure 6. In the fu-

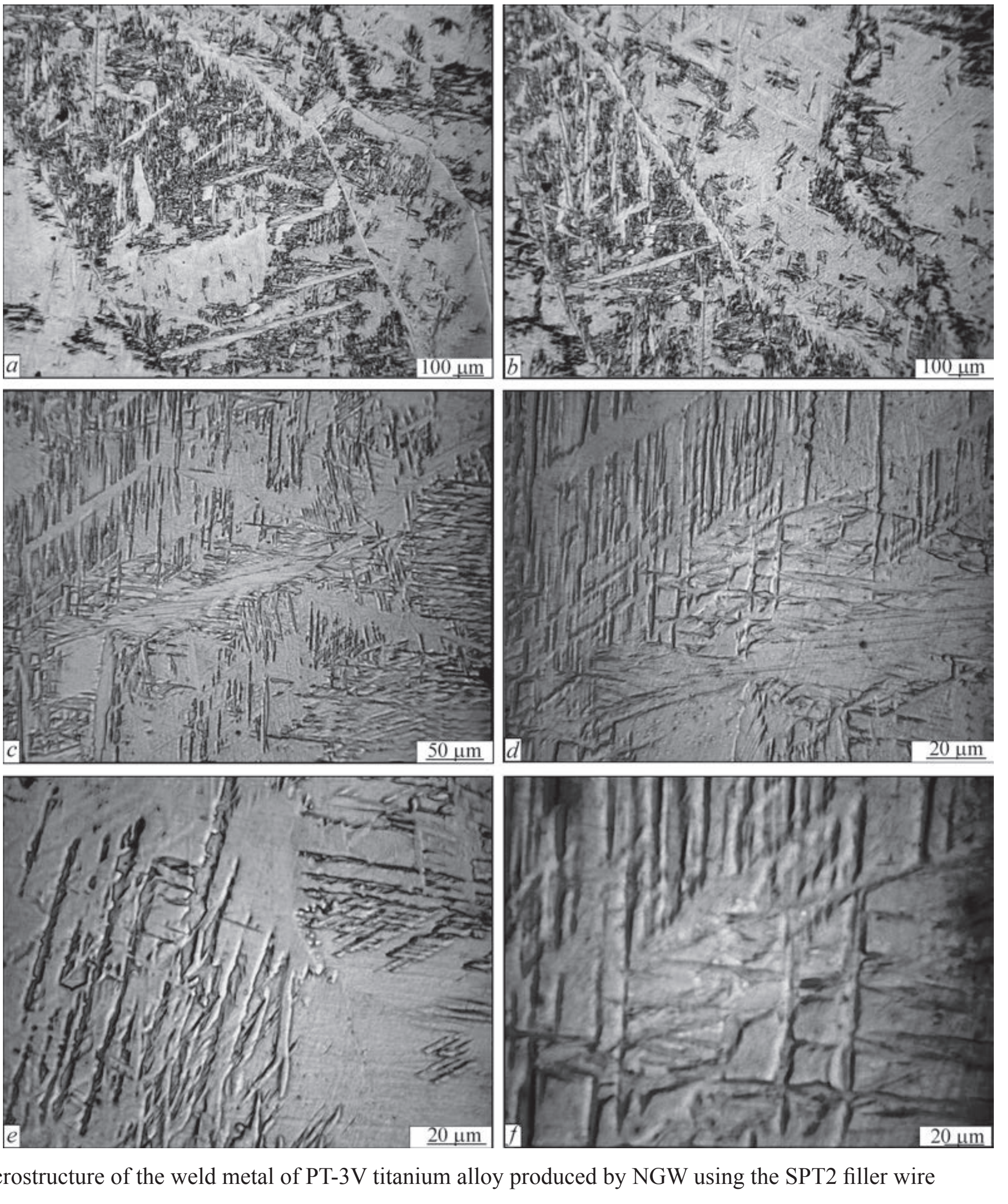

Figure 3. Microstructure of the weld metal of PT-3V titanium alloy produced by NGW using the SPT2 filler wire

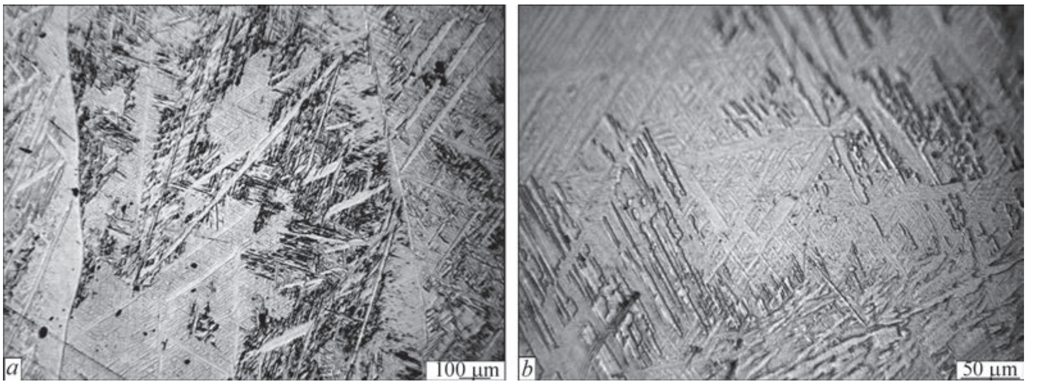

Figure 4. Microstructure of the weld metal in the upper part of the weld of PT-3V titanium alloy produced by NGW using the SPT2 filler wire

sion zone, the formation of fine primary grains is observed (Figure 6, *a*), while the intragranular structure resembles that of the base metal. The microstructure of the fine primary grains is lamellar, consisting of α-phase forming lamellae that can be either parallel or intersect within the former β-grains, which is typical for pseudo-α structures (Figure 6, *b*). This morphology indicates a relatively high cooling rate in this area during welding.

The microstructure of the metal in the fusion zone of the PT-3V alloy welded joint, produced by NGW using 2V filler wire, is shown in Figure 7. Fine primary grains are observed in the fusion zone (Figure 7, *a*), while the intragranular structure resembles that of the base metal (Figure 7, *b*).

The microstructure of the HAZ metal produced using SPT2 and 2V wires, immediately adjacent to the fusion zone — specifically, the large-grain area of the PT-3V alloy — is identical and is shown in Figure 8. The metal in this zone consists of equiaxed primary grains (Figure 8, *a*) with a microstructure similar to the intragranular structure of the weld metal grain (Figure 8, *b*, *c*). The structure contains coarse grains and elongated α-plates, predominantly oriented parallel to the heat gradient (Figure 8, b). A redistributed α-structure is noticeable in the form of loosely ordered overlapping packets. The boundaries of primary β-grains, partially transformed into α-phase, are occasionally observed.

In Figure 8, *d*, dispersed second-phase particles, most likely β-phase, can be seen along the α-plate boundaries. The size of these particles is 0.5 µm or smaller (Figure 8, *d*). The microstructure of the HAZ metal near the base metal (Figure 8, *d*, *e*) is also very

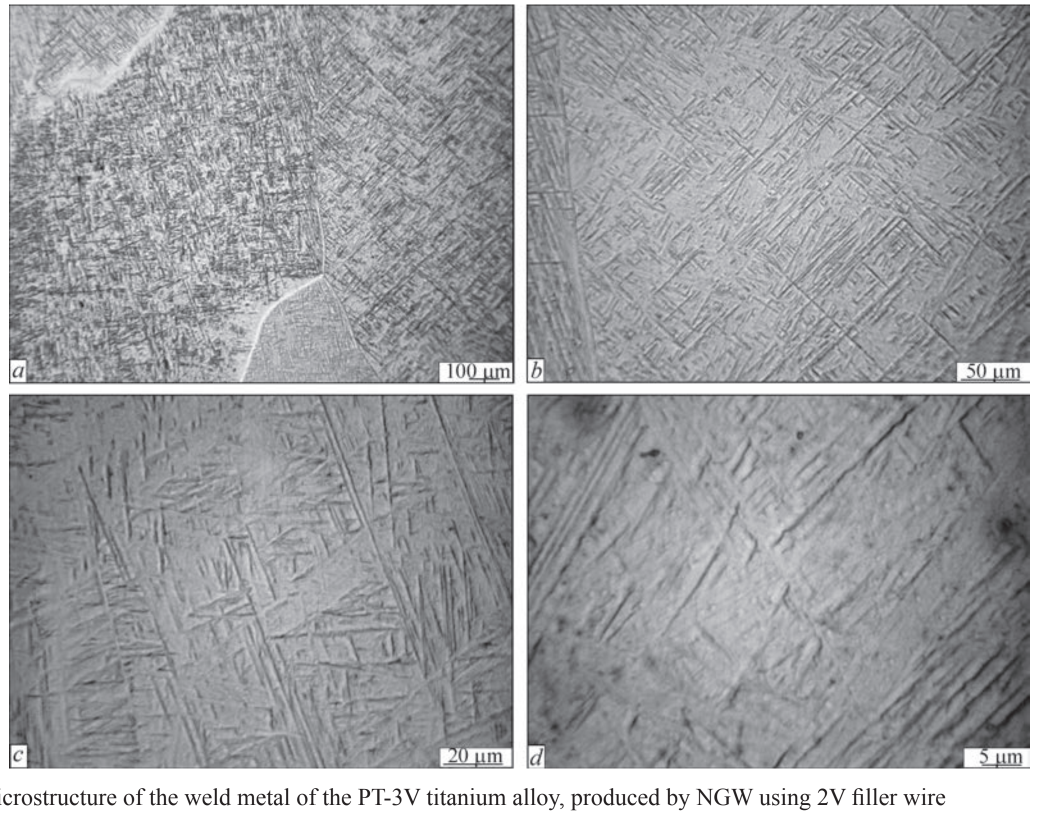

Figure 5. Microstructure of the weld metal of the PT-3V titanium alloy, produced by NGW using 2V filler wire

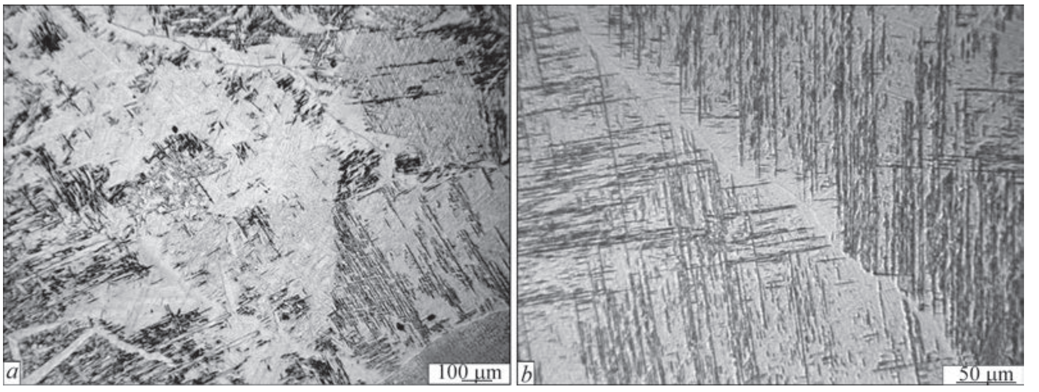

Figure 6. Microstructure of the fusion zone metal of the PT-3V titanium alloy, produced by NGW using SPT2 filler wire

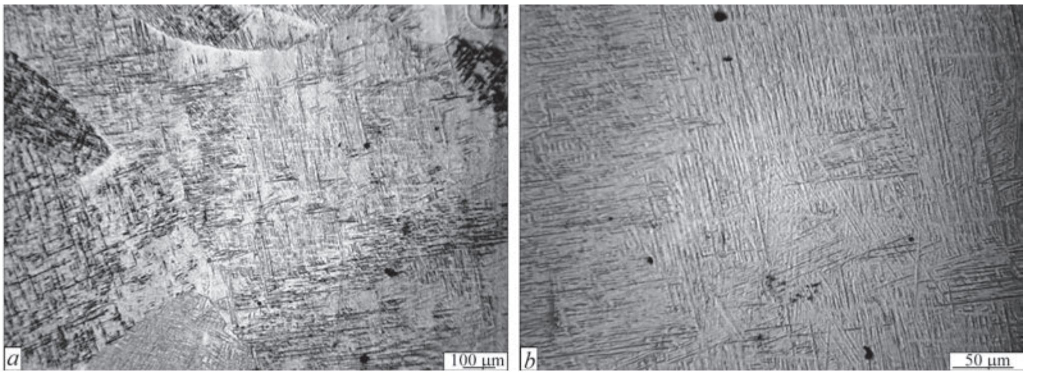

Figure 7. Microstructure of the fusion zone metal of the PT-3V titanium alloy, produced by NGW using 2V filler wire

similar to other areas of the PT-3V alloy welded joint produced by NGW with 2V filler wire.

Thus, the microstructures of the weld metal in PT-3V alloy joints produced by arc welding with SPT2 and 2V filler wires are similar. The similarity of microstructures in different areas of PT-3V welded joints may indicate a close phase composition, which provides several advantages for these filler materials belonging to the pseudo-α alloy class. Specifically, these alloys are practically insensitive to strengthening heat treatment. The martensitic α′-phase formed upon cooling from above the critical temperature has physical and mechanical properties similar to those of the α-phase. Moreover, the amount of β-phase in alloys of this class is so small that its eutectoid decomposition, if it occurs, does not significantly affect the physical and mechanical properties. Thanks to these characteristics, the 2V and SPT2 filler metals exhibit excellent weldability, typical of pseudo-α alloys, and high thermal stability.

DISCUSSION OF RESULTS

Determination of the mechanical properties of welded joints of the new pseudo-α titanium alloy PT-3V, produced by NGW with SPT2 and 2V filler wires, led to the conclusion that the lowest postweld strength values were observed in joints made with 2V filler wire, at 643 MPa (Table 7), which corresponds to 86 % of the base metal strength.

The highest postweld strength values were observed in joints made by NGW with SPT2 filler wire, at 759 MPa (Table 7). The strength of joints produced using SPT2 filler wire is comparable to the strength of the base metal (Table 7). It should be noted that the weld metal strength is somewhat higher, reaching 818 MPa, or 109 % relative to the base metal strength. Failure of the MI-12 specimens during testing of the welded joints occurred through the weld when 2V filler wire was used, and through the base metal when SPT2 filler wire was used. Thus, the weld metal of joints produced with SPT2 filler wire exhibits slightly higher strength — about 9 % greater than the base metal — immediately after welding.

The impact toughness values of the notched welded joint specimens produced with 2V filler wire exceed those of the base metal. This is due to the lower content of alloying elements in the weld metal, which consists of approximately 90 % filler metal from the 2V wire. The impact toughness values of welded joints produced with SPT2 filler wire are about 83 % of the base metal and correspond to the impact toughness values of the weld metal. The conducted studies allow the conclusion that using SPT2 filler wire for NGW of PT-3V titanium alloy enables the formation of a weld metal structure similar to that of the base metal and ensures comparable strength of the welded joint. For a comparative assessment of the performance of

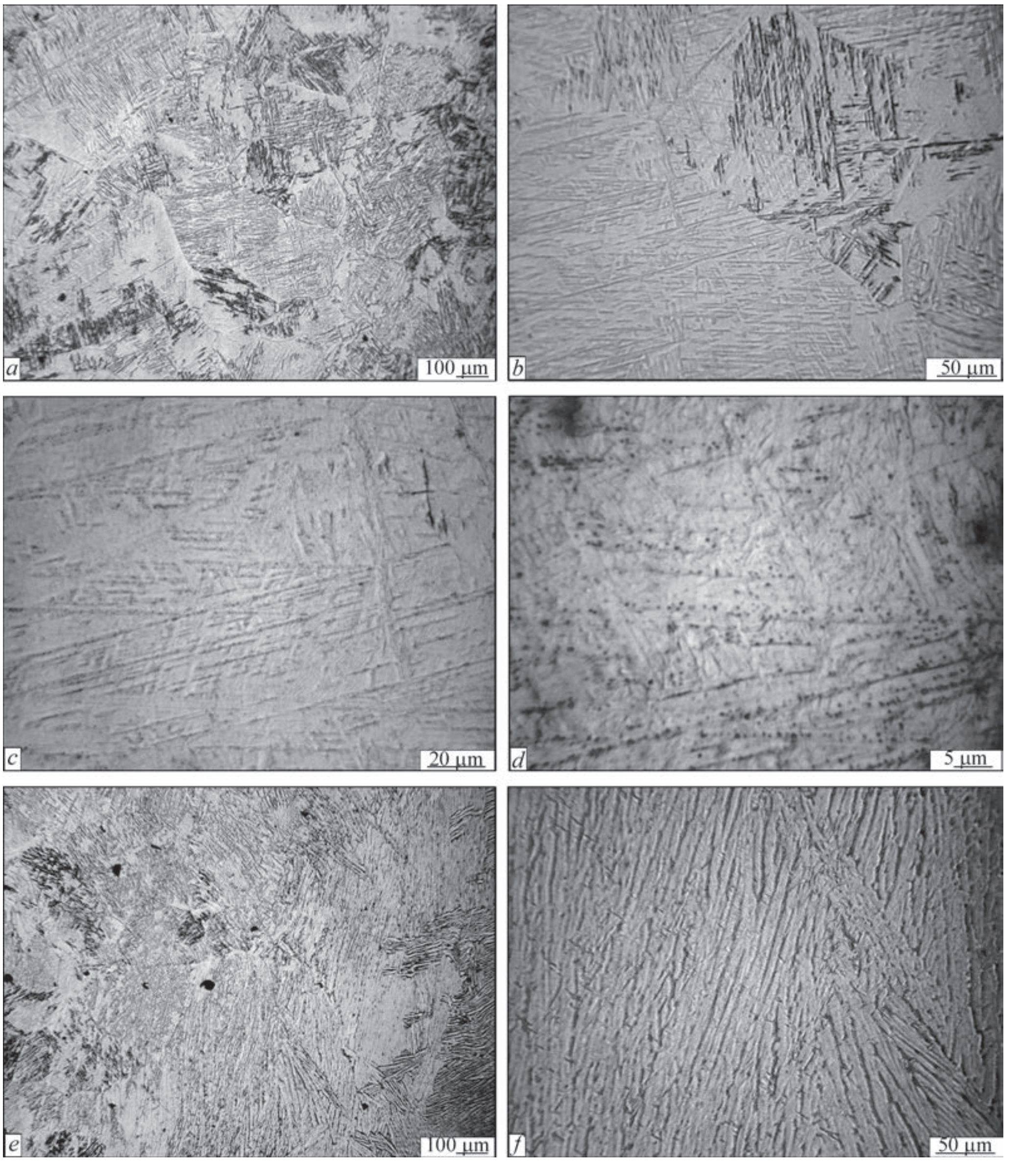

Figure 8. Microstructure of the HAZ metal of the PT-3V alloy, produced by NGW

welded joints produced with SPT2 and 2V filler wires, further studies on low-cycle fatigue strength are required. It should be noted that when using 2V filler wire, the strength of the welded joints is slightly lower than that of the PT-3V base metal. However, during arc welding of titanium alloys, the weld metal is also alloyed through the transfer of elements from the base metal into the weld. This allows the use of filler wire less alloyed than the base metal. High performance of welded joints in thick titanium alloys can be ensured due to the high ductility and impact toughness of the weld metal.

Table 7. Mechanical properties of the base metal and welded joints with a thickness of 45 mm made of PT-3V titanium alloy, welded by EBW*

Specimen	σ_t	σ_{02}	δ,%	ψ, %	*KCV*, J/cm^2	
	MPa				Weld	HAZ
Base metal PT-3V, δ = 45 mm	747	678	12.7	30.8	95.3	
Welded joint, filler metal 2V	643	604		41.2	107	78
Weld metal, filler metal 2V	609	506	18.3	47.4	107	
Welded joint, filler metal SPT2	759	691	12.1	30.1	79	77
Weld metal, filler metal SPT2	818	716	11.8	36.9	79	
Weld metal, filler metal 2V after heating at 780 °C	799	750	10.7	45.1	89.2	

*Average of three results is given.

To increase the strength of PT-3V alloy welded joints when using 2V filler wire, postweld annealing can be applied. Annealing at 780 °C followed by furnace cooling allows the weld metal strength to rise to 799 MPa, with an impact toughness of *KCV* = 89 cm² (see Table 7). However, practical application of annealing is not always feasible for welded joints of thick titanium alloys.

Thus, the use of SPT2 filler wire for NGW of PT-3V titanium alloy with a magnetically controlled arc ensures that the welded joint achieves strength comparable to the base metal immediately after welding.

CONCLUSIONS

1. Filler wires 2V and SPT2, when used for NGW of PT-3V titanium alloy with a magnetically controlled arc, ensure sound formation of the concave weld bead surface. The strength of welded joints made with 2V filler wire is 643 MPa, which is 86 % of the base metal strength.

2. The microstructure of the weld metal in PT-3V alloy joints produced by NGW with SPT2 and 2V filler wires is similar and consists of equiaxed and non-equiaxed primary β-grains. The microstructure within the primary grains is lamellar α-phase. The similarity of microstructures in different areas of the welded joints of PT-3V alloy indicates a close phase composition.

3. The use of SPT2 filler wire for NGW of PT-3V titanium alloy allows the formation of a weld metal structure similar to that of the base metal and ensures comparable strength of the welded joint immediately after welding.

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ORCID

S.V. Akhonin: 0000-0002-7746-2946,
V.Yu. Bilous: 0000-0002-0082-8030,
R.V. Selin: 0000-0002-2990-1131

CONFLICT OF INTEREST

The Authors declare no conflict of interest

CORRESPONDING AUTHOR

S.V. Akhonin
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: akhonin.sv@gmail.com

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