DOI: https://doi.org/10.37434/tpwj2025.09.01

NARROW GAP WELDING OF PT-3V TITANIUM ALLOY WITH A CONTROLLED MAGNETIC FIELD

S.V. Akhonin, V.Yu. Bilous, R.V. Selin, I.K. Petrichenko, L.M. Radchenko, S.B. Rukhansky

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

ABSTRACT

Tungsten inert gas (TIG) narrow-gap welding of titanium alloys is a cost-effective and efficient method for joining thick titanium alloy structures. The technology of narrow-gap welding of titanium alloys with a magnetically-controlled arc enables a wide range of welding parameter adjustments. This study considers the application of narrow-gap welding with a tungsten electrode and a controlled magnetic field for producing joints of PT-3V titanium alloy plates with thicknesses of 45 and 64 mm. The strength of the welded joints of PT-3V titanium alloy produced by narrow-gap welding with a controlled magnetic field reaches 636 MPa, which is 85 % of the base metal strength, and it is comparable to the properties of welded joints made using the conventional gas tungsten arc welding technology. Application of the obtained results allowed welding joints of titanium alloys with variable thicknesses ranging from 45 to 65 mm while maintaining the same number of passes.

KEYWORDS: narrow-gap welding, titanium, titanium alloy, TIG welding, tungsten electrode, controlled magnetic field, heat input, structure, microstructure, mechanical properties, metallography

INTRODUCTION

Narrow-gap welding is an economical and effective way to join thick metal [1, 2]. Reducing the consumption of filler wire, inert gas, and other welding consumables, as well as the labour intensity of preparing the edges of the parts to be welded, are factors that are particularly important when welding titanium and titanium-based alloys [3]. A well-known method of welding titanium is the Gas Tungsten Arc Narrow-Gap Welding (GTAW-NG) using a magnetically-controlled arc, developed at the E.O. Paton Electric Welding Institute of the NAS of Ukraine [4]. This welding method has the following advantages: small width of the produced weld and small volume of the deposited metal. Another advantage is the simple shape of the edges to be welded.

As is known, GTAW-NG can be performed within a wide range of welding current values, welding speeds, and filler wire feed rates [5, 6]. At the same time, it is possible to deposit a metal layer with a thickness from 3 to 8 mm or more in a single pass. The increased thickness of the metal layer deposited in a single pass allows reducing the number of passes required to fill the gap, which in turn improves the efficiency of the welding process. However, the main condition when choosing a welding mode for titanium alloys is producing a defect-free joint [7, 8]. An excessive increase in the thickness of the metal layer deposited in a single pass can cause defects in the weld [9, 10]. A characteristic defect of multilayer narrow-gap welding of titanium alloys is the lack of fusion between the weld metal and the base metal, as well as interlayer lacks of fusion in the weld [11, 12].

The technology of narrow-gap welding of titanium alloys with a magnetically-controlled arc allows changing not only the heat input of the welding process [13–15], but also the parameters of the controlled magnetic field, such as the magnetic induction in the arc zone and the reversal frequency of the controlled magnetic field [16].

Thus, it is advisable to conduct research to determine the influence of such parameters of the process of narrow-gap welding of titanium alloys with a magnetically-controlled arc, such as the magnitude of the magnetic induction of the controlled magnetic field, as well as the value of the heat input, on the properties of welded joints of PT-3V titanium alloy.

THE AIM

of the work is to investigate the influence of the induction value of the controlled magnetic field and the heat input value of the narrow-gap welding process with a tungsten electrode of PT-3V titanium alloy on the structure and mechanical properties of welded joints.

MATERIALS USED IN THE STUDY

To achieve the set aim, multilayer welding was performed on specimens of 45 and 65 mm thick, made of PT-3V titanium alloy in accordance with GOST 1050–88. The length of the test specimens for welding was 600 mm.

A 3 mm titanium filler wire diameter of 2V grade, recommended for PT-3V titanium alloy, was used as an additive. Welding was performed with application of external controlled magnetic field to deviate the

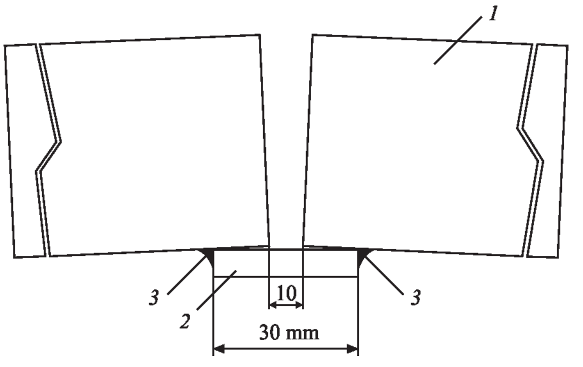

Figure 1. Scheme of assembling specimens for welding: *1* — side walls of a narrow gap; *2* — remaining backing plate; *3* — welds for welding-on the backing plate to the side walls

arc. The work used EVI-2 tungsten electrodes with a diameter of 5 mm. Welding was performed at direct current with straight polarity. A VDU-501 welding current source was used. The welding current was selected within the range of 420–480 A, and the arc voltage was maintained at 12 V by an automatic arc voltage control system. The feed rate of the 2V filler wire of 3 mm diameter into the weld pool varied between 64 and 82 m/h.

The parts were assembled for welding using a remaining backing plate, which was manually welded-on to the back side of the part [17] (Figure 1). This backing plate serves as the bottom wall of a narrow gap when performing the first pass. After completing the root pass, filling passes were performed. To weld a butt with a thickness of 65 mm, 13 passes are required, i.e., a 5 mm thick layer of metal is deposited when welding using the existing technology. If the thickness of the metal layer deposited in a single pass is increased, the overall efficiency of the welded joint production process will be improved.

The scheme of multilayer welding process is shown in Figure 2. Welding is performed with a tungsten electrode that is lowered into a narrow gap. At the same time, the filler wire is fed perpendicular to the electrode into the head part of the weld pool. The controlled magnetic field is created by a special

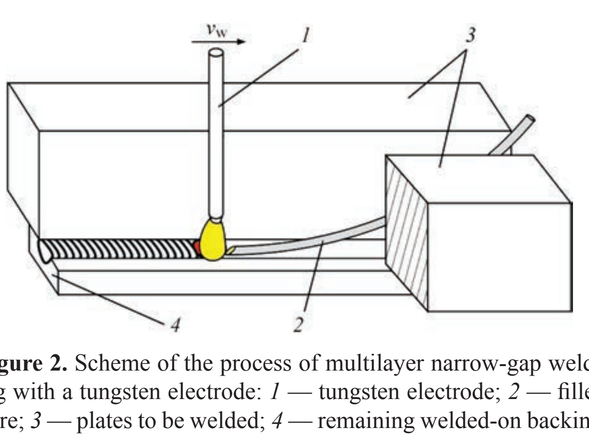

Figure 2. Scheme of the process of multilayer narrow-gap welding with a tungsten electrode: *1* — tungsten electrode; *2* — filler wire; *3* — plates to be welded; *4* — remaining welded-on backing plate

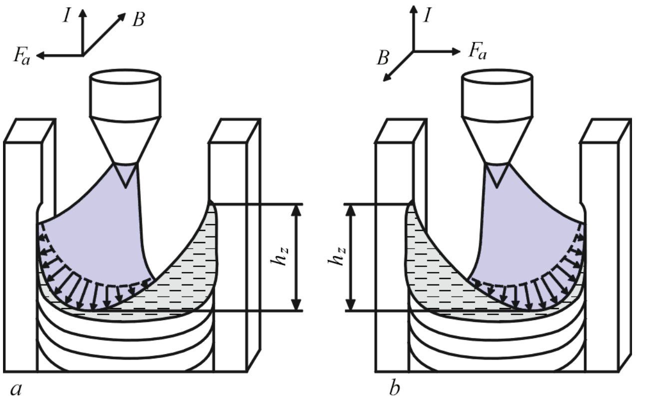

Figure 3. Scheme of melting the side walls of a narrow gap and location of the welding arc: *a*, *b* — extreme positions; h_z — height of the weld metal layer being deposited

electromagnet with a narrow core located in a narrow gap [17]. As a result of the interaction of the magnetic field with the arc current, a Lorentz force arises, which deviates the arc and causes displacement of the anode spot to the side wall.

The scheme of melting the side walls of a narrow gap during narrow-gap welding with a tungsten electrode with an external controlled magnetic field is shown in Figure 3. The value of the anode spot displacement to the side wall is proportional to the magnetic induction value of the controlled magnetic field. From the presented scheme, it can be concluded that in order to ensure guaranteed fusion of the weld metal layer with a height h_z with the side wall, it is necessary to deviate the welding arc so that the anode spot rises along the side wall to the corresponding height h_z and melts the metal.

Welding modes with different values of heat input and magnetic induction of the controlled magnetic field, which ensure high-quality formation of the deposited bead surface and the absence of lacks of fusion of the deposited metal of the weld with the side walls of welded joints of PT-3V titanium alloy are given in Table 1. Macrosections of welded joints are shown in Figure 4.

Welding according to parameters of modes No. 1 and No. 3 ensures high-quality formation of the deposited bead surface of the PT-3V titanium alloy specimen. Moreover, GTAW-NG with a controlled magnetic field and the highest feed rate of the filler wire at 82 m/h (mode No. 3, Table 1) provides the highest height of the deposited metal layer of 7 mm thick in a single pass. It should be noted that when the feed rate of the filler wire grows without increasing the magnetic induction values of the controlled magnetic field at mode No. 2, the formation of lacks of fusion is observed in the weld metal. In order to improve the efficiency of a single pass and deposit a 7 mm thick layer of metal in a single pass, it is necessary to reduce the welding speed and increase the welding current to 480 A. This corresponds to mode No. 2 (Table 1),

Table 1. Modes of narrow-gap welding with a tungsten electrode of PT-3V titanium alloy with an external controlled magnetic field

Mode number	Welding speed V_w, m/h	Induction of the controlled magnetic field, mT	Welding current I_w, A	Heat input (total), kJ/m	Filler wire feed rate, m/h
1	8	8	420	2268	64
2	5	8	480	4147	64
3	8	11	450	2430	82

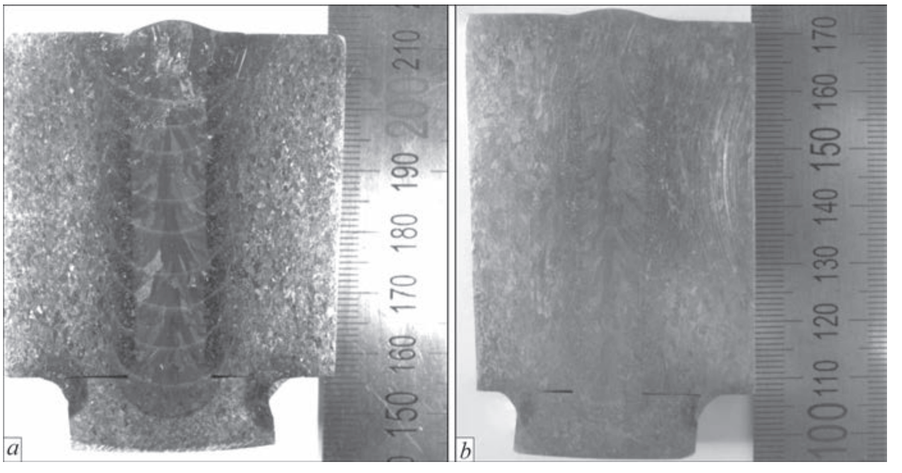

Figure 4. Cross-macrosections of welded joints of PT-3V titanium alloy made by GTAW-NG with a controlled magnetic field: *a* — welded joint of 45 mm thickness, mode No. 1; *b* — welded joint of 65 mm thickness, mode No. 3

which is characterized by a high heat input of the welding process (4147 kJ/m).

If the magnetic induction value of the controlled magnetic field is increased from 8 to 11 mT, the height of the anode spot displacement to the side wall of the narrow gap and the height of the weld metal layer being deposited h_z grows (see Figure 4). In this case, it is possible to increase the feed rate of the filler wire and deposit a 7 mm thick metal layer probably without reducing the welding speed and with a slight increase in the heat input of the welding process, mode No. 3 (Table 1).

STUDY OF THE MICROSTRUCTURE OF WELDED JOINTS OF PT-3V TITANIUM ALLOY PRODUCED BY GTAW-NG WITH A CONTROLLED MAGNETIC FIELD

PT-3V titanium alloy and filler welding wire of 2 V grade belong to the group of pseudo-α alloys. PT-3V alloy contains, by wt.%: Fe — up to 0.25; C — up to 0.1; Si — up to 0.12; V — 1.2–2.5; N — up to 0.04; Ti — 91.39–95; Al — 3.5–5.0; Zr — up to 0.3; O — up to 0.15; N — up to 0.006, other impurities — 0.3. At GTAW-NG with a controlled magnetic field, no more than 10 % of the base metal enters the weld metal [4].

The microstructure of the base metal of the PT-3V alloy is shown in Figure 5. The structure of the base metal consists of equilibrium primary β-grains of various sizes, framed by a continuous or intermittent α-phase band (Figure 5, *a*) of up to 15 μm thick. The intragranular structure consists of lamellar α-phase (Figure 5, *b*) of up to 1.5 μm thick (Figure 5, *b*). A small amount of β-phase may be present in the spaces between the α-plates, which is not always detectable under an optical microscope.

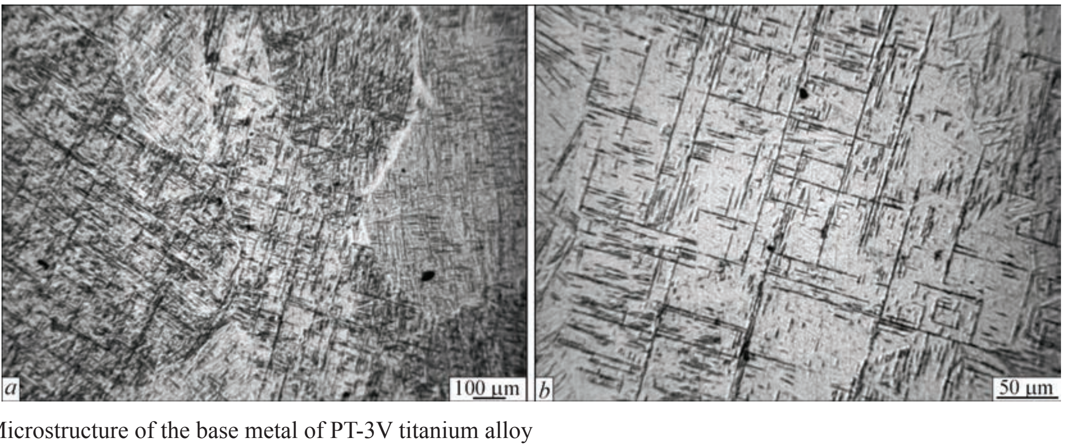

Figure 5. Microstructure of the base metal of PT-3V titanium alloy

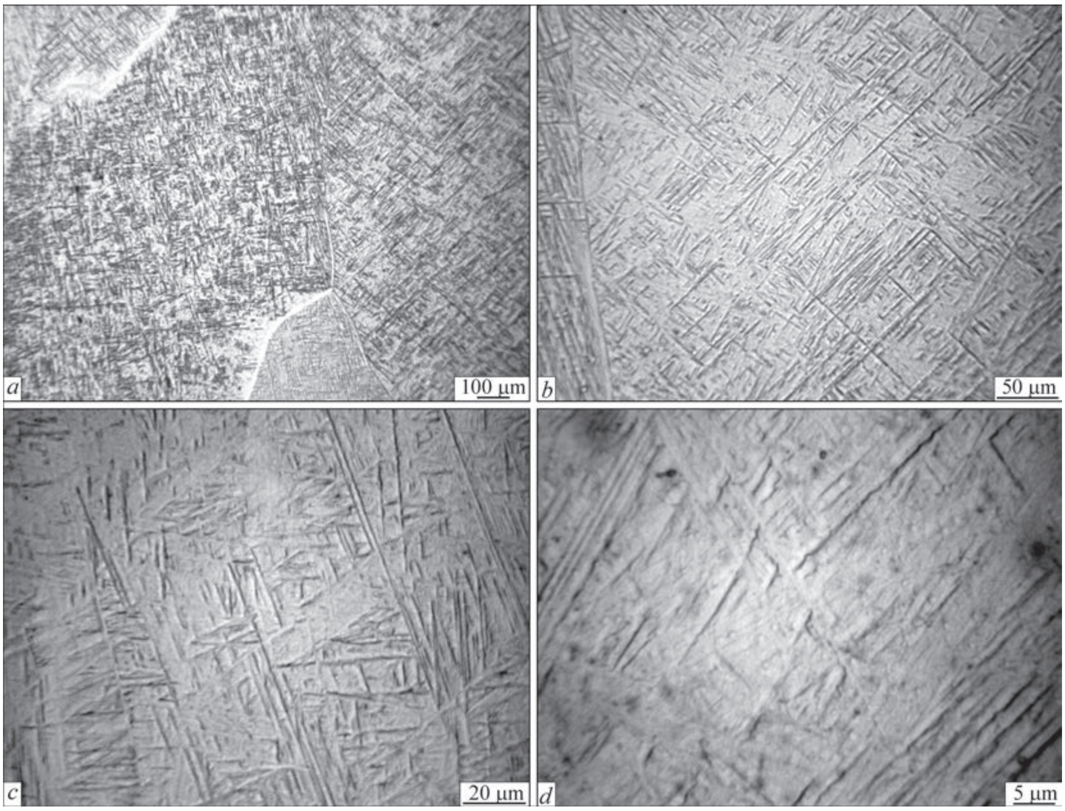

Figure 6. Microstructure of the weld metal of PT-3V titanium alloy made by GTAW-NG with a controlled magnetic field

The microstructure of the PT-3V alloy weld metal produced by GTAW-NG at mode No. 3 in its middle part is shown in Figure 6. Equilibrium and elongated primary grains of various sizes are formed in the weld metal. Despite the differences in the configuration and size of the primary grains, the intragranular microstructure of the weld metal produced by GTAW-NG using 2V wire (Figure 6, *a*, *b*) of the lamellar type is very similar to the microstructure of the base metal. The microstructures of the weld metal produced at modes Nos 1 and 2 are similar (Figure 6, *d*).

The microstructure of the PT-3V alloy weld metal produced by GTAW-NG at mode No. 3 in the fusion zone is shown in Figure 7. In the fusion zone, the formation of fine primary grains is observed (Figure 7, *a*), while the intragranular structure is similar to that of the base metal (Figure 7, *b*).

The microstructure of the metal in the heat-affected zone (HAZ) immediately behind the fusion zone, namely the coarse-grain region of the PT-3V alloy produced by GTAW-NG at mode No. 3, is shown in Figure 8. The metal in this zone consists of equilibrium primary grains (Figure 8, *a*) with a microstructure similar to the internal microstructure in the grain volume of the weld metal (Figure 8, *b*, *c*). In Figure 8, *d*, the distribution of dispersed particles of the second phase, most probably the β-phase, along the boundaries of the α-plates can be observed. The sizes of such particles are 0.5 μm and less (Figure 8, *d*).

The microstructure of the HAZ metal near the base metal of the PT-3V alloy, produced by GTAW-NG at mode No. 3, is shown in Figure 9. The microstructure of the HAZ metal near the base metal (Figure 9, *a*, *b*) is also very similar to other areas of the welded joint

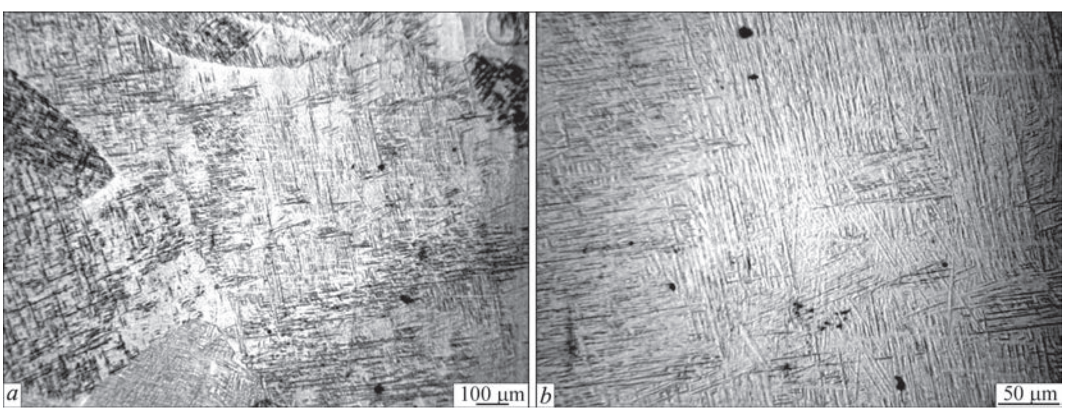

Figure 7. Microstructure of the fusion zone metal of PT-3V titanium alloy produced by GTAW-NG with a controlled magnetic field

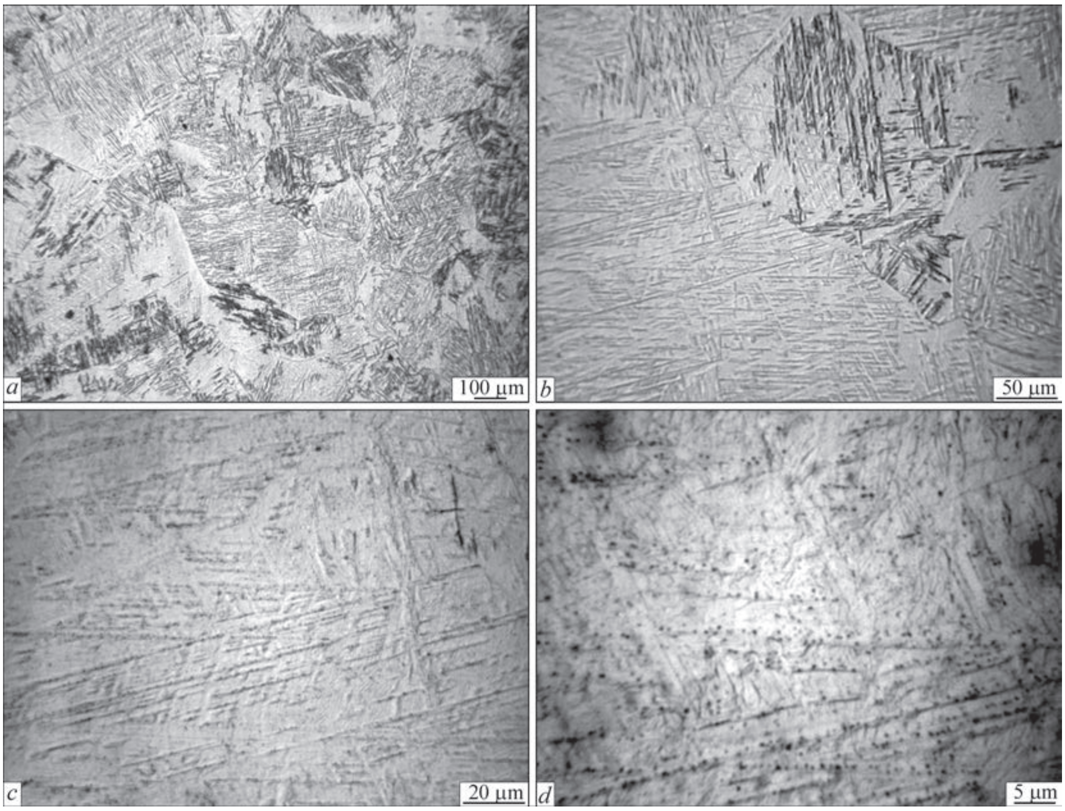

Figure 8. Microstructure of the HAZ metal of PT-3V alloy, produced by GTAW-NG with a controlled magnetic field

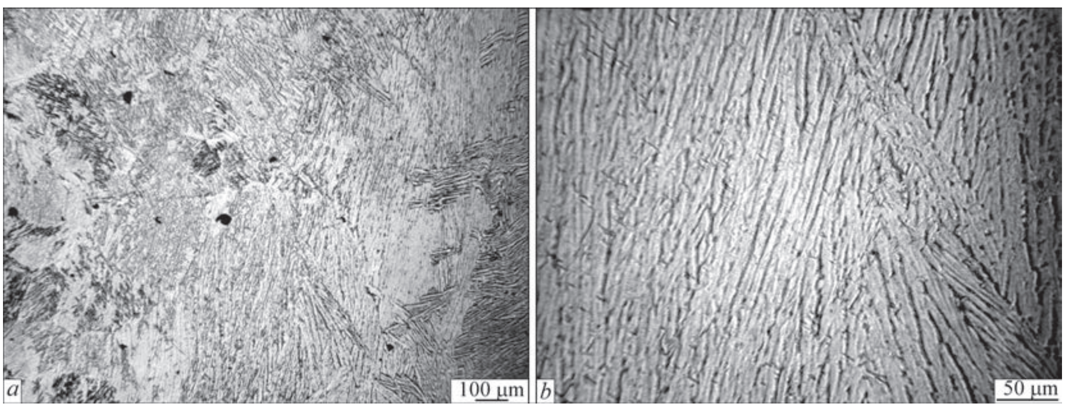

Figure 9. Microstructure of the HAZ metal near the base metal of PT-3V alloy, produced by GTAW-NG with a controlled magnetic field

of the PT-3V alloy, produced by GTAW-NG using 2V filler wire.

Thus, the microstructure of the metal in the welds produced at modes Nos 1, 2, and 3 is similar. The microstructure of the HAZ metal produced at modes Nos 1, 2, and 3 is also similar. However, the dimensions of the HAZ of joints produced at mode No. 2 (Table 2) are the largest, which is associated with the highest value of the heat input of the welding process at mode No. 2.

DISCUSSION OF RESULTS

The determination of the mechanical properties of welded joints of PT-3V titanium pseudo-α alloy, produced by GTAW-NG with an external controlled magnetic field, allowed concluding that the lowest strength values in the post-weld state at a level of 617 MPa are found in joints made at mode No. 2, with values of welding heat input of 4147 kJ/m (Table 3), which is 82 % of the strength of the base metal. The highest strength values in the post-weld state at a level of 643 MPa were found in welded joints

Table 2. Dimensions of the weld and HAZ of welded joints of PT-3V titanium alloy made by narrow-gap welding with a tungsten electrode under an external controlled magnetic field

Mode number	Height of the layer deposited in a single pass, mm	Weld width, mm	HAZ width, mm
1	5	11.6	2.85
2	7.1	12.4	4.95
3	7.0	11.5	2.75

Table 3. Mechanical properties of the base metal and welded joints of PT-3V titanium alloy, produced by GTAW-NG with an external controlled magnetic field*

Specimen type, mode No.	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %	*KCV*, J/cm²	
					Weld	HAZ
Base metal of PT-3V δ = 65 mm	746.6	677.5	12.7	30.8	95.3	
Welded joint, mode No. 1	643.2	603.5	12.7	41.2	107.4	77.9
Welded joint, mode No. 2	617.4	559.7	9.0	38.7	112.2	77.7
Welded joint, mode No. 3	636.5	583.4	14.0	46.2	104.7	79.0

*2V filler wire.

made at mode No. 1, with the lowest values of welding heat input of 2268 kJ/m (Table 3), which is 86 % of the strength of the base metal. The strength values of welded joints made at mode No. 3 with the highest values of magnetic induction of the controlled magnetic field (11 mT, see Table 1) are at a level of 636 MPa, which is 85 % of the strength of the base metal. The mechanical properties of welded joints made at modes Nos 1 and 3 are similar. To find the reasons for the decrease in the strength of welded joints made at modes No. 2 with the highest values of welding heat input and weld and HAZ sizes, additional studies of the microstructure of welded joints are necessary [17, 18].

The impact toughness values of specimens with a sharp notch in the weld metal for welded joints made at modes Nos 1, 2, and 3 exceed the impact toughness values for the base metal. This is associated with a lower content of alloying elements in the weld metal, which consists of 90 % filler metal of 2V welding wire. The impact toughness values of the HAZ for welded joints made at modes Nos 1, 2, and 3 are lower than the impact toughness values for the base metal.

Thus, it was found that it is possible to increase the thickness of the weld metal layer deposited in a single pass from 5 to 7 mm and to increase the overall efficiency of the welding process in a narrow gap of PT-3V titanium alloy by increasing the magnetic induction of the controlled magnetic field to 11 mT. This made it possible to ensure reliable melting of the side walls of the narrow gap and produce a high-quality welded joint. The mechanical properties of welded joints made at a mode with magnetic induction values of the controlled magnetic field of 11 mT are similar to the properties of welded joints made using the existing argon arc welding technology.

The application of the obtained results made it possible to propose a technology for welding PT-3V titanium alloy of variable thickness, namely of 45–65 mm thick, with the same number of passes.

CONCLUSIONS

1. The parameters of the GTAW-NG mode with an external controlled magnetic field of PT-3V titanium alloy were determined, allowing a 7 mm thick layer of metal to be deposited in a narrow gap of 10 mm wide in a single pass.

2. The strength of welded joints made of PT-3V alloy, produced by GTAW-NG with 2V filler wire at a magnetic induction values of the controlled magnetic field of 11 mT, is 636 MPa or 85 % of the strength of the base metal and is similar to the properties of welded joints made using the existing argon arc welding technology.

3. The microstructure of the metal in the welds and HAZ of PT-3V alloy, produced by GTAW-NG using 2V filler wire at modes with elevated magnetic field induction of the controlled magnetic field values, is similar to the microstructure of the metal in welds produced using existing argon arc welding technology.

4. The application of the obtained results made it possible to propose a technology for welding PT-3V titanium alloy of variable thickness, namely 45–65 mm thick, using the same number of passes.

REFERENCES

1. Hori, K., Haneda, M. (1999) Narrow gap arc welding. *J. of JWS*, **3**, 41–62.
2. Dak, G., Khanna, N., Pandey, C. (2023) Study on narrow gap welding of martensitic grade P92 and austenitic grade AISI 304L SS steel for ultra-supercritical power plant application. *Archiv. Civ. Mech. Eng*., 23(**14**). DOI: https://doi.org/10.1007/s43452-022-00540-3
3. Luo, Y., Zhang, Z.L., Zhou, C.F. et al. (2017) Effect of narrow groove MAG welding oscillation parameters on weld formation. *J. Hebei Univ. Sci. Technol*., 38(**1**), 7–12. DOI: https://doi.org/10.7535/hbkd.2017yx01002
4. Akhonin, S.V., Belous, V.Yu., Romanyuk, V.S. et al. (2010) Narrow-gap welding of up to 110 mm thick high-strength titanium alloys. *The Paton Welding J*., **5**, 34–37.
5. Jae-Ho Jun, Sung-Ryul Kim, Sang-Myung Cho (2016) A study on productivity improvement in narrow gap TIG welding. *J. of Welding and Joining*, 34(**1**), 68–74. DOI: https://doi.org/10.5781/JWJ.2016.34.1.68
6. Nguyen, D.H. (2014) *Research on droplet transfer and welding process of oscillation arc narrow gap GMAW*: Master's Thesis, Harbin Institute of Technology, Harbin, China.
7. Sun, Qing Jie, Hai Feng Hu, Xin Yuan, Ji Cai Feng (2011) Research status and development trend of narrow-gap TIG welding. *Advanced Materials Research*, **308**, 1170–1176. DOI: https://doi.org/10.4028/www.scientific.net/AMR.308-310.1170
8. Dong, Z., Tian, Y., Zhang, L. et al. (2024) Research status of high efficiency deep penetration welding of medium-thick

plate titanium alloy: A review. *Defence Technology*, **45**, 178–202. DOI: https://doi.org/10.1016/j.dt.2024.08.004
9. Fang, D.S. (2017) *Study on the characteristics of three-wire indirect arc and its thick-wall narrow gap welding process under gas protection*: Ph.D. Thesis, Dalian University of Technology, Dalian, China.
10. Belous, V.Yu., Akhonin, S.V. (2011) Formation of narrow-gap welded joints on titanium using the controlling magnetic field. *The Paton Welding J.*, **4**, 19–22.
11. Shoichi, M., Yukio, M., Koki, T. et al. (2013) Study on the application for electromagnetic controlled molten pool welding process in overhead and flat position welding. *Sci. Technol. Weld. Join.*, **18**, 38–44. DOI: https://doi.org/10.1179/1362171812Y.0000000070
12. Ding, L., Qin, B., Ge, K. et al. (2023) Microstructures and mechanical properties of thick Ti–6Al–3Nb–2Zr–1Mo joint by magnetron-controlled narrow gap TIG welding. *Metals and Materials Inter.*, 29(**8**), 2304–2315. DOI: http://dx.doi.org/10.1007/s12540-022-01367-6
13. Wang, J., Sun, Q., Feng, J. et al. (2017) Characteristics of welding and arc pressure in TIG narrow gap welding using novel magnetic arc oscillation. *The Inter. J. of Advanced Manufacturing Technology*, **90**, 413–420. DOI: https://doi.org/10.1007/s00170-016-9407-5
14. Wan, L., Huang, Y., Lv, S. et al. (2016) Narrow-gap tungsten inert gas welding of 78-mm-thick Ti–6Al–4V alloy. *Materials Sci. and Technology*, 32(**15**), 1545–1552. DOI: https://doi.org/10.1080/02670836.2015.1131941
15. Fang, N., Guo, E., Huang, R. et al. (2021) Effect of welding heat input on microstructure and properties of TC4 titanium alloy ultra-narrow gap welded joint by laser welding with filler wire. *Materials Research Express*, 8(**1**), 016511. DOI: http://dx.doi.org/10.1088/2053-1591/abd4b3
16. Xinyu Bao Yonglin Ma, Shuqing Xing, Yongzhen Liu, Weiwei Shi (2022) Effects of pulsed magnetic field melt treatment on grain refinement of Al–Si–Mg–Cu–Ni alloy direct-chill casting billet. *Metals,* 12(**7**), 1080. DOI: https://doi.org/10.3390/met12071080
17. Akhonin, S.V., Bilous, V.Yu., Selin, R.V. et al. (2023) Narrow-gap TIG welding of thick steel 20. *The Paton Welding J.*, **6**, 18–23. DOI: https://doi.org/10.37434/tpwj2023.06.03
18. Yujun Hu, Hongjin Zhao, Xuede Yu et al. (2022) Research progress of magnetic field regulated mechanical property of solid metal materials. *Metals,* **12**, 1988. DOI: https://doi.org/10.3390/met12111988

ORCID
S.V. Akhonin: 0000-0002-7746-2946,
V.Yu. Bilous: 0000-0002-0082-8030,
R.V. Selin: 0000-0002-2990-1131,
I.K. Petrichenko: 0000-0002-0476-3983,
L.M. Radchenko: 0009-0008-1097-7137,
S.B. Rukhansky: 0009-0002-1260-3688

CONFLICT OF INTEREST
The Authors declare no conflict of interest

CORRESPONDING AUTHOR
V.Yu. Bilous
E.O. Paton Electric Welding Institute of the NASU
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine.
E-mail: belousvy@gmail.com

SUGGESTED CITATION
S.V. Akhonin, V.Yu. Bilous, R.V. Selin, I.K. Petrichenko, L.M. Radchenko, S.B. Rukhansky (2025) Narrow gap welding of PT-3V titanium alloy with a controlled magnetic field. *The Paton Welding J.*, **9**, 3–9.
DOI: https://doi.org/10.37434/tpwj2025.09.01

JOURNAL HOME PAGE
https://patonpublishinghouse.com/eng/journals/tpwj

Received: 25.02.2025
Received in revised form: 04.04.2025
Accepted: 15.09.2025