Journal of Nano- and Electronic Physics
Vol. **18** No 5, 05035(7pp) (2026)

Журнал нано- та електронної фізики
Том **18** № 5, 05035(7cc) (2026)

OPEN ACCESS

REGULAR ARTICLE

Strengthening the Inner Surfaces of Long Holes in VT22 Titanium by Glow Discharge Nitriding

M.S. Stechyshyn, M.Y. Skyba, D.V. Zdorenko, A.I. Hordieiev, Y.H. Oleksandrenko*

Khmelnytskyi National University, 29016 Khmelnytskyi, Ukraine

(Received 09 December 2025; revised manuscript received 19 October 2026; published online 28 October 2026)

In terms of its structure, the VT22 titanium alloy belongs to the class of two-phase high-strength ($\alpha + \beta$) alloys and is widely used in aircraft manufacturing due to its high specific strength and corrosion resistance. It is used to manufacture fuselage components, wings, landing gear, control systems, aircraft power components, as well as weapon components for the Armed Forces of Ukraine, etc. However, the reliability of these products often depends not only on their strength but also on their tribological properties. Many studies have noted that among the numerous surface hardening methods that improve wearand fretting resistance of titanium alloys, gas nitriding is effective and economically viable; it is technologically simple, ensures stable physicochemical surface characteristics, and allows for the treatment of complex-shaped parts, including those with holes. To intensify the surface hardening process of titanium and its alloys, the method of anhydrous nitriding in a glow discharge (BATR) is promising. Waterless nitriding in a glow discharge (BATR) was performed on the UATR-1 unit, which corresponds to a diode-type model operating on direct current and is additionally equipped with heating elements located in the gas discharge chamber, which made it possible to freely-adjust the power parameters – voltage U and current density j (the ratio of current to the total area of the anode and cathode). This work examines the influence of the technological characteristics of anhydrous nitriding in a glow discharge (temperature, composition of the saturating medium, pressure of the saturating mixture in the gas discharge chamber, and hardening time) on the physicochemical properties of the nitrided layers of the VT22 titanium alloy. The samples for the research were manufactured in the form of bushings, based on the requirements for geometric similarity to the customer's products (ZSU). Dependencies were identified between the physicochemical properties of the inner surfaces of the sleeves (surface microhardness, its distribution along the depth of the hardened layer, and the axial force of sleeve mandrel) and the technological parameters of the nitriding process. As a result of the studies, it was established that the optimal composition of the saturating mixture is 75 % N_2 (nitrogen) + 25 % Ar (argon), and the optimal temperature for the VT22 alloy is 700-750 °C, which allows for a balance between diffusion depth, hardness, and the preservation of bulk mechanical properties. To ensure optimal formation of the nitride phase on the surface and nitrogen penetration into the depth, it is necessary to create an average pressure (60-70 Pa) in the chamber to achieve a balance between the formation of the hardened layer and the depth of nitriding.

Keywords: Nitriding, VT22 titanium, Physicochemical properties.

DOI: 10.21272/jnep.18(5).05035 PACS numbers: 81.65.Lp, 52.80.Hc, 81.05.Bx

1. INTRODUCTION

Titanium and its alloys are distinguished from others by their high strength at both room temperature and elevated temperatures, as well as excellent corrosion resistance and a number of other valuable properties [1].

A major drawback of titanium is its high reactivity at elevated temperatures, which causes it to react with almost all gases, including oxygen, nitrogen, and hydrogen. These gases, when reacting with titanium, form solid solution intermetallic compounds and brittle compounds such as oxides, carbides, nitrides, and hydrides. They impair the material's ductility and weldability, although they increase its hardness and strength, while simultaneously reducing its corrosion resistance [2]. At the same time, a stable oxide film easily forms on the surface of titanium, giving it high corrosion resistance in fresh and seawater, as well as in some acids. Titanium exhibits resistance to cavitation corrosion, cavitation-erosion wear, and stress corrosion [3].

Titanium alloys have a wider range of applications than pure titanium due to their improved properties. In terms of specific strength, they surpass special steels, as well as the strongest aluminum and magnesium alloys. To create alloys, titanium is alloyed with elements such as Al, Mo, V, Mn, Cr, Sn, Fe, Zr, Nb, as well as small amounts of Si. All industrial titanium alloys typically contain aluminum, which increases the tensile strength but reduces their ductility [4].

In terms of its structure, the VT22 titanium alloy belongs to the class of two-phase high-strength ($\alpha + \beta$) alloys and is widely used in aircraft manufacturing due to its high specific strength and corrosion resistance [5-7]. It is used to manufacture fuselage components, wings, landing gear, control systems, aircraft power components,

* Correspondence e-mail: oleksandrenkoyevhen@gmail.com

© 2026 The Author(s). Journal of Nano- and Electronic Physics published by Sumy State University. This article is distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Cite this article as: M.S. Stechyshyn et al., *J. Nano- Electron. Phys.* 18 No 5, 05035 (2026) https://doi.org/10.21272/jnep.18(5).05035

as well as weapon components for the Armed Forces of Ukraine, etc. However, the reliability of these products often depends not only on their strength but also on their tribological properties [5-10]. In works [11-14] it is noted that among the numerous surface hardening methods that increase the wear and fretting resistance of titanium alloys, gas nitriding is effective and economically viable; it is technologically simple, ensures stable physicochemical characteristics of surfaces, and makes it possible to process parts with complex shapes, including those with holes. The formed transitional diffusion layers promote strong adhesion of the surface nitride layer to the substrate, as confirmed by the results of [2].

Ion nitriding, particularly glow discharge nitriding, is a promising method for intensifying the surface hardening of titanium and its alloys. The main scientific results on the development of industrial technologies and equipment for carrying out the process, as well as the theoretical foundations and practical aspects of anhydrous nitriding in a glow discharge (BATR), were developed by V.G. Kaplun and I.M. Pastukh [15, 16].

Glow discharge nitriding has significant advantages over traditional furnace gas nitriding: it is more energy-efficient and less resource-intensive, provides a 3-5 times higher nitriding rate, and allows for precise control of surface nitrogen saturation, which makes it possible to predict the treatment results. In addition, this method does not cause deformation of parts and ensures higher quality of the modified surface [16].

The unique properties of titanium and its alloys, possessing the performance characteristics required for high-temperature structural materials, are increasingly attracting the attention of developers in the military, aerospace, aviation, and oil and gas industries, particularly for the manufacture of gas turbine engine blades and compressor blades for gas transfer units [17]. Their high heat-resistant properties are widely used in high-temperature engineering. However, alongside their high physical and mechanical properties, titanium alloys exhibit low wear resistance and heat resistance, and at temperatures above 500 °C, they demonstrate low corrosion resistance in aggressive environments and a rapid decline in metal strength with increasing temperature, which limits their practical application [3]. Therefore, there is a need to protect titanium alloys from oxidation and to improve their tribological properties, heat resistance, corrosion and wear resistance, etc.

Virtually all kinematic friction pairs with translational motion in mechanical engineering structurally fall into the category of holes with a relatively small diameter, i.e., the ratio of the hole's length (depth) to its diameter exceeds four. This indicator is justified by the fact that the nitriding process of such structural elements is analogous in nature to a hollow-cathode discharge. From the theory of this process, it is known that the field actually penetrates into the bores to a depth of no more than two diameters [18]. At the same time, it should be noted that this value refers to the field boundary where the field strength is only 0.02 (about two percent) of the nominal value at the end of the hole [16, 19]. For blind recesses or holes, the criterion value may be reduced to two.

2. DESCRIPTION OF THE OBJECT AND RESEARCH METHODS

Waterless nitriding in a glow discharge (WND) was performed on the UATR-1 unit, which corresponds to a diode-type model operating on direct current and is additionally equipped with heating elements located in the gas discharge chamber, which made it possible to arbitrarily change the energy parameters – voltage U, and current density j (the ratio of current to the total area of the grid and suspension) [1].

The glow discharge nitriding (GDN) process is carried out in a discharge chamber, the housing of which is grounded and simultaneously serves as the anode, while the workpiece acts as the cathode. The workpiece is suspended on a special hanger made of titanium alloys. This is because the nitriding temperature of titanium significantly exceeds the temperature at which steel is nitrided. The use of steel fixtures at high temperatures (above 700 °C) leads to their sputtering due to ion bombardment. Metal ions deposited on the surface of titanium specimens create a barrier to nitrogen penetration, which reduces the depth of the diffusion layer [16].

The following components are installed in separate cabinets: a gas system with cylinders for gaseous components and a two-stage gas mixture purification system; a control system, which may include a ballast rheostat for selecting a variable power supply mode. The power supply unit consists of a three-phase thyristor voltage regulator and a two-arm diode rectifier. A vacuum system is connected to the chamber via a flexible connection. The chamber and converter are cooled by flowing process water. The gaseous components of the gas mixture are introduced in a specified volume ratio into a mixing cylinder, from where, after being purified of moisture and oxygen, they enter the discharge chamber. A specific vacuum is maintained in the chamber using the vacuum system, creating conditions for a stable glow discharge between the anode and cathode at various electrical parameters characteristic of specific process phases. Modified parts, which are electrically connected to the cathode, are bombarded by the falling stream, which promotes the intensification of all subprocesses characteristic of ATP.

The installation includes a discharge chamber, a vacuum system, a gas supply system, a power supply system, and control and measuring instruments. Each of the systems and components of the installation performs a specific set of functions. The primary task of the gas system is to prepare a high-quality gas mixture in accordance with the requirements of the process mode. The power supply system must ensure not only the formation of an electric potential on the chamber electrodes but also the power execution of control pulses from the control system to maintain a smoldering electric discharge in the gas and prevent even a brief transition to an arc discharge (the latter can inevitably lead to damage to the treated objects).

The technological process is characterized by four process parameters, namely: the composition of the saturating medium, temperature, pressure in the discharge chamber, and the duration of the diffusion saturation process. A distinctive feature of this unit is the use of anhydrous gas mixtures (a mixture of nitrogen and argon) as the saturating medium in the nitriding process, which prevents hydrogen embrittlement of the metal surface. The absence of hydrogen in the saturating medium – which is a good metal reducer and neutralizes oxygen – requires the use of exceptionally pure saturating gases (99.99 %) and a

high degree of tightness in the gas supply system and vacuum chamber. Even a small amount of oxygen (0.1 %) causes the formation of oxides on the metal surface and sharply reduces nitrogen diffusion into the metal. Therefore, unlike systems operating with hydrogen-containing diffusion media (ammonia, a mixture of nitrogen and hydrogen), this system has an oxygen trap in the gas supply system that neutralizes residual oxygen in the diffusion medium before it enters the vacuum chamber.

A generalized structure of the system for vacuum diffusion gas discharge surface modification technology is shown in Figure 1.

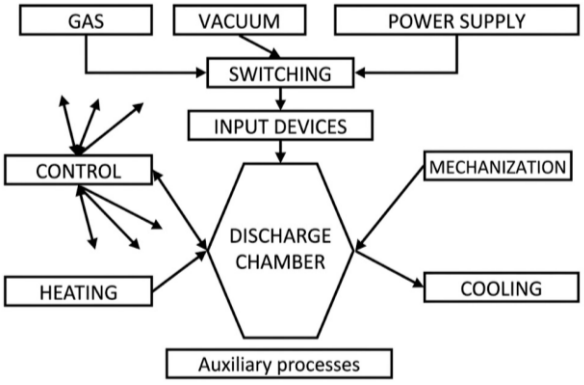


Fig. 1 – General structure of the installation for nitriding in a glow discharge

The system includes: a discharge chamber, a vacuum system, a gas supply system, a power supply system, and control and measurement instruments. Each of the system's components performs a specific set of functions. The primary task of the gas system is to prepare a high-quality gas mixture in accordance with the requirements of the process conditions. The power supply system must ensure not only the formation of an electric potential on the chamber electrodes but also the power execution of control pulses from the control system to maintain a glow discharge in the gas and prevent even a brief transition to an arc discharge (the latter can inevitably lead to damage to the treated objects).

A schematic diagram of the installation is shown in Fig. 2.

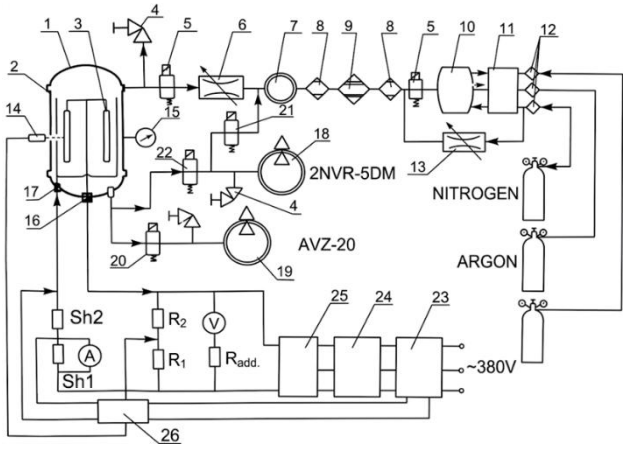


Fig. 2 – Schematic diagram of the "UATR-1" system. 1 – vacuum chamber; 2 – anode; 3 – cathode; 4 – air inlet valve; 5, 20, 21, 22 – electromagnetic vacuum valves; 6, 13 – throttle; 7 – gas flow meter; 8 – moisture separator; 9 – oxygen trap; 10 – gas mixer; 11 – metering device; 12 – filters; 14 – temperature sensor; 15 – vacuum gauge; 16 – cathode current lead; 17 – anode current lead; 18, 19 – vacuum pumps; 23 – voltage regulator; 24 – power step-up transformer; 25 – current rectifier; 26 – glow discharge stabilization unit

The use of a glow discharge not only significantly accelerates the process of nitrogen diffusion saturation of the surface but also substantially alters the process kinetics and the qualitative parameters of the nitrided layer, particularly its physical and mechanical properties and phase composition. This allows for the optimization of the physical and mechanical properties of the surface layer depending on the operating conditions of the structural elements and increases their wear resistance.

The samples for the study of the VT22 titanium alloy were hollow cylinders (bushings) with an outer diameter $D_(\text{out}) = 50 \pm 0.1$ mm, an inner diameter $d_(\text{in}) = 35 \pm 0.05$ mm, and a length $L = 50$ mm. The dimensions of the samples were determined based on the criterion of geometric similarity to the customer's product.

The chemical composition of the VT22 titanium alloy is given in Table 1.

Table 1 – Chemical composition of the VT22 alloy

Alloy	Alloying element content, mass%							
	Al	V	Fe	Zr	Mo	Nb	Cr	Ti
VT22	4.4…5.7	4.0…5.5	0.5…1.5	0.3	4.0…5.5	–	0.5...1.5	Base

The objective of metallographic analysis is to establish a relationship between the qualitative and quantitative characteristics of the structure of metallic materials, on the one hand, and their physical, mechanical, operational, and other properties, on the other. The studies were conducted on specially prepared metallographic sections. To prepare the sections, the test specimens were cut in the diametrical plane after nitriding. To prevent chipping of the layer and warping of the analyzed surface ("section deformation"), the samples were secured in special fixtures (clamps) with copper foil spacers, after which the surfaces under study were ground, polished, rinsed, and etched. For surface etching, a reagent consisting of equal parts of hydrofluoric acid, nitric acid, and glycerin was used.

Analysis of the obtained samples was performed in three stages: microscopy – image analysis to identify the material structure; hardness measurement (hardness testing); X-ray phase analysis.

Microscopic method of structural analysis. Measurements of the nitride zone thickness were performed using a MIM-10 metallographic microscope, which allows for visual observation and photography of the microstructure of metals, as well as quantitative analysis of the phase and structural composition of steels using a semi-automatic built-in device.

The thickness of the nitrided zone of the modified layer was calculated as the arithmetic mean of the measurements taken at 50 points on the tested sample. The total thickness of the nitrided layer was determined in accordance with DSTU 2494-94.

The method for measuring the microhardness of metal and alloy products and samples is standardized and was performed in accordance with DSTU ISO 6507-1:2007.

Microhardness was measured using a PMT-3 device at a load of 0.98 N (0.1 kg), with microhardness values recorded both on the surface and at specific depths within the sample, namely: 0, 25, 50, 100, 200, 300, 500 μm.

X-ray phase analysis was performed on a general-purpose DRON-3 X-ray diffractometer using filtered iron anode radiation, in the 2θ angle range from 20° to 100° with a scanning step of 0.1° and an exposure time of 10 s. X-ray imaging was performed on the flat ends of cylindrical samples subjected to deep nitriding of the modified layer.

The process parameters of glow discharge nitriding significantly influence the physical and mechanical properties, structure, phase composition, and wear resistance of the nitride layer; therefore, studying this influence is an important task.

The aim of the research is to determine the dependence of the characteristics of the nitrided layer (depth, hardness, structure, phase, and chemical composition) on the main parameters of the technological process (pressure, composition of the saturating medium, temperature, and duration of the process). Mixtures of nitrogen and argon (in various ratios) were used as working gases; the saturation temperature varied from 700 °C to 800 °C, the pressure of the gas mixture during the diffusion saturation process ranged from 67 Pa to 320 Pa, and the process duration ranged from 240 min to 300 min.

The application of the glow discharge nitriding method for hardening machine parts poses the challenge of identifying process conditions that yield the best results in terms of the required performance characteristics. Given that the GDS process itself allows for a wide range of variations in the properties of the resulting coatings through simple, easily controlled process parameters, it is possible to optimize them according to specified control characteristics. In this case, the initial parameters of the surface hardening process can include both operational properties: wear resistance [20, 21], strength [22], crack resistance [23], fatigue endurance [24], or internal physical-mechanical properties (layer thickness, phase composition of the diffusion layer, its structure, hardness, etc.).

To determine the optimal amount of nitrogen in the saturating medium, as well as the temperature and pressure in the discharge chamber, a series of technological hardening regimes for VT22 titanium were conducted. Process parameters for nitride layer formation in a glow discharge: process temperature T = 700-750 °C, hardening duration τ = 300 min, chamber pressure varied from 67 Pa to 320 Pa, nitrogen content in the saturating medium in volume fraction from 15 % to 75 %.

3. DESCRIPTION AND ANALYSIS OF RESULTS

During the investigation of VT22 titanium samples, dependencies of the surface microhardness of the nitride layer on the technological parameters of the strengthening process – pressure in the discharge chamber and nitrogen content in the saturating medium – were obtained. The surface microhardness data for the hardened bushings (1-6) and their hardening conditions are presented in Table 2.

To determine the depth of the nitrided layer, cross-sections were prepared from the sleeves and the microhardness was measured; the data were entered into Table 3. For clarity, the dependencies of microhardness variation with the depth of the nitrided layer under different strengthening conditions are shown in Figure 3.

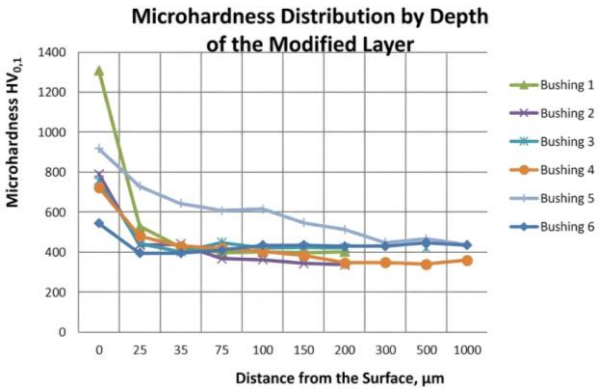


Fig. 3 – Dependence of the change in microhardness of the VT22 titanium alloy on the depth of the nitrided layer as a function of the hardening process parameters

Table 2 – Nitriding conditions for the sleeves (sleeves 1-6)

Sleeve No.	Nitriding conditions	Microhardness H0,1	
		before hardening	after hardening
1	2	3	4
1	Temperature T = 750 °C; pressure p = 320 Pa; mixture: 50 % N_2 + 50 % Ar by volume; time t = 300 min	420	1310
2	Temperature T = 700 °C; pressure p = 320 Pa; mixture: 15 % N_2 + 85 % Ar by volume; time t = 300 min	420	790
3	Temperature T = 700 °C; pressure p = 320 Pa; mixture: 50 % N_2 + 50 % Ar by volume; time t = 300 min	420	760
4	Temperature T = 750 °C; pressure p = 67 Pa; mixture: 75 % N_2 + 25 % Ar by volume; time t = 240 min	420	724
5	The sleeve was preheated in an argon atmosphere to a temperature of 800 °C and held at this temperature for 60 min. The part was then cooled to T = 560°C by evacuating the argon. Next, the sleeve was heated to T = 750 °C	420	918

1	2	3	4
6	Nitriding was performed at T = 700 °C; pressure p = 67 Pa; mixture: 15 % N_2 + 85 % Ar; t = 240 min. The sleeve was heated in a 15 % N_2 + 85 % Ar atmosphere to a temperature of 700 °C and held at that temperature for 240 minutes. Then, the working gas mixture was evacuated from the chamber, and the part was heated to T = 750 °C in a 100 % Ar atmosphere; the sleeve, heated to T = 750 °C, was held at that temperature for 60 minutes and cooled together with the chamber	420	544

Table 3 – Distribution of HV0.1 hardness with respect to the depth of the nitrided layer of VT22 (modes 1–6)

Mode numbers	Depth, μm										
	0 (at the surface)	25	35	50	75	100	150	200	300	500	1000
1	1310	530	426	399	402	399	402				
2	790	435	441	368	363	345	338				
3	760	443	402	448	422	426	422		418		
4	724	481	431	422	403	384	347	350	341	360	350
5	918	729	644	609	615	548	513	449	469	439	439
6	544	395	395	410	435	435	430	431	448	435	418

Analysis of Table 1 and Fig. 1 shows that the highest surface microhardness (up to 25 μm in the thickness of the nitrided layer) is achieved in Mode 1, but it subsequently decreases sharply, as confirmed by the data in Table 2.

Next, the sleeves (1-6) made of VT22 titanium alloy, modified according to the specified conditions, were subjected to deformation drawing using a mandrel in process lubricant. Work hardening of the surfaces of all sleeves occurred during the third drawing cycle, but the axial drawing forces of the sleeves varied significantly. The research results are presented in Table 4.

Table 4 – Experimental data obtained during the deformative broaching of a bushing made of VT22 alloy

Bushing number	Axial drawing forces Q, kH			
	1st cycle	2nd cycle	3rd cycle	3rd cycle
1	3.0	12.0	27.0	grip
2	10.0	16.7	90.0	grip
3	10.0	27.0	grip	
4	6.2	13.4	58.3	grip
5	6.86	11.6	15.2	cracked
6	4.9	10.5	126.5	grip

After analyzing the data presented in Tables 2-4 and the diagram showing the change in microhardness of the VT22 titanium alloy with depth of the nitrided layer under various hardening conditions (Fig. 1), it can be concluded that to improve the operational parameters of the surface hardening process, the nitrogen content must be increased to promote the intensive formation of TiN nitride layers on the alloy surface. This improves hardness and wear resistance, but at the same time can create a dense layer that slows down the diffusion of nitrogen into the depth of the nitrided layer. Therefore, adding argon to the nitrogen atmosphere reduces the formation of the nitride phase on the surface and stimulates bulk diffusion, allowing for deeper modified layers.

Thus, temperature is one of the key factors influencing the kinetics of nitrogen diffusion. Low temperatures (< 700 °C) slow down the nitrogen diffusion process, primarily forming a solid solution in the titanium matrix without significant nitride formation. This helps preserve the mechanical properties of the core. At high temperatures (> 800 °C): nitrogen diffusion is significantly enhanced, but there is a risk of grain coarsening and deterioration of the core's properties (strength, ductility). At the same time, active formation of the TiN phase is observed, which improves wear resistance but may negatively affect fatigue resistance.

The optimal temperature for the VT22 alloy is typically 700-750 °C, which allows for a balance between diffusion depth, hardness, and the preservation of bulk mechanical properties.

Low pressure in the discharge chamber promotes active nitrogen diffusion into the metal, as it reduces the formation of a dense surface nitride layer, which can act as a barrier to further nitrogen penetration. High pressure promotes the formation of thick nitride layers but can reduce the diffusion depth due to surface blocking by nitrides. Therefore, to ensure optimal formation of the nitride phase on the surface and nitrogen penetration into the metal, a moderate pressure must be established in the chamber to achieve a balance between the formation of the hardened layer and the depth of nitriding.

4. CONCLUSIONS

1. The process parameters of nitriding in a glow discharge play a decisive role in determining the phase and structural composition of the VT22 titanium alloy nitrided in a water-free environment within a glow discharge, and consequently in the physicochemical properties of its surface layer hardened by nitriding. Given the controllability of the nitriding process parameters and the ability to adjust them, we have extensive opportunities to tailor the properties of the nitride-hardened surface layer to meet the specific operational requirements of a given product.

2. To improve the performance characteristics of the surface layer, the nitrogen content must be increased to promote the intensive formation of TiN nitride layers on the alloy's surface. The optimal composition of the saturating mixture is 75 % N_2 (nitrogen) + 25 % Ar (argon).

3. The optimal temperature for the VT22 alloy is

700-750 °C, which allows for a balance between diffusion depth, hardness, and the preservation of bulk mechanical properties.

4. To ensure optimal formation of the nitride phase on the surface and nitrogen penetration into the depth, it is necessary to create a medium pressure (60-70 Pa) in the chamber to achieve a balance between the formation of the hardened layer and the depth of nitriding.

REFERENCES

1. I.M. Pastukh, *Visn. Tekhnol. Un-tu Podillya* No 6, 126 (2000).
2. I.M. Pohrelyuk, S.M. Lavrys, V.S. Trush, *Mater. Sci.* **59**, 1 (2023) https://doi.org/10.1007/s11003-023-00736-9.
3. M. Stechyshyn, A. Dykha, V. Oleksandrenko, M. Kindrachuk, A. Martyniuk, Advanced Manufacturing Processes VI, 617 (Cham: Springer: 2025) https://doi.org/10.1007/978-3-031-82746-4_55.
4. H. Shen, L. Wang, *Materials* **17** No 17, 4386 (2024) https://doi.org/10.3390/ma17174386.
5. A.I. Khorev, M.A. Khorev, *Titan* No 1, 40 (2005).
6. A.H. Moliar, A.A. Kotsiuba, A.S. Bychkov, O.Yu. Nechyporenko, *Konstruktsyonnye materialy v samoletostroenii* (Kyiv: KVITs: 2015) [In Russian].
7. O.M. Ivasyshyn, A.H. Moliar, S.L. Antoniuk, V.A. Trofymov, *Tr. Mezhdunar. konf. Ti-2005 v SNH*, 289 (Kyiv: IMF NAN Ukrainy: 2005).
8. A.S. Bychkov, A.H. Moliar, *Otkrytye inform. i kompyuter. integrirovannye tekhnol.* No 71, 18 (2016) [In Russian].
9. S.L. Antoniuk, A.H. Moliar, A.N. Kalyniuk, V.N. Zamkov, *Sovrem. Elektrometallurgiya* No 1, 10 (2003) [In Russian].
10. O.I. Dukhota, M.V. Kindrachuk, V.F. Labunets, *Probl. Tertya ta Znoshuvannya* No 49, 14 (2008) [In Ukrainian].
11. S. Takesue, S. Kikuchi, Y. Misaka, T. Morita, J. Komotori, *Surf. Coat. Technol.* **399**, 126160 (2020) https://doi.org/10.1016/j.surfcoat.2020.126160.
12. O.P. Ostash, V.M. Fedirko, V.M. Uchanin, S.A. Bychkov, O.H. Moliar, O.I. Semenets, V.S. Kravets, V.Ya. Derecha, *Mekhanika ruinuvannia i mitsnosti materialiv. Mitsnist i dovhovichnist aviatsiinykh materialiv ta elementiv konstruktsii* (Lviv: Spolokh: 2007) [In Ukrainian].
13. S. Chakrabarty, S.R. Panda, Sonal, J.S. Jha, S.K. Mishra, *Advances in Mechanical Processing and Design*, 561 (Singapore: Springer: 2021) https://doi.org/10.1007/978-981-15-7779-6_51.
14. V.O. Kralya, O.H. Molyar, A.M. Khimko, D.O. Puhachevs'kyi, *Mater. Sci.* **42**, 853 (2006) https://doi.org/10.1007/s11003-006-0155-9.
15. V.H. Kaplun, P.V. Kaplun, *Ionnoye azotirovaniye v bezvodorodnykh sredakh* (Khmelnitsky: KhNU: 2015) [In Russian].
16. I.M. Pastukh, *Teoriya i praktika bezvodorodnogo azotirovaniya v tleyushchem razryade* (Kharkiv: NNTs KhFTI: 2006) [In Russian].
17. M.S. Stechyshyn, V.V. Liukhovets, N.M. Stechyshyna, D.V. Zdorenko, *Aktualni problemy boiovoho zastosuvannia ta ekspluatatsii i remontu zrazkiv ozbroiennia ta viiskovoi tekhniky*, 4 (Vinnytsia: VNTU: 2025) [In Ukrainian].
18. B.I. Moskalev, *Razryad s polym katodom* (Moscow: Energiya: 1969).
19. I.M. Pastukh, V.V. Liukhovets, *Visn. Khmelnytskoho Nats. Un-tu. Tekhnichni Nauky* No 3, 138 (2016).
20. N.M. Stechyshyna, M.S. Stechyshyn, V.P. Oleksandrenko, A.A. Lytvynenko, A.V. Martynyuk, V.Yu. Sukhenko, M.I. Tsepeniuk, *Mater. Sci.* **57**, 484 (2022) https://doi.org/10.1007/s11003-022-00569-y.
21. M.S. Stechyshyn, M.Ye. Skyba, N.M. Stechyshyna, N.S. Mashovets, N.K. Medvedchuk, *Mater. Sci.* **59**, 249 (2023) https://doi.org/10.1007/s11003-024-00770-1.
22. M.S. Stechyshyn, N.M. Stechyshyna, A.V. Martynyuk, M.M. Luk'yanyuk, *Mater. Sci.* **54**, 55 (2018) https://doi.org/10.1007/s11003-018-0156-5.
23. M.S. Stechyshyn, M.E. Skyba, M.M. Student, V.P. Oleksandrenko, M.V. Luk'yanyuk, *Mater. Sci.* **54**, 395 (2018) https://doi.org/10.1007/s11003-018-0196-x.
24. M.S. Stechyshyn, M.E. Skyba, Yu.G. Sukhenko, M.I. Tsepenyuk, *Mater. Sci.* **55**, 136 (2019) https://doi.org/10.1007/s11003-019-00261-8.

Зміцнення внутрішніх поверхонь довгомірних отворів в титані ВТ22 азотуванням в тліючому розряді

М.С. Стечишин, М.Є. Скиба, Д.В. Здоренко, А.І. Гордєєв, Є.Г. Олександренко

Хмельницький національний університет, 29016 Хмельницький, Україна

За своєю структурою сплав титану ВТ22 відноситься до двофазних високоміцних ($\alpha + \beta$)-сплавів і широко використовується в літакобудуванні, що пов'язано з його високою питомою міцністю та корозійною тривкістю. З нього виготовляють елементи фюзеляжу, крил, шасі, систем керування, силові елементи літаків, а також елементи зброї для ЗСУ тощо. Проте надійність цих виробів часто залежить не тільки від їх міцності, але й трибологічних властивостей. В багатьох роботах відмічено, що серед численних методів поверхневого зміцнення, які підвищують зносо- та фретинготривкість титанових сплавів, ефективним і еко-номічно виправданим є газове азотування, яке технологічно просте, забезпечує стабільні фізико-хімічні характеристики повер-хонь та дає можливість обробляти деталі складної форми, в тому числі і з отворами. Для інтенсифікації процесу поверхневого зміцнення титану та його сплавів перспективним є метод безводневого азотування в тліючому розряді (БАТР). Безводневе азотування в тліючому розряді (БАТР) проводили на установці УАТР – 1, яка відповідає моделі діодного типу на постійному струмі і додатково укомплектована нагрівальними елементами, розміщеними в газорозрядній камері, що дало можливість довільно мі-няти енергетичні параметри – напругу U, і значення густини струму j (відношення струму до загальної площі садки і підвіски).

У роботі розглядається вплив технологічних характеристик безводневого азотування в тліючому розряді (температури, складу насичувального середовища, тиску насичувальної суміші в газорозрядній камері, часу зміцнення) на фізико-хімічні властивості азотованих шарів сплаву титану ВТ22. Зразки для проведення досліджень виготовлялися у вигляді втулок, виходячи з вимог геометричної подібності

до виробів замовника (ЗСУ). Знайдені залежності фізико-хімічних властивостей внутрішніх поверхонь втулок (поверхневої мікротвердості, її розподілу по глибині зміцненого шару, осьової сили дорнування втулки) залежно від технологічних характеристик азотування.

У результаті проведенних досліджень встановлено, що оптимальний склад насичувальної суміші: 75 %N_2 (азот)+25 % Ar (аргон), а оптимальна температура для сплаву ВТ22 становить 700-750 °С, що дозволяє досягнути балансу між глибиною дифузії, твердістю та збереження об'емних механічних властивостей і для забезпечення оптимального утворення нітридної фази на поверхні та проникнення азоту вглиб потрібно створити в камері середній тиск (60…70 Па), щоб досягти рівноваги між формуванням зміцненого шару і глибиною азотування.

Ключові слова: Азотування, Титан ВТ22, Фізико-хімічні властивості.