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INVESTIGATION OF THE WEAR RESISTANCE OF NITRIDED SHKH15 STEEL IN AN ABRASIVE ENVIRONMENT

Abstract. *The study investigates the wear resistance of nitrided ShKh15 steel in an abrasive environment after glow-discharge nitriding in hydrogen-free nitrogen–argon atmospheres. The influence of technological parameters, including pressure and argon content, on the thickness, hardness, phase composition, and hardness gradient of nitrided layers was analyzed using a two-factor rotatable design. Empirical mathematical models describing nitrided layer properties and wear behavior were developed. Experimental results showed that wear resistance, surface hardness, and layer thickness can be controlled and optimized by varying nitriding conditions. The highest wear resistance was achieved under optimal nitriding conditions, significantly exceeding that of quenched steel.*

Keywords: *wear resistance, nitrided layers, glow-discharge nitriding, abrasive environment.*

Problem statement. During grain processing by extrusion, the working components of the extruder (screw and barrel) are subjected to significant operational loads, including high pressure and temperature, as well as a corrosive-abrasive environment, which results in their relatively short service life. Improving the wear resistance of the screw and barrel is therefore a promising area of research.

Analysis of recent studies and publications. Currently, numerous methods exist for improving the wear resistance of structural components, including thermal treatments, thermochemical treatments, thermal spraying, and hardfacing with wear-resistant materials.

Glow-discharge nitriding is one of the effective methods for surface strengthening of metals, providing the possibility to modify the properties of surface layers (hardness, thickness, phase composition, and property gradients through the layer thickness) over a wide range [1, 2]. This makes it possible to optimize the

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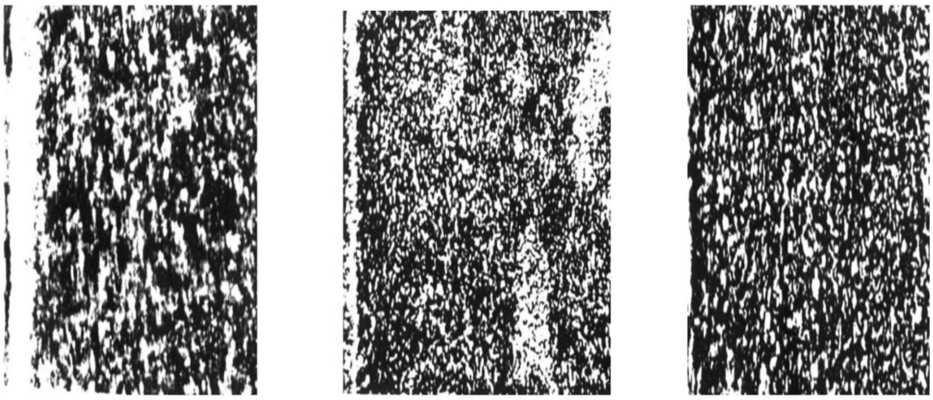
properties of the strengthened surface layer in order to achieve maximum performance characteristics under actual operating conditions of structural elements [3]. Many machine parts and tools operate in abrasive and corrosive-abrasive environments, which leads to surface degradation caused by abrasive particles and the corrosive action of aggressive media. Therefore, ensuring an optimal balance between hardness, ductility, and corrosion resistance of surface layers is of considerable importance.

Presentation of the main research material. We have developed a technology and equipment for thermochemical treatment of machine parts and tools in glow discharge under hydrogen-free atmospheres (nitrogen-argon mixtures) [4]. A distinctive feature of this technology is the elimination of hydrogen embrittlement during diffusion saturation, as well as the improvement of the plastic characteristics of surface layers due to different phase ratios.

Surface modification of ShKh15 steel was carried out in a glow discharge in a nitrogen-argon gas mixture. The properties of the nitrided layer were controlled by four technological parameters: diffusion saturation temperature, pressure in the vacuum chamber, composition of the saturating atmosphere, and nitriding duration.

Theoretical and experimental studies showed that all of the above technological parameters of the nitriding process affect the properties of the nitrided layer. Therefore, the influence of each technological factor during glow-discharge nitriding on hardness, thickness, phase composition, and the property gradient through the thickness of the nitrided layer was investigated.

By varying the technological parameters of the nitriding process, the properties of the nitrided layer can be modified over a wide range, making it possible to obtain a nitride zone with different phase compositions, different thicknesses, or nitrided layers without a nitride zone (Fig. 1).



a b c

Figure - 1. Microstructure of ShKh15 steel (×500) after glow-discharge nitriding in hydrogen-free atmospheres:
a, b – with a nitride zone of different thicknesses; c – without a nitride zone.

To ensure maximum wear resistance of friction pairs operating in an abrasive environment, it is necessary for the surface layers to possess high hardness and maximum thickness. Theoretical and experimental studies of the ion nitriding process for metals have shown that, for ShKh15 steel, high hardness is achieved at temperatures of 560–580 °C, while the maximum thickness of the nitrided layer is obtained at a diffusion saturation duration of 6–8 h.

Therefore, in order to reduce the number of experiments in studying the properties of the nitrided layer and the wear process of nitrided specimens, a second-order two-factor rotatable design was used. During the investigations, the following factors were varied: the composition of the saturating atmosphere within the range of 29–71%, and the pressure in the vacuum chamber within the range of 55–225 Pa. The nitriding duration and temperature were fixed at 240 min and 570 °C, respectively.

To obtain the model (optimization parameter), a second-order algebraic polynomial was used:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{11} x_1^2 + b_{22} x_2^2 , \tag{1}$$

where $b_0, b_1, b_2, b_{12}, b_{11}, b_{22}$ are regression coefficients;
x_1, x_2 are variable factors.

For recording the experimental conditions and processing the experimental data, factor levels were coded. The following variable factors were adopted:

pressure in the vacuum chamber – x_1;

volumetric argon content in the nitrogen mixture – x_2.

When coding the values of x_1 and x_2, the upper level is denoted as +1, the lower level as −1, and the zero level as 0.

The coding of factor x_i is determined by the expression:

$$x_i = \frac{Z_i - Z_{0i}}{\varepsilon_i}, \tag{2}$$

where i is the factor number;

Z_i is the natural value of the i-th factor;

Z_{0i} is the natural value of the zero level of the i-th factor;

ε_i varepsilon is the variation interval of the i-th factor.

Experimental studies were carried out at the levels and intervals presented in Table 1. The design matrix for the second-order composite rotatable design and the results of the experimental studies are presented in Table 2.

Table 1

Levels and intervals of factor variation

Designation	Factors	Levels of Variation					Variation Interval ε
		– 1,414	– 1	0	+ 1	+ 1,414	
Z_1	Pressure, Pa	55	80	140	200	225	60
Z_2	Volumetric argon content, %	29	35	50	65	71	15

Table 2

Working matrix and results of experimental studies

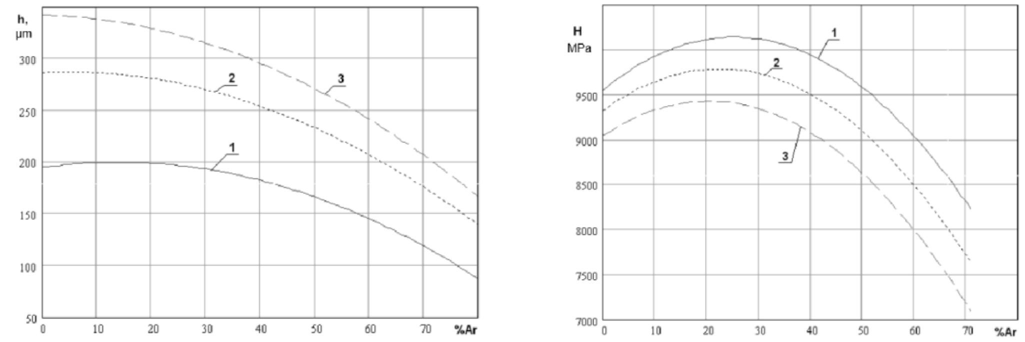
Nitriding Regime No.	Working Matrix		Microhardness $HV_{0.1}$, MPa	Nitrided Layer Thickness, µm
	P, Pa	Ar, %		
1	200	65	7651,5	225,0
2	200	35	9292,4	307,1
3	80	65	8736,0	133,3
4	80	35	10110,4	190,0
5	140	71	7861,6	168,0
6	140	29	9972,3	265,2
7	225	50	8307,9	285,1
8	55	50	9655,6	137,2
9	140	50	9113,0	223,0
10	140	50	9113,0	223,0
11	140	50	9113,0	223,0
12	140	50	9113,0	223,0
13	140	50	9113,0	223,0

Based on the results of experimental studies in accordance with the two-factor rotatable design, empirical mathematical relationships were obtained for the thickness of the nitrided layer (3) and the surface hardness (4) of ShKh15 steel as functions of argon content in the saturating atmosphere and pressure, while maintaining constant values of the other two technological parameters of the nitriding process (τ=240min and temperature 570 °C). Based on these mathematical relationships, the graphs shown in Figs. 2 and 3 were obtained.

$$h(\mu m)=224.5+52.3x_1-34.3x_2-6.4x_1x_2-6x_{12}-5.8x_{22}, \tag{3}$$

$$HV_{0.1}=9171.9-476.5x_1-746.3x_2-66.6x_1x_2-68.6x_{12}-205.8x_{22}. \tag{4}$$

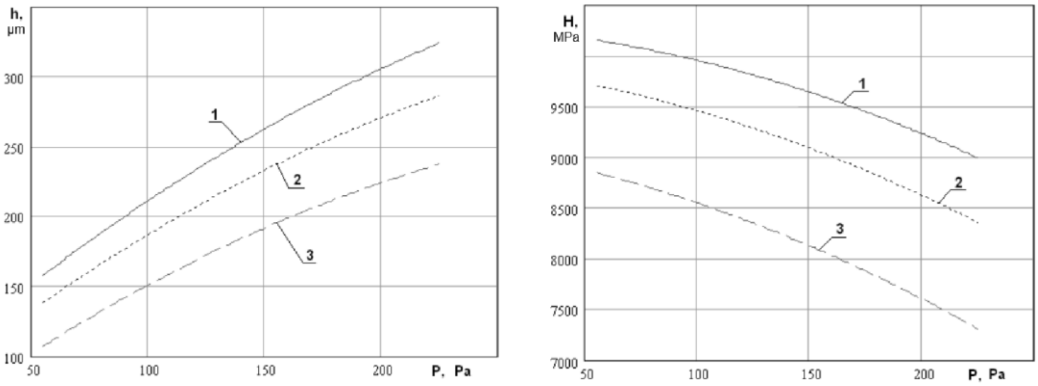
It can be seen from Fig. 2 that the thickness and surface hardness of the nitrided layer vary with increasing argon content in the saturating atmosphere. Maximum values of these parameters are achieved at optimal argon concentrations in the saturating atmosphere. In particular, the maximum thickness of the nitrided layer is formed within the range of 22–27%, while the maximum hardness is achieved at a volumetric argon content of 15–20% in the saturating atmosphere.



a b

Figure - 2 Dependence of the nitrided layer thickness (a) and surface hardness (b) of ShKh15 steel on the argon content in the saturating atmosphere at different pressures: 1 – 80 Pa; 2 – 150 Pa; 3 – 200 Pa.

Fig. 3 shows the dependences of the thickness and surface hardness of the nitrided layer on the pressure in the vacuum chamber at different argon contents.



a, b

Figure - 3 Dependence of the nitrided layer thickness (a) and surface hardness (b) of ShKh15 steel on the pressure in the vacuum chamber during diffusion saturation at different argon contents in the saturating atmosphere: 1 – 35% Ar; 2 – 50% Ar; 3 – 65% Ar.

It can be seen from Fig. 3 that the thickness of the nitrided layer increases with increasing pressure in the vacuum chamber. This is attributed to an increase in the nitrogen potential of the saturating atmosphere as the pressure rises. In contrast, the hardness of the nitrided layer decreases with increasing pressure. This is due to the fact that, with increasing pressure, the amount of argon increases, and the sputtering process begins to prevail over the adsorption process of the reactive gas.

The technological parameters of the nitriding process have a significant influence on the phase composition of the surface layer and on the hardness distribution through its thickness.

Under different nitriding conditions, different phases are formed on the surface: ε, γ′, and α(FeN). Their ratio affects the hardness and corrosion resistance of the surface layer. The presence of the hard ε-phase ($Me_{2-3}N$) contributes to improved corrosion resistance of the surface. Studies show that during glow-discharge nitriding in hydrogen-free atmospheres, all three phases may be present on the surface in different proportions. The content of the ε-phase increases with increasing temperature and with increasing pressure in the vacuum chamber.

Fig. 4 presents the hardness distribution profiles through the thickness of the nitrided layer under different nitriding conditions. It can be seen from Fig. 4 and Table 2 that by varying the nitriding conditions, the hardness gradient through the layer thickness can be changed over a wide range. This has a significant influence on the performance characteristics of structural elements.

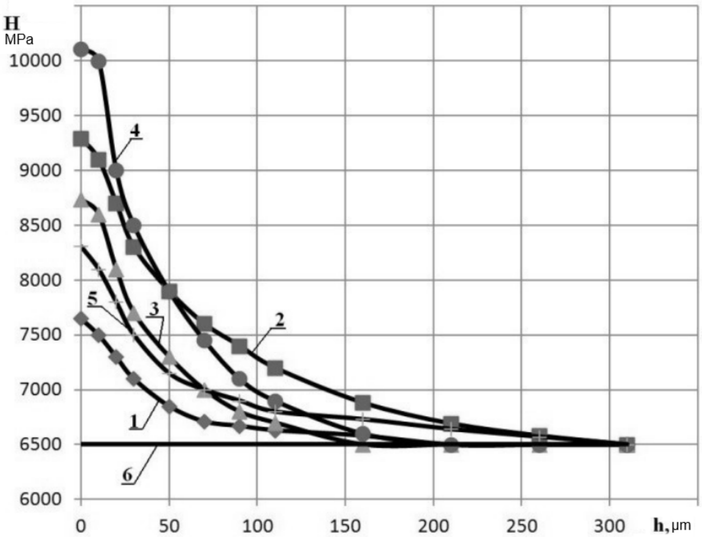


Fig. 4 – Hardness distribution through the thickness of the nitrided layer as a function of nitriding conditions (Table 2):1–4 – corresponding nitriding conditions;
5 – condition No. 7; 6 – quenching.

Table 4 and Fig. 5 present the results of experimental studies on the wear resistance of ShKh15 steel specimens after different nitriding conditions (Table 2) in a model solution using end-face friction machines under a specific load of 0.5 MPa and a sliding speed of 1.37 m/s.

It can be seen from Table 4 and Fig. 5a that the wear resistance of specimens nitrided under different conditions varies significantly and substantially exceeds that of the quenched specimen. The highest wear resistance was exhibited by specimens nitrided under condition 4. After a friction distance of 5.4×10^3 m, the wear of specimens nitrided under condition 4 was 2.5 times lower than that of quenched specimens.

Table 4

Wear kinetics of shkh15 steel after quenching and ion nitriding in glow discharge under different conditions

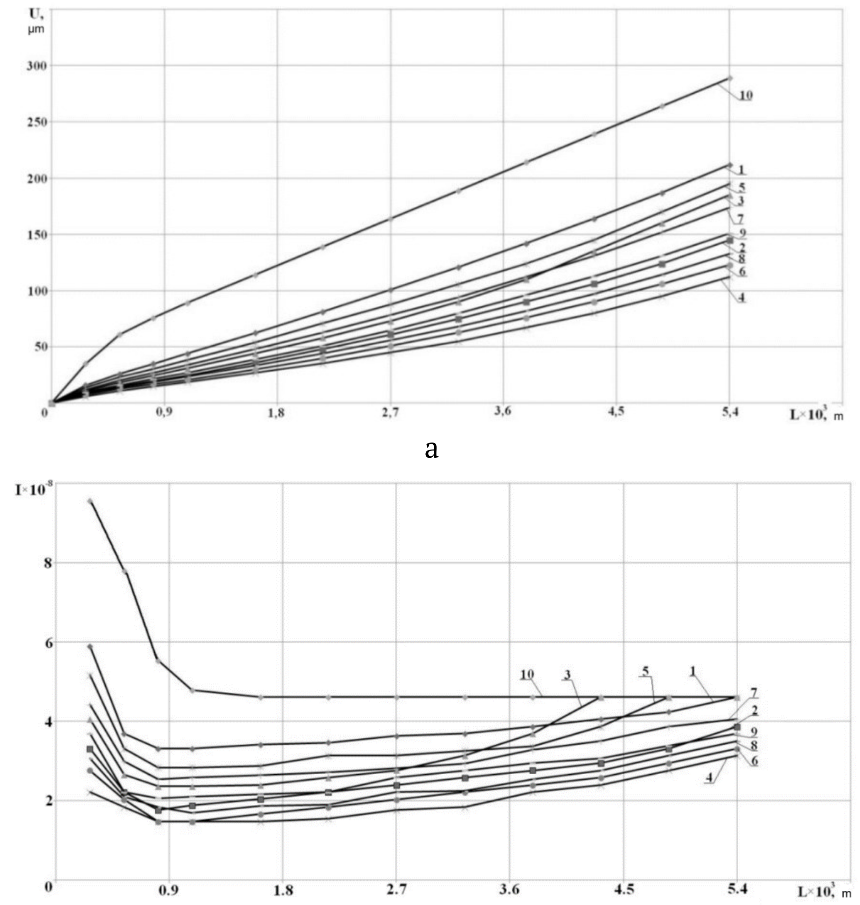
Nitriding Condition No.	Wear, µm											
	Test duration, min											
	15	30	45	60	90	120	150	180	210	240	270	300
	Sliding distance $L \times 10^3$, м											
	0,27	0,54	0,81	1,1	1,6	2,2	2,7	3,3	3,8	4,3	4,9	5,4
1	16	26	35	44	62,5	81,3	101	121	142	164	187	212
2	9	15	19,8	24,9	36	48	61	75	90	106	124	145
3	11	18,2	24,6	31	44	58	73	90	110	135	160	185
4	6	11	15	19	27	35,4	45	55	67	80	95	112
5	14	23	30,7	38,4	54	71	88	105,7	124	145	170	195
6	7,5	13	17	21	30	40	51	63	76	90	106	123
7	12	20,1	27	34	48,3	63	78,3	94,2	112	131	152	174
8	8,3	14	19	23,6	33,7	44	56	68,2	82	97	114	133
9	10	16	21,6	27,3	39	51	65	80	96	112,6	131	151
10	9,79	16,4	22	27,2	40	52	66	81	97	112	132	152
11	10,1	15,6	21	26,8	38,1	50,3	65,7	79	95	111	130	150
12	10,21	16	21,1	27	39,2	51,6	65	79,6	96	113,1	130,8	150,6
13	9,7	16,1	21,8	26,9	38,7	51	64,1	80,3	96,3	112,2	131,1	151,3
quenchin	35	61	76	89	114	139	164	189	214	239	264	289

As shown in Fig. 5b, as the nitrided layer wears out, the wear rate of nitrided specimens gradually approaches the wear rate of quenched steel. This is attributed to the change in hardness through the thickness of the nitrided layer.

Based on experimental studies using a two-factor rotatable design, the following mathematical relationship (5) describing wear as a function of the technological parameters of the nitriding process was obtained:

$$U(\mu m)=152.0+14.8x_1-30.1x_2+1.5x1x_2+3x_{12}+3.9x_{22} \quad (5)$$

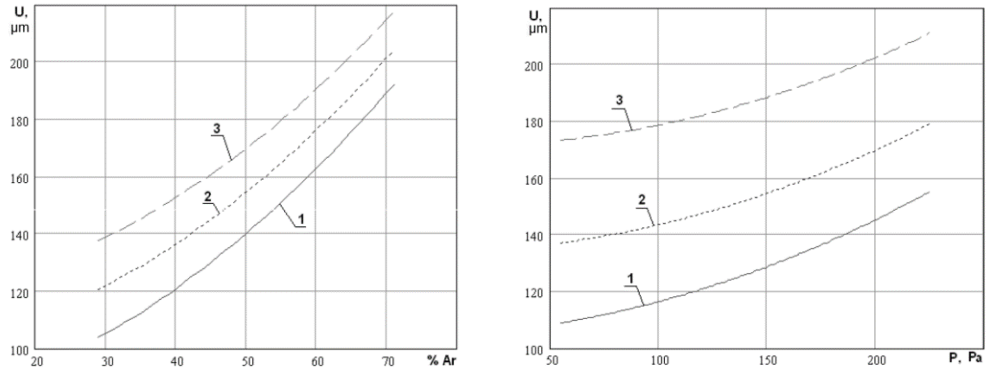
Based on Equation (5), graphs were constructed (Fig. 6) showing the dependence of wear on the technological parameters of the nitriding process. The graphs show that wear increases with increasing pressure and argon content in the saturating atmosphere. This is explained by changes in the properties of the nitrided layer depending on these parameters (Figs. 2–3).



a

b

Figure - 5 Dependence of wear (a) and wear rate (b) of ShKh15 steel after quenching and nitriding under different conditions: 1–9 – nitriding conditions; 10 – quenching.



a b

Figure - 6 Dependence of wear of ShKh15 steel on argon content (a) and pressure (b) in the saturating atmosphere (N_2 + Ar): a – at pressures: 1 – 80 Pa; 2 – 150 Pa; 3 – 200 Pa; b – at argon contents: 1 – 35% Ar; 2 – 50% Ar; 3 – 65% Ar.

Conclusions. Thus, the conducted studies of the properties of the nitrided layer formed during glow-discharge nitriding in hydrogen-free atmospheres, as well as its wear behavior in a model solution for ShKh15 steel, have shown that these properties can be varied over a wide range by adjusting the technological parameters of the nitriding process and optimized according to the criteria of maximum wear resistance, surface hardness, and nitrided layer thickness.

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ДОСЛІДЖЕННЯ ЗНОСОСТІЙКОСТІ АЗОТОВАНОЇ СТАЛІ ШХ15 В АБРАЗИВНОМУ СЕРЕДОВИЩІ

Анотація. *Досліджено зносостійкість азотованої сталі ШХ15 в абразивному середовищі після азотування в тліючому розряді у безводневих азотно-аргонових середовищах. Проаналізовано вплив технологічних параметрів, зокрема тиску та вмісту аргону, на товщину, твердість, фазовий склад і градієнт твердості азотованих шарів із використанням двофакторного рототабельного планування. Розроблено емпіричні математичні моделі, що описують властивості азотованого шару та процес зношування. Експериментально встановлено, що зносостійкість, твердість поверхні та товщину азотованого шару можна керовано змінювати й оптимізувати шляхом варіювання режимів азотування. Найвищу зносостійкість досягнуто за оптимальних параметрів азотування, що суттєво перевищує показники гартованої сталі.*

Ключові слова*: зносостійкість, азотовані шари, тліючий розряд, абразивне середовище.*

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