Problems of Tribology, *V. 26, No 3/101-2021,31-41*

Problems of Tribology

Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2021-101-3-31-41

Influence of the parameters of hydrogen nitrogen nitrogen in a glow discharge on tribological and physico-chemical properties of steel 40X

N.M. Stechishina, M.S. Stechishin, A.V. Martynyuk, N.V. Lukianyuk, V.V. Lyukhovets, Yu.M. Bilyk

Khmelnytsky National University, Ukraine
**E-mail: av.mart@ukr.net*

Received: 5 May 2021: Revised: 20 August: Accept: 15 September 2021

Abstract

One of the modern and effective methods of hardening metals is nitriding in a glow discharge in ammonia or in an anhydrous medium (nitrogen + argon) - BATR. This paper presents the results of experimental studies comparing the results of tribological and physicochemical properties of hardened surfaces obtained by nitriding with autonomous and interconnected BATR modes. The complex of traditionally fixed values of operating parameters (temperature, composition of the gas mixture, pressure and saturation time) without taking into account energy characteristics (voltage, current density and specific discharge power) significantly reduces the technological capabilities of BATR to achieve the necessary physicochemical properties of metal surfaces specified by conditions exploitation. Taking into account the energy characteristics of BATR, a significant reduction in the energy consumption of the nitriding process is achieved. The energy levels of the main subprocesses are significantly different: the formation of nitrides occurs at low energies, surface sputtering occurs at high voltage values, and nitrogen diffusion occurs at increased current density values. In cases where the energy of the flow is insufficient, either a glow discharge may not occur at all, or with a lack of voltage, the nitride ball on the surface is not sprayed and it acts as a barrier that prevents the diffusion process into the inner layers of the metal, which leads to low physicochemical and, correspondingly, tribological indicators of nitrided balls. The quantitative ratio between them and the required operational properties of the metal, respectively, can be achieved only through an independent combination of the energy and operating characteristics of BATR.

Key words: non-hydrogen nitriding in a glow discharge (BATR); wear resistance of nitrided balls; phase composition; voltage; current density; specific power of the discharge.

Introduction

One of the modern and effective methods of hardening metals is nitriding in a glow discharge in ammonia or in an anhydrous medium (nitrogen + argon) - BATR. Nitriding in a hydrogen-free environment excludes the possibility of explosion of the installation and hydrogen embrittlement of surfaces due to the diffusion of hydrogen formed during the decomposition of ammonia into the depth of the metal. In addition, the BATR process is absolutely environmentally friendly. Also, at present, most studies are devoted to nitriding processes with interdependent parameters, i.e., each combination of operating parameters (temperature, composition of the gas mixture and its pressure) automatically corresponds to a combination of energy (voltage, current density), as a result of which the latter are not considered as controlled. process factors [1].

Among all the operating characteristics of the process, the most significant parameter is the preset surface temperature, since to achieve and maintain it throughout the entire nitriding time, a certain specific combination of voltage and current density is required. Providing a given surface temperature due to factors alternative to a glow discharge allows changing the energy parameters of BATR in a wider range. In world practice, ensuring the independence of temperature from the energy characteristics of BATR is achieved by using chambers with "hot walls" [2]. Providing a given surface temperature due to factors alternative to a glow discharge allows not only to reduce the nitriding time, but also opens up fundamentally new possibilities for improving the controllability of the BATR process and obtaining the properties of surfaces of metallic materials specified by operating conditions, depending on the conditions of their operation. Despite the obvious new capabilities of BATR with independent energy parameters, it has not actually been investigated in practical and experimental terms. This paper presents the results of experimental studies comparing the results of tribological and physicochemical properties of hardened surfaces obtained by nitriding with autonomous and interconnected BATR modes.

Purpose of work – study of the influence of energy parameters on the tribological and physicochemical properties of the diffusion layers of steel 40X at BATR with interdependent and autonomous saturation parameters.

Materials and methods of testing

Nitriding was carried out on the UATR-1 unit designed and manufactured at the Podolsk Scientific Physics and Technology Center (PNFTTs) of the Khmelnitsky National University. The installation belongs to a diode-type model with direct current and was additionally equipped with heating elements placed in the gas-discharge chamber, which made it possible to arbitrarily change the voltage value U, and the value of the current density j was determined as the ratio of the current strength to the total area of the parts (samples) of the cage and suspension ($j = I/S$, A/m^2). The design features of the installation for carrying out BATR processes with interdependent and autonomous nitriding modes are described in detail in [3].

Nitriding modes

The influence on the structure, phase composition and, accordingly, on the physicochemical properties of the surface nitrided layers of temperature, composition of the gaseous medium, its pressure and saturation time has been comprehensively studied, for example, in [1 ... 4]. Therefore, saturation was carried out in a mixture of 80 % N_2 (nitrogen) and 20 % Ar (argon) at a temperature of T = 833 K for an hour. The voltage and current strength were chosen arbitrarily, based on the experience of preliminary studies. Technological modes of carrying out BATR processes are given in Table 1.

Table 1

Characteristics of BATR modes

Modes	Experiment serial number								
	1*/1**	2	3	4*/4**	5	6	7*/7**	8	9
Pressure p, torr (Pa)	0,4 (53,2)			0,8 (106,4)			1,2 (159,6)		
Voltage U, V	1100/680	820	515	840/610	515	300	700/540	515	300
Current density j, A / m2 ($j = I/S$)	11/15,3	7,2	3,2	13,2/16,4	7,2	2,8	15,8/17,2	12,8	7,2
Specific power of the glow discharge w, kW / m2	12,1/10,4	5,9	1,65	11,1/10,0	3,7	0,84	11,1/9,3	6,6	2,2

* – modes with interdependent parameters; ** – also, but with a modified suspension shape

The specific power of the glow discharge was determined by the formula:

$$W = UI / S = Uj ,$$

where S – is the total area of parts (samples) and suspension (cathode area).

Experiments 1*, 4*, 7* were carried out under interdependent nitriding regimes (the first series of experiments), i.e. each pressure of the mixture corresponded to the corresponding value of voltage and current density. The second series of experiments (1**, 4**, 7**) was carried out under the same conditions but with a changed shape of the suspension and, therefore, with a different cathode surface area. Experiments 2, 3, 5, 6, 8, and 9 correspond to the autonomous modes of the BATR. At the same time, modes 3, 5 and 8 were carried out at $U = 515B = \text{const}$, and modes 2, 5 and 9 at $j = 7,2\text{A/m}^2 = \text{const}$.

Metallographic studies were carried out on a MIM-10 microscope after etching microsections with a 3 % alcohol solution of nitric acid. The microhardness was determined with a PMT-3 microhardness tester at a loading of 0.98N with fixing the hardness values on the surface and at a distance of 25, 50, 100, 200, 500 μm.

For X-ray phase analysis, a DRON-3 diffractometer was used in the range of angles θ from 20º to 100º with a scanning step 0,1º and an exposure time of 10 s.

Tribological studies of the samples for wear resistance were carried out on a universal machine model 2168UMT according to the disk-finger friction scheme; friction without lubricant (dry); counterbody material - steel ШХ15 with hardness HRC61; pressure in the contact zone p = 16 MPa; controlled linear wear h, which was determined by the change in the linear size of the sample measured along the normal to the friction surface after passing the section of the friction path L in accordance with the accepted measurement step l (Table 2).

Table 2

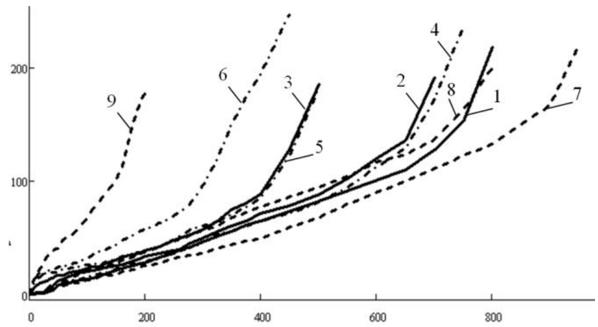
Frequency of measurement of the results of tribological studies

Friction path section, m	0 - 50	50 - 200	200 - 400	400 - 1000	more 1000
Measurement step, m	5	10	25	50	100

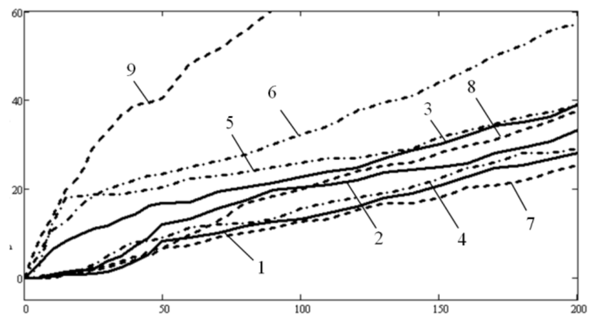
Research results and their discussion

The dependence of the wear resistance of the modified surfaces on the energy parameters of the discharge was confirmed by tribological studies. As a result of the experiments, it was found that under dry friction conditions for surfaces modified at higher energy values, the wear rate (Fig. 1, a) and the running-in period (Fig. 1, b) decrease, and the period of stable wear increases, and, with an increase in the content of alloying elements in steel, this pattern becomes more pronounced.

Of course, under other experimental conditions (for example, when studying the obtained samples for corrosion resistance), the dependence of the tribological properties of nitrided surfaces on the current density and voltage on the chamber electrodes may acquire a different character, but the very existence of such a dependence is beyond doubt, which refutes the provisions given in [5], according to which the energy characteristics of the discharge do not have a significant effect on the results of ATR.



a



b

Fig. 1, a – wear curves of steel;
b – running-in area of wear curves of nitrided steel 40 Kh

The data presented allow us to draw a completely obvious conclusion about the effect of voltage and current density on the characteristics of the modified layer determine the wear resistance of nitrided steels in a glow discharge - but not just essential, but decisive. Moreover, in the field of the energy parameters of the regime, there is a certain limit below which the ATR process generally loses its meaning, since it leads to unacceptable results, and this is despite the fact that the values of the regime remain constant.

This means, in particular, that the set of traditionally fixed operating parameters (temperature, pressure, composition of the gas mixture and the duration of the process) does not give an unambiguous idea of the conditions for carrying out the ATR process, and therefore cannot serve as a basis for predicting its results.

This fact has been repeatedly confirmed when technological processes carried out at similar values of operating parameters, but in different installations (or even in one installation, but using a different suspension), led to completely different results.

This is due to the fact that the factors that determine the effectiveness of the nitriding process in a glow discharge are not only the parameters of the mode, but also such indicators as the cathode distance, the shape and size of the suspension and the test sample (or part), the presence of local exceptions on its surface, and many other factors.

The list of factors that are decisive for ATP, given by the American researcher David Pye in [6], including thirteen items.

Of course, direct consideration of all these indicators would lead to incredible complications in the management of the APR process. However, they can be taken into account indirectly, since the influence of all the listed factors reflect the energy parameters of the process.

It is known that the depth and phase composition of the nitride zone of the surface layer of steel determine its physicochemical properties. Thus, the nitride zone, which consists only of a phase, is characterized by a rather high plasticity, and the zone containing the phase has a lower plasticity, but a higher corrosion resistance [7, 8, 9].

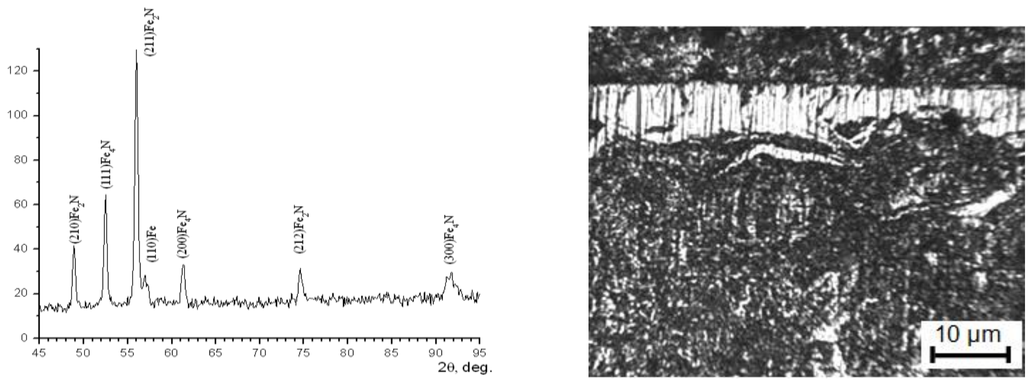
The layer without a nitride zone has the highest plasticity [9, 10]. In general, the thinner the nitride zone, the more plastic the nitrided layer, but the lower its resistance to abrasive and corrosion-mechanical wear.

Thus, according to [11], for parts that are operated in corrosive environments and for wear at low contact voltages, the BATR should be carried out at the maximum possible voltage and current density, which contributes to the formation of a phase and, accordingly, we have a high corrosion resistance, as well as good running-in of friction surfaces. In this case, in order to avoid the transition of a glow discharge to an electrospark one, the condition $w < w_{KR}$ should be observed, i.e. the specific power of a glow discharge should not exceed the critical specific power of the occurrence of an electric arc discharge.

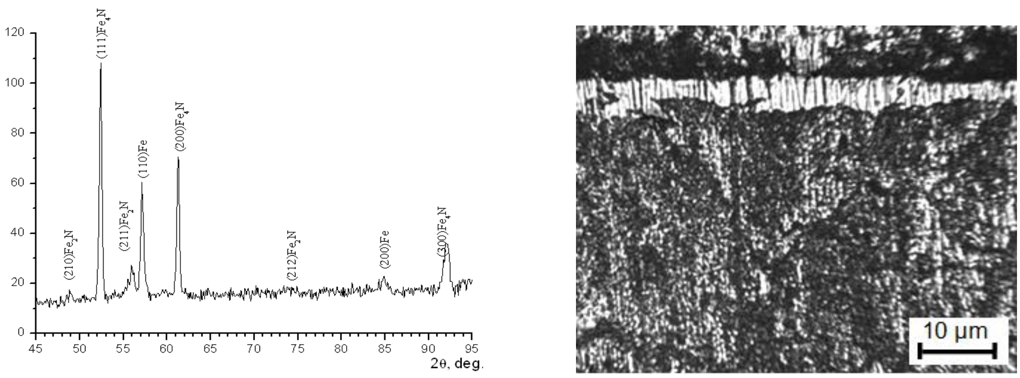
A decrease in voltage and current density leads to an increase in the phase fraction, which contributes to an increase in the fatigue strength of parts operating under conditions of corrosion-mechanical wear (CMC) in corrosive environments [12].

The dependence of the wear resistance of the nitrided surfaces of steel 40Kh on the energy parameters of the discharge is confirmed by the results of testing samples with dry friction (Fig. 1, a, b) nitrided according to modes 6, 9, 3, and 5, which were nitrided at low values of U and j. in wear resistance than samples nitrided at higher values of U and j (7*, 1*, 8, 4* and 2, see Table 1). These samples (6, 9, 3, and 5) are characterized by small running-in periods at a constant wear rate and a high wear rate, determined by the tangent of the tangent to a point in the wear curve section.

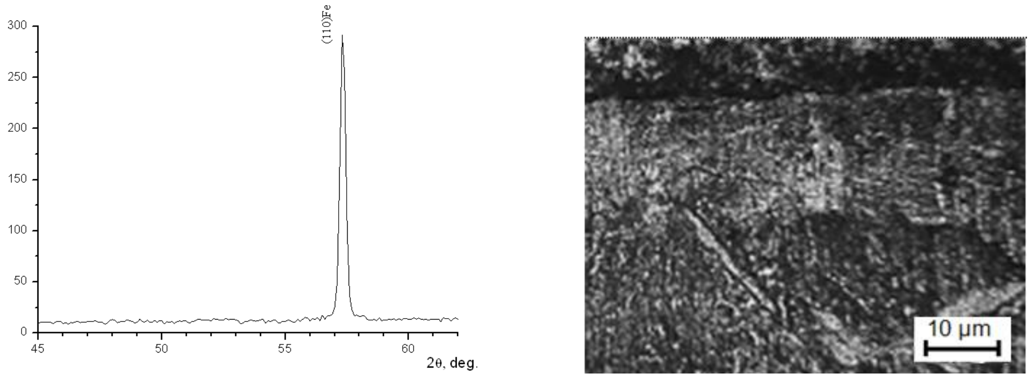
The data of X-ray structural analyzes $\varepsilon, \gamma^{/}$ – (Fig. 2) and microdurometric measurements (Table 3) confirm and explain the results of tribological experiments (Fig. 1, a, b). So, at BATR according to mode 7* (Table 1), a nitride ball of the greatest thickness (Table 3), consisting of phases (Fig. 2, a), is formed on the surface. A decrease in the values of U and j (Table 1) for mode 8 contributes to a decrease in both the thickness of the nitride zone hN (Fig. 2, b) and the thickness of the diffusion layer h (Table 3), which were identified by measuring the microhardness along the depth of the layer. The phase composition of the nitride and diffusion layers remains practically unchanged.



a



b



c

Fig. 2. Diffraction patterns and microsections of 40X steel samples:
a – nitriding according to mode 7;
b – according to mode 5;
c – according to mode 9

Table 3

Thickness of nitride hN, diffusion layers h and surface microhardness HV0.1

№ regime	1*	2	3	4*	5	6	7*	8	9
hN micron	5,88	2,42	0	3,64	3,2	0	8,76	6,6	0
h, micron	400	300	75	300	200	0	300	250	0
HV0,1	796	676	412	647	444	230	842	625	238

Nitriding according to mode 9 corresponds to the case when $w << w_{KP}$, i.e. the specific power of the discharge is much less than the required one and the glow discharge does not occur and, accordingly, $h = hN = 0$ (Fig. 2, c). We have similar cases when nitriding in modes 6, 3 and partly 5, which have low wear resistance.

Thus, it has been established that under conditions of dry friction for surfaces of steel 40Kh nitrided at high energy values, the wear rate and the running-in period decrease (Fig. 1), the latter refutes the statement of K. Keller [13] that the energy characteristics of BATR do not have a significant influence on the results of nitriding. On the contrary, the above BATR results allow one to draw completely obvious conclusions about the significant effect of voltage and current density on the physicochemical and tribological properties of nitrided layers. In addition, there is a certain limit of energy parameters below which (modes 9, 6, 3) carrying out BATR processes does not make sense at all, since it leads to negative results, and this despite the fact that the values of operating characteristics (temperature, composition of the gas mixture, its pressure, etc.) nitriding time) remain unchanged. Thus, the set of traditionally fixed operating parameters of the BATR cannot unambiguously characterize the conditions of the nitriding process and be the main one for predicting its results. This fact is confirmed by the fact that at similar values of the operating parameters, the change of the suspension led to completely different results of nitriding, which is explained by the change in the energy characteristics of the BATR process (Fig. 3).

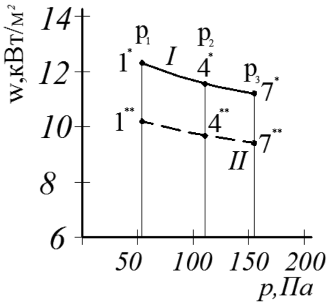


Fig. 3. Dependences of the specific power of the discharge w on the pressure of the gas mixture at interdependent BATR modes: I – modes 1*, 4* and 7*; II – also when changing the shape of the suspension (modes 1, 4** and 7**)**

In addition to comparing the physicochemical and tribological properties of nitrided balls of steel 40Kh at BATR with interdependent and autonomous energy modes of processes, the purpose of the work was also to check the effect of the specific power of the glow discharge w, which in [5] was called the plasma energy density (PEP) and where it is stated, that the dependence of the pressure of the gas mixture on the specific power of the discharge has an extreme character: i.e. the pressure of the gas mixture, which corresponds to the maximum w, ensures the production of a nitrided sphere of the greatest depth [5]. However, studies [3] and the results of our experiments (Fig. 3) do not confirm the existence of such an extreme dependence.

Changing the shape of the suspension led to a change in the values of w (curves I and II in Fig. 3), and in the second case, we have significantly lower energy costs for the nitriding process. However, this is not the main advantage of nitriding, but the main factor is the physicochemical properties of the hardened layers, which provide the specified performance characteristics of the hardened surfaces of parts. So, in works [6, 7, 11, 12] doubts are expressed about the legitimacy of the use of specific power as the only energy criterion due to the possibility of arbitrary combination of its values with different values of voltage and current density at a constant pressure of the gas mixture. The studies given by us have shown that it is more expedient to assess the changes in voltage and current density. The specific power of the discharge can only serve as an estimate of the transition from a "dark" to a glow or to an electric arc discharge.

The study of current-voltage characteristics of BATR with interdependent (without heating) parameters showed their significant difference when changing the shape and size of the suspension (Fig. 4).

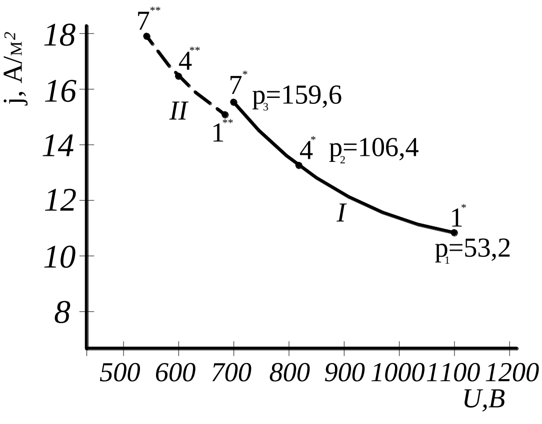


Fig. 4. Current-voltage characteristics of the BATR process at autonomous (interdependent) saturation modes (I and II are different forms of suspensions)

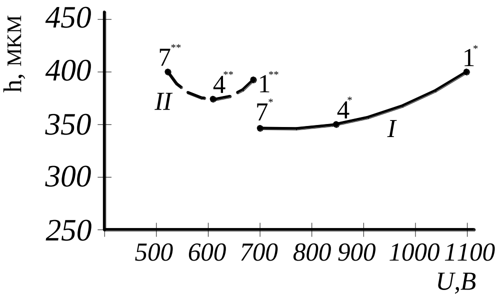
So the change of the suspension led to a shift of the current-voltage characteristic of the process to the left: a decrease in voltage values led to an increase in the current density with a simultaneous decrease in w (Fig. 3). At the same time, the operating parameters (pressure, temperature, mixture composition and nitriding time), as indicated above, remained unchanged. An increase in the mixture pressure also leads to a decrease in voltage with a simultaneous increase in the current density (Fig. 4). Since the increase in the value of the absolute value of the current is much less in comparison with the absolute value of the voltage (Table 1), the result is a decrease in the value of the specific power of the energy flow W (Fig. 3).

According to [3, 5], at a constant composition of the gas mixture in the pressure range of 100 - 120 Pa, a minimum of the active power of the discharge is observed. In our experiments, this dependence is not traced

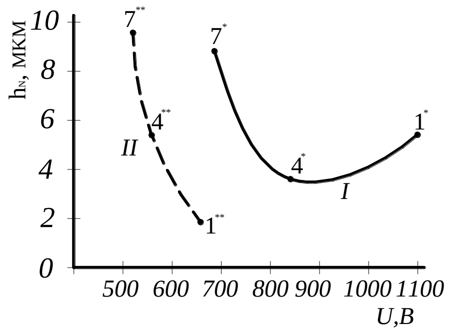
(Fig. 3). Obviously, due to the fixation of not the active power of the energy flow acting on the metal surface and determined by the speed of electrons, but the electric power $(W = Uj)$, which is 35 % - 300 % [3], may be less active.

According to the energy theory, the following main subprocesses occur during BATR: the formation of nitrides, sputtering of the surface, and diffusion of nitrogen into the depth of the metal [3]. The energy conditions for the main subprocesses are significantly different. Thus, the formation of nitrides occurs at low energies and, on the contrary, the surface sputtering process is activated at high voltage values. The higher the current density, the more intensively the diffusion of nitrogen sputtered on the surface occurs deep into the metal with the formation of nitride and diffusion layers [3, 6, 11]. Each of the above processes is primarily implemented in those cases that are energetically most favorable under the given conditions [3]. In our studies, with a constant composition of the gas mixture and its pressure for each batch of samples of a series of experiments, the nitriding time, the main factors influencing the results of BATR are the current-voltage characteristics of the process. In fig. 5 illustrates the results of the dependence of the depths of diffusion h and nitride balls hN on the values of voltage U and current density j under interdependent nitriding modes.

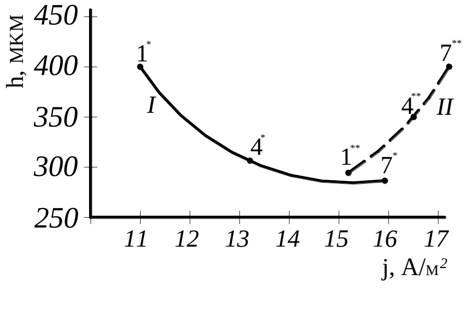
With an increase in the mixture pressure (points 1*, 4* and 7*), the voltage U automatically decreases and the depth of the diffusion layer h decreases (Fig. 5, a) With a changed shape of the suspension (points 1**, 4 ** and 7**) on the contrary, with increasing pressure the values of h increase (Fig. 5, a, curve II). However, at the same time, at a pressure p = 106.4 Pa (points 4** and 4*) there is a minimum of the depth of diffusion h and nitride layers hN (Fig. 3, a; curve II and curve I in Fig. 5, b). On the contrary, with an increase in the mixture pressure (1* / 1**, 4* / 4**, 7* / 7**), the depth of the nitride zone hN increases and, accordingly, the stress decreases (Fig. 5, b). The sharp difference between curves I and II, as well as the presence of minima on curves I and II at points 4* and 4** (Fig. 5, a, b; curve II) indicates the dependence of the BATR processes on the shape, configuration of the suspension, and placement on it. parts, the presence of sharp edges, grooves, holes and the like on the parts. The list of factors that influence the results of BATR is given in [6] and includes 13 items. The presence of a minimum on the curve I (point 4* in Fig. 3, b), in addition to the listed factors, can be justified by a minimum of active (consumed) power at a pressure of p = 106.4 Pa [3, 6].



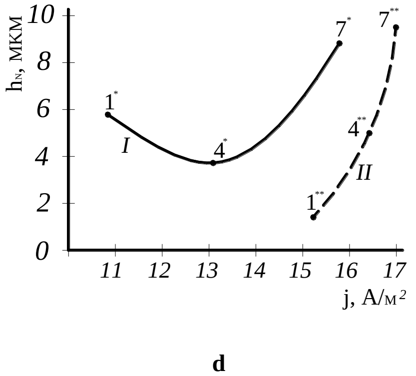
a



b



c



d

Fig. 5. Dependences of the depths of the diffusion sphere h (a) and the nitride zone (b) on the voltage value *U*; also (c, d) on the value of the current density *j* (I and II are different forms of suspensions) with the interdependent characteristics of the BATR

With an increase in the pressure of the gas mixture, the current density j increases and the value of h decreases (curve I in Fig. 5, c). At the same time, the depth of the nitride zone hN increases (curve I in Fig. 5, d). Here, too, at a pressure of p = 106.4 Pa, we have a minimum point (point 4*, curve I in Fig. 5, d).

With a change in the shape of the suspension, j increases with increasing pressure, and also increases, according to the dependences close to a straight line, h and hN (straight lines II in Fig. 5, c and d), which once again indicates the particular importance of taking into account the influence of additional factors on BATR results when designing a suspension, taking into account its shape and surface area, placing parts on the suspension, the presence of grooves, sharp edges on parts, etc.

In autonomous modes of BATR with increasing pressure at U = 515 V = const (points 3, 5 and 8 in Fig. 6), the specific discharge power increases, and at j = 7.2A / m2 = const (points 2, 5 and 9 in Fig. 6) decreases.

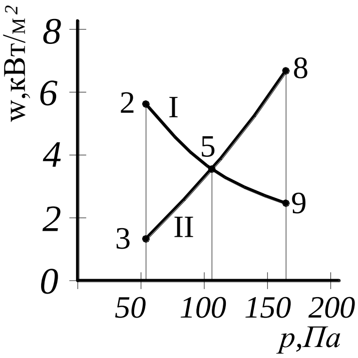


Fig. 6. Dependence of the specific power *w* on the pressure of the gas mixture p at BATR with autonomous saturation modes (curve I – nitriding at *U* = 515B = const and curve II – nitriding at *j* = 7.2A / m^2 = const)

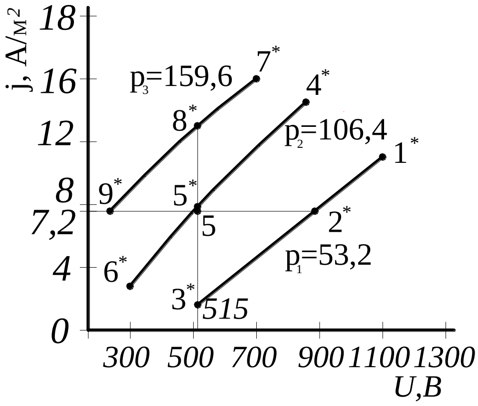
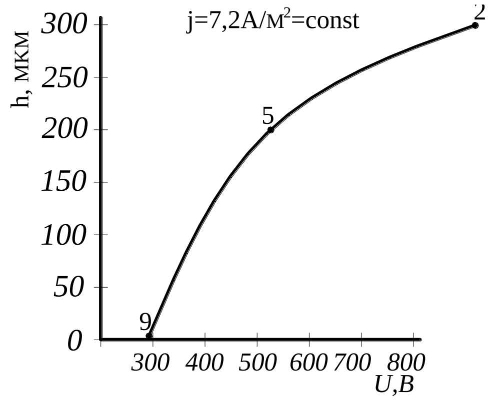


Fig. 7. Dependences of current-voltage characteristics of BATR on the pressure of the gas mixture

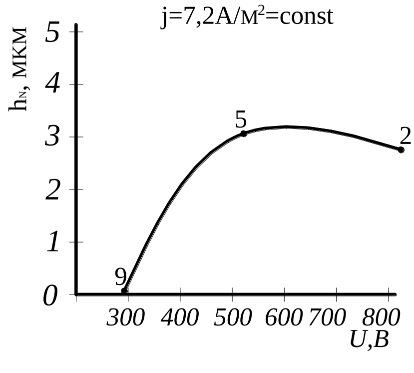
The results of X-ray structural analysis also indicate that the structure and phase composition of steel 40Kh depend on the energy characteristics of the discharge. The energy conditions for the main subprocesses (formation of nitrides, surface sputtering, and nitrogen diffusion), as mentioned above, differ significantly.

Consideration of the current-voltage characteristics shows (Fig. 7) that with increasing pressure p_1, p_2, p_3, the values of U and j increase. The indicated dependencies are straightforward. However, in all cases, the values of U and j for modes with interdependent parameters are higher than for stand-alone modes. In this case, with an increase in pressure, the voltage decreases, however, to ensure a glow discharge in the chamber, the value of the specific current density j rises automatically (points 1*, 4* and 7* in Fig. 7).

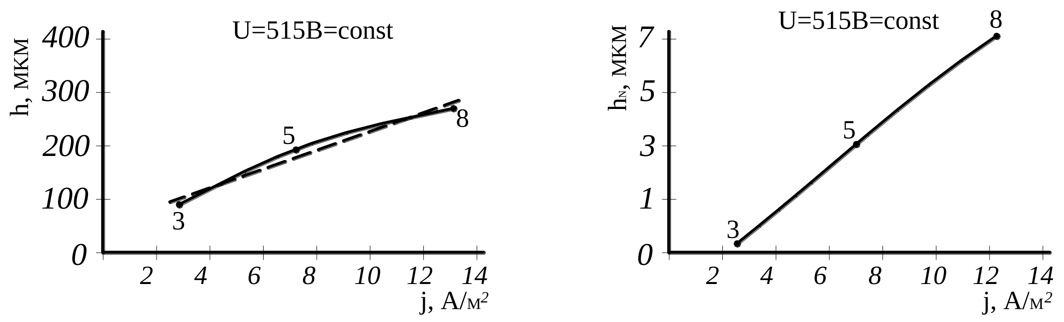
In the autonomous mode of the BATR, with decreasing pressure p, the values of U and j decrease, and at p = 159.6 Pa (point 9 in Fig. 8, a and b) $h = hN = 0$. At a pressure p = 106.4 Pa U = 515 V, and j = 7.2 A/m^2 and, accordingly, we obtain the maximum value of hN (Fig. 8, b; point 5).



a



b



c d

Fig. 8 Dependences of the depth of the diffusion layer *h* (a) and the nitride layer *hN* (b) on the voltage at *j* = 7.2 A / m^2 = const; also c and d on the current density *j* at *U* = 515B = const

In the case of a fixed value U = 515 V, with an increase in pressure and current density j, the values of h and hN increase, practically along a straight-line relationship (Fig. 8, c and d). In this case, at p = 53.2 Pa and j = 3.2 A/m^2, there is no nitride layer at all, hN = 0 (point 3 in Fig. 8, d). The latter is explained by the low value of w = 1.65 kW/m^2 and, as a consequence, the absence of a glow discharge.

The ratio of the intensity of the main subprocesses determines the structure and phase composition of the nitrided layers. Depending on the flow combination of energy parameters, the formation of the nitrided layer can occur in different directions. The intensity of the formation of one or another phase can be different not only in magnitude, but also behind the sign, since the previously formed phase can disappear. Thus, the nitride phase hN, due to further diffusion of nitrogen into the depth of the metal, disappears and a zone of internal nitriding is formed - a nitrogenous solid solution Me [N] (mode 9, a and b), or the nitride layer consists of a small amount of the (Fe4N) phase (mode 3 on Fig. 2, c and d).

According to the results of X-ray structural analysis, at the maximum values of the energy parameters (all modes with interdependent parameters 1*/1**, 4*/4**, 7*/7**, mode 8 and partly 5 with autonomous saturation parameters), a nitrided layer is formed, which consists of (Fe2N), (Fe4N) and (Me [N]) - phases (Fig. 2, mode 7). A decrease in voltage and current density leads to an increase in the phase fraction in the nitride zone of the nitrided layer and, accordingly, to a decrease in the phase (Fig. 2, modes 7, 8). At minimum values of the energy characteristics, a nitride layer does not form on the surface and it consists only of a phase (Fig. 2, mode 9).

Thus, it has been established that under conditions of dry friction for the surfaces of 40Kh steel nitrided at high energy indicators, the wear rate and the running-in period decrease (Fig. 1, b), the latter refutes the statement of K. Keller [13] that the energy characteristics of BATR do not have significant influence on the results of nitriding. On the contrary, the above BATR results allow one to draw completely obvious conclusions about the significant effect of voltage and current density on the physicochemical and tribological properties of nitrided layers. In addition, there is a certain limit of energy parameters below which (modes 9, 6, 3) carrying out BATR processes does not make sense at all, since it leads to negative results, and this despite the fact that the values of operating characteristics (temperature, composition of the gas mixture, its pressure, etc.) nitriding time) remain unchanged. Thus, the set of traditionally fixed operating parameters of the BATR cannot unambiguously characterize the conditions of the nitriding process and be the main one for predicting its results. This fact is also confirmed by the fact that at similar values of the operating parameters, the change of the suspension led to completely different results of nitriding, which is explained by the change in the energy characteristics of the BATR process (Fig. 3 ... 8).

Conclusion

1. The complex of traditionally fixed values of operating parameters (temperature, composition of the gas mixture, pressure and saturation time) without taking into account energy characteristics (voltage, current density and specific discharge power) significantly reduces the technological capabilities of BATR to achieve the necessary physicochemical properties of metal surfaces specified by conditions exploitation. Taking into account the energy characteristics of BATR, a significant reduction in the energy consumption of the nitriding process is achieved.

2. The energy levels of the main subprocesses are significantly different: the formation of nitrides occurs at low energies, surface sputtering occurs at high voltage values, and nitrogen diffusion occurs at increased current density values. In cases where the energy of the flow is insufficient, either a glow discharge may not occur at all, or with a lack of voltage, the nitride ball on the surface is not sprayed and it acts as a barrier that prevents the diffusion process into the inner layers of the metal, which leads to low physicochemical and, correspondingly, tribological indicators of nitrided balls.

3. The priority in the formation of this or that phase $(\varepsilon, \gamma' u \alpha)$, the quantitative ratio between them and the required operational properties of the metal, respectively, can be achieved only through an independent combination of the energy and operating characteristics of BATR.

Designations

BATR hydrogen-free nitriding in a glow discharge; p – pressure; U is the voltage; j is the current density; w is the specific power of the glow discharge; S is the total area of parts (samples) and suspension (cathode area); h is the depth of the diffusion layer; hN is the depth of the nitride zone; HV 0.1 – surface microhardness; KMZ – corrosion-mechanical wear; phases of the nitrided layer: (Fe2N), (Fe4N) and (Me [N]).

Literature

1. Kaplun V. G. Ionic nitriding in hydrogen-free media: monograph / V. G. Kaplun, P. V. Kaplun. - Khmelnitsky: KhNU, 2015.

2. Steel Heat Treatment. Metallurgy and Technologies / edited by G. E. Totten. - Portland, Oregon, USA: Taylor & Francis Group, 2006.

3. Pastukh IM Theory and practice of anhydrous nitriding in a glow discharge / IM Pastukh. - Kharkov: NSC KIPT, 2006.

4. Stechyshyn M.S. Influence of the Ionic Nitriding of Steels in Glow Discharge on the Structure and Properties of the Coatings / Stechyshyn, M.S., Martynyuk, A.V., Bilyk, Y.M., Oleksandrenko, V.P., Stechyshyna, N.M. // Materials Science. - 2017 .-- 53 (3). - pp. 343 - 349.

5. Ionic chemical-thermal treatment of alloys / BN Arzamasov, AG Bratukhin, Yu.S. Eliseev, TA Panayoti. - M.: Publishing house of MSTU im. N.E.Bauman, 1999.

6. Pye D. Practical Nitriding and Ferritic Nitrocarburizing / D. Pye. - Ohio - ASM International, 2003.

7. Sokolova GM Energetic aspects of the model of nitrogen gas in the light / GM Sokolova. Sokolova, I. M. Pastukh // Physical and chemical mechanics of materials. - 2017. - T. 53, No. 3. - P. 71–75.

8. Skiba M.Є. Pre-treatment of the processes of waterless nitrogen treatment in a glowing discharge / M.Є. Skiba, M.S. Stechishin, V.P. Oleksandrenko, V.S. Kurskaya, A.V. Martinyuk // Problems of tribology. - Khmelnitsky. - 2018. - No. 2. - S.6-16.

9. Lakhtin Yu.M., Kogan Ya.D. Structure and strength of nitrided alloys. - M .: Metallurgy, 1982.

10. Stechyshyn, M. S., Stechyshyna, N. M., Martynyuk, A. V., Luk'yanyuk, M. M. Strength and Plasticity of the Surface Layers of Metals Nitrided in Glow Discharge. (2018) Materials Science,. Article in Press.

11. M. S. Stechyshyn, N. M. Stechyshyna, V. S. Kurskoi. Corrosion and Electrochemical Characteristics of the Metal Surfaces (Nitrided in Glow Discharge) in Model Acid MediaMarch 2018, Volume 53, Issue 5, pp 724–731.

12. Stechishin MS Vtomna vitrival_nitovannyh spheres in the corrosive-active centers of grub wyrobnitstv / M.S. Stechishin, M.Є. Skiba, Yu.G. Sukhenko, M.I. Tsepenyuk // FHMM: Lviv. - 2019. - T.55. - No. 1. - S. 125-129.

13 Keller K. Schichtaufbau glimmnitrierten Eisen Werkstoffe / K. Keller // Harterei-Technische Mitteilung. - 1971. - Bd. 26, No. 2. - S. 120-128.

Стечишина Н.М., Стечишин М.С., Мартинюк А.В., Лукьянюк М.В., Люховець В.В., Білик Ю.М. Вплив параметрів водню азоту азоту у тліючому розряді на трибологічні та фізико-хімічні властивості сталі 40Х.

Одним із сучасних та ефективних методів зміцнення металів є азотування у тліючому розряді в аміаку або в безводному середовищі (азот + аргон) - БАТР. У цій статті представлені результати експериментальних досліджень, у яких порівнюються результати трибологічних та фізико -хімічних властивостей затверділих поверхонь, отримані азотуванням з автономними та взаємопов'язаними модами BATR. Комплекс традиційно фіксованих значень робочих параметрів (температура, склад газової суміші, тиск і час насичення) без урахування енергетичних характеристик (напруги, щільності струму та питомої потужності розряду) значно знижує технологічні можливості БАТР для досягнення необхідних фізико - хімічні властивості металевих поверхонь, визначені умовами експлуатації. Враховуючи енергетичні характеристики БАТР, досягається значне скорочення споживання енергії в процесі азотування. Рівні енергії основних підпроцесів істотно відрізняються: утворення нітридів відбувається при низьких енергіях, поверхневе розпилення відбувається при високих значеннях напруги, а дифузія азоту відбувається при збільшених значеннях щільності струму. У випадках, коли енергія потоку недостатня, або тліючий розряд може взагалі не виникати, або при нестачі напруги нітридна кулька на поверхні не розбризкується, і вона діє як бар’єр, що перешкоджає процесу дифузії в внутрішніх шарів металу, що призводить до низьких фізико -хімічних і, відповідно, трибологічних показників азотованих кульок. Кількісне співвідношення між ними та необхідними експлуатаційними властивостями металу відповідно може бути досягнуто лише шляхом незалежного поєднання енергетичних та робочих характеристик BATR.

Ключові слова: безводневе азотування у тліючому розряді (БАТР); зносостійкість азотованих кульок; фазовий склад; напруга; густина струму; питома потужність розряду.