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NITRIDING IN A HELICON DISCHARGE AS A PROMISING TECHNIQUE FOR CHANGING THE SURFACE PROPERTIES OF STEEL PARTS

The main types of state-of-the-art nitriding technologies, their advantages and disadvantages are considered. An innovative technology of ion nitriding in high-frequency helicon-discharge plasma is proposed. The hardening of steel samples *via* ion nitriding in a helicon discharge is experimentally revealed that (in a wide range of operating parameters) allows us to have an influence on the process of diffusion saturation with nitrogen atoms. The results of microhardness measurements along the depth of nitrided steel samples are presented (the steel grade is C45 according to the European standard EN 10027). The possibility of controlling the gradient of the tribotechnical properties of friction parts by changing the parameters of the technological process of ion nitriding in a helicon discharge is shown.

Keywords: nitriding, strengthening, ionic nitriding in helicon discharge, diffusion coatings, increase of wear resistance.

1. Introduction

The studies aimed at further improvement of methods of strengthening of steel by choosing optimal parameters of technological processes, introduction of existing and search for new innovative methods are topical issues.

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Today, there are a large number of different methods of chemical and thermal treatments of materials, in which the surface of metal parts is subjected to saturation by other elements using diffusion implantation. The surface of such a sample is covered with a new layer, which significantly differs from the sample centre by composition, structure, and mechanical properties.

Cementation, nitrocementation and nitriding are the main ways to increase the strength of parts of machines and aggregates by strengthening the surface. Recently, the method of nitriding has been most widely used in practice. Nitriding is a process of chemical and thermal treatment of materials, which includes saturation of the surface layer of the sample with nitrogen. It results in higher wear resistance and hardness of the surface layer of parts. It is practically proved that, after nitriding, the part acquires increased hardness, the wear resistance and contact requirements are improved, and the corrosion resistance significantly increases [1].

The process of ordinary nitriding consists of a number of previous operations. First, we need a preliminary heat treatment of the work piece. It consists of hardening and tempering of steel billet in order to obtain increased durability and viscosity of the product. The tempering is carried out at temperatures of 600–675 °C, which are higher than the maximum temperature of further nitriding that provides hardness to the product, at which steel can be treated with cutting. After the heat treatment, the part is being machined and grinded, which results to its final sizes. Before the nitriding, the areas that are not subject to nitriding have to be protected applying either a thin layer ($\cong 0.01$ mm) of tin by electrolytic method or a liquid-glass coating. At the nitriding temperature, the tin melts on the surface of the steel in the form of a thin film impermeable for nitrogen. After all these procedures, the nitriding actually takes place; then, the product assumes the desired dimensions through grinding [2].

In order to accelerate the activation processes in a gas medium, it is reasonably to use the ion nitriding, which significantly reduces the duration of the process (up to 3 times) and significantly improves the surface quality of the product.

2. Features of Ion Nitriding Process in a Plasma Glow Discharge

Nitriding in the glow discharge today is the most progressive method of increasing the surface properties of steels as compared to traditional furnace nitriding [1]. The advantages include reducing of energy consumption, reducing of time processing [3], expanding of nitrogen control processes, and, therefore, surface properties of steels. Controlled nitriding in the glow discharge gives a possibility for the directed saturation with nitrogen so that a continuous film of iron nitrides does not form on the surface as long as possible, as it blocks further diffusion of nitrogen atoms into the part limiting the thickness of the nitrided layer [4]. In addition, since the transition zone between the nitride layer and the initial base of the steel (interface) has a small thickness length, then, there occurs a significant gradient of a series of properties, which leads to accumulation of defects [5, 6], increase of stresses and, as a result, destruction (spalling) of the nitrated layer [7].

The essence of the technological process of ion nitriding in plasma of the glow discharge is as follows. The glow discharge is activated between cathode (part) and anode, through which the high-energy ions of the gas target the surface of the part and heat it. When the deposition is carried out, the structure of the surface of the part changes, the intensity of adsorption and diffusion are increased. The surface of the work piece is saturated with nitrogen, compounds of nitrogen with metals are formed, therefore, the physical and mechanical properties of the work pieces change, especially, there is an increasing of the hardness of the nitrided layers of the sample [4].

The parameters of the strengthened surface layers of nitrogen samples depend on the voltage between the electrodes, the composition of the gas mixture and the degree of its dilution, the operating temperature in the chamber and the duration of the process as well as the on the location of samples and electrodes. At the nitriding in the glow discharge, the temperature in the chamber is maintained within 470–580 °C, and the voltage is 400–900 V. When we apply the pressure to the gas mixture, it is necessary to take into account the limits of the glow discharge. If the pressure is below 133 Pa, the energy of the ions will not be sufficient to heat the sample to the operating temperature. The pressure higher than 1330 Pa violates the stability of the glow discharge passing into the electric arc, which may lead to melting of the surface of the sample. The optimal pressure in the chamber depends on the size and configuration of the work piece, since the change of the pressure varies the length of the cathode zone of discharge. At the pressure below 133 Pa, the discharge is quenched, and the area of the dark cathode glow near the sample surface (which serves as a cathode) will be at a distance of 10–50 mm, because, precisely at this interval, there is an acceleration of positively charged ions due to the voltage drop between plasma boundary and cathode. In this case, the kinetic energy of the ions in magnitude corresponds to the voltage of the discharge, the ion current is minimal and its density does not exceed 0.5 mA/cm^2. If we raise the discharge voltage to 1000 V, then, ionization of gas will still occur weakly due to the low pressure in the system. Increasing the gas pressure in the working chamber will increase the number of collisions between particles and significantly reduce the kinetic energy of the ions. At the pressure of gas mixture within the 133–1330 Pa, the cathode part of the discharge will reduce from 10 mm to 1 mm, and the ion current density will increase dramatically to 20 mA/cm^2 due to the intense ionization of the gas medium. The value of the discharge voltage will decrease up to 400–500 V. The value of the current density in the range of 0.5–20 mA/cm^2 has not a special effect on the concentration of the diffusion atoms, but only determines the heating temperature of the steel sample [4].

The processes of surface hardening of steels with ionic nitriding in plasma of the glow discharge, their details and the field of application are described in a number of publications of Ukrainian [8–11] and foreign [12–15] authors.

The authors of Ref. [16] studied the effect of the size of the iron nitride phases, their density, the nature of distribution, and chemical composition on mechanical properties of nitrided steel samples. In Ref. [17], authors showed that, during diffusion saturation of steel samples, the structures on their surface were formed by a method similar to decomposition of supersaturated solid solutions in alloys, in which the ageing process takes place.

We have to note that possibilities to control the process of nitriding in the glow discharge are restricted depending on the range of its existence, particularly, on the pressure of the gas and the voltage on the substrate. The density of ion current depends on these two parameters, and hence the effectiveness of the influence on the process of nitrogen diffusion. In addition, significant disadvantages of the above-mentioned method should include high specific power consumption of electricity as well as relatively long process cycle.

The specified disadvantages of the glow discharge result in the new challenges requiring searching for other plasma sources in order to improve the efficiency of ion nitriding.

3. Helicon Source of Plasma

Currently, there are a number of studies of the design and physical properties of an unconventional radiofrequency (RF) helicon plasma source [18–27], which has not been widely practically applied yet. Figure 1 shows a schematic diagram of helicon plasma source with a single-turn flat antenna and a combination of discharge and drift chambers [18, 27].

The helicon discharge (Fig. 1) is activated in a metal cylindrical discharge chamber using an external (in this case, azimuthally symmetric single-turn) antenna, which is located behind the dielectric window and is powered by a high frequency (RF) generator *via* a matching device.

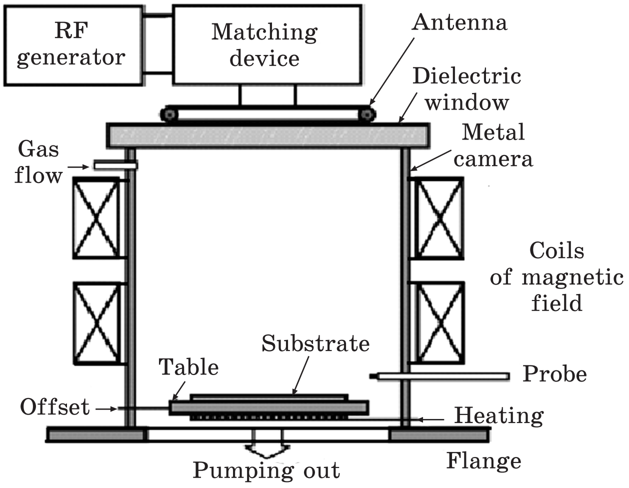


Fig. 1. Principal scheme of a helicon plasma source with a single-turn flat antenna (located behind a dielectric window) and combination of the discharge and drift chambers [18, 27]

If in inductive RF sources of plasma, the introduction of RF energy into plasma is carried out in a narrow skin layer under the antenna, then in helicon sources, due to the external magnetic field, the RF energy is introduced into plasma by electromagnetic waves, which are activated by antenna, and can propagate far into plasma [18, 27–29]. Therefore, the design and spatial arrangement of the antenna, on which the connection of antenna with plasma waves in the helicon plasma depends, plays a significant role in the formation of a helicon discharge. Typically, external antennas are located outside of the discharge chamber (sources with antennas located inside the discharge chamber are also used, but seldom) to activate the helicon discharge. In the helicon sources of plasma with an external antenna located along the discharge chamber, both azimuthally symmetric (ring) and azimuthally unsymmetrical antennas of different geometry are used [21]. In sources with flat antenna, the latter can be of single-turn (ring) [22], of multi-turn (spiral) [23] or even more complex. In these helicon sources, we use the antenna to control the spatial distribution of the input of the RF power into plasma, and hence the magnitude and distribution of the plasma density [18, 27–29].

It is principally for helicon sources to use of an external magnetic field, which performs several functions [18, 27–29]. Firstly, with the application of an external magnetic field, it is possibly to increase significantly the density of plasma in discharge, with the same embedded power, due to the excitation of bulk plasma oscillations of the helicon type, and to control the spatial distribution of plasma. Secondly, the magnetic field allows us to control effectively the intensity and energy of the ion fluxes effecting the product, and to regulate the distribution of the density of plasma along the radius of the plasma flow. Finally, the magnetic field increases the sustainability of the discharge, since the plasma load resistance increases significantly as the field applied. The operating regimes of the source and parameters of the ion flow flowing from the source, essentially depend not only on the magnitude, but also on the configuration of the magnetic field. Thus, the application of an inhomogeneous magnetic field can increase the density of plasma in the processing point of the work piece (table) in several times at the same power as for a standard source with an activation antenna located along the discharge chamber [24] and for a flat antenna source [25]. For creating a magnetic field, both coils and permanent magnets are used [26].

An important advantage of a helicon discharge, as compared with, *e.g.*, a capacitance, is the possibility of relatively simple independent control of values of plasma density on the substrate and the bias potential on the substrate. Plasma density determines the degree of dissociation of the working gas and the magnitude of the ion flow on the substrate, and the supply of an independent bias potential on the substrate allows changing widely the energy of the ions targeting the substrate.

The main advantage of the helicon discharge (in comparison with the usual induction discharges) is an application of a magnetic field, which provides a regime of magnetization of plasma electrons [18, 27–29]. Magnetization is a regime in which the cyclotron frequency of electrons significantly exceeds the frequency of their collisions with atoms and ions. The magnetization of plasma electrons is important for two reasons. Firstly, magnetization of the electrons provides the movement of plasma along the magnetic field (before it exits from the source), which reduces the loss of plasma on the face wall. Secondly, in case of a magnetic field, as we mentioned above, the introduction of high-frequency energy into the plasma is realised not in the thin surface layer (skin-layer), but *via* the electromagnetic waves, which can propagate deeply into plasma and provide the bulk absorption of RF energy and, as a result, increase ionization of the working gas.

Thus, the requirement for the magnetic field is to provide a helicon discharge regime, in which the electromagnetic fields activated *via* the antenna will penetrate into plasma much deeper than in a non-magnetic field. The possibility to realize such regime depends on the intensity of collisions of electrons in the plasma and on the configuration of the magnetic field. RF energy in a source with a flat antenna, in contrast to a standard source, is introduced into the plasma along the magnetic field using helicon waves. Thus, almost up to the highest pressures of the working gas, at which the magnetization of the electrons is provided, the depth of penetration of the RF fields into the plasma of a helicon source with a flat antenna substantially exceeds the depth of penetration of a source without a magnetic field. Helicon sources (under the condition of magnetization of electrons) allow reducing plasma losses on the faces *via* creation of the flows of charged particles directly along the magnetic field. A standard helicon source has this feature only at a non-uniform magnetic field with a magnitude of circa 100 Gs, in the range of lower working gas pressures — 1.33–6.65 Pa. In the same magnetic field, a helicon source with a flat end antenna implements a reduction of plasma losses in a wider range of pressures, 1.33–13.3 Pa, *i.e.*, almost throughout the whole field of magnetization of electrons. For pressures exceeding 13.3 Pa, there is no a magnetization of electrons (at a magnetic field of 100 Gs), and the helicon source passes into the regime of inductively coupled plasma. At such pressures, the use of helicon sources is appropriate only with an enhancement of the magnetic field above 100 Gs [18, 27–29].

In view of the mentioned above, the high-frequency helicon discharge of low pressure [18, 27–29] provides greater possibilities for controlling the nitriding process. It provides high plasma density, a wide range of energy regulation of components of the plasma stream, its composition, the stability of functioning in a wide range of gas pressures, and the ability to direct the ion flow at different angles to the surface to be nitrated. The lack of sprayed electrodes allows keeping a high constant cleanliness of plasma and provides practically unlimited operation life. Helicon plasma sources, which relate to a class of electrodeless high-frequency induction sources with a magnetic field, are capable of generating a dense ($n = 10^{11}$–10^{13} cm^{-3}) low temperature (average electron energy of 3–10 eV) plasma in a wide range of operating gas pressures ($p = 0.067$–13.3 Pa). The advantages of such sources include the simplicity of construction and operation, the possibility of obtaining high-density plasma with a large section ($\varnothing = 30$ cm) and a high degree of homogeneity, which provides a high rate and quality of processing the products with a large surface area.

The given advantages of the helicon discharge allow the nitriding process to be carried out in such a way that the density of nitrogen atoms on the surface of the sample is almost equal to the density of their flow from the surface to the depth. Maintaining such a dynamic equilibrium prevents the formation of nitride film on the surface and, thus, does not inhibit the nitrogen atoms' movement to the deeper layers. Moreover, this motion of atoms depends not only on the equilibrium solubility of N in Fe, but also on the defect concentration of steel, which, in turn, is determined by the intensity of ion bombardment. The appearance of a radiation defect flow from the surface to the bulk of the sample accelerates the diffusion of N atoms in the same direction, which increases the depth of the nitrided layer.

It is important that the controllability of the process makes possible to stretch a depth layer saturated with nitrogen atoms within the solid solution, and thus, extend the interface and lower the nitrogen concentration gradient. In addition to increasing adhesion and reducing local stresses, it is possible to expect an improvement of such properties of the surface layers as tribotechnical characteristics. It is known from the tribology that the hardness of any surface does not always determine its durability. Increasing the hardness of the surface exposed to constant friction *via* common methods (applying hardening coatings, nitriding, carburization, nitrocementation, *etc*.) reduces its plastic properties and increases brittleness [30].

The friction process is practically the interaction of real contact spots, in which high temperatures develop up to melting, as well as large plastic deformations [31], while in the surface and near-surface layers of the material there are alternating stress fields, strains, temperatures, and some chemical processes, *e.g.*, oxidation, are accelerated [32, 33]. In such difficult conditions of the destructive processes, which have a mutual influence, the presence of non-zero plasticity of the material creates conditions for relaxation of local stresses. Different mechanisms exist for relaxation of stresses, including the transformation of the metallographic structure, the emergence of so-called secondary structures, and ‘white layers’. The material seems to adapt to friction conditions by changing its structure and composition.

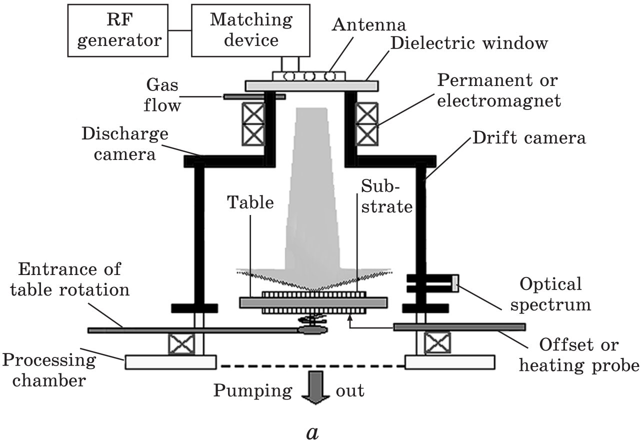
In the presence of such complex processes, the great brittleness of the material reduces the possibility of adapting its structure to the friction conditions. The impossibility of stress relaxation leads to the fact that material cracks, the products of destruction fall into the friction zone, where they begin to behave as abrasive, increasing the degree of wear. Thus, maximum hardness does not itself provide maximum durability, since it is accompanied by almost zero plasticity. The relation between hardness and plasticity should be optimal. Following this condition in our case means the necessity to create (in the process of nitriding) a stretched along the depth a strengthened layer with a minimum nitrogen concentration gradient.

4. Nitriding in a Helicon Discharge: Techniques and Results

4.1. Investigation Method and Technology

Experimental studies of nitriding in the helicon discharge were carried out on the substrates of medium-carbon steel C45 (according to European grading system), since, currently, this material is widely used due to the relatively low cost of rolling.

The nitriding was performed in an ion-plasma vacuum-technological equipment (created at the G.V. Kurdyumov Institute for Metal Physics of the National Academy of Sciences of Ukraine) containing a helicon plasma source (operating frequency — 13.56 MHz) with a multi-turn



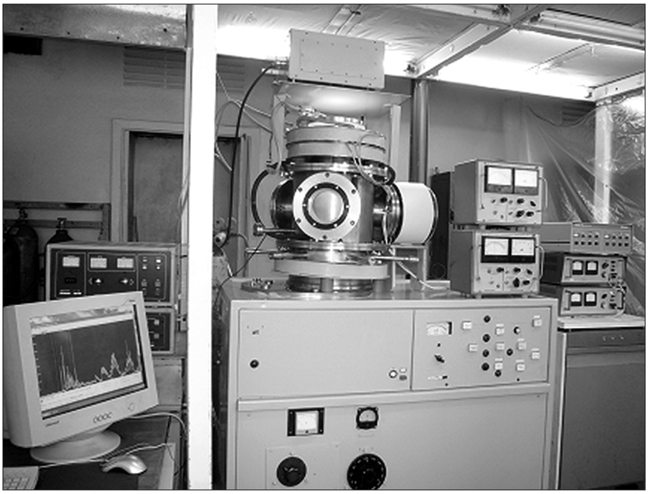


Fig. 2. Schematic image of the construction of the ion-plasma vacuum-technological equipment with a helicon plasma source with separated discharge and drift chambers (*a*) and general view of the equipment (*b*)

antenna located behind the dielectric window, and separate discharge and drift chambers (Fig. 2) [28, 29, 34–37].

In construction of a helicon source, a planar antenna is used to generate a discharge. The antenna is located outside the dielectric window closing the metal or dielectric discharge chamber from the end. In this case, the RF power is introduced along the magnetic field. In our design, we (for the first time) used technological drift chamber and showed the possibility of carrying out technological processes with a high plasma density outside the helicon reactor. The structural features, technical characteristics, and studies of properties of the helicon plasma produced in the ion-plasma vacuum-technological equipment are reported in detail in Refs. [28, 29, 33–37].

Technological process of ionic nitriding of C45 steel in helicon plasma of an ion-plasma vacuum-technological equipment was carried out in

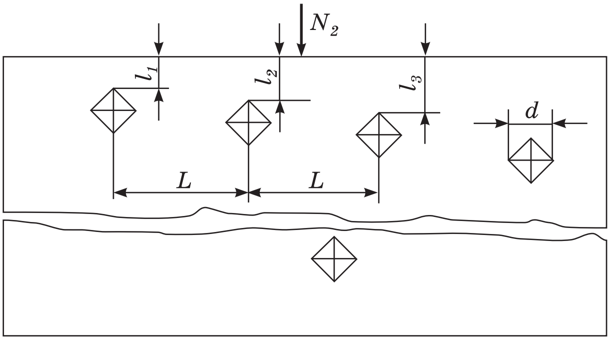


Fig. 3. Schematic arrangement pyramid impressions of the microhardness tester used (in three schemes) to measure microhardness of nitrated layer

two stages [38]: first, preliminary cleaning (purification) of the sample (with helicon plasma in the argon medium); second, direct process of nitriding in the helicon plasma.

Preliminary purification of the surfaces of each sample was performed in two stages as well. Initially, we performed a preliminary pumping of the working chamber of the vacuum-technological equipment to a value of residual pressure of the order of 0.013 Pa. Thereupon, we performed the puffing of working gas (argon) to the working chamber and purification operations.

Cleaning (purification) of the sample was performed at the following technological parameters: pressure of working gas (argon) — 0.93 Pa; the magnitude of the RF generator power — $P = 600$ W; the potential of the working table — $U = -50$ V; the duration of the purification process — 5 min.

The process of nitriding the sample surfaces begins after the completion of the cleaning operation and without the removal of samples from the working chamber. After the cleaning, the working argon gas was pumped out from the working chamber, then we filled the chamber with the working nitrogen gas (or mixture of N and Ar), in the atmosphere of which 'Column' regime of the helicon discharge was realised [29, 35]. The duration of the nitriding process was 30 minutes.

Parameters of the nitriding regimes for steel (C45) samples

Sample No.	Generator power, W	Gas pressure (nitrogen/mixture), Pa	Potential of the table, V	Temperature of the substrate, °C
1	600	0.93	–50	330
2	600	0.93	Floating	330
3	600	0.93	–197	330
4	600	0.93, mixture (argon 30%, nitrogen 70%)	–50	330
5	600	0.66–0.93, mixture (argon 30%, nitrogen 70%)	Floating	330

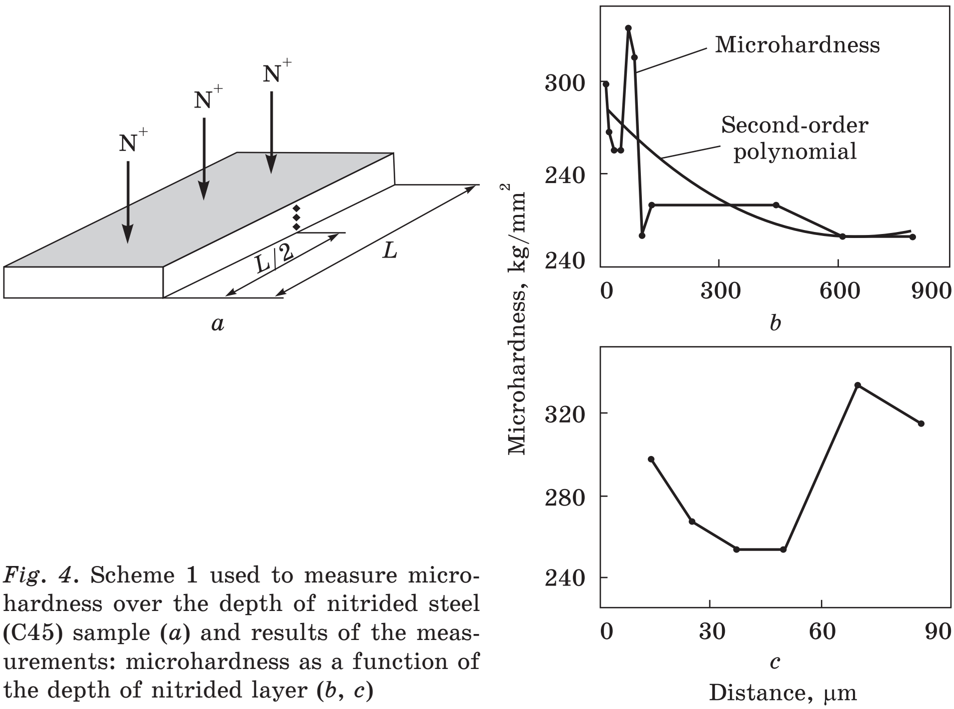


Fig. 4. Scheme 1 used to measure microhardness over the depth of nitrided steel (C45) sample (*a*) and results of the measurements: microhardness as a function of the depth of nitrided layer (*b*, *c*)

Parameters of the nitriding process in the helicon plasma for five samples are contained in Table.

Based on previous studies, optimal technological parameters of nitriding the steel C45 in helicon plasma were established.

Sizes of the samples subjected to nitriding (Fig. 2) were ($W \times L \times H$) $10 \times 20 \times 3$ mm^3. The schemes of the microhardness measurement and arrangement of the pyramid impressions of the microhardness-tester are given in Figs. 3–6. The mutual arrangement of the primary (normal) and tangential (lateral) flows of nitrogen ions is shown in Fig. 6. The side faces of the samples were unprotected from the tangential flow of N ions, in contrast to other faces closed by metal screens.

In our work, the main criterion for formation of properties of the layer nitrided in the helicon discharge is a microhardness, since it enables to determine (locally, along the depth) the effect of the distribution and interaction of diffusing N atoms with Fe ones as the basis of the medium-carbon steel. Changing the conditions of nitriding, the potential on the sample (the energy of the nitrogen ions), the gas pressure (ion current density), the temperature of the sample, the time, it is possible to adjust the properties and structure of the N-saturated layer, thus to select the optimal parameters of the process. To increase the locality of the microhardness measurement along the depth of the nitrid-

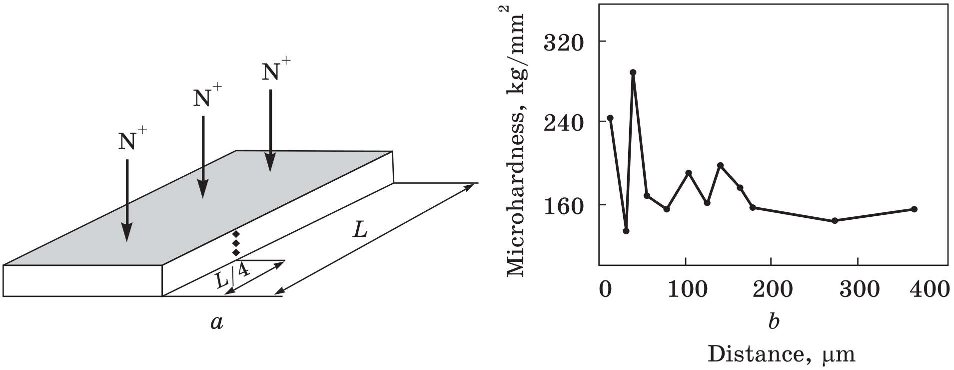


Fig. 5. The same as in the previous figure, but for another measurement pattern (scheme 2)

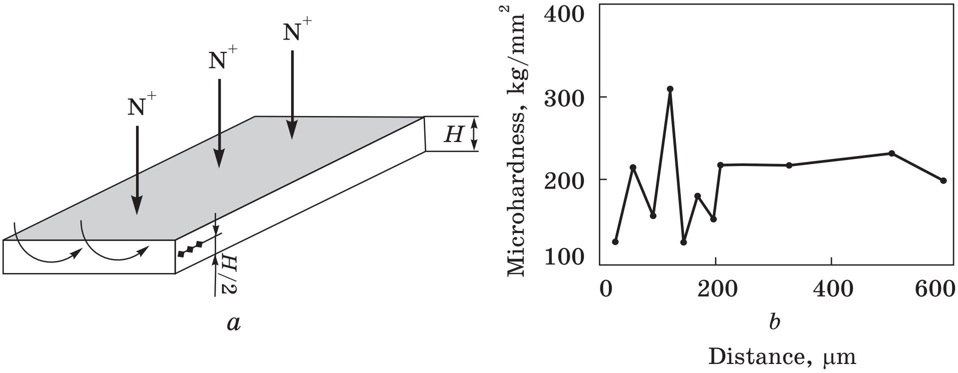


Fig. 6. The same as in Fig. 4, but for another measurement pattern (scheme 3)

ed layer and to eliminate the mutual influence of the metal (deformed because of the pyramid impressions) on the adjacent impressions, they were plotted according to the scheme shown in Fig. 3. We select the loading on the pyramid such to provide the maximal accuracy of the measurement of the diagonal of the impression and minimal distance from the surface and the impressions between each other.

Figures 4–6 exhibit results of the microhardness measurements for nitrated layers taking into account the normal and tangential dropping of N ions. In order to increase the reliability of the obtained results, the measurements were made at two points located close to each other and in directions marked with impression images. Such a scheme for measuring the microhardness allows considering possible differences caused by the different efficiency of nitriding in the discharge in directions relative to surfaces, oriented normally and tangentially to the direction of falling of N ions.

Figure 4, *b* (scheme 1) represents the extrapolation of the microhardness curve *via* the second order polynomial. Such an averaging of the microhardness values along the depth allows suggesting a hypothetical prediction for the profile of the wear resistance curve in case of the sliding friction, since a wear-resistance is also an additive value and represents the sum of interactions between the surfaces of the counter body and the sample at the points of real contact.

4.2. Analysis of Experimental Results

A general view of the dependences of the microhardness distribution over the depth of the nitrogen layer is consistent with all three schemes in Figs. 4–6. Some differences in the absolute values of microhardness can be explained by the measurement error and the effect of the sample, since the sizes of the structural components of steel C45 (mixture: ferrite + cementite tertiary) are commensurable with the magnitude of the microhardness tester pyramid impression.

For all three cases of the plotted microhardness distribution curves $H_\mu = H_\mu(l_n)$ ($n = 1, 2, 3$) in Figs. 4–6, there are two peaks at a depth of 10–20 μm from the surface (Figs. 4, 5) and at a depth of 50–110 μm (Fig. 6). Increase of the depth of the peak positions in case of Fig. 5 can be attributed to ‘additional’ influence of N atoms diffusing through the side face of the sample (shown in Fig. 6 with curved arrows). In cases shown in Figs. 4 and 5, this flow of N atoms on the side faces does not reach the areas of microhardness measurement ($0.5L$, $0.25L$) due to the large diffusion path.

The presence of the microhardness peak closer to the surface can be explained by the strengthening of the crystalline iron lattice due to N atoms dissolved in the Fe lattice. Their concentration on the surface is maximal and decreases with increasing of the depth of the nitrated layer, determining the decrease of microhardness after passing the maximum.

The presence of the second peak can be attributed to the formation of iron nitrides, which increase the microhardness as compared with the previous area of the nitrogen solid solution. Since the effectiveness of the dispersion strengthening of iron with nitride particles is higher than with solid solubility strengthening of nitrogen atoms, the value of the second peak is also higher. The almost axially located decreasing ranges of the curves after passing the first and second peaks indicate that the distribution of N atoms from the surface, where the concentration is maximum and close to the concentration in nitride, and their distribution after the passage of the second peak is similar.

The smaller values of the first peaks in comparison to others may indicate that the penetration of N atoms from the surface is facilitated as compared to the passing through a layer of nitrides, which acts as a barrier. In order to improve the properties of nitrided layers, it is desirable to extend the depth of the first zone (with dissolved N atoms) and to remove the zone of formation of nitrides as far as possible from the surface. This technological process is the most effective at the nitriding in a helicon discharge, which can affect the diffusion of N atoms in a wide range of parameters.

5. Conclusions

In this paper, we develop an effective method for strengthening of the surface of steel parts modifying the near-surface layers applying technology of the ion-plasma nitriding in a helicon discharge.

We showed experimentally the possibility of surface hardening of steel C45 using nitriding using in a helicon discharge, which affects the process of diffusion saturation with N atoms in a wide range of parameters.

The obtained values of microhardness over the depth of the nitrided layer give an opportunity to predict the improvement of the tribotechnical characteristics for nitrided steel parts under sliding friction conditions.

Nitriding in the helicon discharge, obviously, allows separating (by depth) the processes of solid state strengthening with N atoms and dispersion strengthening during formation of the nitride layer, which opens up a possibility to regulate the gradient of the tribotechnical properties of the steel parts being under friction in the process of exploitation.

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АЗОТУВАННЯ У ГЕЛІКОННОМУ РОЗРЯДІ ЯК ПЕРСПЕКТИВНИЙ МЕТОД ЗМІНЕННЯ ПОВЕРХНЕВИХ ВЛАСТИВОСТЕЙ КРИЦЕВИХ ДЕТАЛІВ

Розглянуто основні типи сучасних технологій азотування, їхні переваги та недоліки. Запропоновано інноваційну технологію йонного азотування у плазмі високочастотного геліконного розряду для зміцнення поверхні та приповерхневих шарів деталів, які працюють в умовах тертя ковзання. Експериментально встановлено зміцнення поверхневих і приповерхневих шарів крицевих зразків методом йонного азотування у геліконному розряді, який (у широкому діапазоні параметрів функціонування) уможливлює вплив на перебіг процесу дифузійного насичення атомами Нітроґену. Подано результати міряння мікротвердости за глибиною азотованих зразків криці (C45 за європейським маркуванням криць). Показано можливість реґулювання ґрадієнта триботехнічних властивостей деталів тертя шляхом зміни параметрів технологічного процесу йонного азотування у геліконному розряді.

Ключові слова: азотування, зміцнення, йонне азотування у геліконному розряді, дифузійні покриття, підвищення зносостійкости.

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АЗОТИРОВАНИЕ В ГЕЛИКОННОМ РАЗРЯДЕ КАК ПЕРСПЕКТИВНЫЙ МЕТОД ИЗМЕНЕНИЯ ПОВЕРХНОСТНЫХ СВОЙСТВ СТАЛЬНЫХ ДЕТАЛЕЙ

Рассмотрены основные типы современных технологий азотирования, их преимущества и недостатки. Предложена инновационная технология ионного азотирования в плазме высокочастотного геликонного разряда для упрочнения поверхности и приповерхностных слоёв деталей, работающих в условиях трения скольжения. Экспериментально установлено упрочнение стальных образцов методом ионного азотирования в геликонном разряде, который (в широком диапазоне параметров функционирования) позволяет влиять на протекание процесса диффузионного насыщения атомами азота. Представлены результаты измерения микротвёрдости по глубине азотированных образцов стали (С45 по европейской маркировке сталей). Показана возможность регулирования градиента триботехнических свойств деталей трения путём изменения параметров технологического процесса ионного азотирования в геликонном разряде.

Ключевые слова: азотирование, упрочнение, ионное азотирование в геликонном разряде, диффузионные покрытия, повышение износостойкости.