Cutting tools hardening and sharpening by fast argon and nitrogen atoms

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Abstract. A reamer made of AISI M2 high-speed steel was heated by ions accelerated from the plasma by a bias voltage applied to it and kept at 500°C for 120 min. Microhardness of the reamer surface increased by 1.75 times and the nitride layer thickness reached 130 μm. Nevertheless, radii of the cutting edges increased by 5 times up to ~ 40 μm, which made the tool blunt. Another reamer was heated by a converging beam of fast atoms produced by an immersed in the same plasma concave grid under a negative voltage of 5 kV. Due to uniform removal of the reamer material by the beam, the radii of cutting edges decreased from the initial value ~ 8 μm down to ~ 6 μm.

1. Introduction
Plasma nitriding is a well-established technique for strengthening various machine parts. It improves their corrosion, wear and fatigue resistance [1]. The treatment comprises penetration of atomic nitrogen into the surface of a product and its subsequent diffusion into the bulk. The nitrogen implantation into the surface layer of the product and heating it up to a temperature of effective nitrogen diffusion are carried out by ions accelerated from the gas discharge plasma by a negative bias voltage applied to the product.

In most cases, the abnormal glow discharge is used for the plasma nitriding. A product to be hardened is placed inside a vacuum chamber and connected to feedthrough, for instance, mounted on the chamber top (Fig. 1). The positive pole of a DC power supply is connected to the vacuum chamber and its negative pole is connected to the product. At the nitrogen pressure of ~ 100 Pa and a negative voltage, for example, 700 V, applied to the product an abnormal glow discharge is established between the chamber playing the role of an anode and the product playing the role of a cathode. In this case, the product surface is covered with a bright blue layer of the discharge negative glow. Ions accelerated from the discharge plasma by the applied voltage pass through the cathode sheath of the positive space charge and bombard the product surface.

The product of the pressure p by sheath width d in nitrogen at a voltage of 700 V is equal to \( pd = 0.2 \ \text{Pa-m} \), and \( j/p^2 = 0.01 \ \text{A/m}^2\cdot\text{Pa}^2 \), where \( j \) is current density on the product surface [2]. At a pressure of 50 Pa, the sheath width is equal to 4 mm, and the ion current density is equal to 25 A/m². The heating power density on the product surface \( w \) is equal to 17.5 kW/m². At a stationary temperature \( T \) of the heated product, \( w \) is equal to luminosity \( R^* \) of its surface

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R^* = \omega S BT^4
\]  
(1)
where $\omega$ is emissivity of the product material and the Stefan-Boltzmann constant $\sigma_{S-B}$ is equal to $5.7 \times 10^{-8}$ W/(m$^2$·K$^4$). For a steel product $\omega \approx 0.25$ and at $R^* = 17.5$ kW/m$^2$ its temperature is equal to 1053 K or 820°C, which is quite enough for an effective nitriding. When the nitrogen pressure decreases to 10 Pa the sheath width growth to $d = 20$ mm, the current density diminishes to $j = 1$ A/m$^2$ and the temperature falls to 471 K or 198°C, which is not enough for nitriding.

**Figure 1.** Schematic of a product nitriding in the abnormal glow discharge plasma

An ion accelerated in the sheath at a pressure $p \sim 50$ Pa of argon mixed with nitrogen (30%) after passing a distance of about 0.2 mm collides with a gas atom. Due to charge exchange, it turns into a fast neutral atom. The slow ion produced in the collision is also accelerated by the electric field in the sheath. After passing the same distance of 0.2 mm it turns into the second fast neutral atom, and a new slow ion appears. The charge of one ion is transported through a 4-mm-wide sheath by about 20 particles. They transfer the charge to each other and their average energy amounts to $700/20 = 35$ eV. At this energy, the surface structural defects cannot enhance the nitriding rate, and it is determined only by the temperature. Therefore, to obtain 100-μm-thick nitrided layers using the abnormal glow discharge it takes sometimes 5–10 hours.

At low-pressure $p < 1$ Pa ions pass through the sheath without collisions, bombard the product surface with high energy and due to structural defects, the nitriding rate is appreciably higher [3]. Glow discharge assisted by thermionic emission allows production on high-speed steel substrates at the temperature of 480–500°C and the gas pressure $\sim 0.5$ Pa of nitrided layers with a thickness of 150 μm for only 240 min [1]. The products can be also nitrided at low pressure in the vacuum-arc plasma. It was successfully used for pre-nitriding of cutting tools on planetary rotation system before deposition of wear-resistant coatings [4]. The goal of the present research is the development of a surface hardening technology which could increase the nitriding rate of cutting tools due to bombardment by high-energy ions and a high degree of nitrogen dissociation.

**2. Experimental setup**

To reach the goal it is necessary to produce in a process vacuum chamber at the gas pressure of $p = 0.1$–1 Pa homogeneous plasma with a high degree of nitrogen dissociation. Due to the hollow cathode effect based on the gas ionization in the cathode sheath of glow discharge quite homogeneous plasma can be produced at $p = 0.01$–1 Pa [5]. Plasma emitters of ions have been already produced using this effect [6, 7]. Figure 2 presents the experimental setup based on plasma generation using the hollow cathode glow discharge. Here the process vacuum chamber plays the role of a hollow cathode.

The chamber diameter is equal to 50 cm and its length amounts to 60 cm. There is high-voltage feedthrough on the chamber top. When a product is placed in the chamber and connected to the
feedthrough, it can be negatively biased to 6 kV using a DC bias voltage power supply. Another power supply is connected between the chamber and an anode placed at the chamber bottom. The anode surface area amounts to 50 cm².

A turbo-molecular pump evacuates the chamber to a residual gas pressure of 0.001 Pa. A two-channel gas supply system ensures regulation of the operating gas pressure from 0.01 to 5 Pa. The chamber is equipped with Hiden EQP energy-mass-analyzer (300 AMU mass range and 1000 eV energy range) produced by Hiden Analytical Ltd. (England), which enables monitoring, control and characterization of ions, neutrals, and radicals in the discharge plasma.

In the center of the chamber can be fixed and connected to the high-voltage feedthrough a circular 20-cm-diameter grid. The curvature radius of its concave surface amounts to 20 cm. On a ceramic insulator fixed on the rod of the rotation system is mounted a holder shaped as a hollow cylinder. The system axis is distant from the chamber wall at 5 cm. The holder rotating at a speed of 60 rpm plays the role of a screen protecting the insulator from the deposition of metal films on its surface.

The grid with 7-mm-diameter holes at a distance of 8 mm between their centers is made of 1-mm-thick titanium sheet. When a 26-mm-diameter reamer made of high-speed steel AISI M2 is placed on the holder lines perpendicular to the grid surface pass through the reamer (Fig. 3). For measuring the temperature of the reamer using an IMPAC IP 140 pyrometer manufactured by LumaSense Technologies GmbH (Germany) there is a quartz window on the chamber wall.

Switching on the discharge power supply at the gas pressure in the chamber of ~ 0.5 Pa results in establishing the hollow cathode glow discharge. A uniform plasma separated from the chamber walls with a cathode sheath of positive space charge fills the chamber. The hollow cathode effect ensures the glow discharge maintenance at pressures of 0.005–5 Pa. Due to the bombardment of the chamber by ions from the plasma, its walls emit electrons accelerated in the cathode sheath by the discharge voltage of several hundred volts. In the above pressure range, electrons cross the plasma without collisions and are reflected back near the opposite wall. The mean length \( L \) of the electron path to the anode [5] is equal to

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L = \frac{4V}{S_a},
\]  

(2)
where $V$ is the chamber volume and $S_a$ is the anode surface area. In our case, $V = 0.12 \text{ m}^3$, $S_a = 0.005 \text{ m}^2$ and having traveled a path of $L \sim 100 \text{ m}$, each electron visits all parts of the chamber. This ensures the plasma homogeneity and production in the cathode sheath of additional fast electrons, which greatly contribute to the gas ionization at low pressure.

3. Experimental results

At a gas pressure of $p = 1 \text{ Pa}$ and a discharge current in the anode circuit of $I_d = 2 \text{ A}$ the discharge voltage is equal to $U_d \approx 450 \text{ V}$. Application of an accelerating voltage $U = 6 \text{ kV}$ to the grid immersed in the discharge plasma (Fig. 4) results in an increase in the grid current $I$ from 0.2 to 0.5 A and a decrease in the discharge voltage $U_d$ from 450 to 200 V. These changes are the result of ion-electron emission growth from the grid surface and an increase in the current of secondary electron emission from the chamber walls, bombarded by electrons with energy of 6 keV.

![Figure 3. Photograph of the grid and the reamer](image1)

![Figure 4. The negatively biased grid in plasma](image2)

In the sheath between the plasma and the grid, fast atoms are produced in charge exchange collisions of accelerated ions and gas molecules. At the argon ions energy of 6 keV, their charge-exchange cross-section $\sigma$ amounts to $17 \times 10^{-20} \text{ m}^2$ [8, 9], and the charge exchange length $\lambda = 1/n\sigma$ at $p = 1 \text{ Pa}$ and density of the gas molecules $n = 2.5 \times 10^{20} \text{ m}^{-3}$ [10, 11] is equal to 2.4 cm. At $U = 6 \text{ kV}$ the width of the grid sheath exceeds $\lambda$ and all the ions flowing through the grid form a converging beam of fast atoms (Fig.4) bombarding the reamer.

Hardening of 26-mm-diameter reamers was carried out in argon mixed with nitrogen (30% or 60%) at the gas pressure of 1 Pa of and the discharge current $I_d = 2 \text{ A}$. One of the reamers was hanged on the high-voltage feedthrough and heated up to 500 °C by ions accelerated from the plasma by a negative bias voltage of 5 kV. After the heating, the tool was kept in plasma at this temperature and the bias voltage of 1.5 kV for 120 minutes. Using the optical measuring system MicroCAD premium+ by GFMesstechnik GmbH (Germany) it was found that after the hardening the radii of the reamer’s cutting edges grew up to $\sim 37 \mu \text{m}$ and appreciably exceeded the initial radii $\sim 8 \mu \text{m}$ (Fig. 5). It can be caused by a selective sputtering of the cutting edges by ions heating the reamer during nitriding.

Another reamer was placed on the rotating holder (Fig. 2) and heated by a converging beam of fast atoms produced by the grid up to 500 °C. After the heating, the reamer also was kept in the plasma for 120 min at the same temperature. In this case, the cutting edges radii $\sim 6 \mu \text{m}$ (Fig. 5) of the strengthened reamer did not exceed the original value. This is due to a uniform removal of the
reamer’s material from its surface by the beam of fast atoms. In addition, the beam treatment reduced the roughness of both the front and rear surfaces of the reamer’s cutting edges.

![Figure 5](image)

**Figure 5.** Profiles of the reamer’s cutting edges prior to processing (1), after nitriding with heating by ions, accelerated from the plasma (2), and after nitriding with heating by fast atoms (3)

Another reamer was placed on the rotating holder (Fig. 2) and heated by a converging beam of fast atoms produced by the grid up to 500°C. After the heating, the reamer also was kept in the plasma for 120 min at the same temperature. In this case, the cutting edges radii \( \sim 6 \mu m \) (Fig. 5) of the strengthened reamer did not exceed the original value. This is due to a uniform removal of the reamer’s material from its surface by the beam of fast atoms. In addition, the beam treatment reduced the roughness of both the front and rear surfaces of the reamer’s cutting edges. Vickers microhardness measurements on polished cross-sections of the strengthened reamers (Fig. 6) under a load of 50 g made it possible to determine the thickness of the nitrided layer \( \sim 100 \mu m \) and its microhardness of 1400 HV0.05 on the surface appreciably exceeding microhardness 800 HV0.05 of the bulk.

![Figure 6](image)

**Figure 6.** Polished cross-section of the strengthened reamer and dependence of microhardness on the distance from its surface at the percentage of nitrogen 30\% (1) and 60\% (2) in the mixture with argon

The reasons for a comparatively high nitriding rate are structural defects produced in the surface layer by heating ions and a high degree of nitrogen dissociation by fast electrons oscillating in the plasma. Measured with the Hiden EQP analyzer energy distributions of nitrogen ions bombarding the chamber walls showed that the current densities of atomic and molecular nitrogen ions both grow with the discharge current \( I_d \). However, the ratio of the atomic to molecular ion current densities rises from
0.8 at \( I_d = 0.5 \) A to 0.95 at \( I_d = 1 \) A and to 1.4 at \( I_d = 2 \) A. It means that in plasma produced in the mixture of argon with nitrogen (30%) at the gas pressure of 1 Pa and the discharge current of 2 A the nitrogen dissociation degree exceeds 50%.

4. Conclusions
In comparison with nitriding based on abnormal glow discharge or vacuum arc, the glow discharge with electrostatic electron confinement is remarkable for a high degree of nitrogen dissociation and homogeneity of its plasma, which increases the nitriding rate.

A concave grid immersed in the plasma allows the production of a converging beam of fast neutral atoms. Heating a tool with the beam instead of ions accelerated from the plasma by a negative bias voltage provides the cutting edges sharpening instead of blunting.

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