Strengthening of cutting tools using beams of fast neutral atoms in a low-pressure gas discharge plasma

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Abstract. The surface of a 26-mm-diameter reamer made of AISI M2 high-speed steel has been nitrided in a low-pressure glow discharge plasma. Then a 3-μm-thick wear-resistant TiN coating has been magnetron sputtered on the hardened surface. After the combined processing the reamer’s cutting edges radii grew from the initial value of ~8 μm up to ~37 μm. The reason for the strengthened tool blunting is selective sputtering of the edges by heating ions accelerated from the plasma. Another reamer under nitriding was heated by a beam of fast atoms arriving at the tool surface from an immersed in the plasma concave grid negatively biased to 6 kV. Due to the uniform sputtering of the tool surface by the beam, the edges radii after nitriding and 3-μm-thick TiN coating deposition did not exceed the initial value.

1. Introduction
Vacuum arc deposition of wear-resistant coatings with a microhardness of ~25 GPa significantly increases the service life of tools and machine parts. The thickness of the coatings on the cutting tool for roughing is usually less than 5 microns. With a greater thickness, the radius of the tool cutting edge increases from ~15 μm to 20 μm and more, the values characteristic of a blunt tool.

Before the coating synthesis, the tool is heated at a pressure in the vacuum chamber of ~0.001 Pa by metal ions accelerated from the arc-discharge plasma by a negative voltage of ~1000 V supplied to the tool. After the heating, nitrogen is supplied to the chamber, and at a voltage of ~100 V and a pressure of 0.1–1 Pa, a hard nitride coating is synthesized.

To improve the performance of coated tools and increase their useful life, the surface is nitrided before the coating deposition. The nitrided layer with the thickness exceeding the coating thickness by an order of magnitude is distinguished by high fatigue strength and load-bearing capacity [1]. This reduces plastic and elastic deformations of the tool surface, which prevents the brittle fracture of the hard coating.

Combined strengthening of cutting tools based on the vacuum arc, including preliminary nitriding and deposition of wear-resistant coatings, can be carried out in the same vacuum chamber [2]. The tools are heated to an effective thermo-diffusion temperature of 500 °C by nitrogen and argon ions accelerated from the plasma. Nitriding takes about 120 min, and during this time the cutting edge radius increases significantly due to selective sputtering by ions.

Combined processing, which includes the surface nitriding and coating deposition, could also improve the performance of the tools for finishing. However, here the cutting edge radius ~ $R = 8 \mu$m is about two times smaller than that of the tool for roughing. Because of ion sputtering during nitriding and deposition of a coating with a thickness of 3 μm, the radius of the cutting edge will increase several times, which will make the tool blunt.
Results of the present research show that this can be avoided if, during nitriding, the tool is heated not by accelerated ions from the plasma, but by a beam of fast atoms.

2. Experimental setup
To carry out the research, a vacuum chamber in the form of a hexagonal prism with an inscribed circumference of 60 cm was used (figure 1). A 26-mm-diameter reamer made of AISI M2 high-speed steel was placed on a holder shaped as a hollow cylinder rotating at a speed of 60 rpm. It was distanced from the target of a planar magnetron at 6 cm. The holder is mounted on a ceramic insulator and plays the role of a screen protecting the insulator from the deposition of metal films on its surface. The insulator is fixed on the rod of the rotation system.

Figure 1. Schematic of the experimental setup (a) and a photograph of the reamer and the grid (b).

A 22-cm-diameter grid its surface curvature radius amounting to 22 cm is fixed in the center of the chamber on a rod connected to high-voltage feedthrough mounted at the chamber top. Its concave surface faces the reamer under processing. The lines perpendicular to this surface pass through the center of the reamer. The grid is made of 1-mm-thick titanium sheet with 7-mm-diameter holes at a distance of 8 mm between their centers. It is connected to the negative pole of an accelerating voltage power supply, which allows the voltage up to \( U = 6 \text{ kV} \). The positive pole of the power supply is connected to the grounded chamber. An anode is fixed inside the chamber at additional feedthrough and connected to the negative pole of a discharge power supply its positive pole being connected to the chamber.

The chamber is evacuated by a turbo-molecular pump, which ensures the residual gas pressure of 0.001 Pa. The operating pressure of argon mixed with nitrogen is regulated from 0.1 to 5 Pa using a two-channel gas supply system. On the chamber wall, there is a quartz window (not shown in the figure) for measuring the temperature of the reamer using an IMPAC IP 140 pyrometer manufactured by LumaSense Technologies GmbH (Germany). All systems are controlled using a control panel.

3. Results and discussion
At the gas pressure in the chamber of \( \sim 0.5 \text{ Pa} \), switching on the discharge power supply leads to filling the chamber with a uniform plasma separated from the chamber walls with a cathode sheath of
positive space charge. The hollow cathode effect associated with the multiplication of fast electrons in the cathode sheath [3] ensures the glow discharge maintenance at pressures of 0.005–5 Pa. This discharge has been already used for generation of plasma emitters in ion sources [4, 5]. In our case the chamber plays the role of the hollow cathode, and at a gas pressure of \( p = 1 \) Pa and a discharge current in the anode circuit of \( I_d = 6 \) A the discharge voltage amounts to \( U_d = 450 \) V. Application to the grid immersed in the discharge plasma of an accelerating voltage \( U = 6 \) kV leads to 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. This is due both to an increase in the current of ion-electron emission of the grid and the current of secondary electron emission from the chamber walls, bombarded by electrons with an energy of 6 keV, as well as to the gas ionization in the chamber by fast neutral atoms.

The fast atoms are produced in the sheath between the plasma and the grid in charge exchange collisions of accelerated ions with gas molecules. With an increase in the energy of argon ions from 0.5 to 6 keV, their charge-exchange cross-section \( \sigma \) decreases from \( 30 \times 10^{-20} \) to \( 17 \times 10^{-20} \) m\(^2\) [6, 7], and the charge exchange length \( \lambda = 1/\sigma n \) [8] at \( p = 1 \) Pa and density of the gas molecules \( n = 2.5 \times 10^{20} \) m\(^{-3}\) [9] increases from 1.3 to 2.4 cm. It is less than the width of the grid sheath at \( U = 6 \) kV. Therefore, almost all the ions that have flown through the grid to the reamer turn into fast atoms, bombarding its surface.

Hardening of 26-mm-diameter reamers was carried out in argon mixed with nitrogen (30%) at the gas pressure of 1 Pa of and the discharge current \( I_d = 6 \) A. One of them was heated to 500 °C by ions accelerated from the plasma by a negative bias voltage of 1.5 kV applied to the reamer. After the heating, the tool was kept at this temperature for 120 minutes. Then the magnetron was turned on and at a current of 8 A in the circuit of its titanium target, a TiN coating was synthesized for 90 minutes.

The coating thickness of \( \sim 3 \) μm was determined by measuring with a DectakXT stylus profiler manufactured by Bruker Nano, Inc. (USA) the height of the step between the open and masked surfaces of a polished substrate made of AISI M2 high-speed steel, which was fixed on the same holder close to the reamer. The optical measuring system MicroCAD premium+ manufactured by GFMesstechnik GmbH (Germany) revealed that the initial radius \( \sim 8 \) μm of the reamer’s cutting edges increased after the hardening up to \( 37 \) μm (figure 2), which can be associated with a selective sputtering of the cutting edges by ions during the nitriding.

![Figure 2](image_url)

**Figure 2.** Profiles of the reamer’s cutting edges prior to processing (1), after nitriding for 120 min with heating by ions from the plasma and 3-μm-thick TiN coating deposition for 90 min (2), as well as after nitriding for 120 min with heating by fast atoms and 3-μm-thick coating deposition for 90 min (3).

Another reamer rotated on the insulated holder (figure 1(a)) and was heated by a converging beam of fast atoms produced by the grid immersed in the same plasma. After the heating, the reamer also was kept in the plasma for 120 min at a temperature of 500 °C. Then a TiN coating with a thickness of
-3 μm was deposited on its surface for 90 min. Measurements showed that the cutting edges radii of the strengthened reamer did not exceed the original value. This is due to the uniform removal of the reamer’s material from its surface by the beam of fast atoms.

Figure 3 demonstrates sputtering of the cutting wedges 1 and 6 by accelerated from plasma 2 ions 3 (on the left) and by a beam of fast neutral atoms 7 (on the right). In the first case, the width of sheath 4 between plasma 2 and reamer 1 at the bias voltage of 1.5 kV amounts to 2–4 mm and by three orders of magnitude exceeds the radius of the reamer’s cutting edge of 8 μm. Hence, the area of plasma surface, which emits ions to the cutting edge, by three orders of magnitude, exceeds the edge area. It means that ion current density on the edge is much higher than on the rest of the reamer surface. Profiles of the cutting edge in equal periods of time 5 show that intensive ion sputtering leads to a significantly greater displacement of the cutting edge surface compared with the rest of the surface. As a result, the edge radius increases and the reamer becomes blunt.

![Figure 3. Schematic of the cutting edge sputtering by ions accelerated from the plasma (on the left) and by a beam of fast neutral atoms (on the right).](image)

When the reamer immersed in the plasma is isolated from the vacuum chamber, its floating potential is by about 10 V below the plasma potential. In this case, the energy of the ions bombarding the tool is below the sputtering threshold. When it is heated to the temperature of effective thermal diffusion of nitrogen by a beam of fast atoms, the cutting edge and the rest of the tool surface are sputtered at the same rate. When removing, for successive periods of time, material layers of constant thickness 8, the radius of the cutting edge is reduced, and therefore the tool is sharpened.

In addition, the beam treatment reduced the roughness of both the front and rear surfaces of the reamer’s cutting wedges. Vickers microhardness measurements on polished cross-sections of the strengthened reamer under a load of 50 g made it possible to determine the thickness of the nitrided layer ~ 70 μm and its microhardness of 1300 HV50 at the interface with the TiN coating, which is 1.5 times higher than the microhardness 860 HV50 of the bulk.

4. Conclusions
The results achieved can be used for the development of new technology for combined processing of tools, which includes the surface nitriding and deposition on the hardened surface layer with a thickness of 50–100 μm a wear-resistant coating with a thickness of 3–5 μm. The hardened layer with high load-bearing capacity and fatigue strength reduces plastic and elastic deformations of the tool surface, thus preventing the brittle fracture of the thin hard coating.

In comparison with combined strengthening technology based on the vacuum arc the new technology based on the glow discharge with electrostatic confinement of electrons is remarkable for high homogeneity of the discharge plasma, high degree of nitrogen dissociation, which increases the
nitriding rate and absence of microparticles in the coatings, which makes it possible to keep a high surface finish class of the tool.

Due to the cutting edges sharpening while processing the tool with beams of fast neutral atoms the new technology allows strengthening of the tools for finishing without an increase in the cutting edge radius.

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