Effect Crossed Electric and Magnetic Fields of a Glow Discharge

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Abstract. A new method of processing in a glow discharge plasma in crossed electric and magnetic fields is investigated. This method makes it possible to intensify the process of diffusion saturation of the surface with nitrogen. Volt-ampere characteristics of a glow discharge in crossed electric and magnetic fields are obtained. The effect of ion nitriding in crossed electric and magnetic fields on the hardness and structural-phase composition of tool steels R6M5 and Kh12 is studied.

1. Introduction
In order to raise the endurance of tools their surface is modified by various methods including ion-plasma nitriding characterized by such features as controllability and ecological safety [1-3].

In ion nitriding the parts are heated to the nitriding temperature due to the energy of gas ions bombarding the surface at simultaneous diffusion of nitrogen ions into the treated surface. The processes in the plasma of glow discharge (dissociation, excitation, ionization, etc.) occur in what is known as the region of cathode drop [4]. One of the factors capable to activate these processes may be superposition of magnetic field on the glow discharge, which is used successfully in various gas discharge systems [5, 6].

The aim of the present work consisted in studying the effect of magnetic field on the process of ion nitriding, on the structure, on the phase composition, and on the microhardness of the surface layer of tool steels R6M5 and Kh12.

2. Materials and Research Methods
In order to study the process of ion nitriding and the characteristics of glow discharge in magnetic field we used an experimental installation created on the base of a commercial ELU-5 facility. The facility was equipped with a pulse energy source of type ApEl-M-5PDC, which allowed us to lower the heat load on the electrodes and provided effective arc extinction in a mode of anomalous glow discharge. We placed a standard magnetron (450 x 50 x 100 mm) with magnetic field induction $B = 0.03$ T in the vacuum chamber of the installation (figure 1). The parameters of the discharge were obtained from readings of the display of the switching power supply.

We subjected test pieces of tool steels R6M5 and Kh12 after hardening and tempering at 600°C to nitriding.
The working gas was a mixture of nitrogen, argon, and acetylene (75% N\textsubscript{2} + 20% Ar + 5% C\textsubscript{2}H\textsubscript{2}). The acetylene was used for deactivating the retained oxygen and preventing formation of an oxide film on the surface of the steel, which hinders formation of nitrided layer.

The pressure of the working gas was varied in the range of 5 - 200 Pa and controlled with the help of a VIT-3 vacuum gage. The working temperature (490 - 510°C) was attained in 2 - 3 min. The temperature of the test pieces was measured using a Termiks optical pyrometer.

A quantitative and qualitative analysis of the structure of the alloys was carried out on a Zeiss Axiovert metallographic microscope.

**Figure 1.** Scheme of the experiment

1 – vacuum chamber, 2 – magnet system, 3 – samples, 4 - lines of magnetic induction, 5 – high-density nitrogen plasma, 6 – arc plasma source.

**3. Results and Discussion**

Near of the cathode and on the axis of the system, the superposition of magnetic field leads to:
- Decrease in the plasma potential due to the magnetic confinement of electrons;
- Formation of a radial potential well for ions, which prevents their escape in the radial direction.

**Figure 2.** Radial distribution of magnetic field induction at a distance of 6 mm from the cathode:

1 - measured with a teslameter EM4305 (experimental);
2 - modeled by ELCUT using the finite element method (calculated).

Figure 2 shows the radial distribution of the magnetic field induction, which explains the characteristic behavior of a glow discharge in the magnetic field of Figure 3. The region of propagation of electrons...
is, on the one hand, limited by a relatively high negative potential on the substrate (400-500 V), and on the other hand by a relatively strong magnetic field. Thus, the electrons are forced to oscillate along the lines of force of the magnetic field, which ensures more efficient utilization of their energy.

Figure 4 shows the current-voltage characteristic (VAC) of the discharge obtained at different argon pressures in the chamber. With decreasing pressure, the VAC is shifted to the region of high operating stresses, due to a decrease in the concentration of charged particles. The increase in the residence time of electrons in a glow discharge plasma when the cathode is placed in a magnetic field promotes the displacement of the VAC upward (Figure 4). The VAC of a glow discharge with a magnetic field, in contrast to the conventional circuit, has a steeper rise, which indicates the efficiency of ionization processes [7].

![Figure 3. The glow of the near-cathode region of a glow discharge in a magnetic field at a pressure of 80 Pa (N₂ 75% + Ar 20% + C₂H₂ 5%). U = 420 V, I = 1.8 A.](image)

![Figure 4. VAC for a glow discharge at various pressures, pulse mode 50 kHz, 80%, mixture N₂ 75% + Ar 20% + C₂H₂ 5%:](image)

- a) - 100 Pa (1 - in a magnetic field, 2 - without a magnetic field);
- b) - 5 Pa (1 - without a magnetic field, 2 - with a magnetic field) and 15 Pa (3 - without a magnetic field, 4 - with a magnetic field)

The influence of the magnetic field on the current-voltage characteristic of a glow discharge was investigated in the pressure range 5-15 Pa, the difference in the discharge current at the same pressure in the vacuum chamber is most noticeable after applying a potential to the electrodes (400 V). A similar discharge behavior is associated with its transition from a normal glow discharge to an anomalous one.
Figure 5 - 8 shows the structure of steels R6M5 and Kh12, subjected to ion nitriding in a glow discharge and ion nitriding in a glow discharge with a magnetic field. Analysis of the structure of steels shows the presence of a dark diffusion zone, its size varies depending on the technological parameters of the glow discharge. The diffusion zone is an α-phase - nitrogen ferrite with a bcc lattice. The transition from the nitrided layer to the underlying layers is smooth, which is one of the basic requirements for the microstructure of nitrided steel.

The magnetic field during ion nitriding of R6M5 steel in a glow discharge increases the thickness of the hardened layer from 13 μm to 84 μm (6 times) at a pressure in a vacuum chamber of 44 Pa (Figure 5-6). The magnetic field in the ionizing nitriding of steel Kh12 in a glow discharge increases the thickness of the strengthened layer from 16 μm to 81 μm (5 times) at a pressure in a vacuum chamber of 44 Pa (Figure 7-8). When a magnetic field is used, favorable conditions for the sorption processes are formed, as a result, a high concentration of the diffusing element on the cathode surface is provided and a high concentration gradient is formed. Thus, the intensification of ion nitriding by a magnetic field is due to the acceleration of the diffusion of active nitrogen in the metal.

**Figure 5.** The microstructure of R6M5 steel after nitriding in a glow discharge 
T = 380 °C, t = 4 hours, P = 44 Pa, U = 600 V.

**Figure 6.** The microstructure of R6M5 steel after nitriding in a glow discharge with a magnetic field 
T = 500 °C, t = 4 hours, P = 44 Pa, U = 600 V.

**Figure 7.** The microstructure of steel Kh12 after nitriding in a glow discharge 
T = 380 °C, t = 4 hours, P = 44 Pa, U = 600 V.

**Figure 8.** The microstructure of steel Kh12 after nitriding in a glow discharge with a magnetic field 
T = 500 °C, t = 4 hours, P = 44 Pa, U = 600 V.
4. Conclusion

- VAC of a glow discharge with a magnetic field, has a steeper rise, which indicates the effectiveness of ionization processes.
- The use of a magnetic field in the nitriding of R6M5 and Kh12 steels in a glow discharge increases the thickness of the strengthened layer 5-6 times at 44 Pa, and favorable conditions for sorption processes develop on the cathode surface.

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References
[1] Goncharenko I.M. 2000 Evolution of the structure and phase composition of hardened 4140 steel in the process of plasma nitriding 5–th International Conference on Modification of Materials with Particle Beams and Plasma Flows (Tomsk: Institute of Physics and Technology TPU) pp 330–333
[2] Edenhofer B. 1976 The ion nitrating process – thermo chemical treatment of steel and cast materials Metal and Material Technological vol 8 №8 pp 421–426
[3] Koval N.N. 2000 Elion nitriding of steels 5–th International Conference on Modification of Materials with Particle Beams and Plasma Flows (Tomsk: Institute of Physics and Technology TPU) pp 327–329
[4] Brading H.J., Morton P.H, Earweaker G. 1992 Plasma–nitriding with nitrogen, hydrogen and argon gasmixtures: Structure and composition of coating Surface engineering vol 8 №3 (Birmingham: Elsevier) pp 206–211
[5] Bradley J.W., Arnell R.D., Armour D.G. 1997 Measurement and modelling of the bulk plasma in magnetron sputtering sources Surf. and Coat. Technol. vol.97, (Salford: Elsevier) pp 538–543
[6] Arnell R.D., Kelly P.J. 1999 Recent advances in magnetron sputtering Surface and Coatings Technology vol 112 (Salford: Elsevier) pp 170–176
[7] Vafin R.K., Ramazanov K.N. 2010 Surface Modification of Tool Steel during Ion Nitriding in Magnetic Field 10th International Conference on Modification of Materials with Particle Beams and Plasma Flows (Tomsk: Publishing House of the IOA SB RAS) pp 458–461