Modelling of local ion nitriding in a glow discharge with hollow cathode

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Abstract. The paper presents the results of computer calculations of glow discharge plasma parameters in a hollow cathode zone and modeling of thermal and diffusion processes at local ion nitriding with a hollow cathode. The proposed model of a glow discharge with a hollow cathode with sufficient accuracy allowed to describe the distribution of plasma parameters in a cathode void. Values of plasma parameters in a cathode void formed by a mesh screen and cathode surface were obtained via the probe method. It was found that the use of hollow cathode effect allows to increase the concentration of ions near the treated surface by 1.5 times. The suggested computer model allows to predict the distribution of the temperature field and depth of a diffusion layer at local ion nitriding with a hollow cathode for various configurations and sizes.

1. Introduction
At present the majority of machine-building enterprises apply the process of ion nitriding in a glow discharge [1,2] to harden the surface of manufactured components and goods. In most cases components used in conditions of local wear are subject to surface hardening, therefore it is often sufficient to treat their working surface, which is exposed to severe wear. It should also be noted that the process of ion nitriding is expensive, power-intensive and still time-consuming [3].

Among the variety of intensification methods it is important to focus on local ion nitriding with a hollow cathode. The use of a hollow cathode during ion nitriding in the areas of severe wear of components allows to reduce the treatment period by 2.5 times [4].

Alongside with intensification the treatment itself becomes complicated. In case of local ion nitriding with a hollow cathode the heating rate of a component under the technological screen is higher than in other areas. Hence, there is uneven distribution of temperature within the component during the whole treatment period. Besides, there is no sufficient data on physical and chemical processes that take place in a cathode void of plasma and their influence on a surface of the treated material. Therefore, better understanding of processes that occur in the surface layer of a material during its treatment will enable the increase of nitriding efficiency by specifying the best technological modes.

This paper presents the results of computer calculations of glow discharge plasma parameters in a hollow cathode zone and modeling of thermal and diffusion processes at local ion nitriding with a hollow cathode.
2. Experimental approach

The calculation model consisting of two disk electrodes placed in a cylindrical chamber was used to determine the glow discharge plasma parameters in the area of hollow cathode. At the distance of 5 mm from the cathode the disk mesh with 1 mm cell size (Fig. 1) was placed. Plasma parameters were defined according to the following equations [5]:

\[
\frac{\partial}{\partial t} (n_e) + \nabla \cdot \Gamma_e = R_e - (\mathbf{u} \cdot \nabla) n_e
\]

(1)

where \(n_e\) is the concentration of electrons, \(R_e\) is the volume sources and electron sinks, \(\Gamma_e\) is the electron flow vector, \(\mu_e\) is the electron mobility;

\[
\rho \frac{\partial}{\partial t} (w_k) + \rho (\mathbf{u} \cdot \nabla) w_k = \nabla \cdot \mathbf{j}_k + R_k
\]

(2)

where \(\mathbf{j}_k\) is the diffusion flux vector, \(R_k\) is the specified speed for heavy particles (atoms and ions), \(u\) is the average flow speed, \(\rho\) is the density of mixture and \(w_k\) is the mass content of particles in a mixture.

The theoretical model of local ion nitriding accommodates both thermal and diffusion processes. The process of diffusion is described by the Fick’s equation [6]:

\[
\frac{\partial c}{\partial \tau} + \nabla \cdot (-D \nabla c) = 0
\]

(3)

where \(D\) is the diffusion coefficient; \(c\) is the concentration of a saturant; \(\tau\) is the time of diffusion saturation; \(x\) is a coordinate.

The diffusion coefficient \(D\) is found in accordance with Einstein’s (Arrhenius’s) equation [6]:

\[
D = D_0 \exp \left( - \frac{E_a}{RT} \right)
\]

(4)

where \(D_0\) is the preexponential factor; \(R\) is an absolute gas constant; \(E_a\) is the activation energy; \(T\) is the temperature.

To describe the temperature field the model uses the following thermal conductivity equation:

\[
\rho \cdot C \frac{\partial T}{\partial \tau} + \nabla \cdot (-k \nabla T) = Q
\]

(5)

where \(\rho\) is the material density; \(C\) is the specific heat capacity; \(\tau\) is time; \(k\) is the thermal conductivity ratio; \(Q\) is a specific thermal source.

Series of experiments on an upgraded ELU-5M set-up were conducted to check the validity of local ion nitriding model. Figure 2 shows the scheme of the experiment.

**Figure 1.** Calculation model to define plasma parameters.

**Figure 2.** Scheme of the experiment using ELU-5M set-up:
1 – vacuum chamber, 2 – sample,
3 – screen to create a hollow cathode effect.
3. Results and discussion

As a result of model calculations the distribution curve of ion concentration in a cathode void was obtained. Figure 3 shows the distributions of ion concentration between a cathode and a mesh screen in axial direction of a discharge obtained through modeling and experiments.

![Graph showing concentration of ions in cathode void](image)

**Figure 3.** Concentration of ions in cathode void: solid line – calculated data, dotted line – experimental data.

Dependences are identical with slight deviation in values, which may be explained by a number of factors. It should be taken into account that during processing of probe volt-ampere characteristics it was assumed that electron energy distribution in a void is the Maxwell distribution, and heating of mixture and electrodes due to surface bombardment with charged particles was not considered during modeling.

The maximum concentration of ions was observed in the center of a void and made $3.2 \times 10^{16}$ m$^{-3}$. Hence, the application of a hollow cathode effect during ion nitriding allows to increase the concentration of ions near the treated surface by 1.5 times.

The distribution of a floating potential in a void (Fig. 4) obtained as a result of modeling also gave acceptable similarity with experimental data.

The width of potential fall area amounted to 1-1.5 mm. At the same time the width of the area on the side of a mesh is bigger, which is explained by the distortion of electric field configuration due to holes present on the screen.

As a result of calculations of a computer model the distribution of a temperature field on the surface of a gear wheel was obtained at local ion nitriding with a hollow cathode (Fig. 5) during 8 hours. At the same time the temperature of teeth surface made $\sim 550 ^\circ$C.

The maximum temperature difference between various sections of a 200 mm gear wheel nitraded with/without a hollow cathode amounts to $\sim 35 ^\circ$C (Fig. 5). Thus, the configuration and geometry of the treated component distribution impact the temperature field at local ion nitriding with a hollow cathode.

Figure 6 shows the diagrams of the treated surface in two points A and B obtained through modeling and experiments, which correspond to the maximum and minimum temperature of a surface (Fig.5).
Figure 4. Distribution of a potential in a void: solid line – calculated data, dotted line – experimental data.

The analysis of obtained dependences showed that after heating the component and beginning of an operating mode the temperature remains stable and equals \( T = 550 \) °C until the treatment is finished. This is caused by the steady-state equilibrium between thermal energy input from gas ions and its output from the surface to the external environment. The heating time necessary to heat the treated surface up to the saturation temperature made about 40 min (while the heating rate made 0.2 °C/sec).

Figure 7 shows the estimated and experimental time dependences of temperature in point A during cooling of a component upon completion of local ion nitriding with a hollow cathode.

The diagram of component cooling is of great practical importance and allows to choose the holding period for loading after completion of local ion nitriding with a hollow cathode for components of various sizes and configurations. The given dependences show that the treated surface of a component is cooled down to the temperature of 250 °C (523K) within approximately 30 min.

Figure 5. Computational distribution of temperature on gear wheel surface at local ion nitriding with a hollow cathode.

Figure 8 shows the concentration curve of a saturant along the depth of a diffusion layer for locally nitrated area with a hollow cathode that was obtained through a computational model.
Figure 6. Diagram of surface heating in points A and B during local ion nitriding with a hollow cathode: 1 – master curve, (point A); 2 – master curve, (point B); 3 – measured curve (point A); 4 – measured curve (point B).

Figure 7. Diagram of the treated component surface cooling (point A): 1 – master curve; 2 – measured curve.

The analysis of the obtained dependence shows that the depth of a hardened layer varies from 180 to 220 microns. Ion nitriding with a hollow cathode was carried out at the following modes: $T = 550^\circ C$, $P=60 \text{ Pa}$, $U=500 \text{ V}$, $t=8 \text{ h}$.

Microhardness was measured by depth of the nitread layer at the section of this sample (Fig. 9) in order to define the depth of the hardened layer.

Measurements of microhardness along the sample section showed that the depth of the hardened layer is within the range of up to 220 microns. Thus, experimental data correlate well with the calculation results.

Figure 8. Estimated concentration change of a saturant (nitrogen) along the depth of a diffusion layer of steel 38XMYUA: $T=550^\circ C$, layer of steel 38XMYUA: $T=550^\circ C$, $t=8 \text{ h}$.

Figure 9. Change of microhardness along the depth of a nitread layer of steel 38XMYUA: $T=550^\circ C$, $P=60 \text{ Pa}$, $U=500 \text{ V}$, $t=8 \text{ h}$.

4. Conclusion
The following conclusions can be drawn.
- The model of a glow discharge with a hollow cathode with sufficient accuracy describing the distribution of plasma parameters in a cathode void was established.
- The experimental values of plasma parameters in a cathode void were obtained.
The use of a hollow cathode effect in areas of intense wear of a component allows to achieve the increase in ion concentration near the treated surface by 1.5 times.

- The computer model allowing to predict the distribution of the temperature field and depth of a diffusion layer at local ion nitriding with a hollow cathode for components of various configuration and size was suggested. The computer model also allows to determine the concentration of a saturant by the depth of a diffusion layer.

- It was found that the nitried surface of 200 mm gear wheel is heated up to the temperature of diffusion saturation (550 °C) within approximately ~ 40 min, following which the surface temperature remains invariable until the treatment is completed. This is caused by the established balance between thermal energy supply from high-energy ions of a working gas and its withdrawal through radiation from a surface into the external environment. At the same time the maximum difference of temperatures between areas nitried with/without a hollow cathode makes ~ 35 °C.

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