Modification of the electrode surface in glow discharge plasma with a hollow cathode

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Abstract. The electric discharge with a hollow cathode has long attracted the attention of researchers, both by its physical properties and technological application. The paper considers the influence of the shape of the treatment surface, which takes the geometry of a hollow cathode, on the parameters of a glow discharge.

1. Introduction
An electric discharge with a hollow cathode was first described by F. Paschen in 1916 [1, 2]. Since then, it has been used in electric propulsion thrusters as an electron source, providing a current density at the electrode walls of $j_i \approx 10^5$ A/m$^2$ [3, 4], as a technological tool for modifying the cathode surface with pulsed ionic current of density up to $j_i \approx 10^4$ A/m$^2$ [5], also with a direct current of density $j_i \approx 20$ A/m$^2$ [6], which provides a flow of ions, sufficient for the processing of parts by the method of plasma diffusion. In spite of the wide range of density $j_i$, all these methods have the right to technical application. We consider the glow discharge of direct current, as well as the effect of a hollow cathode on the formation of ion flows on the modified surface of the cathode part.

2. The description of the experiment
Figure 1 shows a photograph of the structure of a cathode sheath formed around a gear wheel during its plasma nitriding in a glow discharge, such as, for example, in installations of Sulzer Metco, Switzerland, 2013. Without considering in detail the structure of the cathode sheath [6], its thickness will be assumed to be a distance $d \approx 10$ mm between the surface of the cathode and the border of the bright glow of the plasma (figure 1, b). It can be seen that at a height of $\sim 2/3 h$ and below, the cathode sheaths of adjacent teeth overlap each other, since the gap width is $z < 2d$. Here the thickness of the sheath $d$ loses its clear outlines, unlike the boundary at the top of the tooth.

Figure 2 shows two cathodes of glow discharge in argon. The material of both cathodes is the same: Al 97.4 %, Si 1.3 %, Fe 0.6 %. Its analogue is 6082 Al. The area of six imaginary planes forming around the cathode parallelepiped form (19×75×12 mm) is...
$S_{\text{Par}} = 5.11 \cdot 10^{-3}$ $m^2$. The total surface area of the cathode, i.e. ribs, hollows, end faces of the part, is $S_{\text{Grid}} = 1.39 \cdot 10^{-2}$ $m^2$. Rib thickness 0.9 mm (length 75 mm), hollow width between adjacent ribs $z = 2.2$ mm; hollow depth corresponding to the height of the rib, $h = 5$ mm (figure 3, a). The cathode sheath thickness $d \approx 6.7$ mm is clearly visible on figure 3, b.

**Figure 1.** Gear (cathode discharge) during plasma nitriding in a dc glow discharge, (a); (b) – the scheme of the cathode sheath: $d$ – the thickness of the sheath on the outer edge of the gear (at the top of the tooth); $z$ – the width of the bottom of the hollow between adjacent teeth; $h$ – hollow depth equal to the height of the tooth [7].

**Figure 2.** The cathode region of a glow discharge with a cylindrical aluminum cathode with a diameter of 6 mm, (a); discharge with a hollow cathode-spiral, (b); both discharges burn in argon at a pressure of 13.3 Pa; bright cathode spots are well distinguishable on both cathodes; the spiral form allows you to see the shape of the discharge inside the hollow cathode

**Figure 3.** Diagram of an aluminum cathode-comb of size 19 $\times$ 75 $\times$ 12 mm, (a); photograph of the cathode discharge region at an argon pressure of 13.3 Pa, (b); the thickness of the sheath surrounding the cathode is $d \approx 6.7$ mm; bright cathode spots are clearly distinguishable on the electrode surface.

The discharge voltage is 480 V, the current density relative to the $S_{\text{Grid}}$ is about $j \approx 0.1$ A/$m^2$, the argon pressure is 13.3 Pa. The picture was taken at a reduced discharge current, so that the details of the cathode contour looked distinctly, while the concentration of the surrounding plasma is relatively small.
Figure 4 shows the current-voltage characteristics of glow discharges obtained with three types of cathodes (figure 3, 4). Two gases were used – argon and oxygen – at a pressure of 13.3 and 10.3 Pa, respectively.

![Current-voltage characteristics of glow discharges](image)

**Figure 4.** Voltage-current characteristics (curves) of glow discharges in argon 1, 2, 4 and in oxygen 3, burning on an aluminum cathode of various shapes: 1 – cathode-spiral, wire diameter 4 mm, argon pressure 10.3 Pa; 2 – a cylindrical cathode with a diameter of 6 mm, argon pressure of 13.3 Pa; 3 – a cylindrical cathode with a diameter of 6 mm, an oxygen pressure of 13.3 Pa; 4 – the cathode in the form of a comb at an argon pressure of 13.3 Pa, the current density is related to the total surface area of the $S_{\text{Grid comb}}$.

In 1.2 hours of burning an oxygen discharge, the surface of an aluminum cylindrical cathode shown in figure 2, a, covered with aluminum oxide, as shown in figure 5. The cathode looks brushed surface. The average hardness of this brushed and loose surface is $HV = 29.2$ with $P = 0.025$. At the same time, the hardness of aluminum, purified from the coating, was $HV = 53.1$ with $P = 0.025$. The measurements were carried out with a DuraScan-20 G 5 hardness tester (manufacturer – Austria).

![Loose surface of the aluminum cathode](image)

**Figure 5.** Loose surface of the aluminum cylindrical cathode (figure 2, a), modified by a glow discharge plasma; the discharge burned in oxygen at a pressure of 13.3 Pa and a current density of $j \approx 12 \ A/m^2$ for 1.2 hours (curve 3 in figure 4); side length of the photograph is 100 micrometers.
3. Discussion of results

The effect of a hollow cathode is manifested, at least, by a twofold increase in current density at the cathode-plasma boundary, due only to the fact that the cathode part of the discharge – usually with a flat cathode – is localized in a hollow whose walls have a negative potential. As a result of multiple oscillations of free electrons reflected from the cathode walls, a bright plasma column with an increased degree of ionization appears on the axis of the hollow. As a result, the current increases not only in the hollow cathode, but also in the plasma of the positive discharge column. The temperature of the cathode $T = 300 \ldots 400$ K.

This effect exists as long as the distance $z$ between the adjacent walls of the cathode remains almost equal to or exceeds approximately twice the thickness of the cathode sheath $d$, figure 1, b. The geometrical dimensions of the hollow and the physical properties of the plasma in it (the electron mean free path $\lambda$ in the cathode sheath) are undoubtedly related when it comes to the formation of a hollow cathode effect.

We assume that the electron mean free path in a weakly ionized argon plasma of a glow discharge:

$$\lambda = \frac{1}{n \sigma} = \frac{kT}{p \pi D^2} \approx 2.3 \cdot 10^{-5} \frac{T}{p} \approx 2.3 \cdot 10^{-5} \frac{500}{13.3} \approx 0.0009 \text{ m} \approx 0.9 \text{ mm}. \quad (1)$$

Here, $n$ and $p$ are the concentration and pressure of argon in the discharge, $m^3$ and Pa, respectively; $T$ is the argon temperature, assumed to be approximately equal to 500 K; $D \approx 3.7 \cdot 10^{-10}$ is the diameter of the argon atom; $k = 1.38 \cdot 10^{-23}$ J/K is the Boltzmann constant.

Experience shows that in order to realize the effect of a hollow cathode in the discharge investigated, it is necessary to maintain the following ratios of the geometrical dimensions of this electrode and the free path of the electron in the plasma near the cathode. The hollow width or the distance between the walls of the cathode is $z > 2d \approx 2 \cdot 6.7 \approx 13$ mm. The ratio of the width of the cathode sheath to the electron mean free path is $f = d/\lambda \approx 6.7/0.9 \approx 7.5\ldots 10$. These ratios are characteristic of plasma processing of machine parts, for example, gear wheels.

The linear form of the voltage-current characteristic discharge with a hollow aluminum cathode $I$ (figure 4) indicates that the electrical resistance of a plasma of a similar discharge (at an argon pressure of the order of 10 Pa) is similar to active resistance and can be defined as:

$$R_{Al} = \frac{\Delta V}{\Delta j \cdot S_{Al}} \approx \frac{360 - 320}{(32 - 3) \cdot 1.37 \cdot 10^{-2}} \approx 100 \text{ Ohm}. \quad (2)$$

Here, the corresponding values of voltage $V$ and current density $j$ are taken from graph 1 on figure 4. In our experiments, a hollow cathode-spiral made of copper wire 2.5 mm in diameter, 18 turns, and an internal spiral diameter of 25 mm were also investigated. The surface area of the copper spiral is $S_{Cu} = 1.22 \cdot 10^{-2}$ m$^2$, the argon pressure is ~10 Pa. The electrical resistance of the plasma in the discharge with the copper cathode was also linear and amounted to $R_{Cu} \approx 1100$ Ohm in the region $\Delta V = 600-400$ V and $\Delta j = 23-8$ A/m$^2$ voltage-current characteristic. The significant difference in the plasma resistance of discharges with aluminum and copper hollow cathodes indicates a significant contribution of the properties of the cold surface of the cathode material ($T \approx 350$ K) to the energy characteristics of the discharge.

References

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