Investigation of parameters and uninterrupted service of a generator of gas-discharge plasma based on a nonsustained hot-cathode arc discharge in gas

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Abstract. The design of an electrode system and the characteristics of a gas-discharge plasma source (generator) based on an arc discharge in gas sustained by thermionic emission are presented. The results of an experimental investigation of the service life of a thermionic (hot) cathode of the plasma generator are reported as a function of the discharge current and voltage and the cathode filament power. It is shown that an increase in the burning voltage from 28 to 60 V considerably reduces the service life of the hot cathode, while the discharge current and the cathode filament power exert a less critical effect on its lifetime. The conditions necessary for achieving long-term service life parameters and high efficiency of plasma generation are found out.

1. Introduction

The generator of gas-discharge plasma based on non-self-sustained hot-cathode arc discharge developed in early 1990-s [1] has been until now the most acceptable facility for surface cleaning, etching, hard surfacing (nitriding), doping and plasma-assisted coating deposition due to simplicity of its design and high efficiency of plasma production [2, 3]. On the other hand, the use of a thermionic (hot) cathode in this plasma generator in addition to its high advantage of producing high-concentration plasma (~ 10^{11} cm^{-3}) at low pressures (≤ 0.1 Pa) and a potential of controlling its parameters in a wide range of operating pressures (0.1÷1 Pa) is, however, limited by its service life (lifetime). Due to high operating temperatures (≥ 2500°C) and bombardment and sputtering by plasma ions, this cathode fails (blows off) within an uncertain period of time (from a few to several tens of hours) under different operating modes, which makes the service life (lifetime) of the hot cathode in particular technological conditions indeterminable. Thus, an investigation of the dependence of the hot cathode lifetime on the plasma generator parameters and operating modes and identification of the conditions for increasing the continuous operation of the plasma generator itself (until replacement of the hot cathode) is of critical importance for achieving an improvement of vacuum-plasma technologies.

2. Gas-discharge plasma generator design and operation

A photograph and a concept scheme of the hot-cathode gas-discharge plasma generator are presented in Fig. 1 (a) and (b), respectively. The main element of the electrode system is a hybrid cathode consisting of a stainless-steel cylindrical hollow cathode *1* (Figure 1) measuring 86 mm in diameter and 380 mm in length and a thermionic cathode made of tungsten wires (filaments) immersed into it *2*. This hybrid cathode is placed into 0.02T magnetic field generated by a solenoid coil *3* and is clamped to a water-cooled flange of the cathode unit *4*, which is electrically insulated from the water-cooled housing of the plasma generator *5* via insulator *6*. The plasma generator in its housing *5*, which is under the anode potential, is placed onto the vacuum chamber, a hollow anode of the discharge *7,* in order to generate gas-discharge plasma by igniting a gas discharge in this chamber, which occurs as follows. When the thermionic cathode is hot enough and a voltage is supplied from the gas-discharge power supply, the electrons emitted from the hot cathode move between the vacuum chamber (anode) and the hybrid cathode (electrically coupled hollow and hot cathodes) along the magnetic field lines towards the anode (inner walls of the vacuum chamber). Since the working gas *8* is fed into the cathode cavity of the plasma generator, a region of elevated pressure is formed near the hot cathode. The presence of a region with increased concentration of the working-gas molecules and a flow of accelerated electrons, whose trajectories are elongated by the magnetic field, makes the ionization processes easier. The electrons, which bounce back from the potential barrier generated by the cathode cavity, oscillate in the cavity and effectively ionize the working gas molecules, causing ignition and burning of a non-self-sustained low-pressure arc discharge. The discharge persists between the cathode, made up by both the hot cathode and the hollow cathode connected to it, and the anode represented by the inner surface of the vacuum chamber. The gas-discharge plasma *9*, generated by this discharge, fills the vacuum chamber cavity and serves as a working medium for surface modification of the pieces immersed into it.

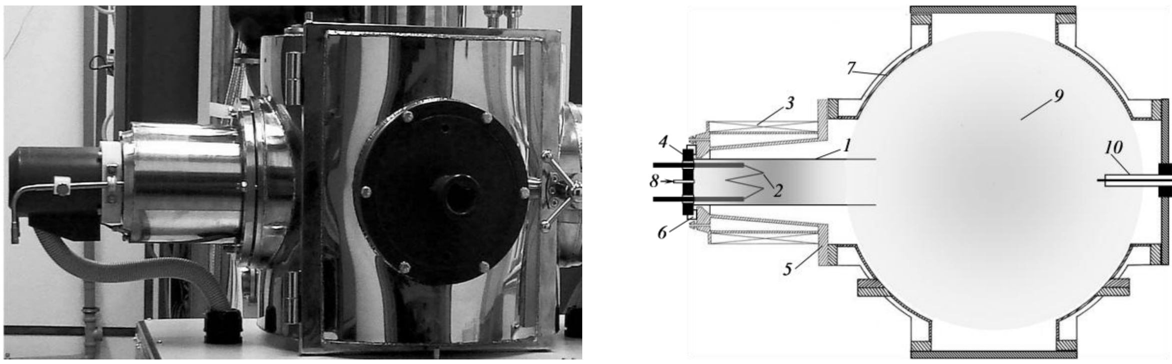

Figure 1. Photograph (a) and a concept scheme (b) of the gas-discharge plasma generator.

The characteristics of this plasma generator and the lifetime of its cathode were investigated during its operation with a cylindrical vacuum chamber 600 mm in diameter and 500 mm in height. The thermionic cathode used in all experiments was represented by a single VA-tungsten wire 0.8 mm in diameter and the length of the operating section 150 mm.

3. Dependence of the lifetime of a hot cathode on the plasma generator parameters

A characteristic feature and advantage of the hot-cathode gas-discharge plasma generator is the fact that its discharge current and hence the concentration of the resulting plasma can be adjusted by varying both the filament power and emissivity of the cathode (filament) and the value of the discharge electrical supply voltage. This is supported by the dependence of the plasma generator discharge current in argon at a pressure of 0.3 Pa on the filament power for different discharge voltage values - Figure 2.

A high discharge current can be achieved by increasing the number of filaments of the cathode, e.g., up to six. In the latter case, given their total filament power P_f=1920 W (320 W per every filament) at the discharge burning voltage U_d=60 V and pressure 0.3 Pa, the discharge current in argon would increase up to I_d=140 A. The flow of this current in the vacuum chamber generated plasma with a concentration n_i=2.4•10^{11} cm^{-3}, which was measured from the saturation ion current of the probe *10* (Figure 1).

The two available mechanisms of controlling the plasma generator discharge current also offer a possibility of sustaining the required current for a wide range of operating pressures. For instance, for the pressure varying from 0.67 to 0.05 Pa, by controlling the consumption of argon from 0.3 to 0.02 cm^3/s discharge current of I_d=22 A could be maintained within the entire pressure range due to an increase in the discharge pressure from 28 to 115 V at the same value of the filament power P_f=320 W. The same discharge current value I_d=22 A was maintained unchanged in the entire working gas pressure interval due to an increase in the filament power from 300 to 490 W for the same discharge voltage U_d=72 V.

The experiment on investigating the influence of the discharge voltage U_d on the hot-cathode lifetime τ was performed for the case of discharge burning in argon at the argon pressure p_{Ar}=0.3 Pa at the voltage values 28, 60 and 85 V and the average filament power P_f for these voltage values within the experimental time 620, 400 and 330 W, respectively, ensured the same discharge current I_d=30 A for every filament voltage used. The dependence under study is plotted in Figure 3.

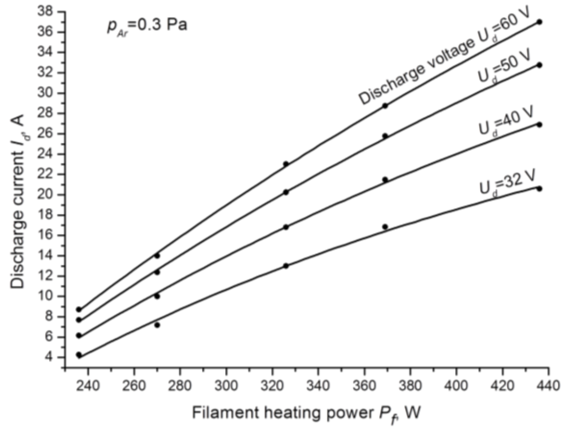

Figure 2. Plasma-generator discharge current versus the hot-cathode filament power for different values of discharge voltage.

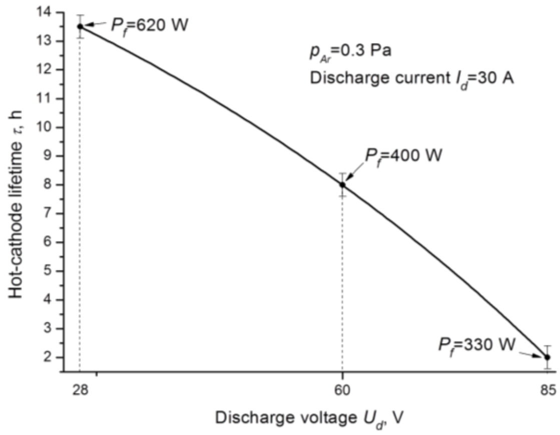

Figure 3. Hot-cathode lifetime as a function of the plasma generator discharge burning voltage.

It is evident from the plot that it is the discharge burning voltage rather than the hot-cathode filament power, which extremely shortens the hot-cathode lifetime. For instance, for a relatively low average filament power P_f=330 W, ruling out excessive overheating and accelerated evaporation of the filament material and a comparatively high discharge burning voltage U_d=85 V, the filament lifetime τ for the discharge current I_d=30 A was found to be 2 hours only. For the same discharge current, the filament lifetime of this plasma generator hot cathode operated in a low-burning-voltage mode (28 V) was found to be 13.5 hours, despite the fact that the average filament power for that mode was quite high P_f=620 W. Thus, it becomes evident that it is the wear of the filament by ion bombardment controlled by the burning voltage rather that the filament wear due to its overheating, which critically affects the cathode lifetime, shortening its service life and that of the plasma generator on the whole. For the discharge burning voltage U_d=60 V and the average (for the mode in question) filament power P_f=400 W and the same discharge current as in the above-mentioned examples (I_d=30 A), the lifetime τ of the hot-cathode filament was found to be 8 hours.

Relying on the results obtained in this experiment, we can formulate a guideline of how to extend the lifetime of tungsten wires in the filament-type hot cathodes operated in gas-discharge plasma generators – in order to do so we have to maintain their discharge burning voltage as low as possible. On the other hand, there is an assumption that a decrease in the discharge burning voltage of the plasma generator would “shorten” the propagation path of the plasma generated in the vacuum chamber, the chamber would not be completely filled with the plasma, and its concentration inside the vacuum chamber far from the generator would be low. This assumption relies on the fact that a decrease in the discharge burning voltage controlling the energy of primary electrons would shorten the path length of the latter in the space of the vacuum chamber due to a faster energy loss in their collisions with plasma particles. In view of this circumstance, the plasma produced by the plasma generator at low burning voltages would exert a significantly lower influence on the substrates located comparatively far from the plasma generator. In order to obtain a quantitative assessment of the effect of decreased plasma concentration far from the generator due to a decrease in the discharge burning voltage, we measured the plasma density at the distance l=330 mm from the outlet of the hollow cathode of the plasma generator using a probe *10* (Figure. 1). The resulting data for the same argon pressure as in the previous experiment are presented in Figure 4.

An analysis of the plot (Figure 4) of the saturation ion current density of the probe far from the plasma for the burning voltages (28, 60 and 85 V) used in the generator in the course of the lifetime tests demonstrated the following:

- the differences in the ion current picked off by the probe and hence the work piece being processed at a comparatively large distance from the plasma generator (l=330 mm) as a function of the discharge burning voltage are negligibly small;
- for the discharge current used in the life-time testing experiments equal to I_d=30 A (dotted line in Figure 4), the difference in the ion current densities obtained for the most differing burning voltages – 85 and 28 V – is as small as 0.0465 mA/cm^2 or ~11.5 % of the maximum ion current density, 0.408 mA/cm^2, which was obtained under these conditions at the burning voltage value 85 V.

Given the fact that the losses in the ion current density for thee burning voltage decreasing from 85 to 28 V at the same discharge current are negligible (~11.5 %), we can conclude that there is no need to considerably increase the discharge burning voltage, which substantially reduces the lifetime of the thermionic cathode of the plasma generator during technological plasma modification of product properties. It should also be noted that considering the burning-voltage data obtained as a result of lifetime tests – Figure 3, by operating the plasma generator at lower burning voltages we could considerably increase the lifetime of its hot cathode, e.g., by a factor of 6.75 in reducing the voltage from 85 to 28 V. On the other hand, a decrease in the ion current density on the work piece being modified, which is associated with the decreasing discharge burning voltage, could be compensated for by a small in value increase in the discharge current due to a higher filament power of the hot cathode of the generator. Specifically, Figure 4 implies that in order to make up for the ion-current loss resulting from the burning voltage decreasing from 85 to 28 V, we have to increase the plasma generator discharge current from 30 to only 33.5 A.

A possible application of the reserve in the discharge current made available by increasing the filament power of the hot cathode, rather than by increasing the filament voltage, without markedly decreasing the cathode lifetime could be determined via investigating the effects of the discharge current on the lifetime of the hot cathode.

Figure 5 depicts the lifetime values obtained as a result of the above investigations for the same hot-cathode filament at the discharge current values I_d equal to 10, 20 and 30 A and the respective filament power values P_f equal to 240, 300 and 400 W for every lifetime test, which ensure the same burning voltage U_d=60 V under all operating conditions under study.

It is evident from Figure 5 that the lifetime of hot cathode decreases nearly linearly with an increase in the discharge current: for the discharge current I_d=10 A it is τ=20 hours, for I_d=20 A – τ=13.4 hours, and for I_d=30 A – τ=8 hours. A threefold increase in the discharge current from 10 to 30 A is observed to result in a factor of 2.5 decrease (from 20 to 8 hours) in the lifetime of the plasma-generator hot cathode. In contrast to this observation, a threefold increase in the discharge burning voltage from 28 to 85 V achieved in the cathode filament lifetime tests using the plasma generator (Figure 3) resulted in a 6.75-fold decrease in the hot-cathode lifetime.

By comparing the cumulative results of all lifetime tests – plots in Figures 3 and 5, we can roughly (towards the lower bound) estimate that that lifetime τ of the generator cathode for the discharge current I_d=10 A at the burning voltage U_d=28 V would have a quite acceptable value for technological applications – no shorter than 33.75 hours. The lifetime τ of the generator hot cathode for the discharge current I_d=20 A and the burning voltage as low as U_d=28 V is also likely to be technologically acceptable – no shorter than 22.6 hours.

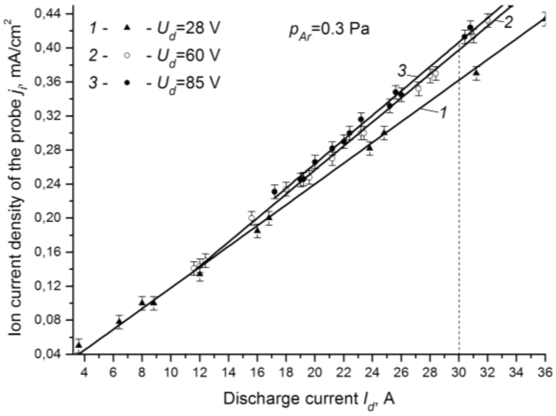

Figure 4. Behavior of the saturation ion current density of the probe far from the plasma generator for the discharge burning voltages 28, 60 and 85 V.

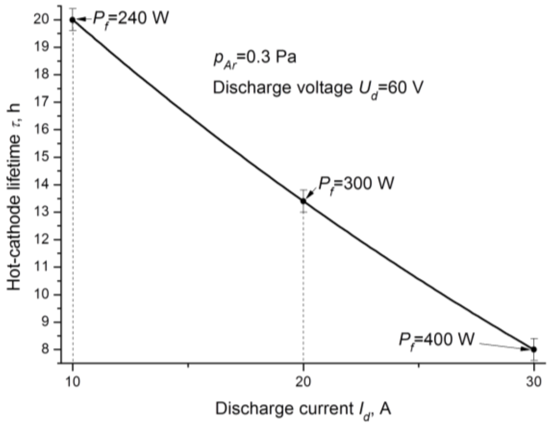

Figure 5. Dependence of the hot-cathode lifetime on the plasma generator discharge current.

4. Conclusion

The investigations of operation modes of a gas-discharge plasma generator relying on a non-self-sustained arc discharge, using a hot cathode made of a tungsten wire measuring 0.8 mm in diameter and 150 mm in the working section, have demonstrated that the lifetime of this cathode and the uninterrupted service of the plasma generator itself could be quite acceptable (more than 20 hours) for technological applications under the following conditions. The plasma generator has to be operated at the hot-cathode filament power providing low pressure of discharge burning (not higher than 28 V). The discharge current has to be not higher than 20 A; with a discharge current of 10 A ensuring 33 hours of an uninterrupted service of the hot cathode.

In order to achieve plasma of elevated concentration in the vacuum chamber space, which is dictated by the requirements of certain technological processes, an increase in the discharge current without any excessive load on the cathode filament reducing its lifetime could be achieved via using several single-type filaments.

Acknowledgement
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