Arc discharges operation in "elion" mode

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Abstract. This paper presents the results of a study of an electron-ion-plasma alitization system using two arc plasma generators: a gas plasma generator based on a non-self-sustained arc discharge with a thermionic cathode "PINK" and a gas-metal plasma generator based on an arc discharge with a cathode spot. The system for discharges supplying and biasing of the samples assumes two sub-modes of operation: the ion cleaning sub-mode (ion sub-mode) and the sub-mode of samples electron heating (electron sub-mode), thus realizing the "elion" mode of the system operation. During the experiments, both the dependences of the average values of currents and voltages of discharges burning and probe measurements of the instantaneous plasma parameters values in both system operating sub-modes were investigated. It is shown, that the electron sub-mode of system operation is characterized by an increased burning voltage, which is caused by the formation of a positive anode drop of more than 10 V in the plasmas. Such a potential distribution in the discharges ensures effective heating of the samples by the discharges plasmas electron component.

1. Introduction

The service life of various metal products subject to thermal chemical influences, as well as friction and wear of product, is very often determined by its surface condition and quality. Accordingly, in order to increase the service life of a metal product and its quality, it is often sufficient to change the characteristics of its surface, such as hardness, wear and corrosion resistance, heat resistance, etc. The chemical and phase compositions of the near-surface layers, in this case, can be changed. One of the most common approaches to changing of the surface elemental composition is the using of the diffusion method of surface saturation. This approach involves heating the workpieces to temperatures characteristic of the effective diffusion of the added element 400-1200°C and makes it possible to obtain modified layers hundreds of microns thick, which is a prerequisite for most applications. Methods of steels surface alloying with metal atoms are of particular interest for the surface alloys obtaining, since such surface alloys obtaining makes it possible to increase the hardness, wear and corrosion resistance, heat resistance, etc., as well as create favorable conditions for further (or joint) saturation of the surface layer with non-metallic atoms (nitrogen, carbon, boron etc.) [1, 2]. In this case, one of the most common metals, the atoms of which are saturated by is aluminum, and the process of the surface diffusion saturation with aluminum atoms is called alitization and is widespread in industry [3, 4]. When using ion-plasma methods of diffusion surface treatment, an important technological issue is to provide heating of the workpieces. Previously [5, 6] preliminary experiments have shown the efficiency of using of the discharge plasma electron component for this. This article is
devoted to the study of the characteristics of the discharges used in the process of electron-ion-plasma alitization and the study of the parameters of the plasma generated by them.

2. Experimental
The experiments were carried out on the "TRIO" technological setup with the vacuum chamber dimensions 600×600×600 mm, which allows the simultaneous using of plasma-physical devices for the generation of gas ("PINK" [7]) and metal (arc evaporator) plasmas in elion (electron-ion [5, 6]) operating mode (figure 1). The chamber was evacuated by a turbomolecular pump with a capacity of 500 l/s. The elion system operation mode implies periodic switching of the plasma-physical devices discharges burning (using a special switching unit) from the main anode – chamber with a surface area of \( \approx 20 \times 10^3 \text{ cm}^2 \) to a stainless steel sample holder with a surface area of \( \approx 200 \text{ cm}^2 \). This switching provides effective heating of the processed samples by the plasma electron component without ion etching of their surface. Ion cleaning of the samples surface, in this case, is carried out in the intervals between their electron heating. The elion operation mode reduces the efficiency of samples ion etching during the processing, which reduces the roughness of the modified surfaces. The process of electron-ion-plasma surface alitization is carried out in an atmosphere of an inert gas argon. The ion and electron system operation sub-modes are switched by a switching unit with a frequency of 1-100 Hz with a controlled duty cycle (fraction) of the electron operation sub-mode in the range of 15-80%. The electric power supply of the discharges was carried out by industrial welding rectifiers of the VD 201 brand to power the non-self-sustaining arc discharge with a thermionic cathode and VD 306 to power the arc discharge with a cathode spot. The tungsten filament of the plasma generator PINK was powered by a filament transformer with a frequency of 50 Hz powered by a regulated autotransformer.

The study of the average values of the discharges burning currents and voltages was carried out using digital multimeters (VICTOR VC980A +), the effective value of the filament current of the "PINK" plasma generator was measured with the help of digital current clamps M226 DIGITAL CLAMP METER. Hall sensors were used to measure the discharge currents instantaneous values.

![Figure 1. Experimental scheme.](image-url)

Probe studies of plasmas were carried out using a system for fixing instantaneous values of the probe I–V characteristic of original design by the HCEI SB RAS. A single cylindrical Langmuir probe with dimensions \( \Phi \ 0.5 \times 6 \text{ mm} \) was located opposite the center of the sample holder, at a distance of
20 mm from its front surface and was oriented parallel to it. The discharges anode served as the base electrode. The investigations were carried out in the elion system operation mode with measurements synchronized with the filament heating voltage of the "PINK" plasma generator near its zero value. At the same time, on the sub-modes switching unit, the switching frequency was set equal to half of the filament heating voltage frequency (25 Hz) and the duty cycle (the fraction of the electron heating sub-mode time) ≈ 50%. Thus, the instantaneous values of the probe I–V characteristic were measured alternately in the ion and electron sub-modes after a period. The total number of measurement points of the probe I–V characteristic is 2000, 1000 for each operating sub-mode.

3. Results and discussions
A change in argon pressure affects the parameters of discharge burning in both ion (figure 2 (a)) and electron (figure 2 (b)) operating sub-modes.

![Figure 2](image_url)

**Figure 2.** Dependences of the average discharges currents of the "PINK" plasma generator (curves 1) and the arc evaporator (curves 3) and the discharge burning voltages of the "PINK" plasma generator (curves 2) and the arc evaporator (curves 4) on the argon pressure at the filament heating current of the plasma generator "PINK" – 115 A: a) in the ion system operation sub-mode; b) in the electron system operation sub-mode.

The upper limit of the operating pressure range is determined by the characteristics of the system vacuum pumping, and the lower limit is due to the arc evaporator operation stability in electron sub-mode with the used power source. The dependence of the parameters of the non-self-sustained arc discharge with a thermionic cathode is typical for devices of this type in both operation sub-modes (ion and electron) and is caused by a change in the mean free path of electrons emitted from the thermionic cathode of the “PINK” plasma generator. An increase in the working gas pressure leads to an increase in the efficiency of the primary electrons energy utilizing for gas ionization and, accordingly, to an increase in the plasma concentration in the region of the discharge plasma anode column. It can be seen that in the studied pressure range in the ion system operation sub-mode, a change in the working gas pressure has little effect on the characteristics of an arc discharge with a cathode spot, which burns mainly in the cathode material vapor. An insignificant increase in its current with a corresponding decrease in the burning voltage can be explained by an increase in the plasma potential value, which is equal to the blocking potential of the negative anode drop near the walls of the hollow anode – chamber. In the electron system operation sub-mode, the dependence of both discharges parameters on pressure is more significant and this is probably due to the peculiarities of the discharges current closure to the small area anode. This feature is that when plasma system operates with a small area anode, the electron saturation current density in a mixed gas-metal plasma is not enough to close the total discharges current, and the plasma is rearranged in such a way as to form a positive anode drop, providing an increase in the plasma electrons collection area, their further
acceleration and additional ionization of the working gas near the anode. Such a rearrangement of the potential distribution in the discharge gap requires an increase in the voltage between the cathodes and the anode, which, under conditions of a fixed output power of the discharge power supplies, leads to a decrease in their output current. In this case, since an important role in the discharge currents closure to the small area anode is played by the working gas ionization processes near the anode, as the electron mean free path increases and, accordingly, the gas ionization efficiency decreases (i.e., the working pressure decreases), the positive anode drop value should grow. This leads to an additional increase in the burning voltage of an arc discharge with a cathode spot and, accordingly, to a decrease in its current with a decrease in the working pressure.

Changing of the filament current of the "PINK" plasma generator in the ion operation sub-mode mainly affects the parameters of a gas non-self-sustaining arc discharge (figure 3 (a)). An increase in the filament current leads to an increase in the temperature of the thermionic cathode, which, in turn, leads to an increase in the current of electrons emitted from it. This leads to an increase in the total current of the non-self-sustained arc discharge and, under conditions of constant power source power, to a decrease in the burning voltage of this discharge. An insignificant increase in the current of an arc discharge with a cathode spot and, accordingly, a decrease in its burning voltage, with an increasing of the filament current of the “PINK” plasma generator, may be associated with an increase in the plasma potential caused by an increase in the number of thermionic electrons, emitted into plasma, participating in the current closure to the hollow anode – chamber and, accordingly, an increase in the plasma concentration and electron temperature in the mixed gas-metal plasma inside the hollow anode, which ensures the closure of the current of both discharges to the anode. In the electron system operation sub-mode, with a change in the value of the filament current (figure 3 (b)), the parameters of the non-self-sustained arc discharge behave similarly to the ion operation sub-mode, taking into account the peculiarities of the appearance and change in the magnitude of the positive anode drop. The increase in the burning voltage of an arc discharge with a cathode spot, with a corresponding decrease in its current, as the filament current increases, is probably explained by the necessity to close the ever increasing total electron current from the mixed gas-metal plasma of discharges to the anode. To ensure such a current closure, it is necessary to increase the value of the positive anode drop, which leads to an increase in the discharge burning voltage.

![Figure 3](image_url)

**Figure 3.** Dependences of the average currents values of the “PINK” plasma generator (curves 1) and the arc evaporator (curves 3) and the burning voltages of the “PINK” plasma generator (curves 2) and the arc evaporator (curves 4) on the heating current of the thermionic tungsten cathode at an argon pressure of 0.2 Pa: a) in the ion system operation sub-mode; b) in the electron system operation sub-mode.

The I–V characteristic of a non-self-sustained arc discharge with a thermionic cathode grows both in the ion and electron system operation sub-modes (figure 4 (a) and (b), respectively), and the current
of the arc discharge with a cathode spot and its burning voltage with a change in the non-self-sustained arc discharge current in the given ranges practically do not change. It can be seen that in both the ion and the electron system operation sub-modes, the current of the arc discharge with a cathode spot and its burning voltage practically do not change with a change in the current of a non-self-sustaining arc discharge in the given ranges.

![Figure 4](image1)

**Figure 4.** Dependences of the average values of the burning voltages of the “PINK” plasma generator (curves 1) and the arc evaporator (curves 2) and the arc evaporator discharge current (curves 3) on the discharge current of the “PINK” plasma generator at a heating current of 115 A and an argon pressure of 0.2 Pa: a) in the ion system operation sub-mode; b) in the electron system operation sub-mode.

The I–V characteristic of an arc discharge with a cathode spot in both system operating sub-modes turns out to be practically flat (figure 5 (a, b)), the current of an arc discharge with a thermionic cathode, as the arc discharge with a cathode spot grows, slightly decreases. This is probably due to a decrease in the potential (the magnitude of the negative anode drop) of the mixed gas-metal plasma with an increase in its concentration in the ion sub-mode of the system operation and, accordingly, an increase in the positive anode drop value with an increase in the total discharge current in the electron sub-mode of the system operation.

![Figure 5](image2)

**Figure 5.** Dependences of the average values of the discharges burning voltages of the arc evaporator (curves 1) and the "PINK" plasma generator (curves 2) and the discharge current of the "PINK" plasma generator (curves 3) on the discharge current of the arc evaporator at a PINK cathode heating current of 115 A and an argon pressure of 0.2 Pa: a) in the ion system operation sub-mode; b) in the electron system operation sub-mode.
The probe studies of the gas-metal plasma parameters, carried out under conditions of joint operation of plasophysical devices in the electron sub-mode of the system operation, confirmed the assumptions about the formation of a positive anode fall near the small area anode. Thus, at an argon pressure of 0.2 Pa, instantaneous values of the current of discharge with a thermionic cathode $I_{\text{peak}} = 44$ A, a current of discharge with a cathode spot $I_{\text{arc}} = 43$ A and their burning voltages, respectively, $U_{\text{peak}} = 71$ V and $U_{\text{arc}} = 44$ V, the plasma potential relative to the anode $U_{\text{pl}} \approx -12$ V, plasma concentration $n \approx 3.4 \times 10^{17}$ m$^{-3}$ and electron temperature $T_e \approx 3$ eV. Thus, at the studied pressure, when the free path of electrons exceeds 20 mm (the distance from the probe to the sample holder – anode in the electron operation sub-mode), the energy with which the electrons come to the anode and heat it is at least 12 eV. The total electron current $I_e = I_{\text{peak}} + I_{\text{arc}} = 87$ A, which provides a heating power of the holder in electron operating sub-mode of more than 1 kW. When the system is switched to the ion operation sub-mode, the discharge currents and their burning voltages change and at the time of measuring of the probe current and potential were: $I_{\text{peak}} = 44$ A, $I_{\text{arc}} = 43$ A, $U_{\text{peak}} = 57$ V, $U_{\text{arc}} = 24$ V. In this case, the plasma potential becomes positive with respect to the anode $U_{\text{pl}} \approx +1.9$ V, that is, a negative anode drop is formed, the plasma concentration becomes $n \approx 1.4 \times 10^{17}$ m$^{-3}$ at an electron temperature $T_e \approx 1.8$ eV. The decrease in the plasma concentration, despite the increase in discharge currents, is probably associated with a change in the plasma distribution in the vacuum chamber. In the electron system operation sub-mode, the plasma is concentrated near the small area anode. In addition, ionization of the gas by electrons accelerated in the positive anode fall additionally locally increases the concentration of charge carriers. In the ion system operation sub-mode, the plasma is more evenly distributed along the large-area hollow anode, which is facilitated by the negative anodic drop, which reflects part of the plasma electrons. An almost twofold decrease in the electron temperature in the ion system operation sub-mode is explained by the fact that in this case electrons during a direct flight from the plasma sources do not go to the sample holder under negative bias, but must bend around it to close to the anode – inner chamber walls. In addition, the negative anode drop reflects part of the low-energy electrons from the plasma, which contributes to an increase in the “tail” of their energy distribution, while in the electron operation sub-mode, all electrons from the plasma that reach its boundary with a uncompensated space charge layer of positive anode drop, are accelerated to the anode, which significantly reduces the path traversed by electrons and reduces the efficiency of their thermalization.

4. Conclusion
The studies have shown that the elion mode, realized during the joint operation of the electric power supply system of a non-self-sustaining arc discharge with a thermionic cathode and an arc discharge with a cathode spot, as well as substrate biasing, is characterized by two different sets of discharge characteristics for the electron and the ion system operation sub-modes. The difference between these sets of characteristics is due to the different anode area in each of the operation sub-modes and, accordingly, different potential distributions in the discharge gap. Studies of the parameters of the gas-metal plasma of discharges during their simultaneous burning, carried out near the sample holder, showed, that in the electron system operation sub-mode, the potential distribution in the plasma is rearranged in such a way as to provide a positive anode drop of more than 10 V. This ensures the acceleration of plasma electrons to the anode and, accordingly, its heating with a power of more than 1 kW. The plasma concentration and the temperature of electrons near the small area anode in the electron operation sub-mode also increase, which can be explained by the redistribution of plasma density in the working chamber volume, as well as by local additional gas ionization in the anodic drop and a decrease in the efficiency of electron thermalization, respectively.

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