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PLASMADYNAMIC STRUCTURE OF ELECTRODE TORCHES AND ITS INFLUENCE ON THE DYNAMICS OF DEVELOPMENT OF PULSED SURFACE DISCHARGE

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An experimental study has been made of the plasmadynamic structure of electrode plasma torches and its influence on the dynamics of development of a high-current pulsed surface discharge with separated torches at atmospheric and low pressures. Much attention has been given to the behavior of the discharge with change in experimental conditions. Consideration has also been given to the jet properties in the outflow of a luminous substance, which manifests itself in the structural properties of photoscans. The mechanism of spatial "spreading" of the channel of the surface discharge with separated torches has been proposed.

In a plane pulsed surface discharge with separated (split) torches, the main plasma-generating substance is the electrode and dielectric material. The plasma-generating substance intensely disintegrates under the action of Joule heat or radiant energy and dense erosion-plasma fluxes are formed due to the pressure increase near the working surface. Under these experimental conditions, the moving erosion plasma flows into the air atmosphere at a normal or low pressure. Stable plasma flows are formed, and the process of interaction of the dense fluxes with the ambient medium is of definite interest. Knowledge of the features of flow of the erosion plasma fluxes extends and deepens the notions of plasma dynamics under specific conditions and makes their practical implementation easier.

Equipment and Methods of Investigation. Experimental investigations of a pulsed surface discharge have been carried out with a plane configuration of the discharge and a parallel arrangement of the electrodes. Such a geometry of it enables us to study physical processes simultaneously in the electrode and wall regions under the conditions of separation and free outflow of electrode plasma torches, which eliminates the contribution of the torch component to the erosion of the electrodes and the collision of supersonic electrode torches [1–4].

The discharge was initiated by application of a high-voltage signal from the control desk of an ultrahigh-speed photorecorder (UPhR) to the igniting electrode located in the discharge gap on the substrate surface approximately at the center of the distance between the electrodes. All the investigations were carried out in the unit-pulse regime and the initial conditions were reproduced after each discharge. The horizontal position of the substrate surface was controlled with a light beam.

The electrophysical characteristics and substantiation of selection of the material of a plasma-generating dielectric have been presented in [5].

The dynamics of development of the discharge was studied with high-speed UPhR cameras and a driven photorecorder (photochronograph) (DPhR). The UPhR camera was used as a photorecorder giving a free-running continuous scan of the process under study and as a time lens giving a sequence of photographs of the process studied. The longitudinal and transverse (relative to the electrodes) images of surface plasma formations were projected on the slit of the devices. In investigating the kinetics of radiation of plasma bunches (plasmoids), the input lens of the UPhR camera was replaced by an achromatic condenser for better spatial resolution, which enabled us to obtain a magnified (×3.5) image on the photoscans.

Experimental Results and Their Analysis. The plasmadynamic structure of electrode torches of a plane pulsed surface discharge with a parallel arrangement of the electrodes and an end working surface was investigated in the present work for different interelectrode spacings and as a function of the substrate material and the ambient pressure.

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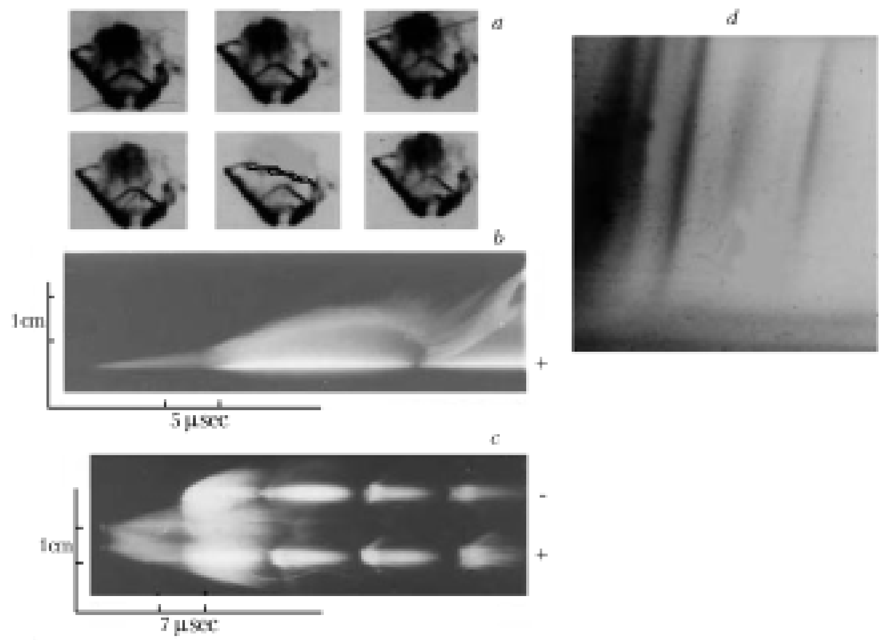

Fig. 1. Photoscans (fragments) of glow of a pulsed surface discharge (atmospheric pressure, fluoroplastic substrate, copper electrodes): a) cinema frames (the diameter of the electrodes is 0.8 cm; the ends are cut at an angle of ~45^{o}; l ~ 0.6 cm; U = 6 kV); b) anode torch (l = 2 cm and U = 6 kV) with the arrangement of the UPhR-camera slit along the torch; c) surface plasma formations, when a DPhR is used (the slit is perpendicular to the electrodes); d) wall plasma formations (C = 150 μF, l = 2 cm, and U = 4 kV).

Electrode torches are formed simultaneously for relatively small interelectrode spacings (~0.6 cm) at atmospheric and low pressures. The outflow of the electrode torches is perpendicular to the electrode plane; however, they repel from each other due to the electromagnetic interaction in the zone of plasma–metal contact (Fig. 1a). This interaction becomes weaker with increase in the interelectrode spacing.

A pronounced normal glow-intensity jump having, as has been established earlier, a gasdynamic origin [1–4] is recorded in the electrode torches at atmospheric pressure at a certain distance from the electrode surface. Furthermore, a pronounced skew shock is also recorded on the lateral surface of the torches. These shocks form a "barrel-shaped" configuration.

For small interelectrode spacings, due to the broadening of the electrode torches, their external zones interact at a certain distance from the surface, which results in the total shock after which the torches exist separately. In this case, we observe a clearly defined discharge channel occurring between the electrodes and "running" along the torches. A simultaneous existence of two channels is recorded in some photographs (Fig. 1a), just as in the case of open discharge with separated torches [1, 2].

As the interelectrode spacing increases, the presence of the substrate exerts an increasingly more substantial influence on the dynamics of development of a discharge and the processes of plasma generation.

For relatively large interelectrode spacings (~2 cm) and at atmospheric pressure, the anode torch is formed from the instant of occurrence of intense prebreakdown glow. Evaluation of the gaskinetic pressure for the prebreakdown stage (N_e = 10^{18} cm^{-3}, T_e = $2{\cdot}10^4$ K, fluoroplastic substrate, copper electrodes) gives a value of the order of $5{\cdot}10^5$ Pa. By the end of the prebreakdown stage, a smeared shock is observed on the photoscans at a distance of the order of 0.27 cm from the anode surface (Fig. 1b). This distance corresponds to a gasdynamic pressure of the order of $4{\cdot}10^5$ Pa, i.e., the calculated and measured values of the pressure are in satisfactory agreement. It should be noted that the velocity of outflow of plasma formations, measured from the slit (free-running) photoscans, is $(2–5){\cdot}10^3$ m/sec by the end of the prebreakdown stage.

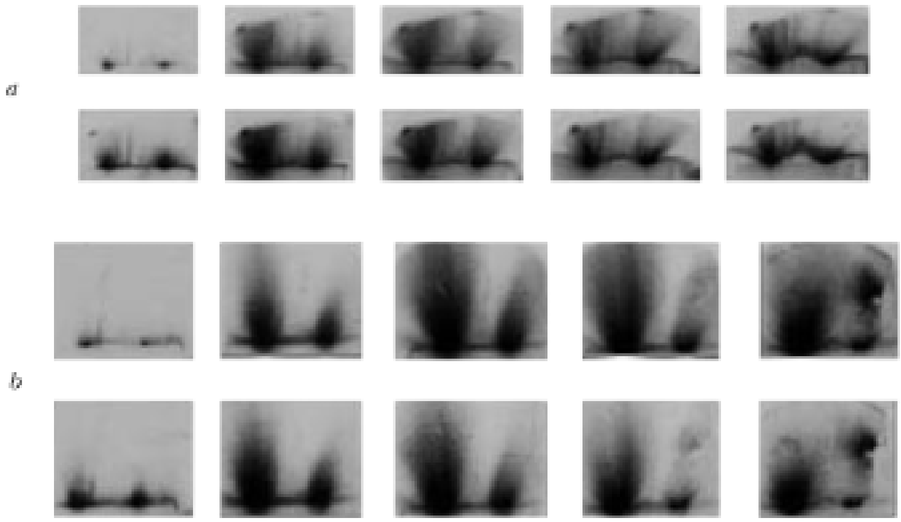

Fig. 2. Cinema frames of glow of the surface discharge at a low pressure (aluminum electrodes, l = 2 cm, U = 6 kV, filming frequency $2.5 \cdot 10^5$ frames/sec): a) fluoroplastic substrate; b) substrate of the crystalline salt NaCl.

From the free-running photoscans (Fig. 1b), it is seen that the shock formed in the anode torch at the instant of breakdown of the interelectrode spacing occurs at a certain distance from the electrode surface, namely, in the region of a smeared shock formed at the prebreakdown stage. Thus, a region of high conductivity is formed above the anode already at the prebreakdown stage.

From the instant of breakdown of the interelectrode spacing, a cathode torch is formed. Electrode torches have a complex gasdynamic structure (Fig. 1b and c). In the first half-period, it is more pronounced for the cathode torch than for the anode one; in the second half-period, the situation is the reverse. In the case of copper electrodes (C = 24 μF, U = 6 kV, diameter 0.2 cm, interelectrode spacing 2 cm) and a fluoroplastic substrate, the maximum distance of the shock from the anode surface is ~1.08 cm in the first half-period and that from the cathode surface is 0.95 cm, which corresponds to a gasdynamic pressure on the section of $70 \cdot 10^5$ and $54 \cdot 10^5$ Pa respectively.

A clearly defined channel is observed only at the instant of partial breakdown. By the end of the prebreakdown stage and after the breakdown of the interelectrode spacing, we have a spatial "spreading" of the current channel and not its clearly defined structure. This is demonstrated by both frame and free-running photoscans (Fig. 1b and c).

Based on the investigations carried out, the spatial "spreading" of the surface discharge can be explained as follows. As has been noted, weak glow in the prebreakdown stage is volumetric in character. From the instant of occurrence of a partial discharge between the cathode and the uncompensated negative space discharge due to the advance of its head part toward the cathode, the channel of this discharge begins to expand in the volume prepared by the shock action of the electrons emitted by the cathode upon application of a high-voltage initiating pulse to the igniting electrode. At the same time, a smeared shock characterized by the high (as compared to the ambient medium) conductivity zone is formed in the anode torch; the smeared shock also begins to entrain the partial-discharge channel. After the breakdown of the interelectrode spacings, ("barrel-shaped") shocks formed in the electrode torches continue to entrain the surface-discharge channel along the torches. In the case of small spacings it "runs" along the torches. However, with increase in the spacing the influence of the substrate is more substantial. It is common knowledge [6, 7] that surface discharge at atmospheric pressure is characterized by the "spreading" of the channel above the surface. Joint action of two mechanisms — "spreading" of the channel above the surface and entrainment by the torches — leads to a spatial "spreading" of the channel of a pulsed surface discharge with a parallel arrangement of the electrodes.

To detect high-brightness zones we obtained frontal frame and free-running photoscans of discharge glow (Fig. 1c). In the frontal frame photoscans, we clearly see equally intense rings corresponding to the tangent to a shock. In the frontal free-running photoscans (the slit of the device is parallel to the substrate surface and follows the line connecting the electrodes), the bifurcation of the glow of plasma formations is pronounced. Both central high-brightness bands are nearly parallel to each other during the entire period of discharge. They refer to the near-electrode

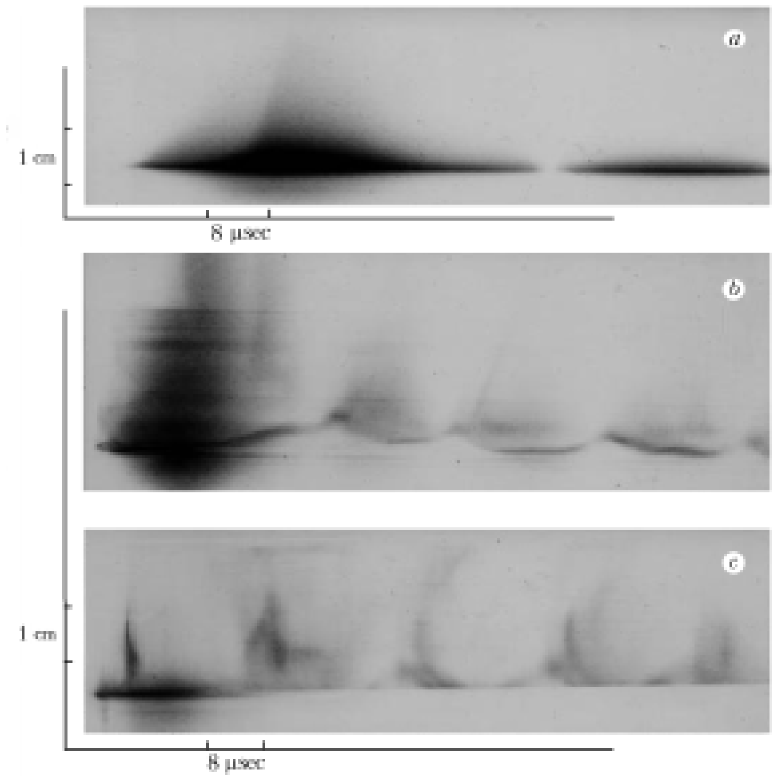

Fig. 3. Typical photoscans of glow of the surface discharge at a low pressure (aluminum electrodes, l = 2 cm, and U = 6 kV): a) anode torch (fluoroplastic substrate); b and c) wall plasma formations (fluoroplastic and NaCl substrates respectively).

plasma formations, i.e., to the region of plasma–metal contact. The other two bands are much less intense; their mutual position changes in accordance with the oscillations of the discharge current. They refer to skew shocks.

As is seen from the frame and slit photoscans of surface-discharge glow, no intense prebreakdown glow is detected at a low pressure, unlike the case of atmospheric pressure (Figs. 2 and 3). From the instant of breakdown of the interelectrode spacing, the discharge channel is localized at the very substrate surface. As the discharge develops further, we detect a difference in the formation of electrode torches and the behavior of the discharge channel with different substrates used. In the case of a fluoroplastic substrate, the electrode torches formed expand more than when crystalline salt is used. The discharge channel begins to be entrained by the torches after ~10 μsec in this case. Due to this it rises above the surface and bends (Fig. 2a and b). In the first half-period, the maximum distance from the surface attains ~0.5 cm. When crystalline salt is used as the substrate, the electrode torches expand to a lesser extent. It is as though the discharge channel "spreads" above the substrate surface; this spreading is of a more pronounced surface character than that of an atmospheric-pressure discharge.

The interaction of the electrode torches becomes weaker with increase in the spacing between the electrodes. The channel (fluoroplastic substrate) is more clearly recorded at the instant of maximum expansion of the torches.

For small spacings between the electrodes and fairly high energies (atmospheric pressure), we observe jet outflow of the erosion plasma, which is more pronounced at a certain distance from the substrate surface (Fig. 1d). Small jets are sometimes observed for relatively small interelectrode spacings.

In the case of low pressure, jet flow is detected for the crystalline-salt substrate. This flow is pronounced at the substrate surface (about 10^6 jets per sec) and is observed in the anode torch (Fig. 3a). The velocity of outflow of the anode jets is $4 \cdot 10^4$ m/sec ($1.5 \cdot 10^4$ m/sec at the substrate surface).

When heat fluxes to the electrode are relatively large, the consumption by evaporation in individual microspots, according to the literature data (for example, [8]), no longer has time to absorb the entire energy supplied to the electrodes, with the result that the surface begins to overheat and a thermal explosion may occur. This process proceeds discretely at certain intervals and is accompanied by the ejection of individual plasma bunches observed in the free-running photoscans in the form of alternating light and dark bands. However, in the present work, the discrete character of arrival of the electrode substance is not recorded for relatively large interelectrode spacings (atmospheric pressure). Apparently, the reason is that the discharge current in this case traverses mainly the external ring zone of the electrodes, and it is as though individual microspots form a single ring spot whose lifetime is of the order of the duration of a half-period of the discharge current. Such a current distribution is a consequence of the complex gasdynamic structure of the electrode torches and of the influence of the substrate. At a low pressure, the peculiarity of the influence of the crystalline-salt substrate leads to the fact that jet flow is recorded in the anode torch and is not recorded in the cathode torch. The mechanism of this phenomenon has not been established.

The central part of the electrodes is heated by heat conduction, and the instant may occur when a fairly high pressure in the central zone is realized. In this case we have an explosive process of evaporation that results in the dropwise removal of the central part of the electrode substance. Tracks of the dropwise phase are observed in the discharge. Nearly spherical particles of the electrode substance are detected on the substrate surface after the discharge.

Jet outflow of the substance of the substrate material is fixed for relatively small interelectrode spacings and high energies. The discharge channel is recorded in this case. For relatively large interelectrode spacings, due to the complex gasdynamic structure of the electrode torches and the influence of the substrate, we have a spatial "spreading" of the discharge channel; jet outflow is not recorded. At a low pressure, the peculiarity of the influence of the crystalline-salt substrate is that the discharge channel is not entrained by the electrode torches and jet outflow of the substrate substance is recorded in the photoscans. In the case of the fluoroplastic substrate, the discharge channel is entrained by the torches and a uniform arrival of the substrate substance is observed.

CONCLUSIONS

1. The dependence of the duration of glow of the first half-period on the substrate material at a low pressure has been found: it is 30 μsec in the case of crystalline salt and ~25 μsec in the case of fluoroplastic; the duration of the remaining half-periods is nearly the same and is equal to 14 μsec.

2. The influence of the substrate material, the gasdynamic structure of the electrode torches, and the ambient pressure on the dynamics of development of a plane surface discharge with a parallel arrangement of the electrodes has been investigated. It has been shown that when the interelectrode spacings are small (~0.6 cm), the discharge channel "runs" along the electrode torches due to their complex gasdynamic structure. When the spacings are relatively large (~2 cm), we have a spatial "spreading" of the discharge channel, which is a result of the simultaneous action of two mechanisms: "spreading" above the substrate surface and motion along the torches. At a low pressure, in the case of a fluoroplastic substrate the discharge channel is entrained by the torches, rises above the surface, and bends; in the case of a crystalline-salt substrate the channel is not entrained by the torches as a result of the influence of the substrate material and the discharge is of a more pronounced surface character.

3. The influence of the channel of the surface discharge on the character of arrival of the substrate and electrode substance: for small (~0.6 cm) interelectrode spacings and fairly high energies of the discharge we observe the discharge channel and outflow of the substance is of a jet character; for relatively large (~2 cm) spacings, no jet properties in the outflow were observed, which is due to the spatial "spreading" of the discharge channel. When the pressure is low, outflow of the substance is of a jet character in the case of the crystalline-salt substrate; in the case of fluoroplastic, the discharge channel rises above the surface and no jet properties are observed in the outflow.

NOTATION

C, capacity of the capacitor, μF; l, length, cm; I, current, kA; N_e, concentration of electrons, cm^{-3}; T, temperature, K; t, time, sec; U, voltage, kV.

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