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Mass and charge composition of polytetrafluoroethylene insulator erosion outputs in vacuum arc discharge plasma

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The elemental and charge composition of the plasma of a pulsed vacuum arc discharge with a molybdenium cathode initiated by fluoroplastic surface flashover has been studied. It has been shown that the content of atomic carbon and fluorine ions in the total particle flow is comparable to the fraction of molybdenum ions. The results indicate that the source of fluorine and carbon was not only the fluoroplastic insulator, but also cathode surface onto which fluorocarbon components were deposited in the intervals between pulses vacuum arc current.

Keywords: cathode spots, insulator surface flashover, vacuum arc, polytetrafluoroethylene erosion, fluorine.

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Relentless focus on study of plasma interaction with surface of polytetrafluorethylene (PTFE) is due this material application in vacuum-arc plasma generation systems and plasma sources of electrons to initiate discharges with cathode spot [1], as well as in pulse plasma engines of small-sized space vehicles [2–4]. In last case the PTFE insulator is intentionally subjected to electrothermal erosion, ant its products are plasma-forming material. As a result of this plasma electrodynamic acceleration small space vehicle receives a thrust pulse [5]. In case of the plasma engine the weight of erodible per time of discharge pulse is important, so the major part of the known studies related to the erosion speed increasing or optimization. Study of mass-charged composition of discharge plasma ions from the erodible surface of PTFE, determining the output and operation parameters of these vacuum-arc devices did not receive sufficient attention.

Method of time-of-flight mass-charge spectrometry in combination with the ion source based on the vacuum-arc discharge is technically simple and effective for quick analysis of elemental and charge composition of plasma of vacuum discharges, including operating under conditions of and at specific parameters rather close to those under which the plasma engines of small-sized space vehicles operate.

In studies the test rig of the ion source based on vacuum arc Mevva-5.RU [6] was used, the test rig was equipped with time-of-flight mass spectrometer [7]. The diagram of the experiment is shown in Fig. 1, *a*.

For the experiment the cathode unit of the ion source was modified. A PTFE tube was used instead of a ceramic insulator, over its surface the breakdown is performed to initiate the vacuum arc discharge. Inside this part a cylindrical cathode with diameter of 6.5 mm, made of molybdenum, was installed with minimum clearances. On PTFE insulator a ring electrode made of stainless steel was installed, it is anode of the initiating discharge (Fig. 1, *b*). Between these electrodes the voltage pulses were applied with idle amplitude 10 kV. After breakdown at end face of the PTFE tube the discharge current reached amplitude of 40 A for some microseconds, an then exponentially decrease for about 50 μs. When the erosion plasma enters the basic gap, to which permanent voltage of 500 V was applied from the charged artificial forming line, the vacuum-arc discharge was initiated between the cathode and the arc anode, which walls formed a cylindrical cavity. Amplitude of the current pulses of the vacuum arc was 300 A at width 250 μs with repetition rate 0.5 s^{-1}. The limit residual pressure in the vacuum system was ensured by turbomolecular pump, and was $2 \cdot 10^4$ Pa.

Three-electrode ion-optical system was used to form an ion beam at accelerating voltage of 30 kV. The time division of accelerated ions to groups in accordance with ratio of mass to charge (M_i/Q_i) is provided during their passage via the drift space after the pulse voltage 6 kV with duration of 100 ns is applied to the system of ring deflecting electrode forming a gate of the time-of-flight spectrometer.

As the deflecting pulse width is much less the time-of-flight of ions τ of the spectrometer base ($L = 1$ m), during the ions movement from the gate to the Faraday cylinder of the spectrometer the ion beam components with different values of M_i/Q are divided to groups during movement. At that in the current measuring circuit of the Faraday cylinder the peaks are observed, they correspond to time when the collector work surface is reached by ion groups with definite value of M_i/Q. The time-of-flight τ, determined as time interval between deflecting pulse application to the spectrometer gate and signal in circuit of Faraday cylinder, relates to M_i/Q by ratio

$$M_i/Q = 2\tau^2 eU/L, \qquad (1)$$

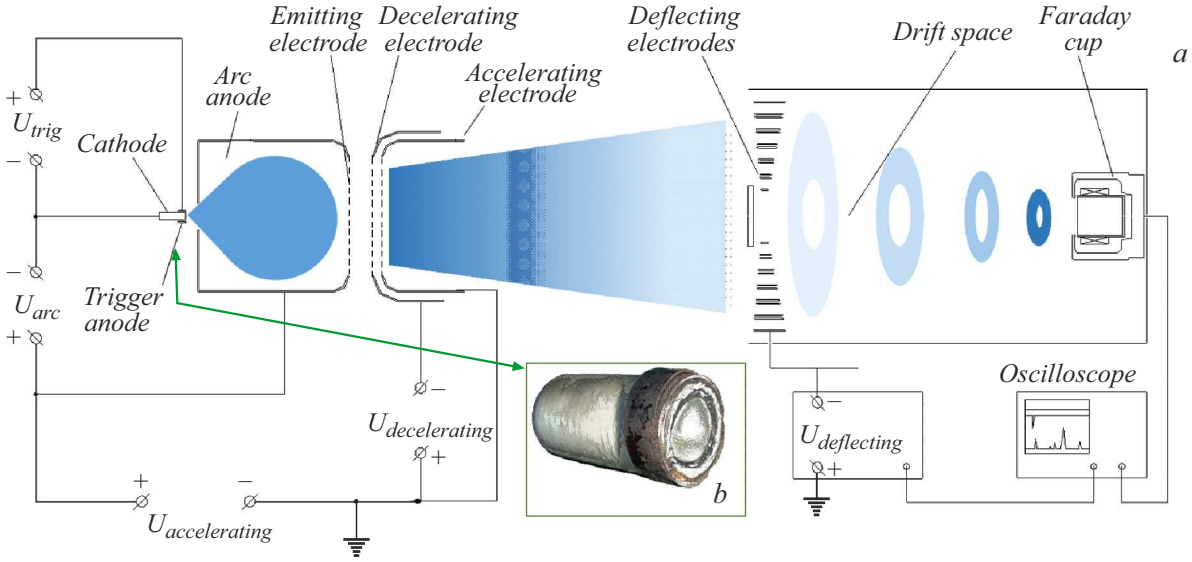

Figure 1. Experiment diagram. *a* — Ion source and time-of-flight spectrometer; *b* — photo of cathode unit in assy.

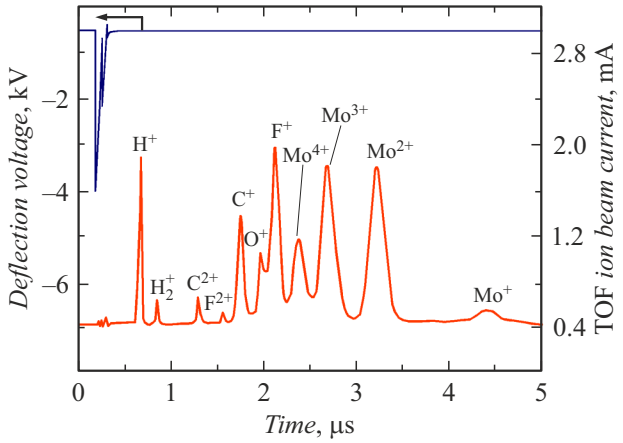

Figure 2. Time-of-flight mass-charge spectrum of ion beam after 50 μs from initiation of the vacuum arc discharge. Top beam — deflecting voltage pulse, bottom beam — signal of Faraday cylinder.

where M_i — ion mass, Q — charge state (degree of ionization) of ion, τ — time-of-flight, U — accelerating voltage, e — electron charge, L — distance from spectrometer gate to collector based on Faraday cylinder.

It is obvious that ratio of ion mass to its charge state is proportional to square of its time-of-flight, so, after determination of time-of-flight for all peaks in spectrum, knowing in advance the correspondence of even one peak to particles with known mass and degree of ionization it is possible to identify all types of particles participating in the beam. For example, it is known that in vacuum arc plasma with molybdenum ion the outermost right peak in the spectrum having the maximum time-of-flight of molybdenum corresponds to single charged ion of molybdenum Mo^+. Hence, for any two peaks in spectrum the ratio is valid

$$(M_{\mathrm{Mo}}/Q_1)/(M_m/Q_x) = \tau_{\mathrm{Mo}}^2/\tau_x^2, \qquad (2)$$

where M_{Mo} — atomic mass of molybdenum, $Q_1 = 1$ — charge state of single charged ion, M_m — desired mass of unknown ion, Q_x — desired charge state of unknown ion, τ_{Mo} — time-of-flight of single charged ion of molybdenum, τ_x — time-of-flight of unknown ion with mass M_m and charge state Q_x.

After simple transformations we get

$$M_m/Q_x = M_{\mathrm{Mo}}(\tau_x^2/\tau_{\mathrm{Mo}}^2). \qquad (3)$$

Using ratios (3) the particles present in time-of-flight spectrum, shown in Fig. 2 were identified.

together with ions of the cathode material — one, two, tree and four times ionized atoms of molybdenum (Mo^+, Mo^{2+}, Mo^{3+}, Mo^{4+}) — in plasma single and double charged ions of fluorine (F^+, F^{2+}), carbon (C^+, C^{2+}), as well as oxygen O^+ and hydrogen (H_2^+, H^+) were registered. The total content of ions of fluorine and carbon in full flow of ionized particles at the given time moment was about 25 and 16% respectively. Fig. 3 shows the content of atomic particles of elements in the ion beam depending on time on background of oscillograms of current pulses of vacuum arc discharge and current density in center of the ion beam obtained under averaging over 16 pulses standardized to maximum value 300 A and 2 mA/cm^2 respectively. At quasi-stationary section of current pulse of arc discharge for time period of 200 μs the content of fluorine ions decreased monotonically from 25 to 18%. Content of carbon ions at the quasi-stationary section of current of basic discharge was at level of 16%.

Presence of oxygen ions O^+ is due to decomposition of molybdenum oxides which presented on the work

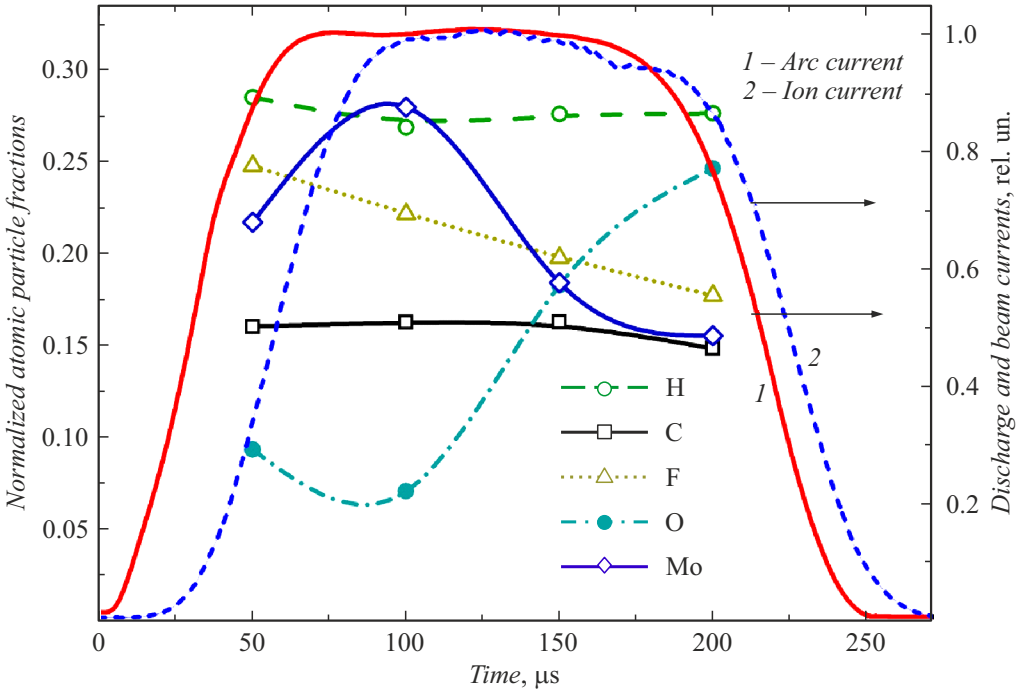

Figure 3. Amount of particles in ion beam vs. time, and oscillograms of current pulses of vacuum arc (*1*) and ion current (*2*).

surface of the cathode as result of its long-term storage in air and presence in residual atmosphere of vacuum chamber in intervals between pulses of discharge current, and further dissociation of molecular oxygen and ionization of atomic oxygen. Dynamics of ions content of oxygen and molybdenum in the beam, and, hence, in plasma of cathode spots of vacuum arc discharge can be explained as follows. At beginning of discharge current pulse the cathode spots of the first kind [8] operate at sections of the cathode surface where the clean metal borders to regions covered with nonconducting films mainly comprising molybdenum oxides. Over time these oxide films destructed, and area of clean metal surface increased. As a result the decrease in content of oxygen particles, and increase in content of molybdenum ions in time interval of 50 to 80 μs were observed. At the same time, as a result of heat diffusion from cathode craters the cathode material was heated, including temperature increasing of non-eroded areas coated with molybdenum oxides, which could lead to increase in their electrical conductivity. Hence, the cathode spots of the vacuum arc discharge can operate on their surface as on clear metal. As a result of plasma action the molybdenum oxides decomposition occurred with further ionization of the component atoms. Due to stoichiometric composition of molybdenum oxide molecules, where larger number of oxygen atoms is per one atom of molybdenum, it is possible to explain the decrease in content of molybdenum ions upon simultaneous increase in content of oxygen ions.

Processes responsible for PTFE erosion products presence in vacuum arc plasma are as follows. During the discharge initiating pulse the work end of PTFE insert was subjected to action of charged particles, predominantly electrons which starting from stage of initial avalanches formation destructed the molecular bonds on the insulator surface. Carbon atoms and fluorine molecules F_2 enter the discharge gap where their ionization occurred. As it was shown in paper [5] the fluorine yield started in 1–1.5 μs after breakdown initiation over the dielectric surface, and continued after decrease in discharge current for 10–15 μs from heated sections of PTFE surface. So, in the discharge system the source of fluorine F_2 was implemented. Under conditions of present paper at initiating discharge current decreasing the vacuum arc current mainly in discharge gap between the cathode and hollow anode already reached its amplitude values. Hence, the cathode spots continue to operate near the PTFE insulator resulting in its erosion and continuation of particles of carbon and fluorine ingress into the discharge gap. Apparently, in the arc discharge plasma the dissociation of molecules F_2 occurred due to rather low bond energy — 1.6 eV. As a result of high oxidation capacity of atomic fluorine the clean molybdenum and its oxides can enter in the reaction with it and form fluorides and oxyfluorides on the cathode surface. When these compounds enter the operation zone of the cathode spots, they can participate in decomposition reactions and further ionization of their component atoms.

The following conclusions may be drawn from the results of present paper.

Plasma of vacuum arc initiated by the breakdown over PTFE surface contains a significant content of fluorine ions, which gradually decreases during time of discharge current pulse from about 30 to 15% in total flow of particles.

Source of fluorine ions is not only surface of PTFE insulator between the cathode and discharge initiating anode, but also surface of vacuum arc cathode, which can contain fluorine-containing compounds formed as a result of interaction of ions and atoms of fluorine with atoms of the cathode material and its oxides.

The obtained results can be useful for researches and technical specialists involved in use of plasma engines based on PTFE ablation. In present paper we pay attention to the experiment fact of fluorine emission, as its presence can be unnecessary during implementation of definite technologies. And vice-versa, generation of ions of atomic fluorine can be unexpected advantage of such discharge system in studies and technological processes, where fluorine ions will be required.

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Conflict of interest

The authors declare that they have no conflict of interest.

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