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The effect of pulsed electron beam and ion treatments of stainless steel electrodes on the electrical strength of vacuum gaps

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It is known that pulsed reflow of electrodes surface with low-energy high-current electron beam to a depth of several microns significantly increases the level of electrical strength of vacuum gaps. The paper presents experimental data indicating the possibility of additional 30% electrical strengthening of vacuum gaps based on steel (12Kh18N10T, Russian analog of AISI 304) electrodes by preliminary irradiating the electrodes (before their surface reflow) with ion flow extracted by a series of short negative bias voltage pulses from argon plasma with density $\sim 10^{19}\,\mathrm{m}^{-3}$.

Keywords: electrical strength of vacuum gap, low-energy high-current electron beam, pulsed ion flow.

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The initiation of electrical breakdown of vacuum gaps (VGs) is commonly associated with geometric or chemical inhomogeneities on the surface of electrodes with a high emission activity: microprotrusions, pores, micro- and nanoparticles, and dielectric or semiconductor films and inclusions [1–3]. The removal of these breakdown initiators by pulsed reflow of the electrode surface with a microsecond wide-aperture low-energy high-current electron beam (LEHCEB) to a depth of several micrometers helps achieve a several-fold increase in pulsed electrical strength of VGs before the first breakdown relative to the strength level of a similar VG with mechanically or electrochemically polished electrodes that were subjected to surface finishing by various traditional methods [2,3]. The possibility of additional electrical strengthening of VGs with steel (12Kh18N10T) electrodes by immersing each electrode in argon plasma with a particle density of $\sim 10^{19}\,\mathrm{m}^{-3}$ prior to LEHCEB treatment and applying a series of short (~ 100 ns) negative voltage pulses with an amplitude above 10 kV, which induce a pulsed ion flux (PIF) from plasma to the surface, was demonstrated in [4]. However, this effect turned out to be statistically unstable (due likely to the use of insufficiently tough treatment regimes).

In the present study, we investigate the VG breakdown statistics after complex PIF + LEHCEB treatment of steel electrodes at a PIF current amplitude of 70 A, which was achieved using the equipment available and is more than 3 times higher than the corresponding value in [4]. Just as in [4], we used electrodes with a „replaceable surface“ in the form of a 0.2-mm-thick foil made of 12Kh18N10T stainless steel (Fig. 1, right panel). Steel disks 30 mm in diameter and 12 mm in thickness rounded along the perimeter of the base with a radius of 6 mm served as the shaping base of these electrodes.

Standard LEHCEB treatment of electrodes of the control batch (24 pcs) was carried out using a „RITM-M“ electron gun with a plasma-filled diode [3] with multi-point explosive-emission electron emitter *1* and processed target electrode *4* (Fig. 1, *a*) being the Penning cell cathodes. The argon pressure in the gun case was $4 \cdot 10^{-4}$ Torr. The distance between the cell cathodes was 20 cm, and the diameter of ring anode *2* was 8 cm. The diameter of the gun case tube was 20 cm. In the treatment cycle, 20 LEHCEB *6* pulses at an accelerating voltage amplitude of 30 kV (deep reflow and surface cleaning mode) were followed by ten pulses at an amplitude of 20 kV (surface polishing mode). The corresponding values of the pulse energy density were estimated at 7 and 4 J/cm^2.

Plasma of the Penning discharge cell of the same „RITM-M“ setup was used for preliminary PIF treatment of electrodes of the experimental batch (24 pcs; see Fig. 1, *b*). Electrode *4* subjected to ion treatment was positioned on insulator *8* behind the plane of diaphragm *7*, which had an aperture 45 mm in diameter, at a distance of 12 mm.

To establish a short-pulse mode of ion treatment, one needs to ensure that the rise time of a negative target bias pulse is shorter than (or at least commensurate with) the time of flight of an ion through the Child–Langmuir equilibrium layer, which is on the order of several tens of nanoseconds. With rapid expulsion of low-inertia electrons deeper into plasma, a layer with a high density of uncompensated ions, which get accelerated toward the cathode by the electric field, is formed. Thus, prior to the formation of an equilibrium ion layer with a characteristic ion transport mode limited by emission from plasma, the target surface is bombarded by a dense pulsed ion flux (Fig. 1, *b*) with its intensity determined both by the dynamics of ion acceleration in the layer and by the kinetics of expansion of the layer itself. A negative-polarity voltage

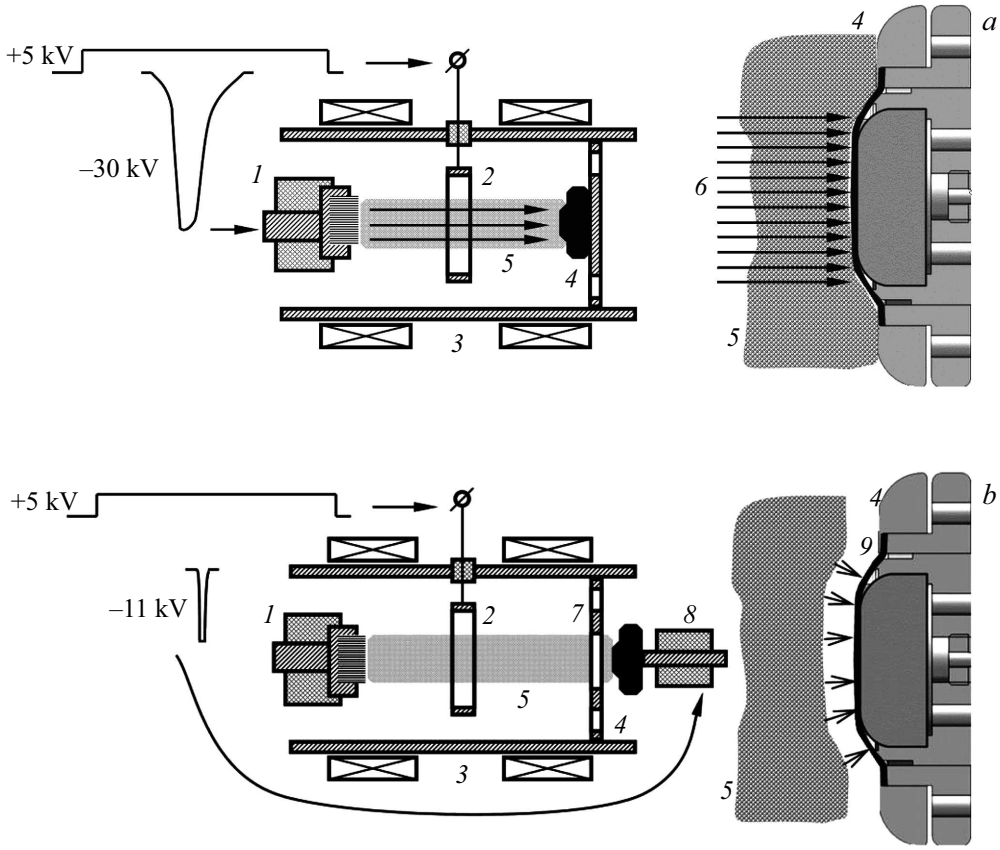

Figure 1. Diagram of electrode treatment. *a* — Low-energy high-current electron beam treatment; *b* — pulsed ion flux treatment. *1* — Explosive emission cathode, *2* — anode, *3* — solenoids of the guiding magnetic field, *4* — target (processed electrode), *5* — plasma, *6* — electron beam, *7* — diaphragm, *8* — target insulator, and *9* — forming ion layer.

pulse with an amplitude of 11 kV, a duration of 100 ns, and a rise time of 20 ns was produced in this experiment by a Vvedenskii cable generator (its design features were discussed in [5]) and fed to processed electrode *4* at moment in time synchronized with the current pulse of the Penning cell. Figure 2, *b* presents the oscilloscope patterns of current calculated from the difference between an incident wave and the one reflected from the electrode at different current values in the Penning cell (Fig. 2, *a*). Both waves were recorded in the same oscilloscope pattern at a matched 50 Ω load (the time shift is specified by the time of propagation of the reflected wave through all sections of the coaxial line). The current amplitudes correspond to ion current density bursts estimated theoretically at $\sim 10^5$ A/m^2 (with the treatment area taken into account) within a hydrodynamic model in the approximation of a step voltage pulse with a linear front [6].

Each electrode of the experimental batch was processed with 100 pulses of ion current with an amplitude of 70 A, which corresponded to the maximum attainable current in the cell of 150 A. Subsequent LEHCEB treatment of the experimental batch of electrodes after rearrangement of „RITM-M“ equipment in accordance with the diagram presented in Fig. 1, *a* was performed in the same regimes as the treatment of the control batch (see above).

The „Proboi“ test stand characterized in [4] was used to examine the pulsed electrical strength of VGs. Single-mode rectangular voltage pulses with a duration of 100 ns, amplitude $U = 200$ kV, and a rise time of 20 ns were applied to them. The electric field strength in the VG was increased by narrowing gap d between the electrodes with a step of 50 μm. Five voltage pulses were applied at each step. This procedure was repeated until a breakdown occurred. The electrical strength of the VG was determined as $E_{br} = U/d_{br}$, where $d = d_{br}$ is the measured final interelectrode distance.

In addition to the main batches, comparatively small VG batches with electrodes made of the same 12Kh18N10T steel, M1 copper, and VT1-00 titanium and subjected to various kinds of complex treatment were tested.

Figure 3 presents the results of the main experiment in the form of superimposed histograms of distribution of the VG electrical strength (determined at the first breakdown) in the control and experimental batches. It follows from the obtained data that statistically stable electrical strengthening of VGs is achieved after preliminary PIF treatment of steel electrodes at an ion current level of 70 A and subsequent

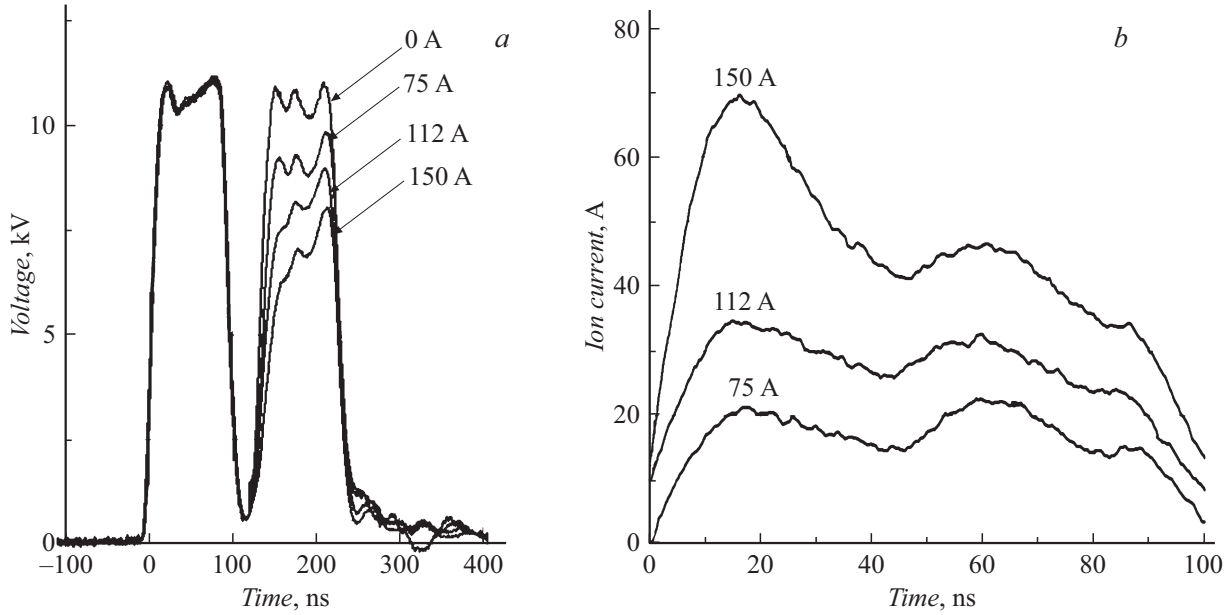

Figure 2. *a* — Dependence of the shape of voltage pulses at the cable generator load (averaged over ten consecutive oscilloscope records) on the discharge current in the Penning cell, which is indicated next to the curves; *b* — the corresponding calculated oscilloscope patterns of current in the circuit of the processed electrode.

LEHCEB treatment. An increase in the average value of electrical strength of VGs from 0.98 to 1.28 MV/cm (approximately by 30%) and a statistical spread typical of such VG tests were noted in this experiment.

The following findings were made in addition to the principal one. Complex treatment of steel electrodes in the reverse order (LEHCEB + PIF) and three-stage treatment (LEHCEB + PIF + LEHCEB), where a PIF is not the first influencing factor, do not shift the histogram of the pulsed electrical strength of VGs relative to the histogram of the control batch. In the case of copper electrodes, the addition of PIF treatment to LEHCEB treatment (with these procedures performed in arbitrary order) also exerts no influence on the pulsed electrical strength of VGs, which is 0.95 MV/cm on the average. In contrast, the introduction of PIF treatmentt before or after LEHCEB treatment induces a more than twofold reduction in the average pulsed electrical strength of titanium electrodes relative to the initial value of 1.5 MV/cm.

The electrophysical regimes of PIF treatment used in the present study are close to those of the so-called low-energy high-intensity plasma-immersion ion (in most cases, nitrogen) implantation that is used for mechanical hardening of metal surfaces. Such regimes are characterized by the emergence of significant thermomechanical stresses in metals, which lead to the formation of a defect structure at depths on the order of tens of micrometers [7,8]. In the present case, PIF treatment was found to trigger the formation of microcracks on the surface of titanium and the removal of impurity inclusions from the surface of stainless steel (without the formation of microcracks) [4]. This is the probable reason why a PIF does, as was noted above, affect different electrode materials in different ways.

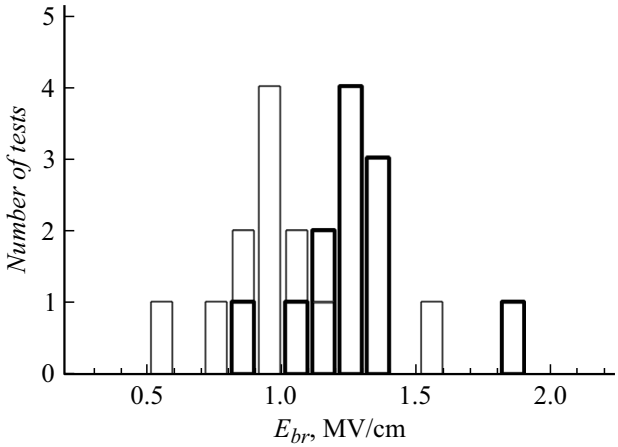

Figure 3. Comparison of histograms of distribution of the pulsed electrical strength of control (thin lines) and experimental (bold lines) vacuum gaps.

The very fact of a significant increase in the pulsed electrical strength of VGs after complex PIF + LEHCEB treatment of steel electrodes indicates that conventional LEHCEB treatment does not ensure their complete cleaning from trace contaminants that may initiate a breakdown. The probable reason behind its inability to remove these contaminants lies in the fact that steels contain impurity inclusions with their sizes exceeding the reflow depth ($\sim 5\,\mu$m) and oxides with a high melting point. The data presented in Fig. 3 suggest that further refinement

of the methods for preliminary cleaning of the surface of stainless steel electrodes prior to LEHCEB treatment should allow one to reach a pulsed electrical strength of VGs of 1.8−2 MV/cm. The relevance of PIF treatment in this context stems from the possibility of combining it with LEHCEB treatment in a single setup within one pumping cycle.

Much attention is paid in literature to the issue of sudden breakdown of vacuum devices after their long-term operation under elevated temperatures (in particular, breakdown between an iron-nickel screen and an anode in compact X-ray tubes) [9]. This breakdown is preceded by the growth of „whiskers“ and „creeping“ of inclusions beyond the initial cathode surface. Preliminary cleaning of electrode equipment by means of PIF treatment performed before sealing off the device (especially in combination with subsequent LEHCEB treatment) may prove to be very promising in terms of extending the warranty period of operation of such devices.

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Conflict of interest

The authors declare that they have no conflict of interest.

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